The effect of densification on Pieve di Cento sands in cyclic simple shear tests

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Abstract The main aim of this work is to study the effectiveness of densification as a mitigation technique against liquefaction, by means of cyclic simple shear tests carried out on specimens reconstituted at several relative densities. The adopted cyclic simple shear apparatus works with a sophisticated control system, which allows to carry out tests in k_0 condition without using confining rings. An Italian sand has been used, retrieved in Emilia Romagna Region (Pieve di Cento) that was affected by 2012 earthquake. Two different sands were tested, both retrieved at Pieve di Cento at different depths. The results of cyclic simple shear tests show that densification increases the resistance to liquefaction. The expression of Booker et al. (1976) has been also used to simulate the trend of excess pore pressure ratio with the ratio between number of cycles and number of cycles at liquefaction of the experimental undrained cyclic tests.

Keywords: soil liquefaction, densification, cyclic simple shear tests.

1 Introduction

The earthquakes may be dangerous not only for inertial and kinematic stresses directly induced on the structure by shaking, but also for possible soil liquefaction phenomena. Owing to earthquake shaking or other forms of rapid loading, liquefaction may occur in loose, saturated soil deposits, causing a rapid loss of soil strength. The effective stresses approach to zero and as a consequence, the soil behavior switches from that of a solid to that of a fluid. Soil liquefaction can cause serious damage to engineering structures and infrastructures, as happened in several places hit by this phenomenon, such as Niigata (Japan) in 1964, Christchurch (New Zealand) in 2011, Emilia Romagna region (Italy) in 2012 or a most recent case in Indonesia in 2018. Within a large European project LIQUEFACT, the University of Napoli Federico II is studying innovative ground improvement techniques suitable for the mitigation of the soil liquefaction risk in densely urbanized areas. Ishihara (1985) considered the relative density (D_r) of the soil the key parameter that rules the triggering of the liquefaction phenomenon, for this reason, the most used liquefaction mitigation techniques are those that induce a soil densification (for instance, by vibro-compaction or dynamic compaction). Denser granular soils show a lower tendency to generate excess pore pressure during cyclic loading than equivalent loose deposits and then their resistance to liquefaction increases. Laboratory tests on densified sands are essential for in-situ design of densification techniques against liquefaction. The experimental results of this research may be needed to provide design tools for these kinds of intervention. In this work cyclic simple shear tests have been carried out because these, unlike cyclic triaxial tests, can simulate stress conditions in situ during an earthquake, allowing the continuous rotation of principle stress axes.

2 Materials, equipment and testing program

2.1 Materials

The tested sands come from a trial site located in Pieve di Cento (Bologna, Italy). Two sands have been tested: a sand retrieved by a backhoe in the first 2 meters and a sand retrieved at a depth of about 3 meters from ground surface. The sand of the first 2 meters has a brownish color, and then called brown silty sand (BSS), while that of 3 meters has a greyish color and thus called grey silty sand (GSS). Their grain size distribution and properties are reported in Fig. 1 and Tab.1.

Table 1 Soil properties of Pieve di Cento sands

Soil properties	BSS*	GSS
Gs	2.667	2.655
e_{max} - e_{min}	1.04 – 0.546	0.884 – 0.442
D_{50} (mm)	0.18	0.30
FC (d<0.075mm) (%)	8	11

*Mele et al., 2019a

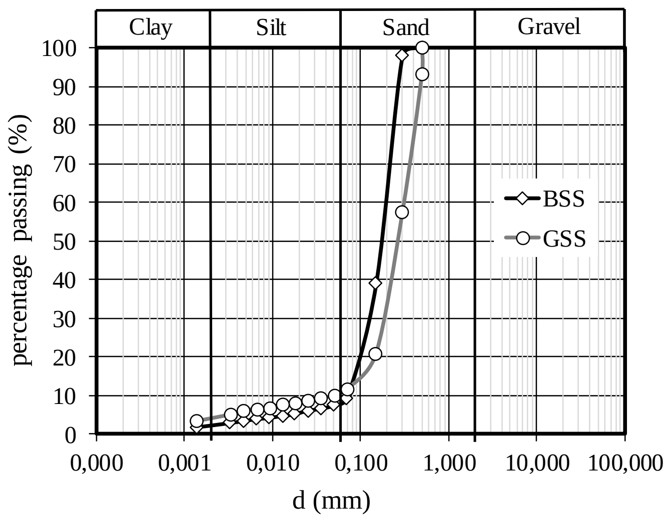


Fig. 1 Grain size distribution curve of Pieve di Cento sands

2.2 Equipment and testing program

As already mentioned, cyclic simple shear tests can simulate stress conditions in situ during an earthquake, allowing the continuous rotation of principle stress axes. In the apparatus available at the University of Napoli (Federico II), two different boundary configurations are possible: flexible boundary (configuration with imposed confining pressure) or rigid boundary (adopting confining rings) (Mele et al., 2019a). In this research, the configuration with confining pressure has been used. In this case, 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.

