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An experimental study on the effects of the sample size and geometry on the liquefaction behaviour of sands

Une étude expérimentale sur les effets de la taille et de la geométrie de l'échantillon sur le comportement à la liquéfaction des sables

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ABSTRACT: The effects of liquefaction are one of the most serious natural hazards observed for a long time around the world, namely in seismically active regions and saturated sandy deposits. As a result, the study of the behaviour of soils susceptible to liquefaction is of the upmost relevance. The material used in this study is Coimbra sand (Portugal), which is an artificial and uniform soil susceptible to liquefaction. In this study, several compression tests were performed, under undrained conditions, with three different types of equipment, namely two different triaxial apparatus and a Hollow Cylinder Apparatus, and different sample sizes. Although triaxial apparatus are often used to determine the behaviour and resistance characteristics of soils, they do not realistically reproduce the field conditions typically induced by earthquake loading. These limitations can be partly overcome by using the hollow cylinder apparatus. The main objective of this work is to understand if the sample's size and geometry influence the sand behaviour under compression in undrained conditions

RÉSUMÉ : Les effets causés par les phénomènes de liquéfaction sont l'un des principaux fléaux observés depuis longtemps dans le monde, principalement dans les régions sismiquement actives où il existe des sols sableux saturés. Cela dit, l'étude du comportement des sols sensibles de liquéfaction est de la plus haute importance. Le matériau utilisé dans cette étude est le sable de Coimbra (Portugal), qui se caractérise para être un sol artificiel de granulométrie uniforme susceptible de liquéfaction. Dans cette étude, plusieurs essais de compression ont été effectués, sous conditions non drainées, avec trois équipements différents, à savoir deux appareils triaxiaux différent et un appareil à cylindre creux, et des échantillons de tailles et géométries différentes. Bien que les équipements triaxiaux soient souvent utilisés pour déterminer le comportement et les caractéristiques de résistance des sols, ils ne reproduisent pas de manière réaliste les conditions de terrain et les charges sismiques. Ces limitations peuvent être partiellement surmontées en utilisant un appareil à cylindre creux. L'objectif principal de ce travail est de comprendre si la taille et la géométrie de l'échantillon influencent le comportement du sable quand il est soumis à des essais de compression sous conditions non drainées.

KEYWORDS: Coimbra sand, Hollow Cylinder Apparatus, Triaxial, sample size and geometry, sample deformation.).

1 INTRODUCTION

Over time, the term liquefaction has come to be related to the phenomenon consisting in the loss of resistance or rigidity of a saturated soil in undrained conditions, in a short period of time, where its rupture may occur (Kramer, 1996). When a cyclic load is applied under undrained conditions, the contractions resulting from the stress path generate positive excess-pore-pressures that may eventually equal the value of the total stress (Kramer, 1996), resulting in the loss of interparticle forces or effective stresses. A fundamental aspect to be taken into account in order for liquefaction to take place is the constitution of the soil, namely its grain size distribution. A soil with a large grain size distribution is less subject to liquefaction than a poorly graded or uniform soil (Tsuchida, 1970).

In view of the above, the study of the shear resistance of Coimbra sand at large deformations takes special importance in the evaluation of its resistance to liquefaction. The present work intends to compare the behaviour of samples subject to the same initial conditions but with different sizes and geometries, when subjected to monotonic compression.

2 EXPERIMENTAL PROGRAM

The laboratory testing program consisted of monotonic compression tests on Coimbra sand using three different types of equipment: two triaxial apparatus and one Hollow Cylinder Apparatus allowing to test solid and hollow section samples. The following sections present a brief description of the laboratory equipment, the sand tested and the experimental procedures.

2.1. Studied material

In this work an artificial sand, named Coimbra sand, was used. This Portuguese reference sand is obtained by washing and sieving a natural sandy soil taken from alluvial deposits located on the banks of the Mondego River, in the region of Coimbra (Cunha, 2010). According to the procedure proposed by Araújo Santos (2015) the sieve nº200 (#0.075mm) from the ASTM series is used first to remove the fines present in the soil. After this the remaining sand is sieved using sieves #40 (#0.425mm) and #100 (#0.125mm) of the ASTM series, the soil fraction retained between these two sieves forming the Coimbra sand.

