Coimbra Sand – Round Robin Tests to Evaluate Liquefaction Resistance

J.A. Santos, R.C. Gomes, J.C. Lourenço, F. Marques
Instituto Superior Técnico, Technical University of Lisbon, Lisbon, Portugal

P. Coelho, R. Azeiteiro, L.A. Santos, V. Marques
Faculty of Sciences and Technology of the University of Coimbra, Coimbra, Portugal

A. Viana da Fonseca, M. Soares, É. Abreu
University of Porto, Faculty of Engineering, Porto, Portugal

D.M.G. Taborda
Geotechnical Consulting Group, London, UK

SUMMARY:
A study on Coimbra calibrated sand with uniform grain size distribution was performed by means of a large number of laboratory element tests, namely drained and undrained monotonic triaxial compression tests, undrained cyclic triaxial tests, hollow cylinder compression tests, bender element tests and undrained cyclic torsional shear tests. The aim of this study is to compare the round robin tests' results obtained at Instituto Superior Técnico of the Technical University of Lisbon, at the Faculty of Sciences and Technology of the University of Coimbra and at the Faculty of Engineering of the University of Porto, considering different laboratory preparation techniques, different stress-paths and different loading frequencies, in order to provide a robust characterization of Coimbra clean sand. The results obtained offer a rare opportunity for comparing the ability of different researchers to prepare similar samples and provide an overview of liquefaction resistance of Coimbra sand based on different experiments.

Keywords: Coimbra Sand, Liquefaction, Monotonic and Cyclic Loading, Laboratory tests

1. INTRODUCTION

Soil liquefaction is one of the most feared and complex phenomena in earthquake geotechnical engineering. The quick loss of soil's resistance and stiffness, due to the increase of the water pore pressure, can have serious effects. However, the liquefaction phenomenon remains poorly explained with respect to loading conditions and in the case of some non-textbook soils (e.g. sands with fines, silts from tailing deposits, residual soils, etc).

Coimbra's region has several alluvial sandy deposits, which have been the focus of a collaborative research project involving various research institutions. In fact, earthquake induced liquefaction has been observed in this region during past earthquakes, namely as the result of the 1755 Lisbon Earthquake, and the existence of important infrastructures susceptible to liquefaction effects is a major concern.

A study on Coimbra calibrated sand with uniform grain size distribution was performed by means of a large number of laboratory element tests, namely drained and undrained monotonic triaxial compression tests, undrained cyclic triaxial tests, hollow cylinder compression tests, bender element tests and undrained cyclic torsional shear tests, performed in three different universities.

2. TESTING PROGRAM

2.1. Overview of testing program

As part of a research project that has been carried out at three Portuguese universities, the experimental program presented in this paper was devised to characterize the fundamental behaviour of Coimbra Sand under different laboratory testing conditions, namely:

- oedometer tests (OC);
- drained and undrained monotonic triaxial compression tests (MTC);
- bender elements tests (BE);
- undrained cyclic torsional shear and triaxial tests (TS and CT).

The samples tested were prepared with different relative densities, D_r, in order to represent relatively loose and dense initial conditions under isotropic confining pressure, σ'_0, of 50, 100, 200, 400, 1000 or 10000 kPa, as detailed in Table 2.1.

Table 2.1. Characteristics of the tests performed

Test ID [(1)]	Lab.	Test device	Drainage	Loading	Initial conditions	
					D_r (%)	σ'_0 (kPa)
OC 40	FCTUC	Oedometer	--	Oedometer compression	40, 80	--
OC 80						--
DMTC 40/50, DMTC 40/100, DMTC 40/200, DMTC 40/400	FCTUC IST	Triaxial	Drained	Monotonic triaxial compression	40	50, 100, 200, 400
DMTC 50/20, DMTC 50/50, DMTC 5/100, DMTC 50/400, DMTC 20/1000, DMTC 50/10000	FEUP	Triaxial	Drained	Monotonic triaxial compression	5, 20 50	20, 50, 100, 400, 1000, 10000
UMTC 25/100, UMTC 36/200, UMTC 80/400	FEUP	Stress path	Drained	Monotonic triaxial compression	25, 36, 80	100, 200 400
UMTC 25/100, UMTC 36/100	FEUP	Stress path	Drained	Monotonic triaxial compression	25, 36	100 , 200
UMTC 40/50, UMTC 40/100, UMTC 40/200, UMTC 40/400	FCTUC IST	Triaxial	Undrained	Monotonic triaxial compression	40	50 , 100 , 200 , 400
DMTC 80/50, DMTC 80/100, DMTC 80/200, DMTC 80/400	FCTUC IST	Triaxial	Drained	Monotonic triaxial compression	80	50 , 100 , 200 , 400
UMTC 80/50, UMTC 80/100, UMTC 80/200, UMTC 80/400	FCTUC IST	Triaxial	Undrained	Monotonic triaxial compression	80	50 , 100 , 200 , 400
UMHCAC 40/50, UMHCAC 40/100, UMHCAC 40/200, UMHCAC 40/400	FCTUC	Hollow Cylinder Apparatus	Undrained	Monotonic HCA compression	40	50 , 100 , 200 , 400
BE 40, BE 80	FEUP	Bender / Extender Elements	--	Bender/Extender elements	40, 80	50, 100, 200, 400
UTS 20/50, UTS 20/200	IST	Torsional Shear	Undrained	Torsional shear	20	50 , 200
UCT 30/20	FEUP	Cyclic Triaxial	Undrained	Cyclic triaxial	30	20
UCT 40/100	FCTUC	Stress path	Undrained	Cyclic triaxial	40	100

