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LIQUEFACT

Assessment and mitigation of Liquefaction potential across Europe: a holistic approach to protect structures/infrastructure for improved resilience to earthquake-induced Liquefaction disasters.

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Report on validation of retrofitting techniques from small scale models

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UPORTO	Universidade do Porto	Portugal
UNINA	Università degli Studi di Napoli Federico II	Italy
TREVI	Trevi Società per Azioni	Italy
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ULJ	Univerza v Ljubljani	Slovenia
UNICAS	Università degli Studi di Cassino e del Lazio Meridionale	Italy
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GLOSSARY

Acronym	Description
ELID	Earthquake Induced Liquefaction Disaster
ESB	Equivalent Shear Beam box
GM	Ground Motion
HPMC	Hydroxypropyl methylcellulose
IPS	Induced Partial Saturation
PPT	Miniaturized Pore pressure transducer
ACC	Miniaturized accelerometer
CPT	Miniaturized Cone Penetration Test

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EXECUTIVE SUMMARY

Recent events have demonstrated that Earthquake Induced Liquefaction Disasters (EILDs) are responsible for significant structural damage and casualties with, in some cases, EILDs accounting for half of the economic loss caused by earthquakes. With the causes of Liquefaction being substantially acknowledged, it is important to recognise the factors that contribute to its occurrence; to estimate the impacts of EILD hazards; and to identify and implement the most appropriate mitigation strategies that improve both building/infrastructure and community resilience to an EILD event. The LIQUEFACT project adopts a holistic approach to address the mitigation of risks to EILD events. The LIQUEFACT project sets out to achieve a more comprehensive understanding of EILDs, the applications of the mitigation techniques, and the development of more appropriate mitigation techniques tailored to each specific scenario, for both European and worldwide situations.

INTRODUCTION, GOAL AND PURPOSE OF THIS DOCUMENT

The aim of this document is to describe the physical geotechnical modelling activities performed at the ISMGEO (Istituto Sperimentale Modelli Geotecnici, formerly ISMES – Italy) laboratory in the frame of the LIQUEFACT project, Work Package 4, Task 4.2 "Small scale centrifuge modelling".

All the experimental phases and all the laboratory procedures applied in the study are carefully detailed, as well as the boundary conditions, the technical solutions adopted and the instrumentation used to monitor the mechanical behaviour of the models during the tests.

Each test is described in a specific sheet that summarizes the experimental conditions and tests results by tables and graphs. The dataset corresponding to this testing programme is available for open access download on the repository of the LIQUEFACT project.

The final goal of this document is to provide all the information necessary to understand and interpret the experimental data.

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SCOPE OF THIS DOCUMENT

This is the final document on the physical modelling activities carried out with the geotechnical centrifuge. It describes the tests performed to simulate in physical models the liquefaction triggering conditions and to evaluate the effectiveness of three remediation techniques.

TARGET AUDIENCE

This report is a public document and provides a large database of experimental data addressed to both internal LIQUEFACT project partners and researchers as well as to external scientists and professionals wishing to further develop the issue of soil liquefaction and mitigation techniques. The document is strictly linked to the relating dataset.

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Report on validation of retrofitting techniques from small scale models

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1. Introduction

The present report describes the activities of small scale centrifuge modelling (Work Package 4, Task 4.2) performed at ISMGEO (Istituto Sperimentale Modelli Geotecnici, formerly ISMES – Italy) laboratory. The centrifuge tests were aimed at assessing the effectiveness of ground treatments against liquefaction, with and without the presence of a structure.

The basic concept of the experimentation was to analyse the seismic behaviour of loose, saturated, about 15 m deep sandy deposits, homogeneous or stratified, subjected to increasing seismic excitations up to liquefaction and to verify the effectiveness of different liquefaction mitigation techniques.

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 analysing the effectiveness of three selected liquefaction remediation techniques. The testing programme was developed and refined in cooperation with the Partners of UNINA and UNIPV. The final scope was to produce a consistent set of experimental data to be used as a benchmark for seismic response studies, numerical simulations, and for in situ trial tests, activities included in other Tasks of the LIQUEFACT project (e.g. Task 2.1 Ground characterization at the four European testing sites, 4.3 Field trials at the selected case study pilot testing site, 4.4 Numerical modelling, 4.5 Liquefaction mitigation techniques guidelines).

More in details, during the first test series, three sandy soils, two soil profiles and five different earthquake input motions were tested, in order to define under which conditions liquefaction occurred. Some tests were carried out under free field condition, in some other a simple structure based on shallow foundations was modelled as well, in order to study the effects of soil-strucure intercation.

During the second test series, 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.

In the third series of tests the effectiveness of the "Induced Partial Saturation" (IPS) technique on the soil liquefaction resistance was tested. The soil models were partially desaturated by air injection from the model bottom, varying the number and position of the injectors.

In this report all the experimental details are described (testing materials, testing apparatuses, model reconstitution and set-up, miniaturised instrumentation, test procedures) and the test results are presented. In particular the results of each test are summarised in four data sheets, where all the specific test informations on the models reconstruction, on the model state once the in-flight equilibrium was achieved and on the seismic behaviour of the model are detailed.

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2. On centrifuge modelling

The mechanical behaviour of a natural soil depends on its "state parameters": its nature (e.g. mineralogical composition), its physical properties (such as water content or relative density), its chemical properties (such as diagenesis, cementation), its effective stress state and its stress history. A physical model can artificially reproduce the mechanical behaviour of a soil only if the model correctly replicates the prototype state.

Due to the intrinsic difficulties involved in reproducing all the relevant aspects of a soil state, some approximation are generally accepted in physical modelling; the skill is to spot the appropriate level of simplification, to recognise the most important features with respect to the engineering problems that have to be considered. Maintaining consistency in the stress field of the physical model is certainly one of the key factors to accurate modelling.

Multi-g physical modelling is based on the principle that, if a model, in which each linear dimension is reduced by a factor N, is subjected to a centrifuge acceleration of $a = Ng$ (where g is the gravity field), the self-weight of any material used for the model is N times larger than in a 1g gravity field. Therefore, a 1/N model at the centrifuge acceleration of $a = Ng$ achieves the equivalent vertical stress of the full scale prototype, assuming that a material with the same mass density is used in the model. If the stress–strain characteristic of the model material is the same as in the prototype, for example if the same soil is used in the model, similarity of strains is also achieved.

If the scaling factor for a generic quantity is defined as: $x^* = x_{prot}/x_{mod}$ (where x_{prot} = the value of the quantity x at the prototype scale and x_{mod} = the value of the quantity x at the model scale), in a soil model prepared from the prototype material (i.e. identical material rheology in the model as in the prototype and density scaling factor $\rho^* = \rho_{prot}/\rho_{mod} = 1$), geometrically scaled down N times with respect to the prototype (geometrical scaling factor $L^* = L_{prot}/L_{mod} = N$) and subject to a gravitational field N times higher than the prototype (gravity scaling factor $g^* = g_{prot}/g_{mod} = 1/N$), the centrifuge acceleration reproduces the same stresses (Eq. 2.1) and strains as in the prototype so that the model exhibits identical mechanical behaviour as the prototype soil (Schofield, 1980).

$$\rho_{prot} \cdot g \cdot L_{prot} = \rho_{mod} \cdot Ng \cdot \frac{L_{mod}}{N} \tag{2.1}$$

The observations from the model can be related to the prototype using the similarity relationships reported in Table 1 which are valid within continuum mechanics (Garnier et al. 2007).

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Table 1 Principal scaling ratios for geotechnical centrifuge modelling

	Variable	Scale factor $X^*=X_{prototype}/X_{model}$	Ng model
L	Length	L*	N
ρ	Soil density	ρ*	1
ε	Strain	ε*	1
σ	Stresses (effective and total)	σ*=x*ρ*g*	1
G	Stiffness	G*=x*ρ*g*/ε*	1
ρ_f	Fluid density	ρ*	1
p	Fluid pressure	p*= x*ρ*g*	1
u	Soil displacement (continuum)	u*=x*ε*	N
v	Velocity	$v^*=(x^*\varepsilon^*g^*)^{0.5}$	1
ü	Acceleration	g*	N^{-1}
t	Time (diffusion phenomena)	$t^*=\mu^*L^{*2}/G^*$	N^2
t	Time (creep)	t*	1
t	Time (dynamic)	$t^*=(x^*\varepsilon^*/g^*)^{0.5}$	N
μ	Dynamic viscosity of fluid	$\mu^*=\rho^*(g^*/x^*\varepsilon^*)^{0.5}$	N^{-1}
K_f	Compressibility modulus of soil	$K_f^*=x^*\rho^*g^*/\varepsilon^*$	1

In centrifuge modelling, the following points should be taken into account:

- The centrifuge acceleration applied to the model is radius dependent; thus the vertical stress distribution of the model is parabolic and it diverges slightly from the linear distribution of the overburden stresses in the prototype:

$$Ng = \omega^2 \cdot R \tag{2.2}$$

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where **ω** is the centrifuge angular velocity and **R** is the distance from the centrifuge axis of rotation. The stress field in a centrifuge model has to be computed according to Equations 2.3 and 2.4 and with reference to Figure 1:

$$d\sigma_v = \rho \cdot g \cdot N \cdot dR \tag{2.3}$$

$$\sigma_v = \int_{R_s}^{R_1} \rho \cdot \omega^2 \cdot R \cdot dR = \frac{1}{2}\rho\omega^2[R_1^2 - R_s^2] \tag{2.4}$$

where $\boldsymbol{\sigma_v}$ is the vertical overburden stress.

- The soil surface and the free water surface of the model are not flat.
- The existence of side walls and a rigid base may affect the behaviour of the model; care is necessary when designing the boundary conditions in the model and the model container, especially for seismic tests (as described in the following paragraphs).
- For dynamic events, velocity is the same in the model and prototype; for flow and dissipative events, the seepage velocity through a centrifuge model is subjected to an increase of self-weight of N times, it is N times larger than that in the prototype, if the same soil and pore fluid are used and identical gradient applied. This inconsistency on velocity, or time scale when same soil and pore fluid are used, means that simultaneous simulation of dynamic and diffusion events is not possible. To have dynamic and inertial effects, and the flow and the dissipative effect occurring simultaneously in the model, soil and pore fluid should be properly choosen. The most commonly adopted strategy consists in using the same soil and a model pore fluid with higher viscosity but similar density to the prototype fluid (Allard and Schenkeveld 1994).

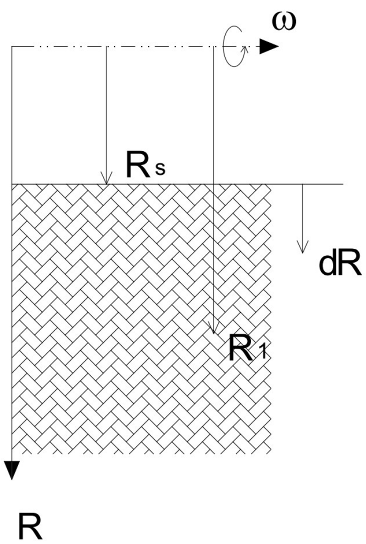

Figure 1 Distortion of centrifugal field

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3. The ISMGEO seismic geotechnical centrifuge

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 (Figure 2 and Figure 3); further details can be found in Baldi et al. (1998). A shaking table is fixed at one hand of the arm; at the other hand the arm holds a swinging platforms 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 unusual shape of the arm offers the following advantages:

- small distortion of the centrifugal field in the model, since its main dimension is parallel to the rotation axis;
- low deflection of the support plane of the swinging basket;
- easy location of instruments close to the rotation axis because of the absence of a central shaft across the arm.

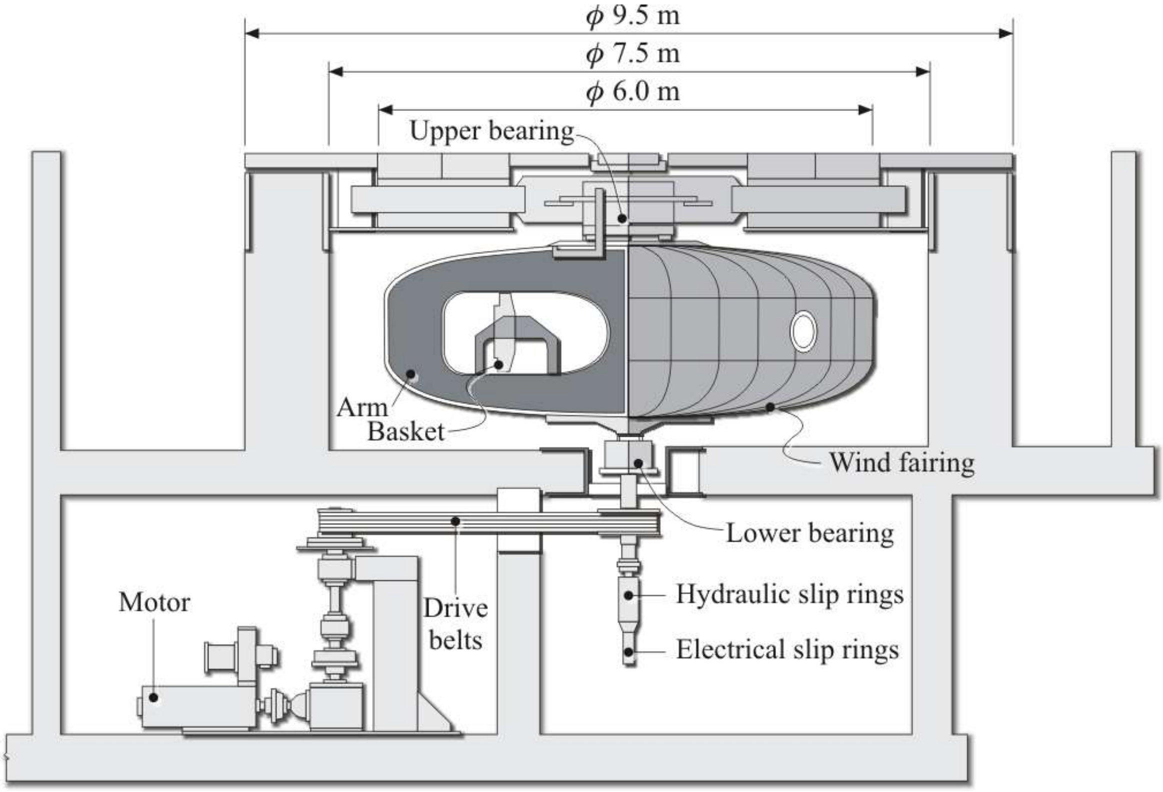

Figure 2 Cross section scheme of ISMGEO geotechnical centrifuge

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Figure 3 View of the ISMGEO geotechnical centrifuge before the installation of the fearing.

Since 2010, the centrifuge houses a single degree of freedom shaking table, which is able to reproduce real strong motions at the model scale. The axis of motion of the shaker is parallel to the centrifuge rotational axis, thus problems related to Coriolis' acceleration are avoided. Unlike most centrifuge shaker solutions, where the shaker is integrated into the swinging basket (Derkxet al., 2006, Imamura et al., 1998, Ma et al., 2006, Matsuo et al., 1998, Shen et al., 1998, Van Laak et al., 1998), the ISMGEO shaker was designed specifically to be fixed to the symmetric double centrifuge arm, as shown in Figure 4 and Figure 5. This arm is of a particularly rigid construction, which makes it suited as reaction base for the shaker.

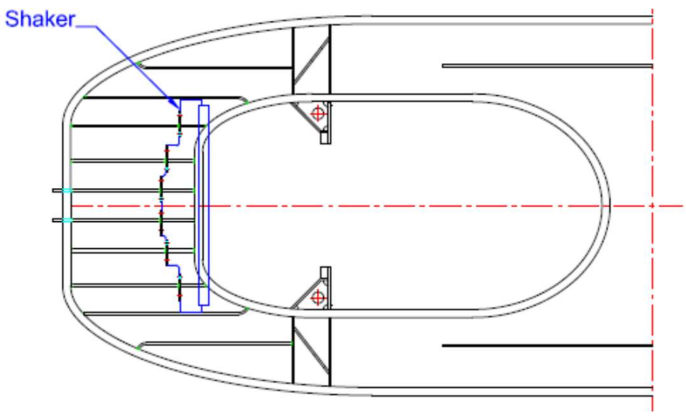

Figure 4 Lateral scheme of the centrifuge arm with shaker installed

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During the centrifuge flight the model container rotates from horizontal towards the vertical position, at the centrifuge acceleration of about 5g the model is moved into contact with the table and released before the application of the dynamic excitation. The shaker excitation is transferred from the shaking table to the model container by mechanical coupling. The table can work under an artificial acceleration field up to 100g, it can provide excitations at frequencies up to 700 Hz and seismic accelerations up to 50g (depending on the driving load) (Table 2 and Figure 6). The shaker is capable of reproducing single degree of freedom strong motions at the model scale (Airoldi et al, 2016).

Figure 5 The shaking table is vertical and installed inside the centrifuge double arm

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Table 2 Main technical specifications of the shaking table

peak operational centrifuge acceleration	100 g
max frequency	700 Hz
max payload at 100g	3.50 kN
peak velocity	0.9 m/s
peak displacement	+/- 6.35 mm
max seismic acceleration	50 g
full load acceleration	16 g

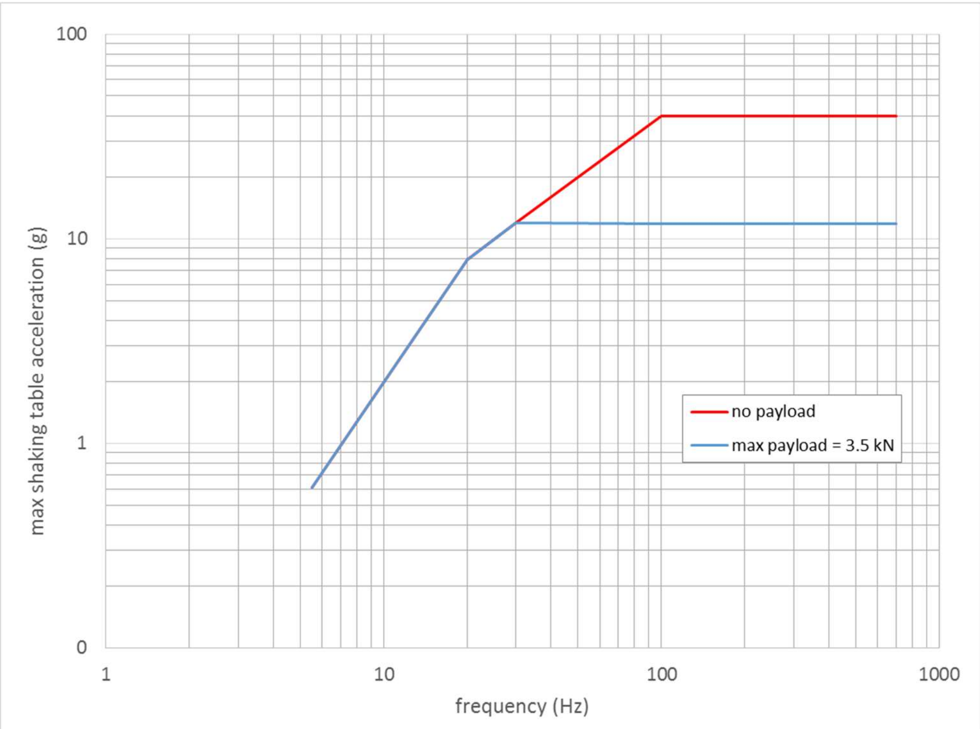

Figure 6 Operating map of peak acceleration vs frequency

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4. The reference prototype

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 characterised by more than 2,000 shocks. The two main events are the May 20 and May 29 earthquakes, characterised by moment magnitude and of Mw=6.1 and Mw=5.9, respectively (www.iside.rm.ingv.it).

Despite the relative low magnitude of these earthquakes, they caused 27 deaths, widespread damage to residential, industrial and historical buildings and extensive liquefaction in various areas of the Emilia Romagna Region, whose surficial effects were craters, sand boils, surface ruptures and fissures and lateral spreading. Particularly, the May 20 shake produced significant liquefaction effects in the localities of San Carlo and Mirabello, which are located about 15 km SE of the epicentre. Many in situ geophysical and geotechnical tests and laboratory tests were carried out in order to evaluate the current condition of the subsoil of the sites of San Carlo and Mirabello. The deposits which experienced liquefaction consist of sandy silt, silty sand and sand, formed by the fluvial activity of the Reno river, present within 12 m from the ground surface. In general, those sandy deposits are topped by a clayey silt layer, about 2 m thick, characterised by a permeability lower than the sandy layers. 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 at a radius of 2172 mm from the centrifuge rotation axis.

As input motions for the tests a ground response analysis for the reference sites was carried out by the Partner of UNIPV in order compute a series of representative ground motions of increasing intensity to be applied to the centrifuge models. The seismic signals were scaled according to the scaling laws reported in Table 1, i.e. the seismic accelerations were multiplied by 50 and the duration of the signal divided by 50 (1 second in the prototype corresponds to 0.02 s in model scale). Frequencies for soil and structure are also 50 times higher than real scale soil and structure.

5. Design and construction of the Equivalent Shear Beam container

The boundary conditions that need to be simulated in dynamic centrifuge tests are very complex: ideally the reduced scale soil model should behave similarly to a soil column subjected to an earthquake. However, the lateral extent of a prototype soil deposit is not replicable in a centrifuge model, where the lateral extent of the soil is necessarily limited by the presence of the container end walls, which introduce an element of dissimilarity with prototype conditions.

A thorough review of the main disturbances to the soil model introduced by the model container in geotechnical earthquake modelling is found in Zeng & Schofield (1996) and Brennan (2003). The design philosophy of the model container discussed herein is based on the mitigation of those boundary effects considered most critical for the typology of test undertaken. These are:

- Bulging of the container side walls during centrifuge swing-up. Under a N-g gravity field the horizontal stresses in the soil model are increased by a factor of N. If the container side walls do not provide sufficient lateral stiffness, excessive bulging may occur, resulting in an alteration of the initial stress-distribution in the soil model. In particular, for lateral bulging exceeding 0.1% of the total soil column height, the lateral earth pressure conditions may change from at-rest to active (Ueno, 1998).

- \`Silo' effect as a result of container wall friction. During centrifuge swing-up, friction between the soil model and the container walls may result in part of the vertical load being carried by the container walls, reducing the vertical stresses \`felt' in deeper portions of the soil model. This phenomenon also acts toward the modification of the initial (i.e. pre-swing-up) stress distribution, affecting the response of the soil.

- Shear stress transmission between soil model and container. The boundary effects relating to shear stress transmission between the model container and soil are different depending on the direction considered. Under unidirectional shaking, such as that imposed by the ISMGEO shaking table, undesired shear stresses are generated along the container walls parallel to the shaking direction. This parasitic effect is avoided if the container moves exactly as the soil. The horizontal base motion generates propagates vertically through the soil model generating shear stresses in the soil acting on the x-z plane, in order to maintain moment equilibrium a soil element must be subjected to complementary shear stresses (Brennan, 2003). If the end walls (i.e. perpendicular to shaking direction) are not able to sustain these complementary stresses the overall stress field is distorted, and significant rocking of the soil may take place (Zeng & Schofield, 1996). As observed by Teymur and Madabhushi (2003), contradictory requirements arise that the boundary walls should be smooth under static loading and rough during dynamic loading. Finally, enough friction must exist between the base of the container and the soil model for the shaking induced shear stresses to be transmitted to the soil.

- Strain dissimilarity between container and soil model. In a homogeneous soil layer of infinite lateral extent the deformation induced by base shaking at a given depth is equal across the entire layer. In a model test this is not verified because of the presence of the container end walls which restrict soil deformation. Moreover, the interaction between the soil and the end walls may generate parasitic P-waves to be transmitted to the soil (Zeng & Schofield, 1996).

In order to mitigate the boundary effects listed above, the ideal model container needs to be stiff enough not to bulge excessively under the working g-field, although at the same time it needs to deform accordingly to the soil during base shaking. Moreover, the friction of its end walls must be high enough to sustain the cyclic induced complementary shear stresses, while the walls parallel to the shaking direction should ideally be friction-less, not to generate any unwanted shear stress if relative movement between the soil and the container takes place. `Silo' effect depends on the container dimensions and on the soil-wall friction characteristics, therefore the container should be as big as possible; this depends on the technical limitations of the shaking table to be used, in terms of both model dimensions and payload.

Several typologies of model containers have been developed and tested to date, however no `ideal' solution has been found and often the satisfaction of one boundary condition comes at the expense of a different boundary effect being generated. All of the adopted solutions involve either flexible or absorbing boundaries, in order to mitigate the interaction between the soil and the container during shaking (Campbell et al. 1991, Brennan et al. 2006).

Typical containers for simulating soil liquefaction are the laminar container, composed by a high number of very thin rigid frames connected by "zero friction" roller bearings providing minimum lateral stiffness, and the Equivalent Shear Beam (ESB) box, composed by rigid and light frames connected by rubber inter-layers having a finite stiffness and whose functioning relies on the soil and container having similar stiffness (Brennan, 2003). A laminar container is ideal in reproducing the large strains occurring in fully liquefied soil. This feature is of major importance when simulating liquefaction of mildly sloping ground (i.e. lateral spreading phenomena) where significant cumulative displacement may be generated during shaking. A ESB container is to be preferred for testing dry sands or saturated soil for small earthquakes, or when the triggering of liquefaction is to be investigated. This type of container has been extensively used and tested for different soil types; detailed information may be found in Zeng & Schofield (1996), Wilson (1997), Steedman et al. (2000), Lee et al. (2013) and Brennan (2003).

The ESB concept was chosen for the centrifuge tests to be carried out as part of the LIQUEFACT project. Although a laminar container provides optimal boundary conditions for fully liquefied soil, its response in the pre-liquefaction phase is non-realistic and may affect the triggering of liquefaction in the soil model. Since one of the aim of centrifuge tests was to investigate the on-set of earthquake induced liquefaction in level ground deposits, where lateral deformations are expected to be negligible, an ESB container was preferred to a laminar one.

An ESB box was specifically designed and constructed for the tests of H2020 LIQUEFACT project.

The container was designed to match the dynamic behaviour of a design soil model constituted of loose saturated sand prior to the generation of earthquake induced excess pore pressure, that would result in softening of the soil and thus in a change of its dynamic behaviour. Full liquefaction of the loose saturated sand during testing is anticipated. After liquefaction has occurred the dynamic response of the ESB box to base shaking would differ from that of the soil, resulting in interaction between the two. However, the disturbance arising from this phenomenon is believed to be localized to the area of the model adjacent to the end walls, since the transmission of the parasitic reflected waves resulting from soil-container interaction would be significantly reduced due to the low stiffness of liquefied soil.

The ESB container design methodology followed consisted of three phases:

- Definition of the design soil model and design earthquake parameters.
- Estimation of the soil model deformation caused by the design earthquake and soil dynamic vibration characteristics.

Iterative process for the definition of the ESB container parameters resulting in a satisfactory match between container and design soil model behaviour when subjected to the design earthquake.

5.1. Design seismic input

The earthquake motion selected as reference for container design resulted from a site response analysis carried out for a site in the Emilia Romagna region, near to the epicenter of the 2012 seismic sequence. Figure 7 reports the time history of the acceleration (top chart) and the Fourier amplitude spectrum (bottom chart) at the prototype scale.

The peak ground acceleration of the ground motion is 0.287g. According to Seed and Idriss (1971), the average seismic demand on a soil column is proportional to 0.65·PGA. This acceleration was taken as reference for container design and represents the acceleration level for which the container performance is optimal (Table 3 and dotted red lines in Figure 7).

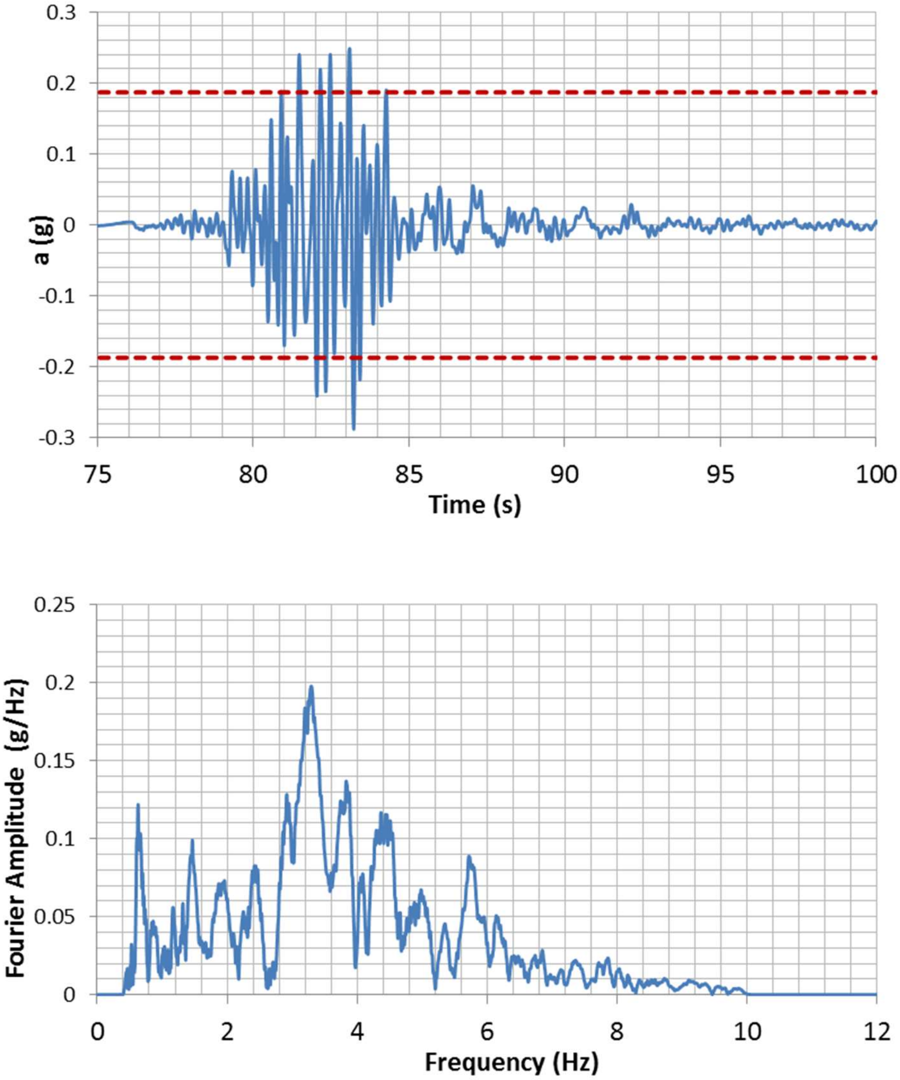

Figure 7 Design Seismic Input

Table 3: Design Seismic Input

	Prototype	Model
G-Level (-)	1	50
PGA (g)	0.287	14.35
Design acceleration (g)	0.187	9.35

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

5.2. Design soil column

The effectiveness of ESB containers in mitigating boundary effects depends on the soil model properties. The first parameter to be defined is the depth of the soil model. This was chosen to be 300 mm, representing a 15 m deep prototype soil deposit under a centrifugal acceleration of 50g. A deeper soil model could have been accommodated on the ISMGEO earthquake simulator, however this was not deemed necessary as field and experimental evidence suggests that at greater depth full liquefaction is likely to be impeded (Steedman & Sharp, 2001).

The container was designed adopting Ticino sand as reference test soil. Table 4 summarizes the design soil parameters considered.

Table 4 Design soil properties

Soil type	***TS4 Sand***
Soil model depth (m)	0.3
Min dry density (kg/m³)	13.65
Max dry density (kg/m³)	16.68
Dry density (kg/m³)	15.00
Specific gravity, G_s (-)	2.68
Relative density, D_R (%)	40
Saturated unit weight, γ_{sat} (kg/m³)	19.39
Shear resistance angle (°)	34
Earth pressure coefficient, K_0 (-)	0.44

5.2.1. Soil column deflection

Knowing the horizontal acceleration coefficient (k_h) the earthquake induced shear stresses induced in the soil model by the vertical propagation of the base motion, can be calculated as a function of the acting vertical stress. The maximum shear stress acting on a horizontal plane (τ_{max}) and the small strain shear modulus (G_{max}) may also be obtained from the equations proposed by Hardin & Drnevich (1972) as a function of depth (z):

$$\tau = k_h \cdot \sigma_v \quad (5.1)$$

$$\tau_{max} = \sqrt{[0.5 \cdot (1 + K_0) \cdot \sigma_v' \cdot sin\varphi]^2 - [0.5 \cdot (1 - K_0) \cdot \sigma_v']^2} \quad (5.2)$$

$$G_{max} = 3230 \cdot \frac{(2.973- \ )^2}{1+e} \cdot \sqrt{p'} \quad (5.3)$$

Figure 8 reports the design shear wave velocity profile derived from G_{max} . Also shown in the figure are the shear wave velocity profiles calculated based on SPT correlations proposed by PEER (2003), Seed et al. (1986) and Otha and Goto (1978), where the equivalent number of SPT blows ($N_{1,60}$) was estimated from the design relative density (D_R) as:

$$N_{1,60} = 46 \cdot \left(\frac{D_R}{100}\right)^2 \quad (5.4)$$

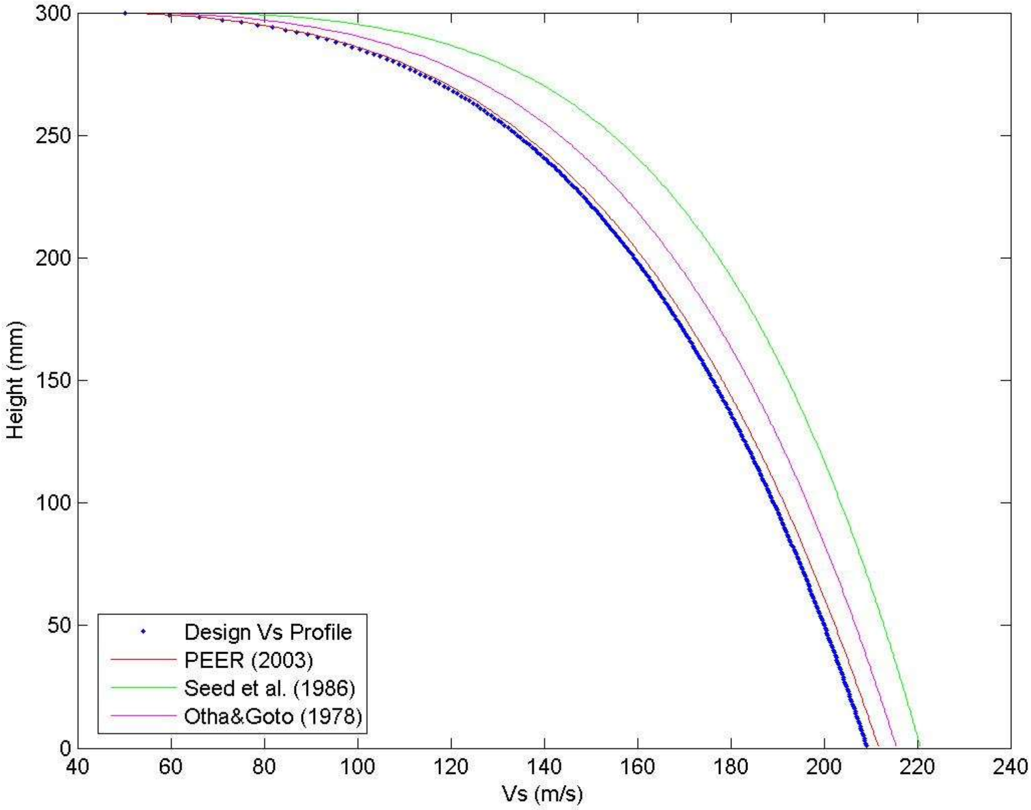

Figure 8 Shear velocity with depth

Based on the quantities calculated with equations 5.1 to 5.3, the shear strain induced in the soil model by the design earthquake can be estimated using the hyperbolic model proposed by Hardin and Drnevich (1972), modified according to Santos and Correia (2003):

$$\gamma = \frac{\tau}{G_{max}} \cdot \left(\frac{\tau_{max}}{\tau_{max} - \tau \cdot 0.385}\right) \quad (5.5)$$

The soil column deflection at any point in the soil model can then be calculated as the integral of the shear strain between the base, which is assumed to be fixed (i.e. no relative movement occurring between the soil model and the base of the container), and the desired depth (z):

$$\delta(z) = \int_z^H \gamma(z) \cdot dz \quad (5.6)$$

5.2.2. Soil column natural frequency

For an ideal design, the ESB container should match the soil column natural frequency ($f_{n,s}$). The small stiffness natural frequency of a soil column can be calculated as:

$$f_{n,s} = \frac{\overline{V_S}}{4H_S} \tag{5.7}$$

where Vs represents the average shear wave velocity of the soil column and Hs the soil column height. For the design soil profile considered, the average Vs is of 168 m/s, yielding a small strain soil column natural frequency of 140 Hz (under a 50g gravity field).

The above estimate is valid for small deformations, and due to soil non-linearity represents an upper bound. As suggested by Zeng & Schofield (1996), an energy method can be used to estimate the soil column natural frequency taking into account the stiffness degradation induced by the design acceleration. This is achieved by calculating the maximum kinetic energy of a soil column per unit area ($K_{e,max}$) and its maximum potential energy ($P_{e,max}$), these can then be equated respectively to the kinetic energy and potential energy of an equivalent SDOF system to determine the equivalent stiffness and mass, from which natural frequency is calculated:

$$K_{e,max} = \int_0^H 0.5 \cdot \rho \cdot (\delta(z) \cdot \omega_n)^2 \cdot dz \tag{5.8}$$

$$P_{e,max} = \int_0^H 0.5 \cdot (\tau \cdot \gamma)_{max} \cdot dz \tag{5.9}$$

$$f_{n,s} = \frac{1}{2 \cdot \pi} \cdot \sqrt{\frac{\int_0^H 0.5 \cdot (\tau \cdot \gamma)_{max} \cdot dz}{\int_0^H 0.5 \cdot \rho \cdot (\delta(z) \cdot \omega_n)^2 \cdot dz}} \tag{5.10}$$

For a 300 mm deep saturated sand deposit characterized by the soil properties listed in Table 4, the resulting natural frequency ($f_{n,s}$) is 98 Hz.

As observed by Brennan (2003), as the dynamic behaviour of the ESB container is defined entirely by its design parameters, the container is not able to replicate changes in soil behaviour induced by cyclic loading, such as the drop in soil natural frequency with EPP generation in saturated sands.

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5.3. Container Model

The dynamic behaviour of the ESB container is defined by the lateral stiffness of the rubber layers (K_i) and by the mass of the aluminium frames (M_f). The lateral stiffness of the rubber layers depends on the layer thickness (t_r) and on the shear modulus of the material (G_r). Deformable layers are constituted of Protek general purpose rubber sheets supplied by Polymax. The shear modulus of this material was measured by Bertalot (2013), by testing 60mm metal-rubber-metal sandwiches in a conventional shear box. The author also investigated the variation of the rubber shear modulus under the range of vertical confining stresses expected during centrifuge testing. The mechanical properties of Polymax Protek rubber used for the container construction are summarized in Table 5. For a given rubber type, the dynamic response of the ESB container is controlled by the following parameters:

- Mass of the aluminium frames (M_f);
- Thickness of the rubber layers (t_r);
- Number of degrees of freedom (i.e. number of rubber layers).

A trial and error iterative procedure was adopted, consisting of calculating the deflected profile of the container and its modes of vibration when subjected to the design earthquake, for different sets of the above variables, until a satisfactorily match with the soil column dynamic response was achieved.

Table 5 Rubber mechanical properties

Material	*Protek Polymax Rubber*
Shear Modulus, $G_{r,0}$ (kPa)	1300
Stress coefficient, m (-)	13
Tensile Strength (kPa)	4000
Elongation at break (%)	250

A final configuration consisting of twelve aluminium rectangular frames with a height of 25 mm each, and eleven 3mm thick rubber inter-layers was selected. This configuration returns a total container height of 333mm. Table 6 summarizes the final configuration selected for the ISMGEO ESB container, while Figure 9 shows the container installed in the centrifuge. In the picture is visible an upper, thin ring used to fix at the top the internal membrane, which seals the soil model; therefore the total height of the container is 350mm.

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Table 6 ISMGEO ESB container characteristics

ISMGEO ESB box	
Number of rings (-)	12
Number of rubber layers (-)	11
Ring mass (kg)	3.4
Height (mm)	333
Internal width (mm)	250
Internal length (mm)	750
Ring height (mm)	25
Ring width (mm)	40
Rubber layer thickness (mm)	3
Empty weight* (kg)	110 (*incl. base)

Figure 9 The new ESB container manufactured for the project

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5.3.1. Container deflection

The deformation of the container under the shear stress distribution induced by the design horizontal base acceleration was calculated as:

$$\delta_i = \sum_1^i \left(\frac{\tau_{xy,i}}{G_{r,i}} \cdot t_r\right) \tag{5.11}$$

$$\sigma_{v,i} = \gamma \cdot N \cdot z_i \tag{5.12}$$

$$\tau_{xy,i} = k_h \cdot N \cdot \sigma_{v,i} \tag{5.13}$$

$$\sigma_{ring,i} = \left(M_f \cdot i \cdot N\right)/A_{ring} \tag{5.14}$$

$$G_{r,i} = \sigma_{ring,i} \cdot m + G_{r,0} \tag{5.15}$$

where i denotes the i-th aluminium ring and $\tau_{xy,i}$ the horizontal shear stress acting on i-th aluminium ring. Figure 10 shows the deformation induced in the ESB container by the design acceleration (i.e. 0.187g), superimposed onto that induced in the design soil column obtained from Eq. 5.7. It should be noted that the ESB containers deforms in a step-wise manner, as its flexibility is concentrated in the rubber inter-layers, while the soil column deforms more homogeneously.

Zeng & Schofield (1996) suggest the use of rough `shear sheets' securely fixed to the container base in correspondence of the end walls, in order to sustain the complementary shear stresses generated in the soil mass by base shaking. The presence of such aluminium shear sheets, together with the relatively high number of aluminium rings adopted minimizes the discrepancy between the soil column deflection profiles and the container deformed shape under the design base acceleration. However, it should be considered that the presence of this shear sheets would cause a slight distortion of the stress field in the soil during centrifuge swing-up.

