The paper was published in the proceedings of the 7th International Conference on Earthquake Geotechnical Engineering and was edited by Francesco Silvestri, Nicola Moraci and Susanna Antonielli. The conference was held in Rome, Italy, 17 – 20 June 2019.

Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions – Silvestri & Moraci (Eds)
© 2019 Associazione Geotecnica Italiana, Rome, Italy, ISBN 978-0-367-14328-2

The specific deviatoric energy to liquefaction in saturated cyclic triaxial tests

L. Mele
University of Napoli Federico II, Naples, Italy

S. Lirer
University Guglielmo Marconi, Rome, Italy

A. Flora
University of Napoli Federico II, Naples, Italy

ABSTRACT: Within the European project LIQUEFACT, cyclic triaxial tests were carried out on an Italian sand, Pieve di Cento sand, taken from a field trial located in Emilia Romagna (Italy), which was affected by liquefaction during the 2012 earthquake. The cyclic resistance curve of that sand was obtained in laboratory on reconstituted specimens with a low confining stress and a low relative density to simulate the natural conditions in field. Based on an energetic model to predict the resistance to liquefaction of unsaturated soils, the role of the specific deviatoric energy to liquefaction ($E_{s,liq}$) has been investigated for saturated soils. For each test the specific deviatoric energy (E_s) has been evaluated with number of cycles and compared to the results of tests on fully saturated sandy soils (Leighton Buzzard, fraction E and Sant'Agostino sand) already published. The specific deviatoric energy increases with number of cycles until liquefaction and the maximum gradient of this curve seems to correspond to the attainment of liquefaction, according to stress criterion (excess pore pressure ratio, R_u = 0.90), save for the tests with a lower N_{liq}. Moreover, it has been noted an interesting dependence from the number of cycles at liquefaction, which seems to be independent from the cyclic deviatoric stress applied and the state of soil, at least in the range of confining stresses (σ_c') and relative densities (D_r) considered in this research ($50<\sigma_c'<100$ kPa and $43<D_r<64\%$). The results of this research seem to confirm the importance of this parameter in the studies of liquefaction of fully saturated sandy soils.

1 INTRODUCTION

Liquefaction is a well known phenomenon marked by a rapid loss of soil strength, which can occur mainly in loose, saturated sandy soil subjected to earthquake shaking or other forms of rapid loading, actually a seismic ground motion may cause an increase of pore water pressure and a subsequent decrease of effective stresses. When they approach to zero the soil behaves temporarily as a viscous liquid, becoming cause of damage to structures and infrastructures. Cyclic laboratory testing, such as cyclic triaxial tests may play an important role within the study of this phenomenon.

The results are usually reported in the CSR-N_{cyc} plane, where CSR is the *Cyclic Stress Ratio*, defined as the ratio between the cyclic deviatoric stress (q) and 2 times the confining stress (σ'_c), while N_{cyc} is the applied number of constant amplitude stress cycles. 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 also be defined as the applied cyclic stress ratio for N_{cyc}=N_{liq}. The obtained curve in the plan N_{liq}-CRR identifies the *Cyclic Resistance Curve*.

Several laboratory tests (Verdugo and Ishihara, 1996; Huang et al., 2004), have shown that liquefaction susceptibility is ruled by grain size distribution, soil fabric and state conditions, such as void ratio, confining pressure (Flora et al., 2012) and degree of saturation (Mele et al., 2018b). Mele et al., (2018b) proposed an energetic approach to quantify the resistance to liquefaction of unsaturated soils. The specific energy to reach liquefaction (E_{tot}) can be defined as the sum of the specific volumetric energy at liquefaction ($E_{v,liq}$) and the specific deviatoric energy at liquefaction ($E_{s,liq}$). $E_{v,liq}$ can be defined as the energy that the soil, under cyclic loading in undrained conditions, spends to change its volume, so it is linked to volumetric strains. $E_{v,liq}$ is a state parameter which depends on confining stress, void ratio and degree of saturation. The specific volumetric energy to liquefaction can be considered as a syntethic parameter which summarizes the three state parameters that identify a cyclic resistance curve (e, σ‘ and S_r). For a saturated soil the volumetric strains are null in undrained conditions, so the specific energy to reach liquefaction is due only to $E_{s,liq}$. It is defined as the sum of the areas of all the cycles in the ε_s-q plane (D_{cyc} in Figure 1 for a single cycle) up to liquefaction, where ε_s is the deviatoric strain and q is the cyclic deviatoric stress. $E_{s,liq}$ can be formally written with the following equation:

