Parametric study to evaluate the performance of horizontal drains as mitigation technique against soil liquefaction

Gianluca Fasano, Valeria Nappa, Emilio Bilotta, Alessandro Flora
University of Naples "Federico II", Italy

ABSTRACT: In the framework of the LIQUEFACT project a series of centrifuge tests were conducted at ISMGEO (Italy) to verify the effectiveness of three mitigation techniques against soil liquefaction. This paper is focused on the study of horizontal drains as mitigation measure against liquefaction. The centrifuge layout with horizontal drains was numerically modelled and the change of boundary conditions reproduced by the FE code Plaxis 2D. Additionally, slightly different layouts from those tested in the centrifuge were also modelled to expand the scope of the experimental work. Horizontal drains were installed in the model, to analyse their effectiveness in reducing the pore pressure build up as a function of their spacing. The soil was characterized by an advanced coupled soils constitutive model implemented in the Plaxis code: PM4sand. The input parameters for the model are evaluated on the basis of both laboratory element tests and centrifuge tests.

1 INTRODUCTION

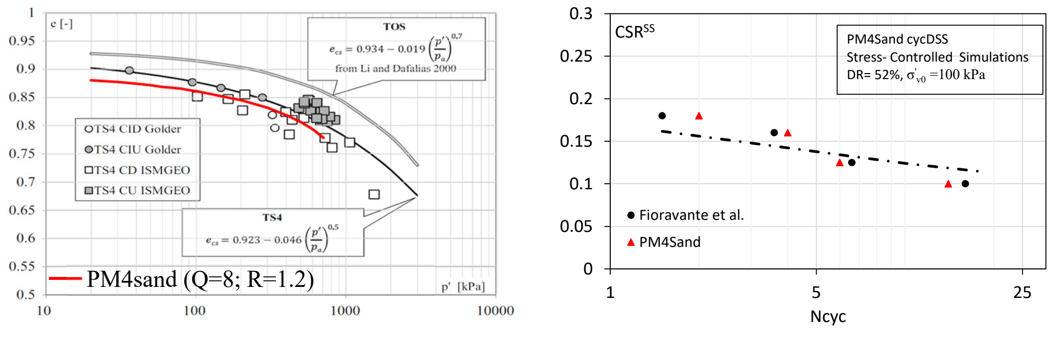
Centrifuge modelling provides a powerful experimental tool for liquefaction study. Although earthquake-induced liquefaction can cause large destruction, it was only after 1964 earthquakes that struck Japan and USA that this phenomenon was brought to the attention of the scientific community (Seed & Lee 1966). On the other hand, liquefaction has been observed in many recent major earthquakes, as in Kobe earthquake of 1995 in Japan, the Kocaeli earthquake in Turkey and the 921 Ji-Ji earthquake in Taiwan in 1999, the Bhuj earthquake of 2001 in India and even in the 2010-11 New Zealand earthquakes, which highlight the need for further research into the complex behaviour of shallow foundations built on liquefiable soils. For instance, in Turkey, the Adapazari district suffered extensive liquefaction induced damage during the Kocaeli earthquake of 1999. Even so, it remains a phenomenon quite difficult to define; proof is that even today a few different definitions can be used (Boulanger & Idriss 2005). There have been numerous projects conducted on centrifuges in recent years that are related to liquefaction studies. In the early 1990's, the VELACS (Verification of Liquefaction Analysis by Centrifuge Studies) project used extensively data from liquefaction tests on centrifuges to verify numerical procedures (Arulanandan & Scott 1993). The challenge now for liquefaction study using centrifuge modelling is not whether it can be simulated in a centrifuge test but how to simulate it properly and how to interpret the test data. LEAP (Liquefaction Experiments and Analysis Projects) (Manzari et al. 2014) is a joint project that pursues to verification, validation and uncertainty quantification of numerical liquefaction models, based on centrifuge experiments. Researchers have attempted to study liquefaction phenomena by conducting centrifuge experiments to investigate effects of complete or near liquefaction in various earth structures. Ground liquefaction is associated with large permanent ground displacements, which can lead to major damages of structures during a seismic event. Earthquake-induced liquefaction is a major concern for structures built on saturated deposits of cohesionless soils in seismically active regions. The effects of this phenomenon continue to cause large direct economic losses as a result of earthquakes. Moreover, the consequences of their collapse can cause serious impediment to post-earthquake emergency operations and impose a long-lasting disruption of social and economic life. Damage to shallow foundations can be particularly severe, mitigation measures being poorly understood (Bardet et al. 1997, Green & Mitchell 2003). In the framework of the LIQUEFACT project a series of centrifuge tests were conducted at ISMGEO (Italy) to verify the effectiveness of three liquefaction mitigation techniques (Fioravante et al., 2019; Fasano et al., 2019). Vertical and horizontal drains were installed in the models, in order to analyse their effectiveness in reducing the pore pressure build up as a function of their spacing. Furthermore, the effectiveness of the "Induced Partial Saturation" (IPS) technique on the soil liquefaction resistance was tested. Model were both in free field conditions and in presence of a simplified structure. In this paper the efficacy of the horizontal drains as mitigation technique against liquefaction was evaluated. Centrifuge tests were reproduced in Plaxis 2D. Starting from the numerical model of the centrifuge test, parametric numerical analyses were carried out to extend the study to different arrangements of drains to obtain design indications.