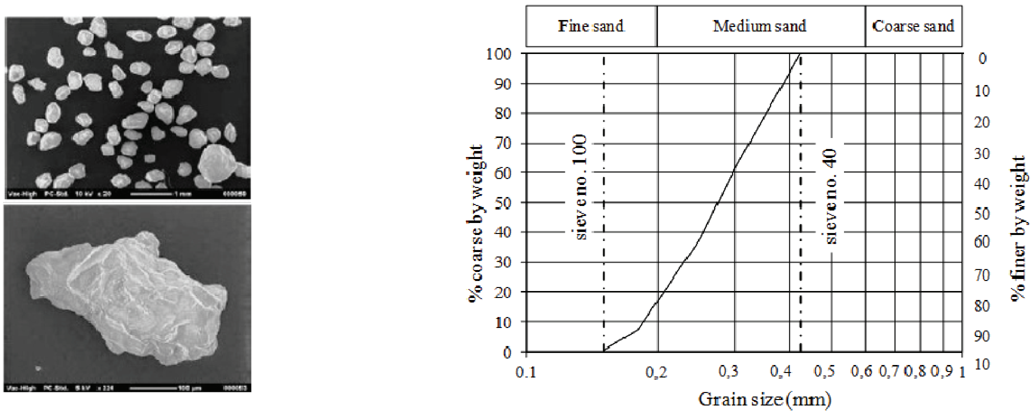
[(1)] The designation identifies the type of drainage (D / U) and loading (OC / MTC / MHCAC / TT / CT), as defined in the 4^{th} and 5^{th} columns, respectively, the relative density of the sample and the confining pressure

2.2. Sand tested

All tests were performed on an artificial sand, named Coimbra Sand, which represents soil conditions of many deposits located along the major Portuguese rivers. As illustrated in Figure 2.1a), the shape of the individual sand particles vary from subrounded to subangular. To avoid soil particle segregation, the sand was graded between no. 40 (0.425 mm) and no. 100 (0.150 mm) sieves of ASTM series (Figure 2.1b)). The mean grain size, D_{50}, is about 0.28 mm and the specific gravity, G_s, is 2.65. The minimum and maximum void ratios are e_{min} = 0.48 and e_{max} = 0.81, respectively.

2.3. Equipments at different research laboratories

The experimental program comprises the Geotechnical laboratories at the Faculty of Sciences and Technology of the University of Coimbra (FCTUC), the Faculty of Engineering of the University of Porto (FEUP) and at Instituto Superior Técnico of the Technical University of Lisbon (IST).



a) Grain shape (Santos, 2009) b) Grain size distribution

Figure 2.1. Characteristics of Coimbra Sand

In order to characterize Coimbra Sand's small-strain stiffness, bender/extender elements were used at FEUP. The bender elements are coupled to the triaxial apparatus. The electronic equipment used for running the bender/extender elements measurements includes a programmable function generator, an integrated unit with input and output amplifiers and an oscilloscope (details in Viana da Fonseca et al., 2009).

The monotonic drained and undrained triaxial testing for this study was performed on triaxial test apparatuses available at FCTUC, IST and FEUP, as well as on a hollow cylinder apparatus (HCA) available at FCTUC. Strain controlled tests were performed. As pointed out by Jefferies & Been (2006), strain controlled tests are preferable over load controlled tests as they provide more detailed data on the post-peak behaviour. The triaxial systems use motorised load frames, deforming cylindrical specimens under constant strain rate. The main differences between the triaxial equipments resides on the specimen's diameter – 70 mm at IST and FEUP and 100 mm at FCTUC– and on the maximum working pressure – 1000, 2000 and 10000 kPa at FCTUC, IST and FEUP, respectively. Regarding the HCA, the specimen inner and outer diameters and height are 150, 200 and 260 mm, respectively, and the maximum working pressure is also 1000kPa. In the FEUP experiments the triaxial tests were performed on a common triaxial apparatus and on a "Bishop-Wesley" apparatus. All of the cells are equipped with Bender/Extender elements, which allowed S and P waves' velocities to be continuously registered during saturation, consolidation and shear.