$$E_{s,sk,liq} = \sum_{N_{cyc}=1}^{N_{cyc}=N_{liq}} \iint_{D_{cyc}} dq \cdot d\varepsilon_s \quad (1)$$

In this paper the energetic approach has been used for saturated sandy soils, to better understand the meaning and the role of $E_{s,liq}$ within liquefaction tests.

2 MATERIALS, TESTING PROGRAMME AND EQUIPMENT

2.1 *Materials*

The sand used for this research comes from Pieve di Cento (Bologna, Italy). It is located in Emilia Romagna region, affected by liquefaction phenomenon during the 2012 earthquake. An area of Pieve di Cento has been chosen by the European Project Liquefact to realize a trial field to test several mitigation techniques. In the first 2 meters of the trial field, the sand was retrieved by a backhoe. It was characterized in laboratory and the grain size distribution curve is reported in Figure 2, while the material properties are shown in Table 1.

The results obtained for Pieve di Cento sand (PdC) have been compared to the results of Mele et al., (2018a) on a standard sand: Leighton Buzzard, fraction E (LB) and on an Italian sand: Sant’Agostino sand (SAS, Mele et al., 2018b). In Table 1, the properties of these two sands are also shown.

2.2 *Testing program and equipment*

Three undrained cyclic triaxial tests (Table 2) using Pieve di Cento sand (PdC) were performed in a stress control mode, on loose and fully saturated specimens. They were prepared at an average initial relative density (D_r) of 45%. The tests were carried out in a Bishop & Wesley

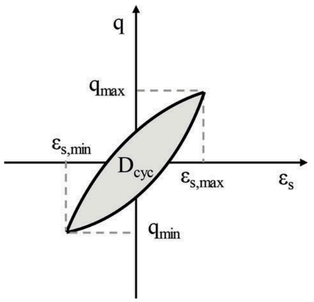

Figure 1. Cycle in q-ε_s plane (Mele et al., 2018b).

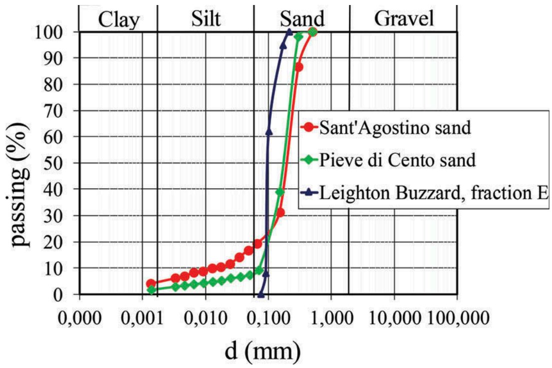

Figure 2. Grain size distribution curves.

Table 1. Material properties of the soils.

Material property	PdC	SAS*	LB**
Fine content (%)	8	20	-
Gs	2.667	2.674	2.65
e_{max}	1.04	1.01	1.01
e_{min}	0.546	0.370	0.613

* Mele et al. (2018b);
** Mele et al. (2018a)

Table 2. Cyclic triaxial tests on Pieve di Cento sand.

