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A laboratory study for the dynamic characterization of sandy soil

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ABSTRACT: Recent earthquakes frequently showed liquefaction of sandy soil. In these case one of the major challenges is the selection of the appropriate residual strength of liquefied materials to assess the post-liquefaction stability of embankments and soil structures. Cyclic triaxial tests have been widely used to asses soil liquefaction potential especially for coarse-grained soils, as in this work. In the framework of the design for the seismic retrofitting of the “Viadotto Ritiro” foundations along the A20 motorway connecting Messina with Palermo, a soil liquefaction study has been carried out. With this aim, a detailed geotechnical characterization has been performed by in situ and laboratory tests including the combined resonant column and torsional shear test (RCTS) and undrained cyclic triaxial tests (CTX). In particular, the paper presents the results of laboratory tests carried out on specimens of a sandy soil to asses liquefaction potential.

1 INTRODUCTION

After Niigata earthquake in 1964, which caused a lot of building damages due to liquefaction, several studies were performed by many Authors in order to understand cyclic behaviour of sands (Seed and Lee 1966; Hyodo et al. 1991; Yoshimi et al. 1984; Vaid et al. 1996; Sladen et al. 1985; Toki et al. 1986). The evaluation of the liquefaction potential during earthquakes is an important subject for geotechnical engineers in seismically active regions. In fulfilling this task, it is of critical importance to assess the cyclic resistance of sandy soil deposits (Capilleri et al. 2018).

Liquefaction is the phenomenon in which granular cohesionless saturated soils (gravel, sand and low plasticity silt) lose its strength for a short interval of time, but long enough to cause significant failures. The liquefaction effects are usually evident on the ground surface (sand boils, large deformation or fracture of the ground, etc.).

Many researches (Huang et al. 2014; Robertson and Wride 1998; Vaid et al. 2001) have clearly indicated that liquefaction susceptibility is primarily ruled by grain size distribution, soil fabric and state conditions, expressed by void ratio and effective confining stresses. Liquefaction susceptibility also depends on the applied stress path, both in terms of cyclic shear stress amplitude and rotation of principal stress axes (Flora et al. 2012).

Cyclic triaxial tests have been widely used to assess soil liquefaction potential since the early 1960s (Seed and Lee, 1996) because they are simple enough and rather common.

In undrained cyclic triaxial tests, the imposed cyclic stress ratio CSR is defined as the ratio between the shear stress τ_d and the normal effective stress σ'_{ref} acting on a plane inclined at 45° relative to the horizontal plane (i.e. on the plane of maximum shear stress):

$$CSR = \frac{\tau_d}{\sigma'_{ref}} = \frac{q_d}{2\sigma'_{ref}} \tag{1}$$

where q_d is the cyclic deviatoric stress. By definition σ'_{ref} is equal to:

Figure 1. Viadotto Ritiro along motorway A20.

$$\sigma'_{ref} = \frac{\sigma'_{1,c} + \sigma'_{3,c}}{2} \tag{2}$$

where $\sigma'_{1,c}$ and $\sigma'_{3,c}$ are respectively the maximum and minimum principal effective stresses acting on the specimen at the end of the consolidation phase. In isotropically consolidated tests ($\sigma'_{1,c} = \sigma'_{3,c}$), σ'_{ref} is equal to the consolidation pressure.

The cyclic resistance ratio, CRR, can be defined as the cyclic stress ratio causing liquefaction in a finite number of loading cycles. The cyclic strength curve conventionally expresses the relationship between CRR and the number of cycles N_{cyc} to initiate liquefaction. Soil liquefaction should be identified as the condition of null effective stress. In cyclic triaxial tests is usually assumed that liquefaction is attained at conventional stress or strain thresholds. The stress-based approach refers to the pore pressure ratio, $R_u=\Delta u/\sigma'_c$, between the cyclically induced pore pressure increment Δu and the confining stress σ'_c. The strain-based approach typically assumes a limit value for the double amplitude axial strain ε_{DA}.