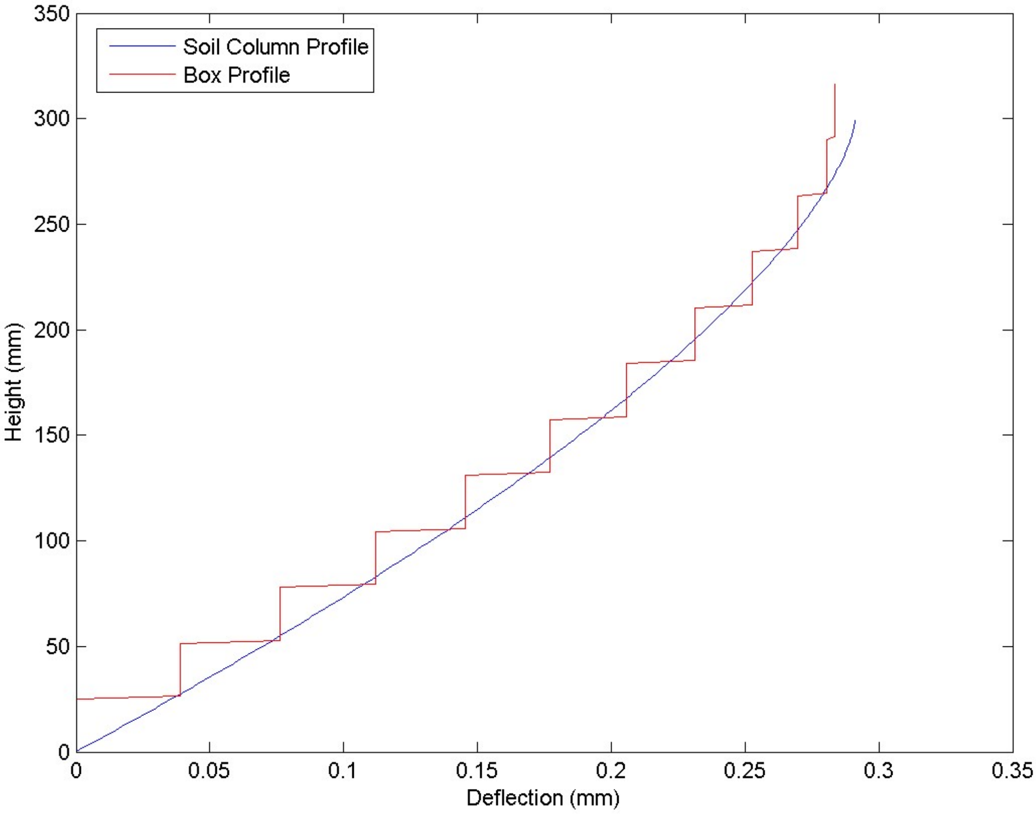

Figure 10 Deflected Soil and Container Profiles under Design Acceleration

5.3.2. Modal analysis

The free-vibration response of the ESB container can be assessed by modelling it as a discrete multi-degree of freedom (MDOF) undamped system, performing a modal analysis. Each degree of freedom (i.e. moving aluminium frame) was characterized by the frame mass (M_f) and a lateral stiffness value which was a function of the rubber shear modulus at the confining stress acting on the corresponding rubber layer:

$$K_i = \frac{F_{h,i}}{\delta_i} = \frac{G_{r,i}}{t_r} \cdot A_{ring} \tag{5.16}$$

The structural matrix (SM) of the equivalent MDOF system is given by:

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$$[SM]=\begin{bmatrix} K_1+K_2 & -K_2 & 0 & & & & \\ -K_2 & K_1+K_2 & -K_3 & \dots & & & \\ 0 & -K_3 & K_1+K_2 & & & & \\ & \dots & & \dots & & \dots & \\ & & & & \dots. & -K_{10} & 0 \\ & & & & -K_{10} & K_{10}+K_{11} & -K_{11} \\ & & & & 0 & -K_{11} & K_{11} \end{bmatrix}\cdot[M_f]$$

where M_f is a 11 by 11diagonal mass matrix whose values represents the mass of each moving alumimium ring. In order to obtain a satisfactory match with the dynamic response of the design soil column a ring mass of 3.4 kg was required.

The eigenvalues of the SM represent the natural frequencies associated to the ESB vibrating modes, while the eigenvectors of the SM correspond to the associated mode shapes (Figure 11). Table 7 lists the natural frequencies of the first five modes of vibration of the ESB container:

Table 7 ESB natural frequencies

Mode	$f_{nc,I}$ (Hz)
First	110
Second	299
Third	487
Fourth	667
Fifth	833

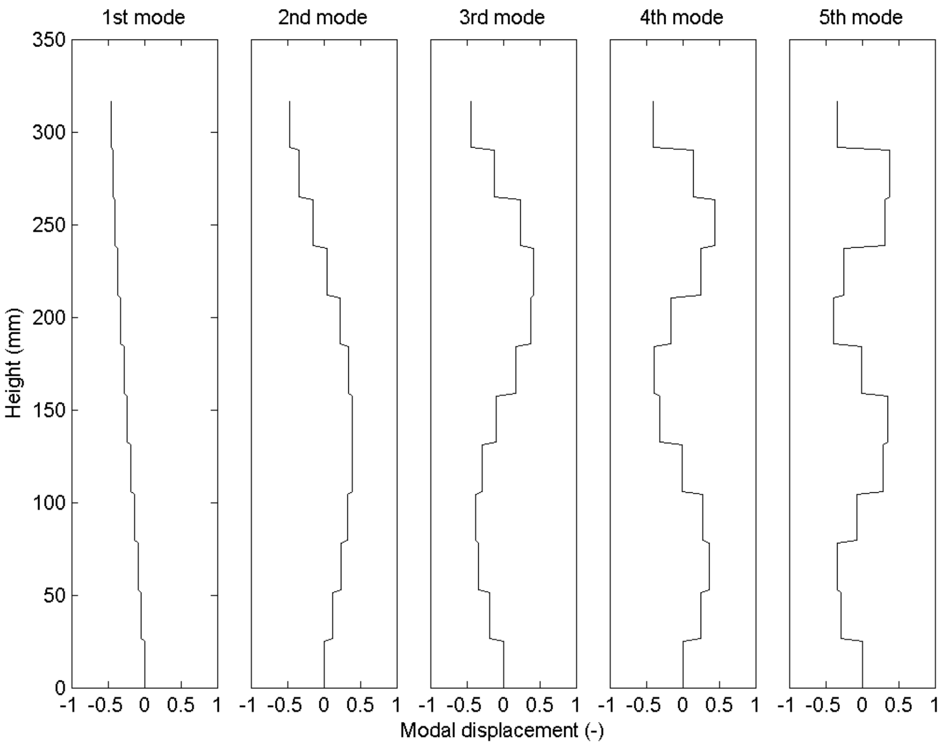

Figure 11 ESB container mode shapes

The ISMGEO centrifuge mounted earthquake simulator produces motions having frequency content up to 700 Hz, while the design record has energy concentrated in a frequency range from 20 to 350 Hz. For this reason the 3rd and higher modes of vibration of the ESB container are likely to remain unexcited during testing. On the contrary the 1st mode occurs at a frequency of 110 Hz (i.e. 2.2 Hz at prototype scale) which is likely to be associated with high excitation energy during earthquake shaking. This may result in significant amplification of the base motion, although the soil model itself, having a similar natural frequency (98-140 Hz), would also resonate when such frequency range is excited, mitigating the interaction between the container and the soil model during resonance. As the damping of the system was considered to be zero the natural frequencies calculated represent an upper bound. However damping of the container system expected to be limited.

As explained above, the desired ring mass is obtained by matching the dynamic response of the ESB box to that of the design soil column. However, this mass differs from that of the solid aluminium rings having a rectangular section 40 by 25 mm and dimensions listed in Table 6, which is of approximately 5.6 kg. In order to reduce the mass of the aluminum frames to the required design value (Table 6), adequately dimensioned hollow slots shall be machined on their outer sides. In the specific case the overall slot volume to be machine into the solid rings is of $8.5*10^{-4}$ m^3.

Several slots having height of 17 mm and depth of 27.8 mm, and covering 73% of the ring outer perimeter are foreseen in order to achieve the desired ring mass of 3.4 kg. In order not to increase excessively the ring flexibility along the horizontal plane, several slots were machined in the rings rather than a single slot each side. In this way the several smaller slots (8 each long side and 2 each short side) were obtained with stiffeners in-between. The excavated portion of the rings consists of U-section.

5.3.3. Static bulging verification

The static loads acting on the inside of the aluminium rings under a N-g field have been calculated by integrating the horizontal stress (σ_h) developing in the soil under at-rest conditions over the internal surface of each ring. The maximum static deflection will occur at the midpoint of the ring longitudinal side.

Static deflection of each ring was calculated modeling the ring longitudinal side as a beam with constrined ends under a homogeneous distributed load:

$$\delta_c = \frac{\sigma_h \cdot h_r \cdot {L_b}^4}{384 \cdot E \cdot I} \tag{5.17}$$

where h_r is the ring height, E is the Young modulus of aluminium and I the moment of inertia of the ring's excavated section (U-section). In order to take into account the presence of the stiffners foreseen along the ring U-section, only the beam length (L_b) used in the calculations was taken equal to the sum of the excavated portions of the ring side. This corresponds to the 84% of the internal length. It should be noted that the bottom ring is fixed to the container base and will not experience any lateral appreciable deformation under soil imposed stresses.

Under the horizontal stresses generating in the design soil column subjected to a 50g field, the maximum ring horizontal deflection is of 0.27mm (model scale). This is within the allowable bulging value of 0.001*H_s (Ueno, 1998), in the specific case 0.3mm (Figure 12).

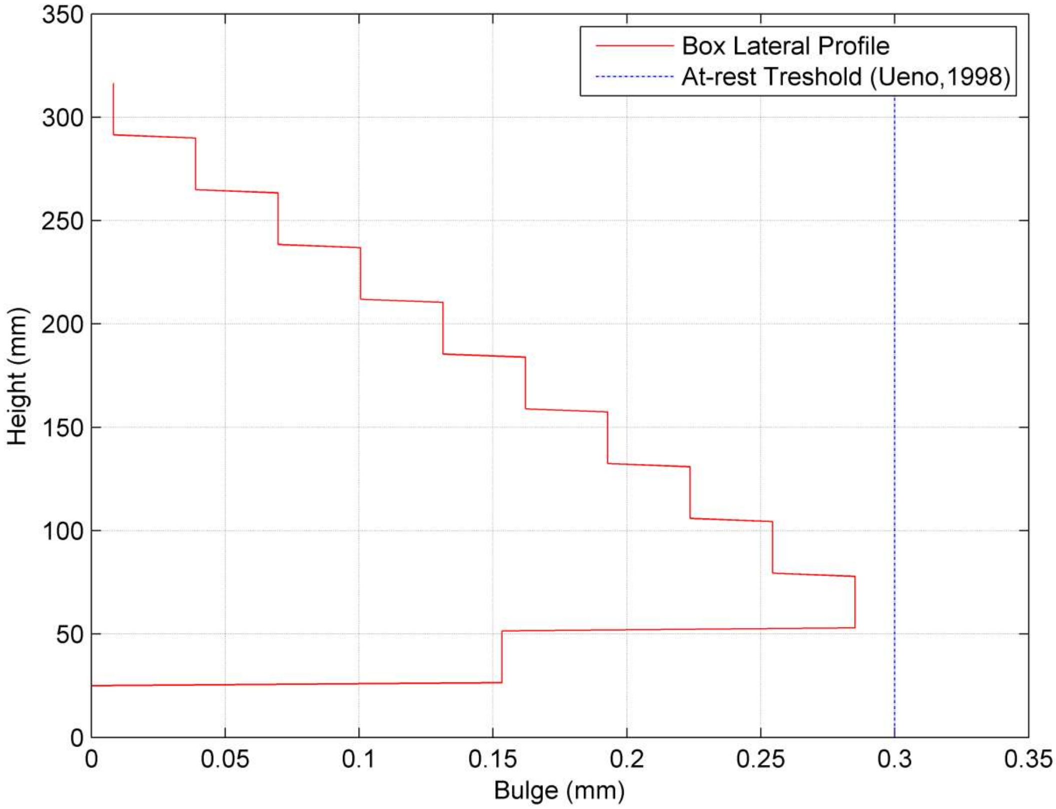

Figure 12 ESB Static Bulging Profile under 50g gravity field

5.4. Construction details

5.4.1. Safety

Bonding beweetn rubber interlayers and aluminium rings can be obtained by the application of an adequate adhesive agent (Bostik 2402 adhesive was used by Bertalot (2013)). Ring surface preparation by sand-blasting as well as the use of appropriate primers for both rubber and metal maximizes bonding strength. In order to obtain optimal bonding, surfaces must be clean prior to the application of the bonding agents. Cleaning surfaces with acetone is recommended in order to get rid of any oil traces.

Bertalot (2013) tested the bonding strength in a shear box apparatus by shearing to failure aluminium-rubber-aluminium sandwiches with a surface area of 3600 mm^2. Failure occurred along the glued interface as expected, at a lateral load of 2.46 kN, corresponding to a shear stress of approximately 682 kPa. Considering the design parameters chosen, the expected maximum working shear stress under the peak acceleration is approximately 80 kPa. Considering a flawless bonding, the factor of safety against shearing at the rubber-aluminium interface is of 8.5.

In case of unexpected bonding failure during centrifuge operations, a safety system is foreseen in order to avoid full detachment of one or more rings. Such safety system consists of 4 steel pins 18 mm in diameter rigidly fixed to the bottom ring. These pins run through vertical hollow slots carved in all top eleven rings, basically pinning them to the fixed base ring.

The four pins were dimensioned in order to sustain the maximum base shear and bending moment potentially occurring as a consequence of rubber bonding failure. The most critical case is given by failure occurring at the rubber interface between ring N°1 (base) and ring N°2, considering an acceleration equal to the design record PGA (approximately 0.3g) and a density of the retained soil (γ_{sat}) of 22 kN/m^3 (saturated soil with D_R=100%). The horizontal force acting on each pin can be estimated as the product of the accelerated mass and the design PGA minus the friction contribution within the soil in correspondence of the shear plane at a depth z calculated multiplying the maximum shear stress at depth z (equation 2.11) by the model area:

$$T_d(z) = \left[M_{tot}(z) \cdot PGA - \tau_{max}(z) \cdot A_{model}\right] \cdot N/4 \tag{5.18}$$

$$T_d = \left[\left[A_{model} \cdot (H - h_r) \cdot \gamma_{sat} + 11 \cdot M_f \cdot (g/1000)\right] \cdot PGA - \tau_{max} \cdot A_{model}\right] \cdot N/4 = 4.11kN$$

Assuming the force T_d applied at the mid-height of ring N°7 (z=0.154m), the design moment acting at the base of a single pin is of:

$$M_d = (T_d \cdot 0.154) = 0.6kN \cdot m = 6 \cdot 10^5 N \cdot mm \tag{5.19}$$

During centrifuge operations the four pins may be rigidly connected by a rigid frame, in order to stiffen the system and allow for the installation of fixed instrumentation. This would reduce the design moment at the base of the pin, however, this reduction is conservatively neglected. The pins shall be constituted of S275 grade steel, and connected to the bottom ring (also constituted of steel) by means of an M18 treaded connection. In order to stiffen the base section, a 3 mm stiffened section of 31mm diameter is foreseen. This section is lodged in a slot carved into the base ring increasing fixity. The bending and shear stress acting at the pin base can be calculated as follows:

$$W_{base\,section} = \frac{\pi \cdot r^3}{4} = 2919mm^3 \tag{5.20}$$

$$\sigma_d = M_d / W_{base\,section} = 205.6N/mm^2 \tag{5.21}$$

$$\tau_d = 1,5 \cdot T_d / A_{pin} = 24.2N/mm^2 \tag{5.22}$$

Considering the yield stress of S275 grade steel:

$$f_{y,d} = f_{y,k} / \gamma_M = 275 / 1.05 = 261.9 N / mm^2 \tag{5.23}$$

The pin section is verified for both bending ($\sigma_{y,d} \leq f_{y,d}$) and shear ($\tau_d \leq f_{y,d}$). When used in conjunction with a rigid stiffener frame, the pin system can also be used as lifting points for the handling of the container.

5.4.2. Payload

The empty ESB container has an overall weight of approximately 120kg (including the base); its internal area is 0.1875m^2 and can accommodate a soil model having a maximum volume of 0.056m^3. Considering the container full of a saturated sand with relative density of 100% (γ_{sat}=22.1kN/m^3), which represents an upper bound for the intended tests, the overall model weight would be approximately 263kg (143kg+120kg). This value largely meets the requirements regarding the maximum allowed payload on the shaking table.

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6. Test soils

The basic concept of centrifuge experimentation was to analyse the seismic behaviour of loose, saturated, 15 m deep sandy deposits, homogeneous or stratified, subjected to increasing seismic excitations up to liquefaction and to verify the effectiveness of different liquefaction mitigation techniques. To this aim, a first series of tests was devoted at investigating the liquefaction triggering conditions, in order to define under which conditions liquefaction occurred and to provide a benchmark dataset to be used as comparison to evaluate the effectiveness of the remediation techniques selected for the project (second and third series of tests).

To this end, it was established to test, during the first test series, three sandy soils: (i) a natural sands retrieved from the site of Pieve di Cento, located near to the reference localities of San Carlo and Mirabello, and tested with and without its natural fine content (natural Pieve di Cento sand and clean Pieve di Cento sand), (ii) a well known Italian clean sand (Ticino Sand) extensively used in the last 40 years for geotechnical experimentations.

The above choice relied on the idea of testing both natural soils, which experienced liquefaction, and for comparison a standard sand for which are available previous seismic analyses from the geotechnical literature, and, on the base of the experimental results, select the testing soil considered more suitable for the following test series for the evaluation of the effectiveness of different liquefaction mitigation techniques.

It's worth noting that the site of Pieve di Cento was selected to retrieve the testing material because in that area a sandy layer, deposited by the same river which generated the sand liquefied at San Carlo and Mirabello, is almost outcropping and it was possible to sample a significant amount of sand from a superficial pit. From grain size analysis Pieve di Cento sand resulted slightly different from the sand liquefied during the 2012 earthquakes.

The grain size curves of the tested soils are shown in Figure 13. Ticino Sand is a uniform coarse to medium sand made of angular to subrounded particles. It is composed by 30% quartz, 65% feldspar and 5% mica. 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.

The main index properties of the testing soils are reported in Table 8.

In some of the tested models, the sandy deposit was topped by a fine grain layer, reconstituted using Pontida Clay (Fioravante and 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, it has a G_s of 2.77, a liquid limit of 24% and plastic limit of 11% and a compression index C_c of 0.2. Grain size analyses indicate a prevalence of silt-size particles (53% by weight) with 30% clay size particles and 17% sand.

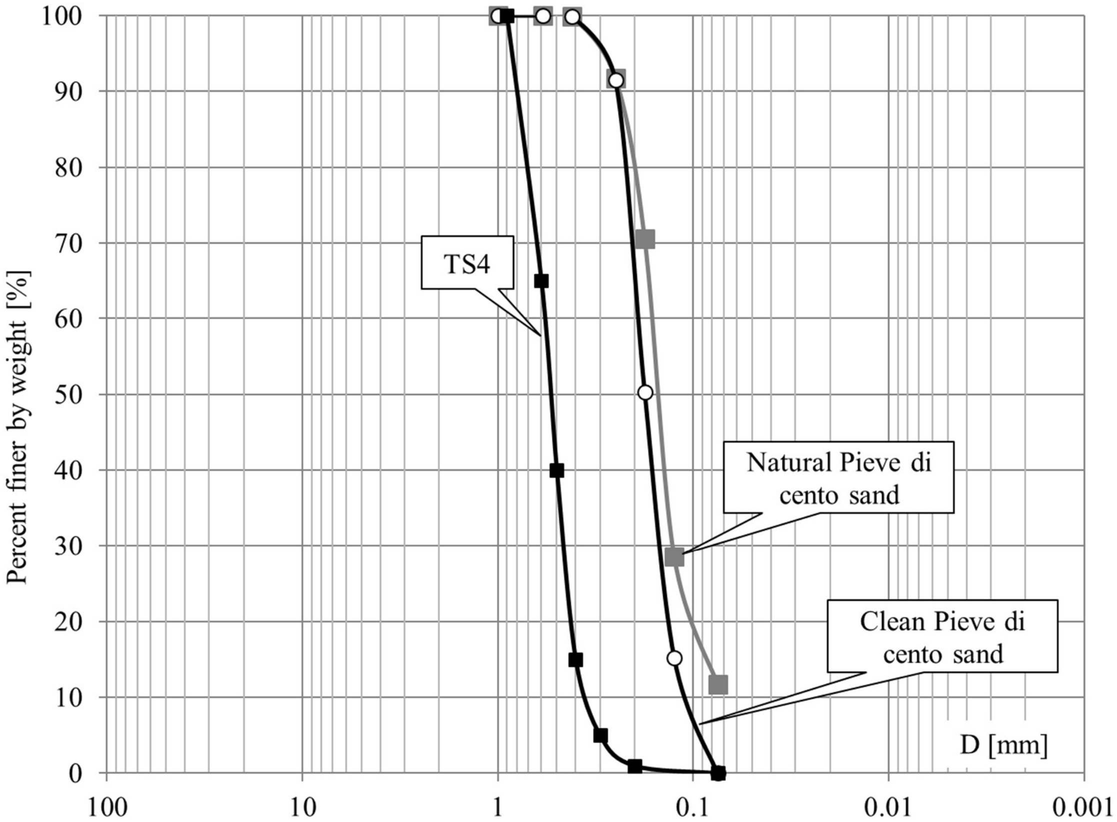

Figure 13 Grain saize distribution of test sands

Table 8 Index properties of sands used for physical models

Sand	γ_{min} (kN/m^3)	γ_{max} (kN/m^3)	e_{min}	e_{max}	G_s	D_{50} (mm)
Ticino	13.64	16.67	0.574	0.923	2.68	0.53
Clean Pieve di Cento	12.55	15.75	0.674	1.101	2.69	0.17
Natural Pieve di Cento	12.18	15.77	0.672	1.165	2.69	0.15

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7. Input motions

A specific site response analysis was carried out by the Partner of UNIPV in order to provide a series of ground motions, corresponding to different seismic hazard levels (Return period, Tr =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 which were simulated in centrifuge.

Among the 21 signals analysed, four ground motions (GMs) were selected for the centrifuge tests, as more suitable to the shaking table capabilities. Their main characteristics are reported in Table 9. The time history of acceleration and Fourier amplitude spectra are shown from Figure 14 to Figure 23 both at the model and prototype scale. As shown in the Figures, the GMs have increasing intensity. It's worth noting that, to be used in centrifuge seismic tests, the computed signals required specific adaptation to shaking table technical specifications (see Table 2). In this particular case, the maximum frequency and acceleration values in flight were limited to 500 Hz and 15g respectively. Those values correspond to 10 Hz and 0.3g at prototype scale. The computed time histories had all maximum acceleration values lower than 0.3g. On the other hand, the records contained a certain amount of information for f>10 Hz; thus a low-pass filter was used to reduce the spectral information for higher frequencies.

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, which 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 programme.

Table 9 Spectrum-compatible rock outcrop acceleration sets for three return periods
Tr: return period; GM_ID Ground Motion ID; M_w: Moment magnitude; Rep: epicentral distance; SF scale factor.

Tr (years)	GM_ID (-)	M_w (-)	R_{ep} (km)	SF (-)	Source file (-)
475	GM17	6.1	97	1.65	KiKnet MYGH041103280724.EW2
975	GM23	5.9	10.1	2.39	ESM IT.ATN..HNN.D.19840507.174943.C.ACC.ASC
2475	GM31	6.9	62.9	1.33	ESM EU.HRZ..HNE.D.19790415.061941.C.ACC.ASC
2475	GM34	6.93	28.64	0.59	NGA RSN765_LOMAP_G01000.AT2

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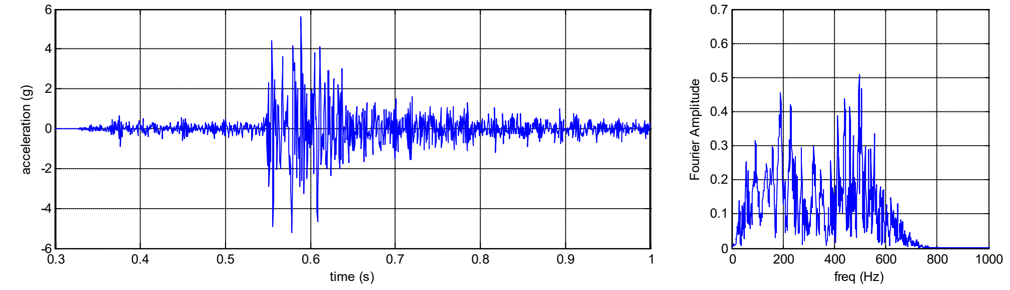

Figure 14 GM17: time history and frequency spectrum at model scale

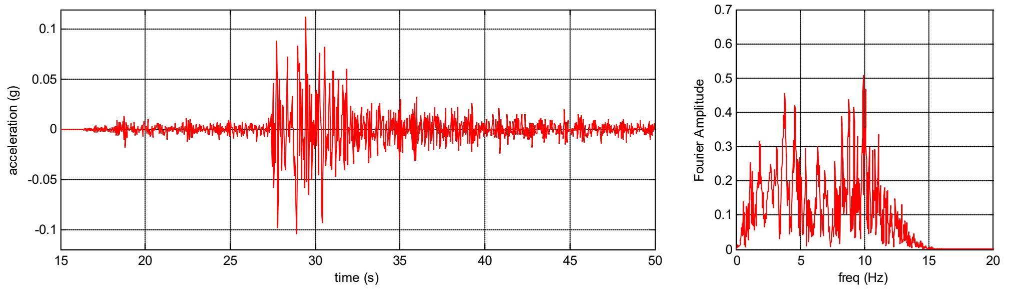

Figure 15 GM17: time history and frequency spectrum at prototype scale

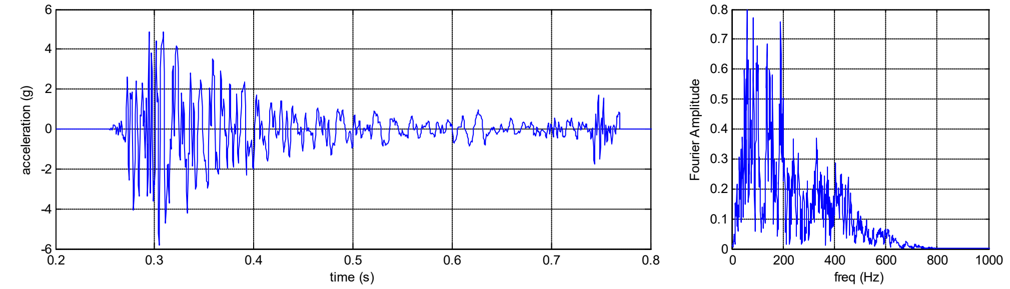

Figure 16 GM23: time history and frequency spectrum at model scale

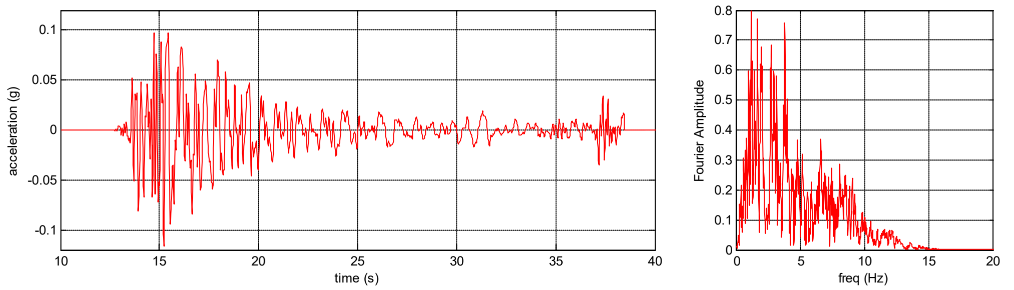

Figure 17 GM23: time history and frequency spectrum at prototype scale

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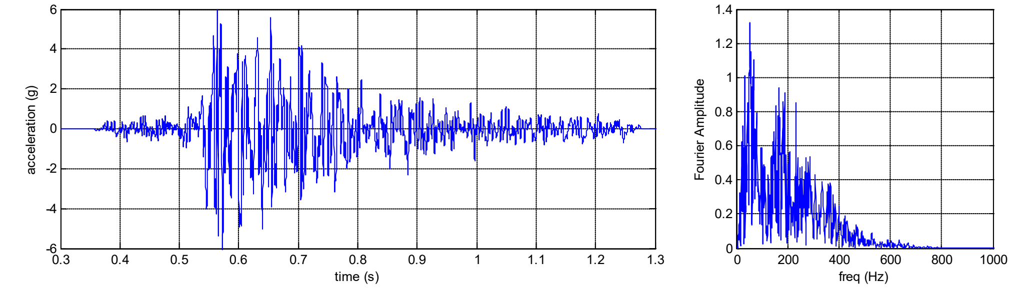

Figure 18 GM31: time history and frequency spectrum at model scale

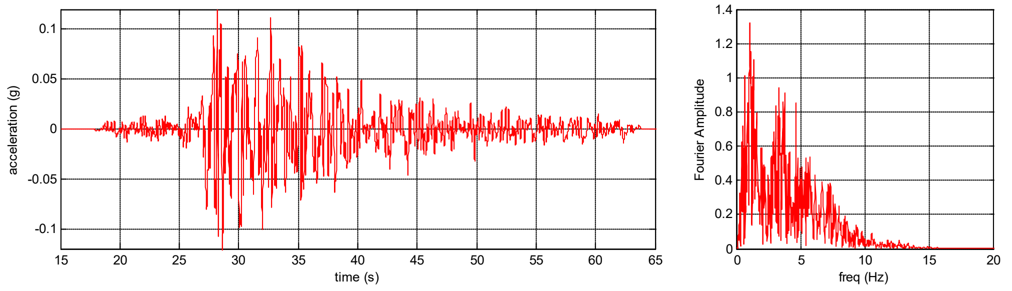

Figure 19 GM31: time history and frequency spectrum at prototype scale

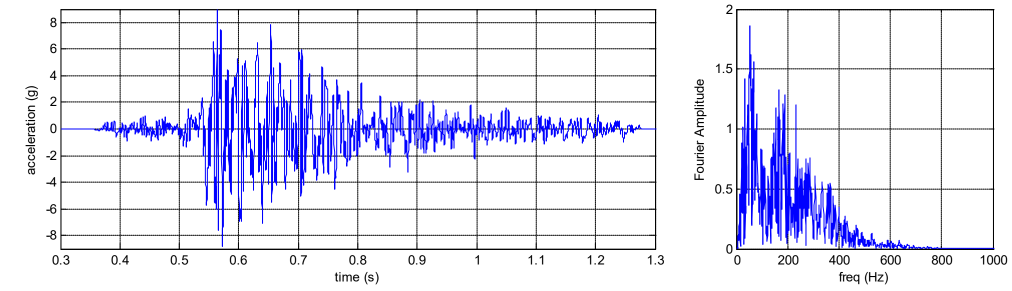

Figure 20 GM31+: time history and frequency spectrum at model scale

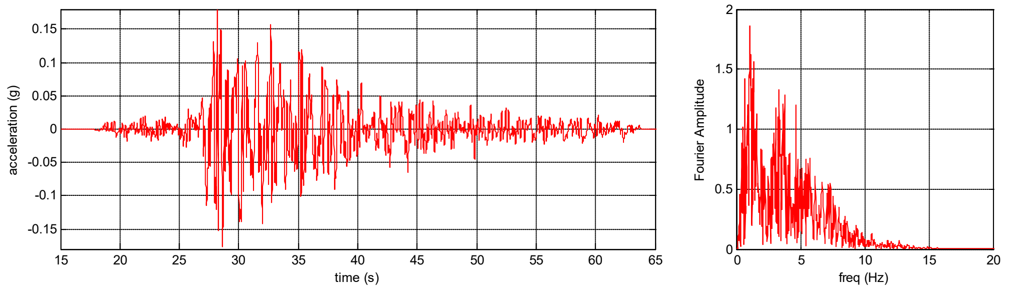

Figure 21 GM31+: time history and frequency spectrum at prototype scale

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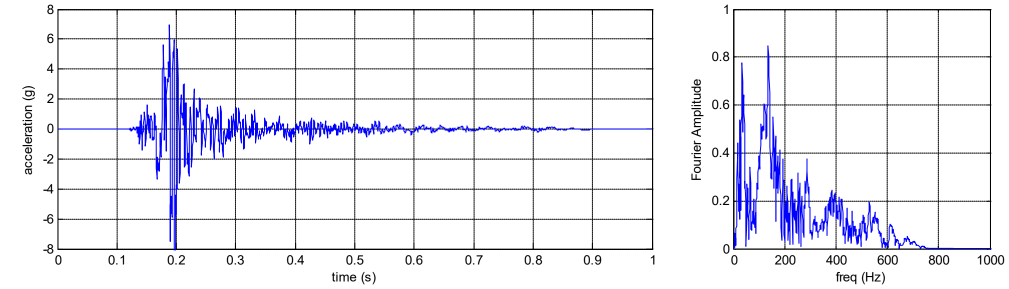

Figure 22 GM34: time history and frequency spectrum at model scale

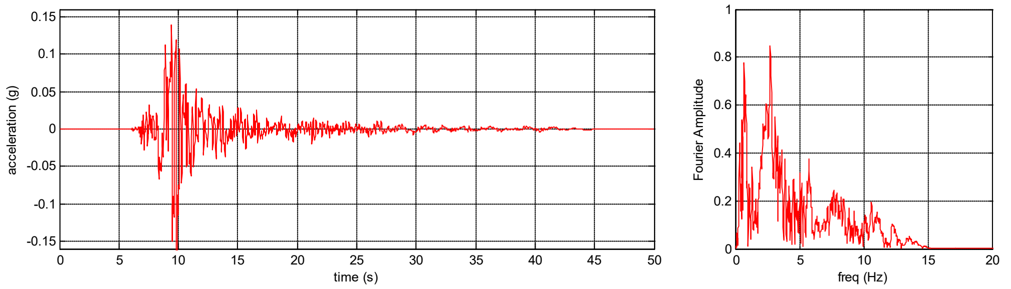

Figure 23 GM34: time history and frequency spectrum at prototype scale

8. Experimental setup

8.1. Model types and model foundation

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

Model 1 represented a homogeneous sand soil profile, **Model 2** represented a homogeneous soil profile topped by a 1.5 m thick fine grained layer of lower permeability. Figure 24 shows the basic configurations of the models with dimensions expressed at model and prototype scales in brackets.

In some tests a simple structure founded on a shallow foundation was included in the models.

The structure scaled model was designed by the partners of UNINA and is shown in Figure 25. The structure is conceived as a single degree of freedom (SDOF) 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 aluminium. The connections of the steel plates is by welding, the connections of the aluminium parts is by screws. The manufactured model, whose dimensions are reported in Figure 25, is shown in Figure 26; it has a mass of 2 kg and a natural frequency of 155 Hz at model scale (3.1 Hz at prototype scale). This frequency value has been measured blocking rigdily the strucutre foundation on a fixed base and hitting the oscillating part. Two accelerometers installed on oscillating part and rigid base respectively registered the osscillation of the structure.

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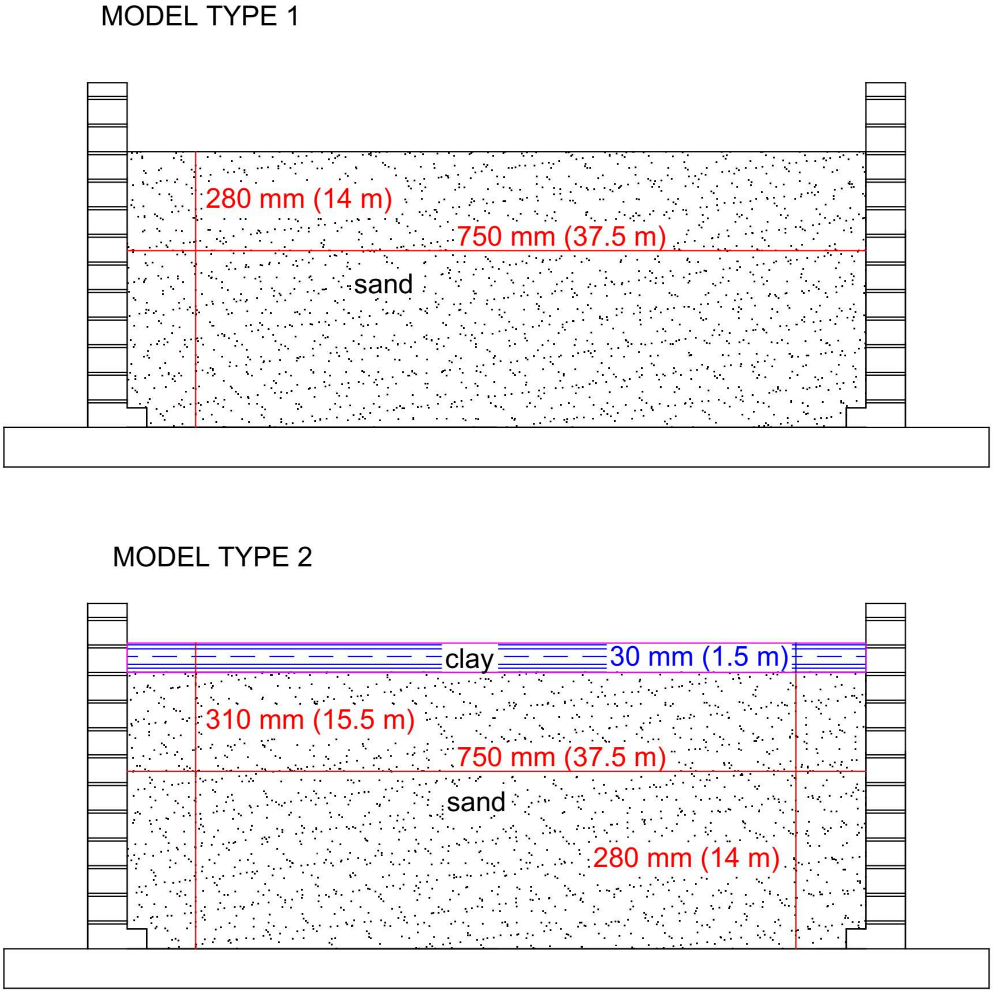

Figure 24 Models configurations and main dimensions

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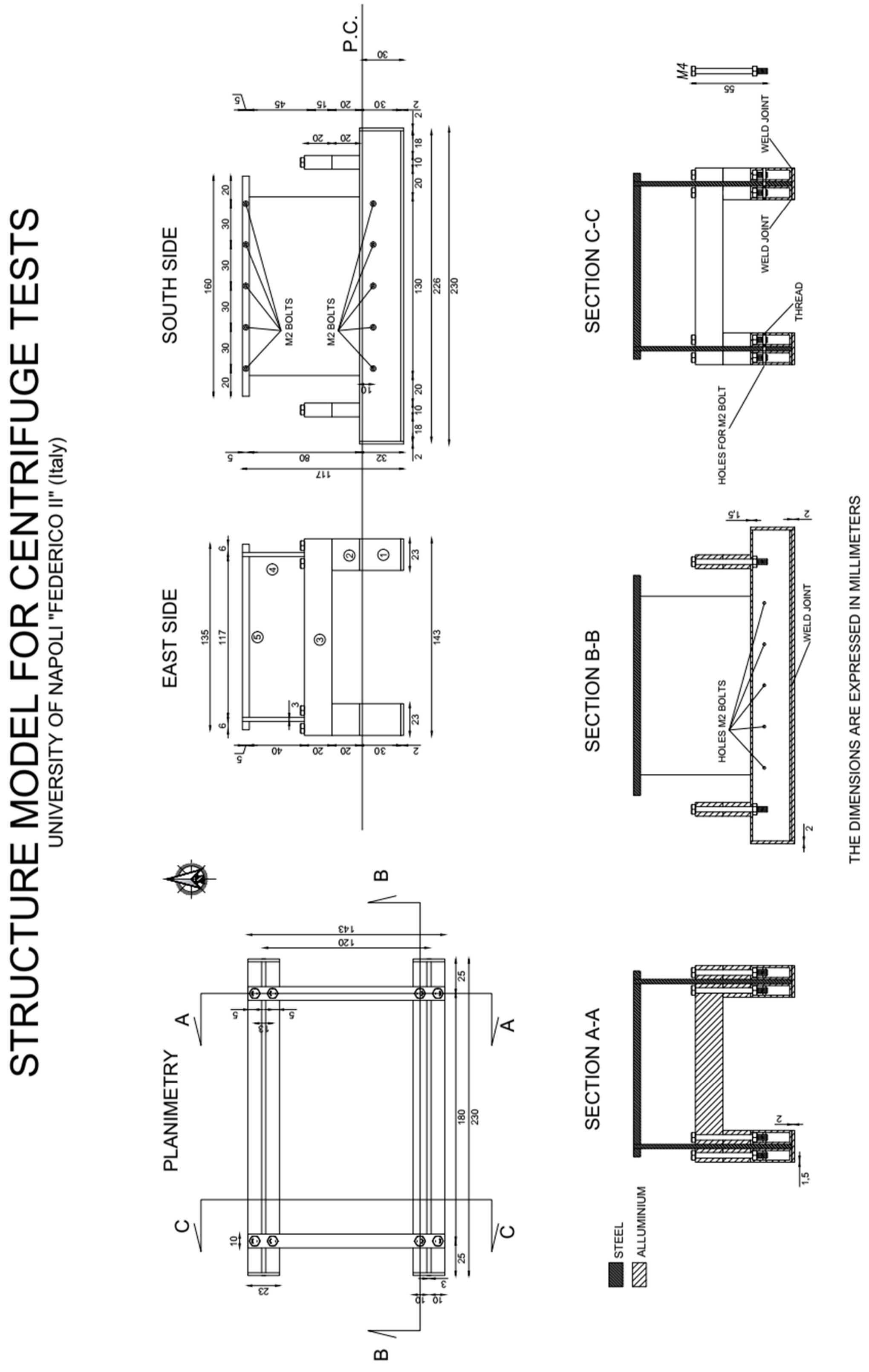

Figure 25 Structure model design

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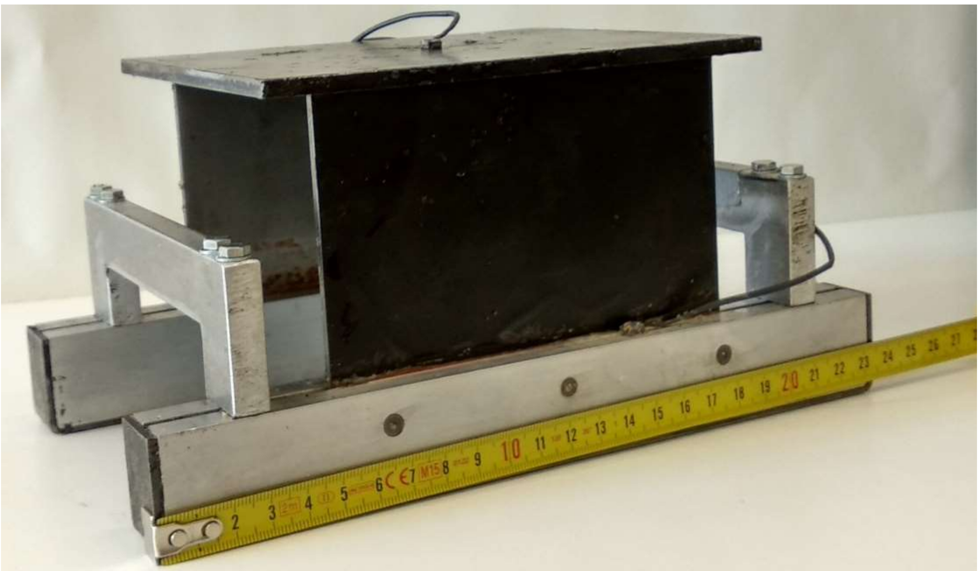

Figure 26 Structure model

8.2. Model reconstitution

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's 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 medium value of relative density during all the experimental phases. The datum for all measures is the top frame of the ESB container. The sand models had a global height of 28 cm, corresponding to 14 m at prototype scale.

Samples of Pontida silty clay were used to prepare the fine grained model layer placed above the sandy profile in some models. Each layer was prepared as follows. Dry clay powder was placed in a mixer and the appropriate amount of deaired tap water was added 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 via a spoon into the consolidometer until an unconsolidated specimen height of 50 mm was obtained. Filter paper and porous disks were placed at the top and bottom of the specimen. During the loading stage, the consolidometer was placed under a rigid reaction frame. The loading steps applied were: 6, 12.5, 25, 50, 100, 200 kPa. The height of specimen after consolidation was approximately equal to 30 mm. The time required to achieve full consolidation was about 13 days.

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.

8.3. Model saturation

At the end of the sand deposition, the models were saturated using a viscous fluid. The use of a viscous fluid rather than water is necessary in dynamic centrifuge testing due to the discord between the scaling ratios for time in dynamic phenomena and in diffusion phenomena (see paragraph 2 and Table 1).

The physical model tested 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°). After testing different chemical products, the most suitable was identified with the powder Ashland Culminal MHPC 50. A mix of water with 2% of this powder gives a fluid with a viscosity included between 40 and 55 cSt and a unit weight of 9.84 kN/m^3, that is approximately the unit weight of water. The correct concentration value was verified by viscometer tests whose results are plotted in Figure 27.

The fluid was prepared as follows: 2/3 in weight of water was heated and mixed with the powder in a concentration of 20 g/l (2%); after 5 minutes of mixing using an electric agitator the remaining third of cold water was added to the solution and mixed for at least half an hour.

