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Sand liquefaction in simple shear tests

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ABSTRACT

Liquefaction is a phenomenon marked by a rapid loss of soil strength and stiffness, which generally occurs in loose saturated sandy deposit during earthquake because of the generation of excess pore water pressure. Several experimental researches concluded that liquefied soil behaves as a fluid during ground movement, but after the earthquake motion ceases, due to the dissipation of excess pore water pressure, the liquefied soil recovers its initial stiffness and returns to behave as a solid. Liquefaction resistance of sandy soil can be studied by means of Cyclic Simple Shear (CSS) test or Cyclic Triaxial (CTX) tests. While CTX tests are widely used in liquefaction studies due to their simplicity, CSS tests are more representative of stress conditions produced during an earthquake by simulating the continuous rotation of the principal stress axes. In this research the preliminary results of CSS tests carried out with confining rings on the sandy samples retrieved in the South of Sicily are reported. The apparatus is described in detail. All samples used were obtained from the same type of Italian sand by using same preparation method to minimize the number of factors influencing the results. Moreover, all tests were conducted by a single operator. All experimental results are reported in the plane cyclic resistance ratio (CRR) and number of cycles where liquefaction occurs (N_{liq}) in order to assess the liquefaction phenomenon.

Keywords: Liquefaction, Cyclic Simple Shear Test, cyclic resistance curve.

1. Introduction

During the last century, earthquakes have been responsible for many human casualties and very high economic and social damage. One of the associated phenomena is the liquefaction of soils, which can have devastating consequences, as evidenced by recent events in Japan (Boulanger 2012) in New Zealand (Cubrinovski et al. 2011) and in the north of Italy, affected in May 2012 by an earthquake of moderate magnitude (Fioravante et al. 2013).

Liquefaction is a phenomenon that occurs in saturated loose granular soils. It is associated with the increase in pore water pressure and consequent decrease of the mean effective stress, which causes the soil resistance to decrease until zero. The soil begins to behave like a liquid, not showing resistance. The build-up of pore pressure is due to the non-existence of drainage in quick loadings which prevents its immediate dissipation. When the pore pressure increases enough to equal the total stress, the effective mean stress is reduced to zero and liquefaction occurs.

Earthquake-induced liquefaction is one of the most dangerous and catastrophic phenomena. As a consequence of the rapid and complete loss of soil strength and stiffness, serious damage to engineering structures occurs (Bardet and Kapuskar 1993; Cetin et al. 2004; Chu et al. 2006; Cubrinovski et al. 2012; Yamaguchi et al. 2012).

To understand the liquefaction phenomenon a deep knowledge of the undrained cyclic behaviour of sandy soils results necessary. Cyclic Triaxial (CTX) tests (Castelli et al. 2017; 2019; Finn et al. 1971; Flora et al. 2012; Lentini and Castelli 2019; Seed and Lee 1966; Silver at al. 1980) and Cyclic Simple Shear (CSS) tests (Da Fonseca et al. 2015; Finn et al. 1971; Ishihara and Yamazaki 1980; Porcino et al. 2008; Silver et al. 1980) are useful tools for evaluating the liquefaction behaviour of soils.

CSS tests are more representative of stress conditions produced during an earthquake by simulating the continuous rotation of the principal stress axes compared with that in the CTX test. On the other hand, while the CSS test is more realistic for representing sand liquefaction behaviour under earthquake loading, the significant no uniformity of stresses and strains is its major disadvantage.

In the CSS test, the soil element, consolidated under the k_0 condition, a vertical effective stress (σ'_{v0}) is applied to the horizontal plane and the horizontal deformation is restrained by a wire-reinforced membrane or stacked rings.

Additionally, a cyclic shear stress (τ_{cyc}) is applied to the horizontal plane to simulate the vertically propagating shear wave generated by earthquake loading.