Test	σ'_c (kPa)	e*	D_r *(%)	CSR
PdC_1	51	0.805	47.5	0.21
PdC_2	56	0.823	43.0	0.16
PdC_3	51	0.769	54.8	0.18

* at the end of consolidation phase

triaxial cell (University of Napoli) on specimens having diameter of 38 mm and height of 76 mm. The saturation phase was obtained in the triaxial apparatus imposing a low isotropic confining effective stress of 10 kPa. After the saturation phase, when the Skempton Coefficient B is higher than 0.98, the specimens were isotropically consolidated at a low confining stresses (σ'_c) of 53 kPa and then the cyclic phase was carried out imposing, after the isotropic consolidation phase, different Cyclic Stress Ratio (CSR), with a frequency of 0.008 Hz. The void ratios and thus the relative densities of the specimens reported in Table 2 have been evaluated at the end of consolidation phase and the average value is 48%.

3 EXPERIMENTAL RESULTS

3.1 *Cyclic triaxial tests*

In the undrained cyclic triaxial tests (Table 2), three several CSR were applied, imposing different solicitation. The results of the cyclic tests are plotted in the four typical planes: q – p'; q - ε_a; CSR - R_u - N_{cyc} and ε_a - N_{cyc}, where R_u is the excess pore pressure ratio defined as $\Delta u/\sigma'_c$, where Δu is the excess pore pressure. Liquefaction occurs when either the pore pressure ratio (R_u) or the double amplitude strain (ε_{DA}) reach the threshold: R_u=0.90 (stress criterion); ε_{DA} = 5% (strain criterion). N_{liq} has been evaluated for each test, using stress and strain criteria and the results are reported in Table 3. As an example, the results of PdC_2 test is shown in Figure 3. A sinusoidal load has been applied (CSR= 0.16; Table 2), as shown in Figure 3(c). During cyclic loading, the stress path moves to the origin of the axes (Figure 3(a)), while in Figure 3(b) the cycles in the plan q – ε_a are plotted. The areas of these cycles have been calculated to evaluate the specific deviatoric energy to liquefaction (eq. (1)). As well-known, during cyclic loading the pore pressure, and thus R_u, increases (Figure 3(c)), at the same time also the axial strains increase with N_{cyc} (Figure 3(d)). According to stress criterion, liquefaction occurs after 33 cycles (Figure 3(c)), while the strain criterion gives a slightly different value of N_{liq}, which is 35 (Figure 3(d)). Mele et al. (2018b) showed that the two criteria of liquefaction give similar results on fully saturated specimens, as shown in Table 3. N_{liq} evaluated by stress criterion (R_u = 0.90) is finally used to plot the cyclic resistance curve of Pieve di Cento sand.