2 NUMERICAL MODEL

2.1 *Constitutive model calibration*

The PM4Sand constitutive model is calibrated to represent Ticino sand using results of laboratory element tests from the literature. The PM4SAND model (Boulanger & Ziotopoulou 2015) is developed based on bounding surface plasticity theory embracing the concept of critical state. The PM4Sand model has 22 input parameters, from which only three are required as model input: the initial relative density (D_{R0}), the shear modulus coefficient used to define the elastic shear modulus (G_0) and the contraction rate parameter used for calibration of the undrained shear strength (h_{p0}). For this study the three primary parameters and two secondary parameters were calibrated against the experimental data published for the Ticino sand (Fioravante & Giretti 2016) while the other parameters have been left with their default values.

The critical state line is defined as a function of model parameters Q and R. Values of Q equal to 8 and R equal to 1.2 were found to give the best fitting of the curve (Figure 1a).



b)

Figure 1. Calibration of the constitutive model against laboratory tests: a) CLS curve; b) CSR curve.

The value of the shear modulus coefficient G_0 was determined in function of the relative density obtained in the centrifuge tests using the follow relationship:

$$G_0 = 167 \times \sqrt{46 \times D_R^2 + 2.5} \quad (1)$$

The parameter h_{p0} scales the plastic contraction rates and is the primary parameter for calibration of undrained cyclic strengths. It is calibrated using an iterative process, in which undrained single-element DSS simulations are conducted to match with a target liquefaction triggering curve by keeping the other parameters fixed. The results of the calibration are shown in Figure 1b. The properties adopted in the numerical analyses are summarized in Table 1.

Table 1. PM4sand parameters

Parameter	Description	Value	Unit
G_0	shear modulus coefficient	624	-
hp_0	contraction rate parameter	0.1	-
p_A	atmospheric pressure	101.3	kN/m^2
e_{max}	maximum void ratio	0.923	-
e_{min}	minimum void ratio	0.574	-
n_b	bounding surface parameter	0.5	-
n_d	dilatancy surface parameter	0.1	-
φ_{cv}	critical state friction angle	33	°
nu	Poisson's ratio	0.3	-
Q	critical state line parameter	8	-
R	critical state line parameter	1.2	-

