

Coimbra Sand – Influence of Non-Plastic Fines In Liquefaction Resistance

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SUMMARY

The soil liquefaction is one of the most feared phenomena in geotechnical engineering. It is well known that the presence of fines (silt and clay particles) affects the resistance of sand to liquefaction. However, recent studies show that no clear conclusions can be drawn in what manner the fines content affects the liquefaction resistance of sand under cyclic loading. This is particularly true for sands containing non-plastic fines. A set of undrained monotonic triaxial compression tests and undrained cyclic torsional shear tests are performed on Coimbra clean sand and Coimbra sand with 20% of non-plastic fines. It is shown that the presence of non-plastic fines in Coimbra Sand can reduce the liquefaction resistance.

Keywords: Liquefaction; sands; non-plastic fines

1. INTRODUCTION

It's well known that non-plastic fines influence the liquefaction resistance of sandy soils. Recent studies shown that this influence can either increase or reduce the sand's liquefaction resistance (e.g. Polito, 1999). According to Todo-Bom (2008), there are numerous studies that have produced conflicting results. Some authors - e.g. Chang *et al* (1982) - based on laboratory and *in-situ* tests, report that a silty sand's liquefaction resistance increase with the increasing of the percentage of non-plastic fines under cyclic loading, while there are authors that report the opposite - e.g. Shen *et al* (1977). Some authors, like Koester (1994), claim that the sand's liquefaction resistance initially reduces with the increase of non-plastic fine, but begins to increase when a limit non-plastic fines content or percentage is reached. Also, there are those - e.g. Tronco *et al* (1985) - who claim that sand's cyclic resistance is more closely related to its skeleton void ratio - the void ratio (e) that would exist in the soil if all of the silt and clay particles were removed - than to its density index (D_r) or the non-plastic fines percentage. In general, for a given void ratio, the variation on a sand's liquefaction resistance is related to the non-plastic fines added, since those fines change significantly the sand's maximum (e_{max}) and minimum (e_{min}) void ratio and therefore change the sand's D_r .

The Eurocode 8 (EC8) presents an empirical diagram (Figure 1.1) for the liquefaction susceptibility evaluation of sandy soils, based on the SPT test. This diagram relates the corrected SPT blow count ($N_1(60)$) needed to achieve liquefaction with the liquefaction resistance, which is defined as a cyclic stress ratio (CSR) - ratio between the cyclic shear stress and the initial overburden pressure ($CSR = \tau_{cyclic}/\sigma'_{vo}$). According to this diagram (Figure 1.1), for a given $N_1(60)$, increasing the fines content increases the CSR and, therefore, increase the sand's liquefaction resistance.

However, a study made by Polito (1999) showed the existence of a limit percentage of non-plastic fines (silts) in which there is a change in the influence of those fines on the cyclic liquefaction resistance (Figure 1.2). If the non-plastic fines percentage is lower than the limit percentage, the sand's D_r reduces and, as consequence, the resistance also reduces. Conversely, if the sand's D_r increase, then the sand's resistance grows. In this case, when the percentage of non-plastic fines is high, the silty sand's cyclic liquefaction resistance can be higher or lower than the clean sand's resistance. These

conflicting results are good example of the difficulty to draw a general conclusion about the influence of non-plastic fines on the liquefaction resistance of sands.

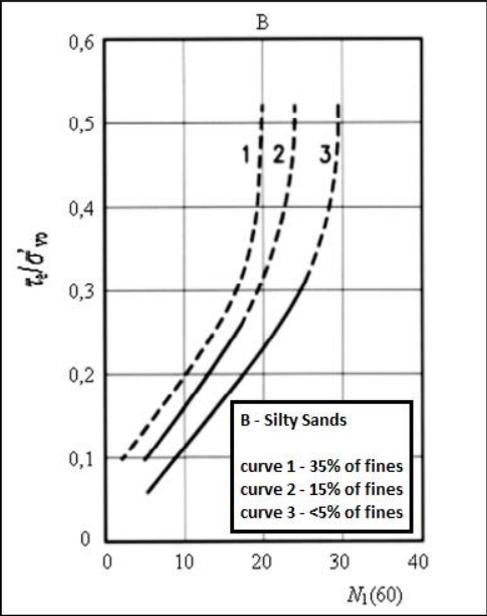


Figure 1.1. Initiation of liquefaction on silty sands for an earthquake with magnitude of 7.5