Through particle size analysis, represented in Figure 1, it was possible to determine that D50≈0.30mm and D10≈0.18mm, which gives a coefficient of uniformity (Cu) close to 1.72. The value of D30≈being 0.25mm, a coefficient of curvature (Cc) close to 1.12 was determined. Also, by the analysis of the granulometric curve, Coimbra sand is composed by 4,55% of material retained on sieve nº40 (#0, 425mm), 64,15% retained on sieve nº60 (#0,250mm) and 31,3% on sieve nº140 (#0,150mm). Thus, according to ASTM standard D 2487-06, Coimbra sand is classified as medium sand (Fonseca 2017) poorly graded (SP) since its (Cu) is less than 4 and has less than 5% fines. And according Araújo Santos (2016), Coimbra sand is a soil subject to liquefaction, Figure 1 shows the particle size distribution of Coimbra sand and as, it can be seen, the curve is within the limits established by Tsuchida (1970) to identify soils susceptible to liquefaction.

To determine the physical characteristics of Coimbra sand, tests were carried out to determine the density of solid particles (G) and the maximum and minimum void ratios. The determination of the density of solid particles (G) followed the procedure indicated in LNEC standard NP 83 of 1965 and a value of 2.65 was obtained. This result is in line with those determined by other authors (Araújo Santos (2015), Fonseca (2017), Santos (2009), Cunha (2010).

The determination of the minimum void ratio followed the procedure established in ASTM standard D 4253-00, obtaining the value of 0.550, the same value obtained by Araújo Santos (2015).

In turn, the determination of the maximum void ratio followed the procedure proposed in ASTM standard D 4254-00, a value of 0.964 being obtaining, a result that is also identical to that determined by Araújo Santos (2015) and Fonseca (2017).

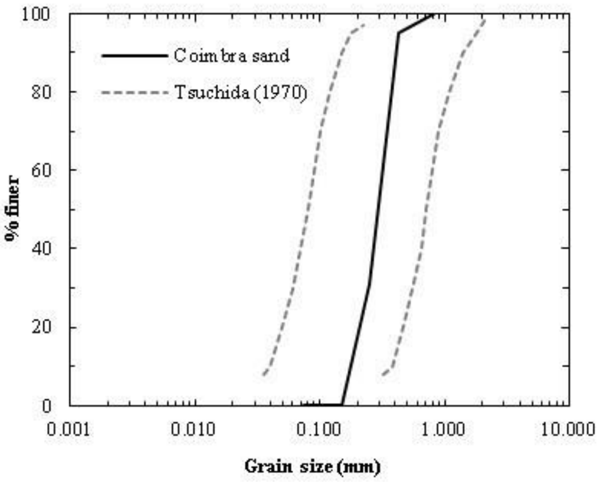

Figure 1. Grain size distribution of Coimbra sand.

2.2 *Samples preparation.*

Sample preparation plays a very important role in the study of soil behaviour. When using reconstituted samples, the methodology adopted should reproduce the process of deposition in situ (Vaid e Negussey, 1988). In fact, due to difficulties and costs associated with retrieving intact sand samples, various sample preparation techniques have been developed in order to simulate natural conditions as reliably as possible. According to Butterfiel and Andrawes (1970) these techniques can be grouped into two groups: (i) techniques in which the relative density is adjusted after the sand has been deposited, (ii) methods in which the relative density is adjusted during the deposition process.

