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Centrifuge modelling in liquefiable ground before and after the application of remediation techniques

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ABSTRACT: This paper describes the small scale centrifuge modelling activities performed at ISMGEO (Istituto Sperimentale Modelli Geotecnici, formerly ISMES – Italy) laboratory in the frame of the H2020 LIQUEFACT project (http://www.liquefact.eu/). The main aim of the experimentation was to analyze the seismic behavior of loose, saturated, sandy deposits, homogeneous or stratified, subjected to increasing seismic excitations up to liquefaction and to verify the effectiveness of different liquefaction mitigation techniques. Some tests were carried out under free field condition, in some others a simple structure based on shallow foundations was modelled. Thirty-seven centrifuge tests were carried out to this aim, organized in three series: the first one aimed at investigating the liquefaction triggering conditions, the second and third ones devoted at analyzing the effectiveness of three selected liquefaction mitigation techniques: vertical drains, horizontal drains and "Induced Partial Saturation" (IPS). Some of the most significant results are presented in this paper.

1 INTRODUCTION

Liquefaction occurs in saturated non plastic soils when seismic loading causes a pore-water pressure build up and a drop of the effective stresses. As a consequence, the soils lose their strength and stiffness and behave like a viscous fluid. Even if the phenomenon has usually a short duration, its consequences on structures can be devastating.

Even if intensively studied since the 1964 Niigata earthquake, seismic-induced liquefaction still caused during recent earthquakes (Kobe earthquake in 1995 in Japan, Kocaeli earthquake in Turkey in 1999, Ji-Ji earthquake in Taiwan in 1999, Bhuj earthquake of 2001 in India, Tohoku earthquake in 2011in Japan, Christchurch 2010-11 earthquakes in New Zealand), major damages of structures and infrastructures, leading to huge economic losses and serious impediment to post-earthquake emergency operations, and highlighting the necessity of further researches, focused in particular on the issue of mitigation measures (Bardet et al. 1997, Green & Mitchell 2003).

In the last 50 years, liquefaction of soils has been mainly studied by means of cyclic triaxial and cyclic simple shear tests. In recent years also the geotechnical centrifuge has been recognized as a powerful experimental tool for liquefaction study. Among other studies, in the early 1990's, the VELACS (Verification of Liquefaction Analysis by Centrifuge Studies) project used extensive data from liquefaction tests on centrifuges to verify numerical procedures (Arulanandan & Scott 1993). LEAP (Liquefaction Experiments and Analysis Projects) is a joint project that pursues to verification, validation and uncertainty quantification of numerical liquefaction models, based on centrifuge experiments (Manzari et al. 2014). The challenge now for liquefaction study using centrifuge modelling is not whether this phenomenon can be simulated in a centrifuge test but how to simulate it properly and how to interpret the test data.

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 (Airoldi et al. 2018; Fasano et al. 2018). Vertical and horizontal drains were installed in the models, in order to analyze 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. Models were tested both in free field conditions and in presence of a simplified structure. In this paper the experimental details are described (testing materials, testing apparatuses, model reconstitution and set-up, miniaturized instrumentation, test procedures) and some preliminary test results are presented.

2 CENTRIFUGE MODELLING

2.1 *The ISMGEO geotechnical centrifuge and model container*

The ISMGEO geotechnical centrifuge is a beam centrifuge made up of a symmetrical rotating arm with a diameter of 6 m, a height of 2 m and a width of 1 m, and a nominal radius to the model base of about 2.2 m. A shaking table is fixed at one side of the arm; at the other side the arm holds a swinging platform which carries the model for static tests. An outer fairing covers the arm and they concurrently rotate to reduce air resistance and perturbation during flight. The centrifuge has a 240 g-ton capacity, this means that the machine has the potential of reaching an acceleration of 600g loading a payload of 400 kg. The shaking table can work under an artificial acceleration field up to 100g and can provide excitations at frequencies up to 700 Hz and seismic accelerations up to 50g. The shaker can reproduce single degree of freedom strong motions at the model scale.

An Equivalent Shear Beam (ESB) box was specifically designed and constructed for the tests of LIQUEFACT project. The box is composed by 12 aluminum rectangular frames with a height of 25 mm each, and eleven 3 mm thick rubber inter-layers was selected. This configuration returns a total container height of 333 mm.

2.2 *Reference prototype, testing soils, seismic input*

One of the focus case study of the LIQUEFACT project is the Emilia region in Italy, where extensive liquefaction phenomena occurred during the 2012 seismic sequence, which lasted over two months and was characterized by more than 2,000 shocks. The two main events are the May 20th and May 29th earthquakes, characterized by moment magnitude and of Mw=6.1 and Mw=5.9, respectively. Despite the relative low magnitude of these earthquakes, they caused 27 deaths, widespread damage to residential, industrial and historical buildings and liquefaction in various areas of the Emilia Romagna Region, with effects at ground surface such as craters, sand boils, cracks and lateral spreading. Particularly, the May 20th shake produced significant liquefaction manifestations in the localities of San Carlo and Mirabello, where shallow fluvial deposits are present, within 12 m from the ground surface, of sandy silt, silty sand and sand, locally topped by a 2 m thick clayey silt layer, of lower permeability. The ground water table is closed to the soil surface (Calabrese et al. 2012, Giretti and Fioravante 2017).