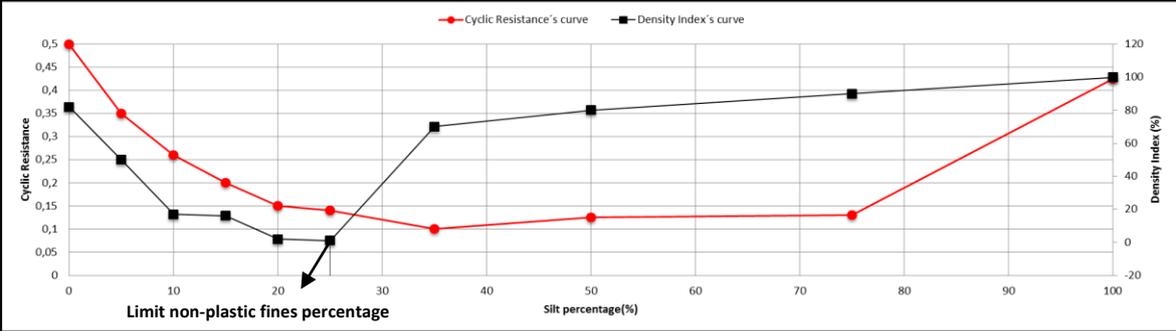


Figure 1.2. Influence of non-plastic fines (silt) on Monterey Sand's liquefaction resistance with $e = 0.68$ (Adapted from Polito, 1999)

In the framework of a research project lead by Portuguese universities, a study is being conducted on the characterization of monotonic and cyclic behavior of a poorly-graded sand known as "Coimbra Sand". This paper describes the work developed at *Instituto Superior Técnico* (IST). The main goal was to study the influence of non-plastic fines in the Coimbra Sand's liquefaction resistance, under monotonic and cyclic loading.

At the IST's Geotechnical Laboratory, a set of undrained monotonic triaxial compression test and undrained cyclic torsional shear test were made on two types of materials:

- i) Coimbra Sand without fines content;
- ii) Silty Sand composed by Coimbra Sand and 20% of non-plastic fines.

Laboratory testing was also made to obtain the physical proprieties of both soils.

2. PHYSICAL PROPERTIES OF THE MATERIALS IN THIS STUDY

2.1. Coimbra Sand

Coimbra Sand is an artificial sand, obtained from alluvial deposits of the Mondego River. The size of the grain particles are between 0.425 mm (#40 sieve) and 0.106 mm (#140 sieve). The grain size curve (Figure 3) shows a high susceptibility to liquefaction, because is within the zone 2 (Liquefiable Soil) defined by Terzaghi *et al* (1996). The physical proprieties are represented in Table 2.1 and were obtained by Santos (2009) and Cunha (2010).

Table 2.1. Physical proprieties of the soils tested

	Coimbra Sand	Silty Sand
Density (G_s)	2.65	2.65
Plasticity index (IP)	NP	NP
$e_{m\acute{a}x}$	0.81	0.78
$e_{m\acute{i}n}$	0.48	0.29

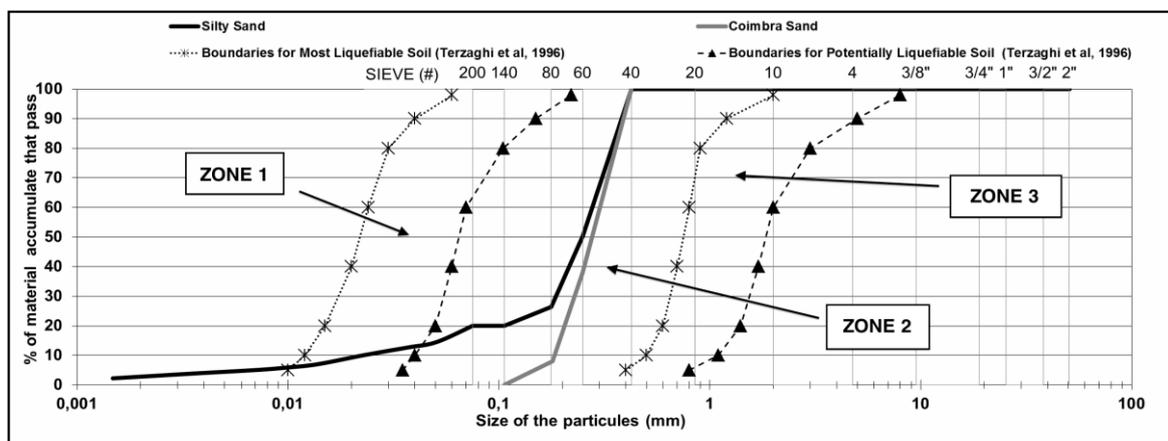


Figure 2.1. Grain Size Curve of Coimbra Sand and Silty Sand – Zones 1 and 3: Potentially Liquefiable Soil; Zone 2 - High susceptibility to Liquefaction.