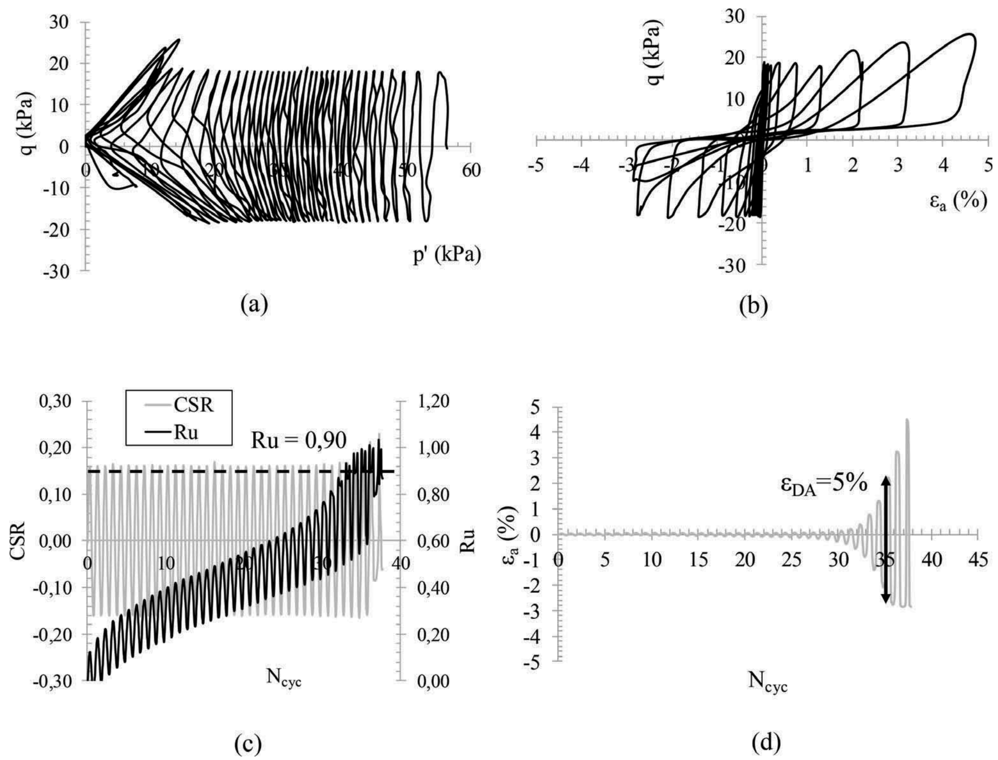

Figure 3. Results of PdC_2 test in plan q-p‘(a); q-εa (b); CSR- Ru-N_{cyc} (c); ε_a-N_{cyc} (d).

Table 3. Results of cyclic triaxial tests on Pieve di Cento sand.

Test	σ'_c (kPa)	D_r* (%)	CSR	N_{liq} (R_u)	N_{liq} (ε_{DA})
PdC_1	51	47.5	0.21	3.1	4.0
PdC_2	56	43.0	0.16	33	35
PdC_3	51	54.8	0.18	12	13

* at the end of consolidation phase

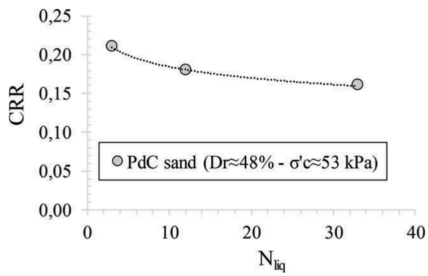

Figure 4. Cyclic resistance curve of PdC sand.

3.2 *Cyclic resistance curve*

The results of the tests (Table 3) were plotted in the plane CRR-N_{liq} (Figure 4), obtaining the cyclic resistance curve for Pieve di Cento sand with an average D_r of 48% and a confining stress of 53 kPa.

3.3 *The specific deviatoric energy to liquefaction*

As mentioned above, the total specific energy to reach liquefaction is given by the specific deviatoric energy to liquefaction ($E_{s,liq}$), being null the specific volumetric energy to liquefaction for a saturated soil in undrained conditions.

Mele and Flora (2019) studied in depth the role of $E_{s,liq}$ for unsaturated sandy soils. They showed that plotting E_s with N_{cyc}, the curve is almost linear in the first cycles but when liquefaction occurs shear strains increase and E_s suddenly increases. The value of E_s for $N_{cyc} = N_{liq}$ is exactly $E_{s,liq}$. The Figure 5 shows the typical trend of E_s with N_{cyc}.

As shown by Mele and Flora (2019), the highest gradient in the curves E_s – N_{cyc}, in general, may indicate the attainment of liquefaction.

To better understand the meaning of $E_{s,liq}$ in saturated conditions, E_s has been calculated for each cycle (eq.(1)) for the tests carried out on Pieve di Cento sand and for some tests performed by Mele el al. (2018a) on Leighton Buzzard, and some tests of Mele et al. (2018b) on Sant'Agostino sand, in saturated conditions.