The ground conditions at the sites of San Carlo and Mirabello were taken as reference case study for the centrifuge experimentation and it was established to test sandy deposits, 15 m deep, homogeneous (clean sand or sand with a small amount of fine) or with a top cap of fine grained soil of lower permeability than the sand, 1.5 m thick, with the ground water table coincident with the soil surface. To reproduce the reference prototype in the centrifuge a geometrical scaling factor N = 50 was adopted and the models were subjected to a centrifugal acceleration of 50 g, imposed in correspondence of the base of the models.

During the first series of tests (analyses of the liquefaction triggering conditions) three sandy soils were tested: a natural sands retrieved from the site of Pieve di Cento, located near to the reference localities of San Carlo and Mirabello and characterized by the same geological and geomorphological setting, and tested with and without its natural fine content (natural Pieve di Cento sand, S3, and clean Pieve di Cento sand, S2); a well known Italian clean sand (Ticino Sand, S1) extensively used in the last 40 years for geotechnical experimentations. The above choice relied on the idea of testing first both natural soils which experienced liquefaction, and, for comparison, a standard sand for which previous seismic analyses are available from the geotechnical literature. Afterwards, on the basis of the experimental results, Ticino sand was selected for the following test series for the evaluation of the effectiveness of different liquefaction mitigation techniques. Ticino Sand is a uniform coarse to medium sand made of angular to subrounded particles. A detailed description of its properties can be found in Fioravante & Giretti (2016) and references therein. Natural Pieve di Cento sand is a fine sand with a fine content of 12%. Clean Pieve di Cento sand is the natural Pieve di Cento sand sieved at the N. 200 ASTM sieve.

In some of the tested models, the sandy deposit was topped by a fine grain layer, reconstituted using Pontida Clay (Fioravante & Jamiolkowski, 2005), obtained from a quarry of fine material located in Pontida, a zone northeast of Bergamo, Italy. Pontida clay is a low plasticity kaolinitic silty clay (specific density, G_s = 2.77, liquid limit, w_L = 24%, plastic limit, w_P = 11%, compressibility index, c_c = 0.2). Grain size analyses indicate a prevalence of silt-size particles (53% by weight) with 30% clay size particles and 17% sand.

A specific site response analysis was carried out by one of the partners of the project (University of Pavia) in order to provide a series of ground motions, corresponding to different seismic hazard levels (return period, T_r =475, 975 and 2475 years), to be applied to the centrifuge models via the shaking table. The motions were computed referring to the Pieve di Centro deep seismic profile, largely studied during previous researches carried out after the 2012 seismic sequence. Calculations were performed and verified using independent approaches. The acceleration time histories were computed at the depth of 15 meters, i.e. at the base of the sandy deposit that was modelled in centrifuge.

Among the 21 signals analyzed, four ground motions (GM17, GM23, GM31, GM34) of increasing intensity were selected for the centrifuge tests, as more suitable to the shaking table capabilities. The four selected GMs, properly scaled, were applied to the models tested during the first test series to investigate the liquefaction triggering conditions. Full liquefaction of the models was achieved only with GM31, that was selected as reference input motion of the following test series. In some cases, to achieve liquefaction it was necessary to amplify GM31; the amplified version of GM31, herein referred to as GM31+, was counted as the fifth input motions of the test program. Figure 1 reports the time history of the acceleration and the Fourier amplitude spectrum of GM31 at the prototype scale.

2.3 *Model types and foundation*

Two types of models were tested in centrifuge, both simulating sandy deposit about 15 m deep, with the groundwater table coincident with the ground surface.

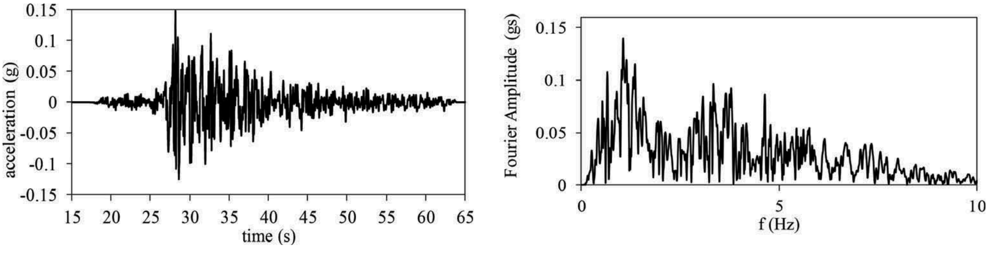
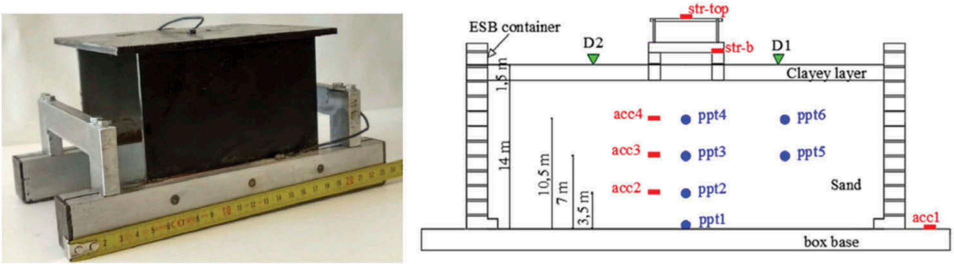


Figure 1. Input signal and Fourier spectrum (prototype scale).