The Cyclic Stress Ratio (CSR) in the CSS test is defined as:

$$CSR = \frac{\tau_{cyc}}{\sigma'_{v0}} \tag{1}$$

Defining N_{liq} as the value of N_{cyc} needed to reach liquefaction for a given value of CSR, the Cyclic Resistance Ratio (CRR) can be also identified as the applied cyclic stress ratio for which $N_{cyc} = N_{liq}$. The obtained curve in the plane CRR-N_{liq} identifies the soil Cyclic Resistance Curve, which depends on grain size distribution, soil fabric, state conditions and degree of saturation (Verdugo and Ishihara 1996; Huang et al. 2004; Mele et al. 2019; Lirer and Mele 2019).

Liquefaction criterion can be defined on the basis of either the pore pressure ratio (r_u) or the axial/shear strain. According to pore water pressure based criteria, liquefaction occurs when the excess pore pressure ratio (r_u) is equal to 1.0, where r_u is defined as the ratio between the excess pore water pressure (Δu) and the effective confining stress (σ_c'). Ishihara (1993) suggested a threshold of r_u equal to about 0.90 - 0.95.

Regarding to the strain criteria, axial strain in double amplitude ε_{DA} in CTX tests and shear strain in double amplitude γ_{DA} in CSS tests are taking into account for the identification of N_{liq} in accordance with the recommendation of the National Research Council (NRC 1985).

CTX specimens were deemed to undergo liquefaction when the axial strain in double amplitude ε_{DA} exceeded 5%, as proposed by Ishihara (1993).

CSS specimens were deemed to undergo liquefaction when the shear strain in double amplitude γ_{DA} exceeded 7.5%, as suggested by other researchers.

In this paper, the preliminary results of liquefaction potential obtained only from the CSS tests are reported for sandy soil of the Pozzallo port area in the South Sicily in terms of Cyclic Resistance Curve. The future final goal of the research activity will that to compare the results obtained by CSS tests with those derived by CTX tests for the same samples.

2. Case study of the Pozzallo port: geotechnical characterization

In the framework of the interventions for ensuring safety of the existent maritime works at Pozzallo port, within the province of Ragusa in the South of the Sicilian Region, an extensive in situ investigation was preliminary carried out, aiming to define the ground layering and mechanical behaviour of the soils.

Among in situ test, boreholes, Standard Penatration Test (SPT), Down-Hole tests (D-H) and Multichannel Analysis Surface Waves (MASW) tests were performed.

In detail, 7 boreholes of which 4 (S01, S03, S05, S06) at a depth of up to 30 meters and 3 (S02, S04, S07) at a depth of up to 45 meters (Fig. 1) were drilled.

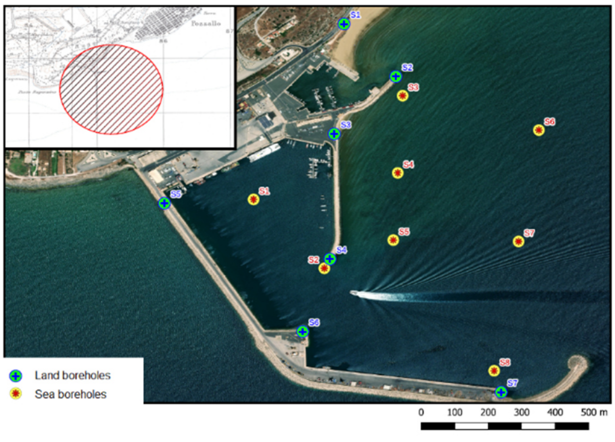


Figure 1. Plan view of the boreholes.

During the drilling, 27 SPT were carried out in all the boreholes, except S01 and S08. Twenty-six undisturbed and eight disturbed samples were retrieved from boreholes to be analysed by standard and advanced laboratory tests.

Finally, 8 offshore boreholes were carried on up to the depth of 6 meters down the seafloor from which 8 disturbed samples were retrieved.

The results obtained by SPT are reported in Fig. 2 in terms of number of blows plotted versus depth. In particular, the number of blows N_{SPT} required to produce a penetration of 300 mm is regarded as the penetration resistance. The blows for the first 150 mm (N_1) of penetration are not taken into account; those required to increase the penetration from 150 mm to 450 mm (N_2+N_3) constitute the requested value N_{SPT}.