In Figure 6a the cyclic resistance curves of Pieve di Cento and Leighton Buzzard sands are plotted and for both sands the stress criterion has been used to evaluate N_{liq}. The tests where liquefaction occurs at the same or very similar number of cycles at liquefaction (as reported in Figure 6a) have been compared in the plan E_s – N_{cyc} (Figure 6b). Some useful information about tests carried out on Leighton Buzzard sand (Mele et al., 2018a) are summarized in Table 4.

The results show that for the same N_{liq}, $E_{s,liq}$ for the two kinds of sand in similar conditions (loose sands and low confining stresses) are similar (N_{liq} = 12 and 33). In particular, the

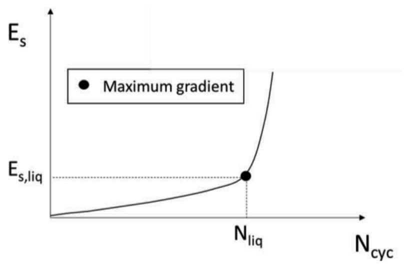

Figure 5. The typical trend of E_s with N_{cyc}.

Table 4. Results of cyclic triaxial tests on Leighton Buzzard sand (Mele et al., 2018a).

Test	σ'_c (kPa)	D_r* (%)	CSR	N_{liq} (R_u)
S3	50	55.0	0.128	12
S7	50	55.0	0.147	4
S8	100	44.0	0.099	33

* at the end of consolidation phase

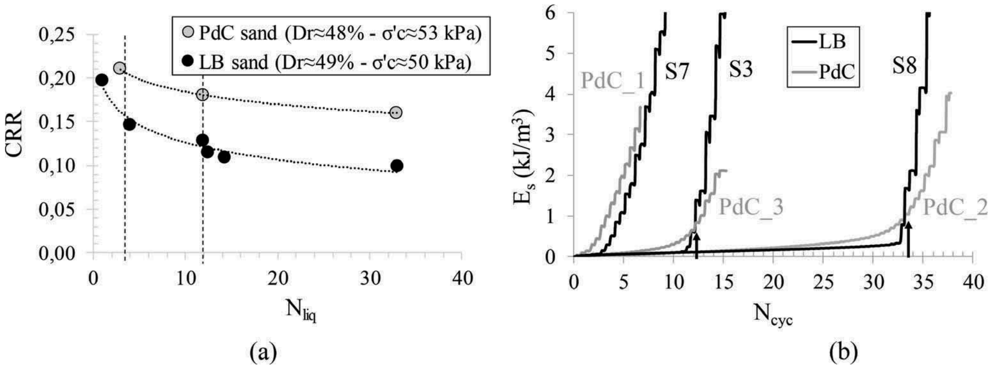

Figure 6. Cyclic resistance curves of PdC and LB sands (a); E_s with N_{cyc} for tests on PdC and LB sands (b).

curves E_s–N_{cyc} intersect each other in corrispondence of the same number of cycles at liquefaction as the arrows show in Figure 6(b). It would seem to be there a strong connection between $E_{s,liq}$ and N_{liq} for saturated tests. It has been stressed that the confining stress of S8 (Table 4) is 100 kPa while it is 56 kPa for PdC_2 (Table 3), despite this difference in term of confining stress, $E_{s,liq}$ is the same. Moreover, even though Pieve di Cento and Leighton Buzzard sands have been tested in similar conditions, Figure 6a shows that the resistances to liquefaction of them are much different, actually PdC sand has a higher cyclic resistance to liquefaction than Leighton Buzzard sand. Despite the difference, at a fixed N_{liq}, $E_{s,liq}$ is almost the same, so $E_{s,liq}$ seems to be indipendent from the CSR applied. It means that though the CRR of PdC is higher compared to that for LB sand at a fixed N_{liq}, the area of a single cycle in the plan q-ε_s for PdC sand is smaller than that of Leighton Buzzard sand, because the sum of the areas of all cycles until liquefaction has to be the same.