(a) (b)

Figure 2. (a) Picture of the structure manufactured for the centrifuge tests; (b) scheme of a tests with the structure (prototype scale).

Model 1 (M1) represented a homogeneous sand layer, Model 2 (M2) represented a homogeneous sand layer topped by a 1.5 m thick fine grained layer of lower permeability.

In some tests a simple structure founded on a shallow foundation was included in the models. The structure is conceived as a single degree of freedom structure and is composed by an oscillating system founded on two beams rigidly connected by rigid bars. The foundations are embedded 3 cm (1.5 m at the prototype scale) from the ground surface. The oscillating portion is made by steel, the foundation is made by aluminum. The connections of the steel plates are by welding, the connections of the aluminum parts are by screws. The manufactured model has a mass of 2 kg and a natural frequency of 155 Hz at model scale (3.1 Hz at prototype scale). The frequency value was measured blocking rigidly the structure foundation on a fixed base and hitting the oscillating part. Two accelerometers installed on oscillating part and rigid base respectively registered the oscillation of the structure. Figure 2 reports a picture of the model structure and scheme of a test with the structure.

2.4 *Model reconstitution, saturation and instrumentation*

The soil models were reconstituted at low density by pluviating in air the dry sand into the ESB container at a very small (about 3 cm) constant height of fall. The height of fall was calibrated in order to obtain a relative density at 1g of about 40%. It is worth noting that the 1g density is lower than the test final density, since during the subsequent phases (saturation, increasing g-level during the centrifuge spin-up) the soil density increased. Weight and volumes of sand were constantly measured during the reconstitution in order to maintain homogeneity in all the soil models.

The position of the top surface was measured at the end of reconstitution and during the subsequent test steps (saturation, centrifuge spin-up) to calculate and update the average value of relative density during all the experimental phases.

Samples of Pontida silty clay were used to prepare the fine grained model layer placed above the sandy layer in some models. Dry clay powder and deaired water were mixed to achieve a water content equal to 42% (1.75 times the liquid limit). Mixing was continued for about two hours under a vacuum of 750 mm Hg. The clay slurry was then transferred into the consolidometer. The height of specimen after consolidation was approximately equal to 30 mm. After the consolidation phase the specimen was unloaded, removed from the consolidometer and placed above the sand model surface just before the test. Under the centrifugal field the clay layer had an over consolidation ratio OCR larger than 20.

Saturation of the models was carried out at the end of the sand deposition using a viscous fluid. The use of a viscous fluid rather than water is necessary in dynamic centrifuge testing due to the discordance between the scaling ratios for time in dynamic phenomena and in diffusion phenomena. The tested physical models were geometrically scale down of a factor N = 50, in consequence it was necessary to adopt a porous fluid with a viscosity 50 times the water viscosity. A solution of water and hydroxypropyl methylcellulose (HPMC) with a concentration of 2% was adopted. This concentration gives a kinematic viscosity of 50 cSt (water kinematic viscosity ≈ 1 cSt at 20°) and a unit weight of 9.84 kN/m3, that is approximately the unit weight of water. The correct concentration value was verified by viscometer tests.

The ESB box with the dry model was placed in the centrifuge basket and covered with a steel plate, sealed and connected to a vacuum pump. The reservoir with the fluid was installed above the ESB box and connected by two pipes, one from the reservoir bottom to the ESB bottom for the fluid flow, one pipe from the ESB top to the reservoir top to keep the two containers under the same level of vacuum. The adopted configuration produced an upward fluid flow whose rate was kept constant, until the permeated volume of fluid was at least equal to the estimated soil volume of voids. At the end of the saturation, the soil surface settlement where carefully measured.