2.2. Silty Sand

The study of the influence of non-plastic fines on Coimbra Sand was done with a silty sand composed by 80 % of Coimbra Sand and 20% of non-plastic silt. The added silt came from a non-plastic siliceous rock dust. The grain size curve of the Rock Dust was obtained by a sedimentation test, according to E196. The Silty Sand's grain size curve (Figure 2.1) is also within the boundaries proposed by Terzaghi *et al* (1996), therefore the Silty Sand has also a high susceptibility to liquefaction.

The Rock Dust and Coimbra Sand particle density (G_s) test was made according to NP83, in which a value of $G_s = 2.65$ was obtained for both materials. G_s The Silty Sand's $e_{m\acute{a}x}$ was obtained according to method A of ASTM D4254-00 (2000). In order to obtain the Silty Sand's $e_{m\acute{i}n}$, a modified Proctor test from ASTM D1557-00 was performed, applying 80 blows on each of the five layers (Head, 1992). The Silty Sand's physical properties are shown in Table 2.1. In Figure 2.2 is possible to see the influence of non-plastic fines (from the Rock Dust) in Coimbra Sand's D_r , for two different void ratios. Since there is a D_r reduction with the increase of the non-plastic fines percentage, it is possible to conclude that the percentage of 20% of non-plastic fines is lower than the limit non-plastic fines' percentage.

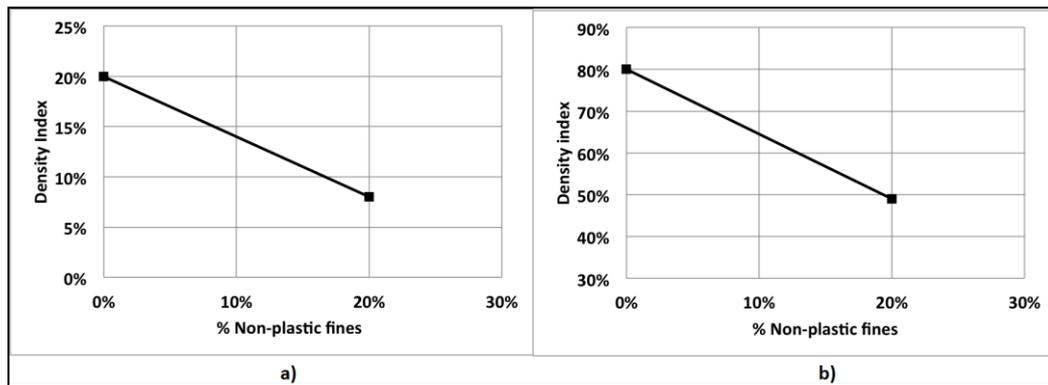


Figure 2.2. Influence of non-plastic fines on the Coimbra Sand's D_r – a) $e = 0.74$; b) $e = 0.54$;

3. PREPARATION OF SAMPLES WITH DIFFERENT VOID RATIOS

In this work, samples of Coimbra Sand with $e=0.74$ ($D_r = 20\%$) and $e=0.54$ ($D_r = 80\%$) were tested. To obtain Coimbra Sand's samples with $e=0.74$, the technique used was to perform dry pluviation using the funnel from the Sand-Cone test, completely open and placed at constant height of 34 cm. The Coimbra Sand's samples with $e=0.54$ were obtained using 3 sieves from the ASTM series placed in the following order from top to down: #20 (0.85 mm) and two #10 (2.00 mm) – to reduce the flux of the pluviation.

The Silty Sand samples were made using dry pluviation using funnel with a flexible tube attached to the spout. Initially the flexible tube was placed at the bottom of the specimen split-mold. The flexible tube was then slowly raised along the center line of the mold, such that the Silty Sand could be deposited without any drop height, avoiding particle's segregation. The target void ratios were obtained by gently tapping on the mold in a symmetrical pattern, after the soil being deposited. At the beginning of this work, the goal was to obtain Silty Sand's samples with the same void ratios as the Coimbra Sand's. But quickly it was possible to verify that, in practice, Silty Sand's samples with $e=0.74$ ($D_r = 8\%$) were impossible to obtain. Therefore, a void ratio $e=0.65$ ($D_r = 30\%$) was adopted for loose Silty Sand.

4. TESTING PROCEDURES

The strain-controlled triaxial and stress-controlled cyclic torsional shear apparatus from the IST's Geotechnical Laboratory was used. All the tested samples had the same nominal diameter of 7 cm. The theoretical height depended of the apparatus used. In the triaxial apparatus, the samples could have 14 or 15 cm in height. In the cyclic torsional shear apparatus, the samples' height was 10 cm.

