# Cyclic simple shear and triaxial tests on Lisbon Region liquefiable sands

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ABSTRACT: The Lower Tagus River Valley area, in Lisbon, Portugal, has been studied for having a high potential liquefaction risk, due to the geological and geomorphological settings and the seismicity associated to the region. This study focuses on the comparison of the cyclic behaviour of three sands collected on site, using two distinct laboratory procedures. Tests with different values of Cyclic Stress Ratio were conducted in both cyclic simple shear and cyclic triaxial testing apparatus to assess the CRR curves of each material in reconstituted conditions. The comparison of the results highlights the main differences caused by distinct cyclic loading stress paths especially in view of the results when inversion or rotation of the principal stresses are induced. The tests also investigate the influence of the fines content and the cycling frequency in the number of cycles required for liquefaction to occur, while discussing the criteria for limit/instability level.

## 1 INTRODUCTION

The Lower Tagus River Valley, located in Lisbon, Portugal, has been affected by severe earthquakes along its history, causing serious damages and many casualties. It is an area with high potential liquefaction risk, due to the geological and geomorphological settings and the seismicity associated to the region (Saldanha et al. 2018).

Within the scope of the European H2020 LIQUEFACT (www.liquefact.eu) research project, a pilot site in this region was set-up where "undisturbed" and "integral" samples were collected. The laboratory testing of these materials for distinct initial conditions is designed to assess their geomechanical behaviour under different cyclic action scenarios, especially when the purpose is to calibrate constitutive models parameters for numerical analyses.

Cyclic liquefaction is affected by various factors, namely load characteristics, soil type, initial shear stress, shear strain amplitude, age or hydraulic conditions (NASEM 2016). The effect of non-plastic fines on soil behaviour has been the focus of much research work. Cubrinovski & Ishihara (2002) and Lade et al. (1998) studied the effect of fines in the packing of particles (maximum and minimum voids ratio), Carrera et al. (2001) tested mine tailings and found that the location of NCL varied with fines content (FC) and Soares & Viana da Fonseca (2016) showed the same for a silt and a silty sand. Furthermore, many authors (Chang 1990, Vaid 1994, Qadimi & Coop 2007, Dash et al. 2010) have studied the influence of FC in the cyclic behaviour of soils. The effect of the presence of non-plastic fines on the soil's cyclic behaviour is a controversial theme. Some studies suggest that the addition of fines to sand increases the liquefaction resistance while others report that the liquefaction resistance decreases with increase of fines content. Chang et al. (1982) verified a general increase of liquefaction resistance with the addiction of fines, for FC >20%, which was proceeded by a drop in resistance for FC<10%. Amini and Qi (2000) also experienced an increase in resistance with increase of fines content, when 10%<FC<50%. On the other hand, many other studies state that the increase of FC decreases the soil resistance to liquefaction (Chang 1990, Vaid 1994, Thevanayagam 2007), for FC between 0–30%. These studies have shown that liquefaction resistance reduces with increase of fines content up to a threshold value, after which the liquefaction resistance increases. Some explanations about sand liquefaction resistance depending on fines content are the "limiting silt content" by Polito & Martin (2001) or the "intergranular void ratio" introduced by Thevanayagam (2007) and Thevanayagam et al. (2016). Zuo & Baudet (2014) found that there is a difference between the threshold value found by experimental data and theoretical methods and this difference is less evident when there is more discrepancy between sand and fines sizes.

Seed & Peacock (1971) compared simple shear tests on $K_0$-consolidated specimens and triaxial tests on isotropically consolidated specimens and concluded that the Cyclic Resistance Ratio of simple shear tests ($CRR_{SS}$) is related to the Cyclic Resistance Ratio of cyclic triaxial tests ($CRR_{TX}$) by means of a coefficient, $c_r$, according to $CSR_{SS} = c_r\, CSR_{TX}$. This coefficient varies between 0.55-0.70 for clean sands with relative densities of 40-85% (Kokusho 2017). On the other hand, Ishihara & Yasuda (1975) compared simple shear and cyclic triaxial tests both performed with specimens under isotropic consolidation. They found a good coincidence of the results of the two tests, showing no significant difference in liquefaction resistance when the specimens were isotropically consolidated in both test methods. Kramer (1996) compiled some references on this topic, in which $c_r$ varies between 0.55 and 0.72 for $K_0 = 0.4$ and 1 to 1.15 for $K_0 = 1.0$ (Finn et al. 1971, Seed & Peacock 1971, Castro 1975).