The results of SPT tests were also used to determine the relative density (Fig. 3) of the soil involved in the study area of the Pozzallo port by means of the best known and most referenced estimation method, developed by Gibbs and Holtz (1957) based on data obtained from calibration chamber tests performed at the US Bureau of Reclamation.

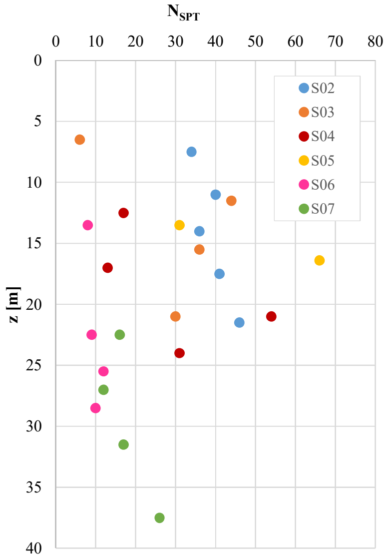


Figure 2. Results of SPT tests.

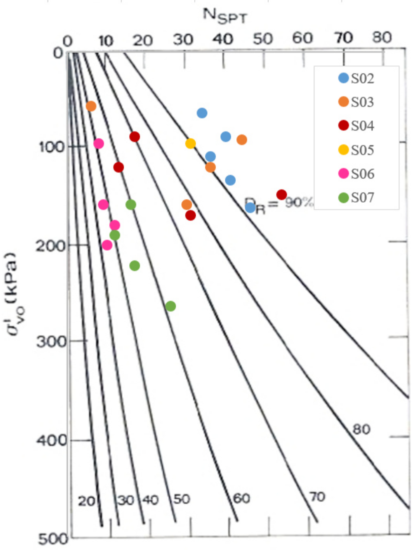


Figure 3. Relative density derived by Gibbs and Holtz (1957) chart.

Fig. 3 highlights low values of relative density especially for the surface sample of the borehole S03 and for S06, by classifying the soil as loose to medium dense sand.

Furthermore, as an example, the particles size distribution curves of two shallow samples retrieved by the boreholes S03 and S06 are compared in Fig. 4 with the particle size range suitable to liquefaction, based on the suggestion of the Italian Technical Regulation (NTC 2018).

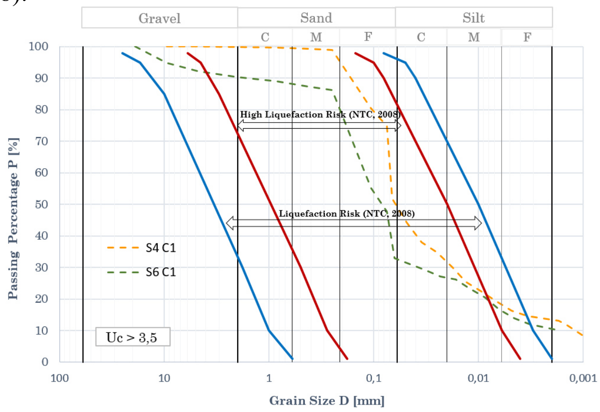


Figure 4. Ranges of grain size distribution of soil along with the boundaries of liquefaction susceptible soil according to NTC (2018)

Taking into account the values of relative density, the results of SPT tests but also the depth of water table and the particle-size distribution of the tested samples, liquefaction phenomena may affect the study area, according to the NTC 2018.

Ground investigation was integrated with careful laboratory testing including standard classification tests and CSS tests on undisturbed specimens to study the liquefaction potential.

3. Experimental program

The advanced laboratory tests were performed by means of the apparatus available (Fig. 5) at the Soil Dynamics and Geotechnical Engineering Laboratory of the University Kore of Enna (Italy).