In the present work the procedure used is the method of gravitational deposition through air, usually called dry pluviation. In this method, the relative density is controlled by the deposition flux, the drop height and the deposition mode. The medium crossed by the grains also influences the deposition (Araújo Santos, 2015), which, in this work, is air. To ensure the control of the relative density and uniformity of the sample, it is essential that the height of fall between the base of the pluviation system and the top of the sample is always constant (Araújo Santos, 2015). In the developed method for ISEC samples, the height of fall is 15 cm. For the UC samples, the height of fall is 20 cm. Another factor to take into account is the flow, which is controlled by the opening of the deposition mechanism. Thus, a smaller number of openings, but with a larger diameter, leads to a larger flow than a larger number of openings but with a smaller diameter and consequently the relative density increases with the decrease in deposition flow (Okamoto and Fityus, 2006). The mesh of opening across the deposition mechanism ensured a uniform spreading of sand inside the sample mould. Along the deposition process, the top surface of the sample remains horizontal during the pluviation process. Thus, there was no need of using sieves to control the deposition mode during the preparation process.

Some pluviation bases have been developed with the aim of obtaining a relative density for a loose-to-medium state, equal to that used in previous studies (Dr = 40%) and guarantying both the homogeneity and repeatability of the samples (Araújo Santos, 2015). The mechanism and techniques developed ensure that the relative density of the sample is always the same. It should be noted that the relative density values here presented refer to the state of samples immediately after its deposition inside the mould.

2.3. *Equipment used.*

The monotonic triaxial compression tests of 50D:100H (D – diameter; H – height of sample, in mm) samples (full section) were performed on the triaxial press available at the Coimbra Institute of Engineering (ISEC). This equipment, whose maximum load capacity is 50 kN, is shown in Figure 2 a). The pressure in the chamber and in the sample is controlled by pressure/volume controllers with a volumetric capacity of 200 mm3, which are able to apply a maximum pressure of 3 MPa. The load cell has a maximum capacity of 16 kN. By means of an LVDT it is possible to measure the axial displacements of the sample during the shearing phase.

The 100D:200H (mm) samples (full section) were tested in a triaxial press of the University of Coimbra (UC), represented in Figure 2 b). The maximum capacity of the press is 50kN and the pressure in the triaxial chamber and in the sample is controlled by manual controllers by means of air/water interfaces. The load cell has a maximum capacity of 25kN. The displacements of the sample are also measured by means of an LVDT.

The hollow samples with 60ID:100OD:200H (ID – internal diameter; OD- outer diameter; H – height of sample; all in mm), were tested in the Hollow Cylinder Apparatus (HCA) of the University of Coimbra (UC). This device was developed to better reproduce the stress paths originated by foundations of offshore structures, where the soils are generally subjected to states of generalized stress such that $\sigma1\neq\sigma3\neq\sigma2$ with rotation of the principal stress axes (Symes, 1983). The existing equipment at the University of Coimbra is a HCA Mark II (Jardine, 1996), state conditions on the soil sample, as well as to control the direction of the principal stress. This equipment contains two sets of instrumentation that allow the study of very small to very large levels of deformation.

2.4. *Description of tests and initial conditions*

The results presented are part of a vast set of tests carried out aiming the characterization of Coimbra sand. In this study only loose samples, with Dr = 40 %, are considered. .


a) b) c)

Figure 2 Equipment used.: a) Triaxial press at ISEC; b) Triaxial press at UC; c) Hollow Cylinder Apparatus at UC.

After all the assembly procedures of the samples in both the triaxial equipment and the HCA, the samples were subjected to saturation processes. In the case of the triaxial equipment, the water percolated upwards between the base and the top of the sample so that the air present in the sample was expelled. The saturation of the sample was verified by measuring the Skempton B parameter and the samples were considered to be saturated and the test continued when this parameter reached, at least, a value of 0.95. In the HCA the sample was subjected to two saturation processes (Araújo Santos, 2015). The first process starts immediately after filling the outer cell and a pressure value is applied so that the suction can be safely removed from inside the sample. By keeping a small pressure differential between the bottom and top of the sample, water flows upwards and the air retained in the sample and hydraulic tubes is collected in a air/water interface. After completion of this procedure, the pressures are increased to the value at which the consolidation stage begins. At this point and maintaining a small pressure differential between the base and the top of the sample, water percolation is possible. This second saturation process ensures the removal of the air inside the sample and the hydraulic tubes that were not previously dissolved when the pressures were increased (Araújo Santos et al., 2019). In the triaxial equipment, after filling the sample with water the pressures were increased to the value that starts the consolidation phase and were kept constant until B>0.95.