In this study, the two thresholds have been assumed $R_{u,liq}$ = 0.9 and $\varepsilon_{DA,liq}$ = 2.5%. This choice is more conservative than the one most often adopted in the literature (i.e. $R_{u,liq}$ = 0.95÷1.00 and $\varepsilon_{DA,liq}$ = 5%). Recent study (Flora et al. 2012), carried out on undisturbed specimens of coarse soil recovered at the site of Cannitello on the Calabria shore of the Messina Strait, have shown that the two thresholds are mutually consistent as most times the two values are reached in undrained cyclic triaxial tests at a similar number of cycles. Furthermore, Sawada et al. (2003) have also shown that the effect of strain threshold on cyclic strength is relevant only for very dense soils, which is not the case of the soil tested in this study.

In the framework of the design for the seismic retrofitting of the “Viadotto Ritiro” foundations along the motorway A20 connecting Messina and Palermo, located in one of the most hazardous Italian seismic areas (Figure 1), a seismic geotechnical characterization has been carried out. With this aim, laboratory tests including resonant column, cyclic torsional shear and undrained cyclic triaxial tests on isotropically consolidated specimens have been performed. In particular, the cyclic behavior of sandy soils with different grain size distributions has been investigated for the liquefaction study of the area.

2 SISMICITY OF THE AREA

Italy is a high seismic hazard country, characterized by urban areas with significant level of seismic vulnerability (Castelli et al. 2016a, 2016c, 2016e; Grasso and Maugeri 2014; Monaco et al. 2011). In Italy recent strong earthquakes include the central Italy earthquake of 24th August 2016 (de Silva et al. 2016), the Emilia Romagna earthquake of the 29th May 2012

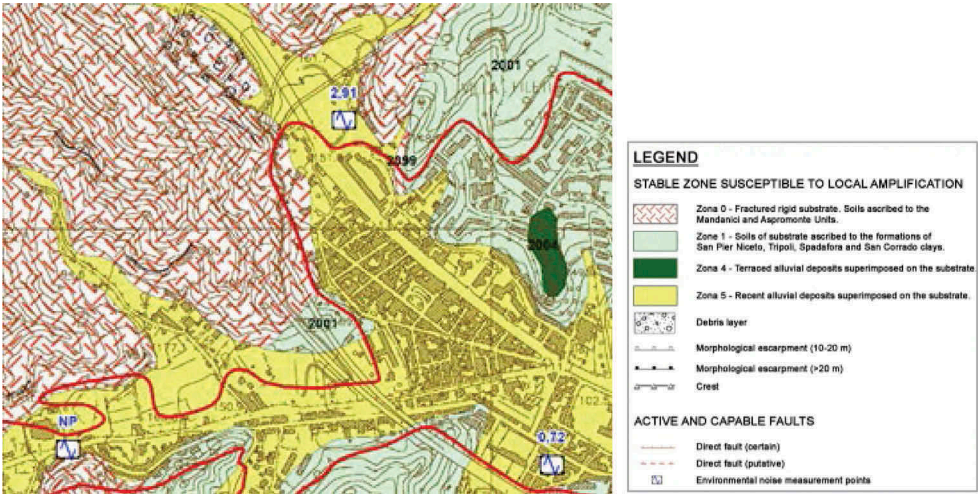


Figure 2. Microzonation map of Messina in the area of Viadotto Ritiro.

(Facciorusso et al. 2016), the L'Aquila earthquake of the 6th April 2009 (Monaco et al. 2013; Santucci de Magistris et al. 2013), the St. Lucia earthquake of the 13th December 1990 occurred in the South Eastern Sicily.

Among Italian regions, Sicily is one of the area most seismically active. In the past, strong earthquakes occurred in the south eastern Sicily (1169, 1693) and in north-eastern Sicily (1908). The area around the Straits of Messina has experienced some of Italy's most destructive earthquakes. The 1908 Messina Straits (Pino et al. 2009) earthquake is one of the most catastrophic events in history: there were more than 100,000 deaths, the cities of Messina and Reggio Calabria, on the opposite sides of the straits, were almost completely destroyed, liquefaction phenomena interested the area. As well known, the characteristics of soil shaking are strongly influenced by local geological, geomorphological (Castelli and Lentini 2010; Castelli et al. 2016b, 2016d, 2016f, 2017; Cavallaro et al. 2006) and geotechnical conditions.

