COIMBRA SAND - INFLUENCE OF NON-PLASTIC FINES IN LIQUEFACTION RESISTANCE

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ABSTRACT

The soil liquefaction is one of the most feared phenomena in geotechnical engineering, since the lost of soil's resistance and stiffness, due to the increase of the water pore pressure, can cause hazards effects. It is well known that the presence of silt and clay particles will in some manner affect the resistance of sand to liquefaction. However, a review of studies published in the late literature shows that no clear conclusions can be drawn as to in what manner changing the fines content affects the liquefaction resistance of sand under cyclic loading. This is particularly true for sands containing non-plastic fines. Many basic concepts of the initiation, development or mitigation of the liquefaction phenomena are not well understood, which prevents the creation of a unique definition of the liquefaction phenomena. A study on Coimbra sand by means of undrained monotonic triaxial compression test and undrained cyclic torsional shear test was performed. Non-plastic silica fines were added in order to study its influence on the liquefaction resistance. Numerical simulations were also made using a cyclic elastoplastic model. The goal was to seek the parameters of the model that are affected by the presence of the fines content.

Keywords: Liquefaction; Sands; Non-Plastic fines; Cyclic Elastoplastic model

1 INTRODUTION

Since the 1960's it is known that the presence of silt and clay particles will in some manner affect the resistance of a sand to liquefaction. However, when reviewing the studies published in the literature they show that no clear conclusions can be drawn as to in what manner altering the fines content affects the liquefaction resistance of a sand under cyclic loading. This is particularly true for soils containing non-plastic fines (silts). There are numerous laboratory studies that have produced conflicting results. Some report that increasing the silt content of a sand will increase liquefaction resistance of the sand, others that it decreases liquefaction resistance of the sand and even some report that it decreases liquefaction resistance until some limiting silt content is reached and then increase its resistance. Additionally, several studies have shown that the liquefaction resistance of silty sand is more closely related to its sand skeleton void ratio than to its silt content. Therefore, there isn't a general conclusion about the effects on non-plastic silts on the liquefaction resistance of sand.

Under a research project, led by Portuguese universities such as IST, FCTUC and FEUP, the characterization of monotonic and cyclic behaviour of the Coimbra Sand is being studied. The work developed in this thesis was made by a research team of IST and the goal was to study the influence of non-plastic fine in the liquefaction resistance of the Coimbra Sand, under monotonic and cyclic loading. A serial of undrained monotonic triaxial compression test and undrained cyclic torsional shear test were made on the Coimbra Sand and on a silty sand made by Coimbra Sand with 20 % of non-plastic silica fines. Numerical simulations of the of the experimental test were also made.

2 GENERAL CARACTERIZATION OF THE MATERIALS

The Coimbra Sand physical proprieties and grain curve has already been and determined by Santos (2009) and Cunha (2010). Therefore, in this work the main concern in the Coimbra Sand was to try to replicate a similar grain curve that they used on in theirs works (figure 2.1). The physical proprieties of the fines (rock dust) on the silty sand were unknown. Consistency limits of the rock dusk were made in order to make prove that the fines were non-plastic, according the NP-143.The silty sand grain curve was obtain by doing the sedimentation test, according the NP-196 (figure 2.1)

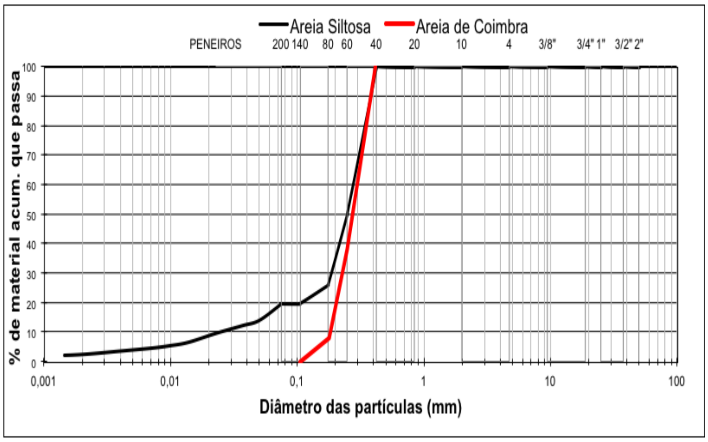


Figure 2.1 – Grain Curve of the Coimbra Sand and Silty Sand

Table 2.1 – Physical proprieties of the test soils

	Coimbra Sand	Silty Sand
Particle density G_s	2.65	2.65
Plasticity Index *PI*	NP	NP
Maximum void ratio	0.81	0.78
Minimum void ratio	0.48	0.29
Fine content	-	20 %

