Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions – Silvestri & Moraci (Eds)
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Full-scale testing of liquefaction mitigation using rammed aggregate piers in silty sands

S. Amoroso
University of Chieti-Pescara, Pescara, Italy
Istituto Nazionale di Geofisica e Vulcanologia, L'Aquila, Italy

K.M. Rollins & P. Andersen
Brigham Young University, Provo, UT, USA

G. Gottardi, L. Tonni & M.F. García Martínez
University of Bologna, Bologna, Italy

K. Wissmann
Geopier Foundation Company, Davidson, NC, USA

L. Minarelli
Geotema srl, University of Ferrara spin-off company, Ferrara, Italy

ABSTRACT: Liquefaction mitigation in silty sands is a major challenge for geotechnical engineers, specialty contractors, and owners. An extensive literature is available for studying densification of vibratory methods whose effectiveness decrease as the fines content increases, while few information are known on the increment of lateral pressure and of the composite stiffening response of piers. In this respect, a full-scale testing was performed in Bondeno (Ferrara, Italy) where liquefaction was observed in the 2012 Emilia earthquake. In this study, ground improvement in silty sand, produced by a group of 16 Rammed Aggregate Piers (RAP), was tested using in situ tests and controlled blasting. An adjacent untreated test area with no RAPs, which experienced liquefaction and significant settlement (70 to 100 mm) following controlled blasting, was also characterized for useful comparison. Relatively high excess pore pressure ratios were recorded in both the panels, while the measured settlement (20 to 40 mm) in the improved panel was significantly lower than in the unimproved panel and sand boils did not develop.

1 INTRODUCTION

Liquefaction mitigation in silty sands is a major challenge for geotechnical engineers, specialty contractors, and owners. As the fines content increases, vibratory methods for densification become progressively less effective and more expensive approaches, such as soil mixing or deep foundations, may be required. However, liquefaction evaluation techniques typically ignore potential increases in liquefaction resistance produced by increased lateral pressure during Rammed Aggregate Pier (RAP) installation, as well as potential increases in stiffness from composite response. In an effort, to investigate the influence of these factors on liquefaction resistance, field scale liquefaction tests, under controlled conditions, are therefore important for a correct quantification of these phenomena.

Previous experiences in the United States and New Zealand (e.g. Ashford et al. 2004, Wentz et al. 2015, Wissmann et al. 2015) show that liquefaction can be induced and monitored in clean sands with controlled blasting. Blast tests make it possible to compare pore pressure generation and settlement in natural and improved soils relative to their geotechnical properties.

Some efforts have also recently focused on studying the soil behavior of siltier deposits during blast-liquefaction test in Italy (Amoroso et. al. 2017, Fontana et al. 2019, Passeri et. al. 2018, Pesci et al. 2018). However, relatively little research is actually available to demonstrate RAP effectiveness in mitigating liquefaction in sandy silts and silty sands. Nevertheless, preliminary results from a case history in Ecuador suggest that RAP ground improvement elements installed beneath a 700 m-long bridge embankment prevented lateral spreading and settlement during the 2016, M_w 7.8 Muisne earthquake (Smith & Wissmann 2018).

In this context, a full-scale test was performed at a silty sand site in Bondeno (Ferrara, Italy) where liquefaction was observed in the 2012 Emilia earthquake (Emergeo Working Group 2013). In this study, 16 RAPs were installed to a depth of 10 m in a 4x4 grid pattern with a pier diameter of 500 mm and a center-to-center spacing of 2 m between piers. Piezocone penetration tests (CPTU) and seismic dilatometer tests (SDMT) were performed before and after installation to evaluate improvement in relative density and at-rest earth pressure produced by the RAP installation. An adjacent test area with no RAPs was also characterized by CPTU and SDMT testing for comparison purposes. To evaluate relative liquefaction resistance after RAP installation, controlled blasting tests were performed on the improved and unimproved test areas (herein referred to as 'panels') using an array of explosive charges detonated sequentially. Excess pore pressure ratios, settlements and accelerations were recorded at both panels. This paper describes the testing program and presents some preliminary results of the blast tests on both the treated and untreated test sites.