The cyclic triaxial testing was performed on a hydraulically actuated Bishop & Wesley stress path cell for 38 mm diameter specimens available at FCTUC, which has a maximum working pressure of 1000 kPa. The extension load was applied by means of a flexible sleeve sealing a plane top cap to an adjustable reaction head, which prevents cell pressure from acting vertically on the sample.

In FEUP, the cyclic triaxial tests were performed on a common triaxial cell with a load capacity of 10 kN and the sine waves were imposed with a constant frequency of 0,1 Hz, after a K_0(=0,5) consolidation. This triaxial cell is also equipped with Bender/Extender elements.

Cyclic torsional shear tests were carried out in a Seiken Model DTC-199 apparatus available at IST. It allows the test of solid and hollow specimens, under either monotonic or cyclic loading conditions for shear strains comprised between $5x10^{-4}$ and $5x10^{-2}$. The tested specimens diameter and height are 70 and 100 mm, respectively and the actual maximum working pressure is 700 kPa.

2.4. Experimental procedures

At the FCTUC and IST laboratories, air-pluviation of dry sand was used to prepare the samples with relative densities of approximately 40 and 80 % (i.e. corresponding to void ratios of about 0.67 and 0.54, respectively). In the case of loose sand, the relative density was controlled by the rate of pouring, which depends on the size and number of openings of a miniature container. For dense sand, the multiple sieving pluviation technique (Miura and Toki, 1982) was used. The rate and characteristics of pouring were methodically tested to ensure the accuracy and repeatability of the technique. The density of the samples was confirmed from the mass and volume measurements after preparation. In FEUP, the specimens were reconstituted through moist tamping technique for an optimum water content of 5% usually adopted for sandy soils. Using a cylindrical vacuum split model the specimens are very easily built for any range of relative densities, being specially suited to obtain very loose specimens.

With the exception of oedometer tests, where dry sand was used, all the remaining tests were performed on fully saturated specimens (Skempton's B-value above 0.98). The saturation was achieved by imposing an upward flow of de-aired water through the specimen (using a differential pressure of less than 10 kPa in order to minimize its disturbance), until a volume of at least twice the voids' volumes were reached, and/or by means of high back-pressure, under an effective stress of less than 30 kPa. The back-pressure was maintained during the next stages in order to ensure saturation during the whole test. Samples were isotropically consolidated under effective stress levels of roughly 50, 100, 200 and 400 kPa before shearing, as detailed in Table 2.1.

All monotonic triaxial compression tests were performed with a constant strain increment (0.01, 0.2 and 0.4 mm/min at FEUP, FCTUC and IST, respectively), which was slow enough to allow pore pressure change to equalize throughout the sample. Those tests were stopped when the piston reached its maximum displacement or when pore pressure dropped sufficiently for cavitation to occur.

In FEUP bender/extender elements were used to investigate the S and P waves velocity in samples with relative density of 40% and 80% with confining pressures of 50, 100, 200 and 400 kPa. The S and P waves' propagation velocity was measured using wave frequencies of 2, 4, 6, 8 kHz and 25, 50, 75 kHz respectively. These same samples consolidated to 400kPa were then sheared to failure in undrained conditions.

In the case of cyclic torsional shear tests, sine waves with a constant frequency of 1 Hz were imposed, while, in cyclic triaxial tests, a constant axial load increment of 1.5 cycles/h was specified for the relatively low strains, typically under 0.3 % of axial strain, after which a constant strain rate of 1 %/h was applied. This strain rate was increased by two, four and eight times once the axial strain exceeded 0.5, 1 and 2 %, respectively. All samples were tested until large double amplitude strains and excess pore water pressures were observed. In FEUP 0.1Hz sinusoidal axial deviatoric loading cycles were adopted.

The oedometer tests were carried out on dry samples with 50 mm of diameter and 18.75 mm of height. In the first loading, the samples were subjected to the following loading scheme: 29, 57, 112, 278, 553 and 1105 to 24271 kPa with load increments of 1103 kPa, approximately. In the case of dense sample, an additional load of 552 kPa was applied, reaching 24823 kPa. In each of the load steps, the specimen's height was determined. The subsequent unloading and reloading stages followed the same loading scheme.

Torsional shear test were performed in order to allow the evaluation of the Cyclic Stress Ratio (CSR) as a function of the number of cycles. A set of seven tests was carried for a relative density of 20% and for confining pressures of 50 and 200 kPa (Marques, 2011).

3. TEST RESULTS

3.1. Small strain behaviour

Figure 3.1 shows the exponential relation between confining pressure, p', and elastic shear modulus, G_0, determined using bender element tests. Figure 3.1 also presents the semi-empirical curve proposed by Hardin & Richart (1963) for sands based on the following expression $G_{max} = A\ F(e)\ (\sigma'_m)^n$, with A a material constant, n a constant which varies with the type of soil and the level of shear deformation and F(e) a function of the void ratio. As expected, the values obtained for the small-strain stiffness compare well with the semi-empirical curves because the material is a common siliceous sand.

