The effect of confinement in liquefaction tests carried out in a cyclic simple shear apparatus

Lucia Mele[1,*], *Stefania* Lirer[2], and *Alessandro* Flora[1]

[1]University of Napoli, Federico II, Napoli, Italy
[2]University of Rome, Guglielmo Marconi, Roma, Italy

Abstract. The cyclic simple shear tests can be used to reproduce in laboratory the complex behaviour of the soil during an earthquake, simulating the continuous rotation of the principal stress axes. In this research a comparison of results between cyclic simple shear tests carried out with confining pressure or confining rings is reported. A cyclic simple shear apparatus is used to carry out tests with confining rings (the conventional way to carry out cyclic simple shear tests) and with a confining pressure applied to the specimen through pressurized water, where the K_0 condition during consolidation is guaranteed by a sophisticated control system. The apparatus, in both the configurations, is described in detail. All tests were carried out on reconstituted specimens of an Italian sand with similar initial conditions, such as low relative density and confining pressure. All experimental results are reported in the plane cyclic stress ratio (CSR) and number of cycles where liquefaction occurs (N_{liq}) in order to evaluate the effect of confinement on the liquefaction resistance of the studied sand.

1 Introduction

An earthquake shaking or a rapid loading in loose saturated sandy soils may cause an increase of pore pressure and a subsequent decrease of effective stresses. When they approach to zero the soil behaves temporarily as a viscous liquid, this phenomenon is called liquefaction, which can be a source of severe damage to structure and infrastructure. This phenomenon has to be studied to better understand the behaviour of the soils subjected to cyclic loading. Cyclic laboratory testing may play an important role within the study of this phenomenon. One of the most popular laboratory testing to evaluate the undrained cyclic resistance to liquefaction of sand is the cyclic triaxial test with uniform periodic loading. However, cyclic triaxial tests cannot reproduce in laboratory the complex cyclic simple shear stress path experienced by the soil during an earthquake. In cyclic triaxial tests the continous rotation of principle stress axes is not possible. These limitations can be overcome by sophisticated testing apparatuses, like cyclic simple shear cells, which allow to simulate in situ stress conditions [6]. While the triaxial test device is well standardized, cyclic simple devices can be much different. For example, some of them use concentric rings, other reinforced membrane [2, 5]. Some reaserchers [1, 5]; have compared the results of cyclic simple shear tests with confining rings and with a reinforced membrane. [5] presented the results of simple shear tests on two different soils, using both rigid and flexible boundary apparatus, where the rigid apparatus consists of a series of concentric rings, while the flexible boundary apparatus is an unrinforced membrane, used to

confine the specimen. The results showed that the response of finer and softer material is similar in both devices, whereas in coarser and stiffer materials the difference in results is more pronounced. The main purpose of this research is to analyse the influence of the kind of confinement on the results of cyclic simple shear tests carried out on an Italian sand, using a cyclic simple shear apparatus which can work with a double configuration, confining pressure and confining rings. This apparatus was purchased with the funds of the European project, LIQUEFACT, by the Department of Civil, Architectural and Environmental Engineering of the University of Napoli (Federico II).

2 Material, equipment and testing program

2.1. Material

Within the European Project (LIQUEFACT) an Italian sand was used for this research. It comes from the field trial of Pieve di Cento, where several liquefaction mitigation techniques have been tested. Pieve di Cento (Bologna, Italy) is located in Emilia Romagna region, affected by liquefaction phenomenon during the 2012 earthquake. The sand was retrived by a backhoe in the first 2 meters of the trial field and it was characterized in laboratory [4]. The grain size distribution curve is reported in Fig. 1. The fine content (d<0.075 mm) is 8%,