The frequency of loading cycles also influences the soil resistance to liquefaction. Once again, there is no consensus on this subject as some authors (Chang et al. 1982, Rascol 2009) concluded that the higher the frequency the more number of cycles are required for liquefaction to occur but others (Dash & Sitharam 2016) stated that the number of cycles decreases as the frequency increases.

The present paper is a contribution to the studies being performed in these soils, to evaluate the liquefaction susceptibility to cyclic loadings and the behaviour of the materials in case of an earthquake. It complements the studies performed at FEUP in the evaluation of soil liquefaction potential based on laboratory data. This work integrates an initial performance of cyclic simple shear and cyclic triaxial tests to analyse the correlations between the corresponding results and the influence of the loading conditions in the results.

## 2 MATERIALS

The materials designated as S1 were selected from the samples collected with a Mazier Sampler (Viana da Fonseca & Pineda 2017). The material S1_M2 was collected at a depth of 2 m below the surface and S1_M7 at 7 m depth. The NB1 material was obtained from a significant weight of sand retrieved in an excavation at a depth of 4-5 m. This soil was air dried and homogenised to have a representative quantity of soil for reconstituted samples (Molina-Gómez et al. 2018). The soils constitute poorly graded sands with different fines content and low uniformity coefficients. The basic properties of the materials are in Table 1 and Figure 1 presents the grain size distribution curves. The soils have no plasticity and are silica sands with around 65% quartz and 5-10% orthoclase. Sand S1_M2 has the highest percentage of fines among the analysed materials while S1_M7 and NB1 have similar FC and grain size curves.

Table 1. Properties of the tested materials.

| Type | S1_M2 | S1_M7 | NB1 |
|---|---|---|---|
| Specific gravity | 2.651 | 2.643 | 2.640 |
| $D_{50}$ (mm) | 0.32 | 0.40 | 0.45 |
| $C_U$ | 3.76 | 1.81 | 2.16 |
| $C_C$ | 1.01 | 0.89 | 0.90 |
| Fines Content (%) | 9.15 | 2.10 | 2.87 |

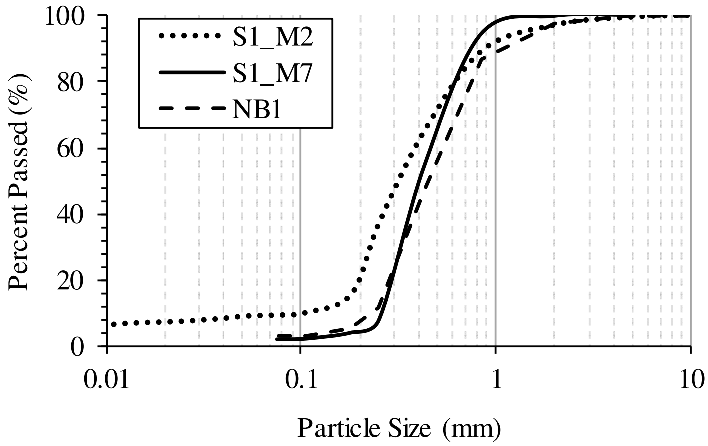


Figure 1. Grain size distribution curves.

# 3 EXPERIMENTAL PROGRAM

## 3.1 *Equipment*

The cyclic simple shear tests were carried out using two different cyclic simple shear equipment, one in the geotechnical laboratory (LabGeoUL) of University of Ljubljana and another in LabGeoFEUP of the Faculty of Engineering of University of Porto. The equipment from LabGeoUL is an EP Servo Control Type, Model No. DTA-136 (Seiken, Inc) with a pneumatic servo controller EO-260 that allows the definition of the cyclic shear conditions. The equipment from LabGeoFEUP uses the software GEOsys 8.7.8 from Wille Geotechnik and allows the execution of static and dynamic shear tests with control of the sample pore pressures. The main differences between the two machines are the confining pressure medium, one with water and other with air, and the application of the horizontal force, one on top and other on the bottom of the specimen. The cyclic triaxial tests were performed in a triaxial cell and a hydraulic frame with a hydraulic system servo-actuator to induce controlled axial loads developed in FEUP (Viana da Fonseca et al. 2013).