2 DESCRIPTION OF FIELD ACTIVITIES

The blast test activities were conducted over a period of one year (November 2017-October 2018), as listed in Table 1.

From November 2017 to January 2018 a preliminary site investigation campaign was aimed at identifying the most suitable blast-experiment site. This choice was guided by the necessity to select a shallow liquefiable layer of silty sands, and to limit the level of vibrations generated by the detonation to an acceptable threshold for people and buildings. In this respect, six sites were initially investigated through CPTUs within the Bondeno municipality (Ferrara, Italy) before to eventually select the trial site, located in a rural area at 1.5 km from the center of the village. The selected test site fulfils the above requirements, having experienced extensive liquefaction phenomena (about 4 to 6 meters long and 1.5 meters large) during the 2012 Emilia seismic sequence (M_L 5.9 and M_L 5.8 on May 20 and 29, 2012, respectively) and being more than 300 m far from a few isolated farms (sometimes ruins) or warehouses.

Table 1. Activities associated with blast tests at Bondeno site.

Phase	Activity	Period
I	Preliminary site campaign for site selection	November 2017-January 2018
II	Geotechnical and geophysical tests for characterization of blast trial site	February-March 2018
III	RAP column installation	March 2018
IV	Geotechnical and geophysical tests one month after RAP installation	April 2018
V	Installation of blast holes, profilometers, accelerometers pore pressure transducers	May 2018
VI	Blast test	4 June 2018
VII	Geotechnical and geophysical tests soon after blasting	June 2018
VIII	Geotechnical and geophysical tests one month and a half after blasting	July 2018
IX	Geotechnical and geophysical tests three month after blasting	September-October 2018

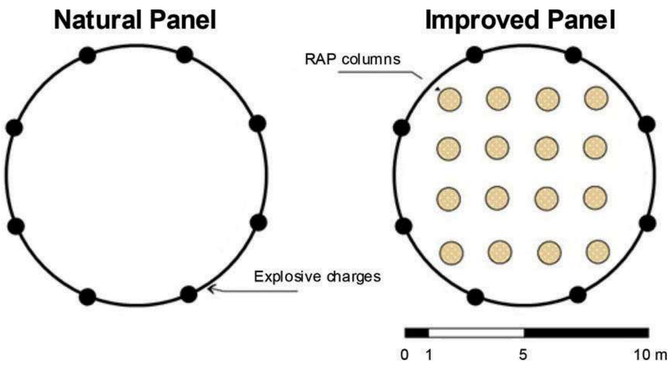

Figure 1. Layout of RAP columns and blast holes for natural and improved panel blast tests.

Therefore, from February to March 2018 an intensive geotechnical and geophysical campaign was carried out to characterize the subsoil at the blast site and to design the RAP columns and the blast experiment. These surveys identified a relatively homogeneous area (60 m x 40 m), which consequently became the focus of further investigations on two blast panels, one for testing the natural soil and one for the improved soil as shown in Figure 1.

Between the end of March and the beginning of April 2018, a 4x4 quadrangular grid (2 m spacing) of RAP columns was installed to a depth of approximately 10 m. RAP impact elements are constructed using displacement techniques with an excavator mounted mobile ram base machine fitted with a high frequency (30 to 40 Hz) vibratory hammer as illustrated in Figure 2. The base machine drives a 250 to 300 mm outside diameter open-ended pipe mandrel fitted with a unique specially-designed 350 to 400 mm diameter tamper foot into the ground. The method uses hydraulic crowd pressure and vertical vibratory hammer energy to displace and densify the liquefiable soils. Crushed gravel (typically graded at 20 to 40 mm in particle size) is fed through the mandrel from a top mounted hopper and compacted in the displaced cavities to create approximately 500 mm diameter, dense, stiff, aggregate pier elements. The construction methodology has been described in detail by Majchrzak et al. (2009) and Saftner et al. (2018).