The tested models were equipped with miniaturised accelerometers (acc), pore pressure transducers (ppt) and displacement transducers (D) to measure horizontal accelerations along the shaking direction, fluid pressure and settlement during and after the earthquake. The transducers were installed in the models during the reconstitution stage, following each model design specifications. Sand pouring was stopped at the level at which the sensors should be installed, the soil surface was levelled and the correct position within the container was measured. The sensors were installed along the longitudinal central axis of the container, in order to minimize the boundary effects on the measures. In this way, all measures are referred to the same section under plane stress condition. It is worth noting that the position and configuration of sensors was changed from test to test depending on the specific test characteristics. In general, a vertical array of 3 or 4 unidirectional accelerometers was installed inside the models to measure seismic wave propagation from bottom to top. The sensitive direction was parallel to the shaking direction of the table. A further accelerometer was fixed to the base of the model container in order to measure the time history applied by the shaking table. A vertical array of four or five miniaturized pore pressure transducers was also installed in the models and allowed the monitoring of pore pressure evolution during and after the shocks. Two further pore pressure transducers were installed outside the influence zone of the foundation, when present. Two linear displacement transducers measured the soil surface vertical displacements, whose tip rested above a thin and light plate, necessary to minimize the tip sinking. As to the model structures, when present, its behaviour was monitored through three displacement transducers and two accelerometers fixed at the base and the top. The data acquisition chain was completed by a National Instruments DAQ system and a Personal Computer installed in the centrifuge and connected to the control room by a wireless system. During the application of seismic shocks all data were recorded with a sampling rate of 5kHz.

2.5 *Testing program*

As explained above the experimental campaign was organized in three series: the first one aimed at investigating the liquefaction triggering conditions, the second and third ones at analyzing the effectiveness of three selected liquefaction remediation techniques.

More in details, during the first test series, three sandy soils (Ticino sand, clean Pieve di Cento sand and natural Pieve di cento, S1, S2 and S3 respectively), two ground profiles (M1 and M2) and five different earthquake input motions of increasing energy (GM17, GM23, GM31, GM34, GM31+) were tested, in order to define under which conditions liquefaction occurred. Some tests were carried out in free field conditions, in some others a simple structure (F) based on shallow foundations was modelled as well, in order to study the effects of soil-structure interaction. The main characteristics of first series of tests is summarized in Table 1.

During the second test series, vertical and horizontal drains (VD and HD) were installed in the models, in order to analyze their effectiveness in reducing the pore pressure build up as a function of their spacing. The efficacy of vertical and horizontal drains was tested both on M1 and M2 ground profiles, reconstituted using Ticino sand (S1), with and without the model structure (F).

Table 1. Test program.

Test number	Model type	Soil	Input signal	ID
1	M1	Ticino Sand	GM17	M1_S1_GM17
2		(S1)	GM34	M1_S1_GM34
3			GM31	M1_S1_GM31
4		Clean Pieve di Cento	GM17	M1_S2_GM17
5		(S2)	GM23	M1_S2_GM23
6			GM 34	M1_S2_GM34
7		Natural	GM17	M1_S3_GM17
8		Pieve di Cento (12%fine)	GM23	M1_S3_GM23
9		(S3)	GM34	M1_S3_GM34
10	M2	S1	GM34	M2_S1_GM34
11			GM31	M2_S1_GM31
12		S3	GM34	M2_S3_GM34
13	M1 with structure	S1	GM31	M1F_S1_GM31
14			GM31+	M1F_S1_GM31+
15	M2 with structure	S1	GM31+	M2F_S1_GM31+

The test motions were GM31, in free field models (M1_S1 and M2_S1 tests), or GM31+, in presence of the model structure (M1F_S1 and M2F_S1 tests). Drains were simulated in the centrifuge models using silicon pipes with an external diameter of 6 mm and an internal diameter of 4 mm. Couples of diametrically opposed holes, 0.5 mm in diameter, were pierced along the pipe. Two subsequent hole couples were pierced at a distance of 5 mm (rotated of 90°).

Specific installation procedures were adopted for vertical and horizontal drains in the models. The tip of each vertical drain was closed with a nut and blocked by heat-shrink tubing. A threaded rod was inserted inside the drain and screwed to its bottom. The drain was then driven into the soil (once the saturation process was completed) just pushing on the threaded rod.

When the drain head was at the same level of the ground surface the insertion was interrupted and the threaded rod was removed. The drains were installed according to a square mesh, the spacing between drains being equal to 5 or 10 diameters (30 and 60 mm, 1.5 and 3 m at the prototype scale, VD1 and VD2 in the test identification code), depending on the test layout. A draft of the two test schemes adopted for M2 ground profiles is shown in Figure 3; it is worth noting that the position and configuration of sensors was changed from test to test depending on the specific test characteristics. During the tests, when the seismic excitation induced excess pore pressure, the vertical drains were free to spill the pore fluid on the ground surface.

As far as horizontal drains are concerned, they were 225 mm long and were installed during the model reconstruction. The sand pouring was interrupted at prescribed heights, as for the installation of miniaturized sensors, and each level of horizontal drains was placed. The ends

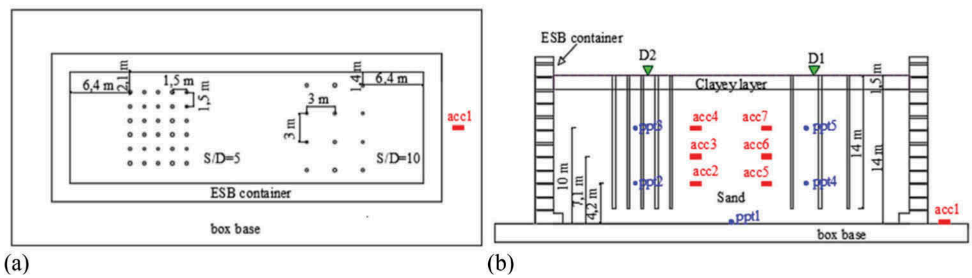


Figure 3. (a) Top and (b) side view of vertical drain tests layout (sizes shown at prototype scale).