A zoom of the Seismic Microzonation map of the area and particularly of Viadotto Ritiro is shown in Figure 2. In the map, the zones identified as homogeneous are characterized by similar parameters as lithological and lithotecnical characteristics, depth of bedrock, geomorphological conditions, etc. The area of the *Viadotto Ritiro* is within the local amplification stable zones (Zone 0, Zone 1 and Zone 5) of the Messina microzonation map.

3 GEOTECHNICAL CHARACTERIZATION

3.1 *Testing program*

Physical parameters were derived from standard classification tests performed on the samples retrieved by geotechnical survey. Most of the samples are coarse-grained soils, classifiable as silty sands to gravelly sands, showing a lower percentage of clayey material.

The plot in Figure 3 compares the range of grain size distribution of the tested samples with cyclic triaxial apparatus with the limiting curves suggested by national guidelines (Norme Tecniche per le Costruzioni NTC, 2018) to single out potentially liquefying soils. It can be noted that samples (S17 Pile 9D C4 S17 Pile 9D C7 and S28 Pile 18D-16S C1) can be expected to liquefy. In particular, two samples show a high liquefaction risk according NTC, 2018.

Since the reliability of laboratory tests largely depends on the ratio between the specimen diameter (D) and the maximum particle size (d_{max}), in the case of a coarse-grained soil many Authors (e.g. Marsal, 1967) suggested that the minimum limit value of this ratio is $D/d_{max} = 5$. It was

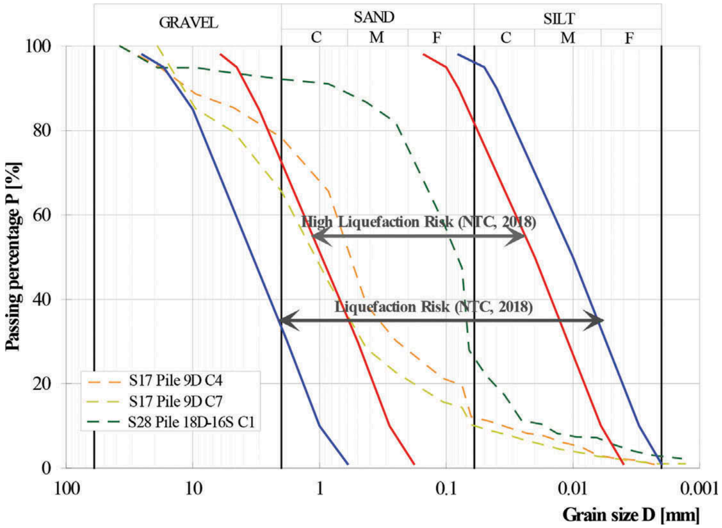


Figure 3. Ranges of grain size distribution of soil along with the boundaries of liquefaction susceptible soil according to NTC (2018).

verified that only few specimens had a very small percentage of particles not strictly respecting such a constraint and the amount of oversize particles resulted so small to be considered acceptable.

3.2 *Testing apparatus*

Soil behavior was analyzed at Kore University of Enna by means of Cyclic Triaxial and Resonant Column/Torsional Shear devices.

The Cyclic Triaxial (CTX) device is composed by three parts: (i) a computer controlled servo-pneumatic system designed to manage vertical load and displacement, cell pressure and back pressure; (ii) a microprocessor controlled drive system in which the double acting pneumatic actuator is digitally controlled and includes an integrated LVDT displacement transducer to control the position and the movement of the piston during the test; (iii) a compact unit that manages the vertical load and displacement, cell and back pressure. The device allows to perform tests on specimen with nominal dimension of 70 mm in diameter and 140 mm in height or 38.1 mm in diameter and 76.2 mm in height.