In the undrained triaxial tests, the loose and dense samples of both materials were consolidated under an isotropic effective stress (p_o') of 50 and 200 kPa. A monotonic compression loading was applied to each triaxial sample, by imposing a strain rate of 0.2 mm/min. Table 4.1 contains the initial conditions of each triaxial sample before the tests. The designation "SEM_CAVI" means that the cavitation's phenomenon was avoided, by applying high backpressure in the sample (around 1 MPa)

In the undrained cyclic torsional shear tests, only the loose samples of Coimbra Sand and Silty Sand were tested, for the same isotropic effective stresses used in the undrained triaxial test. These tests were stress controlled, *i.e.* several values of CSR were applied to the samples and attempts were made to maintain those values constant during the test. The cyclic loading's frequency was 1 Hz. The Table 4.2 contains the initial conditions and the imposed CSR values for each cyclic torsional shear test.

Table 4.1. Initial conditions of the undrained monotonic triaxial compression

Material	e	D_r	p_o' (kPa)	Designation
Coimbra Sand	0.71	24%	50	TXAC_e0.71/p'50
	0.73	23%	200	TXAC_e0.73/p'200
	0.54	82 %	50	TXAC_e0.54/p'50_SEM_CAVI
Silty Sand	0.67	23%	50	TXAS_e0.67/p'50
	0.63	31%	200	TXAS_e0.63/p'200
	0.54	49%	200	TXAS_e0.54/p'200

Table 4.2. Initial conditions of the undrained cyclic torsional shear test

Material	p_o' (kPa)	e	CSR	Designation
Coimbra Sand	50	0.74	0.223	AC_p'50/CSR_0.223
		0.73	0.233	AC_p'50/CSR_0.233
		0.73	0.259	AC_p'50/CSR_0.259
	200	0.74	0.272	AC_p'50/CSR_0.272
		0.74	0.225	AC_p'200/CSR_0.225
		0.73	0.187	AC_p'200/CSR_0.187
		0.73	0.150	AC_p'200/CSR_0.150
Silty Sand	50	0.64	0.203	AS_p'50/CSR_0.203
		0.64	0.151	AS_p'50/CSR_0.151
	200	0.64	0.147	AS_p'200/CSR_0.147
		0.65	0.108	AS_p'200/CSR_0.108

5. EXPERIMENTAL RESULTS

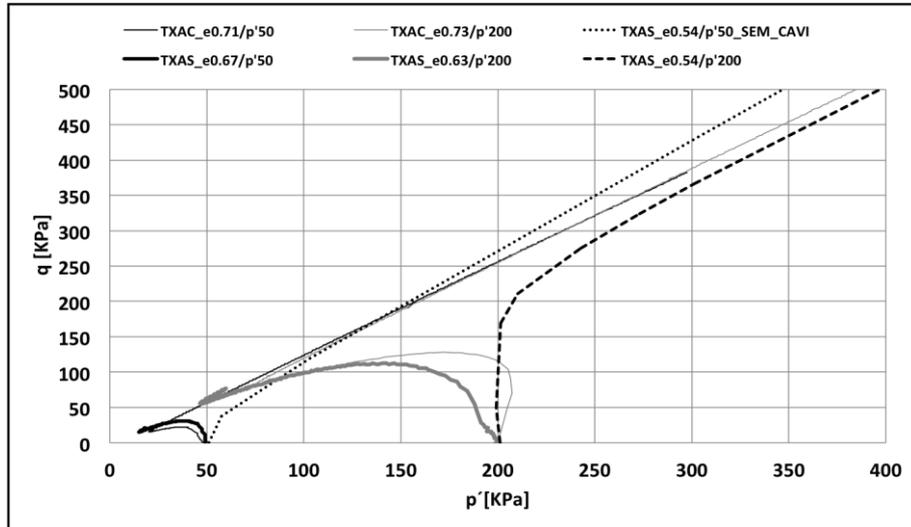
5.1. Undrained Monotonic Triaxial Compression Test

Using the results obtain in the undrained monotonic triaxial compression test, it was possible to study the influence of non-plastic fines in the Coimbra Sand's monotonic behavior. The results of the undrained triaxial tests on loose and dense samples are present in Figure 5.1. The trial test TXAC_e0.54/p'50_SEM_CAVI was aborted in the middle of the test.