of the horizontal drains were connected to three horizontal header pipes (diameter 12 mm) installed along the longitudinal sides of the ESB. Horizontal header pipes were in turn connected to four vertical cases placed at the ESB corners and filled with gravel up to the ground surface. This system allowed the dissipation of pore overpressures with a reduced disturbance on the shear movement of the ESB container. The drains were installed according to a quincunx mesh, the spacing between drains being equal to 5 or 10 diameters (30 and 60 mm, 1.5 and 3 m at the prototype scale, HD1 and HD2 in the test identification code), depending on the test layout. A draft of the model configuration adopted for M2 ground profiles is shown in Figure 4; it is worth noting that the position and configuration of sensors was changed from test to test depending on the specific test characteristics.

The second test series details are summarized in Table 2.

The efficacy of IPS was tested on both model types M1 and M2, reconstituted using Ticino sand (S1), in free field conditions or in presence of the simple model structure on shallow foundation (M1F_S1 test). The test ground motions were GM31 or GM31+. Two cylindrical reservoirs with a global capacity of $V_S = 9.8 \cdot 10^{-3}$ m^3 were installed on the centrifuge beam and rigidly blocked to support the centrifugal acceleration (about 15g at that distance from centrifuge axes). Compressed air at 150 kPa was injected in the reservoirs just before the test. A pressure transducer allowed monitoring the air pressure inside the reservoirs before, during and after the air injection phase. The solenoid valve installed downstream the transducer could be electrically opened and closed by the control room of the centrifuge. A pipe installed along the centrifuge beam arrived to the top of the model container and connected the solenoid valve to the injection system buried within the soil model. The injection system consisted of a single injector (IPS1) or multiple injectors (IPS4), depending on the test layout, fixed to the container bottom along its longitudinal axis, before model reconstitution. One or two pipes run on the container bottom from the injector/injectors toward the longitudinal side wall and then a single pipe run upwards to the top of the model container, where it was

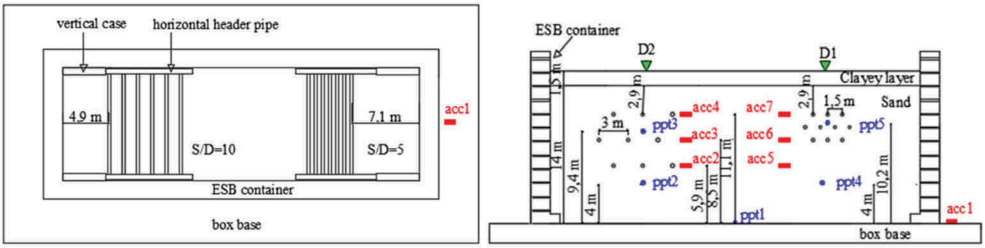


Figure 4. (a) Top and (b) side view of horizontal drain tests layout (sizes shown at prototype scale).

Table 2. Second series of tests.

Test number	Model type	Soil	Drains type	Spacing	ID
16	M1		Vertical (VD)	5D	M1_S1_VD1_GM31
17				10D	M1_S1_VD2_GM31
20	M2			5D	M2_S1_VD1_GM31
21				10D	M2_S1_VD2_GM31
24	M1F (with structure)			5D	M1F_S1_VD1_GM31+
26	M2F (with structure)	Ticino Sand (S1)		5D	M2F_S1_VD1_GM31+
18	M1		Horizontal (HD)	5D	M1_S1_HD1_GM31
19				10D	M1_S1_HD2_GM31
22	M2			5D	M2_S1_HD1_GM31
23				10D	M2_S1_HD2_GM31
25	M1F (with structure)			5D	M1F_S1_HD1_GM31+
27	M2F (with structure)			5D	M2F_S1_HD1_GM31+

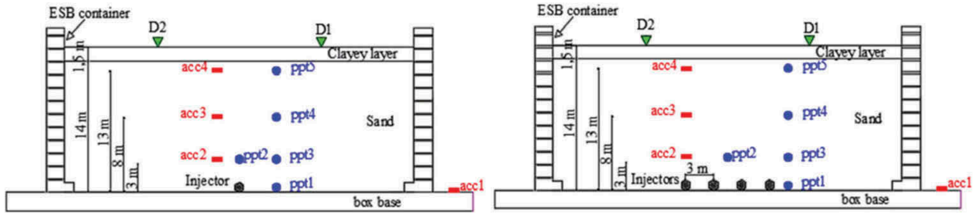


Figure 5. IPS test layout with (a) 1 and (b) 4 injectors (prototype scale).

Table 3. Third series of tests.