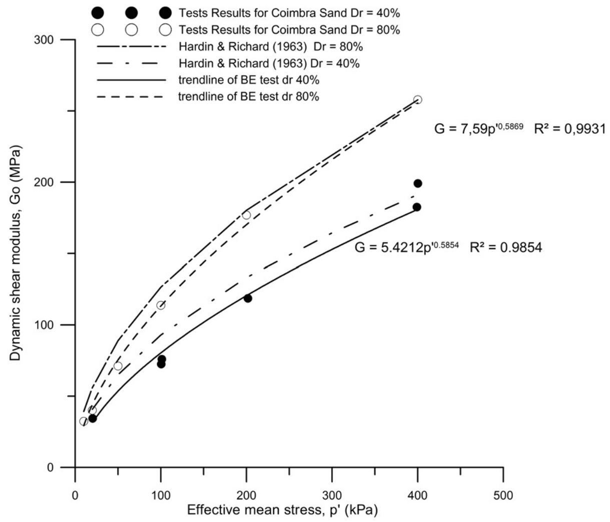
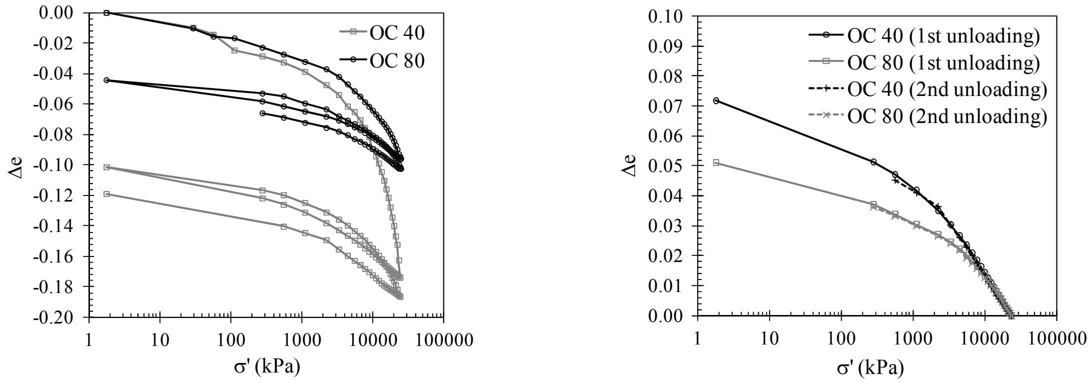


Figure 3.1. Dynamic modulus as a function of the mean effective stress

3.2. Monotonic stress-strain behaviour

3.2.1. Oedometer test

Figure 3.2 compares the variation of the sand's void ratio, Δe, with the effective stress, σ', for the relative densities tested. As would be expected, the overall compressibility of the loose sample (OC 40) is larger, especially once stress exceeds a threshold value of about 50 kPa (Figure 3.2a)). Moreover, it can be observed that the loose sample exhibits lower elastic recovery (e.g., in the first cycle of loading, the elastic recoveries of OC 40 and OC 80 samples are of about 41 and 53%, respectively).



a) Comparison of the overall compressibility b) Comparison of the unloading behaviour

Figure 3.2. One-dimensional effective stress versus void ratio variation for samples with different densities

Although sand behaves almost elastically during unloading, the response of the samples is only similar at the beginning of that stage (Figure 3.2b)). Even for the same sample, the 1st and 2nd unloading curves do not coincide exactly. This suggests that the idealization of a linear dependence between the void ratio and the logarithm of the mean stress is not appropriate, at least, to describe the behaviour of Coimbra Sand under the stress levels applied in the tests.

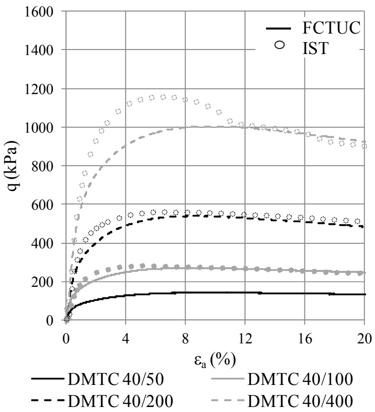
The results also suggest that it is not possible to define a virgin compression line for the sand tested, even considering the high stresses applied (a maximum of about 25 MPa). Although, a compression index (C_c) between 0.35 and 0.40 is suggested by the trend exhibited by the results.