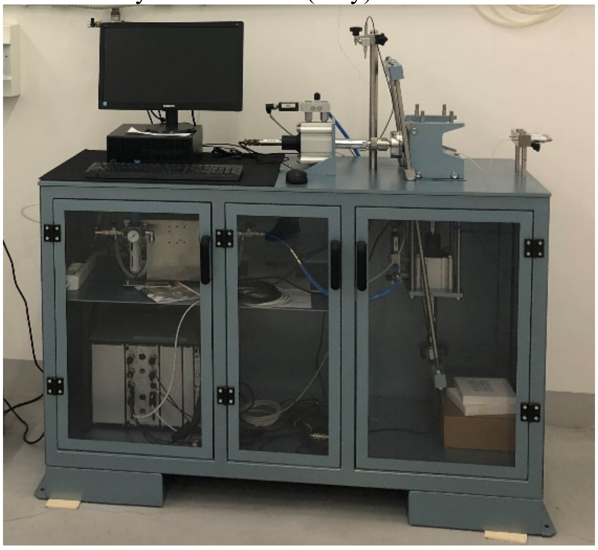


Figure 5. CSS device available at the University Kore of Enna (Italy).

Stress-controlled CSS tests with constant volume approach were carried out for low level of relative density (40 ÷ 50%). The CSS tests were performed according to the ASTM standard D8296-19.

All the samples were prepared by dry tamping technique, were tested under effective stresses of 100 kPa and the applied cyclic loading frequency was 0.5 Hz with sinusoidal loading function.

3.1. Test apparatus

The equipment used for the tests is Cyclic Simple Shear Apparatus. The scheme of the concept is shown in Fig. 6.

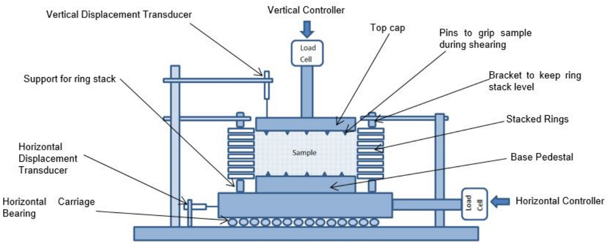


Figure 6. Scheme of the CSS apparatus.

The shear strain is induced by horizontal movement at the bottom of the sample relative to the top. The diameter of the sample remains constant, therefore any change in volume can only be as a result of vertical movement of the top platen.

The system is designed to allow a sample to be consolidated and then sheared under constant volume conditions (simulating an undrained shear of a saturated specimen).

The sample with 70 mm in diameter is positioned on a pedestal and is supported laterally by a rubber membrane secured with O-rings. To maintain a constant diameter throughout the test the sample is restrained by a series of slip rings (Fig. 7).

During shearing the rings slide across each other while keeping the diameter constant. The vertical height of the sample is maintained constant by the vertical actuator under closed-loop control with feedback from the vertical displacement transducer.

The main system components are: base system, integrated multi-axis control system, load cells, horizontal and vertical displacement transducer.

The base system consists of a simple shear load frame fitted with an air receiver with servo-valves for controlling vertical and horizontal load-displacement. It incorporates a control and data acquisition system with two 5 kN actuators. The horizontal and vertical actuators are fixed to the frame, which supplies the reaction to the forces applied. Each actuator has an internal displacement transducer, which relays the actuator piston position back to the computer. The sample is set up in the machine, which has a rigidly fixed top half and a moving bottom half. The top half houses the 50 mm diameter vertical ram. This is housed in a linear bearing to allow vertical movement and prevent horizontal movement. The bottom half is mounted on roller bearings as in a standard shear box.

The integrated multi-axis control system is a compact self-contained unit that provides all critical control, timing and data acquisition functions for the test and the transducers. The control module has two channels, dedicated to the vertical and horizontal actuator for load/displacement respectively. The integrated multi-axis control system directly controls the servo-valve to apply the requested loading rate or waveform.

Two 5 kN load cells are fitted in-line with the horizontal and vertical actuators. The load cells are fitted with a calibration module, allowing the transducers to be changed or moved within the data acquisition system without the need to recalibrate them.

Horizontal displacement transducer ± 15 mm is built into the actuator. It measures the actuator piston position and can also be used as the control transducer for the cyclic strain test. Vertical displacement transducer is calibrated over ± 2.5 mm for controlling the sample height.