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* Mele Lucia: lucia.mele@unina.it

while G_s is 2.667 and e_{max} and e_{min} 1.04 and 0.546 respectively.
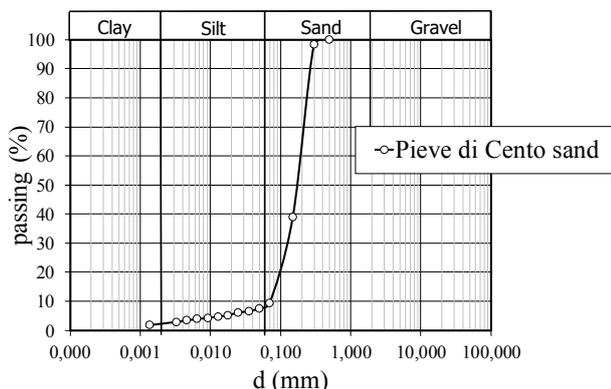

Fig. 1. Grain size distribution of Pieve di Cento sand.

2.2 Equipment and testing program

2.2.1 Equipment

As already mentioned cyclic simple shear tests can simulate stress conditions in situ during an earthquake, allowing the continuous rotation of principle stress axes. At the University of Napoli (Federico II) a new cyclic simple shear equipment has been used. In this apparatus two different configurations are possible: the first one is a configuration with confining pressure (flexible boundary), the second one is that with confining rings (rigid boundary). The configuration with confining pressure uses a latex membrane to confine the specimen and pressurized water allows to apply the cell pressure. To have simple shear conditions, during consolidation phase a k_0 consolidation is possible. The apparatus can adjust the vertical load to maintain a constant diameter, thanks to a sophisticated control system. During the deviatoric phase, in undrained conditions (constant volume) the height of the specimen is constant and the cell pressure changes to maintain the total vertical stress constant. The height of the specimen does not change because the vertical loading ram is locked in a fixed position. The configuration with rings consists in a series of concentric rings used to confine the specimen. During the cyclic phase, in undrained conditions, the volume is constant and to keep the constant diameter, the height of the specimen is maintained constant, it is achieved by allowing changes in the total vertical stress during this phase. In both the configurations, a pore pressure transducer is used to measure the pore pressure during cyclic phase and a horizontal and a vertical LDT are used to measure the axial and shear strains. The configuration with flexible boundary can be advantageous compared to rigid one because the stress state of the specimen is known, while with rings the lateral stress is unknown, because there is not a cell pressure.

2.2.2 Testing program

Three undrained cyclic simple shear tests using Pieve di Cento sand (PdC) were performed with flexible boundary, on loose and fully saturated specimens, while three tests were carried out with rings, in similar conditions (Table 1). In both the configurations the specimens are prepared mixing dry sand with water to reach a degree of saturation of 50% and a relative density (Dr) of 45%. The mixture is placed in a mould to have a cylindrical specimen with a diameter of 70 mm and a height of 26 mm. They are put in cell and saturated.

In configuration with confining pressure, cell pressure increases according to a ramp of pressure together with back-pressure to have an effective stress of 10 kPa.

In configuration with rings, the specimen can be saturated by using flushing. The saturation of the specimen can be checked by B-value through a B-test in the 'flexible configuration', while it is not possible with rings because there is not a cell pressure. When B is higher than 0.95, the specimens are considered saturated. After the saturation, the consolidation phase can start. As mentioned above, in the configuration with flexible boundary a k_0 consolidation can be applied, adjusting the vertical load to have a constant diameter, known the water volume goes out during consolidation and the vertical settlements. In this case, the horizontal stress is imposed, while in rigid configuration the total vertical stress is chosen by the experimenter.

After consolidation phase, different Cyclic Stress Ratio (CSR) are applied, where CSR can be defined as the ratio between shear stress (τ) and vertical effective stress (σ'_v), with a frequency of 0.05 Hz. The void ratios and thus the relative densities of the specimens after consolidation phase are reported in Table 1.

Table 1. Cyclic simple shear tests on Pieve di Cento sand.