Figure 6(b) also shows that when the N_{liq} is different, even though the difference is just 1 cycle (N_{liq} of PdC_1 is 3, while it is 4 in test on Leighton Buzzard), $E_{s,liq}$ is not the same. In this case the curves do not meet each other and the grey curve (PdC_1) reach liquefaction before than the black one (S7).

It would seem to be there a strong connection between $E_{s,liq}$ and N_{liq} for saturated tests.

To understand if this result is influenced by the state conditions of the soil, such as D_r, other two tests with different D_r and the same N_{liq} have been compared. Tests carried out on Sant'Agostino sand in saturated conditions by Mele et al. (2018b) have been considered. For simplicity these two tests are reported in Table 5.

The tests on SAS have the same N_{liq} equal to 3 (Table 5). The curves E_s-N_{cyc} for S_SA1 and S_SA5 have been plotted in Figure 7. Despite the difference in term of D_r (47% for S_SA1 and 64 for S_SA5), as for Pieve di Cento and Leighton Buzzard sands, when N_{liq} is equal, E_s,

Table 5. Results of cyclic triaxial tests on Sant'Agostino sand (Mele et al., 2018b).

Test	σ'_c (kPa)	D_r* (%)	CSR	N_{liq} (R_u)
S_SA1	50	47.0	0.147	3
S_SA5	51	64.0	0.179	3

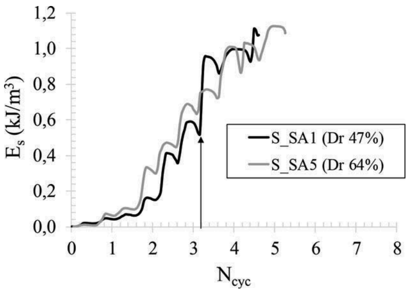

Figure 7. E_s with N_{cyc} for tests on SAS with different D_r and the same N_{liq}.

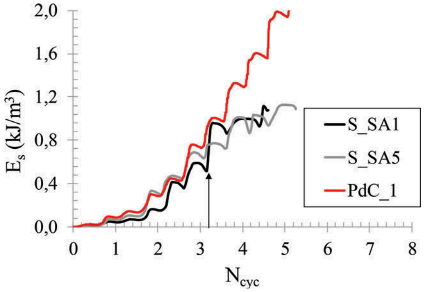

Figure 8. E_s with N_{cyc} for tests on SAS and PdC with N_{liq} =3.

$_{liq}$ is the same, even though it has to noted that the curves intersect each other when the N_{liq} is slightly higher than 3.

To confirm the obtained results, the tests of Figure 7 (S_SA1 and S_SA5) have been further compared to PdC_1 (Figure 8), all of these tests, in fact, have the same N_{liq}, equal to 3.

As shown in Figure 8, $E_{s,liq}$ of the three tests are very similar.

It has to be noted that for these tests (Figure 8) the maximum gradient does not correspond to the exact N_{liq}, evaluated by stress criterion, while it does in the other tests showed in this paper (Figure 6b). The reason could be that when N_{liq} is low (i.e 3), the calculation of E_s (eq. (1)) may be affected by a higher error than it happens for tests with higher N_{liq}, because axial strains suddenly increase.

For each test showed in this paper E_s is finally plotted with the ratio between N_{cyc} and N_{liq} (Figure 9a). All curves have a similar trend, even though E_s of Leighton Buzzard sand grow up suddenly in the last cycles before liquefaction. It could mean that the shape of the curve E_s-N_{cyc} depends on the grain distribution, even though $E_{s,liq}$ seems to be independent from it. Obviously, as mentioned above $E_{s,liq}$ is different in tests with different N_{liq}, but its value is included in a small range (0.5 – 0.9 kPa). The average curve is also reported in Figure 9b.