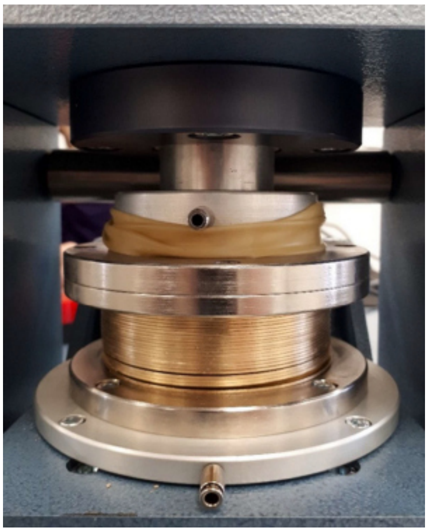


Figure 7. Restrained sample by slip rings.

3.2. Sample preparation and test programs

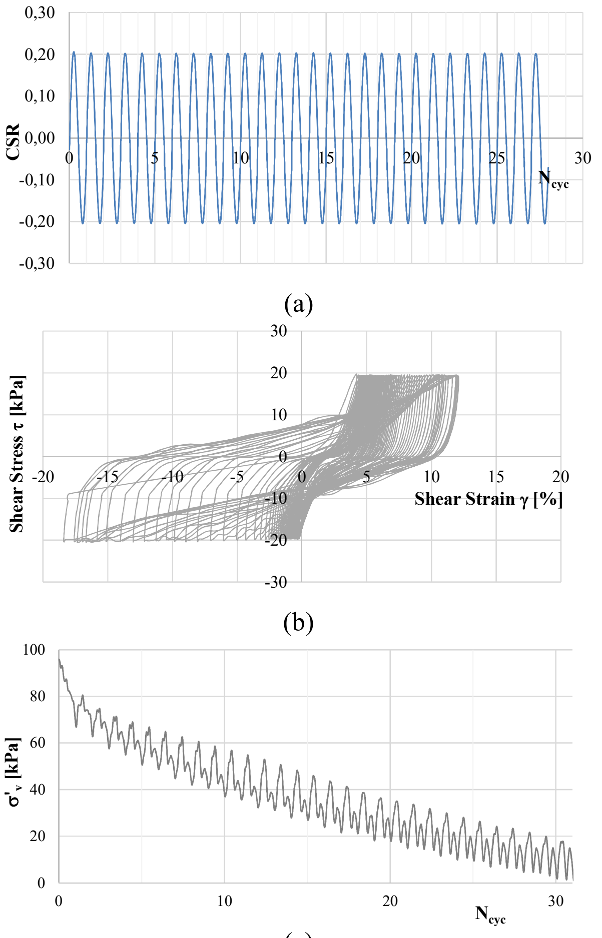
Cylindrical specimens with dimensions of 70 mm (diameter) and 20 mm (height) were reconstituted using the dry compaction technique. The amount of dry sand used each time was identical, and the sand was compacted lightly to achieve the desired height. The relative densities of the specimens were determined from the sand mass and the specimen volume after consolidation. The specimens are not fully saturated because back-pressure cannot be applied in the equipment.

Loading was applied in a stress-controlled mode under undrained conditions. A loading frequency of 0.5 Hz (reflecting a sinusoidal function) was used for obtaining suitable input and output responses, and the tests were controlled until the specimen deformation reached a level where the specified axial strain level was exceeded.

Sand specimens were consolidated under vertical effective stresses of 100 kPa, All the specimens were tested under undrained shear conditions by imposing constant volume conditions. Furthermore, the excess pore pressure generated in the cyclic shear phase was equal to the change in the vertical effective stress.

4. Results and discussion

Liquefaction criterion can be defined on the basis of either the pore pressure ratio or the shear strain, as previously mentioned. In this study, for each applied CSR, the value of N_{liq} was computed with both stress (r_u = 0.9) and strain based criteria (γ_{SA} = 3.75% in single amplitude). The two criteria gave generally similar results for the tested specimens. As an example, Fig. 8 shows the results of the CSS tests in terms of the applied value of CSR (Fig. 8a) that for this sample is 0.21, the hysteresis loop (Fig. 8b) and the effective vertical stress plotted against the number of cycles.