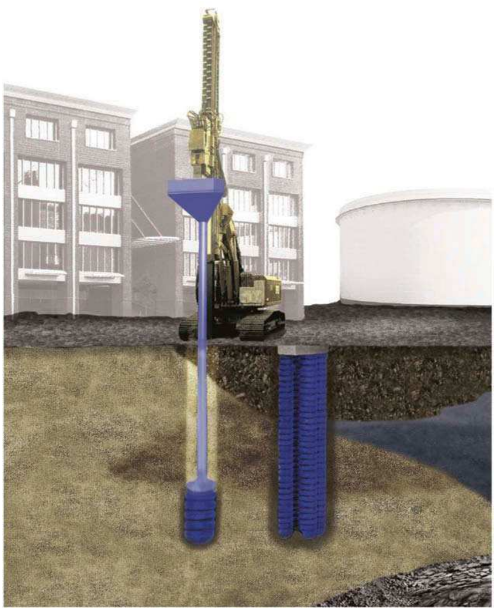

Figure 2. Illustration of the RAP column installation scheme with vibratory hammer and hopper/mandrel for gravel installation (https://www.geopier.com/Geopier-Systems/Rammed-Aggregate-Pier-Systems/Impact-System).

At the end of April 2018 supplementary geotechnical and geophysical tests were performed to evaluate the RAP effectiveness one month after the construction. During May 2018 blast holes, profilometers, accelerometers, pore pressure transducers were installed in preparation for the blast experiment that took place on June 4th, 2018.

Three post-blast site campaigns were then performed in June, July and September 2018, with the aim of comparing the variation with time of the geotechnical and geophysical parameters before and after the blast experiment in both the improved and unimproved areas.

3 SITE INVESTIGATIONS

The geotechnical characterization of the blast trial area consisted of piezocone tests, seismic dilatometers tests, boreholes and standard penetration tests, with retrieval of disturbed and undisturbed samples, reaching on average 15 m of depth. As an example, Figure 3 shows the profiles of a CPTU test carried out prior to the RAP installation, in terms of corrected cone resistance q_t, pore pressure u_2, and classification results provided by the well-known Soil Behaviour Type (SBT) approach (Robertson 2009). The piezocone interpretation revealed the following stratigraphic units:

i. clay and silty clay from ground level to 2 m in depth;
ii. intermediate soils (silts, clayey silts and sandy silts) from 2 to 3.5 m;
iii. sands and silty sands from 3.5 to 17 m, with occasional lenses of intermediate soils.

Estimates of the fine content (*FC*) calculated from CPTU according to Robertson & Wride (1998) have been reported as well. It is worth observing that, in these sediments, the computed *FC* values appear to be generally underestimated in comparison with those obtained from laboratory tests, which typically vary in the range 20-40% (García Martínez et al. 2018).

The CPTU profile of Figure 3 may be undoubtedly assumed as representative of the stratigraphic arrangement of the whole area, where a very limited horizontal spatial variability has been detected.