According to the NP-83, the rock dust's particle density, G_s, is similar to the Coimbra Sand's particle density (2.65), therefore the it has been assume that the silty sand's G_s is also 2.65. The maximum void ratio of the silty sand was obtained according to the method A of the ASTM D 4254-00. For the minimum void ratio, there is no applicable ASTM procedure for determining the minimum void ratio of soils with 20% of fines, since the vibratory table method (ASTM D4253) is limited to a maximum fines content of 15%. Modified Proctor test (ASTM D1557-00) were performed on the soil mixture but applying 80 blow instead of 27 on each of the five layers, as recommended by Head (1992).

3 PREPARATION OF SAMPLES WITH DIFERENTS VOID RATIO

The Coimbra Sand specimens were deposited by dry pluviation. The technique used to obtain specimens with e=0.74 is represented in figure 3.1 a) and consiste the fall of the sand with a fixed height of (34 cm) and flow. For specimens with e=0.54, the dry pluviation was achieved by using sieves, like in figure 3.1 b), in the following order, from top to down: #20 (0.85 mm) and two #10 (2.00 mm).

b)

a)

Figure 3.1 – Dry pluviation of the Coimbra Sand specimens- a) loose sand; b; dense sand

The Silty Sand specimens were made using dry funnel deposition (figure 3.2). This was performed by placing mixture into a funnel with a small tube attached to the spout. The tube was placed at the bottom of the specimen split-mold. The tube was slowly raised along the centre line of the mold, such that the silty sand was deposited without any drop height, to avoid particle's segregation. The desired density was achieved by gently tapping on the mold in a symmetrical pattern, as necessary. During this work, it was impossible to made specimens of Silty Sand with e=0.74. The biggest void ratio possible to obtain is about 0.65 for the silty sand. (Table 3.1).

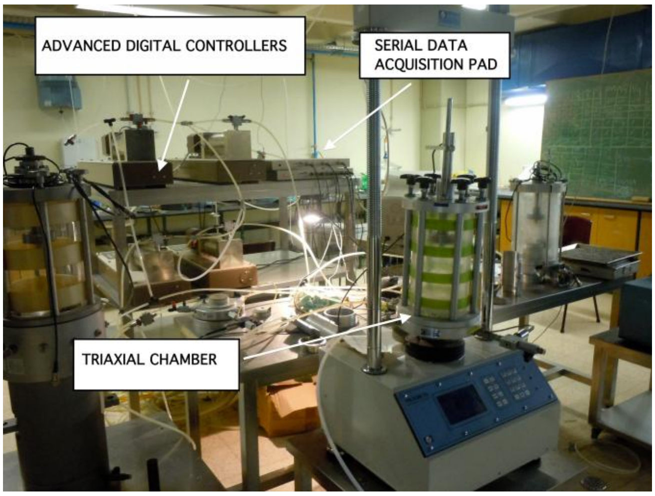
Table 3.1 - Density index and void ratio desired to test

Coimbra Sand		Silty Sand	
$e = 0.74$	$e = 0.54$	$e = 0.65$	$e = 0.54$
20%	80%	30%	49%

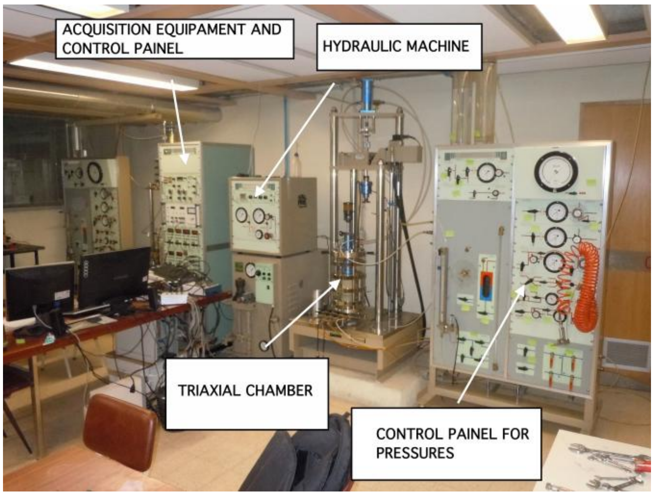
Figure 3.2 – Dry funnel deposition of the Silty Sand specimens