Test	Boundary	σ'_h (kPa)	σ'_v (kPa)	e^*	Dr^* (%)
PdC_1_F	Flexible	33.4	58.9	0.818	44.9
PdC_2_F	Flexible	23.8	61.5	0.834	41.7
PdC_3_F	Flexible	29.3	60.5	0.805	47.6
PdC_1_R	Rigid	-	49.6	0.800	48.6
PdC_2_R	Rigid	-	49.5	0.803	48.0
PdC_3_R	Rigid	-	50.0	0.810	46.6

*at the end of consolidation phase

3 Experimental results: Cyclic simple shear tests

Six undrained cyclic simple shear tests were carried out on Pieve di Cento sand in similar conditions (low relative densities and low confining pressures) with different CSR (Table 2). Liquefaction occurs when the excess pore pressure ratio (R_u) is equal to 0.90 (stress criterion) or when shear strain in double amplitude is 5% (Υ_{DA}). In saturated conditions these two criteria should give the same results as shown by [3] in triaxial conditions. In Table 2 is reported N_{liq} evaluated by strain criterion.

Table 2. Results of cyclic simple shear tests.

Test	σ'_h (kPa)	σ'_v (kPa)	Dr* (%)	CSR	N_{liq} (Υ_{DA})
PdC_1_F	33.4	58.9	44.9	0.130	8
PdC_2_F	23.8	61.5	41.7	0.115	18
PdC_3_F	29.3	60.5	47.6	0.115	20
PdC_1_R	-	49.6	48.6	0.134	6
PdC_2_R	-	49.5	48.0	0.125	10
PdC_3_R	-	50.0	46.6	0.110	55

*at the end of consolidation phase

As an example, the results of PdC_2_F are shown in the typical plane: CSR with N_{cyc} (Fig.2a); τ-Υ (Fig.2b); R_u and Υ with N_{cyc} (Fig.2c) and σ'_v and σ'_h with N_{cyc} (Fig. 2d). As shown in Fig. 2a the applied value of CSR is 0.115 and during cycles the area of cycle in the plan τ-Υ increases. Fig. 2c confirms that the stress and strain criteria of the attainment of liquefaction give a similar result in term of number of cycles at liquefaction (N_{liq}=17 with stress criterion and 18 with strain criterion). In Fig. 2d effective stresses are plotted with N_{cyc}. The effective vertical stress starts from a value of 61 kPa and decreases during cycles (black curve), while the horizontal stress starts from 23 kPa and decreases until to reach 0 (grey curve). This graph can be obtained just with a flexible configuration because the effective horizontal stress is known (the stress state of the specimen is completely known). It can be noted that the difference between the vertical and the horizontal stresses decreases until to become 0, which means that an isotropic stress state is attained. It can be further noted that at the end of consolidation phase and when cyclic shear phase starts, the ratio between σ'_h and σ'_v and thus k_0 is 0.39.

As an example, the results of the test PdC_2_R are shown in Fig. 3. The cycles $\tau - \Upsilon$ are reported in Fig. 3a, while in Fig. 3b the trend of shear strain is plotted with N_{cyc}. It can be noted that liquefaction occurs after 10 cycles (Tab. 2) according to strain criterion.

To compare the results of tests with and without confining rings two tests have been considered: PdC_2_F and PdC_3_R, even though the CSR is slightly different: 0.115 and 0.110, respectively.

The results of the test PdC_3_R, compared to PdC_2_F are shown in Fig. 4. The cycles in the plan τ-Υ are reported in Fig.4a while the shear strains are plotted with N_{cyc} in Fig.4b. Figure 4a show that the response of the soil in the plan τ-Υ is similar even though a small difference in term of CSR. Figure 4b shows that the amplitudes of shear strains of PdC_2_F are higher in the first cycles than those of PdC_3_R, while the difference in term of N_{liq} is due to a different CSR.
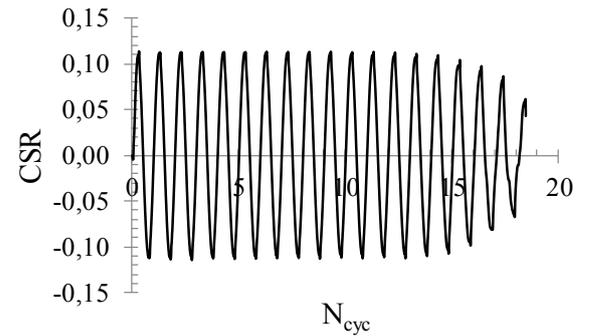