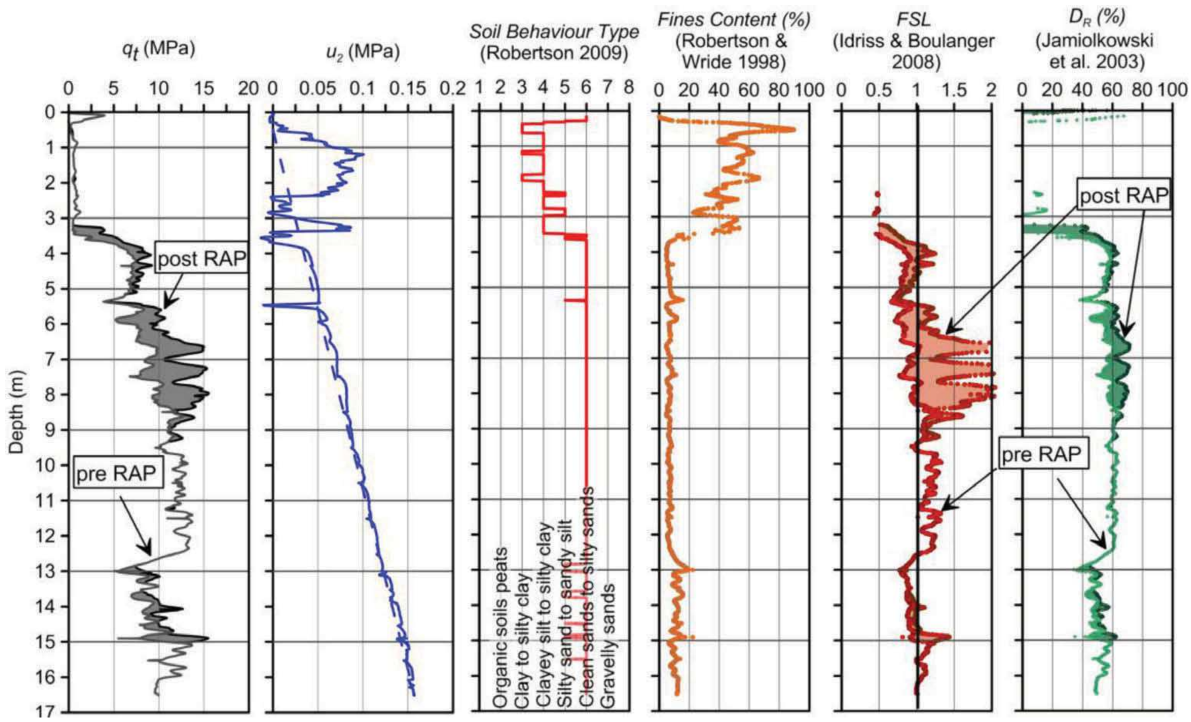

Figure 3. Typical CPTU profile at Bondeno test site along with interpreted relative density (D_R) and factor of safety (*FSL*) against liquefaction before and after RAP treatment.

By applying the well-established CPTU-based procedure proposed by Idriss & Boulanger (2008) for the assessment of liquefaction susceptibility and preliminarily estimating the fines content *FC* by Robertson & Wride (1998), a potential liquefiable layer has been identified from 3 to 8 m in depth. Results, expressed in terms of safety factor against liquefaction, *FSL*, are shown in Figure 3. A moment magnitude $M_w = 6.14$ and peak ground acceleration $a_{max} = 0.22$g have been adopted in the calculation, according to the ongoing seismic microzonation study on the Bondeno municipality.

For useful comparison, the q_t profile from a post-RAP CPTU, carried out close to the pre-RAP one, is also shown in the figure. As can be clearly observed, cone resistance increases from 3 to 9 m in depth after piers installation, being particularly evident from 5.5 to 8.5 m. The post-RAP profile for *FSL*, also included in the figure, allows capturing very clearly the densification effect caused by the pier installation from 5.5 to 8.5 m in depth. Furthermore, profiles of the relative density (D_R) computed with the correlation proposed by Jamiolkowski et al. (2003) show, at the same depth interval, an increase in D_R of approximately 10 % after piers installation.

Following such soil features, for each test panel blast charges of 0.5 and 2 kg were designed for depths of 3.5 and 6.5 m, respectively, with a minimum of eight blast holes equally distributed around a 5 m-radius ring.

4 PRELIMINARY RESULTS

The blast experiment involved two sequences of blast charges, one in the natural and one in the improved panel, that were detonated separately with a time delay of three hours. Pore pressure transducers, settlement profilometers and accelerometers measured response, during and after the detonations, to document the generation and subsequent dissipation of the excess pore pressure, the vertical ground deformations, and the blast-induced ground motions, respectively. Topographical surveys were carried out to measure ground surface settlements using a variety of different techniques.