4 TESTING PROCEDURES

The triaxial and cyclic torsional shear apparatus of the IST's Geotechnical Laboratory were used in this study. Description of apparatus can be shown on the Figure 4.1. The specimens used in the triaxial apparatus had 7 cm in diameter and could have 14 or 15 cm in height. The specimens used in the cyclic torsional shear apparatus had 7 cm in diameter and 10 cm in height. All specimens were normally consolidated under an isotropic effective stress (p') and the tests were made under undrained conditions. The tables 4.1 and 4.2 shows the initial conditions of the Coimbra Sand and Silty Sand's specimens used for the undrained monotonic triaxial compression and undrained cyclic torsional shear tests. In the TXAC_e0.54/p50_SEM_CAVI test, the pore pressure was high enough to avoid the cavitation's phenomenon. During the undrained cyclic torsional shear test, the cyclic loading was applied under frequency of 1 Hz and attempts were made to keep the shear stress (or CSR) constant.



a)



b)

Figure 4.1 – Apparatus description a) Triaxial; b) cyclic torsional shear

Table 4.1 – Initial conditions of the undrained monotonic triaxial compression

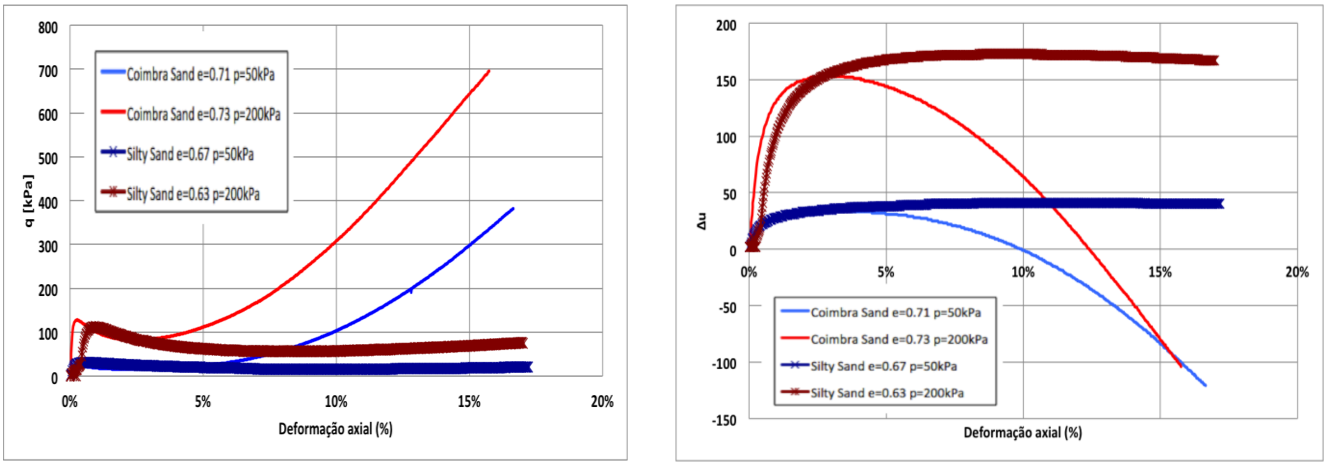
Material	e	p' [kPa]	Designation
Coimbra Sand	0.71	50	TXAC_e0.71/p'50
	0.73	200	TXAC_e0.73/p'200
	0.54	50	TXAC_e0.54/p50_SEM_CAVI
Silty Sand	0.67	50	TXAS_e0.67/p'50
	0.63	200	TXAS_e0.63/p'200
	0.54	200	TXAS_e0.54/p'200