Ten undrained cyclic simple shear tests (Tab. 2) were carried out on fully saturated sands specimens (BSS and GSS) with several relative initial densities. In table 2, also the tests performed by Mele et al. (2019a) have been reported. The specimens are prepared mixing dry sand with water to reach a degree of saturation of 50% and the desired value of relative density (D_r). 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: cell pressure increases together with back-pressure to have an effective stress of 10 kPa. The saturation of the specimen can be checked by B-value through a B-test. When B is higher than 0.95, the specimens are considered saturated. After the saturation, the k_0 consolidation phase starts: the horizontal stress is imposed and vertical stress is automatically adjusted to have a constant diameter. 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. For Brown silty sand two average relative densities have been investigated: 45 and 74%, while 46 and 67% for grey silty sand.

Table 2 Cyclic simple shear tests on Pieve di Cento sands.

Test	Soil	σ'_v (kPa)	e**	D_r** (%)	CSR
PdC_1_B(45)*	BSS	58.9	0.818	44.9	0.130
PdC_2_B(45)*		61.5	0.834	41.7	0.115
PdC_3_B(45)*		60.5	0.805	47.6	0.115
PdC_4_B(45)		62.4	0.819	44.7	0.110
PdC_1_B(74)		60.0	0.659	77.1	0.155
PdC_2_B(74)		59.5	0.653	78.3	0.130
PdC_3_B(74)		61.4	0.713	66.2	0.110
PdC_1_G(46)	GSS	58.6	0.683	45.5	0.130
PdC_2_G(46)		62.0	0.687	44.6	0.117
PdC_3_G(46)		53.4	0.670	48.4	0.120
PdC_1_G(67)		51.5	0.587	67.2	0.153
PdC_2_G(67)		54.0	0.581	68.5	0.150
PdC_3_G(67)		55.9	0.598	64.7	0.130

*Mele et al. (2019a); ** at the end of consolidation phase

3 Experimental results

3.1 Cyclic simple shear tests and cyclic resistance curves

Ten undrained cyclic simple shear tests were carried out (Table 2) in order to evaluate the effect of densification on Pieve di Cento sands. It can be noted that in all the tests, the applied vertical stress σ'_v ranges between 51.5 and 62.4 kPa.

In order to identify the attainment of soil liquefaction, both stress and strain criteria have been adopted: excess pore pressure ratio $r_u = 0.90$, where r_u is defined as the ratio between Δu (excess pore pressure) and σ'_v (at the end of consolidation phase), or shear strain in double amplitude $\Upsilon_{DA} = 5\%$ (Υ_{DA}).

As an example, the results of test PdC_1_G(46)and PdC_3_G(67) are shown in Figs. 2 and 3 in the typical planes: CSR-N_{cyc}; τ-Υ; r_u and Υ with N_{cyc} and σ'_v and σ'_h with N_{cyc}. As shown in Fig. 2a the applied value of CSR is equal to 0.130 for both the tests PdC_1_G(46) and PdC_3_G(67): during cyclic loading, in both cases, the areas of cycles in the plan τ-Υ increase (Figs. 2b and 3b). The Figs. 2c and 3c show that the stress and strain criteria of the attainment of liquefaction give similar results in term of number of cycles at liquefaction (N_{liq}=9 with stress criterion and strain criterion for PdC_1_G(46) while for PdC_3_G(67) N_{liq}=70 for strain criterion and N_{liq}=74 for stress criterion).

In Figs. 2d and 3d effective stresses paths of both tests are plotted with N_{cyc}. It can be observed that the effective vertical and horizontal stresses decrease during the cycles: the difference between the vertical and the horizontal stresses decreases until to become 0, which means that an isotropic stress state is attained for both tests.