3.2.2. Triaxial compression test

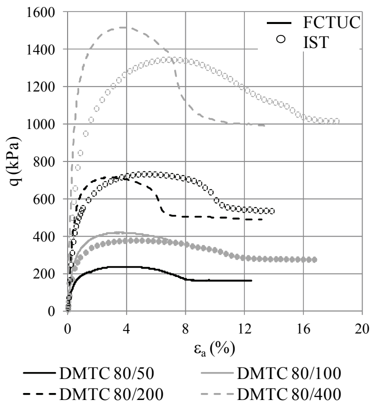
Figure 3.3 shows the drained behaviour of Coimbra Sand under monotonic triaxial compression. This figure compares the results obtained in IST and FCTUC. The stress-strain trajectories find a good agreement between the data of the two laboratories, despite the existence of minor differences in the peak value for the sample consolidated under 400 kPa, for loose and dense states (Figure 3.3a) and b)).

A larger difference between the results of the two laboratories can be seen in the variation of the volumetric strain with the axial strain (Figure 3.3c) and d)). It seems that the loose samples from IST present a more dilative behaviour than those from FCTUC. Conversely, the dense FCTUC's samples are more dilative. These differences can be explained by several factors, namely the sample preparation technique (despite being prepared by pluviation in both laboratories, the techniques were developed independently), samples' sizes (FCTUC samples are larger), the acquisition equipment (a pressure/volume controller is used to measure the sample volume changes and a transducer fixed outside the cell is used for the axial displacement measure, which may not be sufficiently precise).

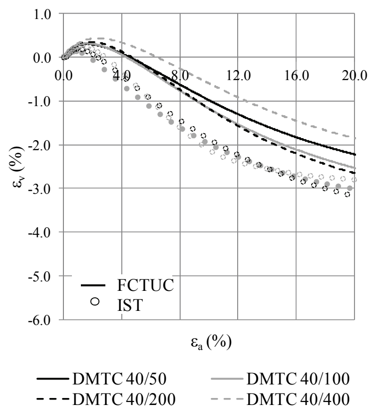
Figure 3.4 shows the undrained behaviour of Coimbra Sand under monotonic triaxial compression, where the results obtained in IST and FCTUC are compared. A good agreement in the stress path of samples can be observed (Figure 3.4a) and b)). The differences in the stress-strain behaviour of the loose samples, particularly in terms of generation of pore water pressure, suggest, as observed for drained loading, that the samples are characterised by distinct dilatancy rates.



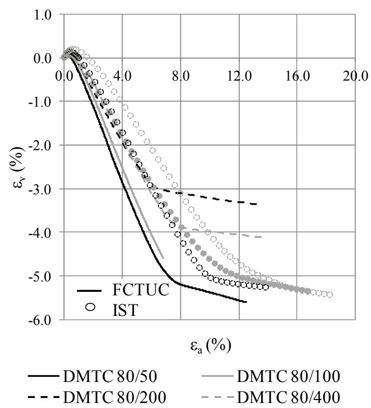
a) Stress-strain behaviour of loose samples



b) Stress-strain behaviour of dense samples



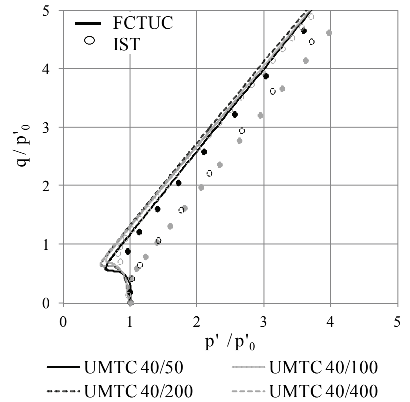
c) Variation of the volumetric strain with the axial strain of loose samples



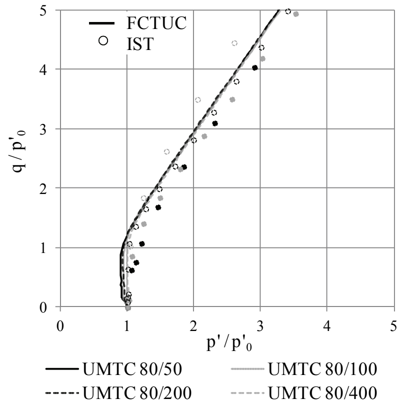
d) Variation of the volumetric strain with the axial strain of dense samples

Figure 3.3. Drained behaviour of Coimbra Sand under monotonic triaxial compression (FCTUC and IST)

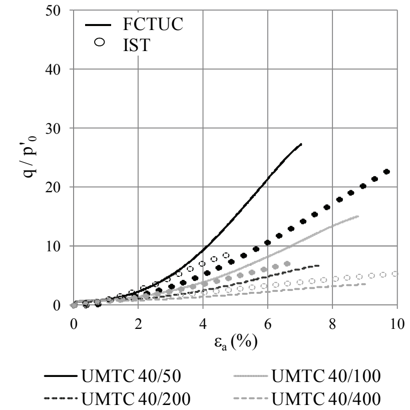
The stress-strain paths tend to a q/p' value typically comprised mostly between 1.30 and 1.40, with the larger ratios corresponding to the dense samples, which suggests that Critical State has not yet been reached in these tests.