Test number	Model type	Soil	Number of injector	ID
28	M1	Ticino Sand	1	M1_S1_IPS1_GM31
29		(S1)	1	M1_S1_IPS1_GM31+
30			4	M1_S1_IPS4_GM31
31			4	M1_S1_IPS4_GM31+
32	M2		1	M2_S1_IPS1_GM31
33			1	M2_S1_IPS1_GM31+
34			4	M2_S1_IPS4_GM31
35			4	M2_S1_IPS4_GM31+
36	M1F (with structure)		4	M1F_S1_IPS4_GM31+
37	M1F (with structure)		4	M1F_S1_IPS4_GM31++

connected to aforementioned part of the injection system. The single injector consisted of one nozzle with 13 mm in diameter and injection surface of 133 mm^2. The single injector was placed in the correspondence of the vertical axis of the model.

The multiple injectors array was composed by four nozzles with an effective diameter of 0.9 cm and a centre-to-centre distance of 6 cm; the global surface of injection was 2.54 cm^2; the array was placed along the longitudinal axis of the container and was spread along a distance of 18 cm. The air pressure of the reservoir was monitored during the injection process and the values of air pressure before and after the injection are the injection reference parameters. A draft of the model configuration adopted for M2 ground profiles is shown in Figure 5; it is worth noting that the position and configuration of sensors was changed from test to test depending on the specific test characteristics.

The IPS tests details are summarized Table 3.

3 RESULTS

The main purpose of the physical modelling was to reproduce (i) the seismic response of homogeneous and layered sandy model deposits in both free field conditions and with the presence of a simple model structure, subjected to several earthquakes of increasing energy, up to liquefaction triggering; (ii) some of the main features of three selected techniques of ground treatment against liquefaction in free field; (iii) soil-structure interaction behavior under dynamic conditions, in untreated and treated soils. A series of 37 tests was carried out to this aim. For the sake of brevity in this section some results of few selected tests are reported; in particular results of tests carried out on homogeneous ground profiles (M1), reconstituted using Ticino sand (S1) and excited applying ground motion GM31 are presented.

3.1 *First series of tests: reference model M1_S1_GM31*

Among the 15 tests carried out to investigate the liquefaction triggering conditions, the test assumed as reference for the other test series is the M1_S1_GM31 model (homogeneous

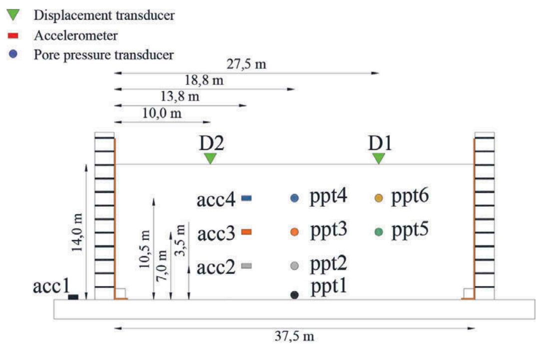


Figure 6. M1_S1_GM31 test layout (prototype scale).

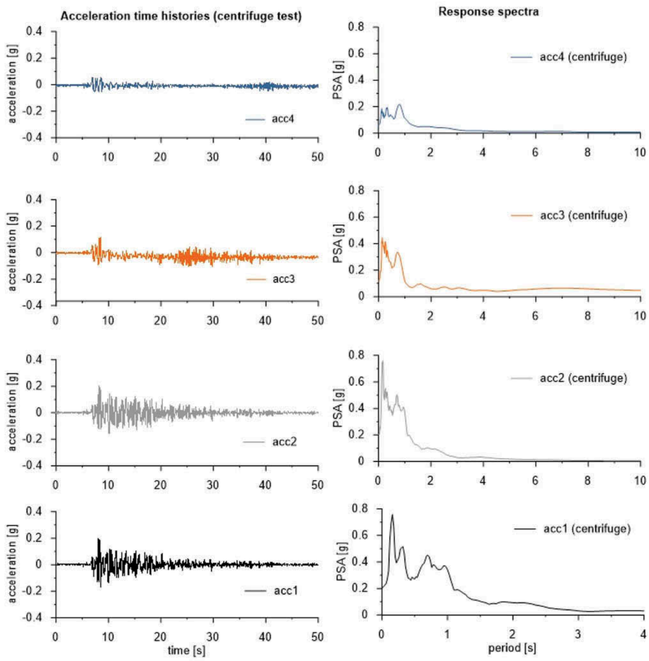


Figure 7. M1_S1_GM31 time history of acceleration and response spectra (prototype scale).

model, Ticino sand, free field condition, ground motion GM31), whose instrumentation layout is shown in Figure 6.

Results of the test are reported in Figure 7 in terms of acceleration time histories recorded during the test by the accelerometers (acc) and respective response spectra and in Figure 8 in terms of pore pressure build up measured by the pore pressure transducers (ppt). It is evident the de-amplification in terms of accelerations at the top of the model indicating that the liquefaction occurred. Correspondingly, value of excess pore pressure ratio, R_u, of about 0.67, 0.86, 0.95 and 0.98 were achieved at the locations of ppt1, ppt2, ppt3 and ppt4 respectively.