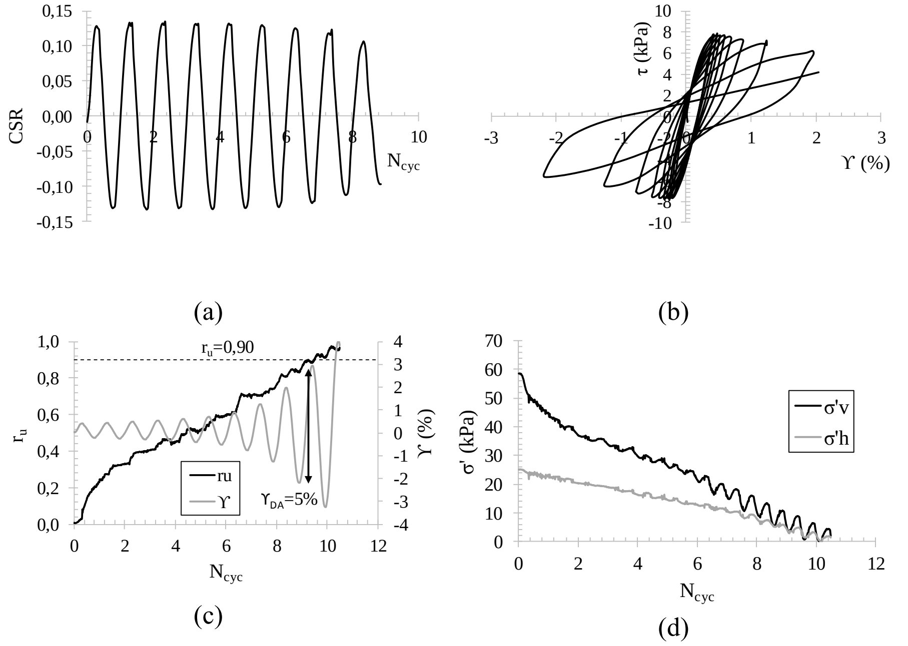
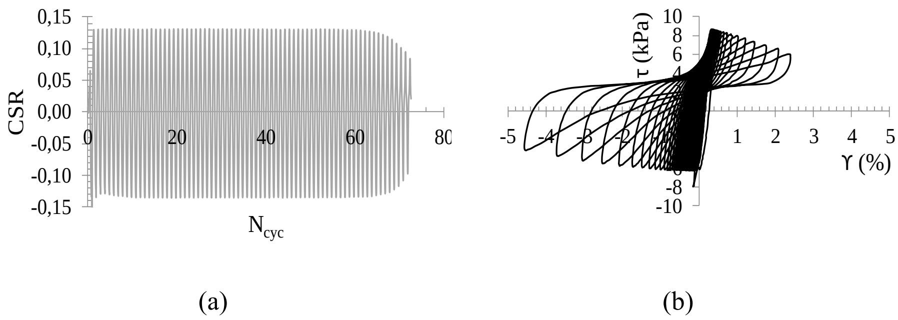
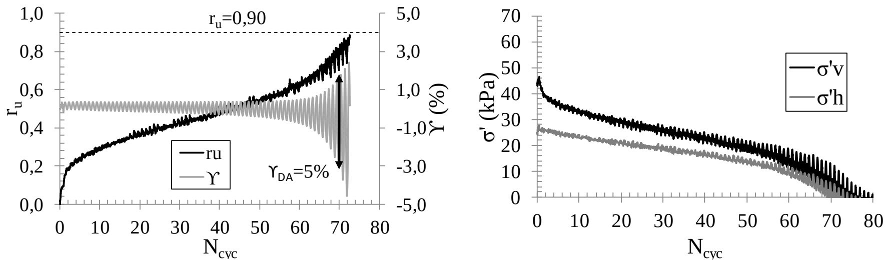


Fig. 2 Results of cyclic simple shear test (PdC_1_G(46)): CSR with N_{cyc} (a); τ-Υ (b); r_u and Υ with N_{cyc} (c) and σ'_v and σ'_h with N_{cyc} (d).





(c) (d)

Fig. 3 Results of cyclic simple shear test (PdC_3_G(67)): 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).

The results of cyclic simple shear tests have been reported in the plan CRR – N_{liq} (Fig. 4), where N_{liq} has been evaluated by stress criterion (r_u=0.90). It is noteworthy that despite the fact that the grain size distribution curves are slightly different in term of D_{50} (0.18 and 0.30 mm respectively for BSS and GSS) and fines content (8 and 11% respectively for BSS and GSS), the cyclic resistance curves can be considered the same for the specimens reconstituted at low relative density (45 and 46% respectively for BSS and GSS).
Considering the higher relative density the curve is unique even though the values of D_r are different (74 and 67% respectively for BSS and GSS). It implies that the effect of densification on GSS is much more important than that on BSS. It could be due to a difference in term of effective vertical stress. It is worth noting that for tests on GSS with an average Dr of 67%, the effective vertical stresses are slightly lower (σ'_v ≈53.8 kPa) than that for BSS with an average Dr of 74% (σ'_v ≈60.3 kPa), as shown in Table 2. As well known, when the confining stress increases the resistance to liquefaction decreases (Vaid and Thomas, 1995; Vand and Sivatayalan, 1996).