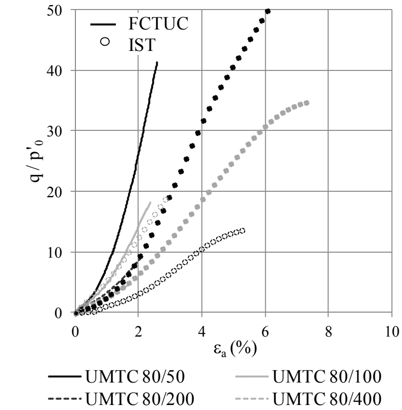
a) Stress path of loose samples



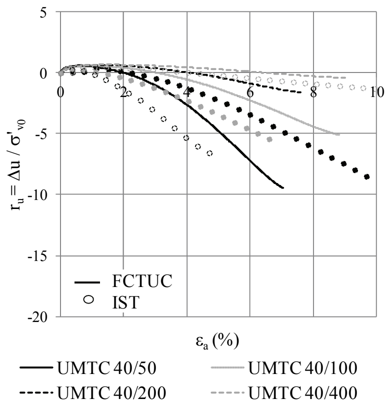
b) Stress path of dense samples



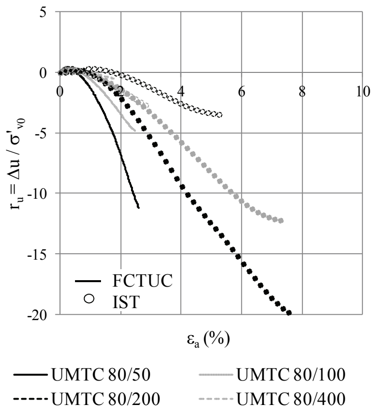
c) Stress-strain behaviour of loose samples



d) Stress-strain behaviour of dense samples



e) Variation of pore pressure ratio with the axial strain of loose samples



f) Variation of pore pressure ratio with the axial strain of dense samples

Figure 3.4. Undrained behaviour of Coimbra Sand under monotonic triaxial compression (FCTUC and IST)

While the main aim was to obtain comparable results between the different Universities, FEUP's tests were mainly performed in drained conditions in order to define the CSL ("Critical State Line").

In addition to the drained tests, two undrained tests were performed with relative densities of 36 and 25% with a confining stress of 200kPa and 100kPa, respectively. Both the undrained tests liquefied. Soil fabric, as highlighted by some researchers, is a very important factor that may explain the different behaviour exhibited by the samples. Due to particles reorientation, soil samples may have more or less resistance depending on the soil deposition method (or, in this case, depending on the sample preparation method). As it was noted by some researchers, samples reconstituted using a moist tamping technique usually lead to looser and more contractive soil samples. Nevertheless if all range of force-particle interaction is studied then it is possible to know which the safe side is. Furthermore, when attempting to determine the CSL, it has been shown (Jefferies & Been, 2006) that fabric may an influence on the volumetric strain behaviour but not on peak or ultimate shear stress. Therefore, it can be assumed that the critical state angle is independent of the sample fabric. Figure 3.5 represents the CSL of Coimbra Sand. As it can be seen, there were two tests that did not reach the CSL, probably due to the reasons pointed out above. Also it was noticed that for same initial void ratios, only those that were subjected to with higher confining stresses reached the CSL, due to their proximity to this final state.

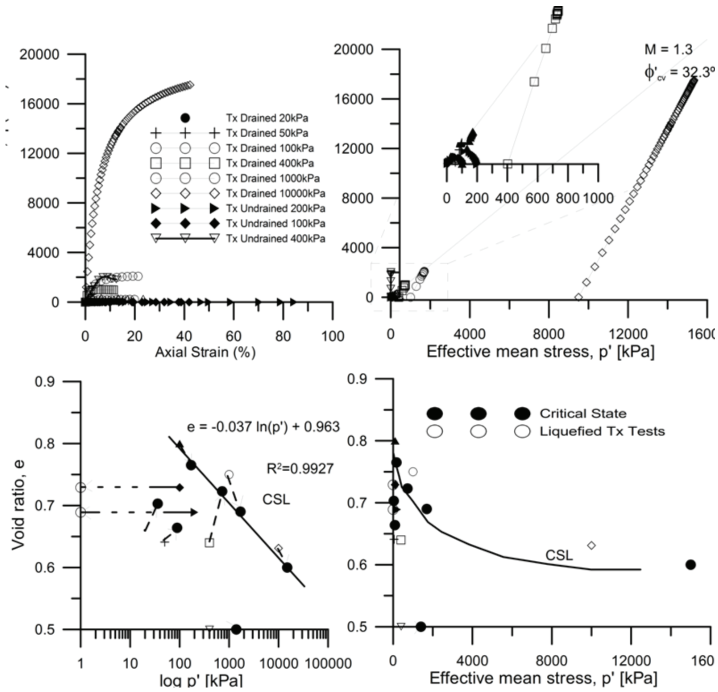


Figure 3.5. Triaxial tests results (FEUP)