The ESB with the dry model was placed in the centrifuge basket. The ESB was covered with a steel plate, sealed and connected to a vacuum pump. The reservoir with the fluid was installed above the ESB and connected by two pipes, one pipe 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 (Figure 28). 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. The saturation process lasted about 7 hours. At the end of the saturation, the soil surface settlement where carefully measured.

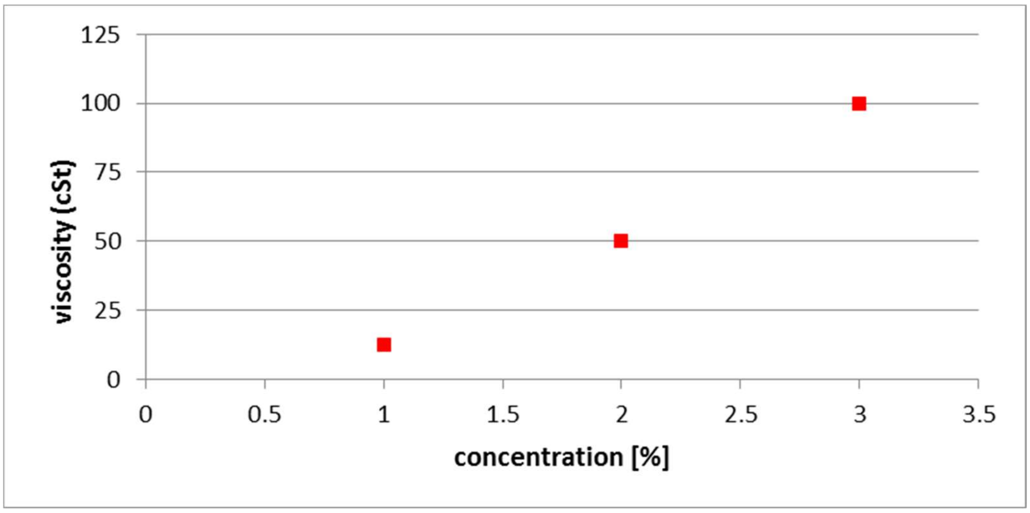

Figure 27 HPMC Viscosity vs Concentration

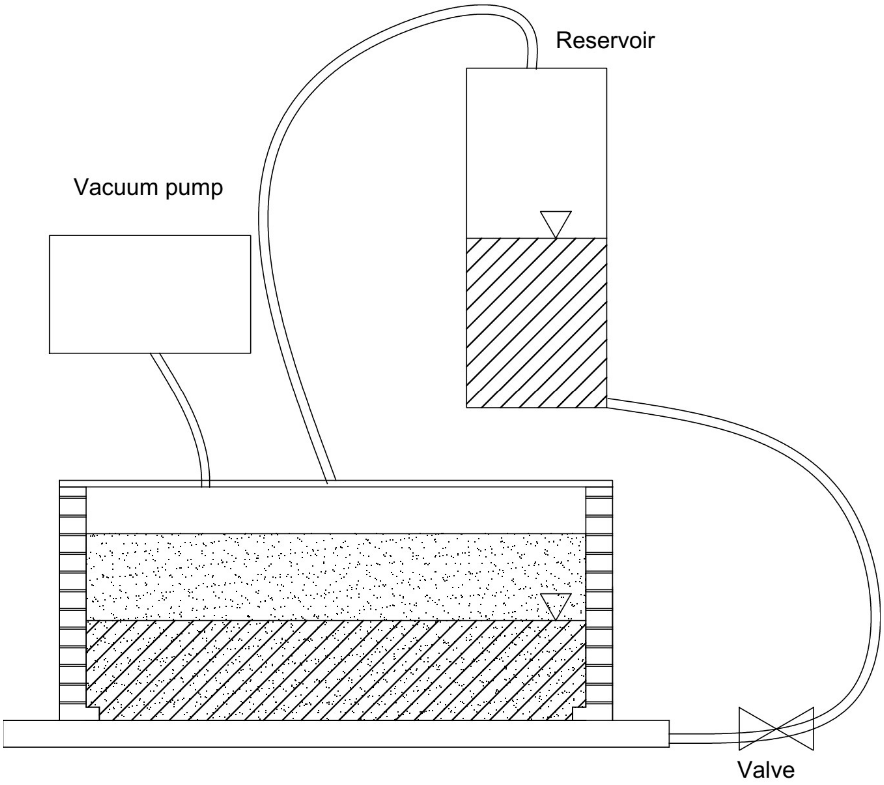

Figure 28 Saturation device diagram

8.4. Model instrumentation

The tested models were equipped with miniaturised accelerometers, pore pressure and displacement transducers 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.

A general layout of the instrumentation used during the tests is shown in Figure 29. It's worth noting that the position and configuration of sensors was changed from test to test depending on the specific test characteristics, so the exact layout of the instrumentation is specified in the test summary sheets reported in the next sections.

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 in the soil profiles. The sensitive direction was parallel to the shaking direction of the table, their number and position varied as a function of models characteristics and is reported in the technical datasheet of each test. 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 4 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.

Figure 30 reports a picture of the miniaturised transducers. Two types of accelerometers were used in the tests, PCB 352C22 piezoelectric ceramic uniaxial accelerometers (single axis, measurement range ±5000g, sensitivity 10mV/g) and ADXL78 MEMS by Analog Devices (single axis, measurement range ± 70g, sensitivity 25.65 mV/g). The miniaturised pore pressure transducers are EPB-PW by TE Connectivity with pressure range 0-15 bar, sensitivity 12.5mV/V, equipped with a sintered bronze filter. The accelerometers worked under severe environmental conditions since submerged in the viscous fluid for the whole duration of the experiment, in some tests some of them failed.

The data acquisition chain is 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.

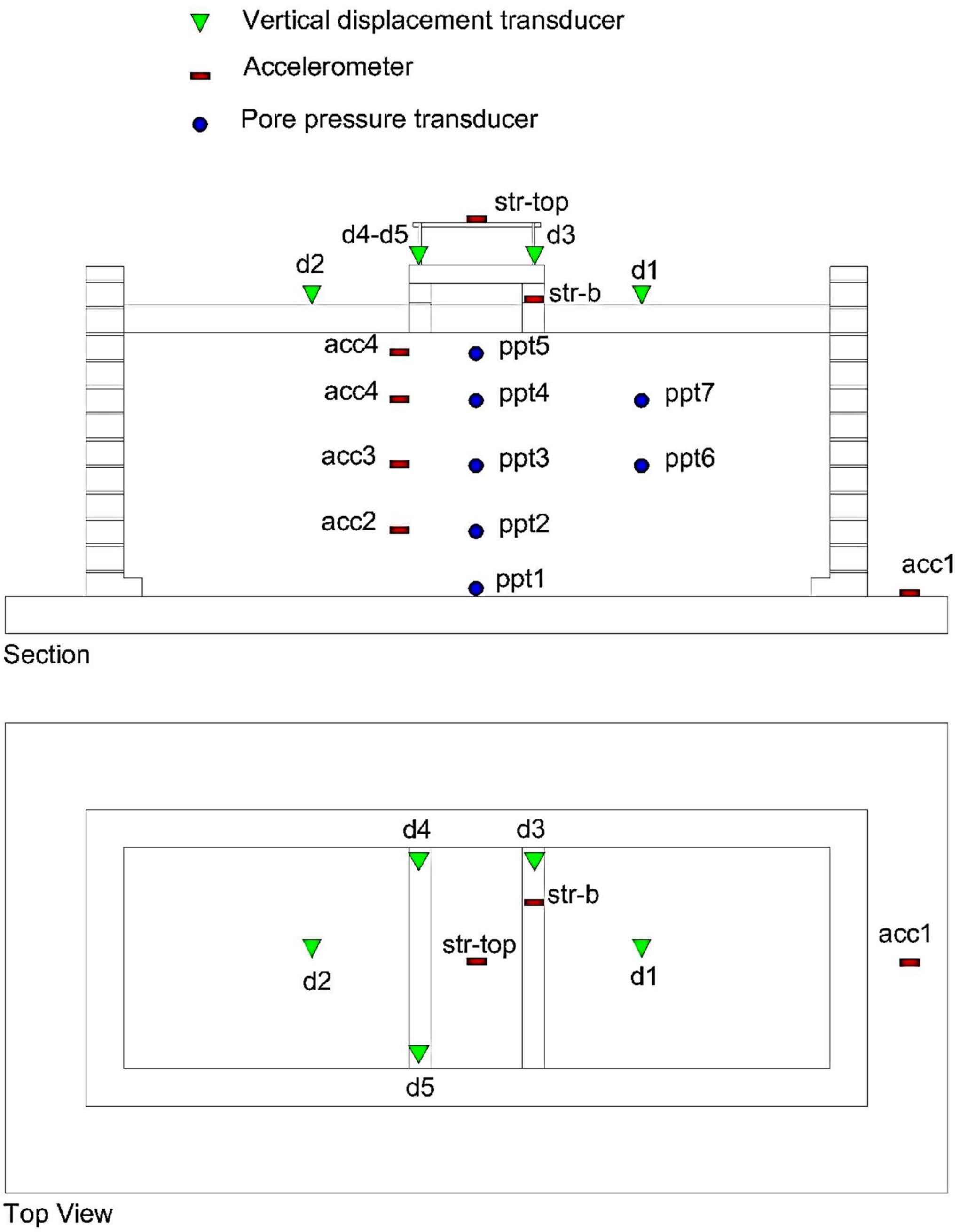

Figure 29 General test layout

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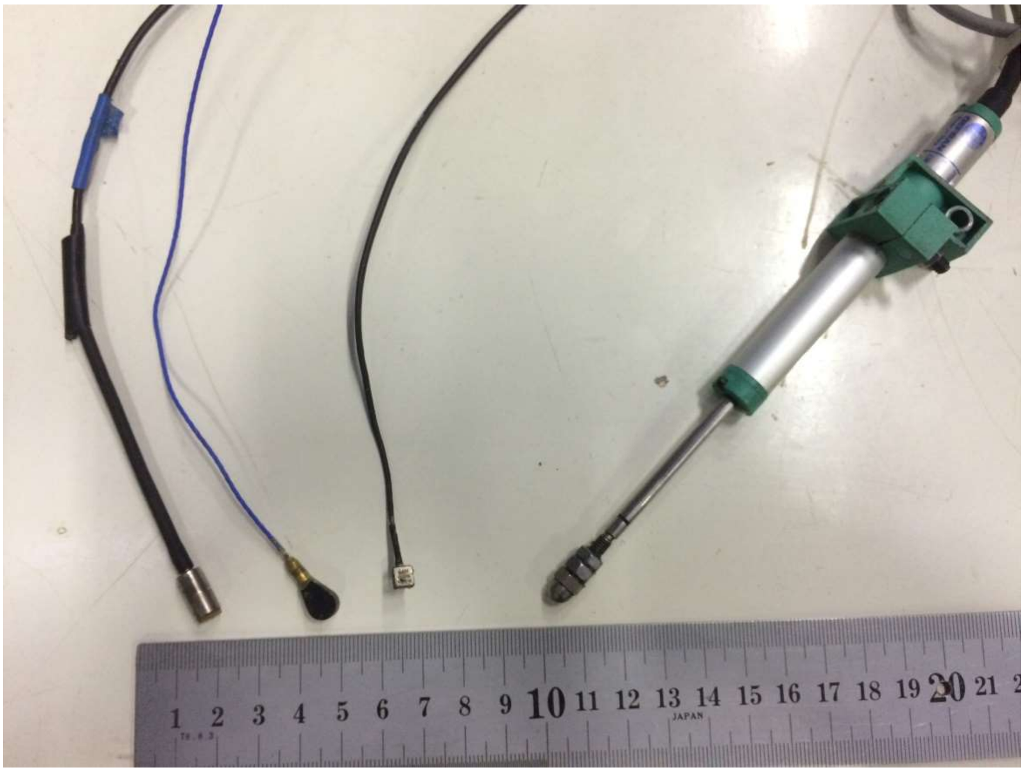

Figure 30 from left to right: pore pressure transducer, piezoelectric accelerometer, MEMS accelerometer, linear potentiometer

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8.5. Model Drains

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°, as evidenced in Figure 31). Permeability tests indicated a permeability coefficient of the model drains of $1.7{\cdot}10^{-2}$ m/s (the permeability coefficient of Ticino Sand at a relative density of 40% is $1.66{\cdot}10^{-3}$ m/s).

Figure 31 Pierced pipe used to model a drain, pipe external diameter is 6 mm

Specific installation procedures were adopted for vertical and horizontal drains in the models. As shown in Figure 32, 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 vertical drains were 275 mm and at the end of the installation procedure their tip was from 5 to 15 mm distant from the container bottom (depending on the tested model, i.e. homogeneous deposit or two layered model). The drains were installed according to a square mesh, the spacing between drains being equal to 5 or 10 diameters (30 and 50 mm, 1.5 and 3 m at the prototype scale), depending on the test layout. A draft of the two test schemes adopted is shown in Figure 33. Depending on the test layout, the number of drains was 30 (spacing equal to 5 diameters) or 12 (spacing 10 diameters). The minimum distance of the drains from the ESB longitudinal walls was 27.5 mm (4.5 diameters), as shown in Figure 34. 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.

Figure 32 Vertical drain ready to be driven in the soil

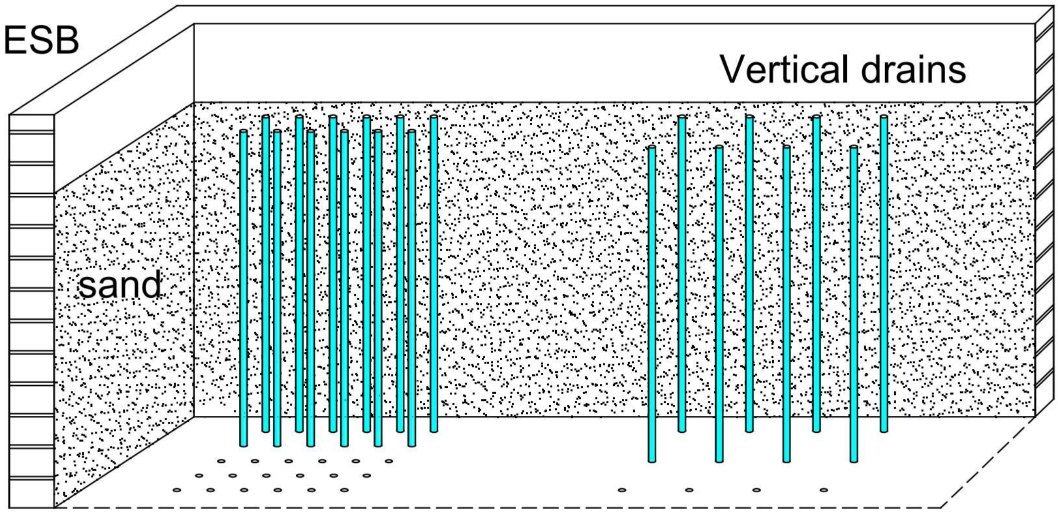

Figure 33 Sketch of vertical drains (on the left spacing = 5 diameters, on the right spacing = 10 diameters)

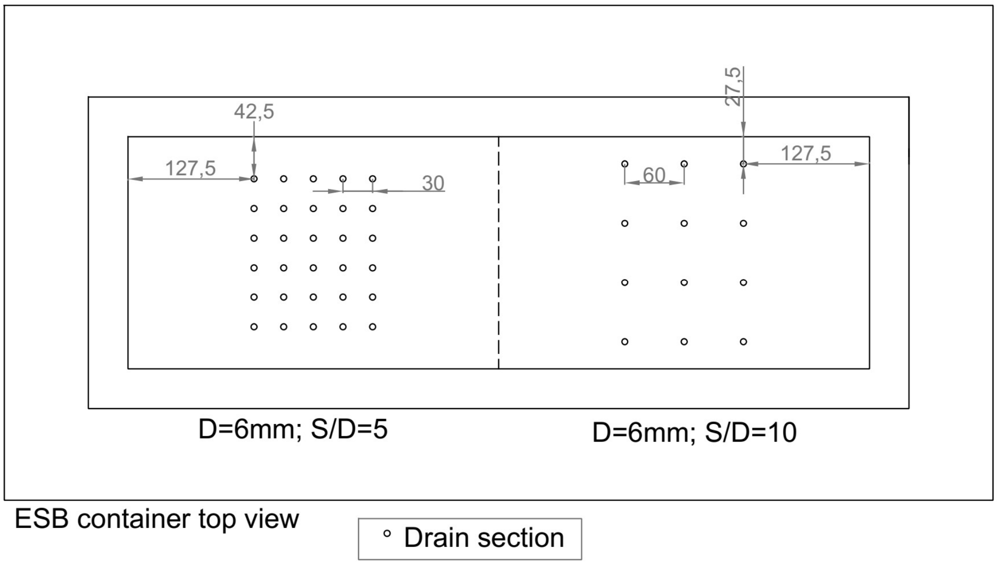

Figure 34 Top view of vertical drains model showing the interaxes values (in mm) for the two square patterns

As to horizontal drains, 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 miniaturised sensors, and each level of horizontal drains was placed. The ends of the horizontal drains were connected to three horizontal header pipes (diameter 12 mm) installed along the longitudinal sides of the ESB (Figure 35). 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), depending on the test layout. A draft of the two test schemes adopted is shown in Figure 36. Each layer of drains consisted of 3 or 4 pipes. The total number of horizontal drains was 9 or 10. The top row of drains was placed at a distance of 58 mm (about 10 diameters) from the sand surface, the bottom row was 118 mm or 170 mm above the container bottom, in the case of larger or smaller spacing, respectively. The external rows of drains were at least 97.5 mm distant from the ESB walls.

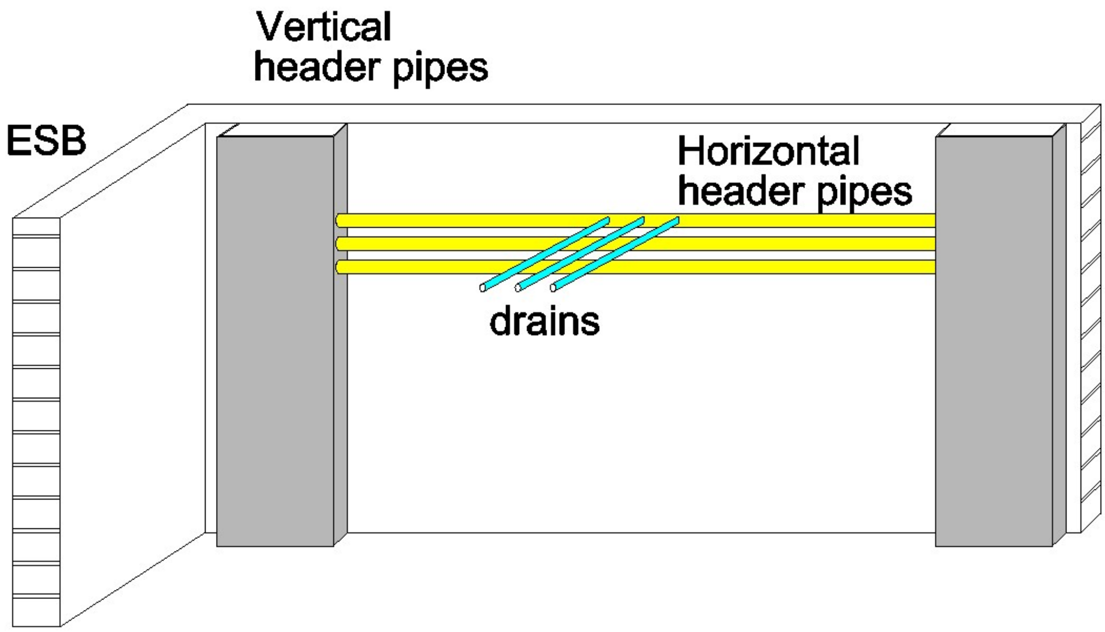

Figure 35 Sketch of horizontal drains

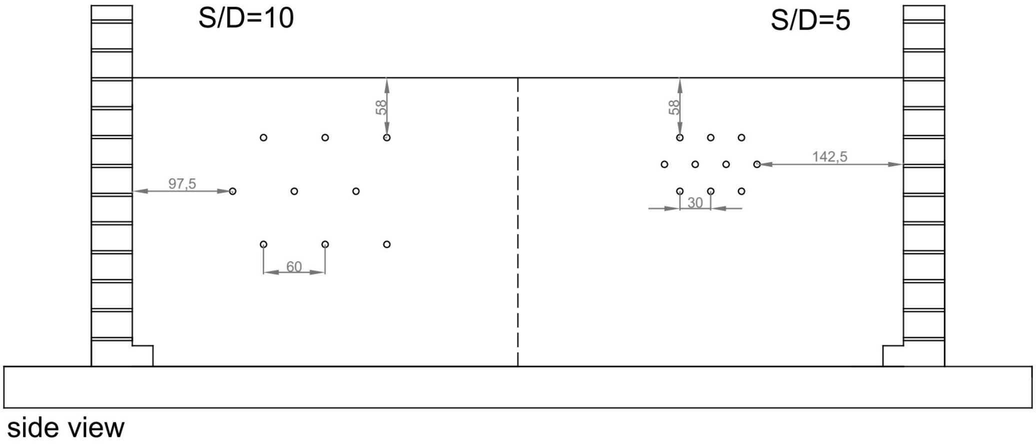

Figure 36 Side view of horizontal drains model showing the interaxes values (in mm) for the two quincux patterns

8.6. In-flight air injection apparatus

To simulate the air injection technique in centrifuge models, the injection must be carried out during the centrifuge flight, when the stress field in the model is similar to the in-situ stress state, thus reducing the soil disturbance.

The system developed by ISMGEO to this aim was composed by two air reservoirs, an air pressure transducer, a solenoid valve and connection pipes that go down to the injectors placed at the base of the soil model (Figure 37).

Two cylindrical reservoirs with a global capacity of $V_S = 9.8 \cdot 10^{-3}$ m^3 were installed on the centrifuge beam (Figure 38) 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 3.95 m long pipe, 4 mm in internal diameter, 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.

This consisted of a single injector or multiple injectors, depending on the test layout, fixed to the container bottom along its longitudinal axis, before model reconstitution (see Figure 39 and Figure 40). 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 connected to aforementioned part of the injection system.

The single injector (Figure 39) consisted of one nozzle with 1.3 cm in diameter and injection surface of 1.33 cm^2. The single injector was placed in the correspondence of the vertical axis of the model. The multiple injectors array (Figure 40) 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 the pressure before, P_{ini}, and after the injection, P_{fin}, are the injection reference parameters.

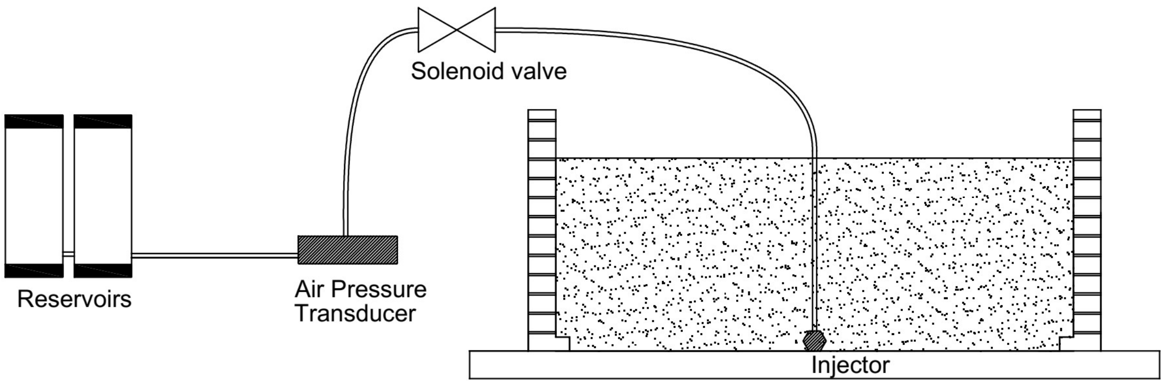

Figure 37 In-flight air injection apparatus

Figure 38 In-flight air injection reservoirs installed in the centrifuge

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Figure 39 IPS-1 nozzle system installed at the bottom of the ESB (on the left is visible an accelerometer, on the right a pore pressure transducer)

Figure 40 IPS-4 nozzles system installed at the bottom of the ESB

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8.7. In-flight sand characterization

The mechanical behaviour of the testing soils was checked using the results of in-flight miniaturized Cone Penetration Tests (micro CPT). The ISMGEO miniaturised electrical piezocone. Used for the tests has a diameter d_c = 11.3 mm, an apex angle of 60° and a sleeve friction of 11 mm in diameter and 37 mm in length. One load cell measures the cone resistance and another one measures the cone resistance plus the shaft friction, up to forces of 9.8 kN. A Druck PDCR42 pressure transducer (35 bar capacity) has been installed on the tip for interstitial pressure measurements. The test were carried out in a steel cylindrical strongbox whose internal diameter is 400 mm. The soil tested were Ticino Sand and natural Pieve di Cento sand.

Figure 41 shows a CPT model test scheme and a top view of the model container. The boundary conditions for the tests were: D/dc = 35, where D is the internal diameter of the container; S/dc = 17, where S is the CPT distance from the side wall. These values, according to Bolton et al. (1999) are large enough to minimise any scale effects on the results. The tested samples were dry (saturation does not affect the cone resistance in quartz sands as those used in the present experimentation) and were reconstituted at about the same test conditions of the models for dynamic tests.

The in-flight relative density of the Pieve di Cento Sand model was about 50%, that of the Ticino models was about 55%.

The adopted penetration rate was 0.2 mm/s for Pieve di Cento Sand and 2 mm/s for Ticino Sand, the difference in penetration rates gave a negligible effect on tests results since dry sand is not affected by strain rate effects. Tests results on both sands are plotted in Figure 42.

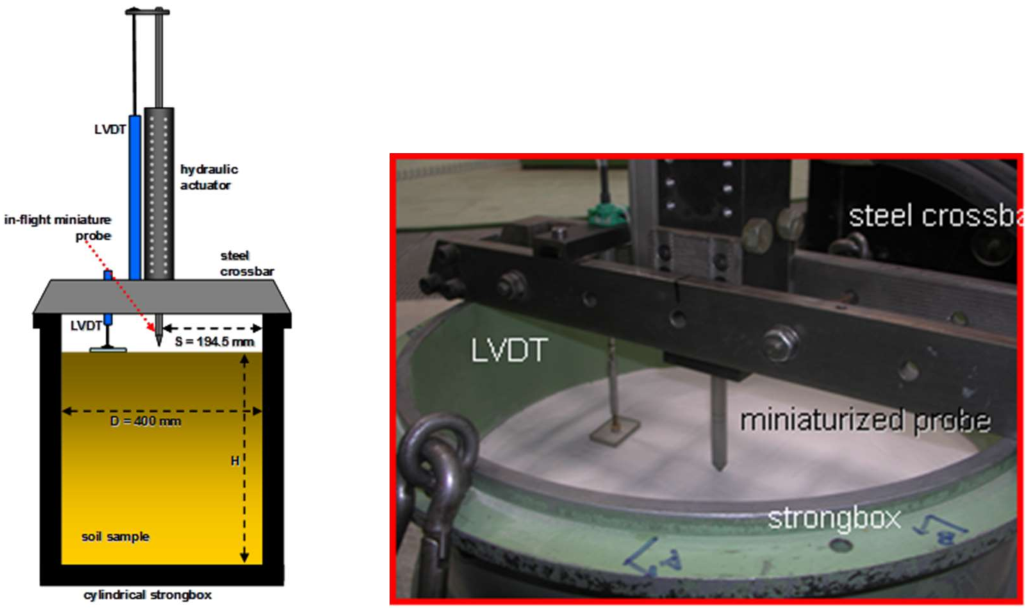

Figure 41 microCPT device

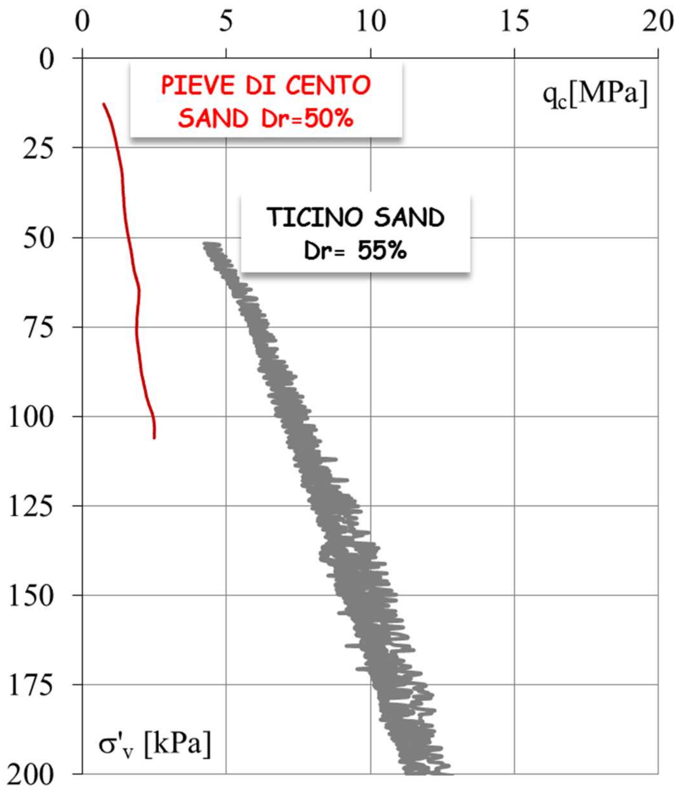

Figure 42 Results of miniaturised CPTs

In flight small-strain characterization of the sandy models was attempted during the project. The idea was to perform Bender Elements measures directly in centrifuge models before every seismic test in order to obtain the small strain shear stiffness of the models. Two bender elements were embedded into the sand models with a tip-to-tip distance of 20 cm, one used as transmitter, the other as receiver. The transmitter bender was excited with a sinusoidal electrical signal with a frequency of 5kHz; the received signal was acquired with a sampling rate of 15kHz.

Despite the numerous attempts, it resulted not possible to obtain reliable wave velocity measures results by this technique due to technical issues. All the electric signals going from the rotating machine to the control room are channelled on electric slip rings installed in the upper portion of the centrifuge rotation axis. The electric noise created during the centrifuge rotation covered the signal of the Bender Elements.

9. Test procedure and programme

As detailed in the previous sections, each soil model was reconstituted at 1g to the target relative density ($D_R \approx 40\%$) by pluviating, in air, the dry sand into the ESB container, maintaining a constant height of fall. During the pluvial deposition, at fixed model heights, the pluviation was interrupted and the instrumentation designed for the specific tests (accelerometers, pore pressure transducers, horizontal drains) were inserted into the soil mass. After deposition, the sand was saturated using the viscous fluid and the saturation system described above. If required by the test programme, the clay layer was placed above the sand surface. In the specific tests with the vertical drains, the pipes were driven in the models.

The centrifuge was then accelerated to 5g. At 5g the ESB was moved into contact with the shaking table and released. The centrifuge speed was slowly increased up to the target angular velocity (which, in all the tests carried out, corresponded to an acceleration of 50g imposed in correspondence of the model bottom). At 50g the model was allowed to consolidate, until the self weight equilibrium was reached: the soil surface settlements ended and the pore pressure reached a constant value, as monitored by the potentiometers and by the pore pressure transducers respectively; therefore the input ground motion was triggered. In case of Induced Partial Saturation type of tests, before triggering the input motion, the air injection was carried out.

During all the aforementioned test stages, the soil surface settlement was measured; to account for the average value of the current soil density at each stage, a linear distribution with depth of the vertical displacement was assumed, as simplified working hypothesis.

To achieve the Validation of retrofitting techniques from small scale models, the testing programme was developed and refined in cooperation with the Partners of UNINA. The final scope was to produce a consistent set of experimental data to be used as a benchmark for seismic response studies, numerical simulations and in situ trial tests, activities included in other Tasks of the LIQUEFACT project (e.g. Task 2.1 Ground characterization at the four European testing sites, 4.3 Field trials at the selected case study pilot testing site, 4.4 Numerical modelling, 4.5 Liquefaction mitigation techniques guidelines).

The main porpouse of the physical modelling was to reproduce:

- The seismic response of homogeneous and layered sandy model deposits in free field conditions and with the presence of a simple model structure, subjected to several earthquakes of increasing energy, up to the liquefaction triggering.
- Some of the main features of three selected techniques of ground treatment against liquefaction in free field.
- Soil-structure interaction behaviour under dynamic conditions, in untreated and treated soils.

A series of **37 tests** was carried out, the following 'parameters' varied from test to test:

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- Sand type (2 types of clean sands, 1 sand with a fine content of about 12%).
- Soil profile (homogeneous sandy soil and sandy soil with a crust of finer layer at the top, of lower permeability)
- Ground Motion (4 earthquakes of increasing return period + 1 with increased energy)
- Ground treatment technique (vertical drains, horizontal drains, induced partial saturation)
- Soil-Structure interaction behaviour induced by the presence of a structure with shallow foundations.

Table 10 summarises the entire testing programme and indicates schematically the main features of each test. Modelling parameters listed in the table are explained below.

Model type: indicates if a model reproduces a homogeneous sand deposit (model type M1) or a sandy deposit covered by a silty-clay layer (model type M2);

Sand: indicates which type of sand was used to build the model: (S1) Ticino sand, (S2) Pieve di Cento cleaned sand, (S3) Natural Pieve di Cento sand with a natural fine content of about 12%;

Ground Motion: four ground motions computed for the Emilia-Romagna region were provided by the Partner of UNIPV, each ground motion refers to a different return period (GM17, GM23, GM34, GM31); one more ground motion of amplified amplitude was applied when liquefaction was not achieved (GM31+);

Structure: the scaled model of a simple structure was built in collaboration with the Partners of UNINA, installed on some models to simulate soil-structure interaction effects (M1F = model type 1 with Foundation; M2F = model type 2 with foundation);

Vertical Drains: installed at a spacing, S of 5 times or 10 times the drain diameter, D (VD1 = vertical drains at spacing of 5 diameters; VD2 = vertical drains at spacing of 10 diameters);

Horizontal drains: installed at a spacing, S of 5 times or 10 times the drain diameter, D (HD1 = horizontal drains at spacing of 5 diameters; HD2 = horizontal drains at spacing of 10 diameters);

Induced Partial Saturation (IPS): air sparging technique simulated using a system with 1 injector (IPS1) or 4 injectors (IPS4).

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Table 10 Geotechnical Centrifuge Testing Programme

Test number	File Name	Model Type	Sand	Ground Motion	Structure	Drains	IPS
1	M1_S1_GM17	1	1	17	-	-	-
2	M1_S1_GM34	1	1	34	-	-	-
3	M1_S1_GM31	1	1	31	-	-	-
4	M1_S2_GM17	1	2	17	-	-	-
5	M1_S2_GM23	1	2	23	-	-	-
6	M1_S2_GM34	1	2	34	-	-	-
7	M1_S3_GM17	1	3	17	-	-	-
8	M1_S3_GM23	1	3	23	-	-	-
9	M1_S3_GM34	1	3	34	-	-	-
10	M2_S1_GM34	2	1	34	-	-	-
11	M2_S1_GM31	2	1	31	-	-	-
12	M2_S3_GM34	2	3	34	-	-	-
13	M1F_S1_GM31	1	1	31	yes	-	-
14	M1F_S1_GM31+	1	1	31+	yes	-	-
15	M2F_S1_GM31+	2	1	31+	yes	-	-
16	M1_S1_VD1_GM31	1	1	31	-	Vert. S=5D	-
17	M1_S1_VD2_GM31	1	1	31	-	Vert. S=10D	-
18	M1_S1_HD1_GM31	1	1	31	-	Horiz. S=5D	-
19	M1_S1_HD2_GM31	1	1	31	-	Horiz. S=10D	-
20	M2_S1_VD1_GM31	2	1	31	-	Vert. S=5D	-
21	M2_S1_VD2_GM31	2	1	31	-	Vert. S=10D	-
22	M2_S1_HD1_GM31	2	1	31	-	Horiz. S=5D	-
23	M2_S1_HD2_GM31	2	1	31	-	Horiz. S=10D	-
24	M1F_S1_VD1_GM31+	1	1	31+	yes	Vert. S=5D	-
25	M1F_S1_HD1_GM31+	1	1	31+	yes	Vert. S =10D	-
26	M2F_S1_VD1_GM31+	2	1	31+	yes	Vert. S=5D	-
27	M2F_S1_HD1_GM31+	2	1	31+	yes	Horiz. S=5D	-
28	M1_S1_IPS1_GM31	1	1	31	-	-	1 inj.
29	M1_S1_IPS1_GM31+	1	1	31+	-	-	1 inj.
30	M1_S1_IPS4_GM31	1	1	31	-	-	4 inj.
31	M1_S1_IPS4_GM31+	1	1	31+	-	-	4 inj.
32	M2_S1_IPS1_GM31	2	1	31	-	-	1 inj.
33	M2_S1_IPS1_GM31+	2	1	31+	-	-	1 inj.
34	M2_S1_IPS4_GM31	2	1	31	-	-	4 inj.
35	M2_S1_IPS4_GM31+	2	1	31+	-	-	4 inj.

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Test number	File Name	Model Type	Sand	Ground Motion	Structure	Drains	IPS
36	M1F_S1_IPS4_GM31+	1	1	31+	Yes	-	4 inj.
37	M1F_S1_IPS4_GM31++	1	1	31++	Yes	-	4 inj.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

10. Test Results

10.1. First series of tests

The first series of tests is composed by tests numbered from 1 to 15 in Table 10. The main purpose of this series of tests was to reproduce the seismic response of homogeneous and layered soil models, in free field conditions and with a simple model structure on shallow foundations, subjected to several earthquakes of increasing energy, up to the liquefaction triggering.

Experimental targets achieved are:

- Reproduction of liquefaction conditions on homogeneous sand models (Model 1) and on layered soil models (homogeneous sand topped by a clay layer, Model 2) in free field conditions and with a model structure at the top surface (Model 1F and 2F).
- Reproduction of the dynamic behaviour of three types of sands (Ticino, Pieve di Cento Clean sand, Natural Pieve di Cento with a fine content of 12%).
- Evaluation of the triggering conditions of sand liquefaction in both models (1 and 2), reconstructed with the three different sand types, testing 5 different seismic input motions (GM17, GM23, GM34, GM31, GM31+).
- Evaluation of post liquefaction settlements.
- Production of a consistent set of experimental data to be used as a benchmark for seismic response studies and for numerical simulations, activities included in other Tasks of the LIQUEFACT project (e.g. Tasks 2.1 and 4.4).
- Selection of the sand material (Ticino sand) and ground motions (GM31 and GM31+) to be used in the second and third test series.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

10.1.1. Test summary sheets

The experimental programme of the first series of tests is reported in Table 11. The results of each test are summarised in four data sheets. The set of information that can be found is:

Reconstruction:

- Sketch of the model with (1) sensors ID and positions after deposition, (2) model structure position when present (mm at model scale);
- Sand characteristics after deposition (average values of dry density, relative density and void ratio).

Equilibrium at centrifuge angular velocity of 15.08 rad/s, before the shock:

- Soil material characteristics (average values of dry density, saturated density, relative density, void ratio, degree of saturation);
- Position of the (1) model base, (2) free ground surface and (3) sand/clay interface when present, expressed as radius from centrifuge rotation axis;
- Position of PPTs and ACCs expressed as radius from centrifuge rotation axis;
- Pore pressure, u_0 values as measured by the PPTs before the shock.

Seismic Excitation:

- Time histories measured by the installed miniaturised accelerometers
- Input motion applied by the shaker (ACC1)
- Excess pore pressure [$\Delta u(t) = u(t)-u_0$] versus time measured during the shock by PPTs
- Vertical Displacement of the soil surface vs. time recorded during the shock.

All data are reported at model scale

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Table 11 First series of tests

Test number	Test Name	Model Type	Sand	Ground Motion	Structure
1	M1_S1_GM17	1	1	17	-
2	M1_S1_GM34	1	1	34	-
3	M1_S1_GM31	1	1	31	-
4	M1_S2_GM17	1	2	17	-
5	M1_S2_GM23	1	2	23	-
6	M1_S2_GM34	1	2	34	-
7	M1_S3_GM17	1	3	17	-
8	M1_S3_GM23	1	3	23	-
9	M1_S3_GM34	1	3	34	-
10	M2_S1_GM34	2	1	34	-
11	M2_S1_GM31	2	1	31	-
12	M2_S3_GM34	2	3	34	-
13	M1F_S1_GM31	1	1	31	Yes
14	M1F_S1_GM31+	1	1	31+	Yes
15	M2F_S1_GM31+	2	1	31+	Yes

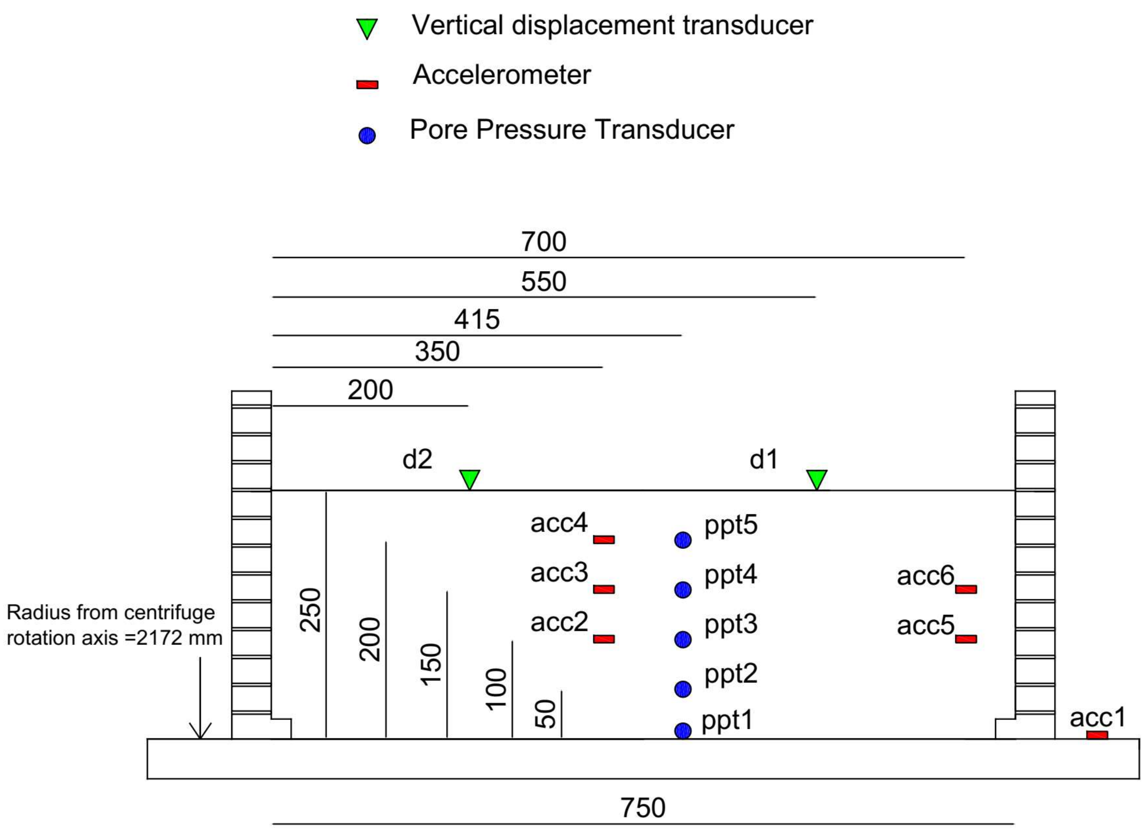
Test 1: M1_S1_GM17

Model description

The model consists of a homogenous soil profile of Ticino sand, the ground motion applied was the number 17.