2.2 *Numerical simulation of the centrifuge test*

Centrifuge tests were performed at the ISMGEO (Istituto Sperimentale Modelli Geotecnici – Italy) laboratory in the framework of the LIQUEFACT project. The aim of the tests was to analyse the seismic behaviour of loose, saturated, sandy deposits, both homogeneous and stratified, subjected to increasing seismic excitations up to liquefaction and to verify the effectiveness of three liquefaction mitigation techniques (Fioravante et al., 2019). The centrifuge tests represent a benchmark model for the numerical analyses. Numerical analyses are performed to provide insight of advanced constitutive model on capacity to simulate the centrifuge tests response and to obtain a reference numerical model which can be used for different geometrical layouts to provide indications for the design of the most effective mitigation techniques. In this section the simulation of the test with the horizontal drains is shown. The drains in the centrifuge modelwere deployed with two different spacing to diameter (s/D) ratios equal to 5 (on the right side of the model) and 10 (on the left side of the model). A layout of the benchmark test with the indication of the adopted instrumentation is provided in Figure 2.

Numerical models are developed and analysed using the FE code Plaxis 2D. The soil was characterized by PM4sand constitutive model calibrated as shown in the previous section. The drains were modelled by imposing a constant hydraulic head condition along their surface. Tied degrees of freedom between vertical sides were used as boundary conditions to reproduce the equivalent shear box used in the centrifuge. This option proposed by Zienkiewicz et al. (1989) connects the nodes on the same elevation at the left and right model boundaries. The nodes at the base of the finite element model were fixed in the vertical direction and a time history of acceleration was applied in the horizontal direction. Drainage across the top surface is allowed whereas flow across the lateral boundaries is restricted. The input signal used in the centrifuge test is shown in Figure 3a. The results of the simulation are shown in terms of pore pressure ratio R_u (Figure 3), defined as the ratio between the generated excess pore pressure and the initial effective vertical stress, obtained during the shaking in the points 3 and 5 shown in Figure 2. Despite some differences, mainly in the rate of pore pressure dissipation after the significative duration of shaking terminates (i.e. after 20 s), the comparison shows that both in the centrifuge test and in the relevant numerical model liquefaction did not occur in the drained ground (R_u<0.7).

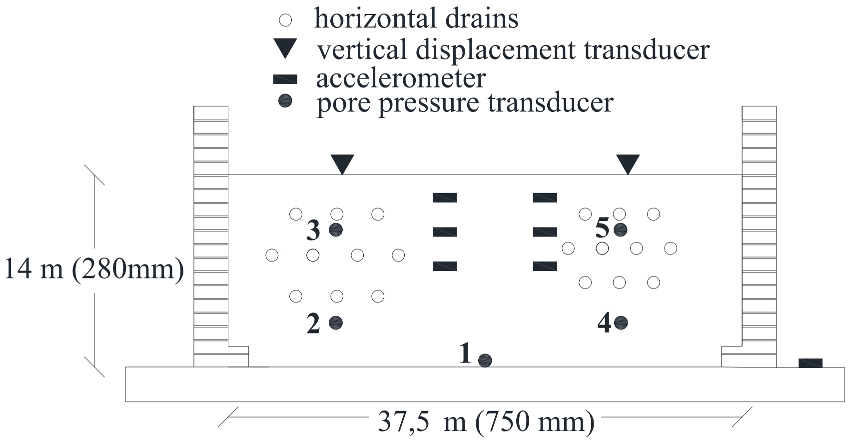
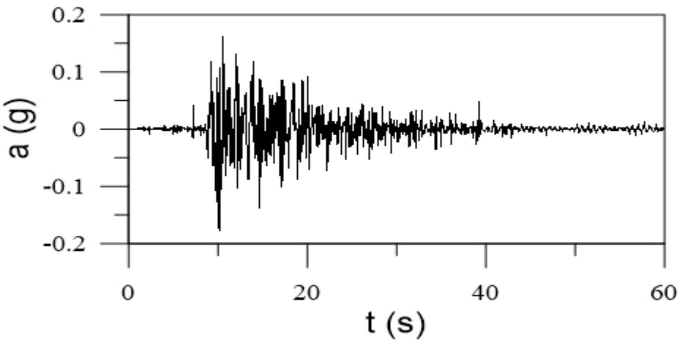
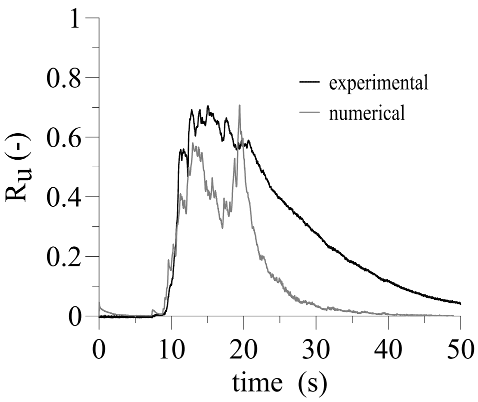