Table 4.2 - Initial conditions of the undrained cyclic torsional shear tests

Material	p' [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
		0.74	0.272	AC_p'50/CSR_0.272
	200	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 DISCUSSION OF TEST RESULTS

Using the results obtained in the undrained monotonic triaxial compression test, it was possible to study the influence of non-plastic fines in the monotonic behaviour of the Coimbra Sand. The figure 5.1 represents the comparison between the loose states of the Coimbra Sand and Silty Sand's triaxial results.



a) b)

Figure 5.1- Comparison between the undrained monotonic triaxial compression test results of Coimbra Sand and Silty Sand - a) $\varepsilon_a - q$; b) $\varepsilon_a - \Delta u$

Although the void ratio used in both soils weren't the same, it is possible to see that the Silty Sand, even with a lower void ratio, has a more contractive behaviour than Coimbra Sand (Figure 5.1 b)). Both soils appears to have a limited period of strain-softening behaviour, but in Coimbra Sand this behaviour changes to a hardening behaviour near of 2 to 4% of axial deformation, while in the Silty Sand this changes only happens near 15 % (Figure 5.1 a)).

It is possible to conclude that the presence of non-plastic fines increases the contractive and softening behaviour of the Coimbra Sand and, therefore, its liquefaction potential. An estimation of the linear critical void ratio line (CVR) parameters of both soils has made by doing logarithmic regressions with the final states of the undrained monotonic triaxial compression test.

Table 5.1 – Critical void ration line parameters

	Coimbra Sand	Silty Sand
λ	0.089	0.039
Γ	2.25	1.78

A typical set of undrained cyclic torsional shear test loading test results for Coimbra Sand is shown in figure 5.2. Throughout the test, it wasn't possible to maintain CSR constant - (a) and (d). It wasn't possible to determine whether this behavior was caused by the soils's softening or if the loading frequency was too high and therefore not giving enough time to the speciment to react to the loading. For both Coimbra Sand and SIlty Sand, at the beginning of cyclic loading the pore water pressure increases gradually and stable hysteresis were formed. When the pore water pressure reaches 70 % of the effective confining stress, a stage of liquefaction takes place characterized by a sudden large increase of pore pressure to become almost equal to the effective confining stress. Also this liquefaction stage is characterized by the formation of instable hysteresis.