## 3.2 *Test procedures*

The specimens were prepared with the moist-tamping technique and a water content of 5% to facilitate compaction until the required initial void ratio. On all tests, the procedures included percolation first with $CO_2$ and then with de-aired water, saturation until a minimum B parameter of 0.98, and isotropic consolidation until the desired initial stresses. For S1_M2 and S1_M7, the confining pressure applied was 70 kPa, determined based on the approximated *in situ* at rest stress state and the fact that the CSS equipment in UL does not have enough precision for low confining pressures. On the other hand, the consolidation of tests on NB1 was 100kPa. The dimensions of the specimens were 70 mm diameter and 140 mm height in triaxial tests and 71 mm diameter with variable height in cyclic simple shear tests (depending on the equipment used, 33 mm or 44 mm height for LabGeoUL and LabGeoFEUP equipment, respectively).

In the cyclic simple shear (CSS) the control of load induces the force horizontally. In this case, a rotation of the principal stresses is applied. In the cyclic triaxial tests (CTx), the load application is vertical. A rubber ring fixes the top cap to the plate attached to the piston and by previously inducing vacuum between the two parts (under very accurate constant loading control), allows inducing axial loading cycles in compression and extension, for specimens consolidated isotropically. The testing was performed under load control, choosing a specific amplitude corresponding to the desired CSR. In this case, there is an inversion of the principal stresses, as the deviatoric stress varies between positive and negative values.

## 4 RESULTS AND DISCUSSION

### 4.1 *Cyclic simple shear tests*

A series of tests was performed in the cyclic simple shear equipment, in both laboratories. The objectives were to find the liquefaction resistance curves for these materials and compare the results of three soils in terms of fines content. Table 2 presents a summary of the cyclic simple shear tests, the void ratio at the end of consolidation (prior to shear), the frequency of cycling and the confining pressure. The CSR of the cyclic simple shear tests is calculated as $CSR_{SS} = \tau_{cyc} / \sigma'_{v0}$. Two criteria were used to detect liquefaction triggering. As a first approach the criterion of pore pressure build up to 100% ($r_u = \Delta u / \sigma'_c = 1$) was adopted. However, the tests performed at LabGeoFEUP, namely the tests on NB1 material, were cycled at a high frequency (1 Hz) and the equipment was not able to maintain the tangential stress constant until $r_u$ reached 1, as the load control (PID) was not adequate. Thereby, to interpret the results of NB1, two curves were plotted. The NB1_max represents the number of cycles when $r_u$ reached 1, given that in the end part of the test, the CSR was no longer constant. This number of cycles was considered the maximum as it is the point where the pore pressure equals the cell pressure. The alternative approach was to plot a straight line from the origin to the point when the tangential stress begins to decrease (on the tangential stress *versus* vertical stress plot), and consider that number of cycles as the minimum (Fig. 2). The “real” liquefaction resistance curve is somewhere between these two curves. More tests with lower frequency of loading are being performed to correct these uncertainties.

Table 2. Cyclic simple shear tests.

| Specimen | Test number | e | Freq (Hz) | p'$_0$ (kPa) |
|---|---|---|---|---|
| S1_M2 | CSS1 | 0.65 | 0.1 | 70 |
| S1_M2 | CSS2 | 0.71 | 0.1 | 70 |
| S1_M2 | CSS3 | 0.63 | 0.1 | 70 |
| S1_M7 | CSS1 | 0.82 | 0.1 | 70 |
| S1_M7 | CSS2 | 0.81 | 0.1 | 70 |
| S1_M7 | CSS3 | 0.74 | 0.1 | 70 |
| NB1 | CSS1 | 0.77 | 1.0 | 100 |
| NB1 | CSS2 | 0.77 | 1.0 | 100 |
| NB1 | CSS3 | 0.68 | 1.0 | 100 |
| NB1 | CSS4 | 0.74 | 1.0 | 100 |