The Resonant Column/Torsional Shear (RCTS) is a combined device in which the specimen has a fixed-free configuration and nominal dimension of 50 mm in diameter and 100 mm in height or 38.1 mm in diameter and 76.2 mm in height). In RC tests, sinusoidal torsional forces are generally applied at high frequencies, so as to reach the resonance conditions. For low and medium levels of deformation torsional forces are generally applied at frequencies between 1 and 100 Hz. At higher levels of deformation, the frequency of torsional forces ranges from 0.01 to 1 Hz. RC and CTS tests have been carried out on cylinder soil samples with 50 mm of diameter and 100 mm of length, by the use of electromagnetic actuators, in order to perform both RC and CTS tests with the same equipment on the same sample.

The specimens were consolidated isotropically to the estimated vertical in situ stress. At the end of the consolidation stage, the cyclic and/or dynamic tests were performed with increasing shear load levels, to investigate the behavior of the soils for different values of shear strains.

In particular, to determine the shear modulus G reduction and the increasing of damping ratio D with shear deformation γ, several tests were performed by Resonant Column/Cyclic Torsional Shear apparatus. RC and CTS tests have been carried out on cylindrical soil samples with 50 mm of diameter and 100 mm of length, with the same equipment on the same sample.

Table 1. Initial conditions of isotropically consolidated undrained cyclic tests.

Borehole	Sample	Stress path	e_o	σ'_0 [kPa]
S17 Pile 9D	C4	CCIU	0.640	350
S17 Pile 9D	C7	CCIU	0.639	400
S28 Pile 18D-16S	C1	CCIU	0.570	400

The cyclic triaxial test have been performed on specimens of $D = 70$ mm in diameter, and $H = 140$ mm in height.

The experimental program, detailed in Table 1, included 8 resonant column tests, 8 cyclic torsional shear tests, and 3 undrained triaxial cyclic tests. Isotropic consolidation was adopted in all tests and at the beginning of the consolidation stage, the saturation degree was very high, as the measured values of the pore pressure parameter B were always 0.98.

3.3 *RCTS test*

RC and CTS tests have been carried out on cylindrical soil samples with 50 mm of diameter and 100 mm of length. The specimens have been tested to the estimated in situ effective confining stress. Experimental results have been obtained for mean effective confining pressure $\sigma_{0'}$ in the range 150÷600 kPa.

At the end of the consolidation stage, the tests were performed with increasing shear load levels to investigate the behavior of the soils for different values of shear strains spanning between 0.0001% and 1%. As usual, the tests were interpreted in terms of linear equivalent parameters, i.e. shear modulus G and damping ratio D.

Figure 4 shows the experimental results obtained from RC and CTS test in terms of shear modulus G and damping ratio D versus shear strain γ.

Clay fraction is a key parameter to represent soil non-linear behavior. As know, soils with low clay fraction have a low threshold strain linear level beyond which the decay of stiffness and the increase of damping are quite pronounced. Soils with higher clay fraction are characterized by higher value of the linear threshold, showing a minor reduction of stiffness and lower damping values in the non-linear range.

