MICRO-ERT LABORATORY MEASUREMENTS FOR SEISMIC LIQUEFACTION

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Liquefaction of soils is one of the most dangerous secondary effects of an earthquake. It deals with a drastic reduction of effective stresses and loss of bearing capacity in sandy, poorly consolidated, saturated soils. The rapid set-up of excess pore pressure (order of seconds) does not permit their dissipation and they increase until the critical point of liquefaction is reached. At this point, the saturated sandy system acts as a pressurized non-Newtonian fluid, which loses its shear strength and causes the fracturing of confining layers resulting in the typical liquefaction phenomena at the ground surface: sand boils, linear fractures, punctual uplift of sand, deformations and significant settlements. The liquefaction susceptibility is nowadays assessed by the so-called Simplified Approaches (Seed and Idriss, 1971; Robertson and Wride, 1998; Youd and Idriss, 2001; Boulanger and Idriss, 2014). These are based on in-situ geotechnical tests and in particular the Cone Penetration Test (CPT) and Standard Penetration Test (SPT), allow to evaluate by semi-empirical correlations a factor of safety (FS) given by the ratio between the Cyclic Resistance Ratio (CRR) and Cyclic Stress Ratio (CSR). The CSR is the load induced by a hypothetical earthquake, mainly depending on the local seismic hazard at the site, and the CRR is the soil resistance, which depends on the soil materials and their physico-mechanical properties.

On the other hand, liquefaction susceptibility has not been well discussed from the point of view of geophysical parameters. The most important works on the subject are those of Hunter, (2003) and Ishihara and Tsukamoto, (2004) which stress the importance of measuring P and S waves in order to characterize soils prone to liquefaction. By following these studies, de Franco *et al*. (2018), suggests a first approach to attain the geophysical susceptibility to liquefaction. They demonstrate that it is possible to identify soils prone to liquefaction by measuring their seismic velocities (v_p and v_s): the first one acts as a proxy of the degree of water saturation and the second one as a proxy of the geotechnical soil class.

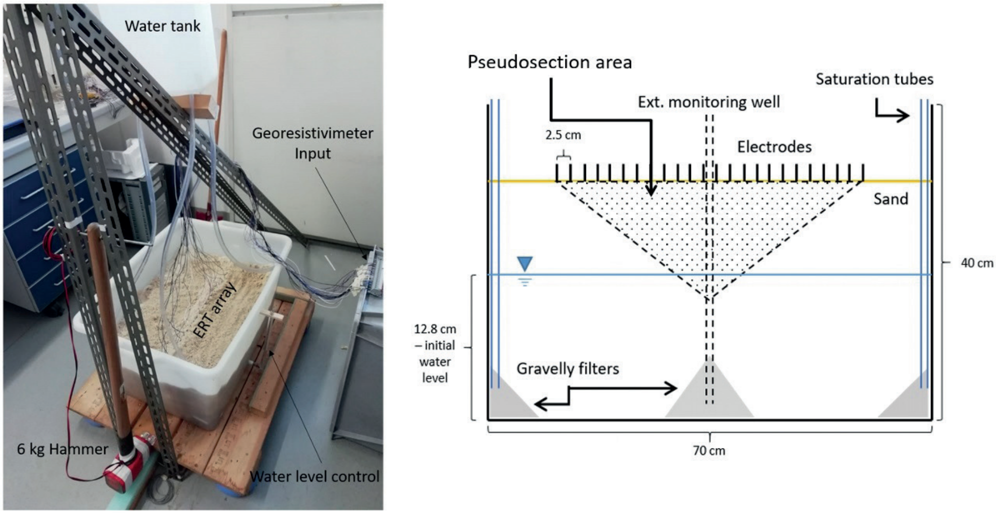

Fig. 1 - Experimental setup: a sledgehammer is used as seismic source. Each hit is followed by an ERT measurement to evaluate the effect of the seismic input.

The most recent literature suggest the use of geophysics as a tool for identifying the liquefied zones after earthquakes (Abu Zeid *et al*., 2012; Apostolopoulos *et al*., 2013; Giocoli *et al*., 2014). Applied geophysics techniques were also used to quantify the phenomenon, evaluating the differences in electrical resistivity before and after the detonation of explosive charges in a liquefiable unit (the so called *Blast Tests*, *e.g*. Amoroso *et al*., 2017).

The hypothesis, which we want to test in this work, is the following: during the generation of the excess pore pressures, grains of sand "vibrate" and they tend to separate from each other at each cycle of the seismic input. If so, we should observe be two important variations in at least two geophysical parameters, without producing sensitive settlements or displacements: electrical resistivity and v_s velocity.

In the light of this hypothesis and to test it, a simple laboratory experiment has been conducted, trying to validate the abovementioned statement, in particular from the point of view of electrical resistivity. Jinguuji *et al*., (2003), were the first who try to follow the process in the laboratory, studying the variation in density pre and post liquefaction using electrical resistivity and cyclic dynamic loads. On the contrary, the proposed experiment consisted of micro-ERT (Electrical Resistivity Tomography) time-lapse measurements carried on a sandbox subjected to an impulsive "seismic" input, simulating a real ERT field acquisition.