Figure 3.6 shows the critical state line determined from selected triaxial tests performed in all laboratories. As it can be seen, a good agreement is found with FEUP's proposal in Figure 3.5. In effect, the inclination of this curve (λ), 0.037 is lower than the typical values for river sands, which are in order of 0.16 (Atkinson, 1993). Probably, the critical state is defined by a curve instead of a line, and λ will increase for higher confining pressure tests. This will be confirmed in future tests.

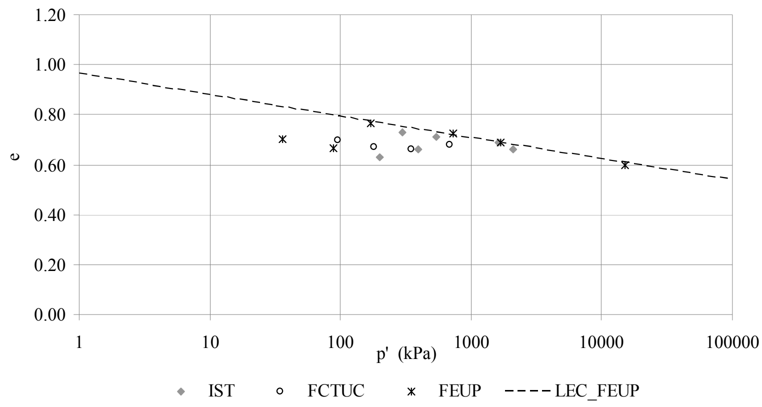


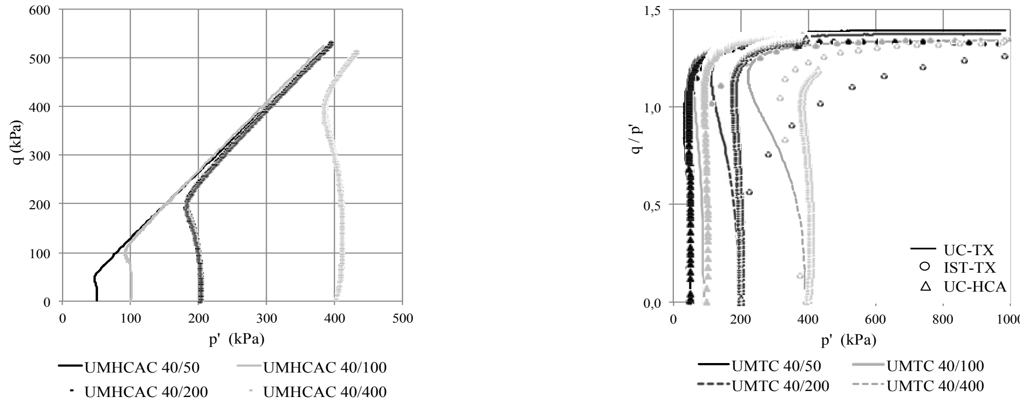
Figure 3.6. Critical State Line for Coimbra Sand (all laboratories)

The λ value is related with C_c by the relation $\lambda = C_c / \ln(10)$. Being C_c approximately 0.35, λ will be 0.152, which is much more coherent with the nature of the tested soil.

The results show considerable scatter. Indeed, it is very difficult to define the initial void ratio of the sample. For example, if a 140 mm height sample has a 1 mm deviation in the height, it will have a deviation in the void ratio of about 0.015. If that deviation is in the radius, the void ratio will exhibit a deviation of about 0.05, leading to the large scattering shown in Figure 3.6. This can be avoided by testing larger samples, but in small samples this is an inherent preparation error. It may also happen that not all the points correspond to the critical state, but only to the final stress-strain state of the test.

3.2.3. Hollow cylinder apparatus test

The stress paths of the four tests carried out in the Hollow Cylinder Apparatus are plotted in Figure 3.7a. It can be seen that, even if the sample preparation technique was the same, the last test (p'=400kPa) appears to be slightly denser than the other tests. The use of large area specimens only allows to reach a maximum deviatoric stress of 500kPa to be reached, which is lower than that achieved on the other two other triaxial equipments, as it is shown in Figure 3.7b. Comparing all the compression tests, one can conclude that all the samples tend to the same value of q/p', i.e. 1.35. However, the contractive behaviour of the HCA samples generates less excess pore water pressure than that observed in the normal triaxial samples.



a) Stress paths of UMHCAC test for each effective stress levels.

f) Comparison of the stress path of all the monotonic compression tests carried out on the different equipment.