Figure 2. Layout of the centrifuge test.

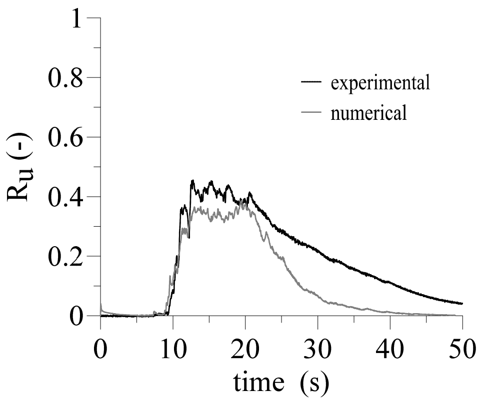
The smaller the spacing among drains, the lower the generated excess pore pressures.



a)



b)



c)

Figure 3. Input signal and comparison of the pore pressure ratio R_u numerical and experimental: b) point 3 (S/D=5); c) point 5 (S/D=10)

Once that the model was validated against the experimental data, a numerical analysis on the same model without horizontal drains was carried out in order to have a reference "no-drains" condition to compare and to assess the effectiveness of the mitigation technique. The results in terms of pore pressure ratio obtained in the same points indicated before are then plotted in Figure 4, showing that without drains liquefaction would occur (R_u>0.8).

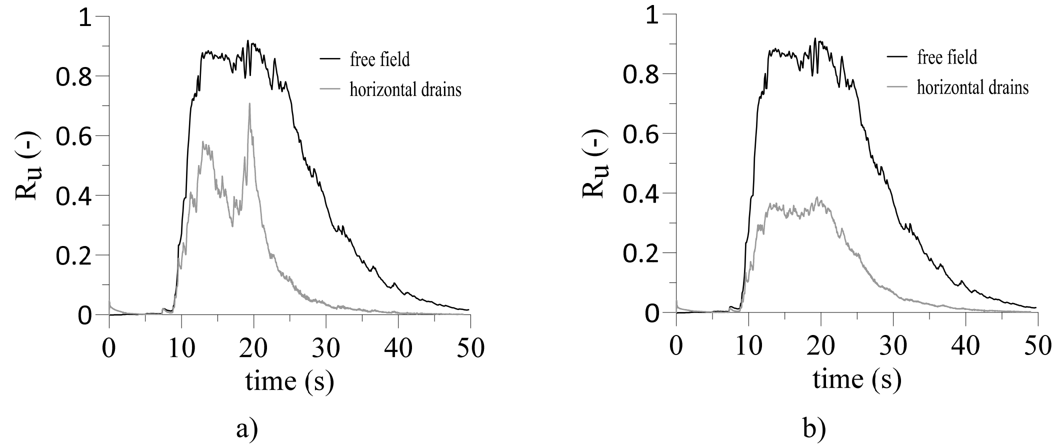


Figure 4. Comparison of pore pressure ratio obtained by FE analyses with and without horizontal drains a) point 3 (s/D=5); b) point 5 (s/D=10)

3 PARAMETRIC ANALYSES

3.1 *Numerical model*

Parametric numerical analyses were carried out with the aim to evaluate the effect of different geometric configurations of the horizontal drains. The drains were modelled varying their spacing *s* and their depth *H* from the water table, in a range of possible realistic configuration of the drains. The analyses carried out are summarized in Table 2 in which the spacing and the depth are presented in dimensionless form (s/d and H/d respectively), by dividing them by the diameter of the drains (Table 2).