1 – Reconstruction

Scheme and geometrical dimensions of the model as reconstructed at 1g. The following dimensions refer to the model scale



Ticino sand

Dry density [kN·s^2/m^4]	**1.482**
Relative density [%]	**33.95**
Void ratio [-]	**0.81**

2 – Equilibrium at centrifuge angular velocity ω= 15.08 rad/s before the shock

Ticino sand, average values

Dry density [kN·s²/m⁴]	**1.522**
Saturated density [kN·s²/m⁴]	**1.949**
Relative density [%]	**47.42**
Void ratio [-]	**0.76**
Degree of saturation [%]	**99.0**

Radii from centrifuge rotation axis

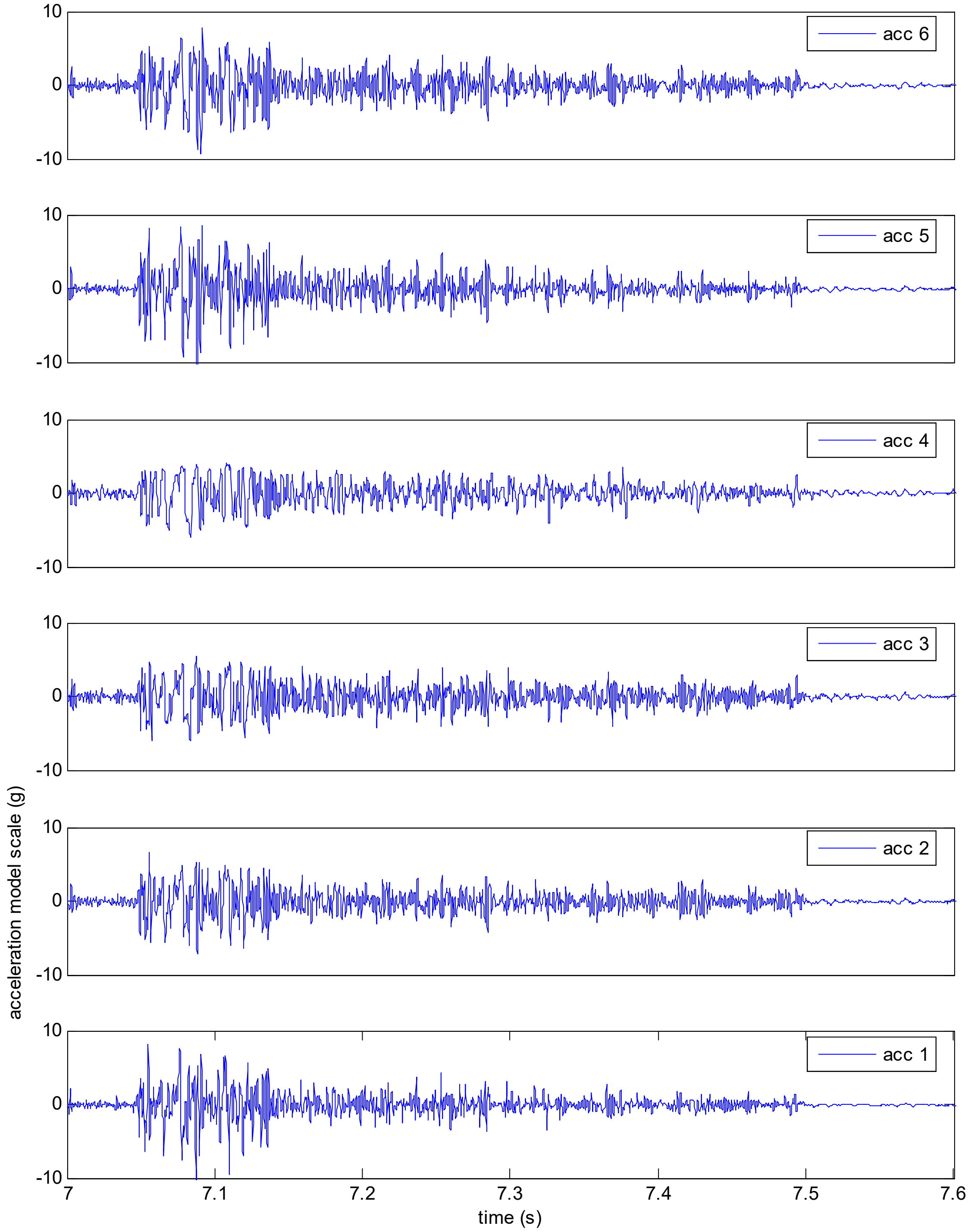
	Radius (mm)
model base	2172.0
free ground surface	1928.4

Pore Pressure Transducer	**Radius (mm)**	**Value before the shock u_0 (kPa)**
ppt5	1977.1	21.9
ppt4	2025.8	32.5
ppt3	2074.6	55.8
ppt2	2123.3	75.3
ppt1	2172.0	93.9

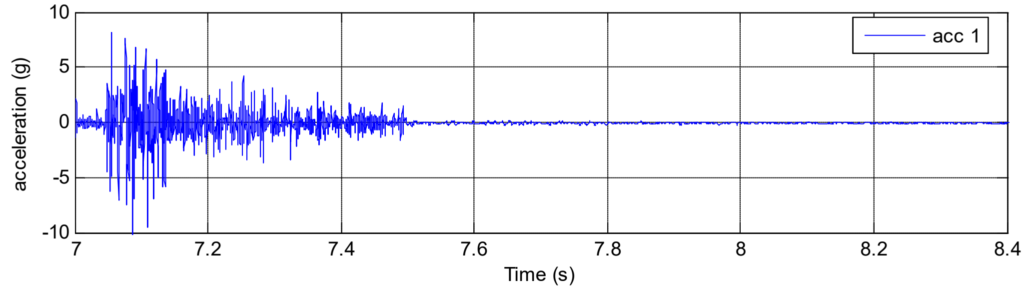
Accelerometer	**Radius (mm)**
acc6	2025.8
acc5	2074.6
acc4	1977.1
acc3	2025.8
acc2	2074.6
acc1	2172.0

3 – Seismic Excitation

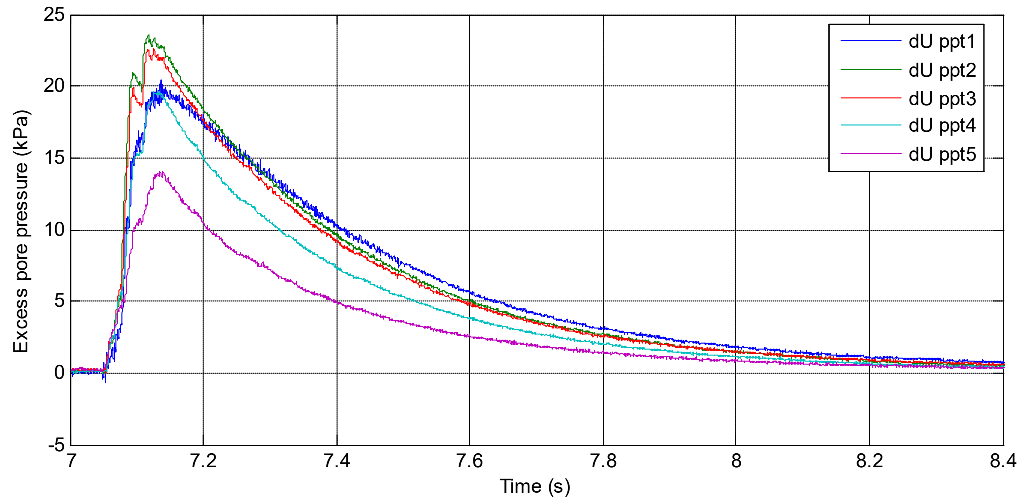
Accelerometers time histories



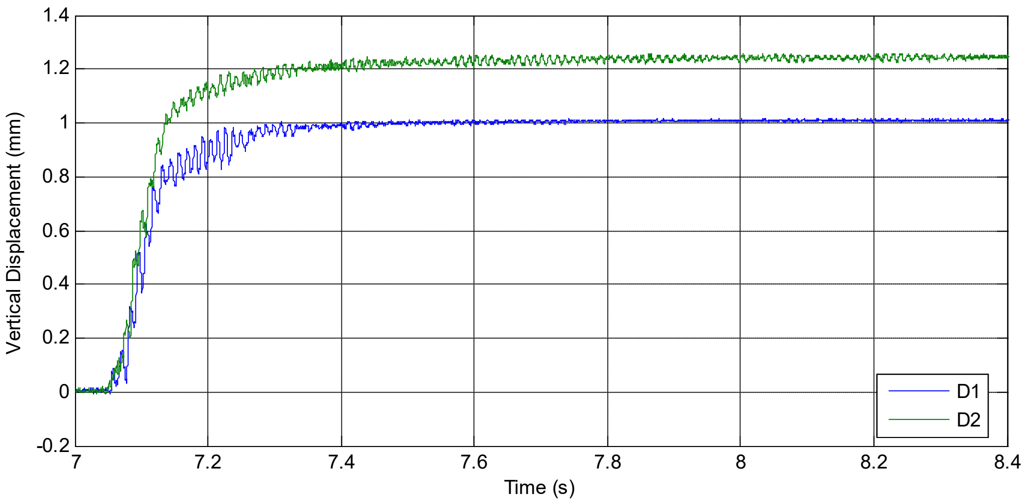
Input motion



Excess pore pressure $\Delta u(t) = u(t) - u_0$ vs. time



Vertical displacements vs. time



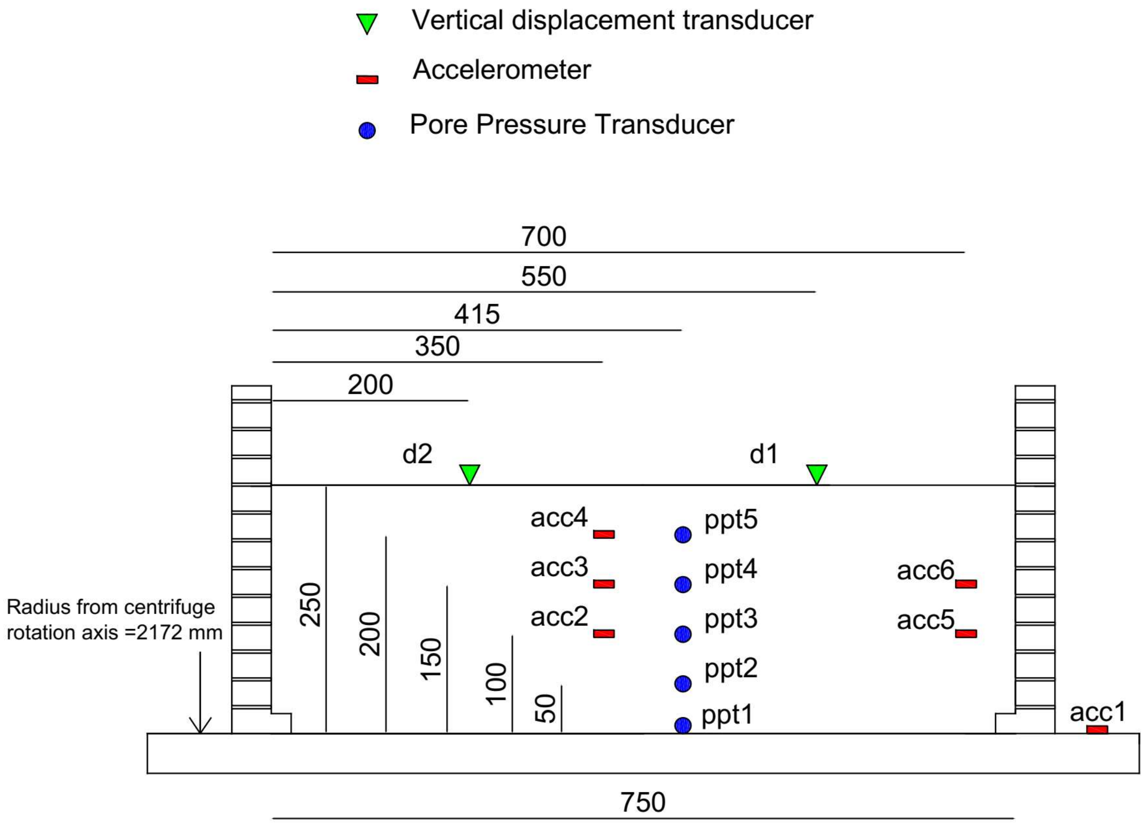
Test 2: M1_S1_GM34

Model description

The model consists of a homogenous soil profile of Ticino sand, the ground motion applied was the number 34.

1 – Reconstruction

Scheme and geometrical dimensions of the model as reconstructed at 1g. The following dimensions refer to model scale.



Ticino sand

Dry density [kN·s^2/m^4]	**1.482**
Relative density [%]	**33.95**
Void ratio [-]	**0.81**

2 – Equilibrium at centrifuge angular velocity ω= 15.08 rad/s before the shock

Ticino sand, average values

Dry soil density [kN·s²/m⁴]	**1.529**
Saturated soil density [kN·s²/m⁴]	**1.954**
Relative density [%]	**49.83**
Void ratio [-]	**0.75**
Degree of saturation [%]	**99.0**

Radii from centrifuge rotation axis

	Radius (mm)
model base	2172.0
free ground surface	1929.6

Pore Pressure Transducer	Radius (mm)	Value before the shock u_0 (kPa)
ppt5	1978.0	22.0
ppt4	2026.5	32.4
ppt3	2075.0	55.7
ppt2	2123.5	75.0
ppt1	2172.0	93.3

Accelerometer	Radius (mm)
acc6	2026.5
acc5	2075.0
acc4	1978.0
acc3	2026.5
acc2	2075.0
acc1	2172.0

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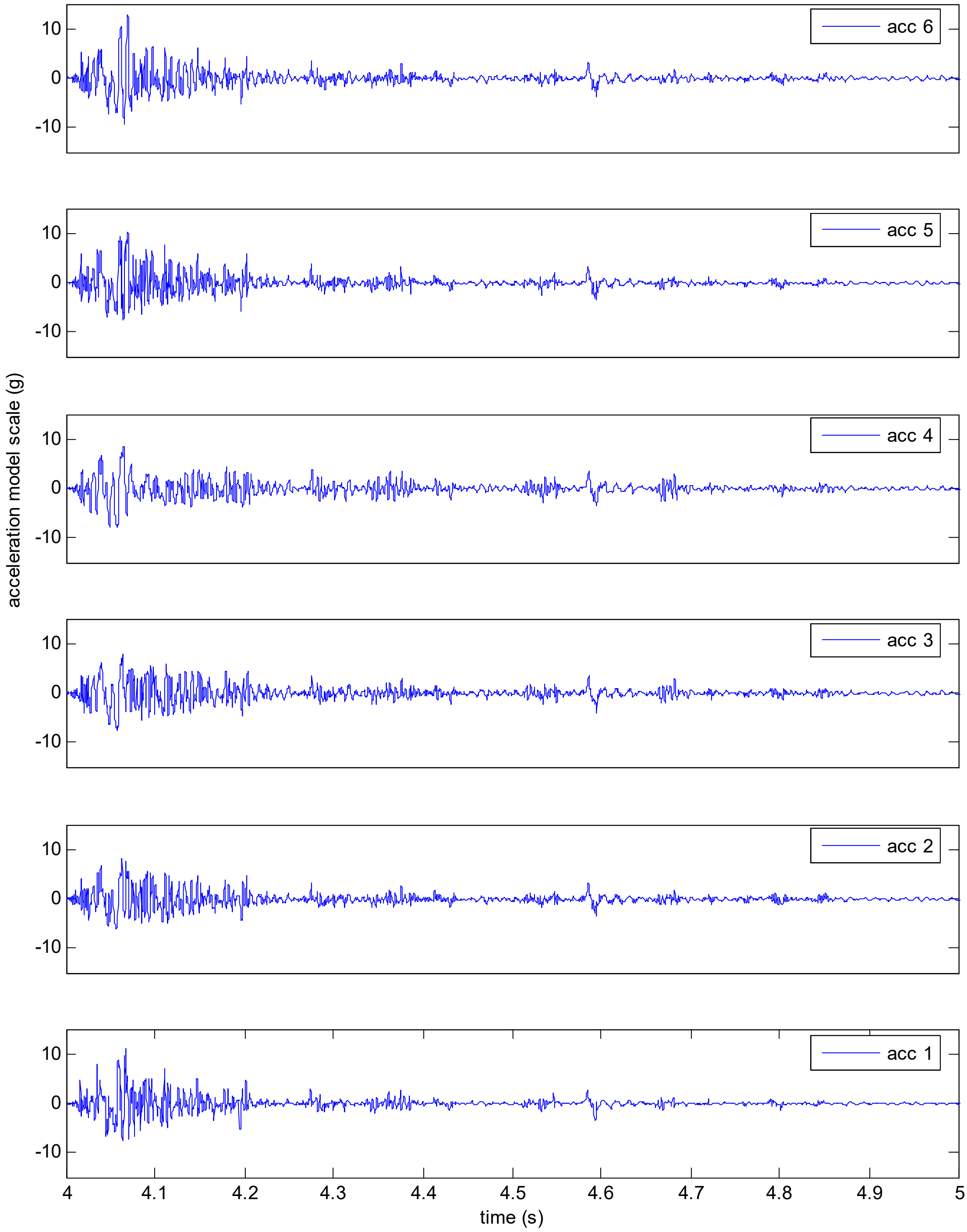
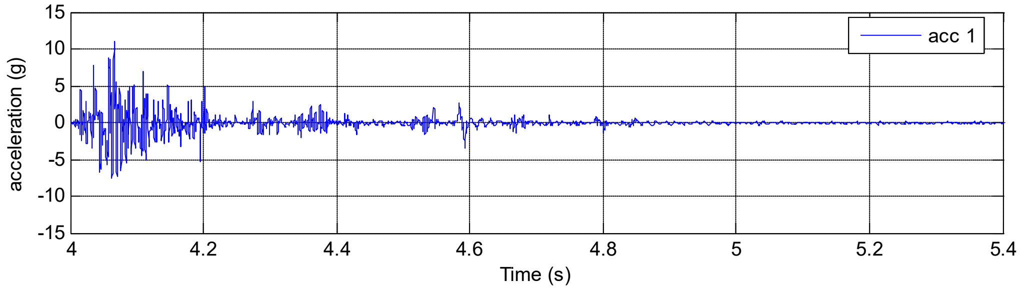
3 – Seismic Excitation

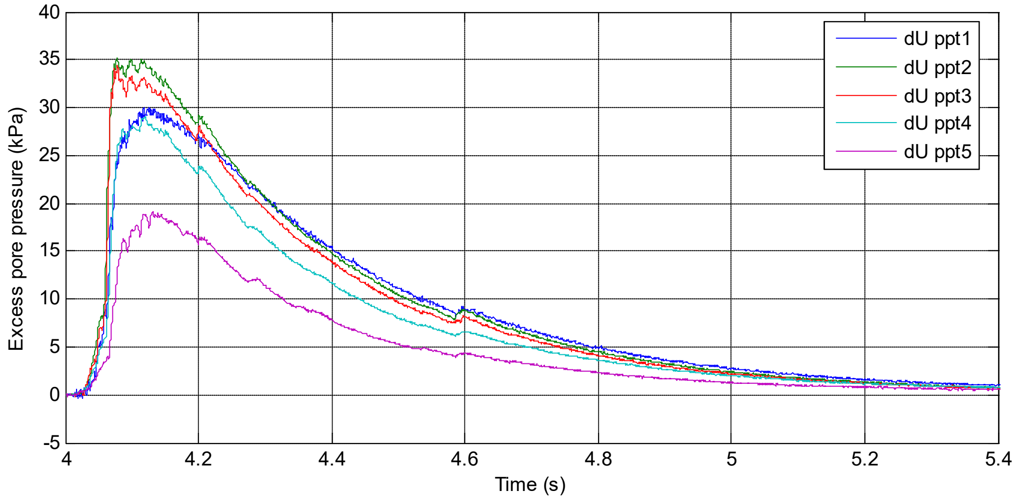
Accelerometers time histories



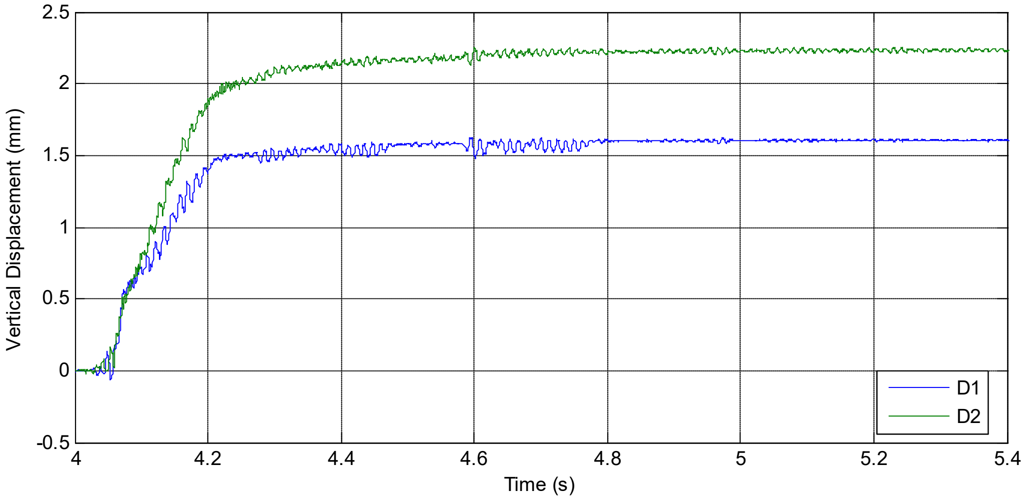
Input motion



Excess pore pressure $\Delta u(t) = u(t) - u_0$ vs. time



Vertical displacements vs. time



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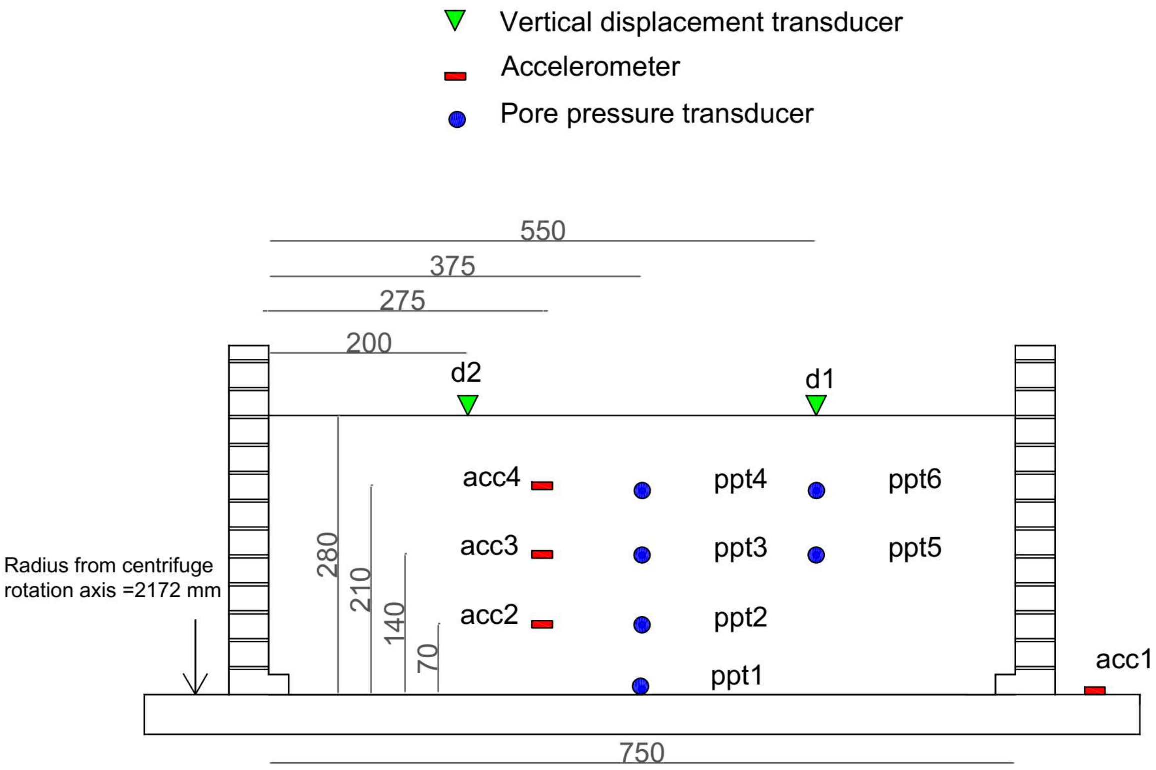
Test 3: M1_S1_GM31

Model description

The model consists of a homogenous soil profile of Ticino sand, the ground motion applied was the number 31.

1 – Reconstruction

Scheme and geometrical dimensions of the model as reconstructed at 1g. The following dimensions refer to model scale.



Ticino sand

Dry density [kN·s^2/m^4]	**1.489**
Relative density [%]	**36.51**
Void ratio [-]	**0.80**

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2 – Equilibrium at centrifuge angular velocity ω= 15.08 rad/s before the shock

Ticino sand, average values

Dry density [kN·s^2/m^4]	**1.522**
Saturated density [kN·s^2/m^4]	**1.950**
Relative density [%]	**47.54**
Void ratio [-]	**0.76**
Degree of saturation [%]	**99.1**

Radii from centrifuge rotation axis

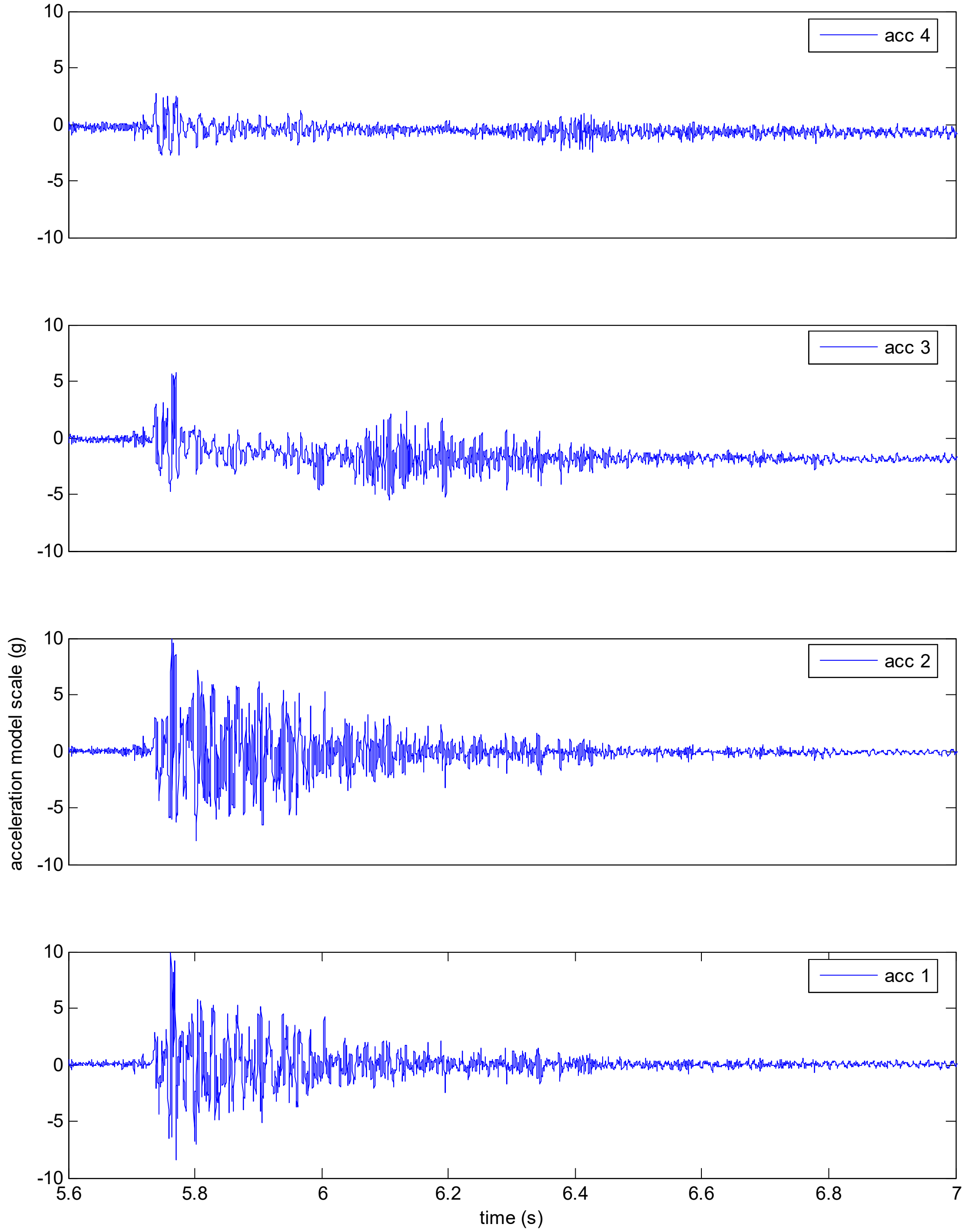
	Radius (mm)
model base	2172.0
free ground surface	1897.9

Pore Pressure Transducer	**Radius (mm)**	**Value before the shock u_0 (kPa)**
ppt6	1966.4	20.8
ppt5	2035.0	63.2
ppt4	1966.4	20.1
ppt3	2035.0	45.9
ppt2	2102.5	79.6
ppt1	2172.0	100.5

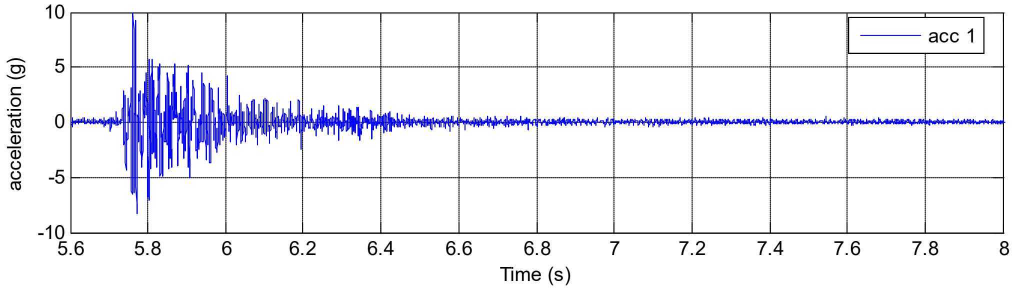
Accelerometer	**Radius (mm)**
acc4	1966.4
acc3	2035.0
acc2	2102.5
acc1	2172.0

3 – Seismic Excitation

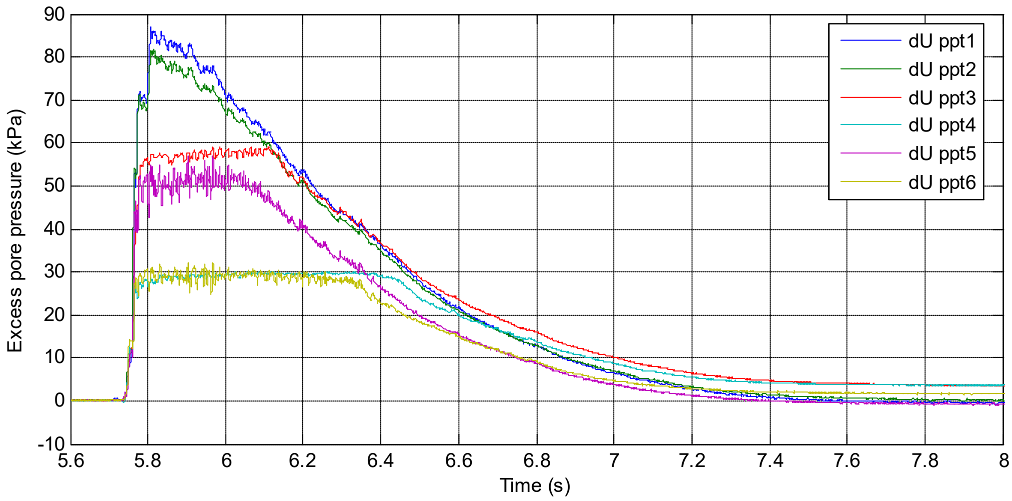
Accelerometers time histories



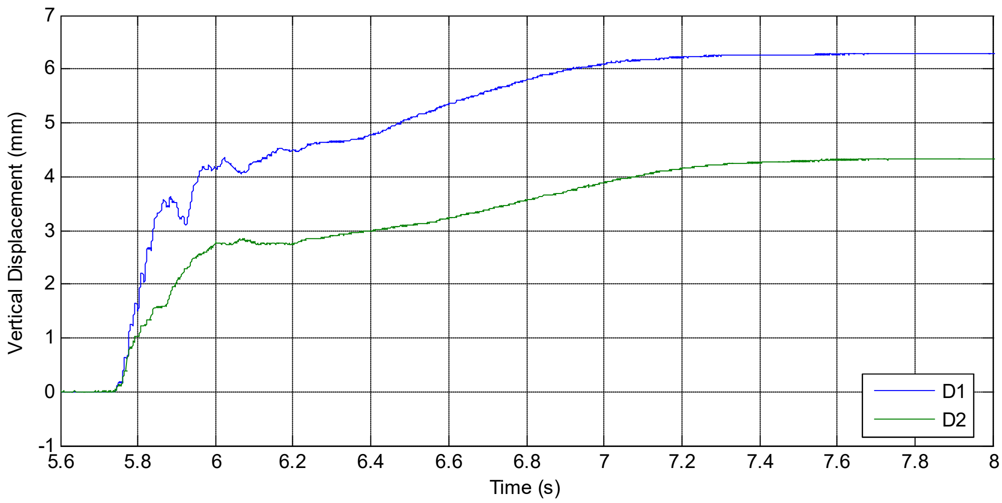
Input motion



Excess pore pressure $\Delta u(t) = u(t) - u_0$ vs. time



Vertical displacements vs. time



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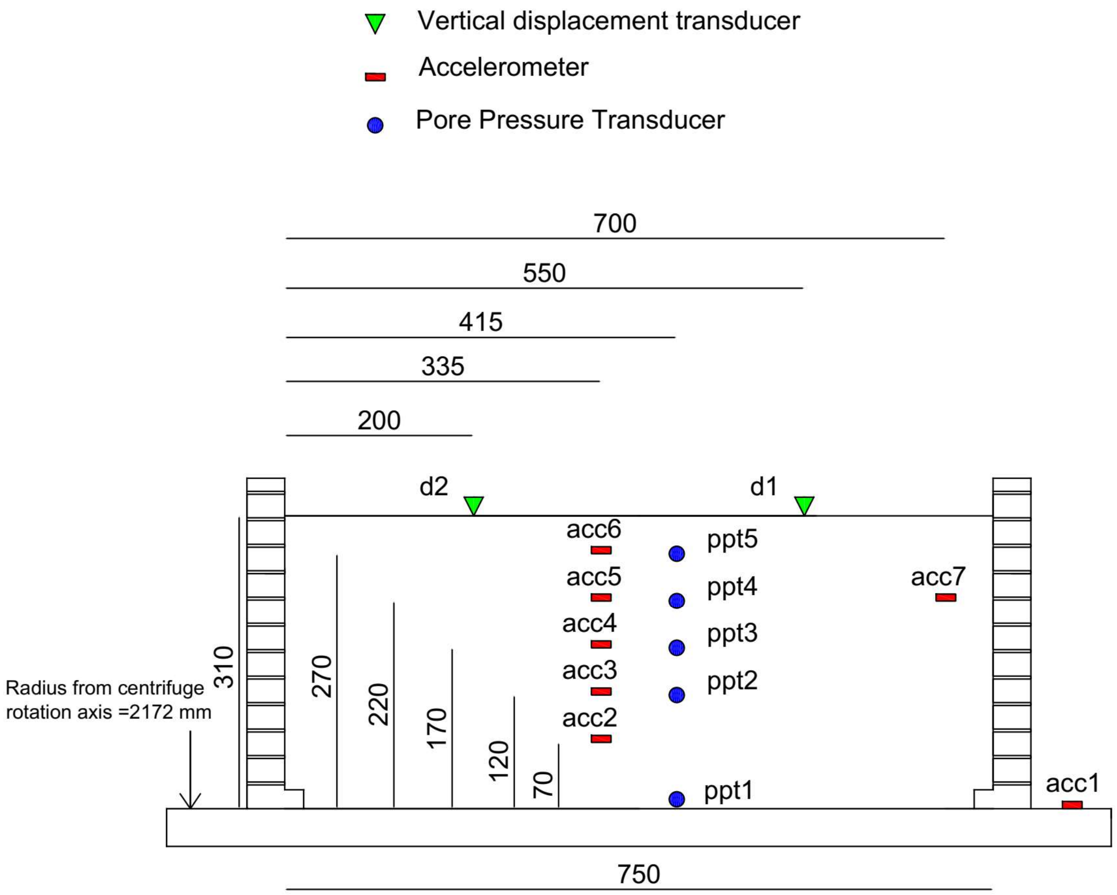
Test 4: M1_S2_GM17

Model description

The model consists of a homogenous soil profile of Pieve di Cento clean sand, the ground motion applied was the number 17.

1 – Reconstruction

Scheme and geometrical dimensions of the model as reconstructed at 1g. The following dimensions refer to model scale.



Ticino sand

Dry density [kN·s^2/m^4]	**1.395**
Relative density [%]	**40.96**
Void ratio [-]	**0.93**

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2 – Equilibrium at centrifuge angular velocity ω= 15.08 rad/s before the shock

Ticino sand, average values

Dry density [$kN{\cdot}s^2/m^4$]	**1.473**
Saturated density [$kN{\cdot}s^2/m^4$]	**1.920**
Relative density [%]	**64.83**
Void ratio [-]	**0.83**
Degree of saturation [%]	**99.1**

Radii from centrifuge rotation axis

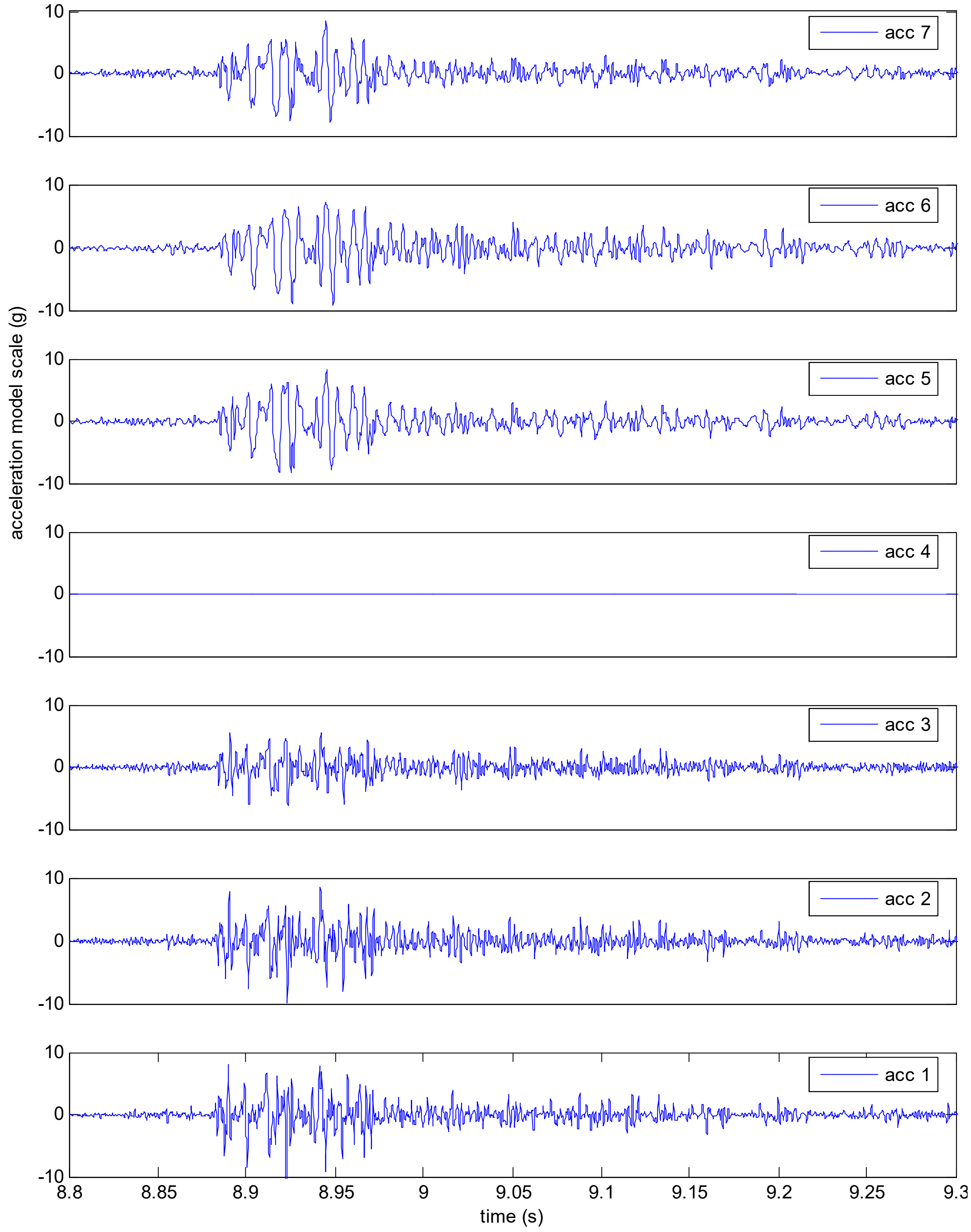
	Radius (mm)
model base	2172.0
free ground surface	1878.1

Pore Pressure Transducer	**Radius (mm)**	**Value before the shock u_0 (kPa)**
ppt5	1916.1	16.6
ppt4	1963.5	35.5
ppt3	2010.9	50.8
ppt2	2058.2	70.0
ppt1	2172.0	116.4

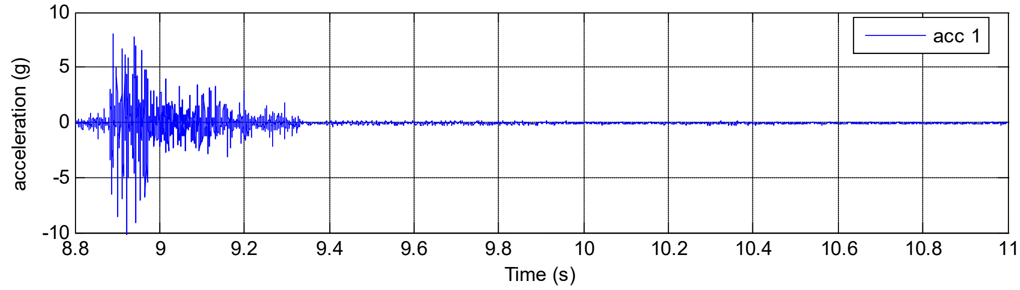
Accelerometer	**Radius (mm)**
acc7	1963.5
acc6	1916.1
acc5	1963.5
acc4	2010.9
acc3	2058.2
acc2	2108.0
acc1	2172.0

3 – Seismic Excitation

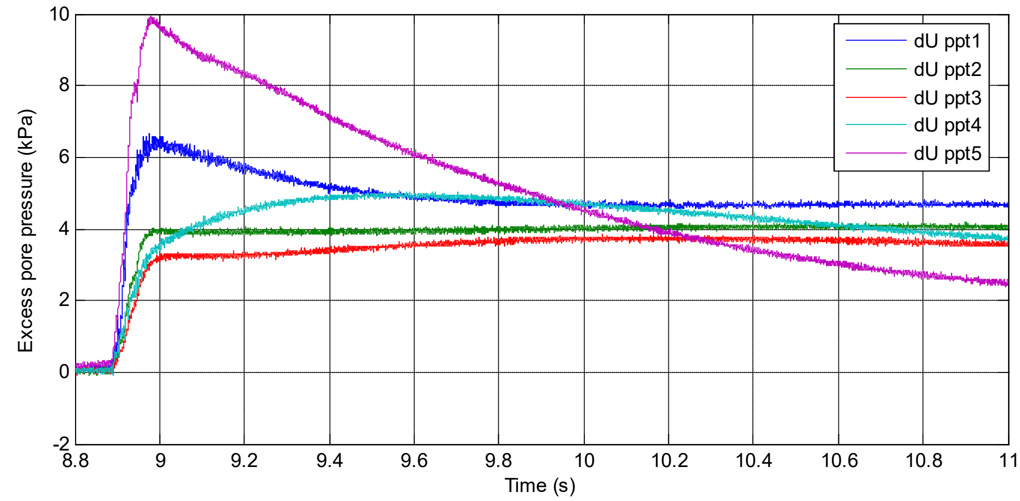
Accelerometers time histories



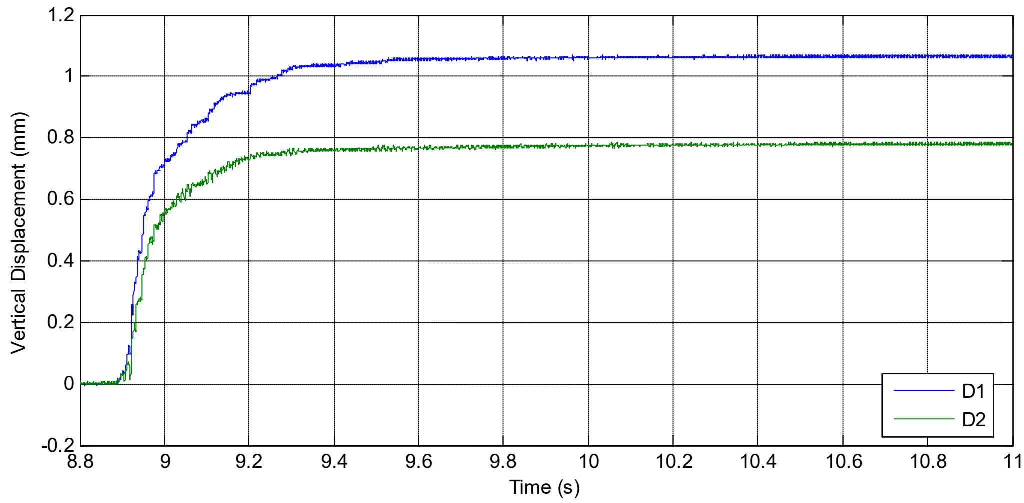
Input motion



Excess pore pressure $\Delta u(t) = u(t) - u_0$ vs. time



Vertical displacements vs. time



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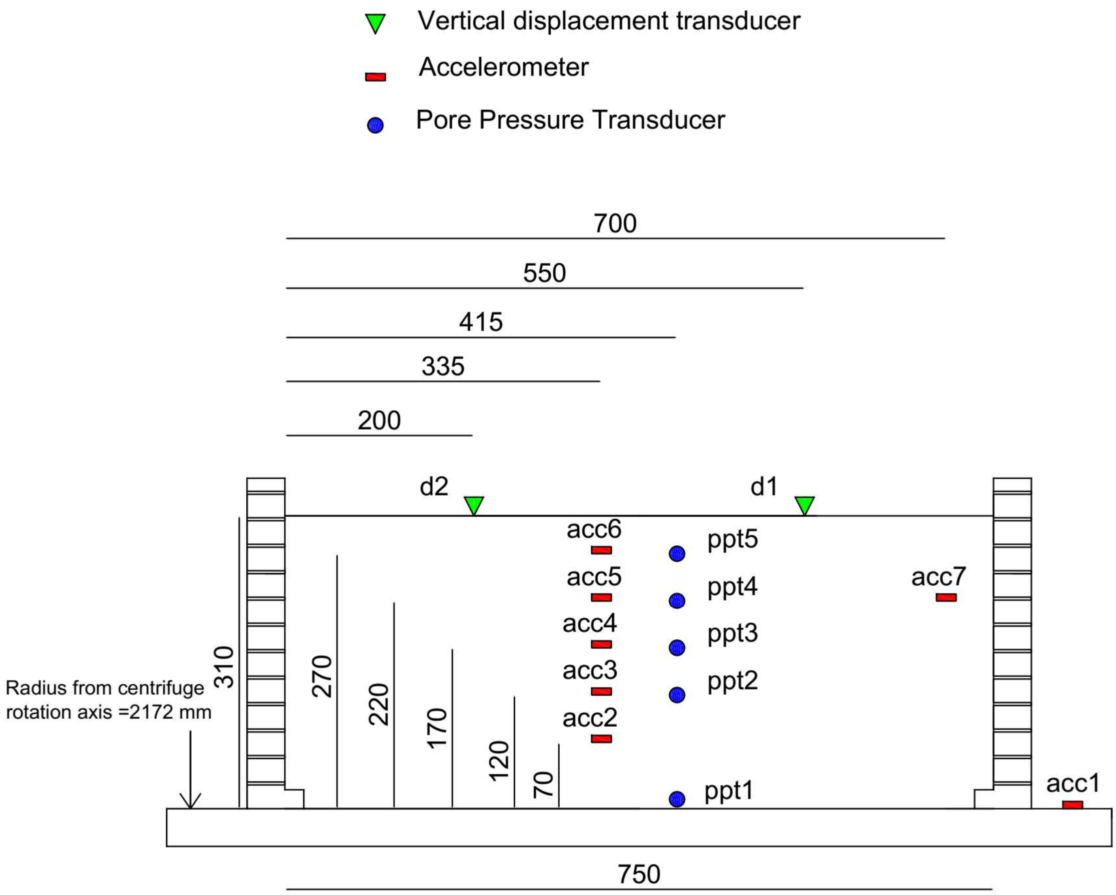
Test 5: M1_S2_GM23

Model description

The model consists of a homogenous soil profile of Pieve di Cento clean sand, the ground motion applied was the number 23.