(a)
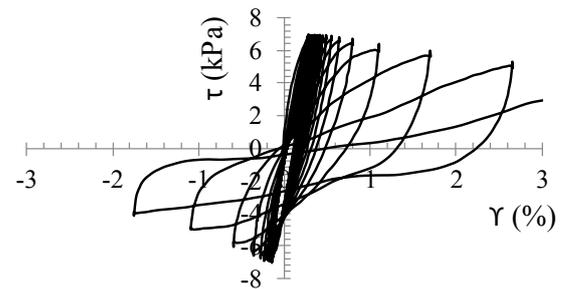
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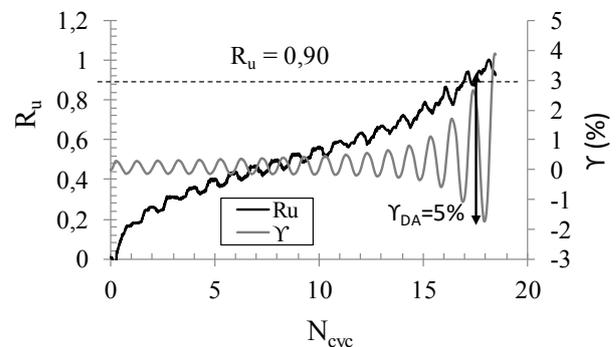
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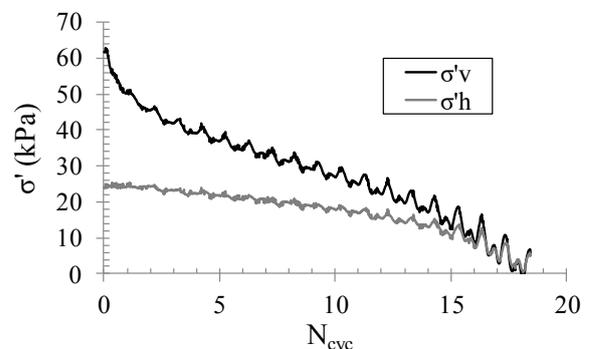
(d)

Fig. 2. Results of cyclic simple shear tests with Flexible boundary (PdC_2_F): CSR with N_{cyc} (a); τ-Υ (b); R_u and Υ with N_{cyc} (c) and σ'_v and σ'_h with N_{cyc} (d).
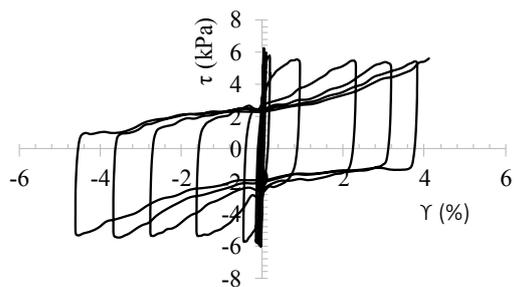
(a)
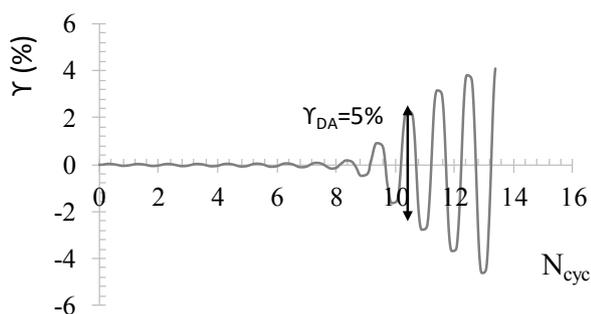
(b)