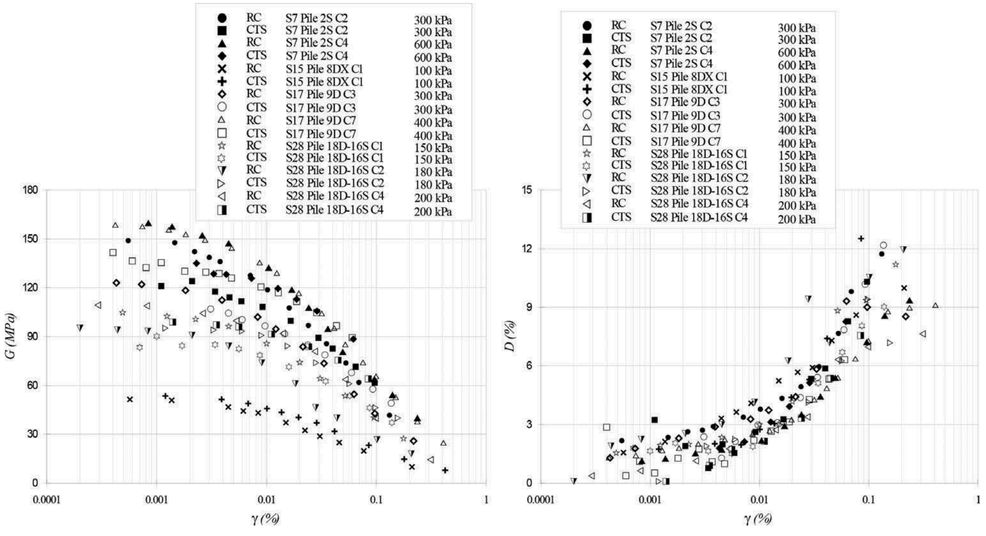
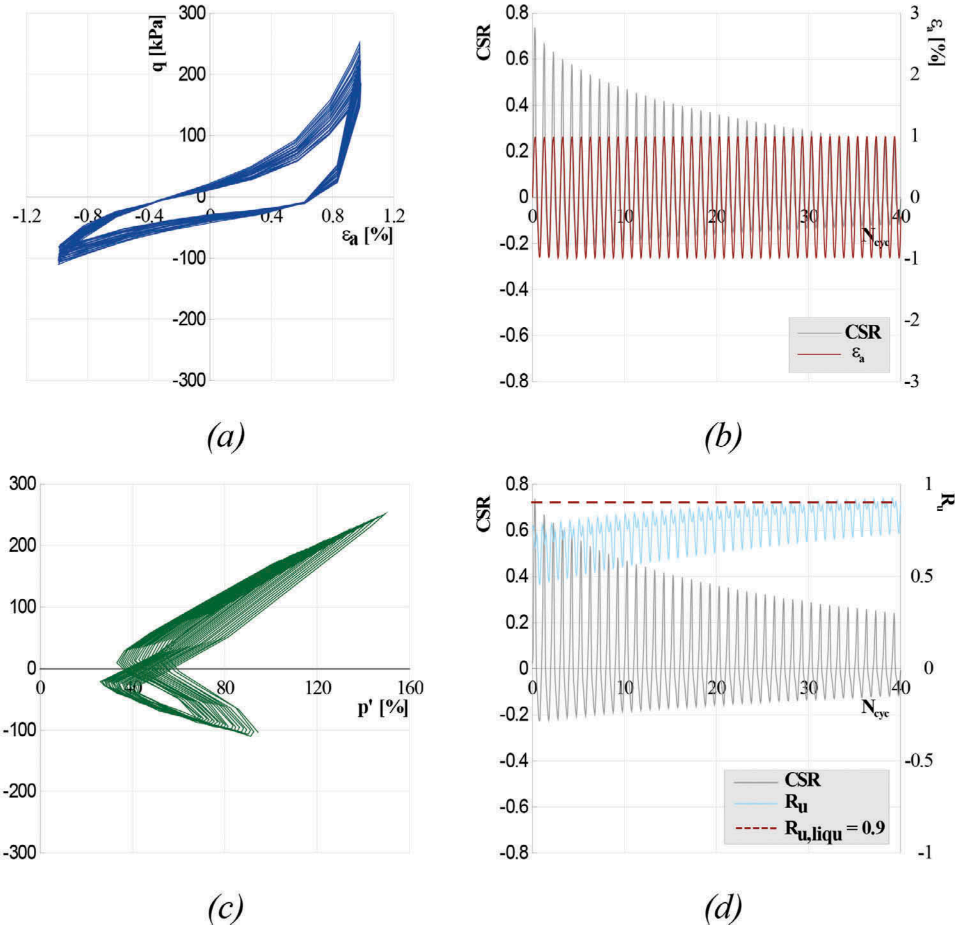


Figure 4. Shear modulus and damping ratio versus shear strain from RC and CTS tests.