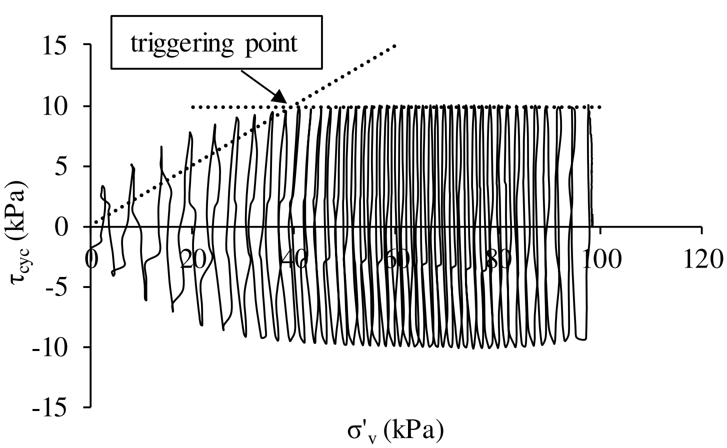

Figure 2. Approach to interpret the CSS tests on NB1

Figure 3 presents the results of the cyclic simple shear tests. Although in each material, one of the tests was performed with a voids ratio slightly different, the points seem to fit the curve so they were considered in the analysis. Examining the influence of fines content, and comparing S1_M2 with S1_M7, the soil with higher fines content (S1_M2 with 9.15% FC) has lower liquefaction resistance, as for the same value of CSR the number of cycles required for liquefaction is lower. This corroborates the hypothesis proposed by some authors, which state the cyclic strength of soils decreases with the increase in fines content up to a threshold value (Polito & Martin 2001, Thevanayagam 2007, Dash et al. 2010). Although the exact position of the NB1 curve is uncertain, it is clear that it will fall closer to S1_M2 than S1_M7. This contradicts the expected tendency, as NB1 has a similar grain size distribution and fines content as S1_M7. This behaviour is possibly related to particle shape and potentially fabric differences.

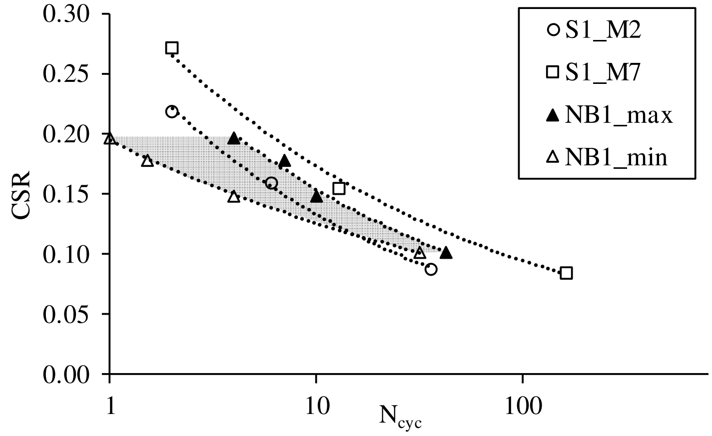

Figure 3. Cyclic simple shear test results

## 4.2 *Cyclic triaxial tests*

Additionally, some cyclic triaxial tests were performed in the same initial conditions and state as the CSS tests. Table 3 presents a summary of the cyclic triaxial tests. The criterion used to detect the initiation of liquefaction was the same as in the CSS tests ($r_u$ = 1). The CSR is calculated as $CSR_{TX} = \sigma_{dc} / (2\sigma'_{3c})$.

Table 3. Cyclic triaxial tests.

| Specimen | Test number | e | Freq (Hz) | p'$_0$ (kPa) |
|---|---|---|---|---|
| S1_M2 | CSS1 | 0.72 | 1.0 | 70 |
| S1_M2 | CSS2 | 0.72 | 1.0 | 70 |
| S1_M2 | CSS3 | 0.72 | 0.1 | 70 |
| S1_M2 | CSS4 | 0.74 | 1.0 | 70 |
| S1_M2 | CSS5 | 0.71 | 1.0 | 70 |
| S1_M2 | CSS6 | 0.71 | 1.0 | 70 |
| S1_M7 | CSS1 | 0.81 | 1.0 | 70 |
| S1_M7 | CSS2 | 0.81 | 1.0 | 70 |
| S1_M7 | CSS3 | 0.81 | 1.0 | 70 |
| S1_M7 | CSS4 | 0.82 | 0.1 | 70 |
| S1_M7 | CSS5 | 0.82 | 1.0 | 70 |
| NB1 | CSS1 | 0.78 | 0.1 | 100 |
| NB1 | CSS2 | 0.77 | 1.0 | 100 |
| NB1 | CSS3 | 0.79 | 1.0 | 100 |
| NB1 | CSS4 | 0.78 | 1.0 | 100 |
| NB1 | CSS5 | 0.76 | 1.0 | 100 |