Geometrical model implemented in Plaxis 2D is reported in Figure 5. The boundary conditions adopted are the same described in the previous section. Water table is set to 0.46 meters depth from the top ground surface, according to the condition modelled in the centrifuge test.

The drains were placed along three rows extended to the whole domain in order to obtain indefinite system and to have an independent distribution of excess pore pressure between drains. These assumptions avoid the introduction of other geometric variables.

Table 2: Parametric analysis set.

Model	(s/d)	(H/d)
H/d=5_s/d=5	5	5
H/d=5_s/d=10	10	5
H/d=5_s/d=15	15	5
H/d=10_s/d=5	5	10
H/d=10_s/d=10	10	10
H/d=10_s/d=10	15	10
H/d=15_s/d=5	5	15
H/d=15_s/d=10	10	15

Figure 6 shows the results of the analyses in terms of the maximum pore pressure ratio R_u profiles obtained at middle section during the shaking. It is evident the beneficial effect of the horizontal drains in reducing the pore pressure ratio with respect to the “no-drain” condition.

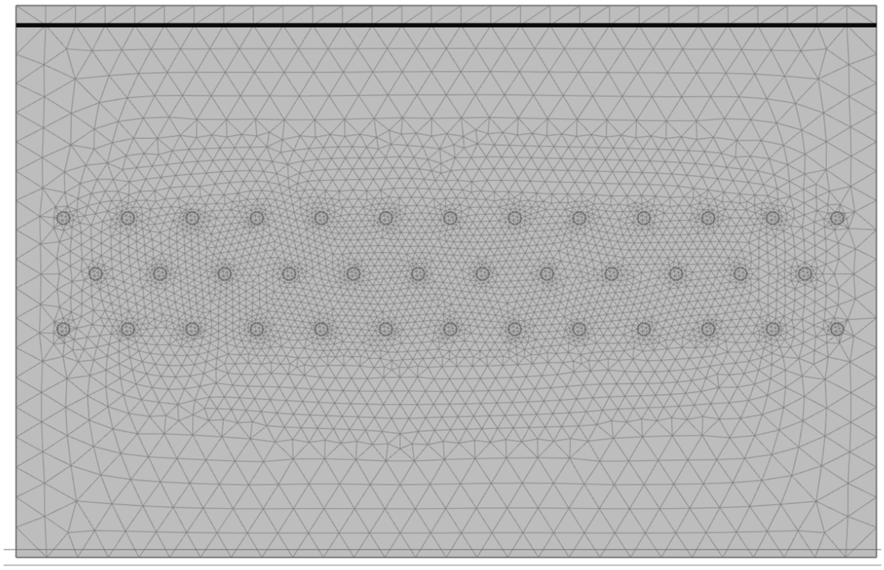


Figure 5. Example of numerical model implemented in Plaxis 2D (H/d=15; s/d=5).

The use of a small spacing reduces the pore pressure ratio in the area between the drains and increases it in the area outside, as occurs in the case of s/d equal to 5. A more homogeneous distribution of the drains yields to a reduction of the pore pressure ratio in the whole model. It is worth nothing that when the spacing is lower than or equal to the depth H, the R_u profiles are independent from the spacing. The pore pressure dissipation at the top of the model causes a less reduction of the shear stiffness and then it produces an increment of the pore pressure at the base of the model.