(a) (b)

(c) (d)

Figure 5. Results of the tests on sample S17 Pila 9D C4.

As shown in the Figure 5, the maximum values of shear modulus G_{max} and damping ratio D_{max} are influenced by confining stress to which the specimens were tested. In particular, G_{max} ranges from 50 and 160 MPa and D_{max} ranges from 7 and 12 % for effective confining pressure in the range 150÷600 kPa.

3.4 *Cyclic triaxial test*

The specimens (diameter $D = 70$ mm, height $H = 140$ mm) were tested in a triaxial apparatus. In all the cyclic tests, the axial loading was applied through uniform sinusoidal cycles with constant amplitude at a frequency of 0.1 Hz. Isotropically consolidated undrained cyclic tests (CCIU) were carried out. Stress parameters p' and q are used for representing effective mean principal stress, $p' = (\sigma'_1 + 2\sigma'_3)/3$ and deviator stress $q = (\sigma'_1 - \sigma'_3)$, respectively. The conditions of the cyclic triaxial tests and a synthesis of the test results obtained are summarized in Tables 1-2.

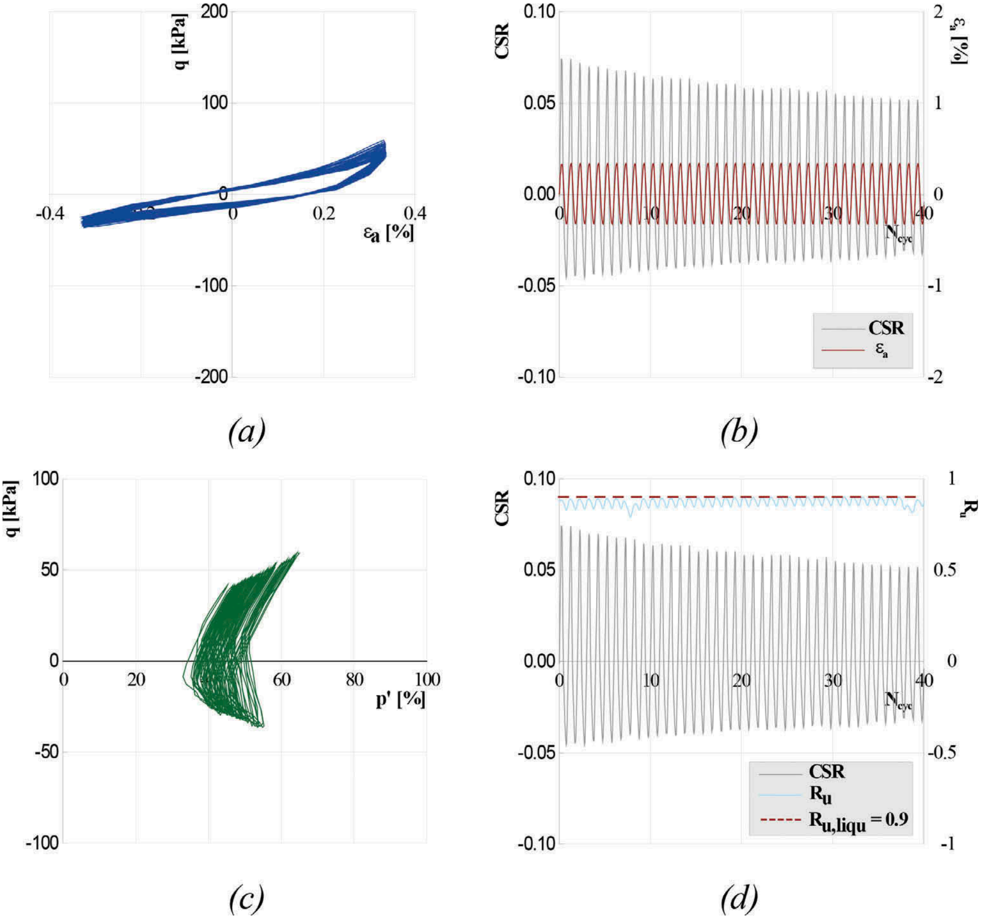
Figures 5-6 show, in four different plots, the test results on samples S17 Pile 9D C4 and S17 Pile 9D C7 respectively. In particular, the plots represent the variation of the deviator stress q with the axial strain ε_a (a), the variation of the cyclic stress ratio CSR and the axial strain ε_a with the number of cycles N_{cyc} (b), the variation of effective mean stress p' with the deviator stress q (c), the variation of the cyclic stress ratio CSR and the pore pressure ratio R_u with the number of cycles N_{cyc} (d) for two of samples tested.