1 – Reconstruction

Scheme and geometrical dimensions of the model as reconstructed at 1g. The following dimensions refer to model scale.



Ticino sand

Dry density [kN·s^2/m^4]	**1.395**
Relative density [%]	**40.96**
Void ratio [-]	**0.93**

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2 – Equilibrium at centrifuge angular velocity ω= 15.08 rad/s before the shock

Ticino sand, average values

Dry density [kN·s²/m⁴]	**1.478**
Saturated density [kN·s²/m⁴]	**1.924**
Relative density [%]	**66.26**
Void ratio [-]	**0.82**
Degree of saturation [%]	**99.1**

Radii from centrifuge rotation axis

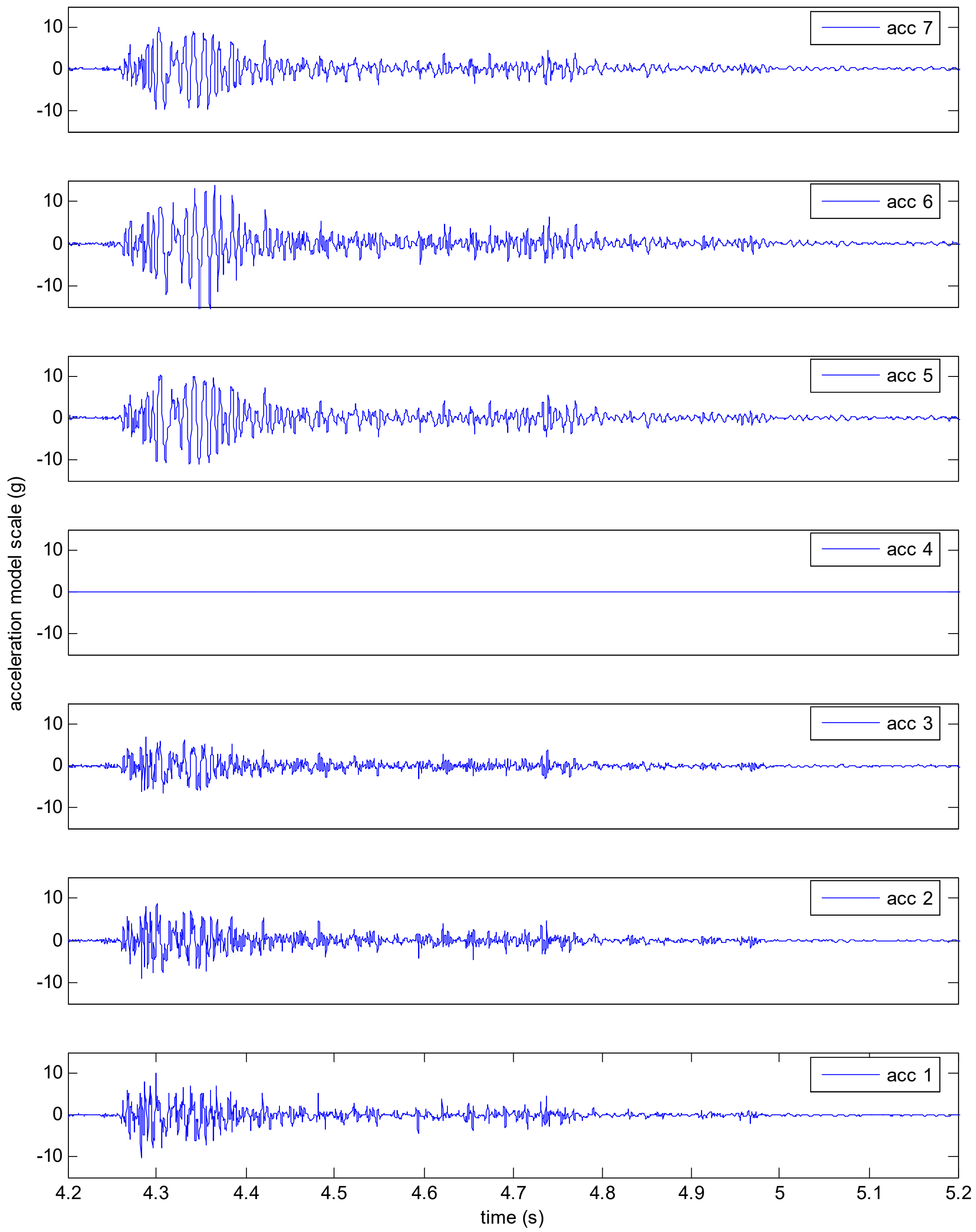
	Radius (mm)
model base	2172.0
free ground surface	1879.1

Pore Pressure Transducer	Radius (mm)	Value before the shock u_0 (kPa)
ppt5	1916.9	16.9
ppt4	1964.1	35.8
ppt3	2011.4	50.8
ppt2	2058.6	70.1
ppt1	2172.0	116.4

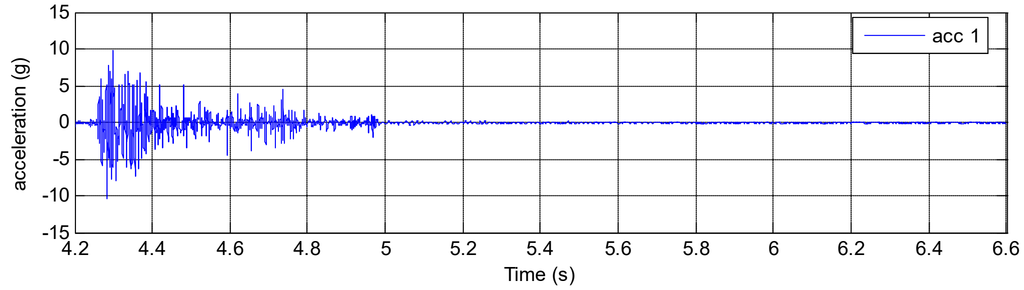
Accelerometer	Radius (mm)
acc7	1964.1
acc6	1916.9
acc5	1964.1
acc4	2011.4
acc3	2058.6
acc2	2109.0
acc1	2172.0

3 – Seismic Excitation

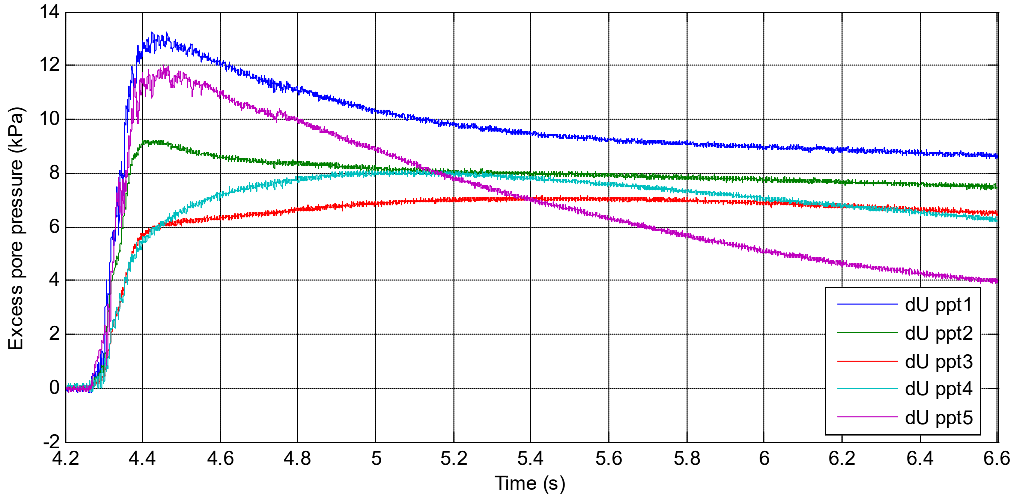
Accelerometers time histories



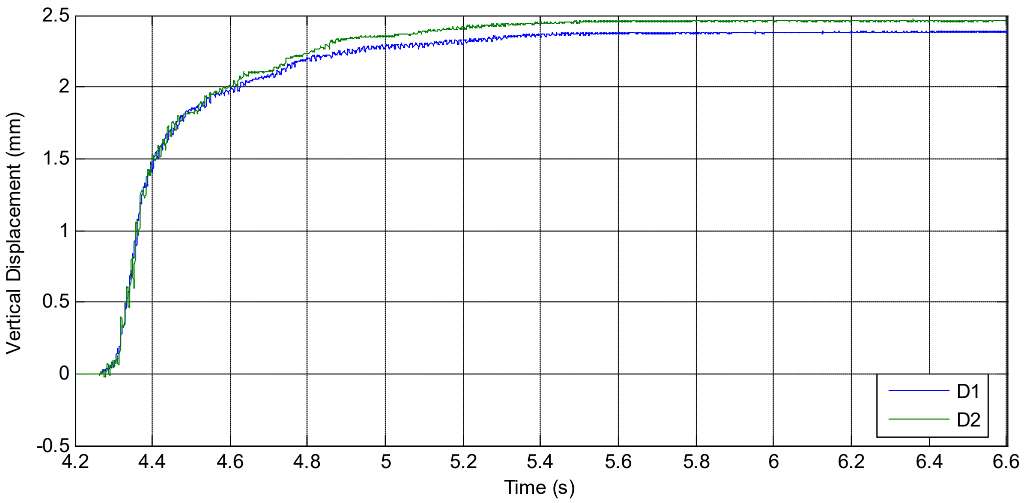
Input motion



Excess pore pressure $\Delta u(t) = u(t) - u_0$ vs. time



Vertical displacements vs. time



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

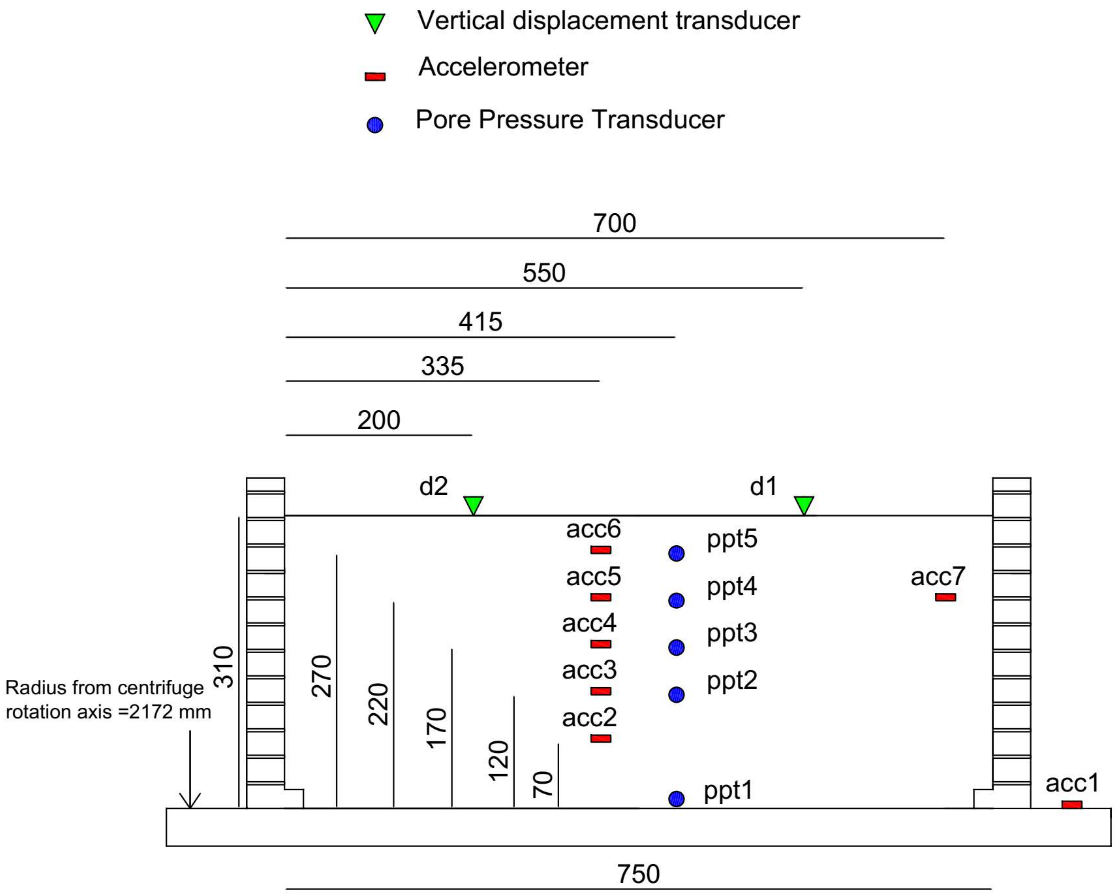
Test 6: M1_S2_GM34

Model description

The model consists of a homogenous soil profile of Pieve di Cento clean sand, the ground motion applied was the number 34.

1 – Reconstruction

Scheme and geometrical dimensions of the model as reconstructed at 1g. The following dimensions refer to model scale.



Ticino sand

Dry density [kN·s²/m⁴]	**1.395**
Relative density [%]	**40.96**
Void ratio [-]	**0.93**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

2 – Equilibrium at centrifuge angular velocity ω= 15.08 rad/s before the shock

Ticino sand, average values

Dry density [kN·s^2/m^4]	**1.491**
Saturated density [kN·s^2/m^4]	**1.932**
Relative density [%]	**69.94**
Void ratio [-]	**0.80**
Degree of saturation [%]	**99.1**

Radii from centrifuge rotation axis

	Radius (mm)
model base	2172.0
free ground surface	1881.6

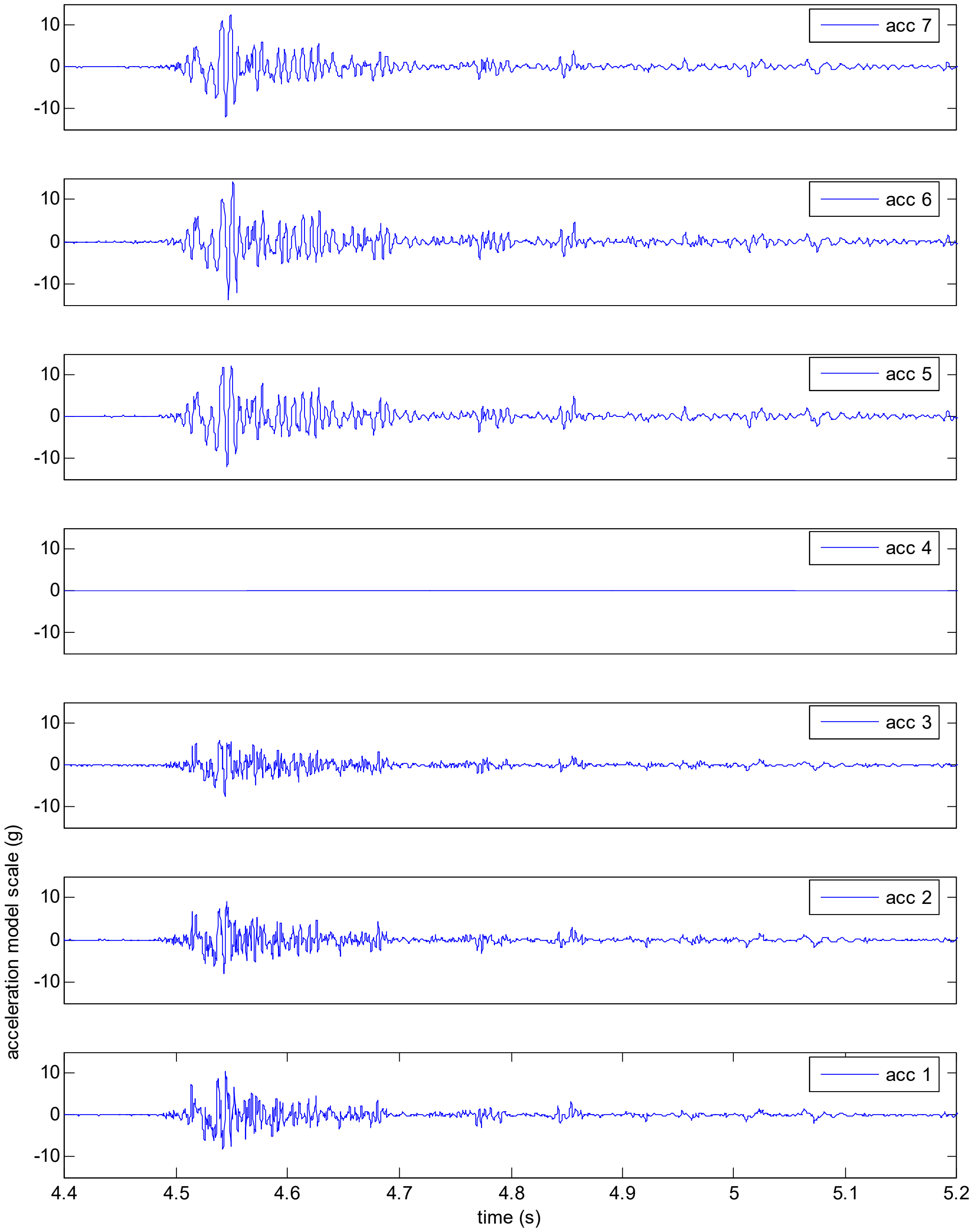
Pore Pressure Transducer	**Radius (mm)**	**Value before the shock u_0 (kPa)**
ppt5	1919.1	13.3
ppt4	1965.9	36.1
ppt3	2012.7	50.7
ppt2	2059.6	70.2
ppt1	2172.0	115.9

Accelerometer	**Radius (mm)**
acc7	1965.9
acc6	1919.1
acc5	1965.9
acc4	2012.7
acc3	2059.6
acc2	2110.0
acc1	2172.0

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

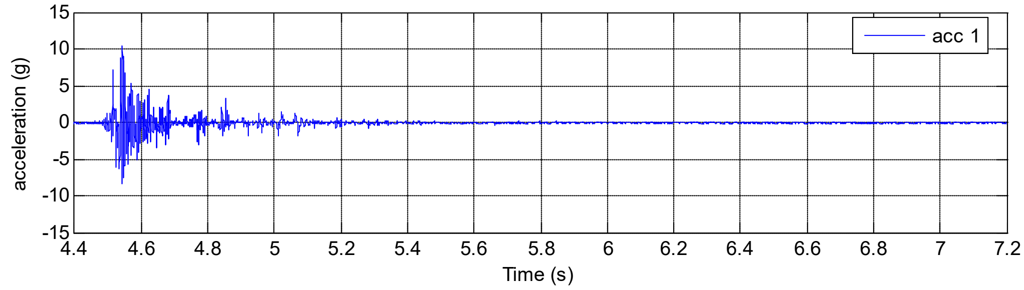
3 – Seismic Excitation

Accelerometers time histories

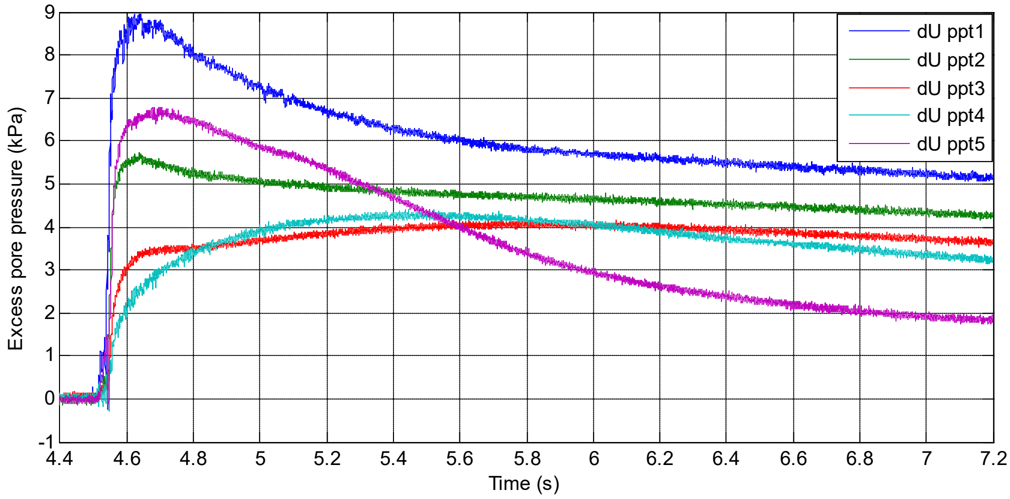


This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

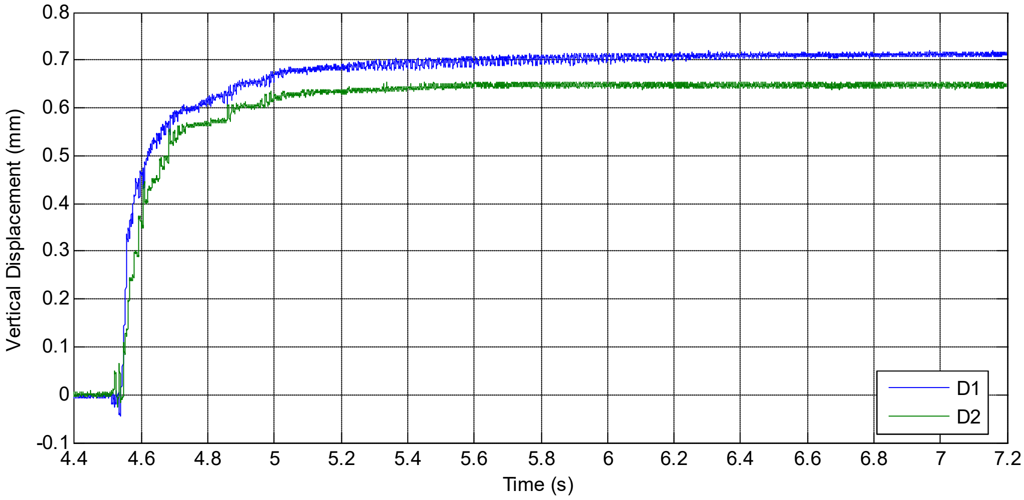
Input motion



Excess pore pressure $\Delta u(t) = u(t) - u_0$ vs. time



Vertical displacements vs. time



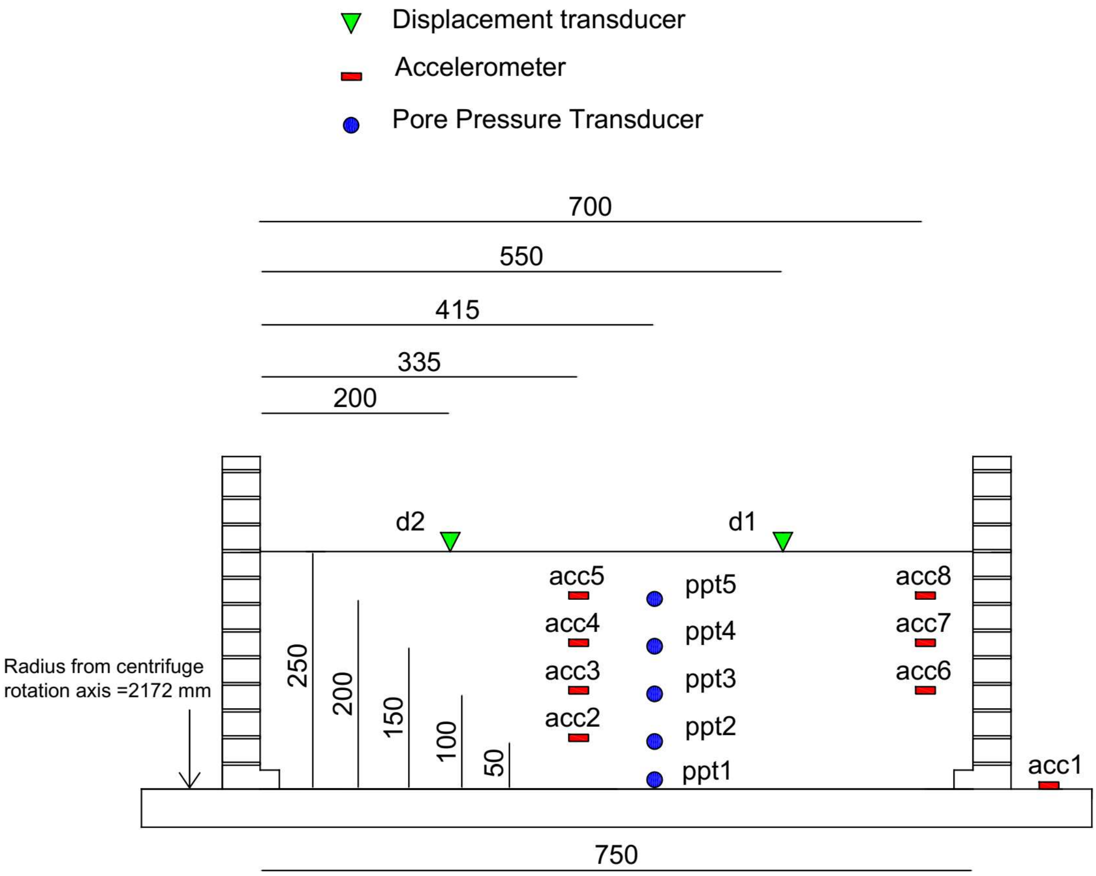
Test 7: M1_S3_GM17

Model description

The model consists of a homogenous soil profile of natural Pieve di Cento sand, with 12% of fine content. The ground motion applied was the number 17.

1 – Reconstruction

Scheme and geometrical dimensions of the model as reconstructed at 1g. The following dimensions refer to model scale.



Ticino sand

Dry density [kN·s^2/m^4]	**1.313**
Relative density [%]	**23.75**
Void ratio [-]	**1.05**

2 – Equilibrium at centrifuge angular velocity ω= 15.08 rad/s before the shock

Ticino sand, average values

Dry density [kN·s^2/m^4]	**1.425**
Saturated density [kN·s^2/m^4]	**1.877**
Relative density [%]	**56.46**
Void ratio [-]	**0.89**
Degree of saturation [%]	**96.3**

Radii from centrifuge rotation axis

	Radius (mm)
model base	2172.0
free ground surface	1941.3

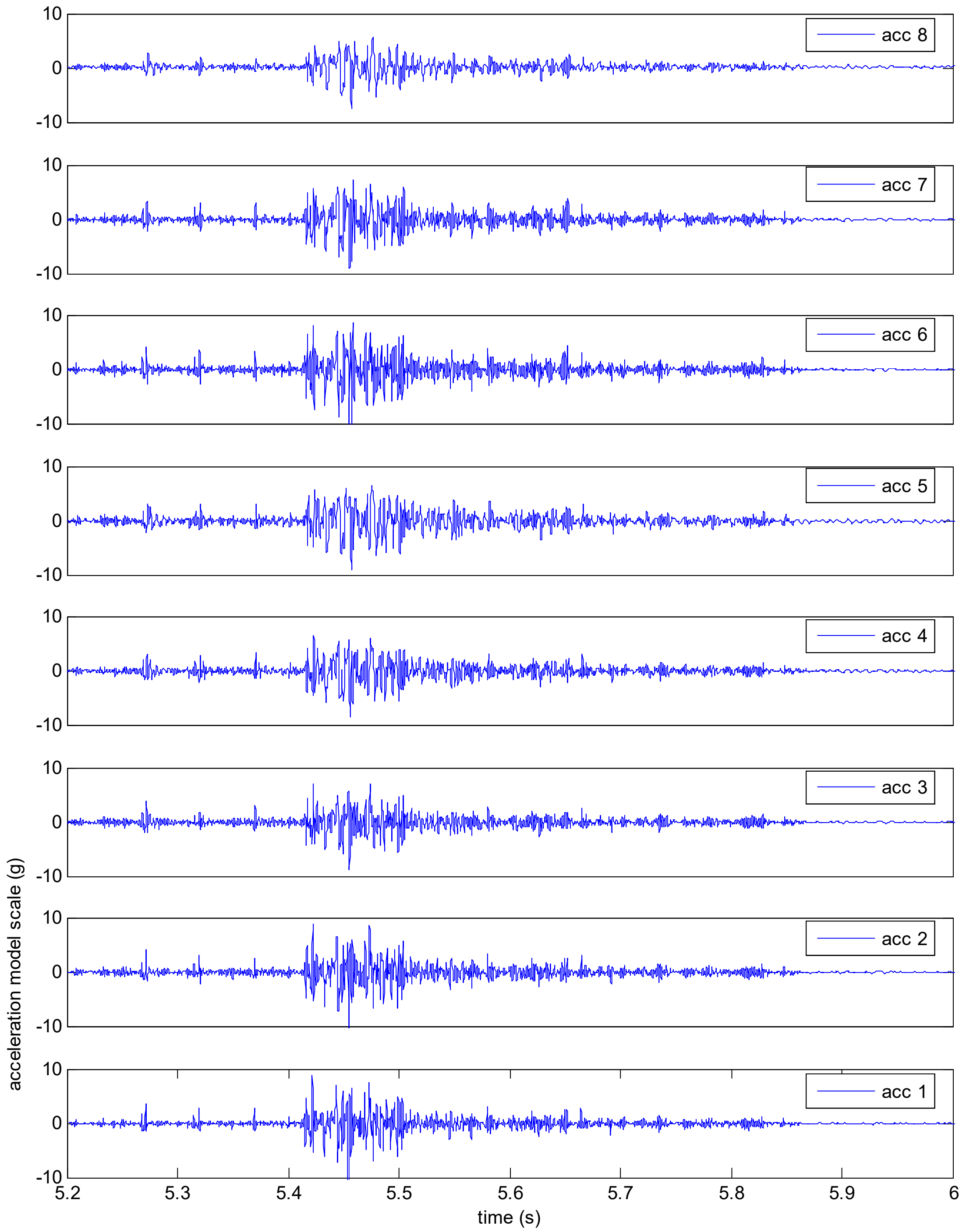
Pore Pressure Transducer	**Radius (mm)**	**Value before the shock u_0 (kPa)**
ppt5	1987.5	28.7
ppt4	2033.6	40.5
ppt3	2079.7	65.0
ppt2	2125.9	93.7
ppt1	2172.0	91.1

Accelerometer	**Radius (mm)**
acc8	1987.5
acc7	2033.6
acc6	2079.7
acc5	1987.5
acc4	2033.6
acc3	2079.7
acc2	2125.9
acc1	2172.0

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

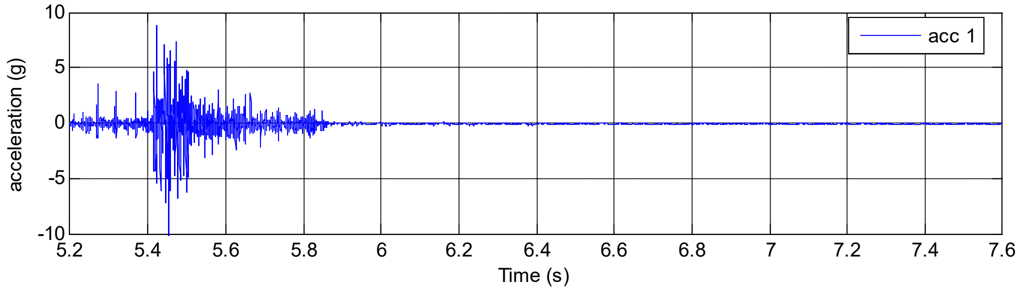
3 – Seismic Excitation

Accelerometers time histories

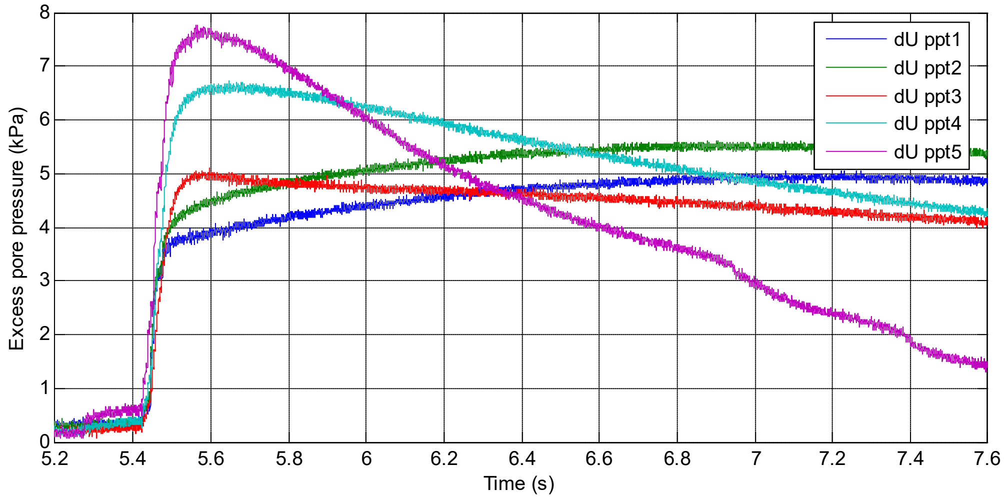


This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

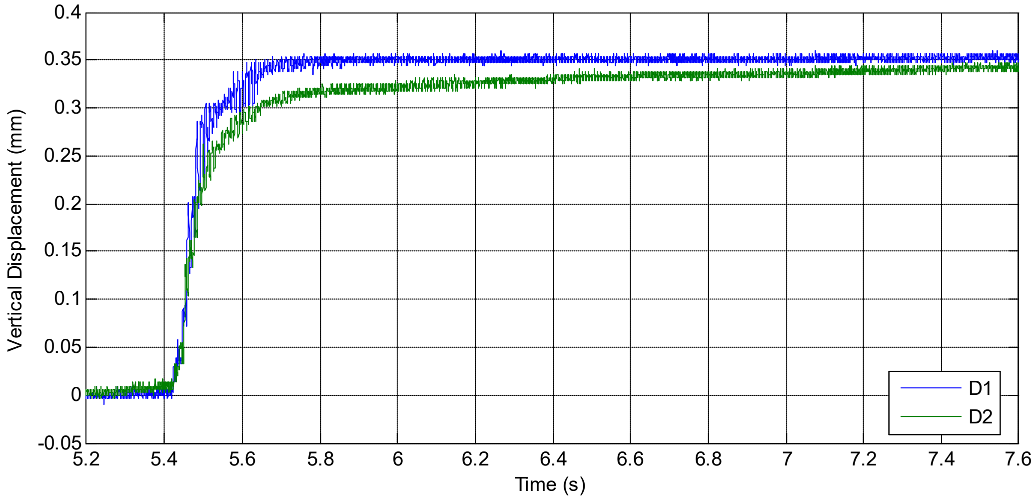
Input motion



Excess pore pressure $\Delta u(t) = u(t) - u_0$ vs. time



Vertical displacements vs. time



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

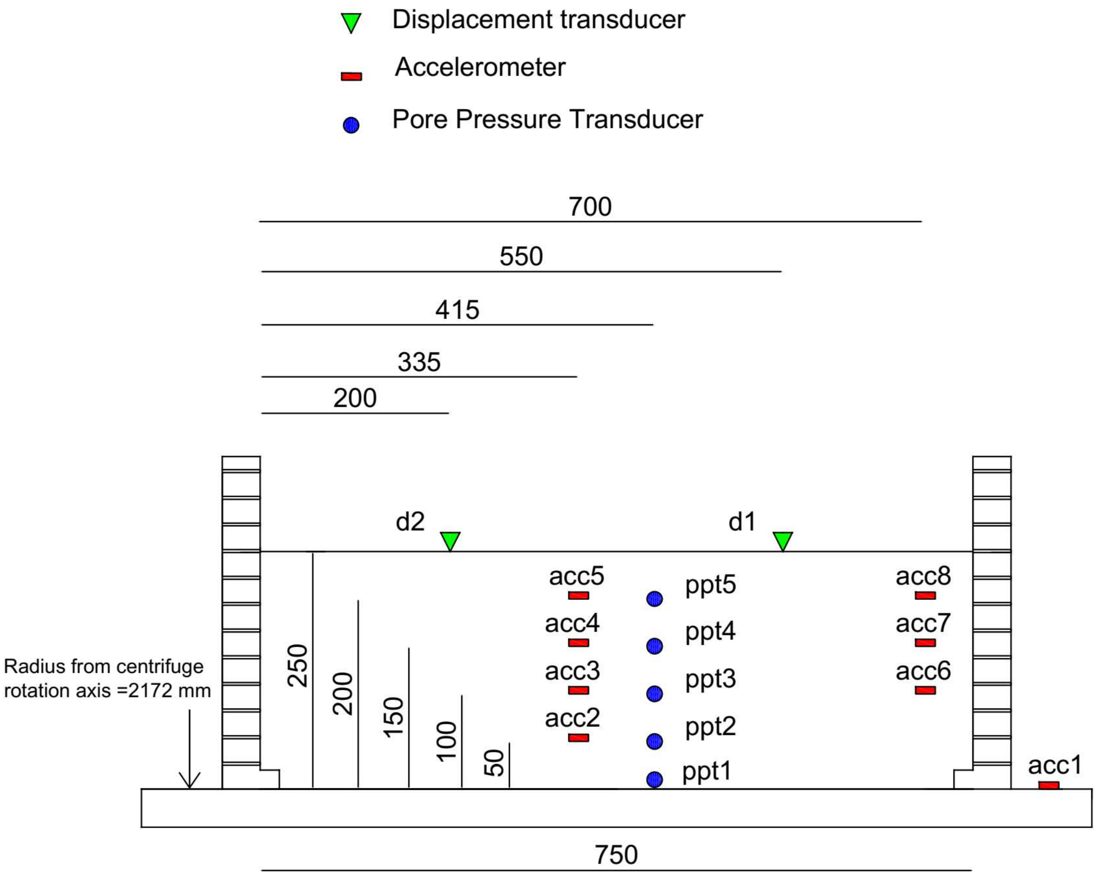
Test 8: M1_S3_GM23

Model description

The model consists of a homogenous soil profile of natural Pieve di Cento sand, with 12% of fine content. The ground motion applied was the number 23.

1 – Reconstruction

Scheme and geometrical dimensions of the model as reconstructed at 1g. The following dimensions refer to model scale.