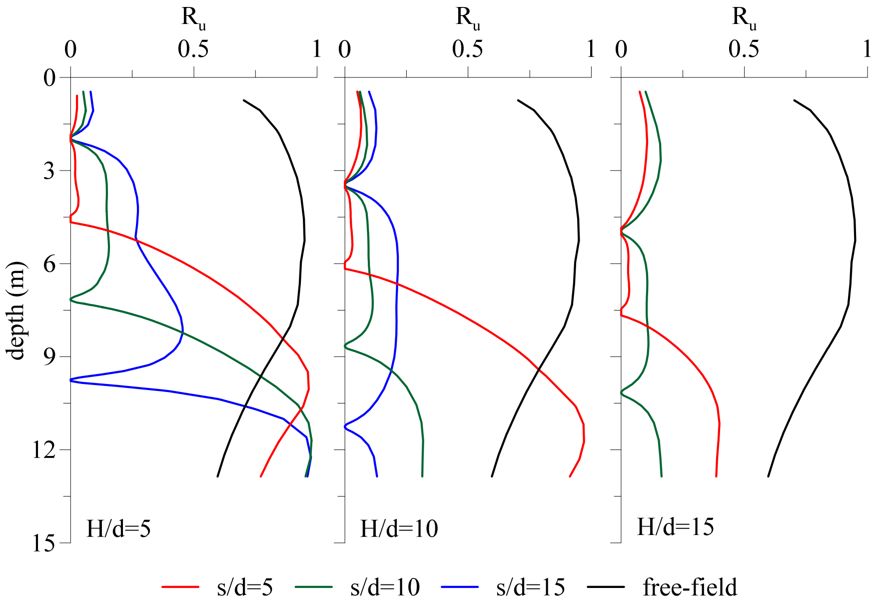


Figure 6. Vertical profiles of maximum excess pore pressure ratio (R_u).

In Figure 7 the effect of the drains in terms of spectral accelerations calculated at the top of the model is shown. Without drains a de-amplification of the accelerations with respect to the input signal is observed for low periods, indicating the occurrence of liquefaction. The presence of drains produces an amplification of the spectral accelerations at the top of the model compared to the case without drains. A single exception is observed for the case of H/d = 5 and s/d = 10. In this case there is a large de-amplification of the spectral accelerations. This effect is probably due to the distribution of the pore pressure at the base of the model which create an isolation effect.

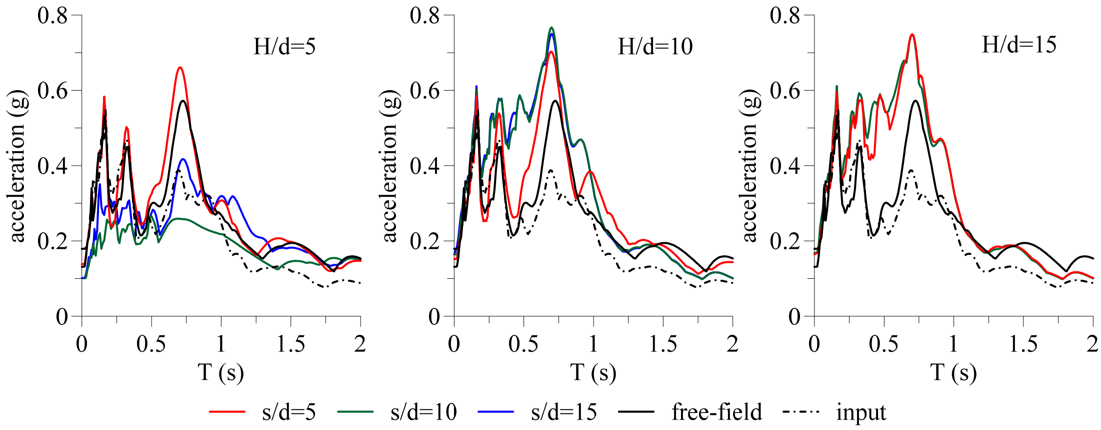


Figure 7. Acceleration response spectra of input motion and top ground surface acceleration.