Figure 4 provides an aerial photo taken by a drone after both the blasts. It can be easily observed that liquefaction has been induced in the natural panel, as clearly indicated by the

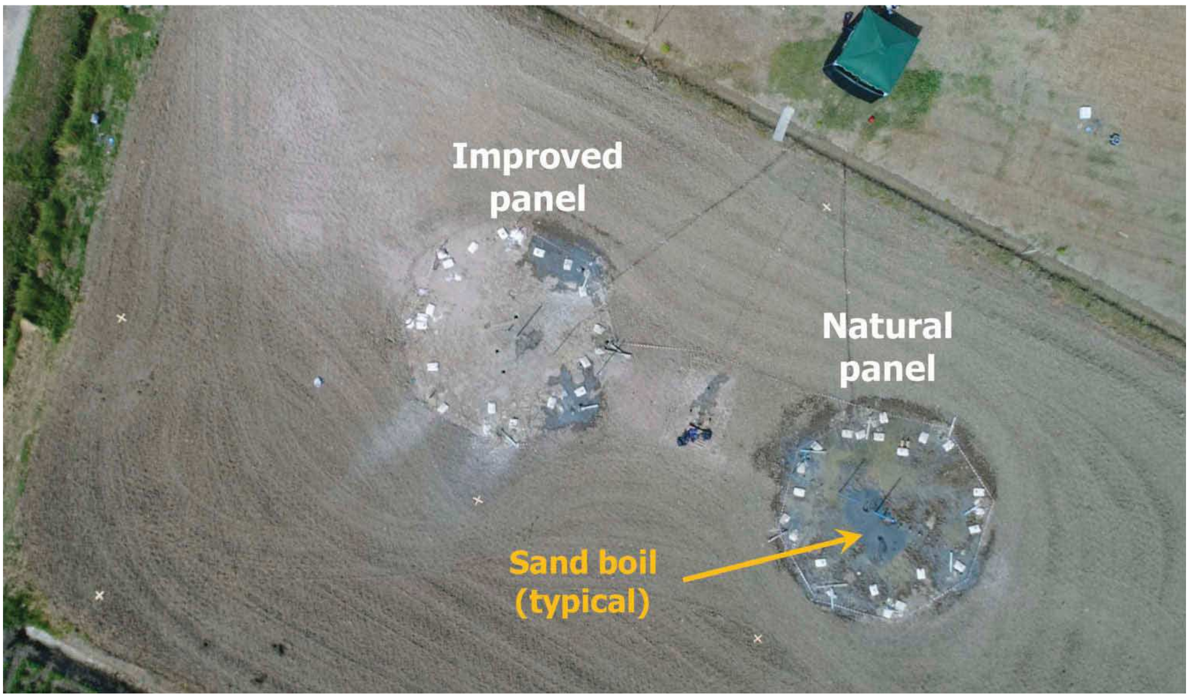

Figure 4. Aerial photo showing liquefaction-induced sand boils within the natural panel but no sand ejecta within the margins of the RAP group in the improved panel after completion of both blast tests.

sand ejecta. In contrast, no liquefaction features are observed within the improved panel. Limited sand ejecta is visible on the blast ring, where the charges were located, but this is beyond the limits of the RAP group and likely developed within unimproved soils. The observed reduction in sand ejecta is significant considering that ejecta was a major source of settlement and building damage in the Christchurch, New Zealand earthquake sequence in 2010-2011 (van Ballegooy et al. 2014).

Excess pore pressures measured by the transducers were used to compute excess pore pressure ratios ($R_u = \Delta u/\sigma'_o$) in the untreated and treated panels, where Δu is the measured excess pore pressure and σ'_o is the initial vertical effective stress prior to the blast. Soil unit weights were interpreted from the SDMT tests. In the untreated panel, R_u values reached 1.0, indicating liquefaction, from a depth of 4 to 9 m. Plots of R_u versus time after blasting are presented in Figure 5 for transducers at a depth of 5 m in the treated and untreated panels. In the untreated panel, the blasting sequence produced R_u values near 1.0 which persisted for 15 to 30 seconds and then dissipated to near static levels in about 4 minutes. In the improved panel, peak R_u values were somewhat lower (R_u = 0.75) than in the untreated panel, but dissipated at a similar rate.