Ticino sand

Dry density [kN·s²/m⁴]	**1.313**
Relative density [%]	**23.75**
Void ratio [-]	**1.047**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

2 – Equilibrium at centrifuge angular velocity ω= 15.08 rad/s before the shock

Ticino sand, average values

Dry density [kN·s^2/m^4]	**1.428**
Saturated density [kN·s^2/m^4]	**1.878**
Relative density [%]	**57.25**
Void ratio [-]	**0.88**
Degree of saturation [%]	**96.3**

Radii from centrifuge rotation axis

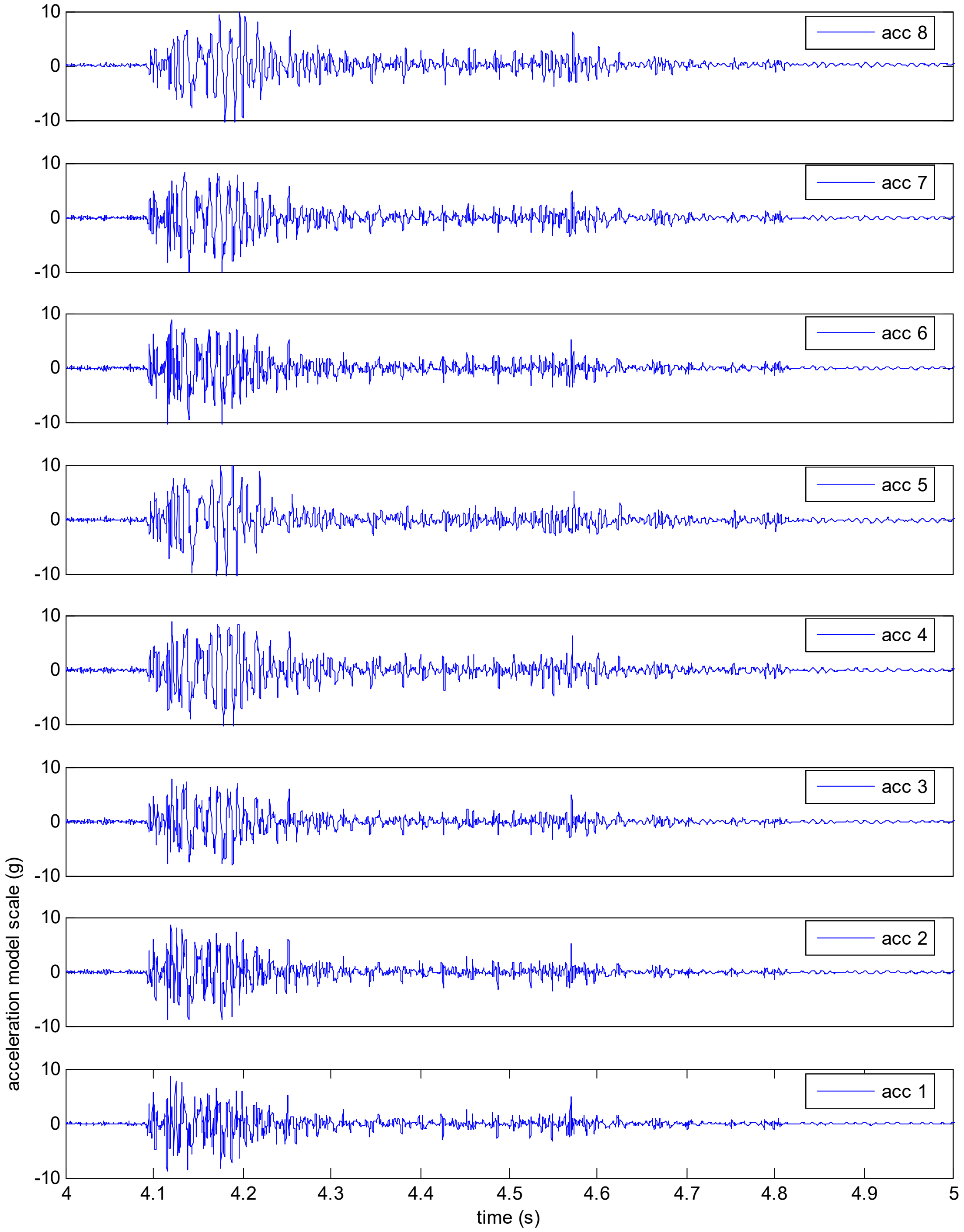
	Radius (mm)
model base	2172.0
free ground surface	1941.8

Pore Pressure Transducer	Radius (mm)	Value before the shock u_0 (kPa)
ppt5	1987.8	29.0
ppt4	2033.9	40.6
ppt3	2079.9	64.8
ppt2	2126.0	93.7
ppt1	2172.0	90.6

Accelerometer	Radius (mm)
acc8	1987.8
acc7	2033.9
acc6	2079.9
acc5	1987.8
acc4	2033.9
acc3	2079.9
acc2	2126.0
acc1	2172.0

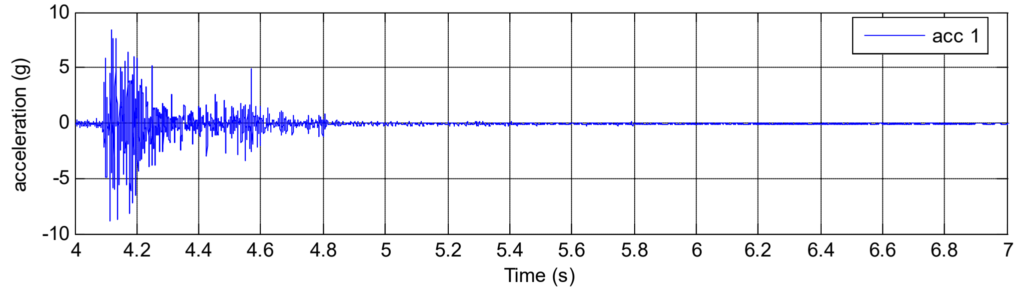
3 – Seismic Excitation

Accelerometers time histories

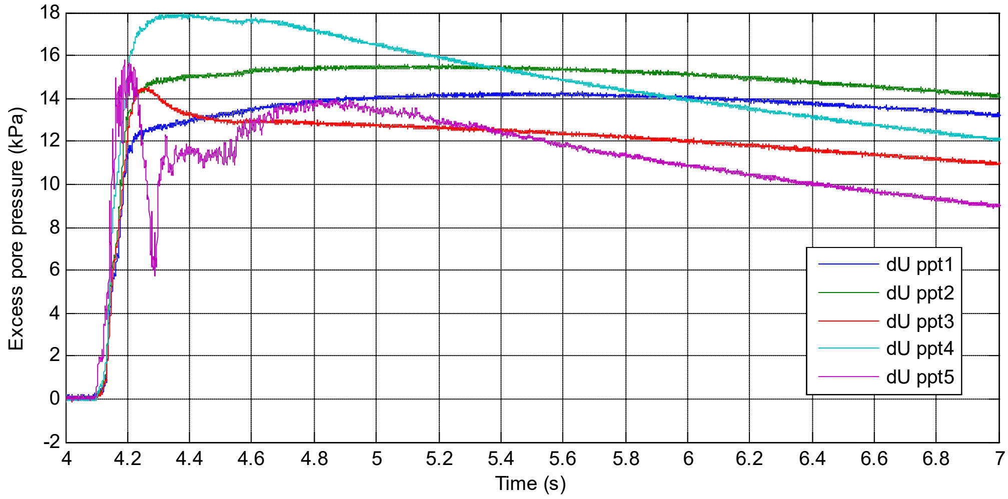


This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

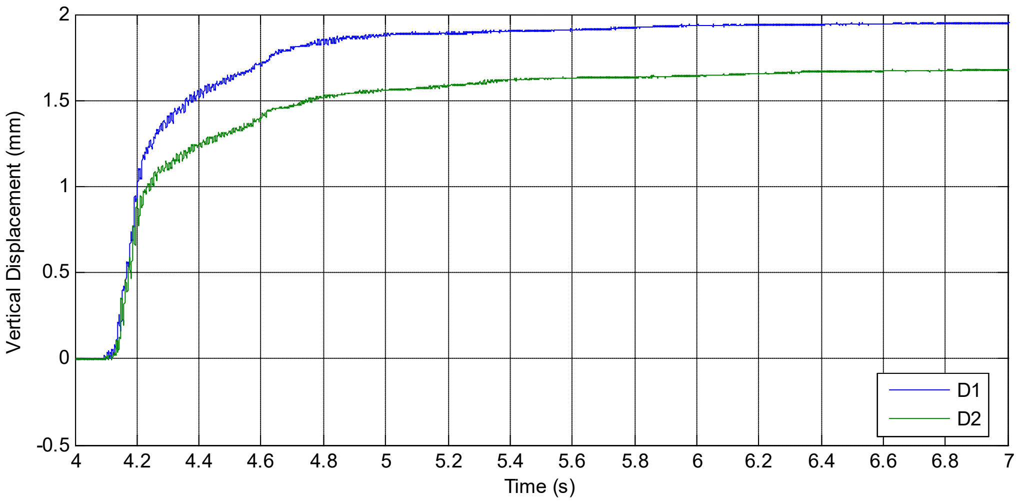
Input motion



Excess pore pressure $\Delta u(t) = u(t) - u_0$ vs. time



Vertical displacements vs. time



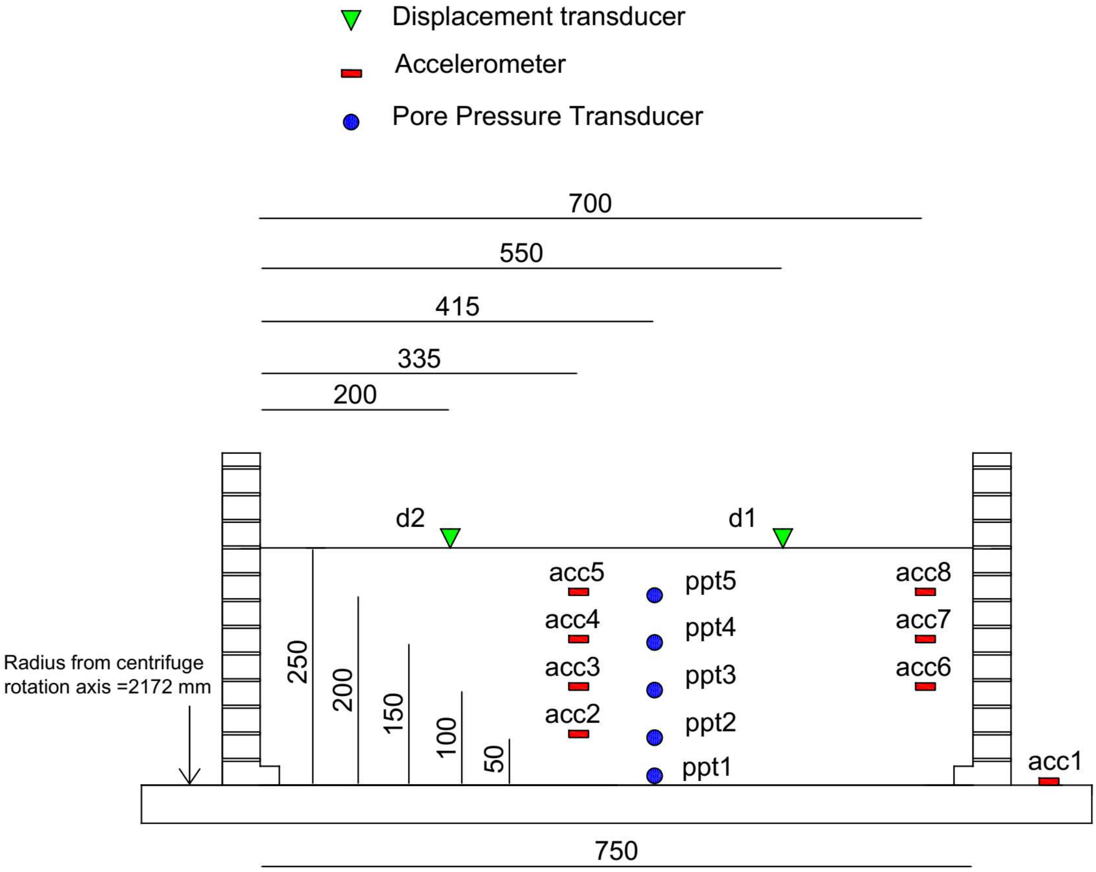
Test 9: M1_S3_GM34

Model description

The model consists of a homogenous soil profile of natural Pieve di Cento sand, with 12% of fine content. The ground motion applied was the number 34.

1 – Reconstruction

Scheme and geometrical dimensions of the model as reconstructed at 1g. The following dimensions refer to model scale.



Ticino sand

Dry density [kN·s²/m⁴]	**1.313**
Relative density [%]	**23.75**
Void ratio [-]	**1.05**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

2 – Equilibrium at centrifuge angular velocity ω= 15.08 rad/s before the shock

Ticino sand, average values

Dry soil density [kN·s^2/m^4]	**1.441**
Saturated soil density [kN·s^2/m^4]	**1.886**
Relative density [%]	**60.69**
Initial void ratio [-]	**0.87**
Degree of saturation [%]	**96.3**

Radii from centrifuge rotation axis

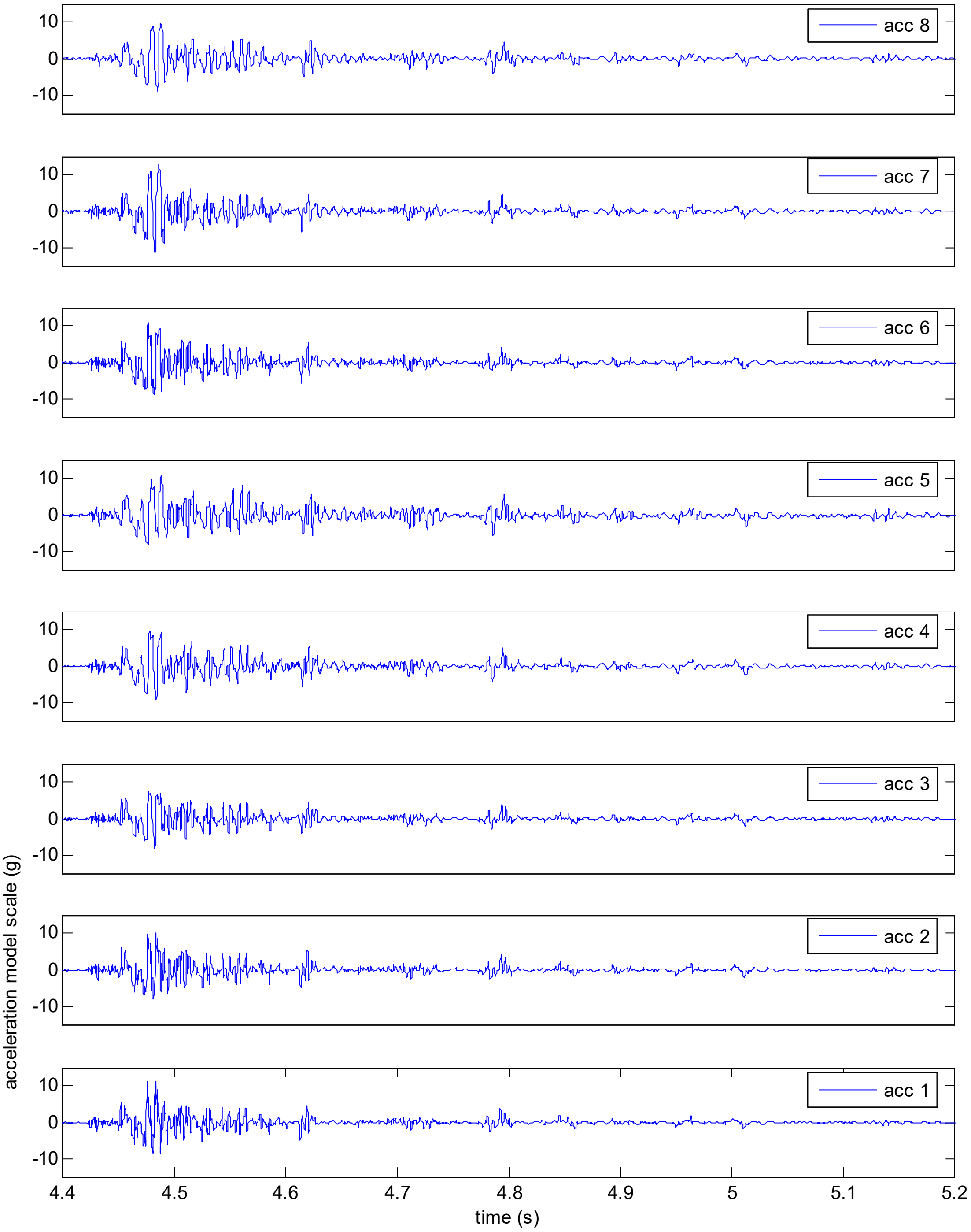
	Radius (mm)
model base	2172.0
free ground surface	1943.8

Pore Pressure Transducer	**Radius (mm)**	**Value before the shock u_0 (kPa)**
ppt5	1989.5	29.7
ppt4	2035.1	40.8
ppt3	2080.7	64.8
ppt2	2126.4	93.8
ppt1	2172.0	90.7

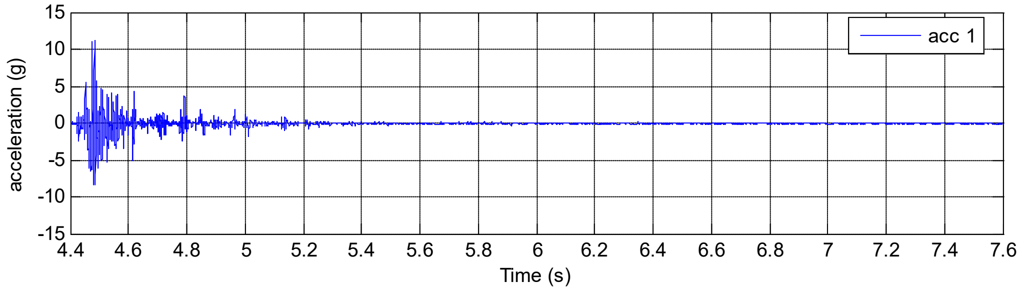
Accelerometer	**Radius (mm)**
acc8	1989.5
acc7	2035.1
acc6	2080.7
acc5	1989.5
acc4	2035.1
acc3	2080.7
acc2	2126.4
acc1	2172.0

3 – Seismic Excitation

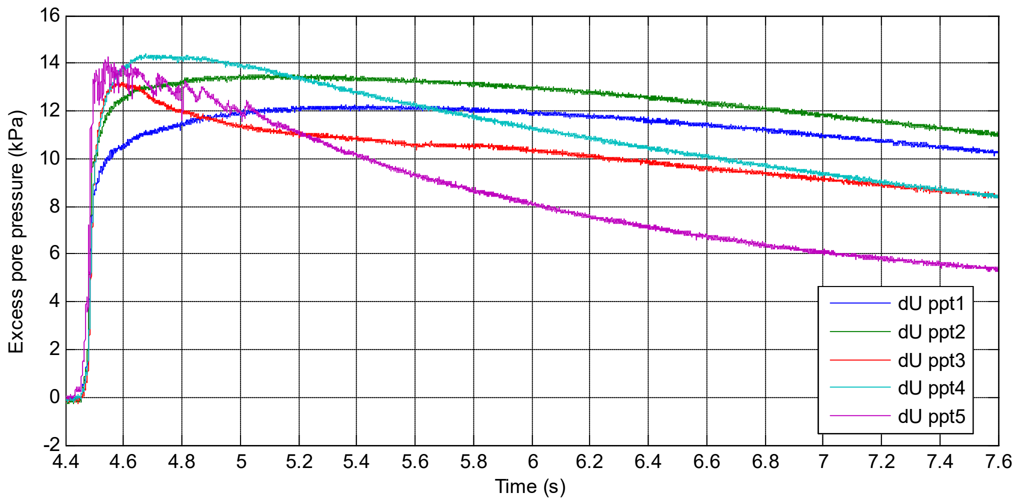
Accelerometers time histories



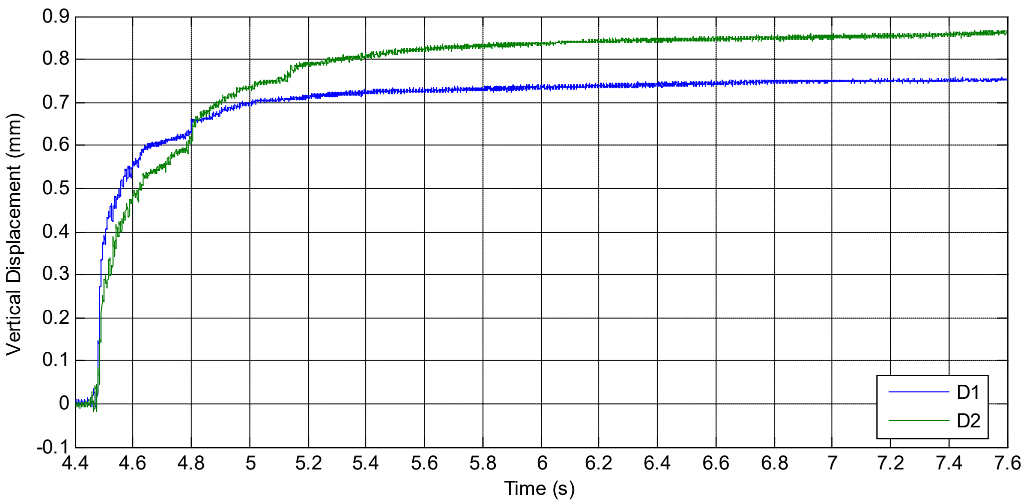
Input motion



Excess pore pressure $\Delta u(t) = u(t) - u_0$ vs. time



Vertical displacements vs. time



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

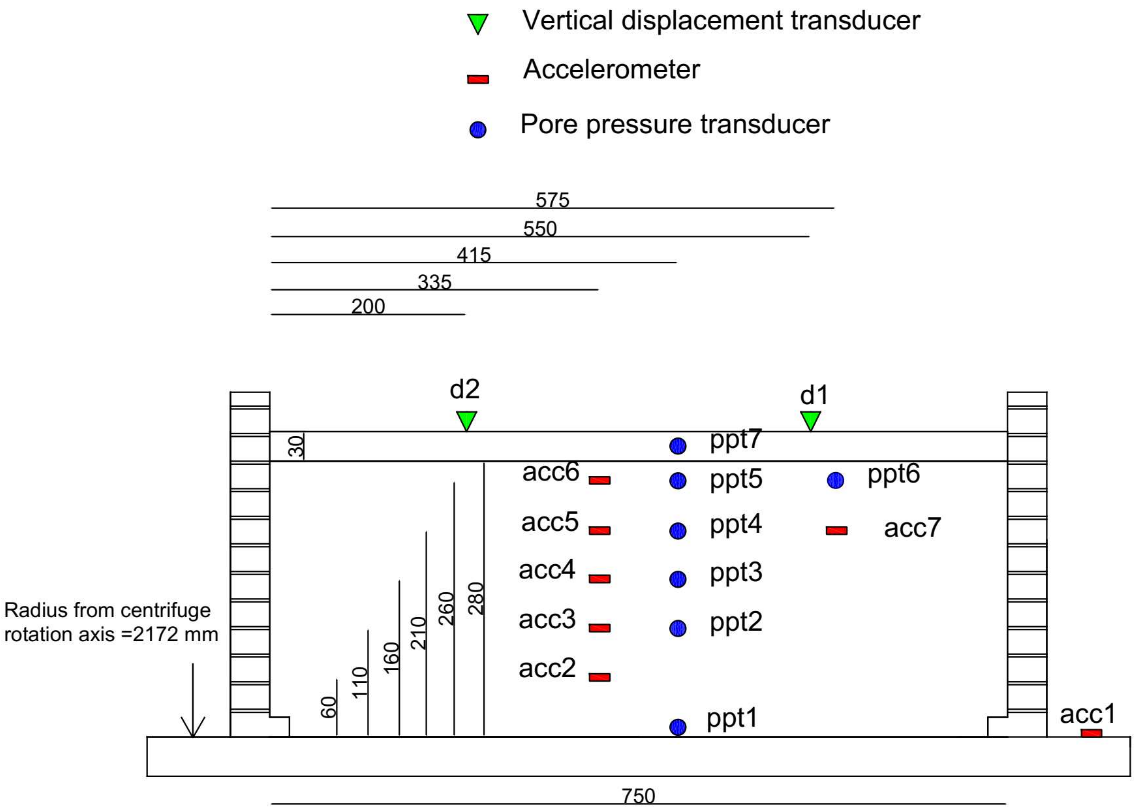
Test 10: M2_S1_GM34

Model description

The model consists of a two layers soil profile of Ticino sand and Pontida clay, the ground motion applied was the number 34.

1 – Reconstruction

Scheme and geometrical dimensions of the model as reconstructed at 1g. The following dimensions refer to model scale.



Ticino sand

Dry density [kN·s^2/m^4]	**1.514**
Relative density [%]	**44.93**
Void ratio [-]	**0.77**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

2 – Equilibrium at centrifuge angular velocity ω= 15.08 rad/s before the shock

Ticino sand, average values

Dry density [kN·s^2/m^4]	**1.535**
Saturated density [kN·s^2/m^4]	**1.962**
Relative density [%]	**51.93**
Void ratio [-]	**0.75**
Degree of saturation [%]	**99.9**

Pontida clay, average value

Mass density [kN·s^2/m^4]	**2.160**

Radii from centrifuge rotation axis

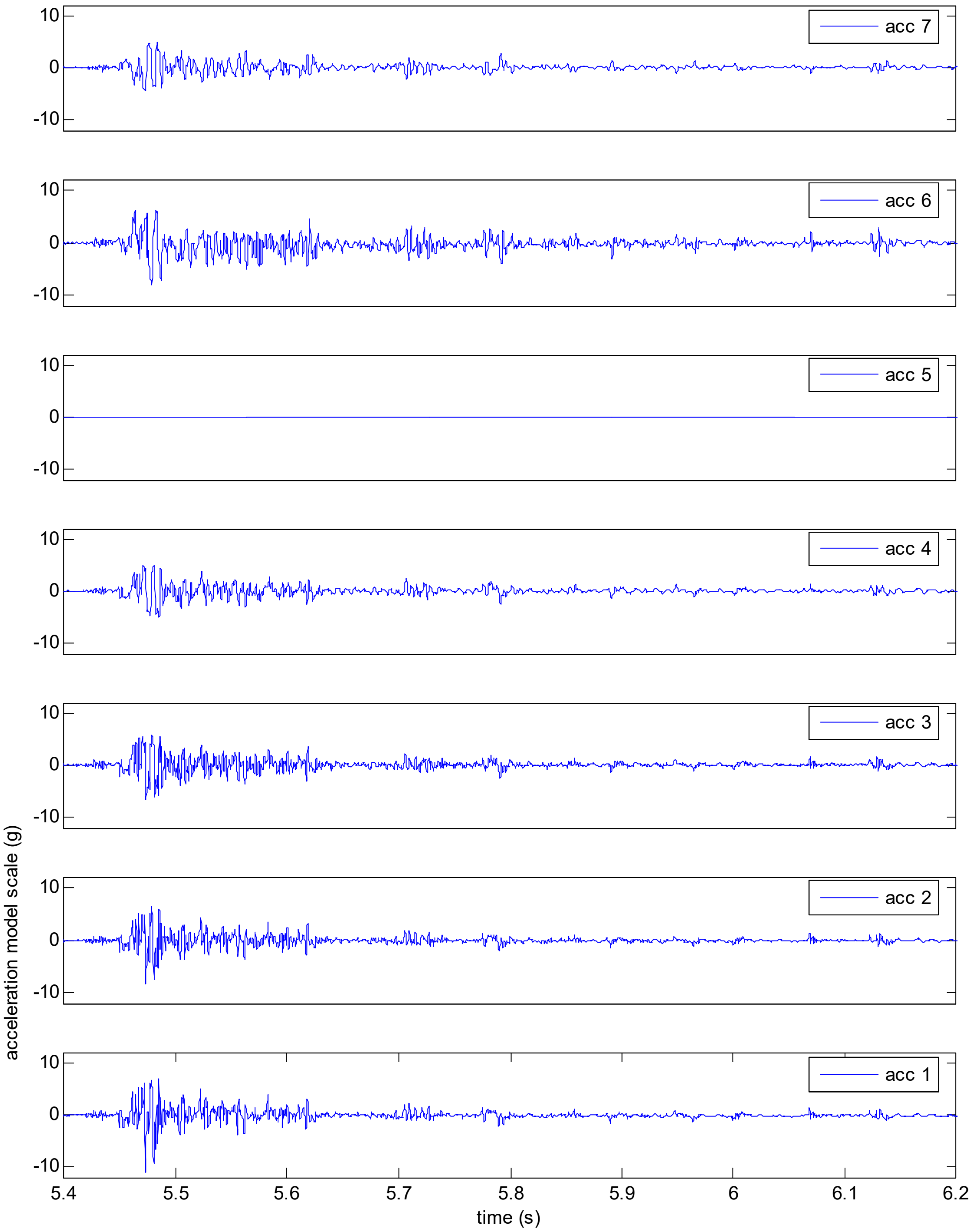
	Radius (mm)
model base	2172.0
free ground surface	1866.1
sand/clay interface	1895.8

Pore Pressure Transducer	**Radius (mm)**	**Value before the shock u_0 (kPa)**
ppt7	1881.0	-6.5
ppt6	1915.6	8.2
ppt5	1915.6	9.1
ppt4	1964.9	28.5
ppt3	2014.2	51.5
ppt2	2063.5	88.7
ppt1	2172.0	120.4

Accelerometer	**Radius (mm)**
acc7	1964.9
acc6	1915.6
acc5	1964.9
acc4	2014.2
acc3	2063.5
acc2	2112.8
acc1	2172.0

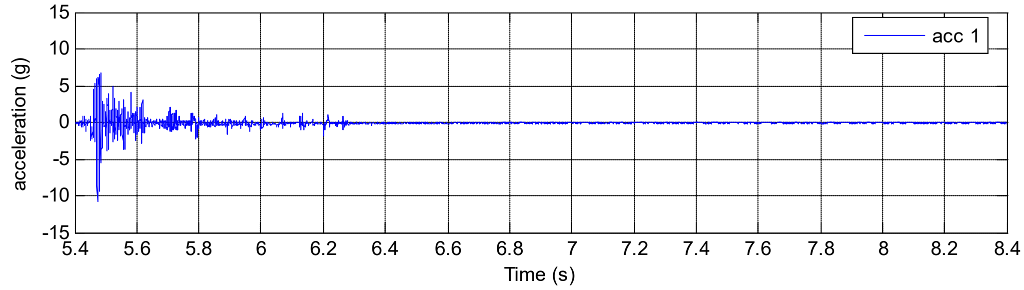
3 – Seismic Excitation

Accelerometers time histories

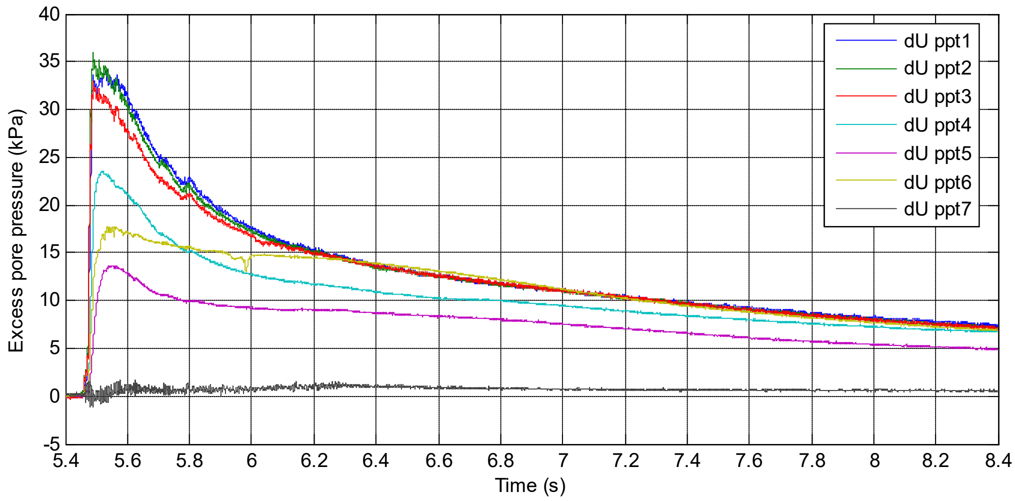


This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

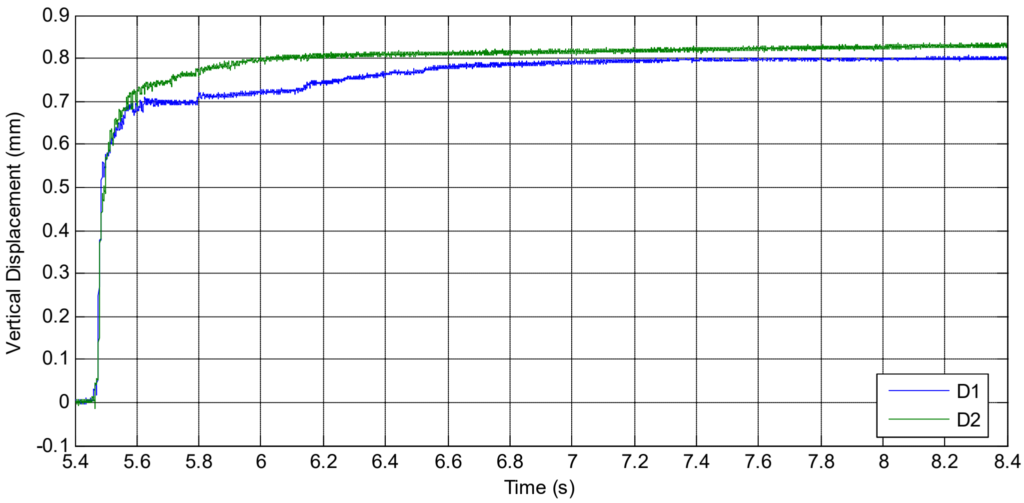
Input motion



Excess pore pressure $\Delta u(t) = u(t) - u_0$ vs. time



Vertical displacements vs. time



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

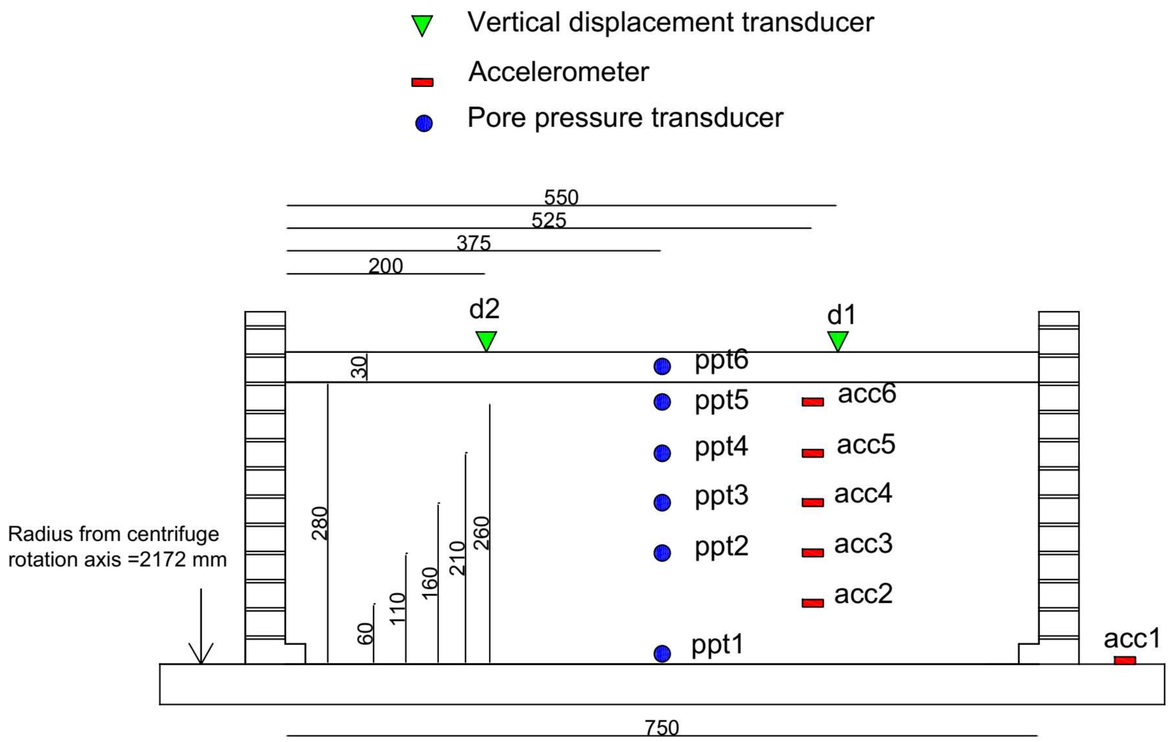
Test 11: M2_S1_GM31

Model description

The model consists of a two layers soil profile of Ticino sand and Pontida clay, the ground motion applied was the number 31.

1 – Reconstruction

Scheme and geometrical dimensions of the model as reconstructed at 1g. The following dimensions refer to model scale.



Ticino sand

Dry density [kN·s^2/m^4]	**1.487**
Relative density [%]	**35.76**
Void ratio [-]	**0.80**

2 – Equilibrium at centrifuge angular velocity ω= 15.08 rad/s before the shock

Ticino sand, average values

Dry density [kN·s^2/m^4]	**1.531**
Saturated density [kN·s^2/m^4]	**1.957**
Relative density [%]	**50.54**
Void ratio [-]	**0.75**
Degree of saturation [%]	**99.3**

Pontida clay, average value

Mass density [kN·s^2/m^4]	**2.160**

Radii from centrifuge rotation axis

	Radius (mm)
model base	2172.0
free ground surface	1865.4
sand/clay interface	1895.1

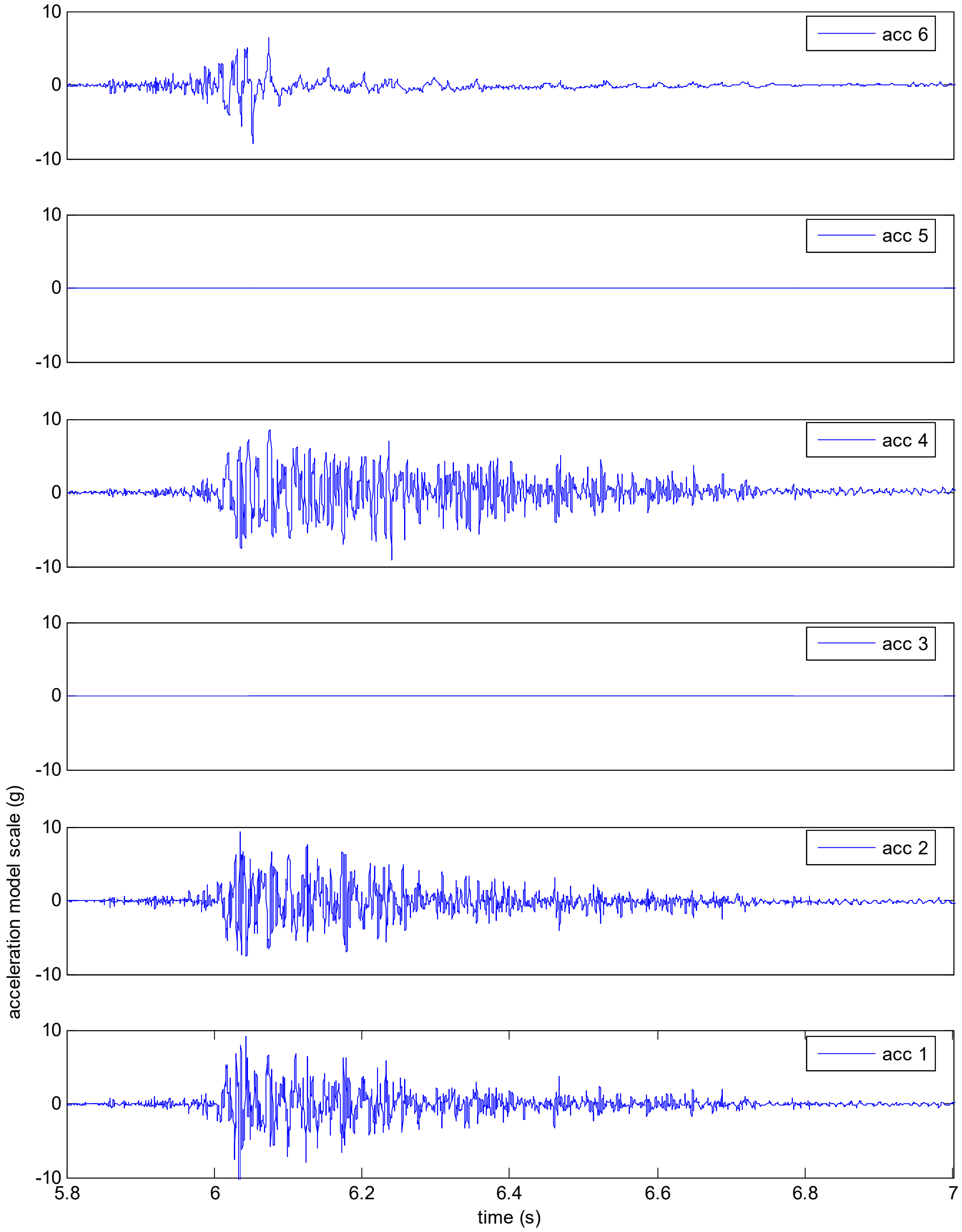
Pore Pressure Transducer	**Radius (mm)**	**Value before the shock u_0 (kPa)**
ppt6	1885.5	1.25
ppt5	1919.5	19.2
ppt4	1968.0	42.7
ppt3	2016.6	49.9
ppt2	2065.2	-
ppt1	2172.0	124.7

Accelerometer	**Radius (mm)**
acc6	1919.5
acc5	1968.0
acc4	2016.6
acc3	2065.2
acc2	2113.7
acc1	2172.0

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

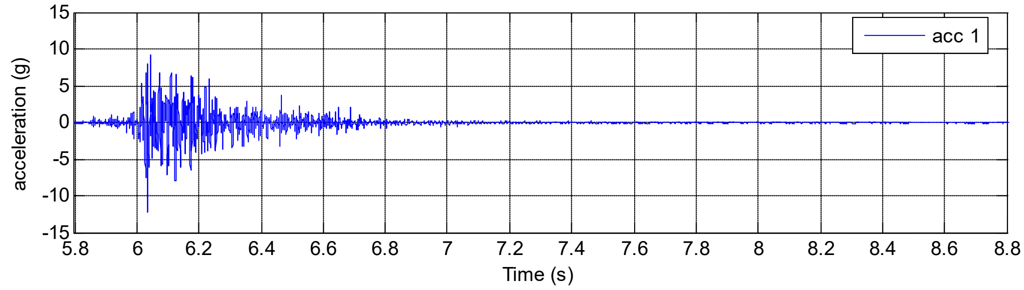
3 – Seismic Excitation

Accelerometers time histories

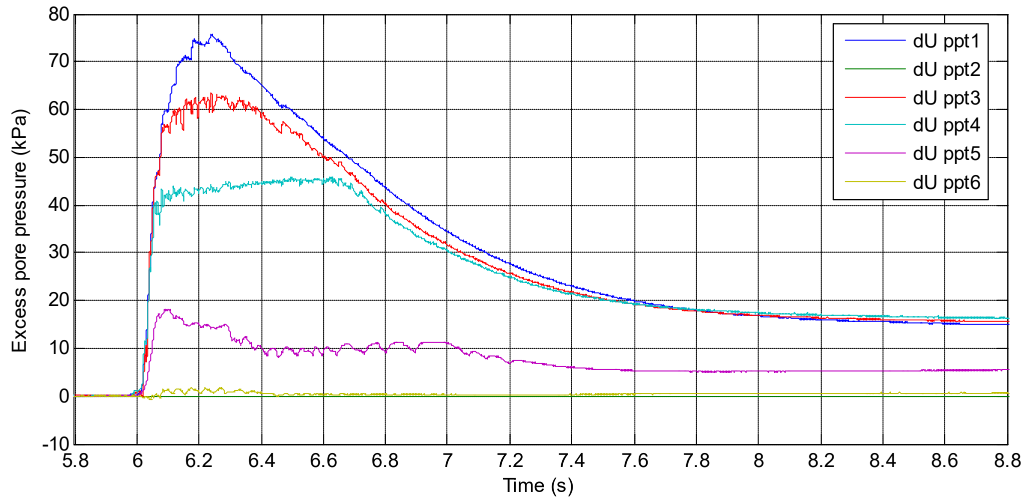


This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

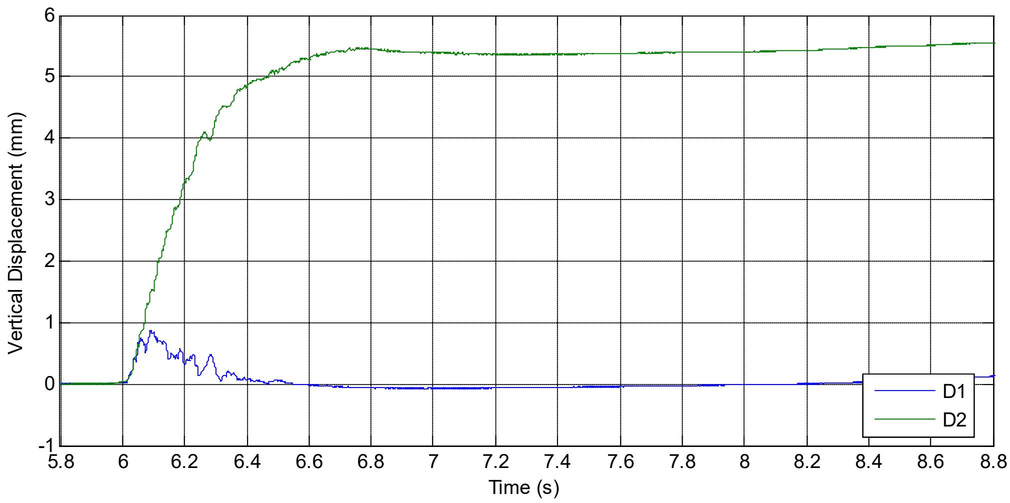
Input motion



Excess pore pressure $\Delta u(t) = u(t) - u_0$ vs. time



Vertical displacements vs. time



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

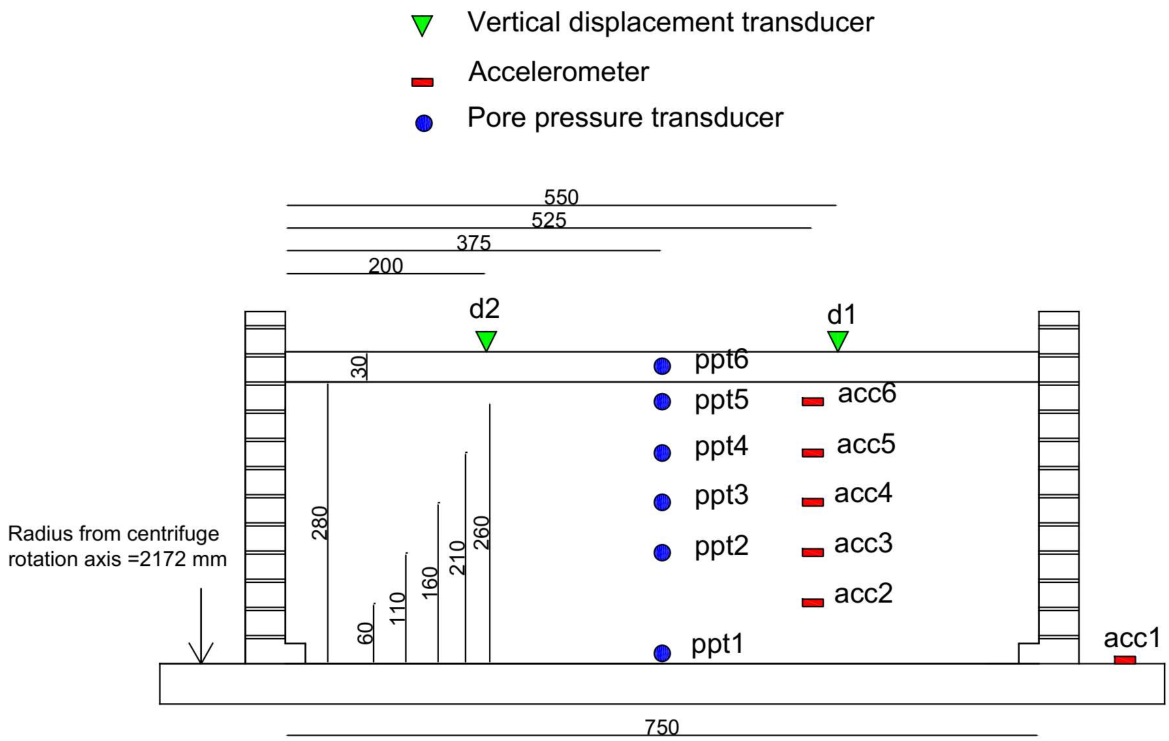
Test 12: M2_S3_GM34

Model description

The model consists of a two layers soil profile of natural Pieve di Cento sand and Pontida clay, the ground motion applied was the number 34.