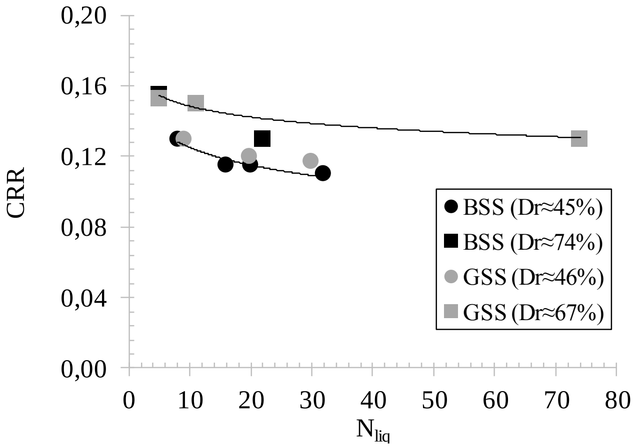


Fig. 4 Cyclic resistance curves of Pieve di Cento sands ($51.5<\sigma'_v< 62.4$ kPa).

Fig. 4 shows the effectiveness of densification as mitigation technique against liquefaction. After the mitigation intervention, the seismic action (CSR) leads to an excessive pore pressure without reaching liquefaction, in fact the pore pressure build-up decreases for higher relative densities of the specimens, as can be noted comparing Figs. 2c and 3c, where for a fixed CSR the specimen with a higher relative density reaches liquefaction after more cycles.

3.2 Pore pressure generation (Booker et al., 1976)

To predict the pore pressure generation of sands, several models have been presented in literature (Seed et al., 1975; Booker et al., 1976; Baziar et al., 2011 and Chiaradonna et al., 2018). In this paper, the expression of Booker et al., 1976 has been considered. The trend of excess pore pressure ratio (r_u) versus N/N_{liq}, where N is the number of cycles during the test, while N_{liq} is the number of cycles necessary to cause liquefaction, can be written using the following expression (Booker et al., 1976):

$$r_u = \frac{2}{\pi} arc\cos\left[\left(\frac{N}{N_{liq}}\right)^{\frac{1}{2\beta}}\right] \quad (1)$$

where β is an empirical constant which depends on the soil type and test conditions. The experimental curve (r_u-N/N_{liq}) of almost all tests have been plotted in Fig. 5 where also the theoretical curve (eq. (1)) is shown, assuming a β equal to 1.1, calibrated to have the best fitting with the experimental data.

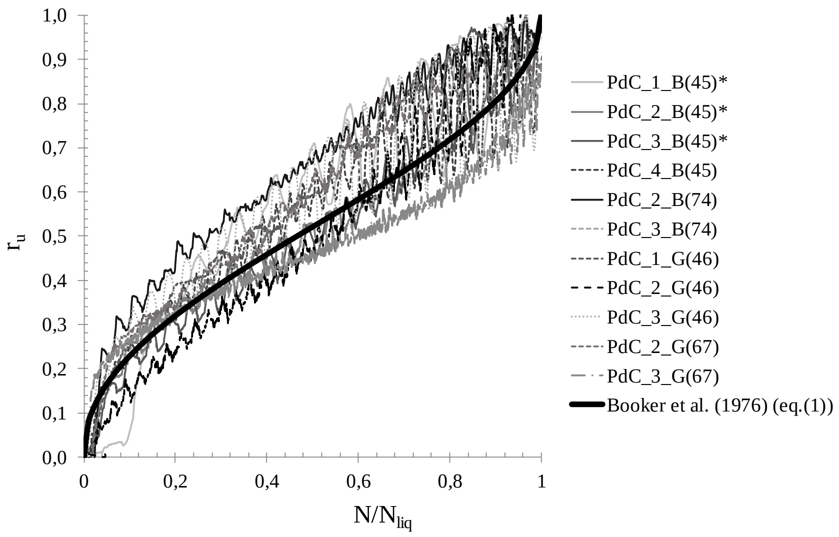


Fig. 5 Pore pressure ratio generation versus N/N_{liq}.

4 Conclusions

In order to evaluate the effect of the densification on fine sands, which come from Pieve di Cento, affected by liquefaction during 2012 earthquake, tests with two different relative densities have been carried out using a cyclic simple shear apparatus. Two similar Pieve di Cento sands have been characterized and tested. The results of the tests give similar results in term of CRR-N_{liq}, even though the curve of GSS with an average value of D_r for 67% is the same of the curve of BSS with an average value of 74%. This apparent strange behavior can be due to a difference in term of confining pressure. Further tests could be useful to confirm the hypothesis. The results show that when the D_r increases the resistance to liquefaction increases regardless of the kind of sand. It implies that densification may be used as an effective mitigation technique against liquefaction. The trend of pore pressure generation has been also evaluated using Booker expression (eq.1), where the parameter β has been calibrated to have the best fitting with the experimental results, it is assumed equal to 1.1.

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