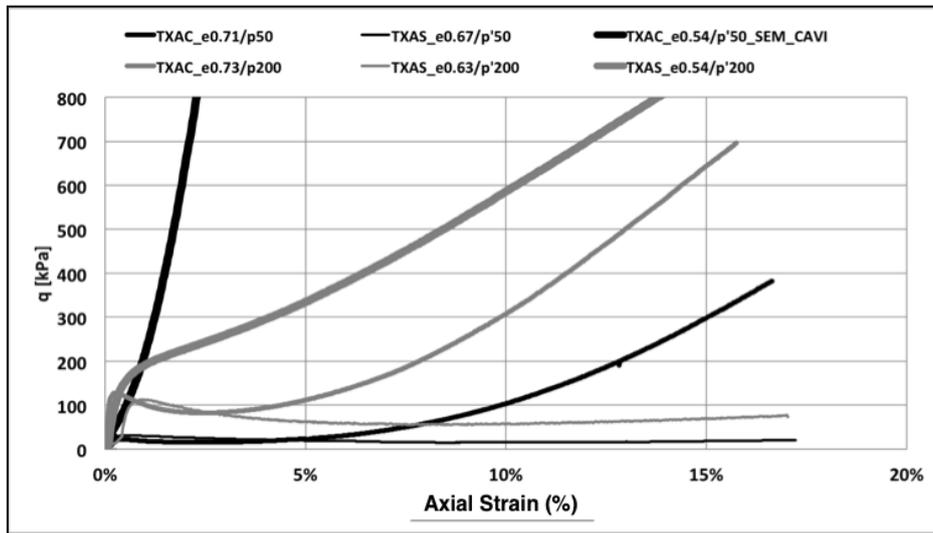
For the loose samples, the stress path in the p' - q diagram are very similar for both soils (Figure 5.1 a)). In the Figure 5.1 c) is possible to observe that Silty Sand exhibit a more contractive behavior, even for a smaller void ratio (more dense). Figure 5.1 b) shows both soils with softening behavior starting at about 0.5 to 1% of axial deformation (ε_a). For Coimbra Sand this behavior changes to a hardening behavior (increase of deviator stress, q) at 2 to 4 % of ε_a , while in the Silty Sand this transition occurs just at 15% of ε_a . This shows a reduction of the Coimbra Sand's resistance with the addition of non-plastic fines. Since there was a transition from strain-softening to hardening behavior in all the samples tested, it is possible to conclude that these samples suffered limited liquefaction.

On the dense samples with $e=0.54$, the presence of non-plastic fines in the Coimbra Sand reduce the D_r from 80% to 49 % (Figure 2.2 b)). Therefore, it is not surprising that the dilatation of the dense Silty Sand's sample is lower than the Coimbra Sand's (Figure 5.1 c)) samples.

a)



b)



c)

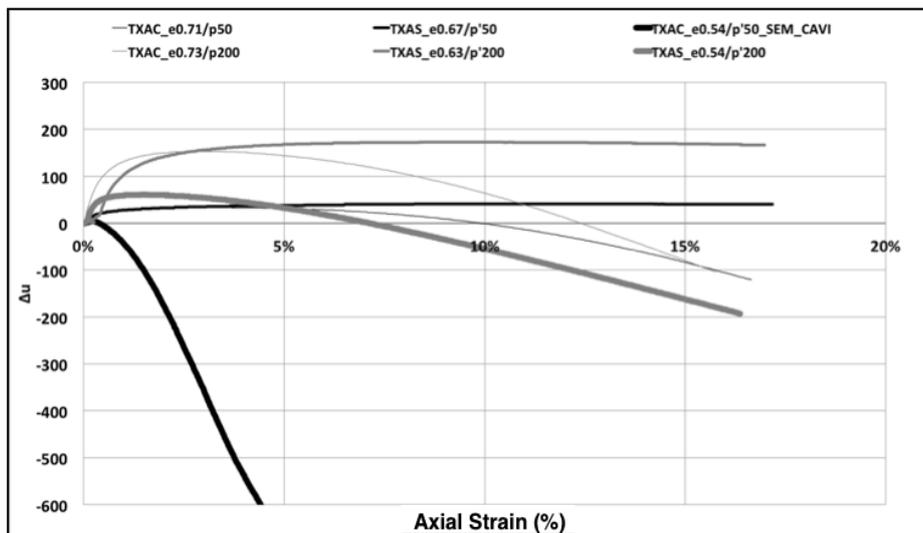


Figure 5.1. Results from undrained monotonic triaxial compression test – a) $p'-q$; b) $\varepsilon_a - q$; c) $\varepsilon_a - \Delta u$

For the estimation of the critical void ratio line (CVR) of both soils, it was considered that the final state of the triaxial test reached the critical state, as a simplified hypothesis. The presence of non-plastic fines on Coimbra Sand caused a translation and attenuated the slope in its CVR. As a result, the critical stress of Coimbra Sand for a certain e (p_c') was reduced, e.g. for $e=0.65$, p_c' of Coimbra Sand is 950 kPa, while for Silty Sand is 30 kPa (Figure 5.2).