Settlement profilometers indicate that liquefaction and subsequent reconsolidation occurred within a zone from about 3 to 10 m below the ground surface which is consistent with the expected zone of liquefiable sediments. In the unimproved panel, volumetric strains were similar to what would be expected using prediction equations proposed by Zhang et al. (2002). Volumetric strains in the improved panel were on the order of 20% of those measured for the unimproved panel, despite excess pore water pressure values that resulted in R_u values of about 0.7.

Topographical surveys performed using both conventional and drone photogrammetry, indicate that settlement within the unimproved panel was between 70 and 100 mm after both blasts. In contrast, settlement within the improved panel was between 20 and 40 mm. Liquefaction induced settlements in the unimproved panel would likely be excessive for many structures, whereas the reduced settlements in the improved panel would likely be tolerable for many structures.

The mechanisms responsible for the reduced settlement in the panel treated with RAP columns are presently the subject of on-going research.

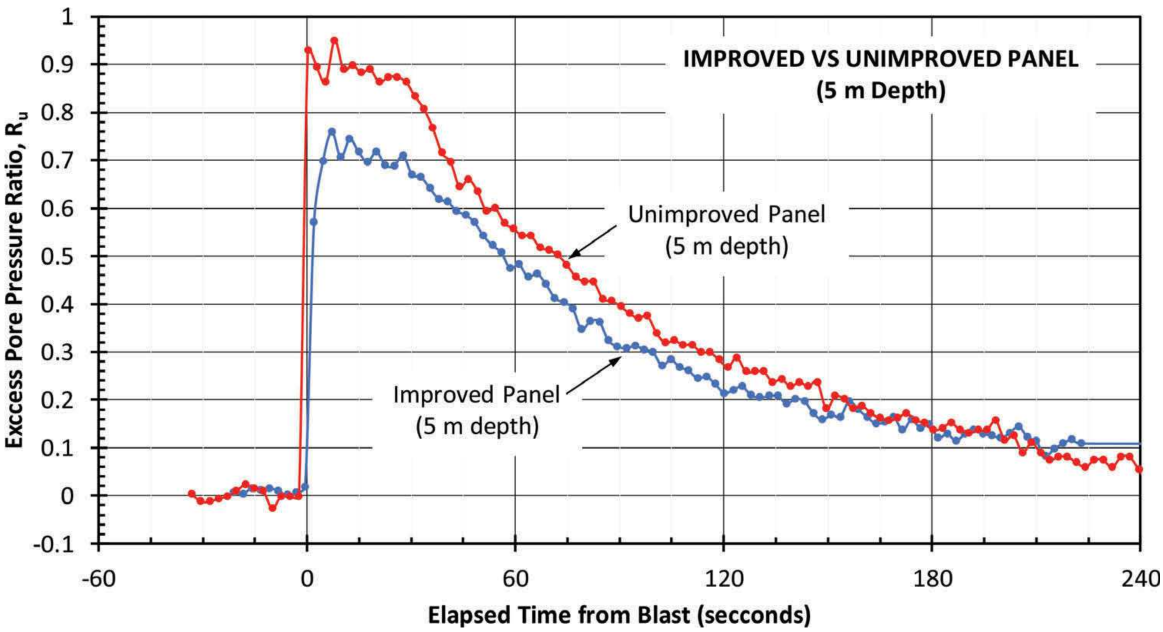

Figure 5. Comparison of preliminary measured excess pore pressure vs. time curves for improved and unimproved panels at a depth of 5 m below the ground surface.

5 SUMMARY AND CONCLUSIONS

Full-scale blast-induced liquefaction tests were recently carried out in Italy to evaluate the effectiveness of Rammed Aggregate Piers (RAP) in mitigating liquefaction hazards in silty sands. Tests were performed on treated and untreated panels at a profile where silty sands liquefied and produced numerous sand boils during the 2012 M_w 6.1 Emilia earthquake. The controlled blasting experiment induced liquefaction in natural untreated soils composed of silty sands from 3 to 9 m below ground and produced surface settlements of 70 to 100 mm. Numerous boils were observed and volumetric strains within the liquefied layers were similar to those that would be expected from earthquake-induced liquefaction. Within the improved panel, excess pore pressure ratios were somewhat lower than in the unimproved panel, but still greater than 75 %. Despite these relatively high excess pore pressure ratios, the measured settlement (20 to 40 mm) was significantly lower than in the unimproved panel and sand boils did not develop within the treated panel. In this case, RAP treatment was effective in reducing liquefaction-induced settlement to acceptable levels for many structures in comparison with the untreated soil.