Table 2. Results of isotropically consolidated undrained cyclic tests.

Borehole	Sample	CSR	Liqu	N_{cyc}	N_{cyc}	γ
				$R_u = 0.9$	$\varepsilon_{DA} = 0.9$	%
S17 Pile 9D	C4	0.288	yes	30	–	1.50
S17 Pile 9D	C7	0.056	yes	28	–	0.50
S28 Pile 18D-16S	C1	0.233	no	–	–	–

In the isotropically consolidated tests, the stress-based approach was adopted to indicate the liquefaction, which was conventionally considered to be attained when the pore pressure ratio R_u reached the value of 0.9. As reported in Table 2, according to this criterion, liquefaction was observed in two of the tests executed.

For the sample S17 Pile 9D C4 (Figure 5) liquefaction was reached for $N_{cyc} = 30$ while the limit value for the double amplitude axial strain ε_{DA} was not reached. For the sample S17 Pile 9D C7 (Figure 6) liquefaction occurs with a minor number of cycles ($N_{cyc} = 28$). For the sample S28 Pile 18D-16S C1 liquefaction was not reached. The results obtained on the coarser soil (specimens S17 Pile 9D C4 and S17 Pile 9D C7) are consistent with the boundary curve reported in the Figure 3, while this is not the case for the finer soil (sample S28 Pile 18D-16S C1). The cyclic resistance curve is reported in Figure 7.



(a) (b)

(c) (d)

Figure 6. Results of the tests on sample S17 Pila 9D C7.

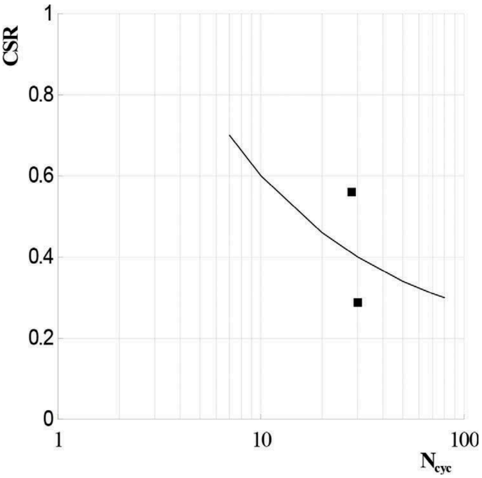


Figure 7. Cyclic resistance curve.

4 CONCLUDING REMARKS

In the framework of the design for the seismic retrofitting of the "*Viadotto Ritiro*" foundations along the A20 motorway connecting Messina with Palermo, located in one of the most hazardous Italian seismic areas, a soil liquefaction study has been carried out. The area was interested to liquefaction during historical earthquakes and, in particular, during the 1908 Southern Calabria - Messina earthquake. The paper presents the preliminary results of the seismic geotechnical characterization performed by undrained cyclic triaxial tests carried out on isotropically consolidated specimens of sandy soil with the purpose to study liquefaction effect.

It has been known that the cyclic resistance of sandy soils to liquefaction is influenced by a number of factors, such as the number of cycles, the fines content, stress histories, the age of the depositions, etc. The results of laboratory investigation show that the cyclic resistance of the tested sands increased with the decrease in the initial confining stress and decreases as the silt content increases. The results also confirmed that the coarsest material has a lower tendency to liquefy.

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