3.2 *Second series of tests: effect of horizontal drains*

In the second series of tests the effectiveness of drains (vertical and horizontal) as mitigation technique against liquefaction was evaluated. A layout of the models M1_S1_HD1_GM31

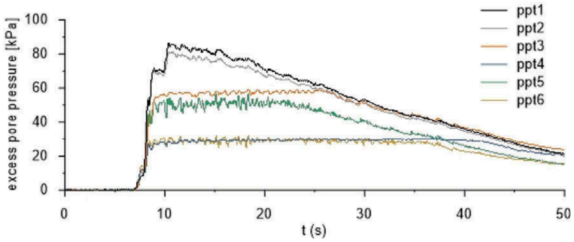


Figure 8. M1_S1_GM31 pore pressure build up (prototype scale).

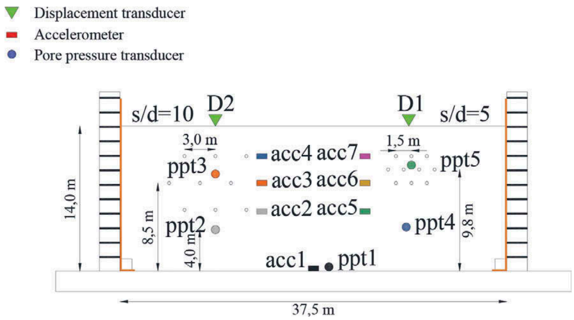


Figure 9. M1_S1_HD1_GM31 andM1_S1_HD2_GM31 test layout (prototype scale).

and M1_S1_HD2_GM31 with the indication of the adopted instrumentation is provided in Figure 9.

The drains in the centrifuge models were 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). Figures 10 and 11 show the results in terms of acceleration time histories, response spectra and pore pressure build up recorded during the shaking. Figures 10 and 11 show a reduction of the pore pressure developed by both models (i.e. drains configuration) and an increase in the seismic amplification from the bottom of the models towards the surface, in contrast with the de-amplification effects observed in model M1_S1_GM31 when liquefaction occurred. PPT3 and PPT5, deployed among drains, show that pore pressure dissipation is anticipated if compared to the reference model M1_S1_GM31 (see PPT4 and PPT6 at similar depth, Figure 8).

3.3 *Third series of tests: effect of Induced Partial Saturation (IPS) technique*

The efficacy of IPS technique was tested in the third series of tests. A layout of the model M1_S1_IPS4_GM31 (in which four nozzles were installed for the air injection), with the indication of the adopted instrumentation is provided in Figure 12.

The results in terms of accelerations, response spectra and pore pressures build up are shown in Figures 13 and 14.

The potential of such a technique as mitigation against soil liquefaction, can be seen in the figures, as it reduces the tendency to develop excess pore pressure. Pore pressure measurements show a lower rate of excess pore pressure dissipation at the end of shaking compared to the reference model M1_S1_GM31, that seems consistent with the reduced permeability associated with lower saturation degree.

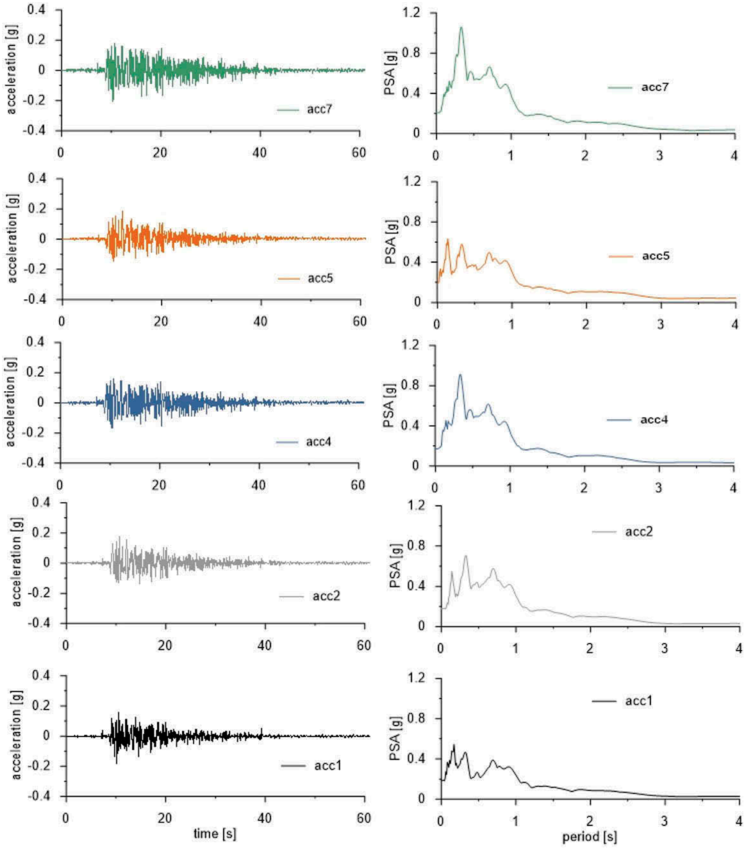


Figure 10. M1_S1_HD1_GM31 and M1_S1_HD2_GM31 time history of acceleration and response spectra (prototype scale).