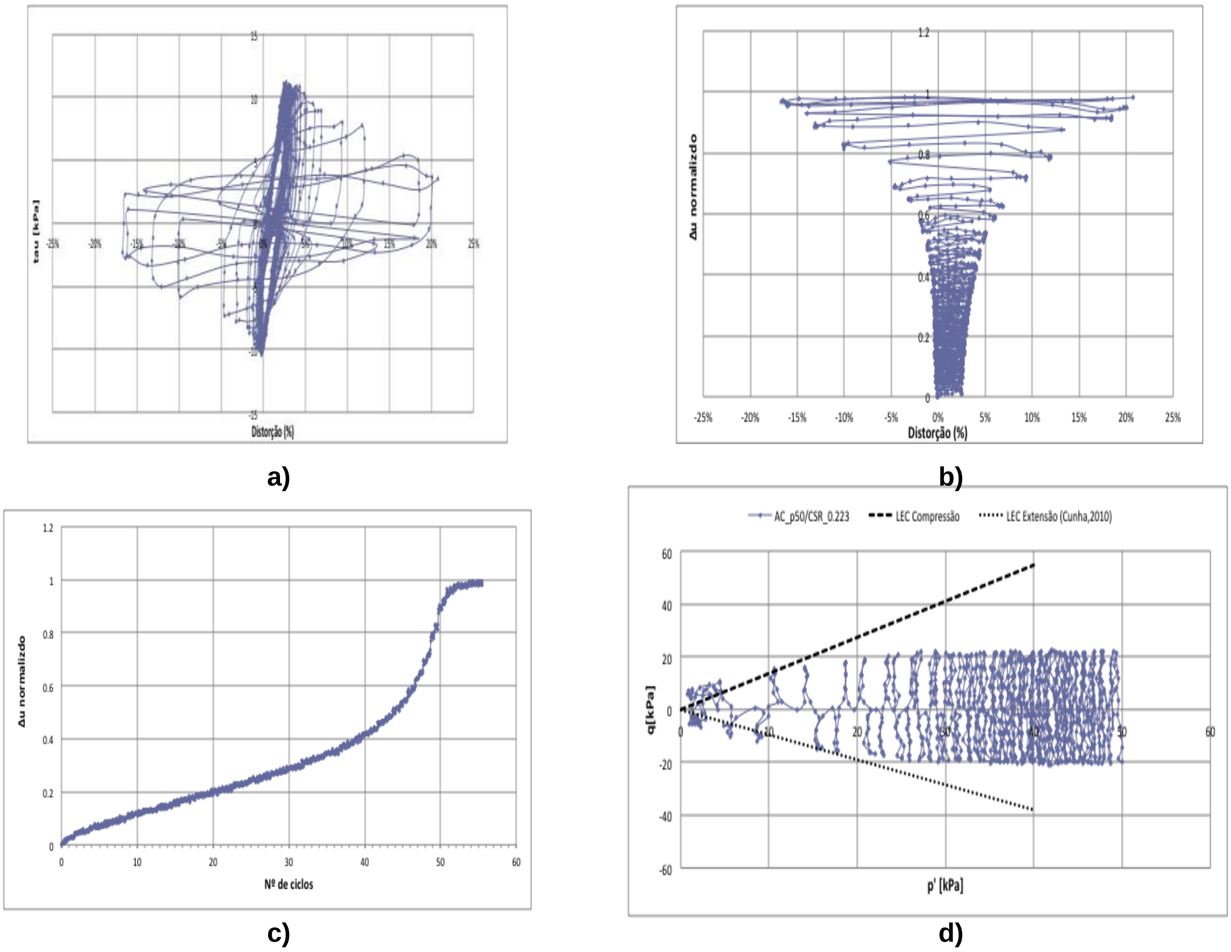


Figure 5.2- Example of undrained cyclic torsional shear test loading test results (AC_p50/CSR_0.223) : a) $\gamma - \tau$; b) $\gamma - \Delta u/\sigma_c$; c) $N - \Delta u/\sigma_c$; d) $p' - q$

All specimens tested underwent liquefaction after some cyclic loading. For a constant *CSR*, the Silty Sand's specimens need less number of cycles to achieve liquefaction than the Coimbra Sand specimens (figure 5.3). In other words, the undrained cyclic torsional shear test, -for the range of CSR values that were tested - showed that the presence of non-plastic fines reduces the Coimbra Sand's resistance to liquefaction, under cycle loading. There is some possibility that the Silty Sand liquefaction resistance could be higher than the Coimbra Sand, for CSR greater than 0.25 or 0.3, if the logarithmic regressions lines obtain for the Silty Sand maintain the same tendency for bigger CSR (figure 5.3).

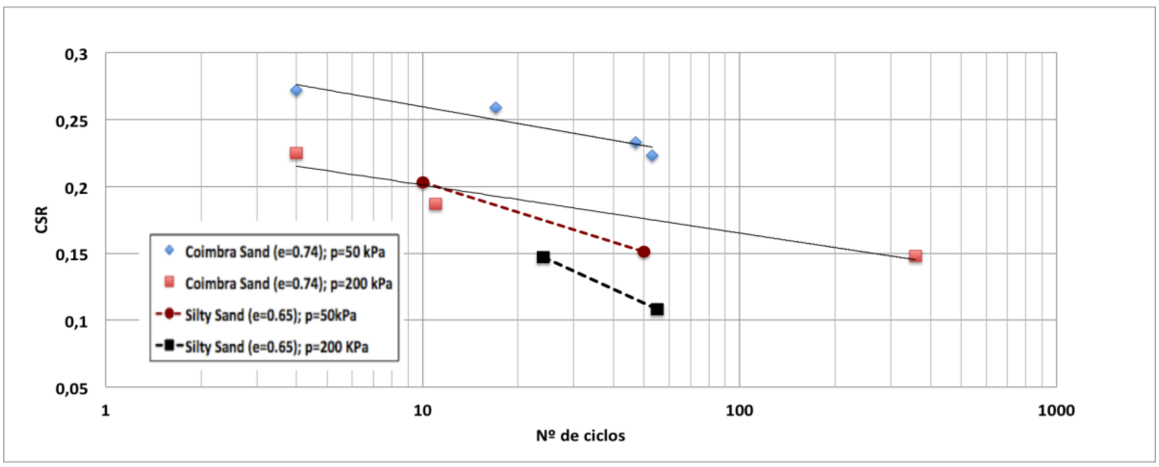


Figure 5.3 – Liquefaction curves

6 NUMERICAL SIMULATION

The next step was to make numerical simulation to replicate the experimental test. The numerical tool used was the GEFDYN software, developed in the *École Centrale Paris,* which included the Hujeux constitutive law. The following Hujeux constitutive parameters were used for numerical simulation:

Table 6.1 – Hujeux parameters for the Coimbra Sand and Silty Sand

		Coimbra Sand			Silty Sand		
		e=0.74		e=0.54	e=0.65		e=0.54
	$p[kPa]$	50	200	50	50	200	200
Indirect Parameters	a_1	0.01	0.045	0.006	0.005	0.0045	0.005
	a_2	0.02	0.09	0.003	0.01	0.009	0.01
	c_1	0.51	0.52	0.06	2.0	0.6	2.0
	c_2	0.205	0.26	0.03	1.0	0.3	1.0
	$\alpha_{\psi_{static}}$	1	3.5	1	1.0	1.0	1.0
	$\alpha_{\psi_{dynamic}}$	0.03			0.4		
	b	0.1			0.1		
Direct Parameters	$G_0\ [MPa]$	93.28	162.4	136.9	43.0	74.5	95.4
	$K_0[Mpa]$	155.5	270.7	228.2	72.3	124.1	159
	β	19.6		17.3	44.62		39.49
	$p'_{co}[kPa]$	311.2		2944.3	31		517.35
	$\psi\ (°)$	33.9			32.7		
	$\phi_{pp}(°)$	33.9			32.7		
	d	3.1			12.99		

The direct parameters can be obtained for experimental data or known correlations. The indirect parameters are obtain by calibration or adjustment of simulated curves with the experimentaltypical set of undrained monotonic triaxial compression simulation and the comparison with the experimental results for Coimbra Sand, in loose state and for p'=50 kPa, is shown in figure 6.1

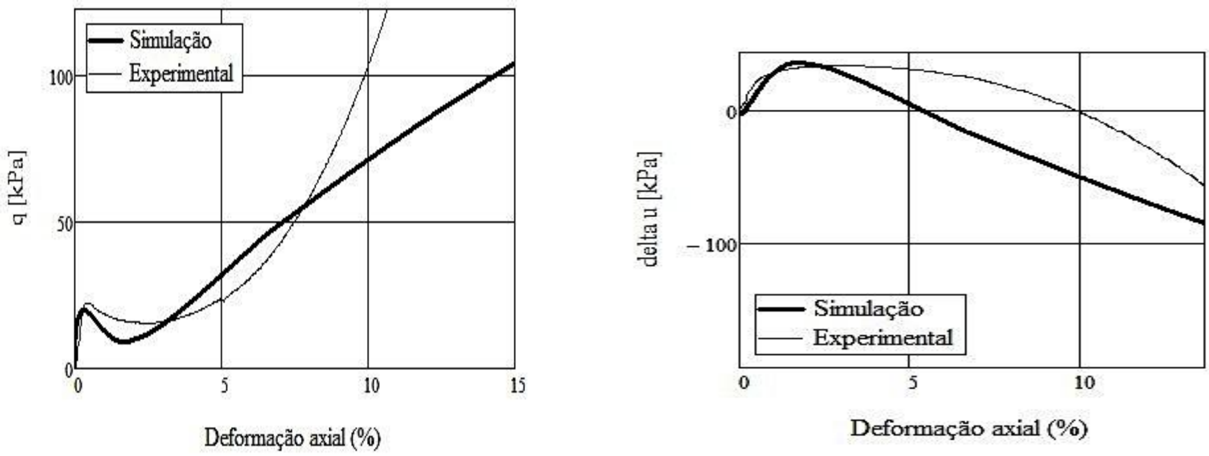
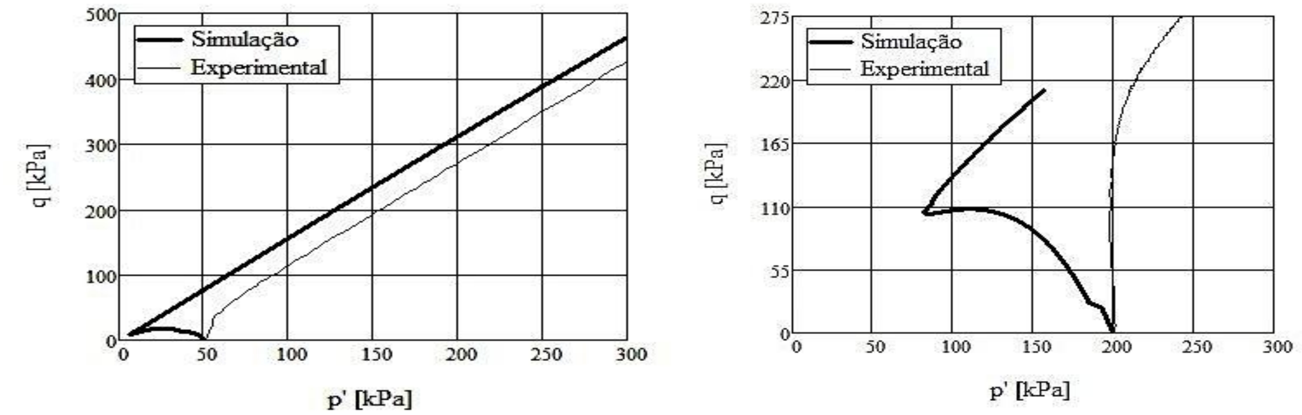