Because data analyses are still ongoing, the presented results represent preliminary evaluations that will be refined to develop more in-depth studies that will illustrate, compare and integrate the information derived from the different instrumentation and observations. Additional research is necessary to understand the fundamental mechanisms leading to the reduction in settlement within the treated panel.

ACKNOWLEDGEMENTS

The study was primarily funded by Geopier® Foundation Company (Davidson, North Carolina, United States). A special thanks also to Releo s.r.l. (Ferrara, Italy) who provided the installation of the Rammed Aggregate Piers free of charge. Special thanks also to INGV-FIRB Abruzzo project ("Indagini ad alta risoluzione per la stimadella pericolosità e del rischio sismico nelle aree colpite dal terremoto del 6 aprile 2009", http://progettoabruzzo.rm.ingv.it/it), to INGV-Abruzzo Region project ("Indagini di geologia,sismologia e geodesia per la mitigazione del rischio sismico", L.R. n. 37/2016) and to CIRI Edilizia e Costruzioni, University of Bologna, Italy (TIRISICO PROJECT "Tecnologie Innovative per la riduzione del rischio sismico delle Costruzioni", Project no. PG/2015/737636, POR-FESR 2014-2020) for the financial contribution to this research activity.

REFERENCES

Amoroso, S., Milana, G., Rollins, K.M., Comina, C., Minarelli, L., Manuel, M.R., Monaco, P., Franceschini, M., Anzidei, M., Lusvardi, C., Cantore, L., Carpena, A., Casadei, S., Cinti, F.R., Civico, R., Cox, B.R., De Martini, P.M, Di Giulio, G., Di Naccio, D., Di Stefano, G., Facciorusso, J., Famiani, D., Fiorelli, F., Fontana, D., Foti, S., Madiai, C., Marangoni, V., Marchetti, D., Marchetti, S.L., Martelli, L., Mariotti, M., Muscolino, E., Pancaldi, D., Pantosti, D., Passeri, F., Pesci, A., Romeo, G., Sapia, V., Smedile, A., Stefani, M., Tarabusi, G., Teza, G., Vassallo, M.& Villani F. 2017. The first Italian blast-induced liquefaction test (Mirabello, Emilia-Romagna, Italy): description of the experiment and preliminary results. *Annals of Geophysics* 2037-416X, 60(5), S0556, 19 pp.

Ashford, S., Rollins, K.M. & Lane, J. 2004. Blast-induced liquefaction for full-scale foundation testing. *Journal of Geotechnical and Geoenvironmental Engineering* 130(8),798–806.

Emergeo Working Group. 2013. Liquefaction phenomena associated with the Emilia earthquake sequence of May-June 2012 (Northern Italy). *Natural Hazards and Earth System Sciences* 13 (4): 935–947.

Fontana, D., Amoroso, S., Minarelli, L. & Stefani M. 2019. Sand liquefaction phenomena induced by a blast test: new insights from composition and texture of sands (late Quaternary, Emilia, Italy). *Journal of Sedimentary Research*, 89(1):13–27.

Garcìa-Martinez, M.F., Tonni, L., Gottardi, G., Amoroso, S., Rollins, K.M. & Minarelli L. 2018. Indagini in sito per la caratterizzazione di un terreno suscettibile di liquefazione in preparazione all'esecuzione di un blast test. *Incontro Annuale dei Ricercatori di Geotecnica*, IARG 2018; Proc. conf., Genova, 4–6 July 2018.

Idriss, I.M. & Boulanger, R.W. 2008. Soil liquefaction during earthquakes. *Earthquake Engineering Research Institute*, MNO.12, 261 pp. Oakland, CA.