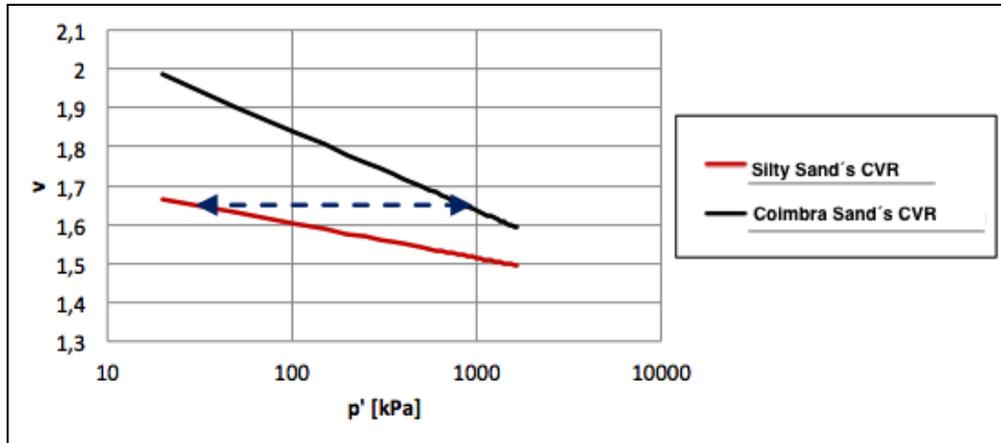


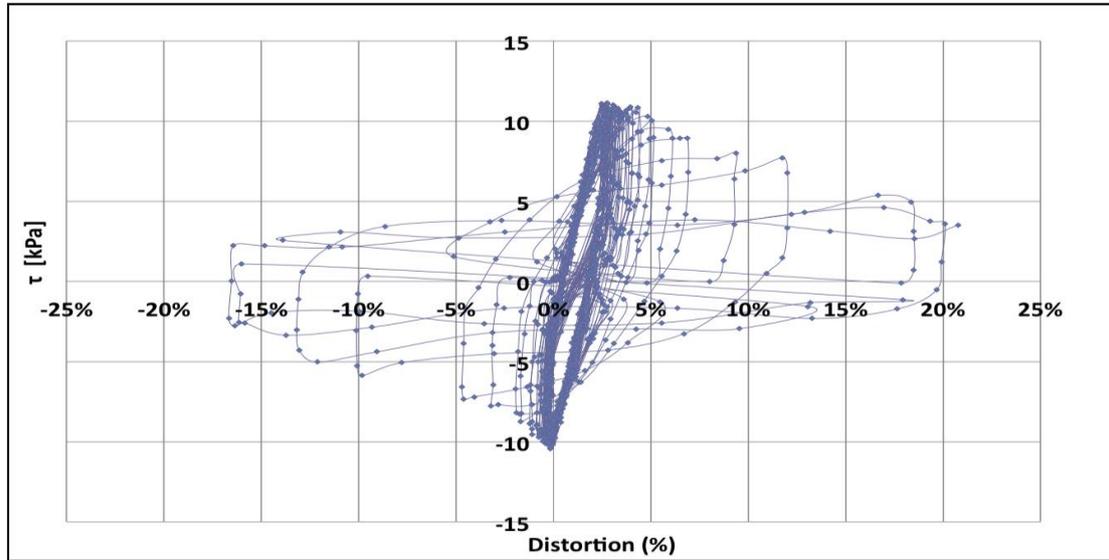
Figure 5.2. Critical void ratio line (CVR) of the tested soils

The triaxial results show that the presence of non-plastic fines increases Coimbra Sand's contractive behavior, making it less resistant and more susceptible to liquefaction.