4 CONCLUSIONS

In this paper the potential of horizontal drains as mitigation technique against liquefaction was investigated. Numerical parametric analyses were carried out by the FE code Plaxis2D. The soil was characterized by an advanced coupled soils constitutive model implemented in the Plaxis code: PM4sand. The input parameters for the models are evaluated on the base of both laboratory element tests and centrifuge tests. A centrifuge test with horizontal drains, carried out for the LIQUEFACT project, was reproduced in Plaxis 2D and the results of the simulation was shown, indicating a good ability of the numerical model to reproduce the experimental behaviour. Consequently, different numerical models were analysed by varying the drain spacing and their depth, in a range of possible realistic layouts. It was assessed that the geometrical configuration has a crucial role in reducing the pore pressure build-up. In particular the distribution of drains should be as more uniform as possible, by increasing the spacing or the depth, in order to minimize the pore pressure build-up. In conclusions the technique seems to be effective as a mitigation technique against liquefaction. Further studies are needed to evaluate the impact below a structure.

REFERENCES

Arulanandan, K. & Scott, R. F. 1993. Project VELACS—Control test results. *Journal of geotechnical engineering*, American Society of Civil Engineers, 119(8), 1276–1292.

Bardet, J. P., Idriss, I. M., O'Rourke, T. D., Adachi, N., Hamada, M. & Ishihara, K. 1997. North America-Japan workshop on the geotechnical aspects of the Kobe, Loma Prieta and Northridge earthquakes. *Dept. of Civil Engineering, University of Southern California, February*.

Boulanger, R. W. & Idriss, I. M. 2005. New criteria for distinguishing between silts and clays that are susceptible to liquefaction versus cyclic failure. *Proc., Technologies to Enhance Dam Safety and the Environment, 25th Annual United States Society on Dams Conf*, 357–366.

Boulanger, R. W. & Ziotopoulou, K. 2015. *PM4Sand (Version 3): A sand plasticity model for earthquake engineering applications*.

Fasano G., Bilotta E., Flora A., Fioravante V., Giretti D., Lai C.G. & Özcebe A.G. (2018). Dynamic centrifuge testing to assess liquefaction potential. *Physical Modelling in Geotechnics, Proc. 9th Int. Conf. on Physical Modelling in Geotechnics* (ICPMG 2018), July 17-20, London, United Kingdom, Volume 2, 955-960

Fioravante, V. & Giretti, D. 2016. Unidirectional cyclic resistance of Ticino and Toyoura sands from centrifuge cone penetration tests. *Acta Geotechnica*, Springer Berlin Heidelberg, 11(4), 953–968.

Fioravante, V., Giretti, D., Moglie, J., Bilotta, E., Flora, A., Fasano, G. & Nappa, V., 2019. Centrifuge modelling in liquefiable ground before and after the application of remediation techniques. *7th International Conference on Earthquake Geotechnical Engineering ICEGE,* Rome, ITALY

Green, R. A. & Mitchell, J. K. 2003. A closer look at Arias intensity-based liquefaction evaluation procedures. *2003 Pacific Conference on Earthquake Engineering*.

Manzari, M. T., Kutter, B. L., Zeghal, M., Iai, S., Tobita, T., Madabhushi, S. P. G., Haigh, S. K., Mejia, L., Gutierrez, D. A. & Armstrong, R. J. 2014. LEAP projects: concept and challenges. *n Proceedings, 4th International Conference on Geotechnical Engineering for Disaster Mitigation and Rehabilitation*, 109–116.

Seed, B. & Lee, K. L. 1966. Liquefaction of saturated sands during cyclic loading. *Journal of Soil Mechanics & Foundations Div*, 92(ASCE# 4972 Proceeding).

Zienkiewicz, O. C., Bicanic, N. & Shen, F. Q. 1989. Earthquake input definition and the trasmitting boundary conditions. *Advances in computational nonlinear mechanics*, Springer, 109–138.