Figure 6.1 – Numerical simulation of the triaxial test TXAC_e0.71/p50 and the comparison with the experimental data - a) $\varepsilon_a - q$; b) $\varepsilon_a - \Delta u$;

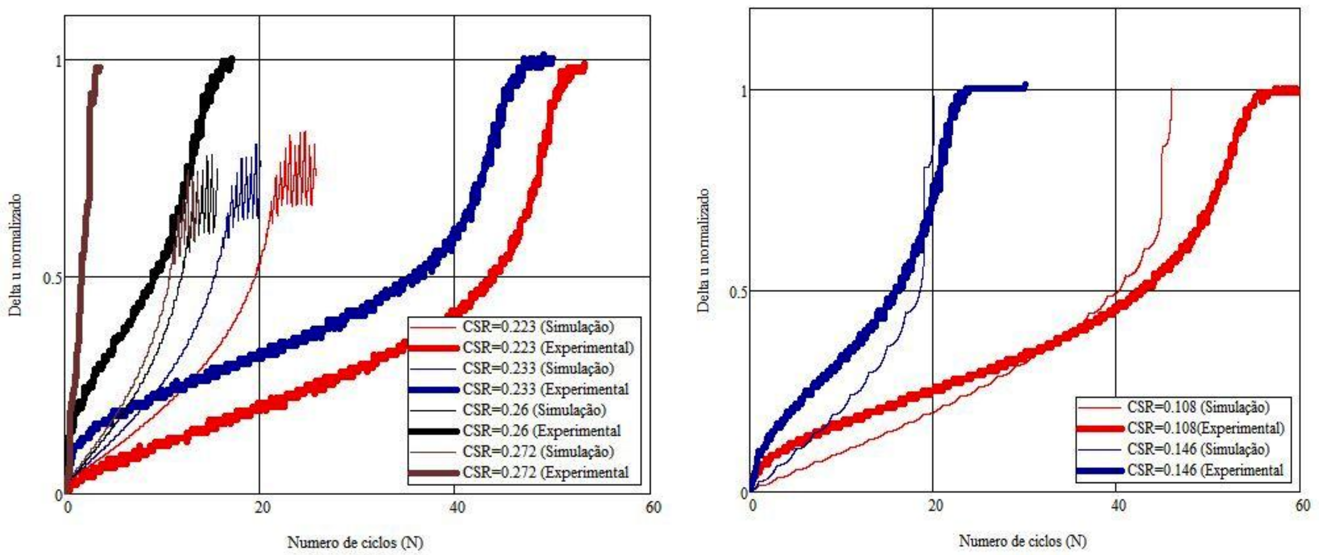
Although the adjustment with experimental and simulation data isn't prefect for axial deformation bigger than 2%, it is possible to see that the simulation reproduces the behavioural tendency of the triaxial experimental data. This set of results could be observed in the loose state of both soils. The quality of the adjustment tends to get worse with the increase of the p'. In the triaxial numerical simulation for denser state (e=0.54) in both soils, no adjustment was possible to made between the experimental and simulation data (figure 6.2):



a) b)