After the saturation process, samples were isotopically consolidated for an effective initial stress state of 200 kPa. This process was identical for both types of equipment. This stress state was maintained for 12 hours, so that creep phenomena are allowed, with the shearing stage beginning when creep rates are considered low. The results of the monotonic tests, under undrained conditions, performed on triaxial equipment and the HCA are presented in the following section. Table 1 summarises the main characteristics of the tests.

In order to compare the compression tests carried out in both equipment (triaxial press and HCA), special care should be taken while performing the test in the HCA in order to keep a triaxial stress state, where the coreferential and radial stress (σ_θ and σ_r, respectively) are equal. According to equation (1) and (2), proposed by Hight et al. (1983), to ensure this condition along all the test, the inner (p_i) and outer (p_o) stresses must remain equal throughout all the test. This condition is achieved by imposing the right conditions in the software used to control the equipment and to monitor the test.

$$\sigma_r = \frac{p_o \cdot r_o + p_i \cdot r_i}{r_o + r_i} \tag{1}$$

$$\sigma_\theta = \frac{p_o \cdot r_o - p_i \cdot r_i}{r_o - r_i} \tag{2}$$

Table 1. Tests designations and initial conditions.

Tests	Dimensions (mm)	Dr (%)	p´$_0$ (kPa)
TX_ISEC_CU_40/200	50D:100H	40	200
TX_UC_CU_40/200	100D:200H	40	200
HCA_CU_40/200	60ID:100OD:200H	40	200

3 COMPARISON OF COIMBRA SAND BEHAVIOUR

This section presents the results of the tests carried out, as well as their interpretation. Both strength-stress-strain and sample's shape deformation interpretation are performed.

3.1 The effect of sample size and geometry in the strength-stress-strain behaviour

Figure 3 shows the monotonic shear tests under undrained conditions, in which the stress paths (q-p') are illustrated. Since all the samples have the same initial state consolidation (Dr = 40% and p' = 200 kPa) is used in this work, it is possible to verify the influence of the sample size and geometry on the behaviour of the Coimbra sand.

Starting by comparing the results obtained in full section samples, it is possible to conclude that, regardless the sample size, the Coimbra sand presents a deformation behaviour by hardening. From the analysis of Figure 3, it is possible to see that both tests carried out on triaxial presses show a contractile behaviour until a minimum value of the deviatoric stress is reached, corresponding to the Phase Transformation State, followed by an expansive behaviour until the end of the test. It should be noted that in none of the tests the Critical State is reached, as there is a reduction in the deviatoric stress until the sample failure.

When comparing the TX_UC_CU and HCA_CU tests, whose samples have the same size but distinct geometry (full and hollow cross section, respectively), Figure 3 shows that, although the hollow sample presents a general behaviour identical to that previously identified, a lowest value of yield stress is reached in HCA test. This distinct behaviour may be explained by its hollow shape, which can lead to distinct evolution of strain and stress along the specimen when compared with full section specimens.

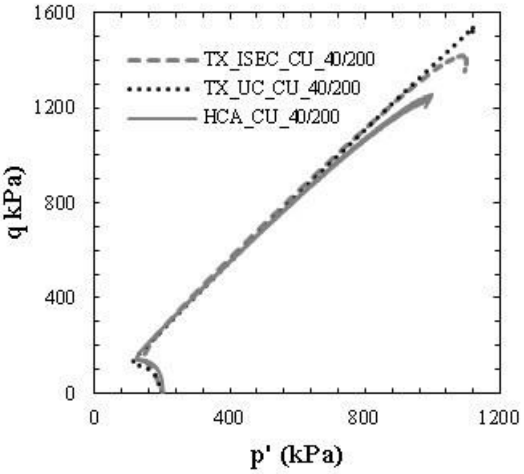

Figure 3. Stress paths of the compression tests under undrained conditions of the Coimbra sand.