Figure 4 shows the cyclic resistance curves for the three materials. The frequency of the cyclic loading was 1 Hz in the majority of tests. However, one test with each material was performed with a frequency of 0.1 Hz (represented in the graphs by the open symbols). The lower frequency points seem to fit the curve for each material, therefore they were considered in the definition of the curve equation. This is not enough information to state any conclusion about the influence of frequency in the cyclic resistance of soils, but it justifies the comparisons made below and are in accordance with well known references (Beyzaei et al. 2018).

In the case of the cyclic triaxial tests, the effect of the fines content in the liquefaction resistance curves is not that evident as the NB1 curve has a lower slope. Nonetheless, comparing the S1_M2 and S1_M7 curves, the cyclic strength of soils seems to decrease with an increase in fines content, as occurred in the cyclic simple shear results.

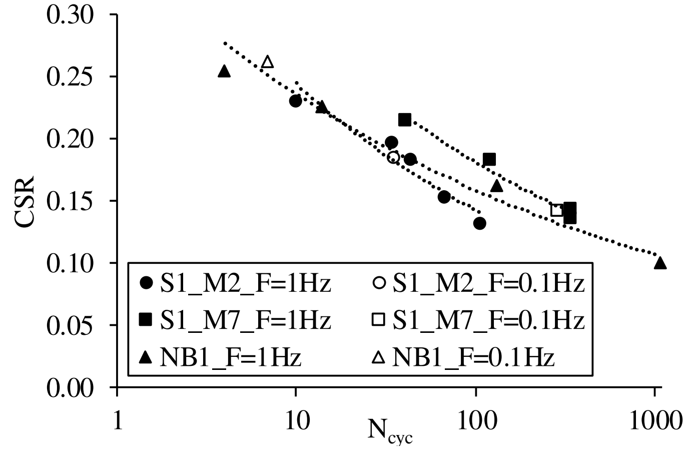

Figure 4. Cyclic triaxial test results

## 4.3 *Comparison of cyclic simple shear and cyclic triaxial tests*

Figure 5 presents the results of the CTx (filled symbols) and the CSS (open symbols) tests. Tests performed under cyclic triaxial conditions present higher resistance than cyclic simple shear tests, as the specimens require more cycles to reach liquefaction, in the same conditions. These conclusions contradict some predictions based on the research of other authors (Finn et al. 1971, Seed & Peacock 1971, Ishihara & Yasuda 1975) that found a good coincidence between the results of cyclic simple shear and cyclic triaxial tests when both specimens were consolidated in isotropic conditions.

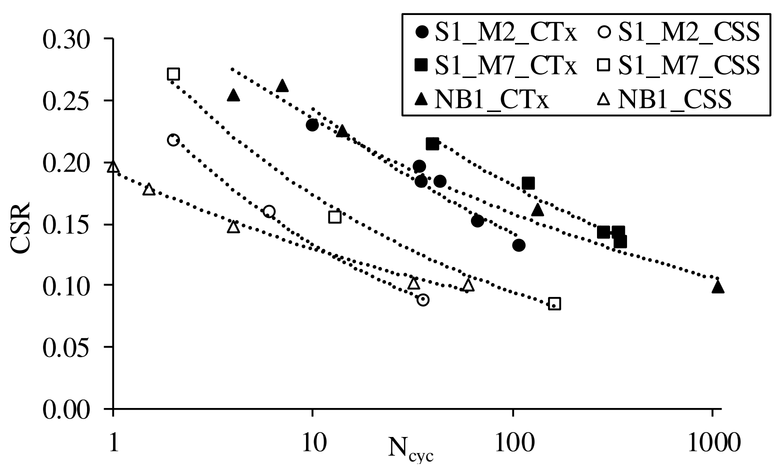

Figure 5. Comparison between CSS and CTx test results

Comparing the curves corresponding to the same material but different test method, a correlation between $CSR_{SS}$ and $CSR_{TX}$ based on the number of cycles necessary for liquefaction occurrence can be found. The parameter $c_r$ is the relationship between $CSR_{SS}$ and $CSR_{TX}$, defined in equations 1 and 2 for S1_M2 and S1_M7 respectively. Due to the uncertainty in the curve for NB1 in cyclic simple shear tests, a relationship for this material was not proposed.