1 – Reconstruction

Scheme and geometrical dimensions of the model as reconstructed at 1g. The following dimensions refer to model scale.



Ticino sand

Dry density [kN·s²/m⁴]	**1.303**
Relative density [%]	**20.48**
Void ratio [-]	**1.06**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

2 – Equilibrium at centrifuge angular velocity ω= 15.08 rad/s before the shock

Ticino sand, average values

Dry density [kN·s^2/m^4]	**1.388**
Saturated density [kN·s^2/m^4]	**1.867**
Relative density [%]	**46.21**
Void ratio [-]	**0.94**
Degree of saturation [%]	**99.1**

Pontida clay, average value

Mass density [kN·s^2/m^4]	**2.160**

Radii from centrifuge rotation axis

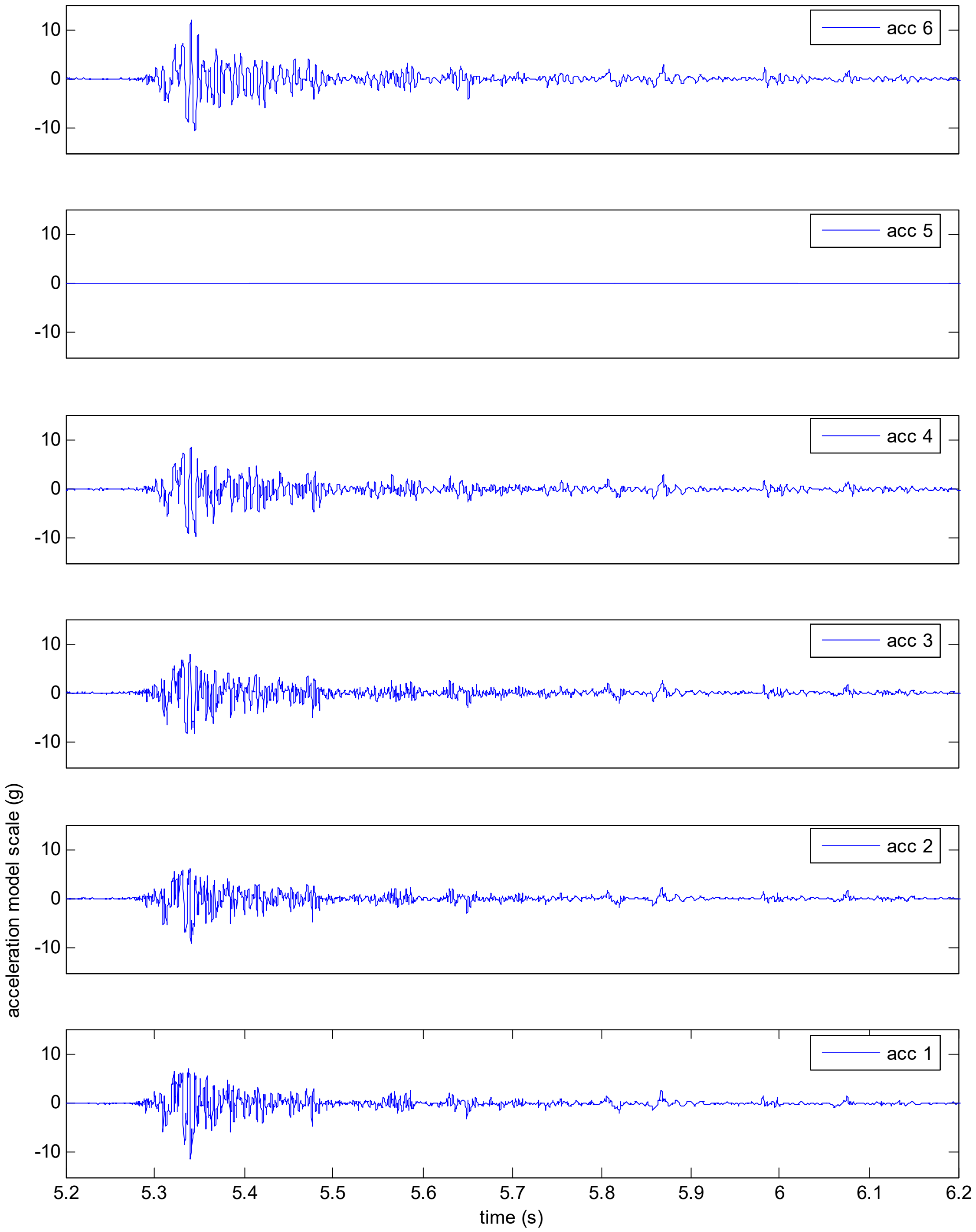
	Radius (mm)
model base	2172.0
free ground surface	1878.8
sand/clay interface	1907.7

Pore Pressure Transducer	Radius (mm)	Value before the shock u_0 (kPa)
ppt6	1895.4	-2.1
ppt5	1928.2	28.9
ppt4	1975.1	49.5
ppt3	2022.0	62.8
ppt2	2068.9	55.6
ppt1	2172.0	127.9

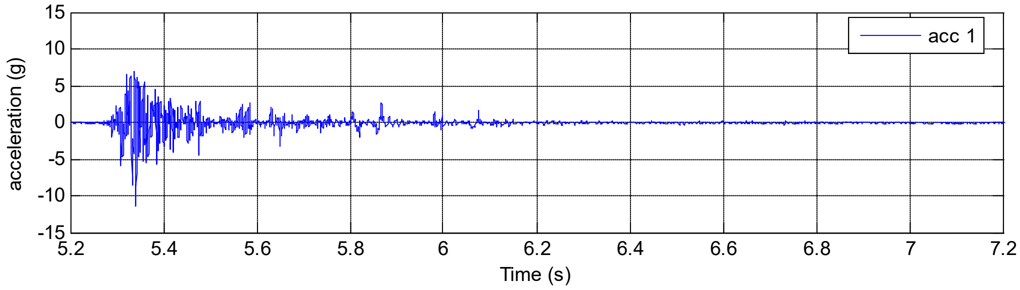
Accelerometer	Radius (mm)
acc6	1928.2
acc5	1975.1
acc4	2022.0
acc3	2068.9
acc2	2115.7
acc1	2172.0

3 – Seismic Excitation

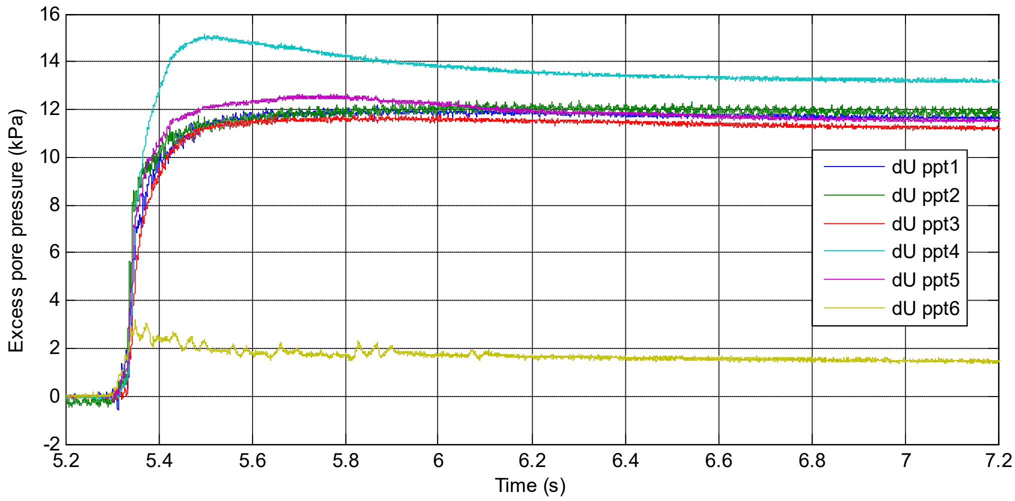
Accelerometers time histories



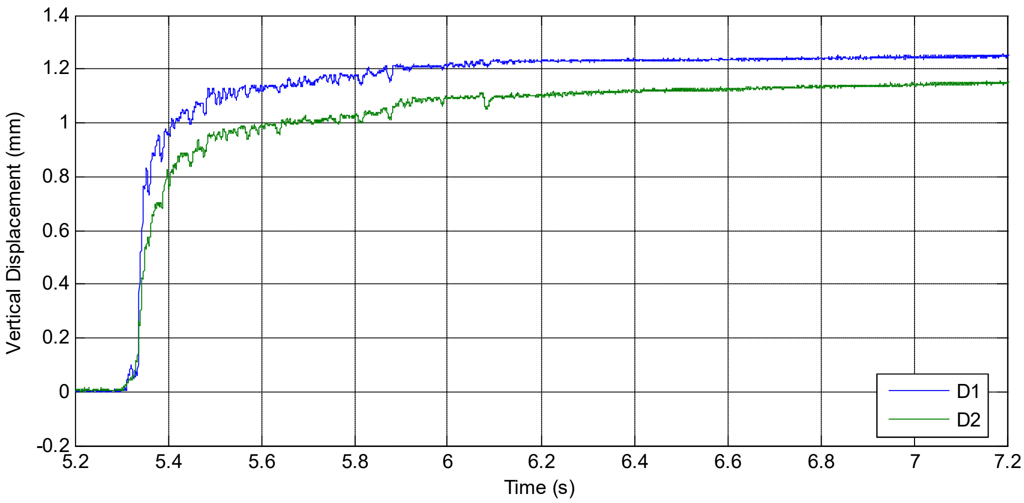
Input motion



Excess pore pressure $\Delta u(t) = u(t) - u_0$ vs. time



Vertical displacements vs. time



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

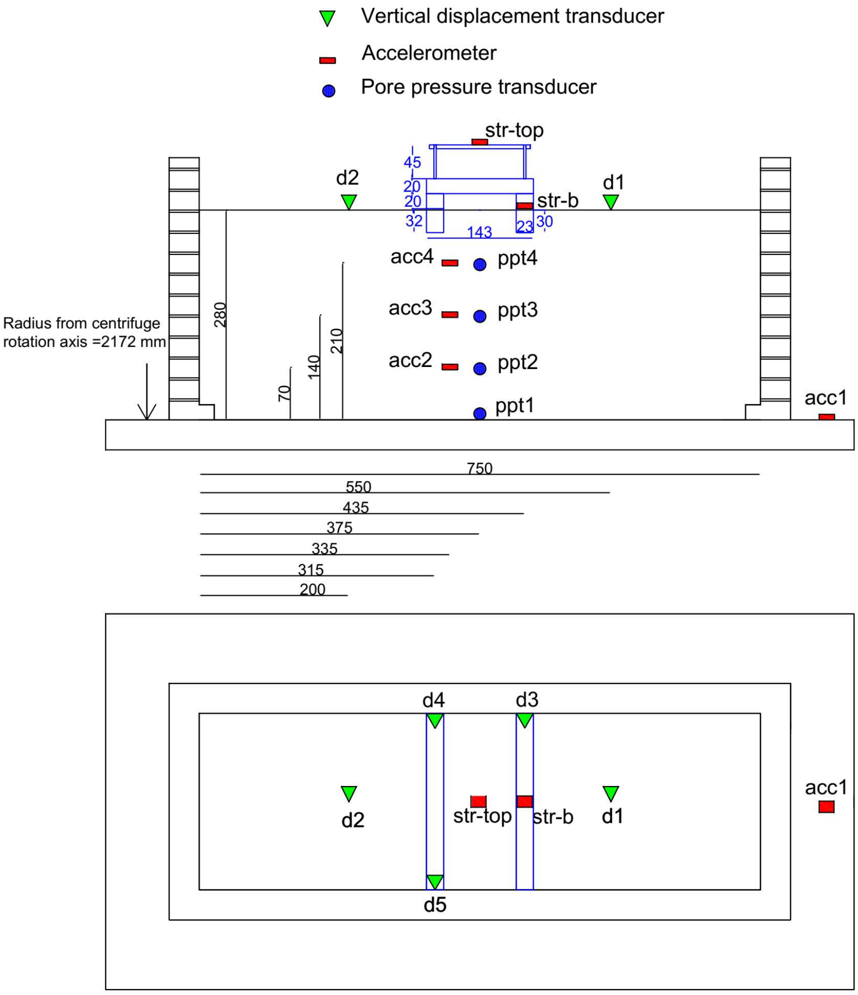
Test 13: M1F_S1_GM31

Model description

The model consists of a homogenous soil profile of Ticino sand, with a model structure with shallow foundations. The ground motion applied was the number 31.

1 – Reconstruction

Scheme and geometrical dimensions of the model as reconstructed at 1g. The following dimensions refer to model scale.



Ticino sand

Dry density [kN·s^2/m^4]	**1.493**
Relative density [%]	**37.80**
Void ratio [-]	**0.80**

2 – Equilibrium at centrifuge angular velocity ω= 15.08 rad/s before the shock

Ticino sand, average values

Dry density [kN·s²/m⁴]	**1.526**
Saturated density [kN·s²/m⁴]	**1.963**
Relative density [%]	**48.89**
Void ratio [-]	**0.76**
Degree of saturation [%]	**100.0**

Radii from centrifuge rotation axis

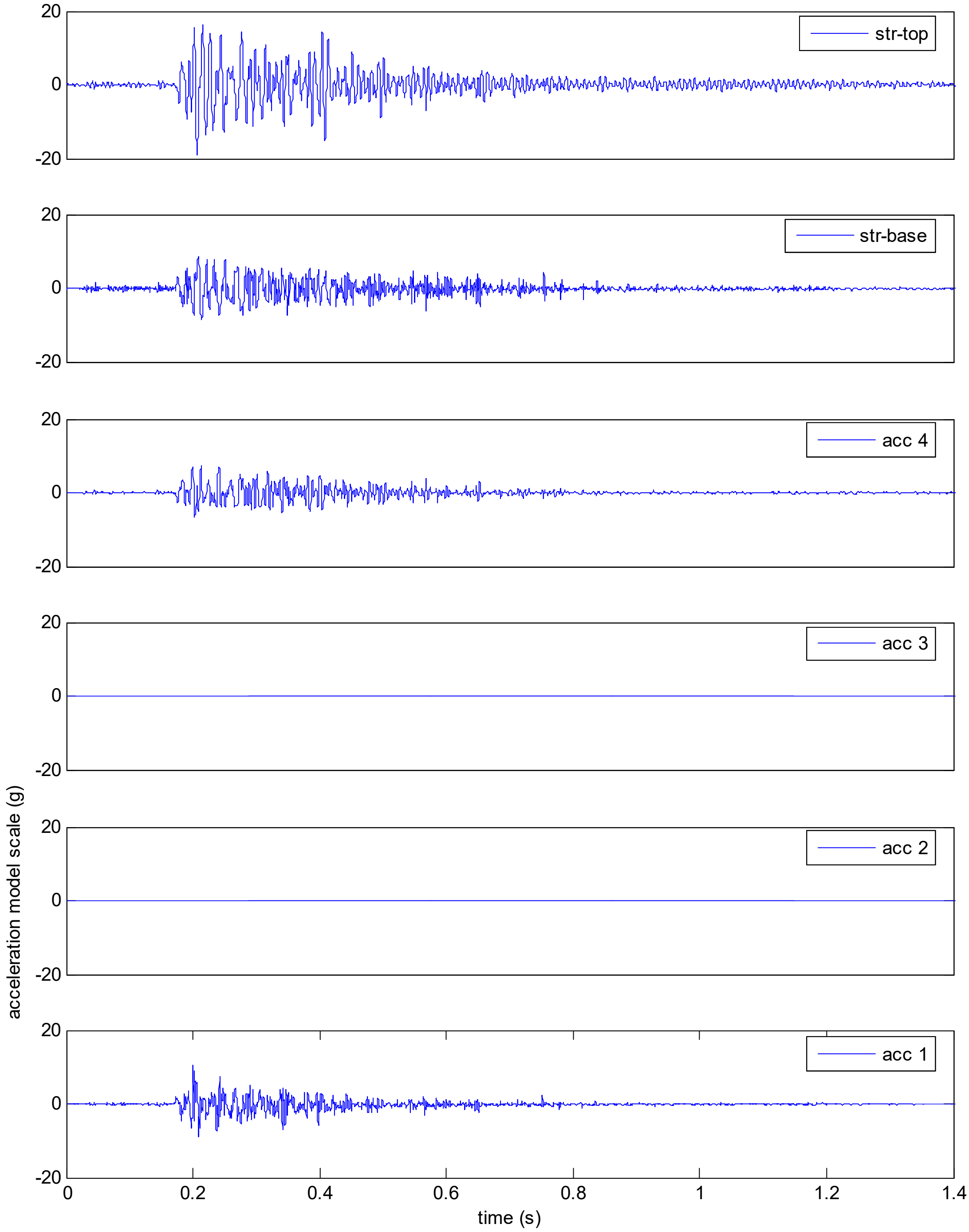
	Radius (mm)
model base	2172.0
free ground surface	1898.0

Pore Pressure Transducer	**Radius (mm)**	**Value before the shock u_0 (kPa)**
ppt4	1966.5	18.1
ppt3	2035.0	52.4
ppt2	2103.5	77.1
ppt1	2172.0	114.1

Accelerometer	**Radius (mm)**
acc4	1966.5
acc3	2035.0
acc2	2103.5
acc1	2172.0

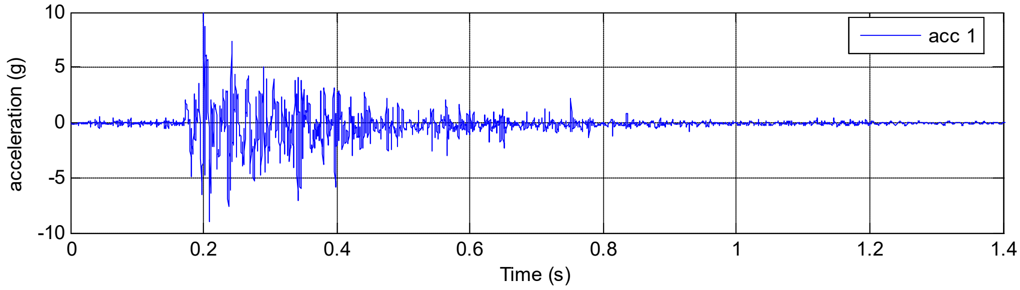
3 – Seismic Excitation

Accelerometers time histories

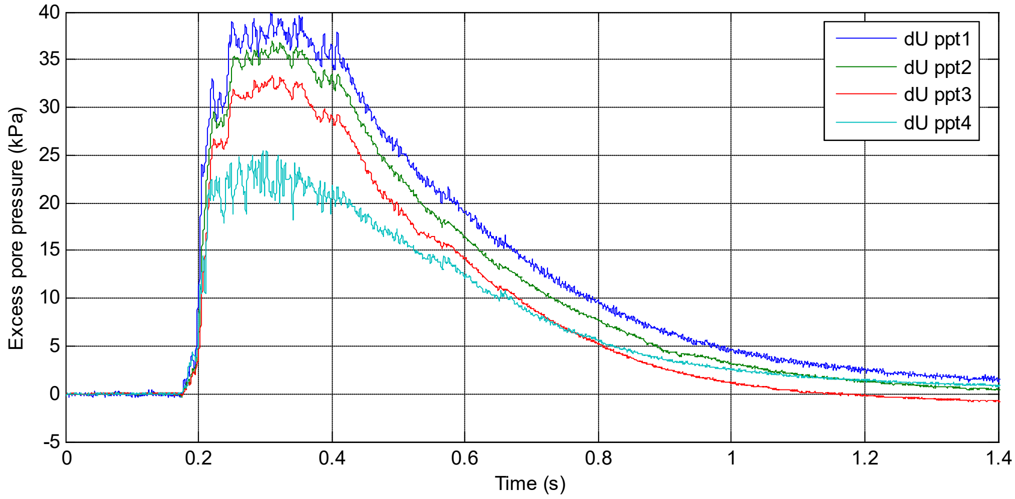


This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

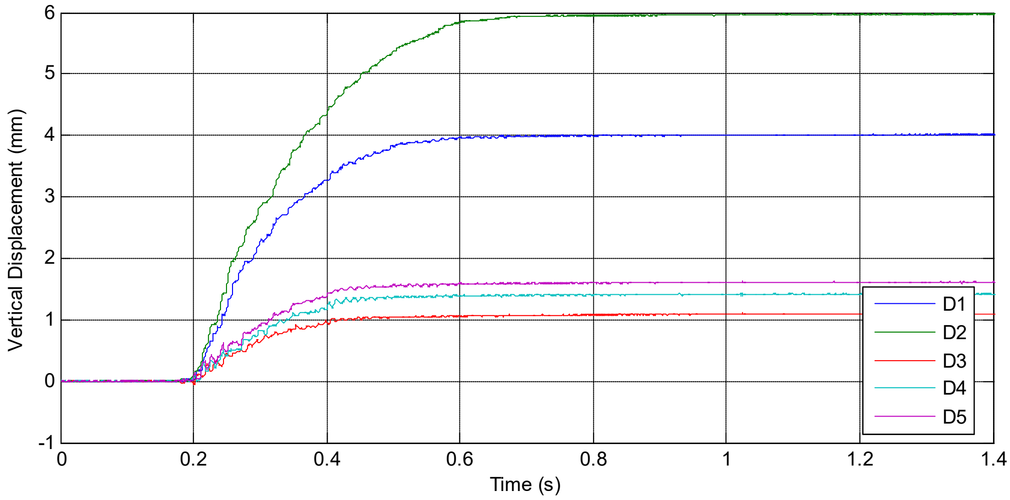
Input motion



Excess pore pressure $\Delta u(t) = u(t) - u_0$ vs. time



Vertical displacements vs. time



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

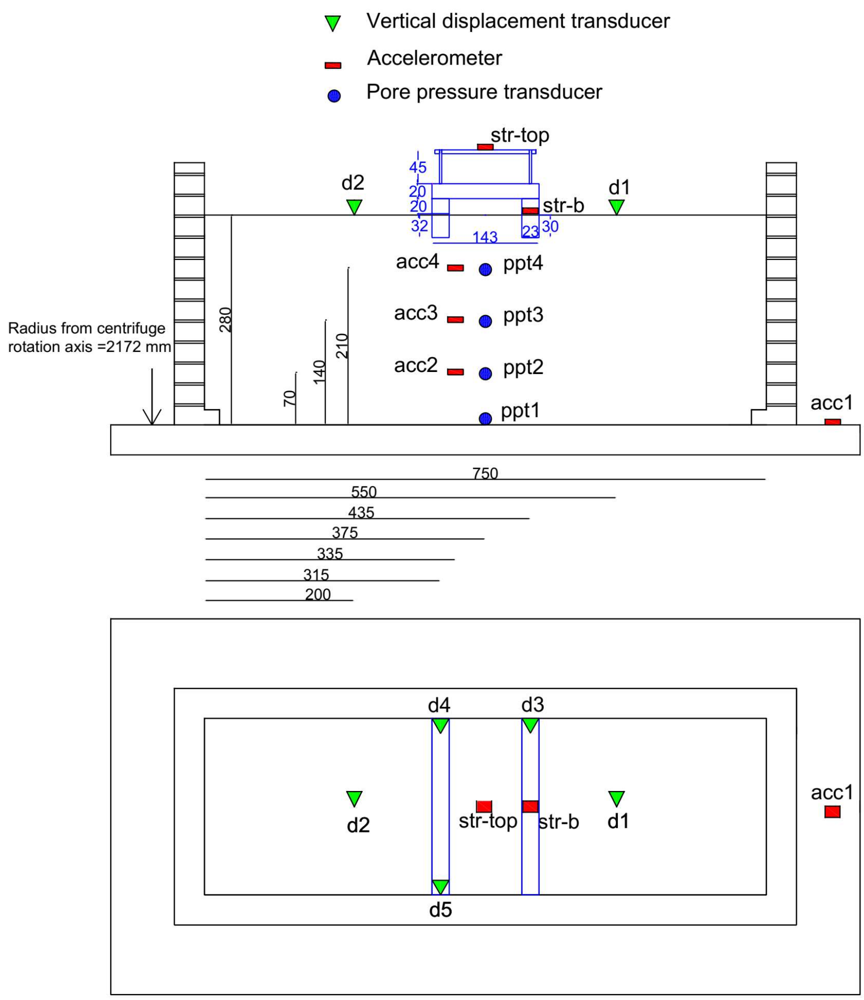
Test 14: M1F_S1_GM31+

Model description

The model consists of a homogenous soil profile of Ticino sand, with a model structure with shallow foundations. The ground motion applied was the number 31+.

1 – Reconstruction

Scheme and geometrical dimensions of the model as reconstructed at 1g. The following dimensions refer to model scale.



Ticino sand

Dry density [kN·s^2/m^4]	**1.493**
Relative density [%]	**37.80**
Void ratio [-]	**0.80**

2 – Equilibrium at centrifuge angular velocity ω= 15.08 rad/s before the shock

Ticino sand, average values

Dry density [kN·s^2/m^4]	**1.537**
Saturated density [kN·s^2/m^4]	**1.970**
Relative density [%]	**52.60**
Void ratio [-]	**0.74**
Degree of saturation [%]	**100.0**

Radii from centrifuge rotation axis

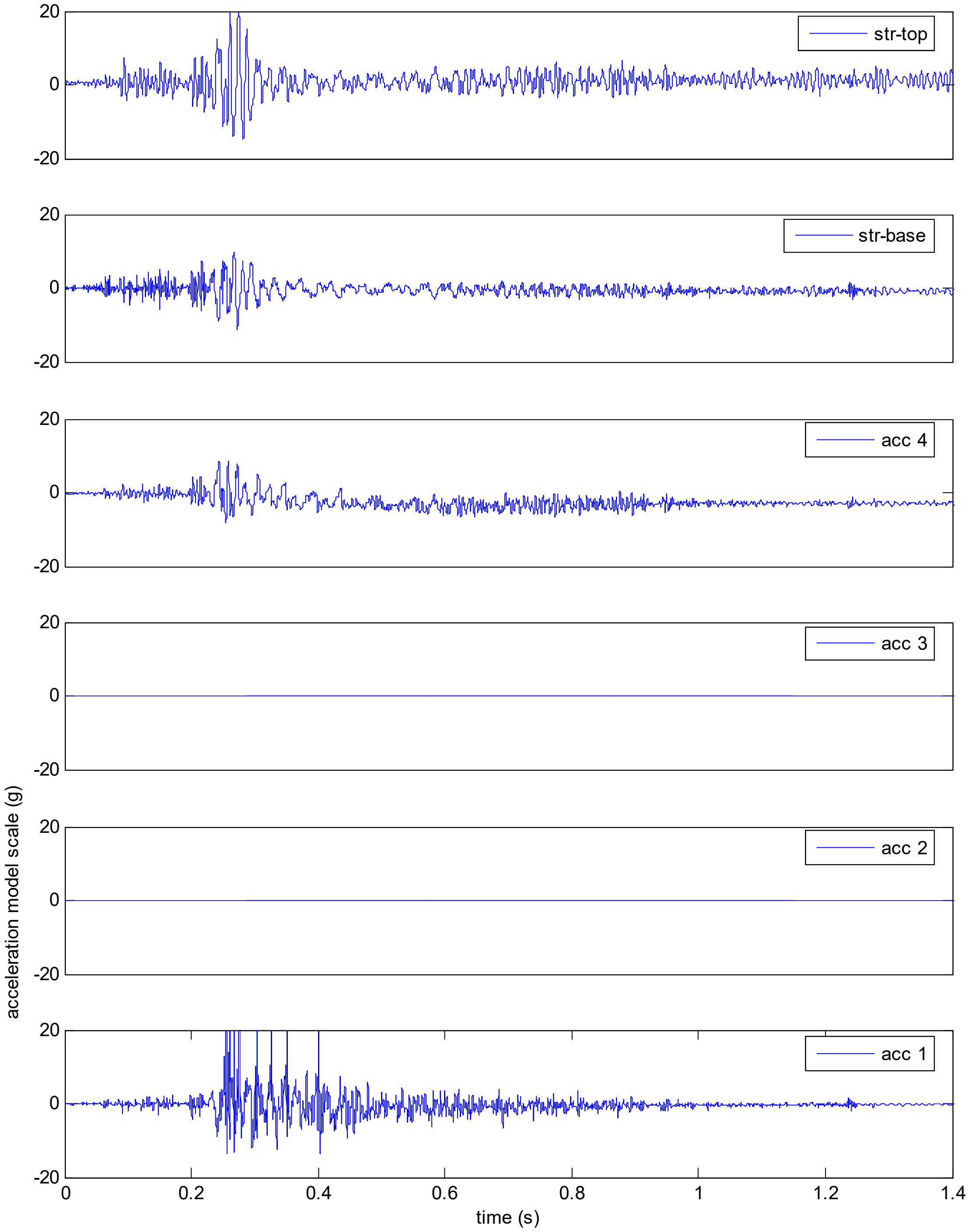
	Radius (mm)
model base	2172.0
free ground surface	1900.0

Pore Pressure Transducer	Radius (mm)	Value before the shock u_0 (kPa)
ppt4	1968.0	18.4
ppt3	2036.0	51.1
ppt2	2104.0	76.5
ppt1	2172.0	114.3

Accelerometer	Radius (mm)
acc4	1968.0
acc3	2036.0
acc2	2104.0
acc1	2172.0

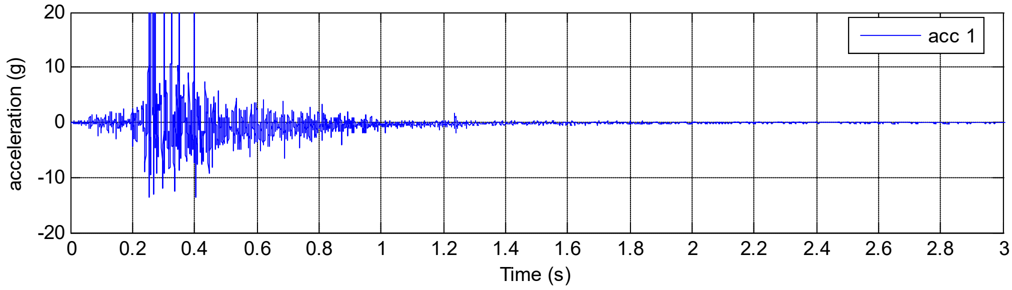
3 – Seismic Excitation

Accelerometers time histories

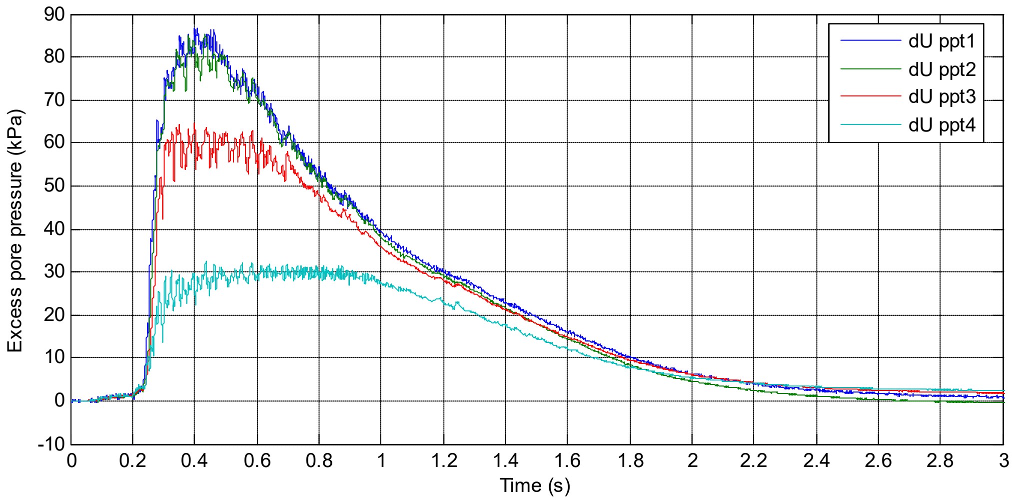


This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

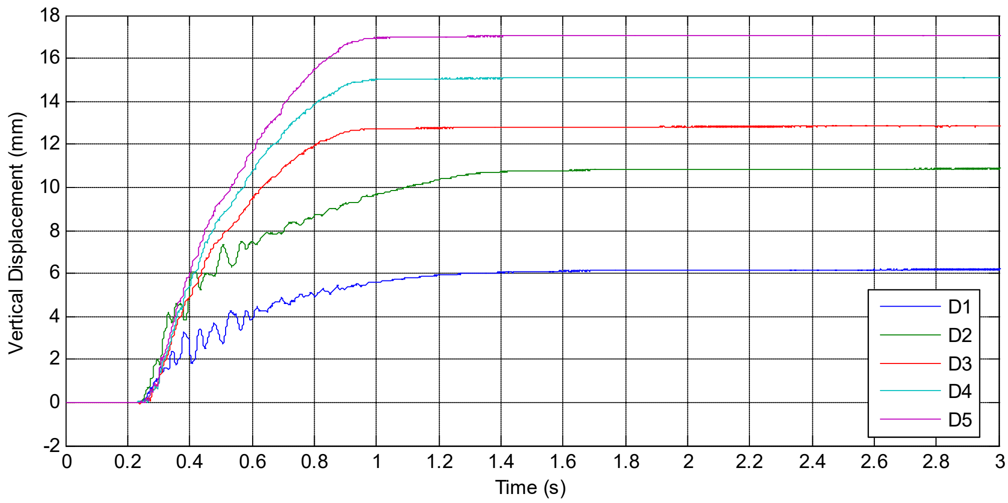
Input motion



Excess pore pressure Δu(t) = u(t) - u_0 vs. time



Vertical displacements vs. time



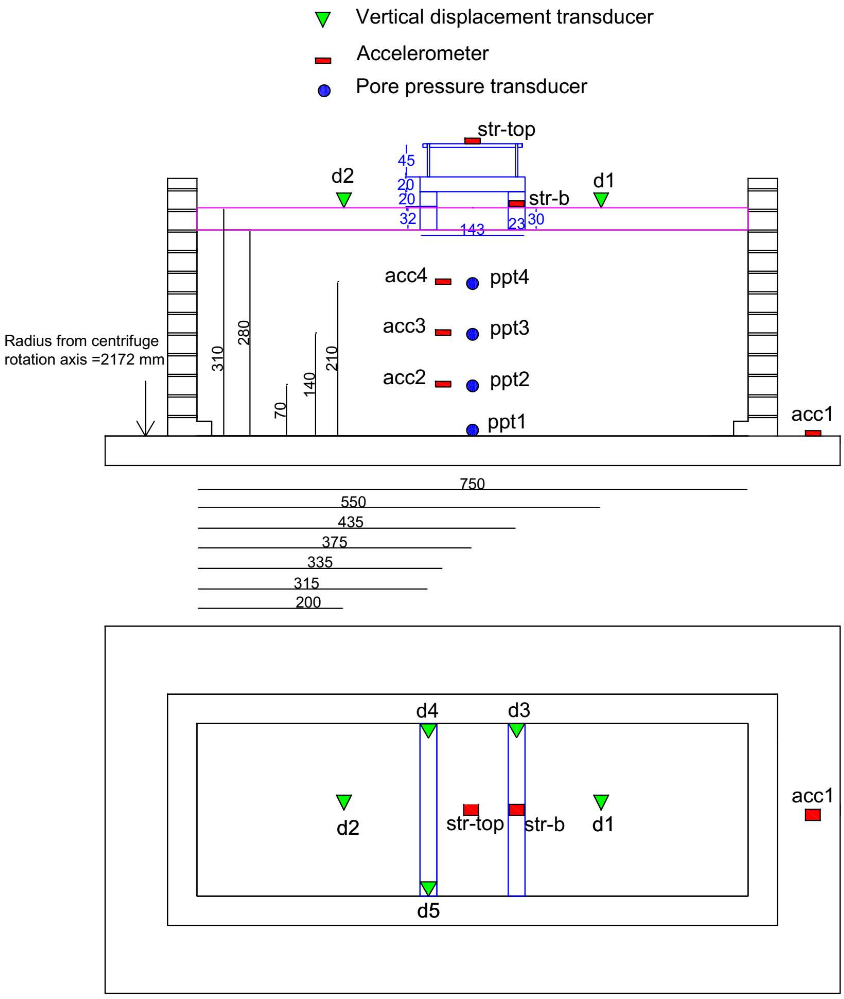
Test 15: M2F_S1_GM31+

Model description

The model consists of a two layers soil profile of Ticino sand and Pontida clay, with a model structure with shallow foundations. The ground motion applied was the number 31+.

1 – Reconstruction

Scheme and geometrical dimensions of the model as reconstructed at 1g. The following dimensions refer to model scale.