Figure 3.7. Undrained behaviour of Coimbra Sand under monotonic compression test.

3.3. Cyclic stress-strain behaviour

3.3.1. Cyclic triaxial test

Two cyclic triaxial tests were performed at FCTUC and three at FEUP. In accordance with the behaviour observed in monotonic tests, for the same loading, loose sample tends to generate larger excess of pore water pressure, Δu, in each cycle, N. The results are plotted in Figure 3.8.

3.3.2. Cyclic torsional triaxial test

For shear strains comprised between 2 and 4%, the secant shear modulus, G_{sec}, is approximately 6 MPa for a confining pressure of 50 kPa and ranges between 9 and 13 MPa for a confining pressure of 200 kPa. As expected, the higher G_{sec} stands for the higher confining pressure.

Figure 3.8 shows the relation between CSR and number of cycles for confining pressures of 50 and 200 kPa and relative density of 20%. It can be seen that the lines for p'=50 and p'=200 kPa are almost parallel. The liquefaction resistance decreases with the increase of confining pressure.

The values presented are coherent with the liquefaction resistance for UCT 40/100 and UTC 30/20. In UCT 40/100 test a CSR of 0.20 was achieved with 14 cycles and in UTC 30/20 a CSR of 0.42 was achieved with only 2 cycles. If the confining pressure and relative density are the same, the number of cycles needed for liquefaction in a triaxial test is higher than in a torsional shear test.

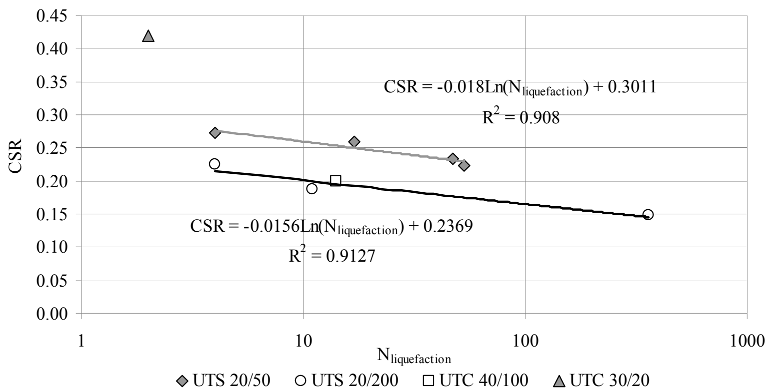


Figure 3.8. Relation between CSR and number of cycles

4. CONCLUSIONS AND FUTURE STUDIES

In this paper, round robin tests carried out at three different laboratories were compared. Although similar sample preparation techniques and test procedures were adopted, samples tested at different laboratories show different volumetric behaviour (in drained tests) or pore pressure generation (in undrained tests). This difference can be explained by small variations of the preparation techniques, samples' sizes or the lack of precision of the acquisition equipment. Moreover, it is very difficult to define the initial void ratio of the sample, as small sample deviations in sample measures may represent significant void ratio variations. This can be avoided by testing larger samples, but in small samples this is an inherent preparation error.

A first proposal for the CSL is shown. Its inclination is lower than the usual values for river sands. Probably, the CSL is more appropriately defined by a curve rather than a line, and λ will increase for higher confining pressures.

ACKNOWLEDGEMENT
This research was carried out as part of research project PTDC/ECM/103220/2008: "Tools for performance-based design in liquefiable deposits". The authors are grateful to the following funding bodies: Fundação para a Ciência e a Tecnologia (FCT), FEDER/UE and QREN.

REFERENCES

Atkinson, J. (1993). An introduction to the mechanics of soil and foundations through critical state soil mechanics. McGraw-Hill Inernational (UK) Limited.

Marques, F. (2011). Coimbra Sand – Influence of non-plastic fines in liquefaction resistance. MSc. thesis, Instituto Superior Técnico, Portugal (in Portuguese).

Hardin, B.O. and Richart, F. E. Jr. (1963). Elastic wave velocities in Granular soils, Journal of Soil Mechanics and Foundations Divisions, ASCE, 89 (1): 33-65.

Jefferies, M. and Been, K. (2006). "Soil liquefaction. A Critical State Approach". Taylor & Francis. 479 pp. USA and Canada.

Miura, S. and Toki, S. (1982). A sample preparation method and its effect on static and cyclic deformation-strength properties of sand. Soils and Foundations, 22: 1:61–77.

Santos, L.N. (2009). Behaviour of Coimbra Sand under monotonic loading. MSc. thesis, University of Coimbra, Portugal (in Portuguese).

Viana da Fonseca, A.; Ferreira, C.; Fahey, M. (2009). A framework interpreting bender element tests, combining time–domain and frequency–domain methods. Geotechnical Testing Journal, ASTM. 32(2), 1–17.