$$c_r = \frac{CSR_{ss}}{CSR_{tx}} = 0.614{N_{cyc}}^{-0.056} \quad (1)$$

$$c_r = \frac{CSR_{SS}}{CSR_{tx}} = 0.673 {N_{cyc}}^{-0.055} \tag{2}$$

The plot of these curves is in Figure 6. It is perceptible that the $c_r$ value decreases with the number of cycles necessary to liquefaction. These results show that the $c_r$ varies significantly with the number of cycles. However, focusing the attention on the number of cycles that defines an earthquake motion to trigger liquefaction (between 10 and 15), the values of $c_r$ are between 0.53 and 0.60, similar to those adopted for the comparison of CSS on $K_0$-consolidated specimens and CTx on isotropically consolidated samples (Kramer 1996, Kokusho 2017).

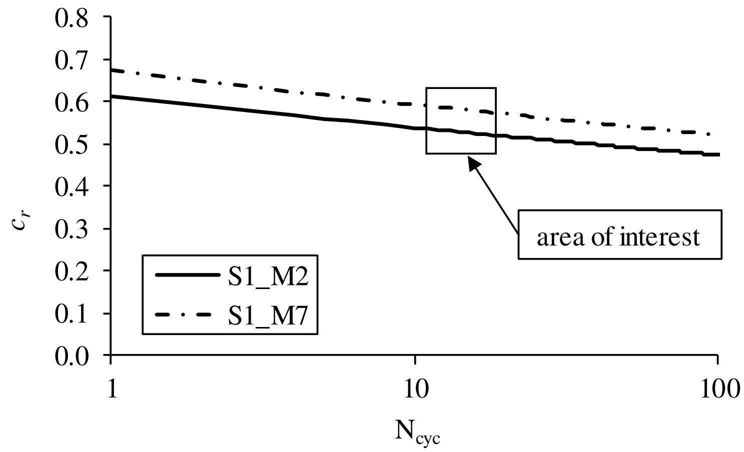


Figure 6. $c_r$ relationship with the number of cycles

## 5 CONCLUSIONS

This paper is a contribution to the studies performed in granular soils from Portugal territory to evaluate their liquefaction susceptibility to cyclic loading and their behaviour in case of seismic events. This work describes the preliminary results of tests in cyclic simple shear and cyclic triaxial tests. The influence of CSR on the number of cycles required for liquefaction to occur is discussed, as well as the influence of the loading pattern (inversion or rotation of the principal stresses) and the cyclic loading frequency in the specimens' behaviour. Based on the results obtained, the following conclusions arise:

- Within the percentages of fines used in this study, it seems that the material with higher percentage of fines has lower liquefaction resistance. This tendency is only clear in the CSS results comparing S1_M2 and S1_M7. The NB1 curve is closer to S1_M2 which contradicts the expected tendency, as NB1 has a similar grain size distribution and fines content as S1_M7. This behaviour might be related to particle shape and potentially fabric differences.
- Even though all tests were isotropically consolidated ($K_0$ = 1), the relationship between $CSR_{SS}$ and $CSR_{TX}$, $c_r$, is not 1;
- A relationship between $c_r$ and the number of cycles required to liquefaction was obtained and $c_r$ decreases with the increase of $N_{cyc}$;
- The cyclic loading frequency appears to not influence the liquefaction response of the samples in both cyclic simple shear and cyclic triaxial tests as the results of tests with different frequencies fit the same liquefaction resistance curves.

These results are very limited to make any clear assumption of the observed trends, so more tests are being conducted to confirm them, namely with different fines contents, different densities and for different cyclic conditions.

## ACKNOWLEDGEMENTS

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