(a)

(b)

(c)

Figure 8. Results of the CSS test.

Fig. 9 presents the comparison between the two liquefaction criteria used to define N_{liq}.

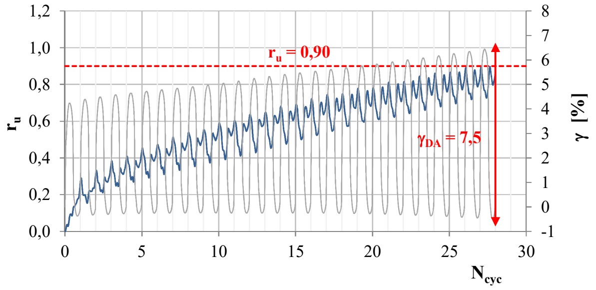


Figure 9. Results for CSR 0.21.

In particular, the results obtained for CSR = 0.21 highlights that the cyclic number obtained for stress (r_u = 0.9) and strain criteria (γ_{DA} = 7.5% in double amplitude) is similar for this specimen. Generally, for all tested samples, similar values of N_{liq} was found by using both stress and strain criterion.

The goal of the undrained CSS tests is that to quantify the soil resistance to earthquake induced liquefaction, expressed by the Cyclic Resistance Ratio (CRR).

Defining N_{liq} as the value of N_{cyc} needed to reach liquefaction for a given value of CSR, the CRR can be also identified as the applied cyclic stress ratio for which $N_{cyc} = N_{liq}$. The obtained curve in the plane CRR-N_{liq} identifies the soil Cyclic Resistance Curve. For this reason, the results of the tests are plotted in terms of the well-known cyclic resistance curve CRR - N_{liq}.

Fig. 10 shows that the sandy soil needed around 14, 28 and 264 cycles respectively to liquefy (for different values of CSR equal to 0.13, 0.21, 0.25).

Finally, the data were fitted by using the equation reported in Fig. 13 as CRR = a N^b where a and b are equal to 0.4667 and -0.231 respectively.

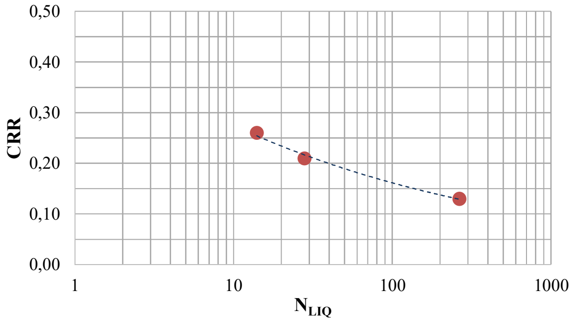


Figure 10. Cyclic resistance curves.

5. Conclusions

In recent years, a significant research effort has been focused on assessing the performance of structures founded on potentially liquefiable materials. As a result, there is a need for laboratory test data. To address this need, a CSS testing program on liquefiable sands has been undertaken using the CSS device available at University Kore of Enna (Italy).

The CSS test is one of the laboratory testing devices that has been widely used to assess soil behaviour, particularly in response to earthquakes loading. In this paper, the preliminary results obtained from the CSS tests on reconstituted specimens of natural sand from the harbour area in the city of Pozzallo (South Sicily, Italy) are presented.

The CSS tests were carried out with confining rings on the sandy samples retrieved in the South of Sicily. All experimental results are reported in the plane cyclic resistance ratio (CRR) and number of cycles where liquefaction occurs (N_{liq}) in order to assess the liquefaction phenomenon.

The results of in situ SPT tests and the laboratory cyclic simple shear tests performed show that sands are susceptible to liquefaction.

The obtained results emphasise the soil liquefaction development of the Pozzallo sand initiated by accumulation of excess pore pressure and the decrease of the effective and shear stresses in the simple shear stress conditions. However, further research is still required to understand the cyclic properties of sandy soils collected from Pozzallo.

The future final goal of the research activity will that to compare the results obtained by CSS tests with those derived by CTX tests for the same samples.

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