Figure 6.2 – Numerical simulation of the triaxial test in denser state (e=0.54) and the comparison with the experimental data, in $p' - q$ diagram;– a) TXAC_e0.54/p50 b) TXAS_e0.54/p200

Also, despite of several attempts to calibrate the parameter $\alpha_{\psi_{dynamic}}$, it was not possible to make, in the undrained cyclic torsional shear simulations, a reasonable adjustment between the simulation and experimental data (figure 6.3). For the undrained cyclic torsional shear simulations, the shear stress (or CSR) was kept constant:



a) b)

Figure 6.3 – Numerical simulation of the undrained cyclic torsional shear in both soils and the comparison with the experimental data, in $N - \Delta u/\sigma_c$ diagram;– a) Coimbra Sand b) Silty Sand

There is a suspicion that the main cause for the bad quality of the adjustments in the numerical simulations is that the direct parameters obtained are not representative of the both soils. Most of direct parameters, such as p'_{co}, β e o d, depends on the position of the CVR line. Since the CVR obtained in this work was only estimation and assume to be linear in the logarithmic scale, is possible that the real CVR of both materials is a non-linear line in logarithmic scale. That would explained why the quality of the adjustment gets worse for lowers values of void ratio. On the undrained cyclic torsional shear simulations, despite the contribution of the CVR line's uncertain position, one of the causes for the bad quality of the adjustments in the numerical simulations was the fact that the shear stress was constant along the simulation, while in the experimental testing it wasn't possible to maintain the shear stresses constant. That's why in the simulation the liquefaction was achieved for lower cycles than the experimental data.

7 CONCLUSIONS AND SUGGESTION FOR FUTURE WORKS

At the end, it has been proved that the non-plastic fines influence the Coimbra Sand's liquefaction, by the following reasons:

- Increase the liquefaction susceptibility on Coimbra Sand, in monotonic loading
- The Coimbra Sand with 20% of non-plastic needs less numbers cycles that the situation without fines, to achieve liquefaction, for a given and constant CSR between the range of values studied in this work
- There is some possibility that the Silty Sand liquefaction resistance could be higher than the Coimbra Sand, for CSR bigger than 0.25 or 0.3, if the logarithmic regressions lines obtain for the Silty Sand maintain the same tendency for bigger CSR. Since only 2 points were obtain for each confinement pressure on the Silty Sand, no clear conclusions can be drawn.

In general, the non-plastic fines lower the Coimbra Sand's liquefaction resistance, in cycle and monotonic loading.

According to the numerical simulations, it was possible to conclude that the critical state approach used in this work was not enough to do a exact determination of the CVR lines, for both soils. Is possible that the effective confinement pressure used in this work wasn't big enough to achieve the liquefaction and to well observer the critical state of both soils triaxial specimens

Based on the results obtained in this work, the following suggestions are made for future works:

- It will be necessary perform a mechanical and physical characterization on the Coimbra Sand for other non-plastic fines percentage rather than 20%, in order to understand the evaluation of the Coimbra Sand's liquefaction resistance with the increase amount of non-plastic fines.

- Is important to apply bigger effective confinement pressure in order to achieve liquefaction on the undrained monotonic triaxial compression.
- Carry out undrained cyclic torsional shear:
    - For higher CSR values, to see if the Silty Sand liquefaction resistance is greater that the Coimbra Sand.
    - With lower loading frequency (ex:0.1 Hz) to understand if in those conditions, the CSR value drops again during the test.
- A complementary study of critical state of the Coimbra Sand, with or without fines, is important to be made in order to understand it's susceptibility to liquefaction and to obtain better quality adjustments between the numerical simulations and experimental data.
- Perform undrained cyclic torsional shear simulations with CSR not constant.

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