Fig. 3. Results of cyclic simple shear tests with Rigid boundary (PdC_2_R): τ-Υ (a); Υ with N_{cyc} (b).
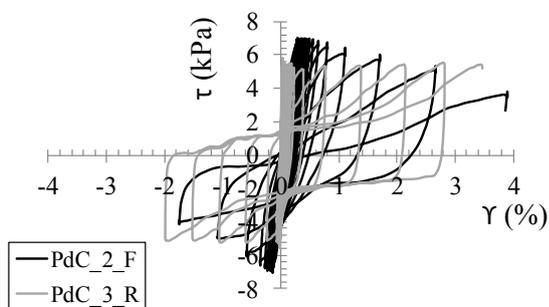
(a)
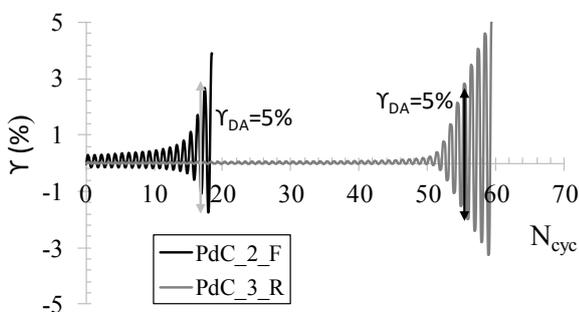
(b)

Fig. 4. Results of cyclic simple shear tests with Flexible and Rigid boundary: τ-Υ (a); Υ with N_{cyc} (b).

3.1 Cyclic resistance curve

Plotting the results in the plan CRR-N_{liq} (Fig. 5), it can be noted that the cyclic resistance curve is unique. By contrast, [5] found two different cyclic resistance curves, where the curve of rigid boundary is below the corresponding one for flexible boundary. It could be true, even though in this research, this difference could not be noted because the cyclic resistance curve of Pieve di Cento sand is very flat. Further tests on several sands could be useful to better understand the effect of confinement in liquefaction tests.
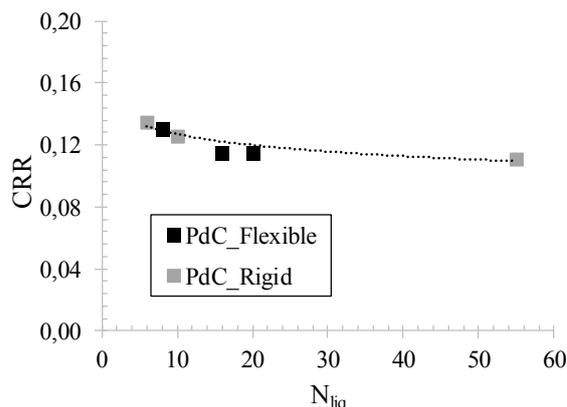

Fig. 5. Cyclic resistance curve of Pieve di Cento sand.

To conclude, the tests with a confining pressure seem to be better that tests with confining rings because, in this case, the stress state of the specimen is completely known.

4 Conclusions

In order to study the effect of confinement in liquefaction tests, the results of cyclic simple shear tests with a flexible boundary (confining pressure) and rigid boundary (confining rings) are compared and discussed. The same apparatus is used to carry out tests with a double configuration thanks to a sophisticated control system. In particular, two tests with and without confining pressure have been compared in the plan $\tau - \Upsilon$ and Υ with N_{cyc}, even though the applied CSR is slightly different. Despite some limitations with rigid boundary the results in term of CRR-N_{liq} are compared to the results obtained with a confining pressure. The obtained curve seems to be unique, but it can due to the shape of the curve, which is very flat. In conclusion, the great advantage of tests with flexible boundary is that the stress state of the specimen is completely known, so these tests may be considered better than those with rings.

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