A 70x45x40 cm box is filled with fine sand (HOSTUN Sand) (Fig. 1 right panel). The sandbox is equipped with four tubes at each angle to saturate the system gradually from the bottom. A monitoring well is installed externally to the tank to control the water level and its oscillations. The sandbox is positioned above a wood plate where a sledgehammer pendulum of 6 kg is used to hit the system generating the seismic input (Fig. 1 left panel). On the surface of the sand, 24 inox steel electrodes are connected to Syscal Pro georesistivimeter for ERT measurement. Resistivity data were acquired for all the experimental steps with a Schlumberger configuration of 121 quadrupoles measured every about 130 s. The experiment was divided in four main steps:

1. *Saturation step*: every ERT 0.5 l of water was poured in the model. This step ends when the water table reaches a depth of approximatively 8.7 cm below ground surface;
2. *Stationary step*: ERT time-lapse measurements for back-ground analysis;
3. *Dynamic step*: the pendulum hits 7 times the system at the beginning of each ERT. During this step, the water level increase was monitored through the external pipe.

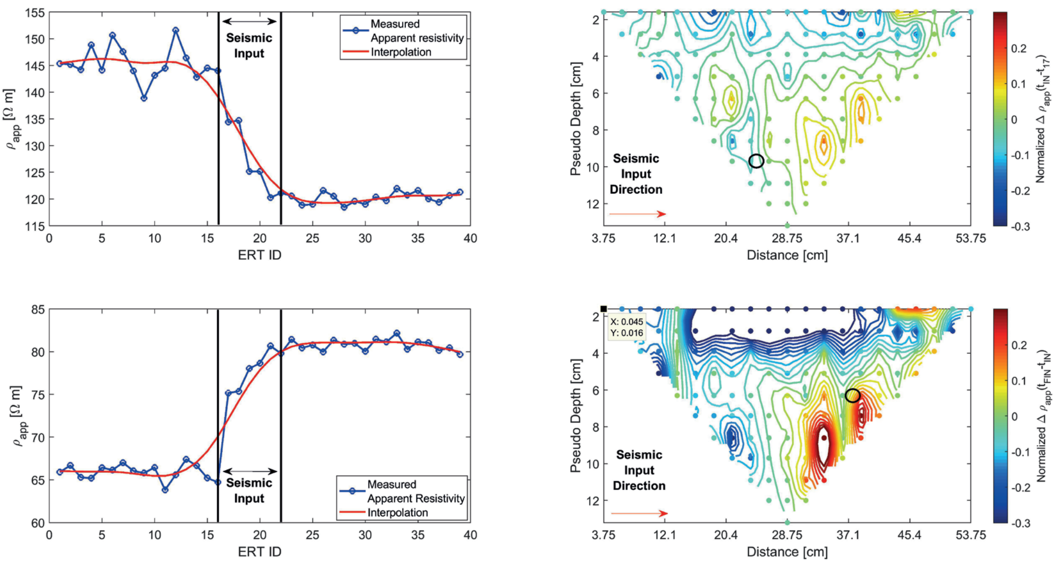

Fig. 2 - ERT time-lapse measurements from step 2 to step 4. Left panels: ϱ_{app} resistivity variations for the two nodes highlighted with black circles in the right panels. Right panels: ϱ_{app} variations during the seismic input (upper) and post-seismic input (lower) across the sandbox, normalized with respect to the initial pseudosection.

4. *Post-dynamic step*: ERT time-lapse measurements of the post-dynamic pressure dissipations.

The most important result obtained was reached in the Dynamic step (Fig.2). The initial water level was at 8.7 cm below ground surface. After the first hit, perturbations of apparent resistivity (ϱ_{app}) were observed up to the seventh hammer hits. The produced variations of ϱ_{app}