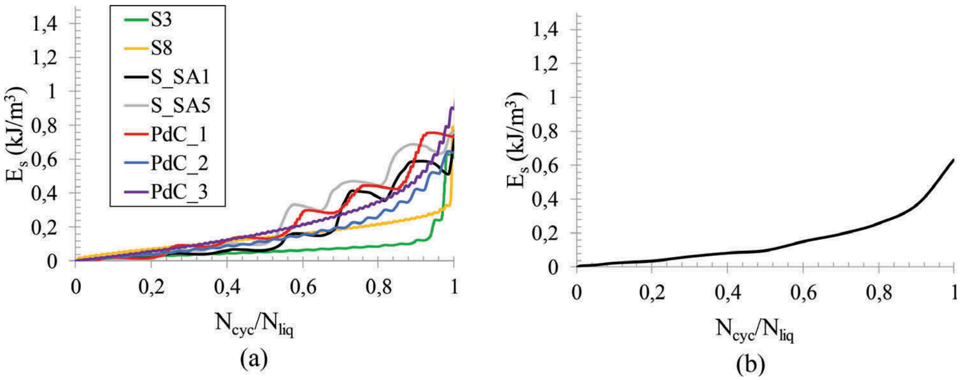

Figure 9. E_s with N_{cyc}/N_{liq} (a); Average curve in the plan E_s-N_{cyc}/N_{liq}.

4 CONCLUSIONS

In order to investigate the role of the specific deviatoric energy to liquefaction of a fully sandy soil, cyclic triaxial tests have been carry out on an Italian sand (Pieve di Cento sand). These results have been compared to the results of different sands, tested in previous researches. It has been noted that the specific deviatoric energy increases with number of cycles until liquefaction. The maximum gradient of the curve E_s-N_{cyc} may identify the attainment of liquefaction, even though for lower N_{liq}, the maximum gradient occurs before than N_{liq} evaluated with stress criterion (R_u = 0.90). The final value of E_s (specific deviatoric energy to liquefaction) reaches the same value when the number of cycles at liquefaction is the same. It means that there could be a strong correlation between $E_{s,liq}$ and N_{liq}, regardless of the CSR, which is applied during the deviatoric phase and the state parameters of the soil (confining stress and relative density), at least in the range considered in this research ($50<\sigma_c'<100$ kPa and $43<D_r<64\%$). This relationship has been found and reported in the paper. Although it must be confirmed by further tests in different conditions, $E_{s,liq}$ seems to be an interesting parameter in the studies of liquefaction of sandy soils in saturated conditions.

ACKNOWLEDGEMENTS

This work was carried out as part of the European project Horizon 2020 – Assessment and Mitigation of liquefaction potential across Europe: A holistic approach to protect structures infrastructures for improved resilience to earthquake – induced liquefaction disasters – “LIQUEFACT” (grant agreement No. 700748).

REFERENCES

Flora A., Lirer S., Silvestri F. 2012. Undrained cyclic resistance of undisturbed gravelly soils. *Soil Dynamics and Earthquake Engineering* 43: 366–379.

Huang T., Huang A., Kuo Y., Tsai M. 2004. A laboratory study on the undrained strength of a silty sand from Central Western Taiwan. *Soil Dynamics and Earthquake Engineering* 24(9-10): 733–743.

Mele L., Flora A., Lirer S., d‘Onofrio A., Bilotta E. 2018a. Experimental Study of the injectability and effectiveness of laponite mixture as liquefaction mitigation technique. *Geotechnical Earthquake Engineering and Soil Dynamics V, Austin (Texas)*, ASCE. DOI: 10.1061/9780784481486.028

Mele L., Tan Tian J., Lirer S., Flora A., Koseki J. 2018b. Liquefaction resistance of unsaturated sands: experimental evidence and theoretical interpretation. *Géotechnique*. DOI: 10.1680/jgeot.18.p.042

Mele L. & Flora A. 2019. On the prediction of liquefaction resistance of unsaturated sands. *Soil Dynamics and Earthquake Engineering* (submitted).

Verdugo R. & Ishihara K. 1996. The steady state of sandy soils. *Soils and Foundation* 36(2): 81–91.