Figure 4 shows all tests normalized as a function of the consolidation stress. From the analysis of Figure 4 it is possible to conclude that, independently of size and geometry, the overall behaviour of the tested samples is similar. The small discrepancies may reflect small variations in the relative density that may arise during the assembly process of specimens. However, since the adopted sample preparation method for both small and tall or full and hollow sample was the same, it is possible to conclude that the pluviation process ensure a hight level of homogeneity of sand samples, even when prepared by different operators.

As Figure 4 enlarges the initial phase of the tests, the initial contraction of the samples is noticeable. It can be seen that the phase transformation state of all the tests is very close, namely in the TX_UC_CU and HCA-CU tests, whose sample have a different geometry. The visible discrepancy between the two full section samples TX-ISEC_CU and TX_UC_CU is attributed to some king of densification process during the sample preparation rather than to any influence of sample size. This small relative density difference can be easily identified in Figure 5.

The representation of the stress-strain curves in Figure 5 highlights the small discrepancies in relative density at the beginning of the shear stage. As previously mentioned, the stiffer behaviour observed in TX_ISEC_CU sample is due not to any size effect, when compared to the 100D:200H mm sample but to some densification process occurred during any stage prior to shear stage. On the other hand, the geometry of the sample influences the stress-strain behaviour of the sample. Analysing Figure 4, HCA_CU sample appears to have a relative density slightly higher that TX_UC_CU, whose sample dimensions are identical. However, despite reaching a higher deviatoric stress in the Phase Transformation State, HCA_CU sample shows a softer behaviour when it starts do dilatate. This disparity may arise from the different deformation mode of samples, as it is shown in the following section.

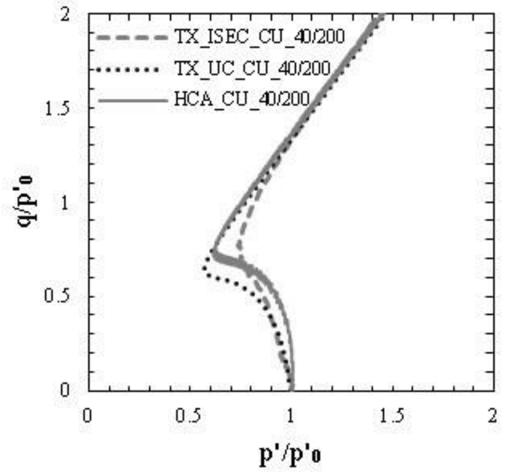

Figure 4. Normalised stress paths of the compressive tests under undrained conditions of the Coimbra sand.

Despite the differences previously identified, the overall behaviour of sand samples is identical, presenting a softening behaviour until the Phase Transformation State followed by an hardening behaviour until reaching the end of the test or the Critical State. The performed test ended when the axial strain reached sensibly 15%, where a very small plateau, followed by a decrease in the yield stress with increasing strains, can be identified.

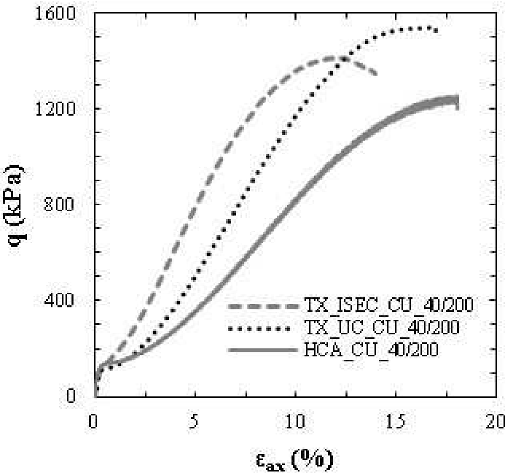

Figure 5. Stress-strain curves from compression tests under undrained conditions of the Coimbra sand.

Figure 6, which shows the normalized stress-strain curves, helps to verified if the Critical states was, or was not, reached at the end of the test. It can be seen that, independently of sample size and geometry, although more pronounced stress-strain patterns are presented, the two components of the stress state do not remain constant. Thus, the Critical State was not reached in the tests carried out. Once more, the slightly higher relative density of the TX_ISEC_CU test is visible, helping to justify the observed differences between different size samples.