Jamiolkowski M., Lo Presti D.C.F. & Manassero M. 2003. Evaluation of Relative Density and Shear Strength of Sands from Cone Penetration Test and Flat Dilatometer Test. *Soil Behaviour and Soft Ground Construction*; GSP 119: 201–238.

Majchrzak, M., Farrell, T. & Metcalfe, B. 2009. Innovative soil reinforcement method to control static and seismic settlements. In Magued Iskander et al. (ed), *Contemporary Topics in Ground* Modification, *Problem* Soils, *and* Geo-support; Proc. intern. conf. GSP 187: 313–320. Reston: American Society of Civil Engineers (ASCE).

Passeri, F., Comina, C., Marangoni, V., Foti, S.& Amoroso S. 2018. Geophysical tests to monitor blast-induced liquefaction, the Mirabello (NE, Italy) test site. *Journal of Environmental and Engineering Geophysics* 23(3): 319–333.

Pesci, A., Amoroso, S., Teza, G. & Minarelli, L. 2018. Characterisation of soil deformation due to blast-induced liquefaction by UAV-based photogrammetry and terrestrial laser scanning. *International Journal of Remote Sensing and Remote Sensing Letters*, 1366–5901.

Robertson, P.K. 2009. Interpretation of cone penetration tests – a unified approach. *Canadian Geotechnical Journal* 46(11): 1337–1355.

Robertson, P.K. & Wride, C.E. 1998. Evaluating cyclic liquefaction potential using the cone penetration test. *Canadian Geotechnical Journal* 35(3): 442–459.

Schneider, J.A., Randolph, M.F., Mayne, P.W., Ramsey, N.R. 2008. Analysis of factors influencing soils classification using normalized piezocone tip resistance and pore pressure parameters. *Journal Geotechnical and Geoenvironmental Engineering*, 134(11): 1569–1586.

Saftner, D.A., Zheng, J., Green, R.A., Hryciw, R. & Wissmann, K. 2018. Rammed aggregate pier installation effect on soil properties. *Institution of Civil Engineers-Ground Improvement; Proc*. 171(2): 63–73. London: ICE Publishing.

Smith, M.E. & Wissmann, K. 2018. Ground Improvement Reinforcement Mechanisms Determined for the Mw 7.8 Muisne, Ecuador, Earthquake. In Scott J. Brandenberg & Majid T. Manzari (ed)., *5th Geotechnical Earthquake Engineering and Soil Dynamics Conference: Liquefaction Triggering, Consequences, and Mitigation, GEESDV 2018; Proc. intern. conf., Austin*, *10-13 June 2018*, GSP 290: 286–294. Reston: American Society of Civil Engineers (ASCE).

van Ballegooy, S., Malan, P., Lacrosse, V., Jacka, M.E., Cubrinovski, M., Bray, J.D., O'Rourke, T.D., Crawford, S.A. & Cowan, H. 2014. Assessment of Liquefaction-Induced Land Damage for Residential Christchurch. *Earthquake Spectra*, 30(1): 31–55.

Wentz, F.J., van Ballegooy, S., Rollins, K.M. Ashford, S.A. & Olsen, M.J. 2015. Large scale testing of shallow ground improvements using blast-induced liquefaction, *6th International Conference on Earthquake Geotechnical Engineering, 6ICEGE; Proc. Intern. Conf., Christchurch, 1-4 November 2015*.

Wissmann, K.J., van Ballegooy, S., Metcalfe, B.C., Dismuke, J.N. & Anderson, C.K. 2015. Rammed aggregate pier ground improvement as liquefaction method in sandy and silty soils. *6th International Conference on Earthquake Geotechnical Engineering, 6ICEGE; Proc. Intern. Conf., Christchurch, 1-4 November 2015*.

Zhang, G., Roberson, P.K. & Brachman, R.W.I., 2002. Estimating liquefaction-induced ground settlements from CPT for level ground. *Canadian Geotechnical Journal*, 39(5): 1168–1180