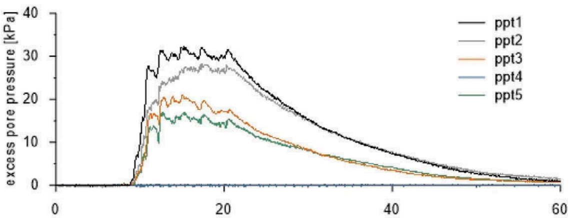


Figure 11. M1_S1_HD1_GM31 and M1_S1_HD2_GM31 pore pressure build up (prototype scale).

4 FINAL REMARKS

The centrifuge tests carried out at ISMGEO for the LIQUEFACT project represent a consistent set of experimental data useful to catch the behavior of the liquefiable soil and to evaluate the efficacy of different possible mitigation techniques against liquefaction. The experimental data obtained can be used as a benchmark for numerical simulations to extend the study to an assessment of a possible mitigation technique against liquefaction.

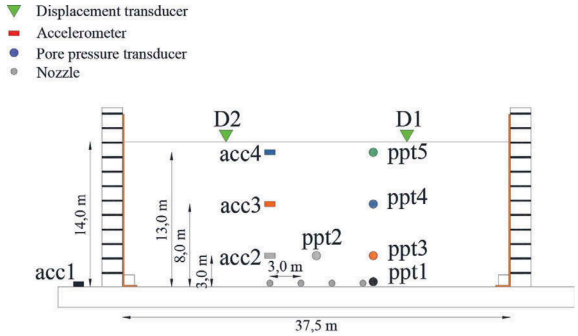


Figure 12. M1_S1_IPS4_GM31 test layout (prototype scale).

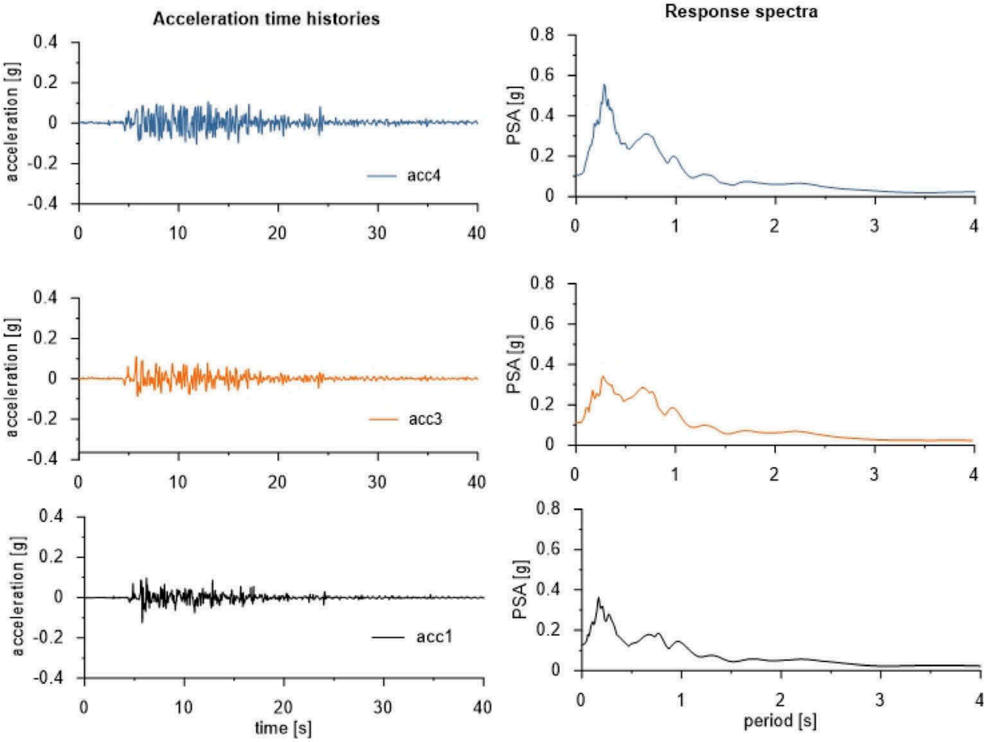


Figure 13. M1_S1_IPS4_GM31time history of acceleration and response spectra (prototype scale).

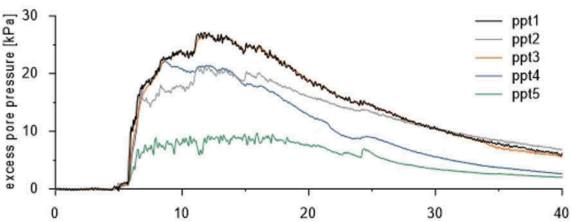


Figure 14. M1_S1_IPS4_GM31 pore pressure build up (prototype scale).

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