To conclude the discussion of the strength-stress-strain behaviour, it is important to analyse the excess of pore pressure generated during the compression tests. From the analysis of Figure 7, it is possible to see that, in all tests, during the initial contractive behaviour, a positive excess of pore water pressure is generated, until a peak that corresponds to the moment when the sand ceases to have a contractive behaviour and starts to have an expansive behaviour, where there is a negative generation of pore water pressure. Comparing TX_ISEC_CU and TX_UC_CU, whose samples differs in size, the different excess of pore pressure generated results from the discrepancy in relative density, as previously identified. Despite this difference, the rate of pore pressure generation is identical in both samples. On the other hand, comparing samples with different geometry (full and hollow cross section), it is possible to identify a different pore pressure generation pattern with the increase of the axial strain. After reaching the Phase Transformation State, the hollow cylinder sample (HCA_CU test) appears to present a lower rate of pore pressure generation than the generation observed during the shear stage of the TX_UC_CU test. This test also presents a positive pore pressure peak more pronounced, i.e., a sharper transition from contractive to dilatant behaviour is observed in full section samples. The hollow sample appears to have smother transition from softening behaviour to hardening behaviour, which governs the development of pore pressure with the increase of the axial strain. Considering an axial strain level of 15%, a difference of sensibly 100 kPa in pore pressure can be observed. Although the available data do not allow a definitive conclusion, the shape of the HCA_CU curve shows tendencies to converge towards the same final value of excess of pore pressure. According to the deformation mode illustrated in Figure 8, the authors theorizes that this behaviour should result of an increase in the sample volume involved in the resistance mechanism of the sample.

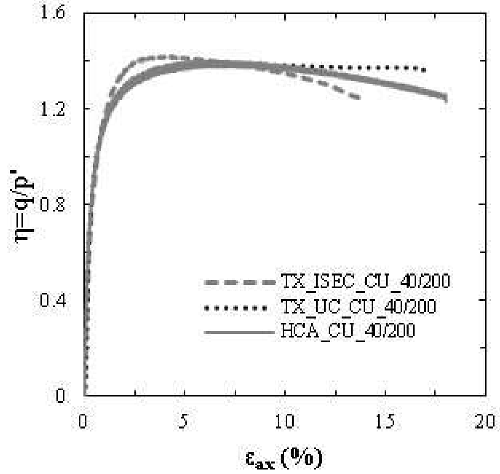

Figure 6. Normalised stress-strain curves of the compression tests under undrained conditions of the Coimbra sand.

3.2 *Comparison of samples deformation mode*

Triaxial tests results can be affected by several errors, being the axial stress one of the main sources of error (Coelho, 2000). This stress is determined by the ratio between the axial load measured by the load cell and the cross-sectional area of the specimen. Therefore, as the cross-sectional area of the specimen varies during the tests, it is necessary to estimate the radial extension of the specimen at each instant (Araújo Santos, 2015). When it is not possible to perform this measurement, indirect methods are used to relate the radial strain to other quantities, namely axial and volumetric strain, measured during the various stages of a test (Coelho, 2000). According to this author, during the shear stage, the estimation of the cross section depends on the deformation mechanism of the specimen. In compression tests, three types of mechanisms are usually accepted (Coelho, 2000): i) deformation maintaining the cylindrical shape (straight cylinder); ii) deformation through a parabolic shape (embrittlement); iii) localized deformation in a given section of the specimen (bulging deformation).

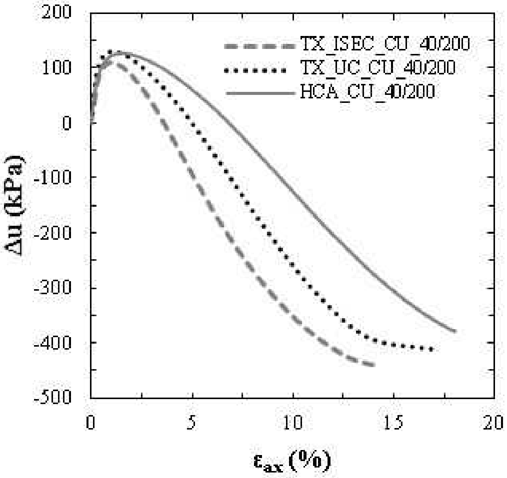

Figure 7. Interstitial pressure-strain variation curves of the compression tests in undrained conditions of the Coimbra sand.