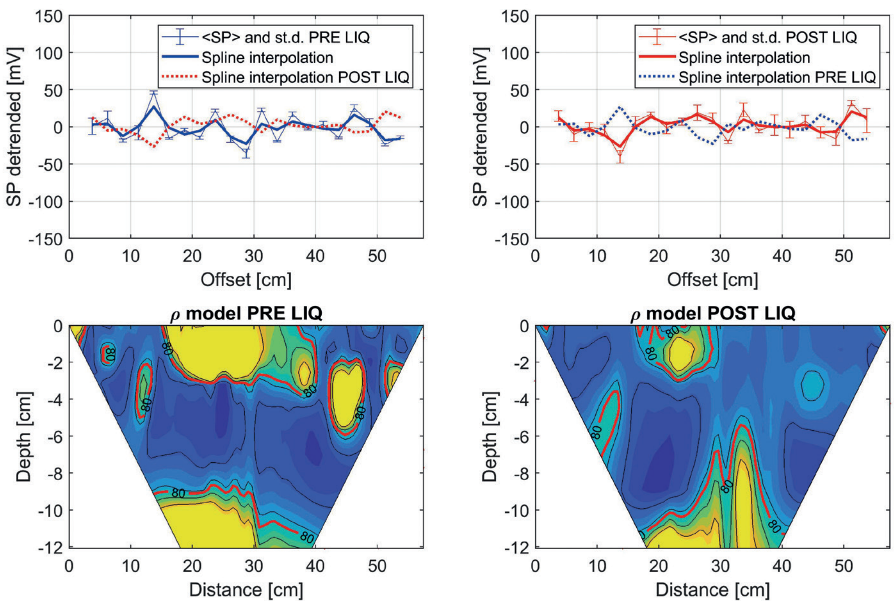

Fig. 3 - The self-potential (sp) collected data. The left upper panel represents the sp detrended data collected before the dynamic step and (left lower panel) the initial resistivity model related. On the other hand, the right upper panel represents the sp detrended data collected after the dynamic step and (right lower panel) the final resistivity model related.

reached an average value of ±50% during the process and these variations are preserved in the time-lapse inverted models. A preliminary interpretation of the presented data could be the following: the left part of the model exhibit excess pore pressure (negative variations), which permitted the water to flow upwards while the right part exhibits consolidation phenomena (positive variations). This interpretation could be confirmed by the increase in the average level of the water table in the external well, with a rate of about 0.25 cm/hit, and with the measures of self-potentials done during the experiment. In fact, the measured self-potential before and after the Dynamic stage, is affected by local variations that might be related to the flow of water in the sand (Fig. 3).

These preliminary results indicate that ERT could be a suitable technique to the time-lapse monitoring of the setting up of pore water pressures and liquefaction process.

References

Abu Zeid, N. *et al*. (2012) 'Electrical resistivity tomography investigation of coseismic liquefaction and fracturing at San Carlo, Ferrara Province, Italy', *Annals of Geophysics*, 55(4), pp. 713–716. doi: 10.4401/ag-6149.

Amoroso, S. *et al*. (2017) 'The first Italian blast-induced liquefaction test (Mirabello, Emilia-Romagna, Italy): Description of the experiment and preliminary results', *Annals of Geophysics*, 60(5). doi: 10.4401/ag-7415.

Apostolopoulos, G. *et al*. (2013) 'Geophysical Investigation for the Detection of Liquefaction Phenomena in an Archaeological Site, Lechaion, Greece', (September 2013). doi: 10.3997/2214-4609.20131379.

Boulanger, R. W. and Idriss, I. M. (2014) *CPT and SPT based liquefaction triggering procedures*, *Center for Geotechnical Modeling*. Available at: https://faculty.engineering.ucdavis.edu/boulanger/wp-content/uploads/sites/71/2014/09/Boulanger_Idriss_CPT_and_SPT_Liq_triggering_CGM-14-01_20141.pdf (Accessed: 20 March 2018).

de Franco, R. *et al*. (2018) 'Geophysical characterization of liquefaction-prone areas: the Quistello test site, central Po Plain, Northern Italy', *Soil Dynamics and Earthquake Engineering*.

Giocoli, A. *et al*. (2014) 'Electrical resistivity tomography for studying liquefaction induced by the May 2012 Emilia-Romagna earthquake (Mw=6.1, northern Italy)', *Natural Hazards and Earth System Sciences*, 14(4), pp. 731–737. doi: 10.5194/nhess-14-731-2014.

Hunter, J. . A. A. (2003) 'Some observations of Vp, Vs, depth and porosity from borholes in water-satured unconsolidated sediments', in *SAGEEP*, pp. 650–661.

Ishihara, K. and Tsukamoto, Y. (2004) 'Cyclic strength of imperfectly saturated sands and analysis of liquefaction', *Proceedings of the Japan Academy, Series B*, 80(8), pp. 372–391. doi: 10.2183/pjab.80.372.

Jinguuji, M., Kunimatsu, S. and Toprak, S. (2003) 'A monitoring and visualization technique for liquefaction using resistivity', in *Earthquake Resistant Design of Lifeline Facilities and Countermeasures Against Liquefaction*.

Robertson, P. K. and Wride, C. (Fear) (1998) 'Evaluating cyclic liquefaction potential using the cone penetration test', *Canadian Geotechnical Journal*. NRC Research Press Ottawa, Canada, 35(3), pp. 442–459. doi: 10.1139/t98-017.

Seed, H. B. and Idriss, I. M. (1971) 'Simplified Procedure for Evaluating Soil Liquefaction Potential.', *Journal of the Soil Mechanics and Foundations Division*, 97(9), pp. 1249–1273.

Youd, T. L. and Idriss, I. M. (2001) 'Liquefaction Resistance of Soils: Summary Report from the 1996 NCEER and 1998 NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils', *Journal of Geotechnical and Geoenvironmental Engineering*, 127(4), pp. 297–313. doi: 10.1061/(ASCE)1090-0241(2001)127:4(297).