5.2. Undrained Cyclic Torsional Shear Test

There are several definitions for initiation of liquefaction. In this work it was assumed that the soil's liquefaction initiate when $\Delta u = p_o'$ or $\Delta u_{norm} = 1$. A typical set of undrained cyclic torsional shear test results for Coimbra Sand is shown in Figure 5.3 (test AC_p'50/CSR_0.223). Unfortunately, it wasn't possible to maintain CSR constant during the tests. Possible reasons for this behavior include apparatus' technical issues or the loading frequency was too high and therefore not giving enough time to the system to react. For both Coimbra Sand and Silty Sand, at the beginning of cyclic loading the pore pressure increased gradually (Figure 5.3b) and stable hysteresis were formed (Figure 5.3a). When Δu_{norm} reached nearly 0.7, an almost sudden large increase of Δu_{norm} occurred, until $\Delta u_{norm} = 1$, and also instable hysteresis started to form. In the test represented in Figure 5.3, 53 loading cycles (N) were needed to achieve Coimbra Sand's liquefaction.

a)



b)

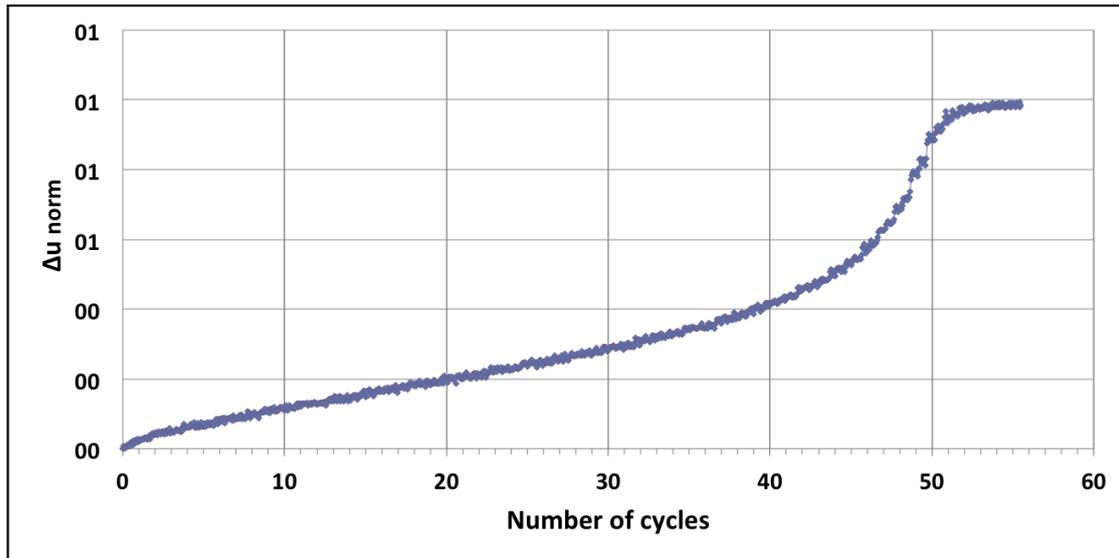
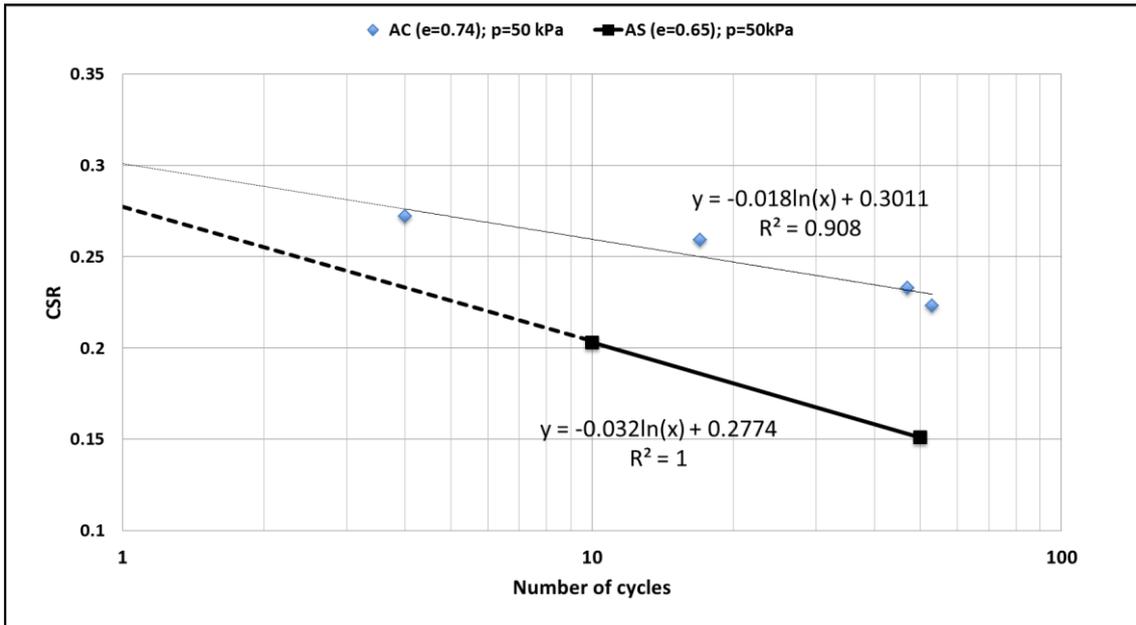