Figure 8 shows the final deformations of the tests performed. The thicker black line represents the deformation, and the thinner black line represents the initial state of the sample. It should be noted that, on average, the tests performed in this study reached levels of axial strains in the order of 15%. Regarding the triaxial tests (TX_ISEC_CU and TX_UC_CU) it is possible to verify that the deformations are identical, presenting deformations by embrittlement. The top and bottom bases restrain the deformation of the sample, typifying a clear example of the effects of the tops on the characterisation of soils in triaxial tests. Moreover, it is possible to conclude that the use of full section specimens with different dimensions does not influence the way the specimen will deform.

Comparing the deformations modes of the hollow and full specimens (HCA_CU and TX_UC_CU) represented in Figure 8, it is possible to conclude that the failure mechanisms are very distinct. Contrary to the full section sample, which presents a parabolic shape, the hollow specimen developed a localized bulging deformation, where no top and bottom effects are visible. This conclusion may explain the differences highlighted in the previous section, namely those observed in Figure 7. The common cross section correction applied in the data treatment (assuming a straight cylinder) may lead to an underestimation of stresses, as it is shown by Mulabdic´ (1993).

4 CONCLUSIONS

The study material of the present work is an artificial sand, called Coimbra sand, which comes from alluvial deposits along the banks of the Mondego River. By analysing the granulometry of the Coimbra sand, and taking into account its production process, it can be classified as being a poorly graded sand. According to Tsuchida (1970) limits, the Coimbra sand is a soil susceptible to liquefaction.

From the analysis of the Coimbra sand behaviour, it was possible to conclude that, regardless of the sample dimensions

Coimbra sand presents a similar behaviour. The main differences are small discrepancies in the relative density and small differences in the sample assembly that may influence the results in the shear stage of the test. However, by comparing samples with distinct geometry (hollow and full cross section), there are some divergences that can neither be explained by relative density nor sample assembly differences. This conclusion is reinforced by the analysis of the deformation mode. While full section samples tend to present a parabolic deformation, hollow specimen present a bulging deformation. Since the same area correction was used in the treatment of the data, the computed stresses in the hollow cylinder apparatus may not be totally accurate.

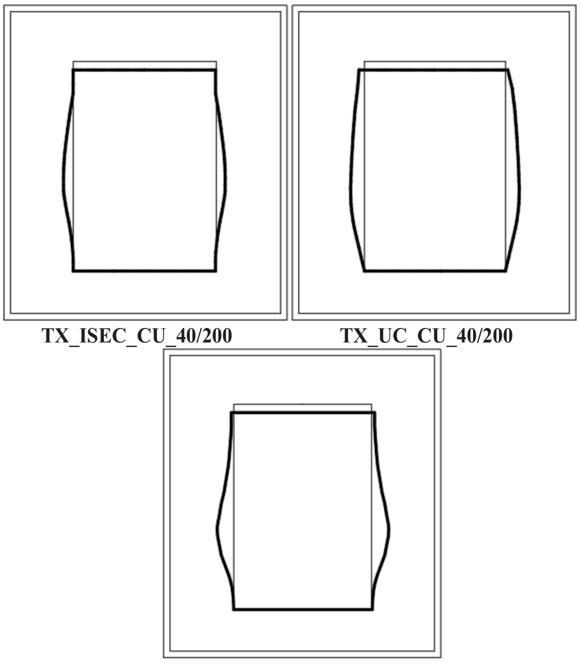
TX_ISEC_CU_40/200 **TX_UC_CU_40/200**

Figure 8. Deformations of the tests performed.

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