Figure 5.3. Undrained cyclic torsional shear test (AC_p50/CSR_0.223): a) $\gamma - \tau$; b) $N - \Delta u_{norm}$

Figure 5.4 a) shows the relation $N - CSR$ from the undrained cyclic torsional shear test. Considering CSR and p_o' during the test, it is possible to see that, for the range of CSR values tested, the Silty Sand's samples needed less loading cycles than Coimbra Sand's to achieve liquefaction. In other words, the undrained cyclic torsional shear tests, with the initial conditions that were imposed on the samples, proved that the presence of 20 % of non-plastic fines reduces Coimbra Sand's liquefaction resistance, under cyclic loading. If the regression lines maintain the same tendency for CSR values outside the range of values tested (dashed line), it is possible, for $p_o' = 200 \text{ kPa}$, that the Silty Sand's liquefaction resistance could be higher than the Coimbra Sand's resistance, for CSR greater than 0.21 (Figure 5.4 b)). However, the Silty Sand's regression line was obtained only with 2 points and therefore more tests are needed to confirm this tendency.

a)



b)

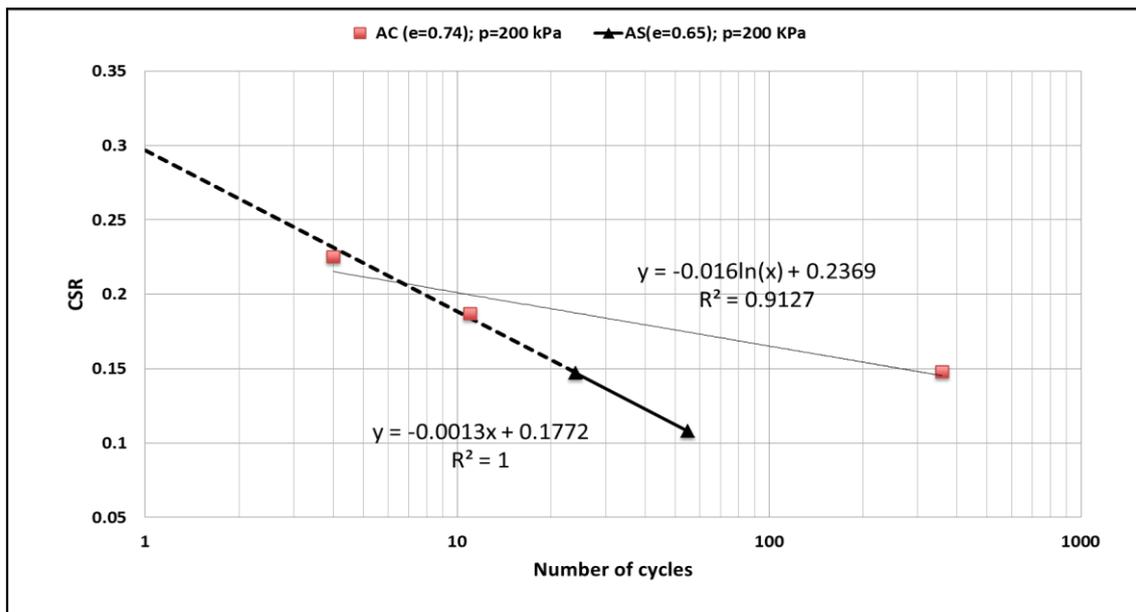


Figure 5.4. Liquefaction curves – a) $p_o' = 50 \text{ kPa}$; b) $p_o' = 200 \text{ kPa}$

5. CONCLUSIONS

A set of undrained monotonic triaxial compression tests and undrained cyclic torsional shear tests were performed on Coimbra clean sand and Coimbra sand with 20% of non-plastic fines.

It was proved that the presence of 20% of non-plastic fines has a major influence on Coimbra Sand's monotonic and cyclic liquefaction resistance by:

- increasing the contractive behavior, making the soil more susceptible to liquefaction under monotonic loading;
- reducing the number of cycles needed to achieve liquefaction, for a given and constant CSR between the range of values studied in this work, i.e. it contributes for the reduction of Coimbra Sand's cyclic liquefaction resistance.

As this paper describes an ongoing research, the planned works include studies for higher non-plastic fines content in order to get the whole evolution of Coimbra Sand's liquefaction resistance with the increase amount of non-plastic fines.

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