Ticino sand

Dry density [kN·s²/m⁴]	**1.501**
Relative density [%]	**40.66**
Void ratio [-]	**0.79**

2 – Equilibrium at centrifuge angular velocity ω= 15.08 rad/s before the shock

Ticino sand, average values

Dry density [kN·s^2/m^4]	**1.537**
Saturated density [kN·s^2/m^4]	**1.965**
Relative density [%]	**52.49**
Void ratio [-]	**0.74**
Degree of saturation [%]	**100.0**

Pontida clay, average value

Mass density [kN·s^2/m^4]	**2.160**

Radii from centrifuge rotation axis

	Radius (mm)
model base	2172.0
free ground surface	1866.6
sand/clay interface	1896.1

Pore Pressure Transducer	Radius (mm)	Value before the shock u_0 (kPa)
ppt6	1966.8	30.5
ppt5	2035.2	63.9
ppt4	1966.8	32.6
ppt3	2035.2	66.8
ppt2	2103.6	90.4
ppt1	2172.0	121.2

Accelerometer	Radius (mm)
acc4	1966.8
acc3	2035.2
acc2	2103.6
acc1	2172.0

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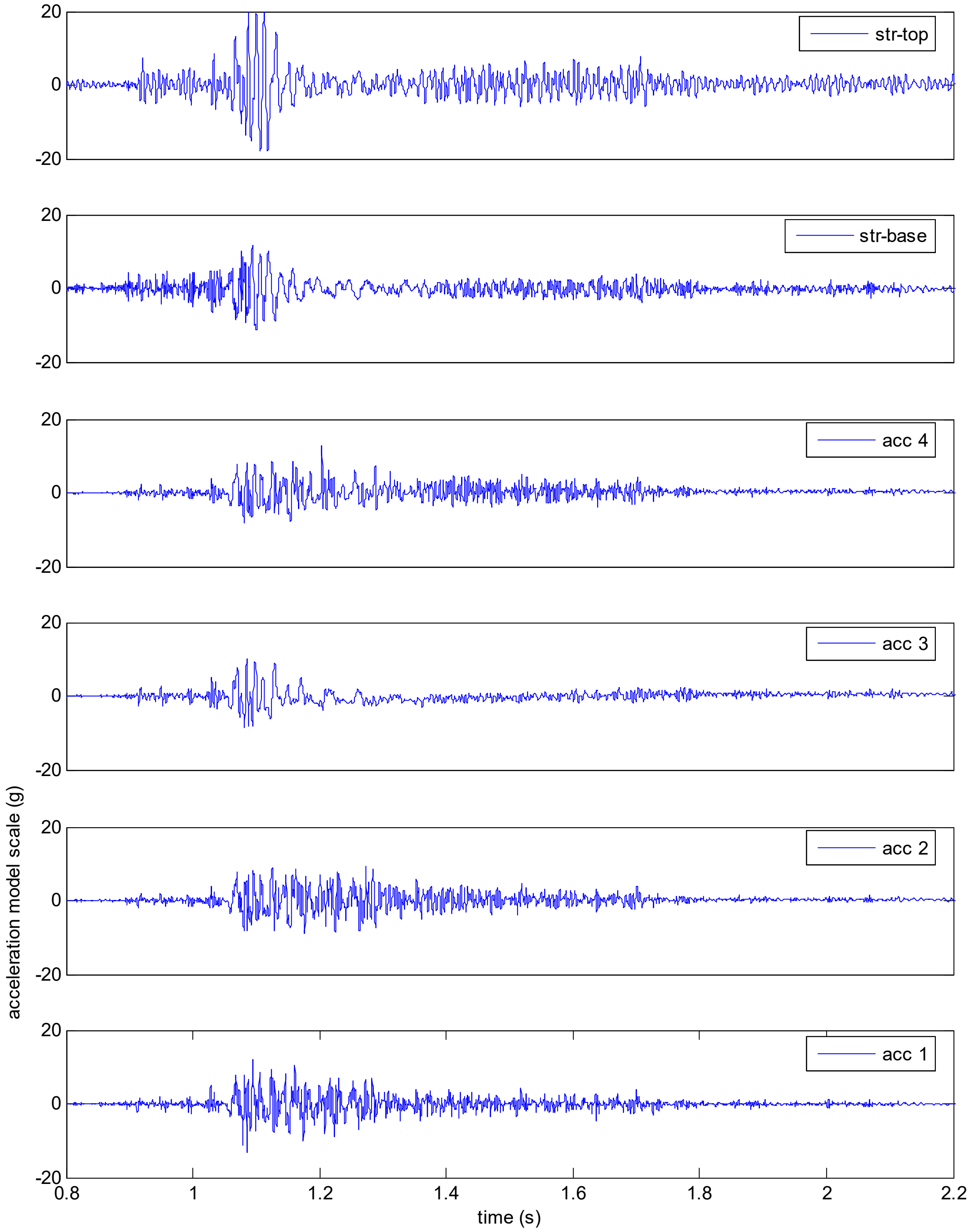
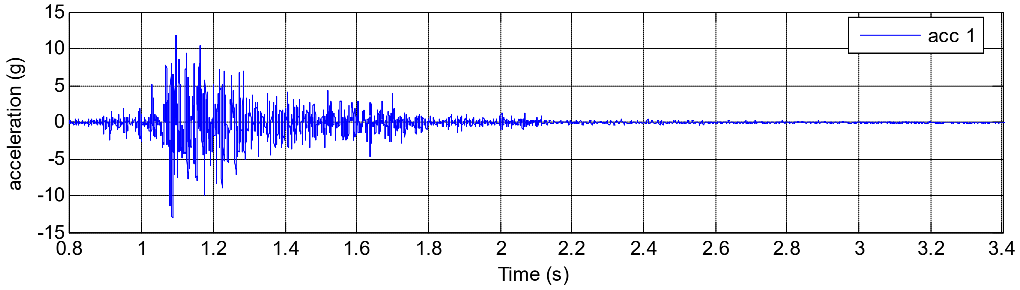
3 – Seismic Excitation

Accelerometers time histories

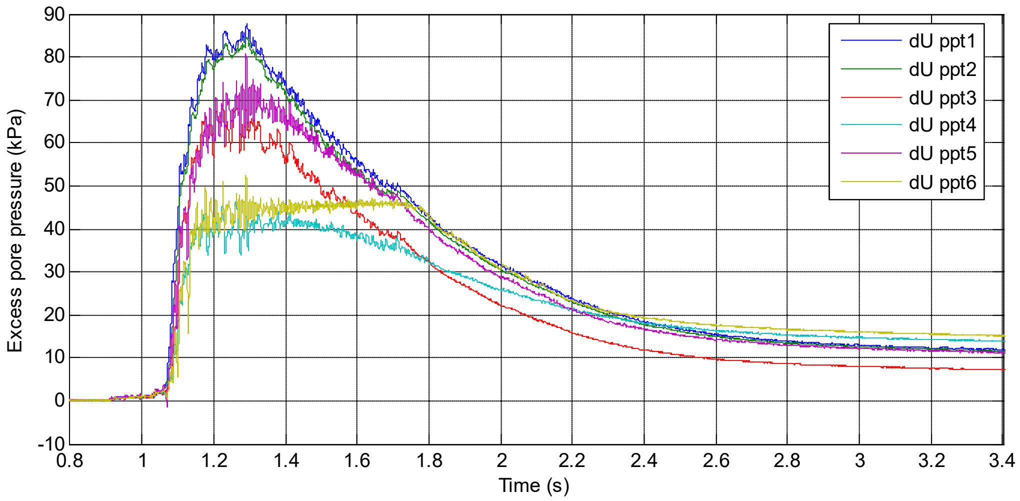


This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

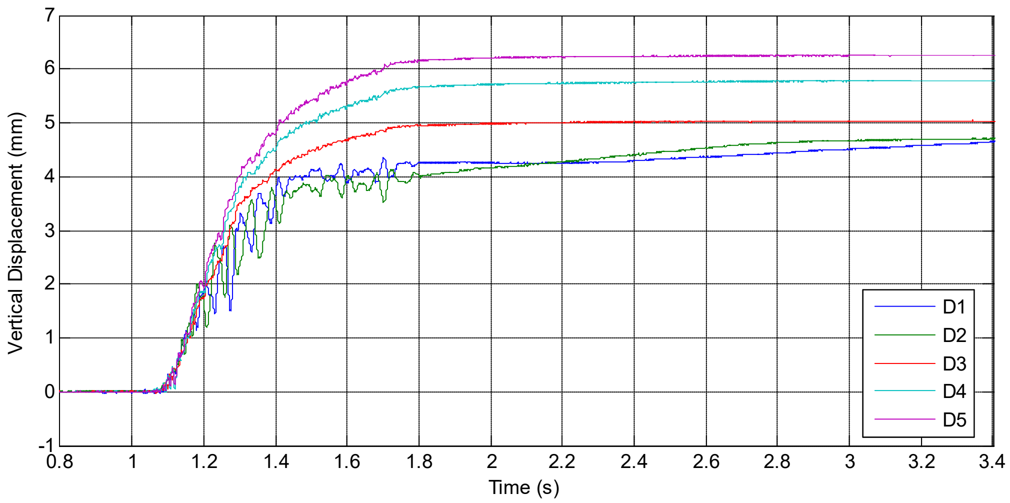
Input motion



Excess pore pressure $\Delta u(t)= u(t)- u_0$ vs. time



Vertical displacements vs. time



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

10.2. Second series of tests

The second series of tests consisted of 12 tests numbered from 16 to 27 as summarised in Table 10. The objective of these tests was to reproduce some of the main features of the vertical and horizontal model drains, installed as ground improvement technique, in free field conditions and with a simple model structure on shallow foundations. The efficacy of vertical and horizontal drains was tested both on model type 1 (homogeneous sand) and model type 2 (homogeneous sand topped by a clay layer). The soil adopted was Ticino sand and the applied ground motions were GM31, in free field models, or GM31+, in presence of the model structure.

The test schemes were established with the collaboration of the partners of UNINA and TREVI, two test configurations were adopted.

- Vertical drains: square mesh, model drains installed at a spacing (centre-to-centre distance) 5 times or 10 times the drain diameter.
- Horizontal drains: quincunx mesh, model drains installed at a spacing (centre-to-centre distance) 5 times or 10 times the drain diameter.

Experimental targets achieved are:

- Evaluation of excess pore pressures development during the shock and the aftershock dissipation rate with the presence of vertical or horizontal drains.
- Evaluation of post liquefaction settlements.
- Production of a consistent set of experimental data which can be used as a benchmark for the numerical simulations and in situ trial activities included in other Tasks of the LIQUEFACT project (e.g. Tasks 4.3, 4.4 and 4.5).

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10.2.1. Test summary sheets

The experimental programme list of the second series of tests is reported in Table 12. The results of each test are summarised in four data sheets. The set of information that can be found is:

Reconstruction:

- Sketch of the model with: (1) sensors ID and positions after deposition (2) model drains configuration (3) model structure position when present (mm at model scale);
- Sand characteristics after deposition (average values of dry density, relative density and void ratio).

Equilibrium at centrifuge angular velocity of 15.08 rad/s, before the shock:

- Soil material characteristics (average values of dry density, saturated density, relative density, void ratio, degree of saturation);
- Position of the (1) model base, (2) free ground surface and (3) sand/clay interface when present, expressed as radius from centrifuge rotation axis;
- Position of PPTs and ACCs expressed as radius from centrifuge rotation axis;
- Pore pressure, u_0 values as measured by the PPTs before the shock.

Seismic Excitation:

- Time histories measured by the installed miniaturised accelerometers
- Input motion applied by the shaker (ACC1)
- Excess pore pressure [$\Delta u(t) = u(t)-u_0$] versus time measured during the shock by PPTs
- Vertical Displacement of the soil surface vs. time recorded during the shock.

All data are reported at model scale

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Table 12 Second series of tests

Test number	Test Name	Model Type	Sand	Ground Motion	Drains	Spacing	Structure
16	M1_S1_VD1_GM31	1	1	31	V	5D	-
17	M1_S1_VD2_GM31	1	1	31	V	10D	-
18	M1_S1_HD1_GM31	1	1	31	H	5D	-
19	M1_S1_HD2_GM31	1	1	31	H	10D	-
20	M2_S1_VD1_GM31	2	1	31	V	5D	-
21	M2_S1_VD2_GM31	2	1	31	V	10D	-
22	M2_S1_HD1_GM31	2	1	31	H	5D	-
23	M2_S1_HD2_GM31	2	1	31	H	10D	-
24	M1F_S1_VD1_GM31+	1	1	31+	V	5D	Yes
25	M1F_S1_HD1_GM31+	1	1	31+	H	5D	Yes
26	M2F_S1_VD1_GM31+	2	1	31+	V	5D	Yes
27	M2F_S1_HD1_GM31+	2	1	31+	H	5D	Yes

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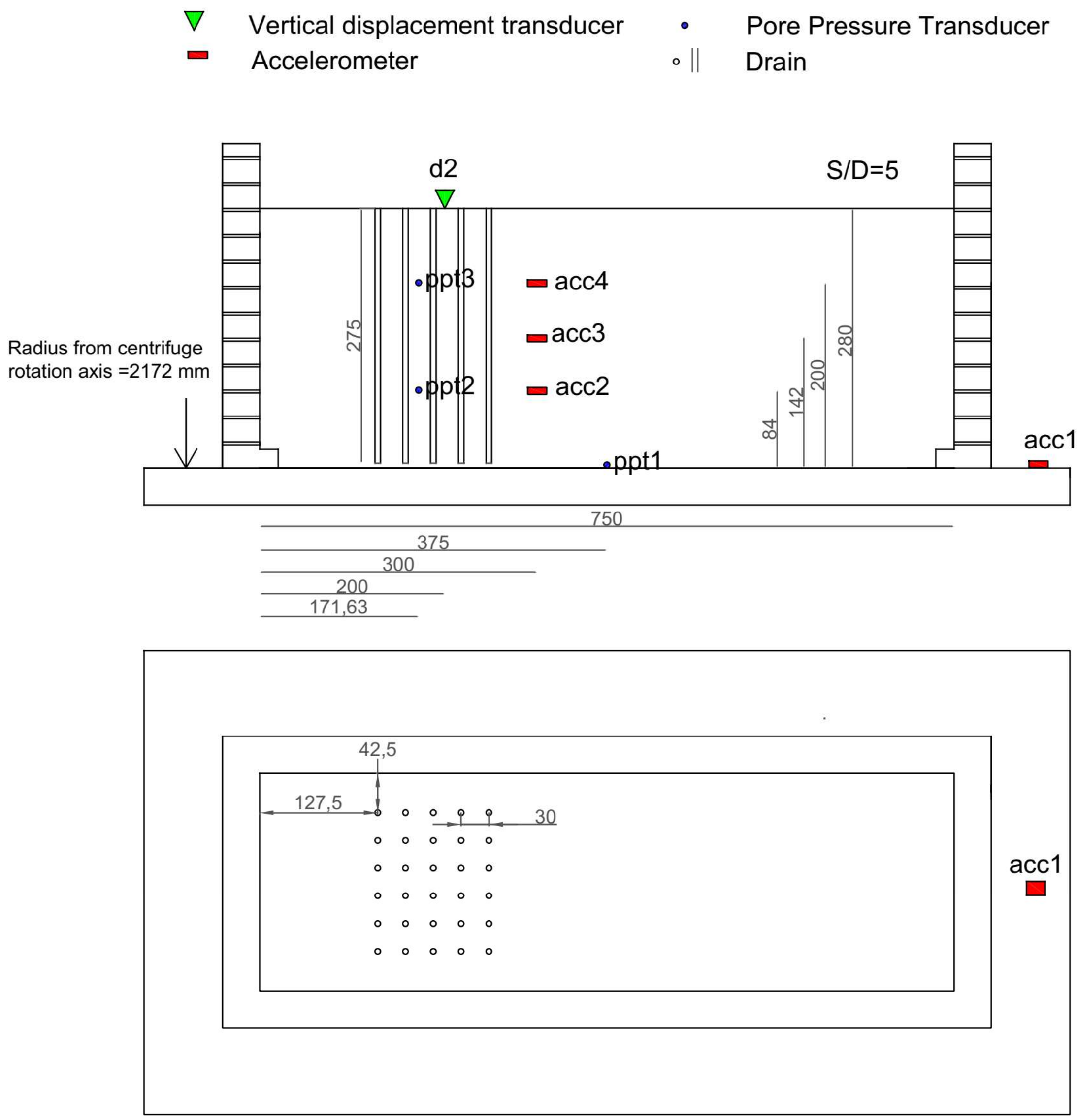
Test 16: M1_S1_VD1_GM31

The model consists of a homogeneous soil profile of Ticino sand, the ground motion applied was the number 31. Model vertical drains installed at a spacing of 5 diameters S/D=5.

Models characteristics



Ticino sand

Dry density [kN·s^2/m^4]	**1.499**
Relative density [%]	**40.01**
Void ratio [-]	**0.79**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

2 – Equilibrium at centrifuge angular velocity ω= 15.08 rad/s before the shock

Ticino sand, average values

Dry density [kN·s²/m⁴]	**1.521**
Saturated density [kN·s²/m⁴]	**1.952**
Relative density [%]	**47.16**
Void ratio [-]	**0.76**
Degree of saturation [%]	**99.8**

Radii from centrifuge rotation axis

	Radius (mm)
model base	2172.0
free ground surface	1895.9

Pore Pressure Transducer	**Radius (mm)**	**Value before the shock u_0 (kPa)**
ppt3	1974.8	19.5
ppt2	2089.2	72.6
ppt1	2172.0	131.5

Accelerometer	**Radius (mm)**
acc4	1974.8
acc3	2032.0
acc2	2089.2
acc1	2172.0

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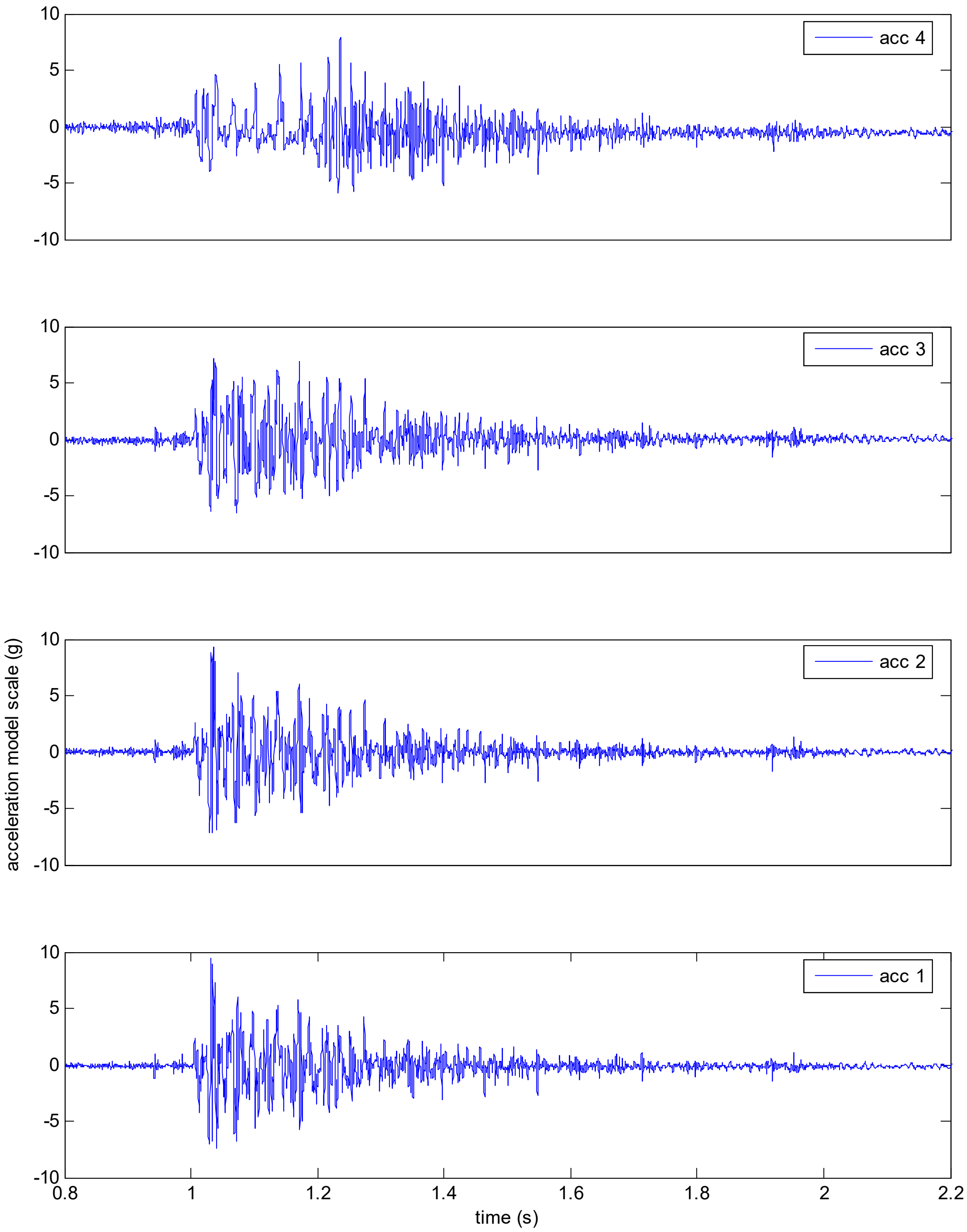
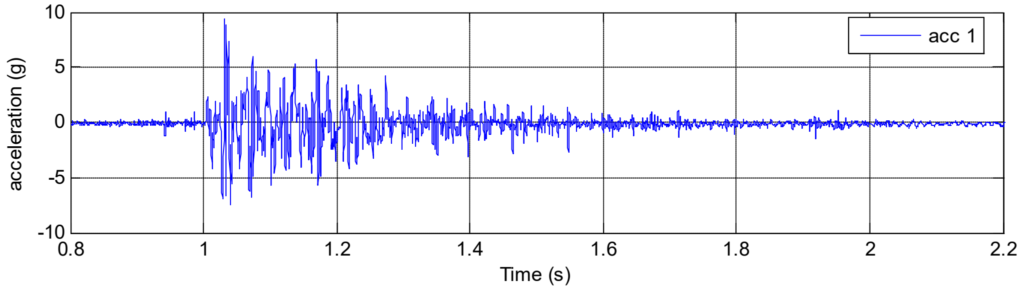
3 – Seismic Excitation

Accelerometers time histories

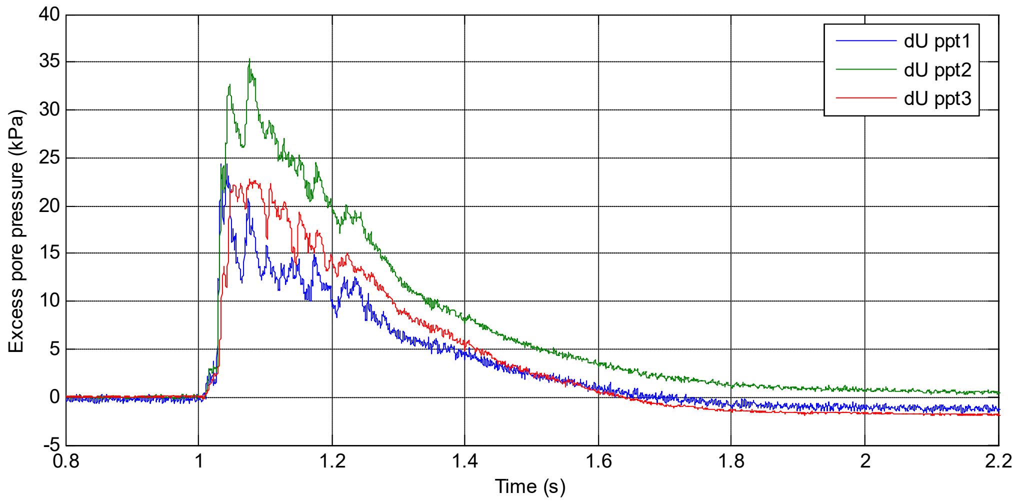


This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

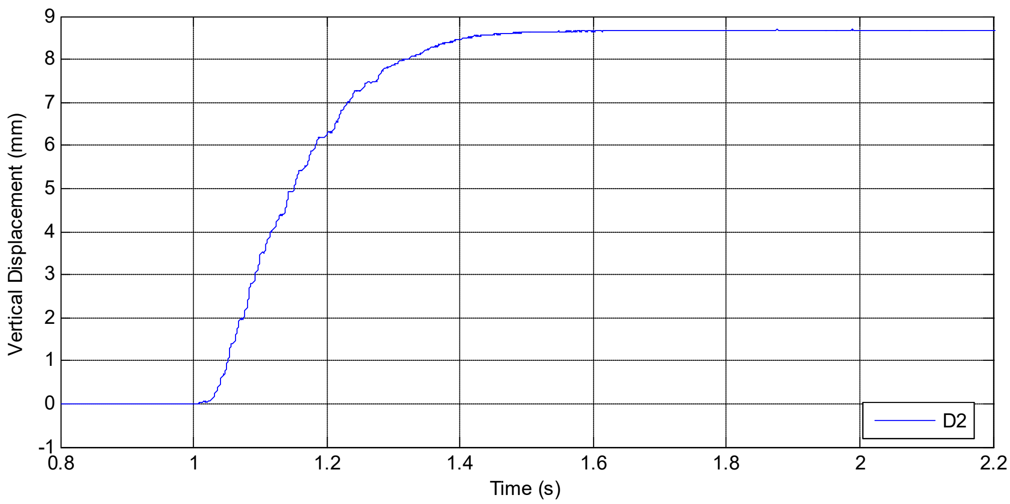
Input motion



Excess pore pressure $\Delta u(t) = u(t) - u_0$ vs. time



Vertical displacements vs. time



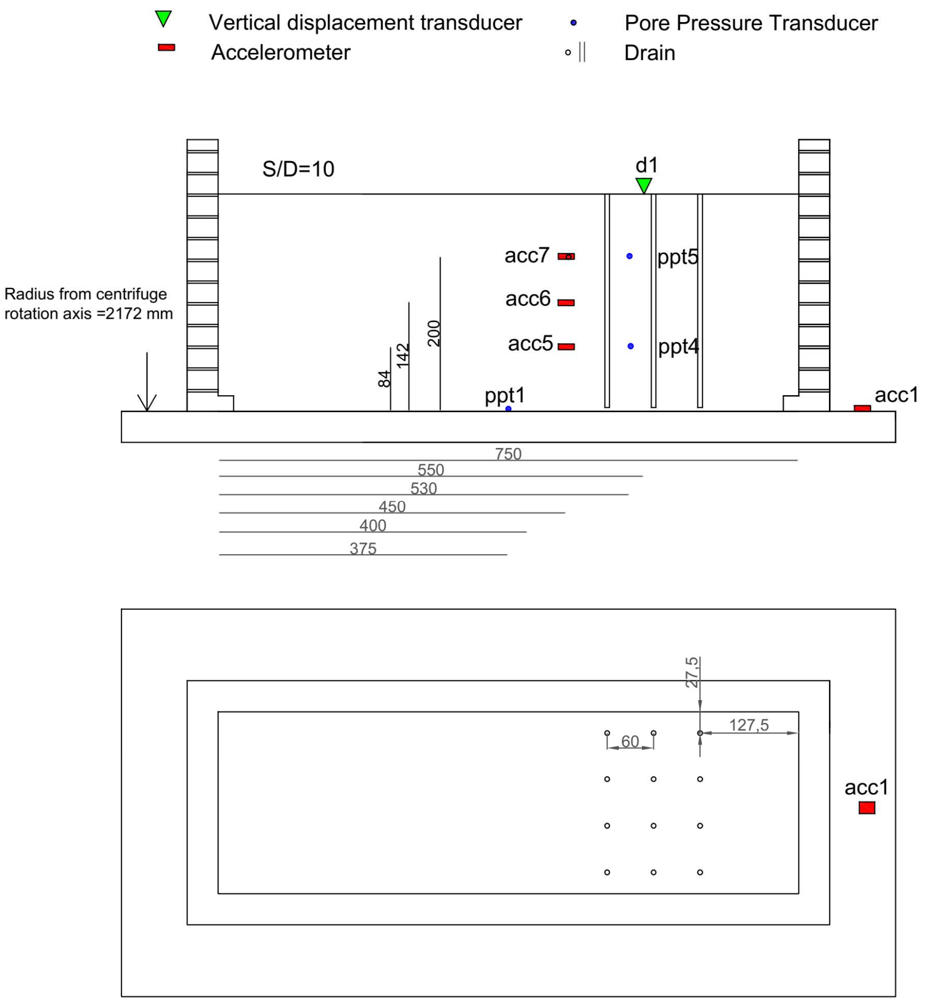
Test 17: M1_S1_VD2_GM31

Model description

The model consists of a homogeneous soil profile of Ticino sand, the ground motion applied was the number 31. Model vertical drains installed at a spacing of 10 diameters S/D=10.

1 – Reconstruction

Scheme and geometrical dimensions of the model as reconstructed at 1g. The following dimensions refer to model scale.



Ticino sand

Dry density [kN·s²/m⁴]	**1.499**
Relative density [%]	**40.01**
Void ratio [-]	**0.79**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

2 – Equilibrium at centrifuge angular velocity ω= 15.08 rad/s before the shock

Ticino sand, average values

Dry density [kN·s^2/m^4]	**1.521**
Saturated density [kN·s^2/m^4]	**1.952**
Relative density [%]	**47.16**
Void ratio [-]	**0.76**
Degree of saturation [%]	**99.8**

Radii from centrifuge rotation axis

	Radius (mm)
model base	2172.0
free ground surface	1895.9

Pore Pressure Transducer	Radius (mm)	Value before the shock u_0 (kPa)
ppt5	1974.8	18.4
ppt4	2089.2	82.1
ppt1	2172.0	131.5

Accelerometer	Radius (mm)
acc7	1974.8
acc6	2032.0
acc5	2089.2
acc1	2172.0

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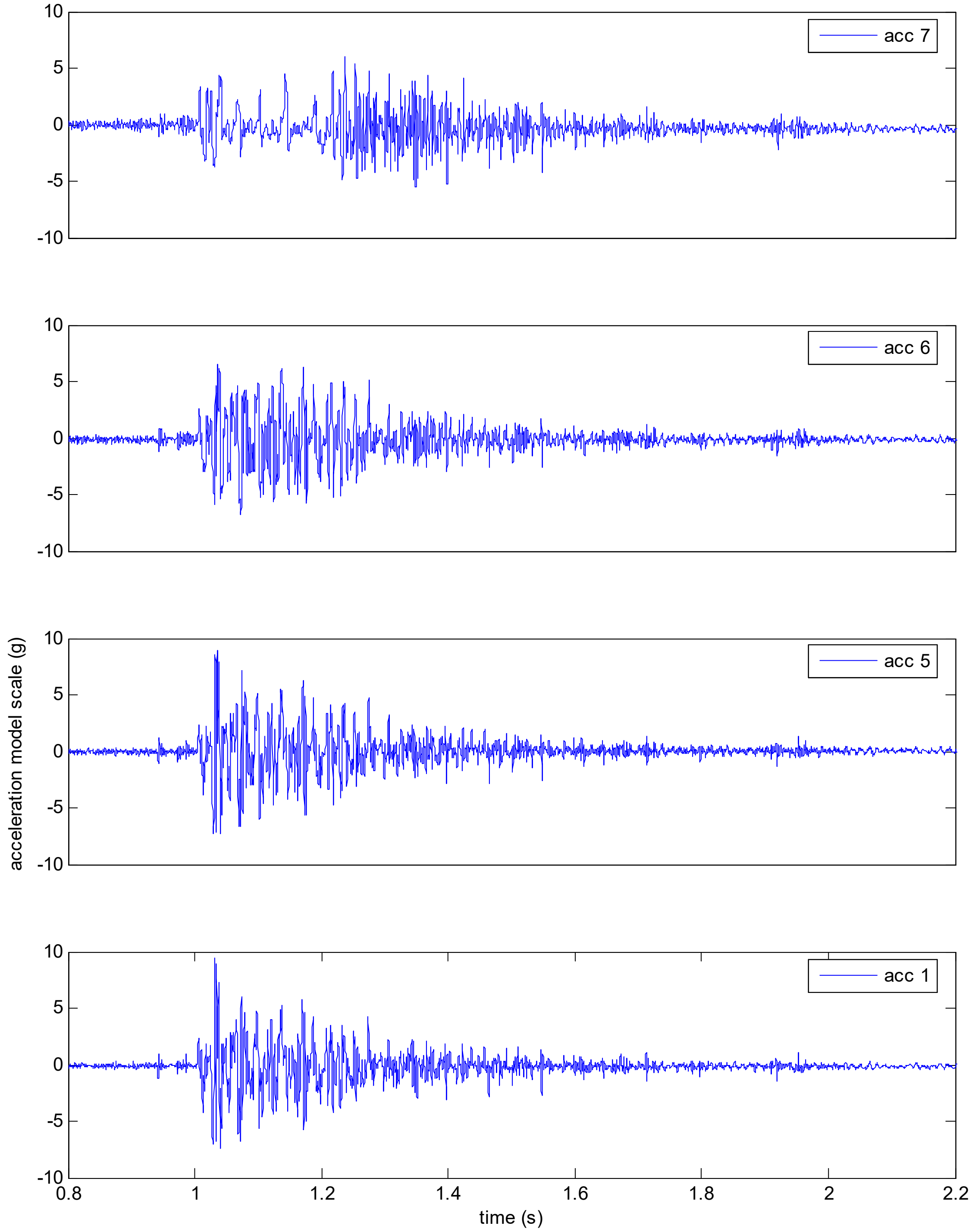
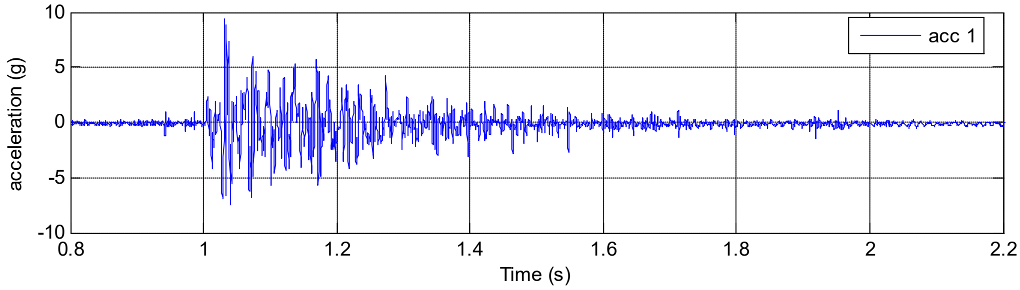
3 – Seismic Excitation

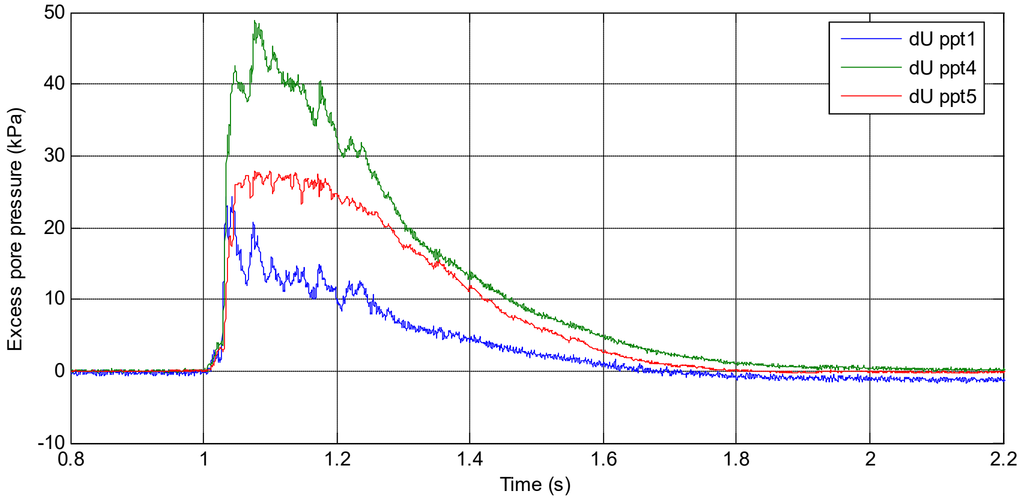
Accelerometers time histories



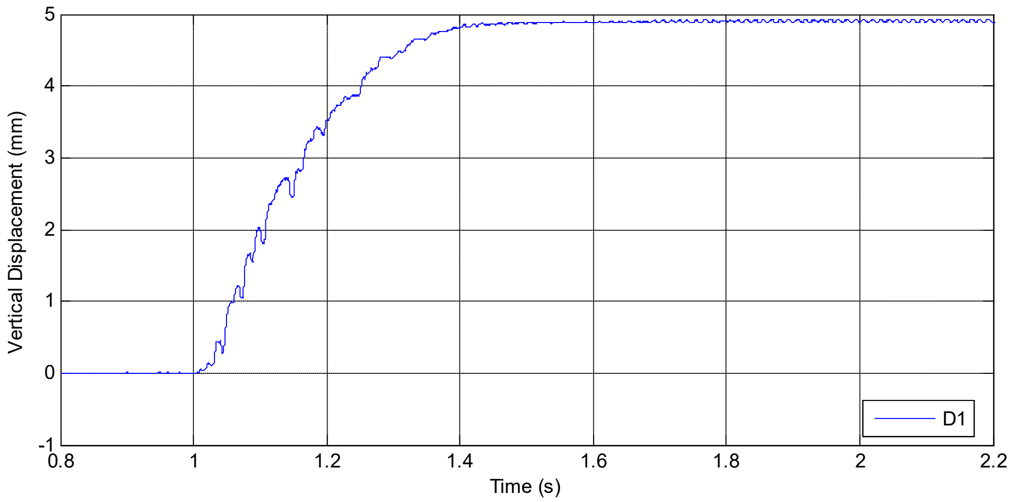
Input motion



Excess pore pressure $\Delta u(t) = u(t) - u_0$ vs. time



Vertical displacements vs. time



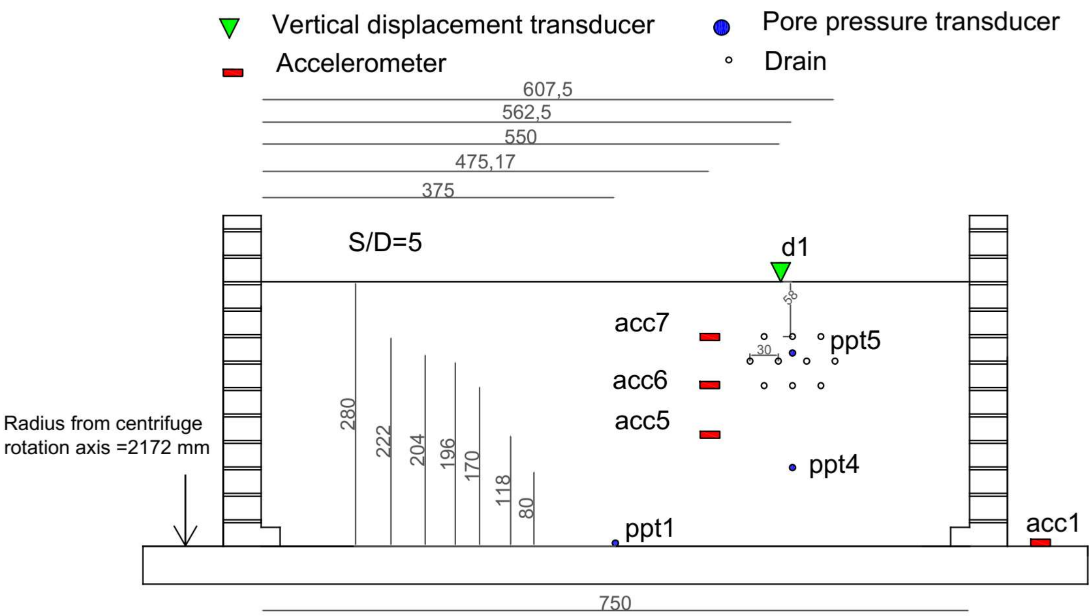
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

Test 18: M1_S1_HD1_GM31

Model description

The model consists of a homogeneous soil profile of Ticino sand, the ground motion applied was the number 31. Model horizontal drains installed at a spacing of 5 diameters S/D=5.

Models characteristics



Ticino sand

Dry density [kN·s^2/m^4]	**1.497**
Relative density [%]	**39.14**
Void ratio [-]	**0.79**

2 – Equilibrium at centrifuge angular velocity ω= 15.08 rad/s before the shock

Ticino sand, average values

Dry density [kN·s²/m⁴]	**1.543**
Saturated density [kN·s²/m⁴]	**1.971**
Relative density [%]	**54.48**
Void ratio [-]	**0.74**
Degree of saturation [%]	**100.0**

Radii from centrifuge rotation axis

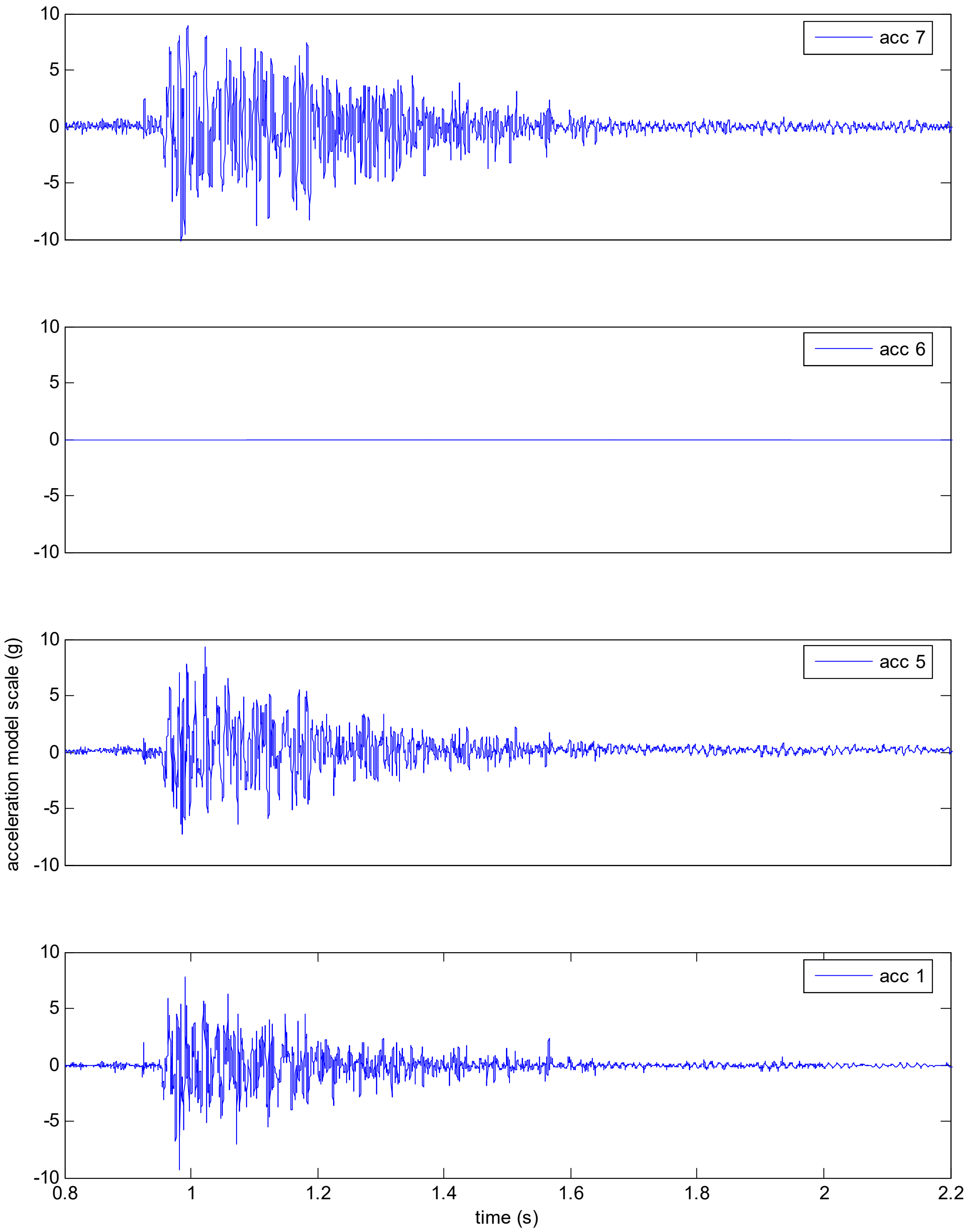
	Radius (mm)
model base	2172.0
free ground surface	1899.4

Pore Pressure Transducer	**Radius (mm)**	**Value before the shock u_0 (kPa)**
ppt5	1974.1	37.4
ppt4	2094.4	-
ppt1	2172.0	118.3

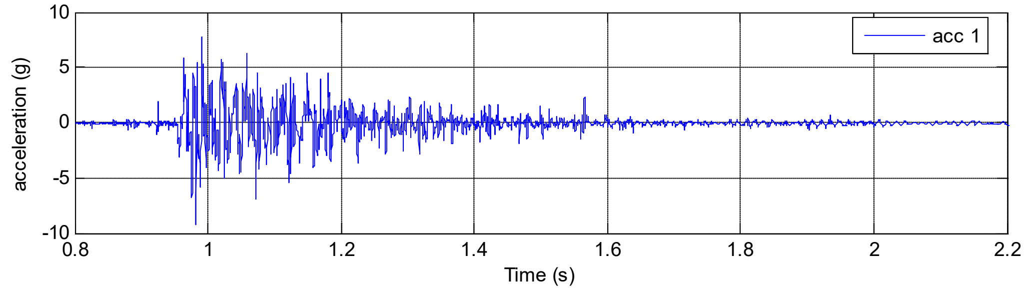
Accelerometer	**Radius (mm)**
acc7	1956.6
acc6	2007.1
acc5	2057.5
acc1	2172.0

3 – Seismic Excitation

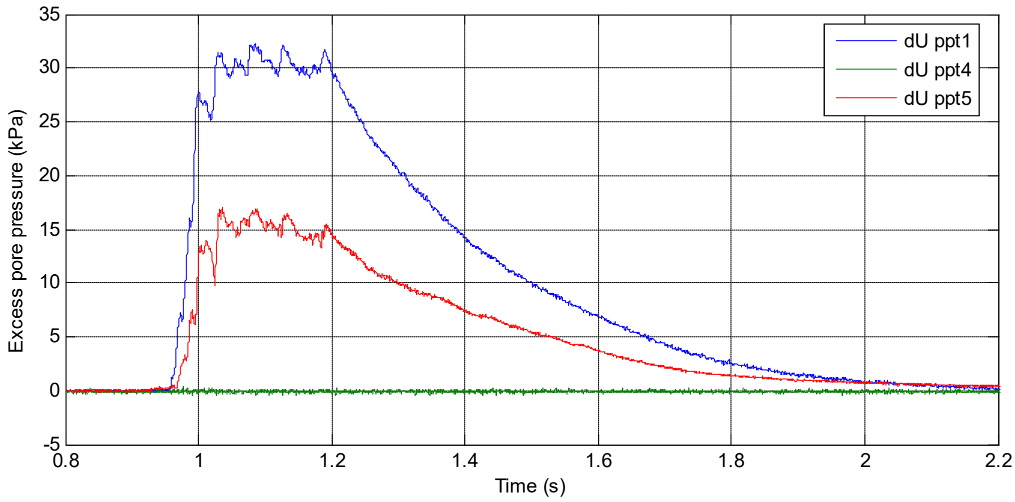
Accelerometers time histories



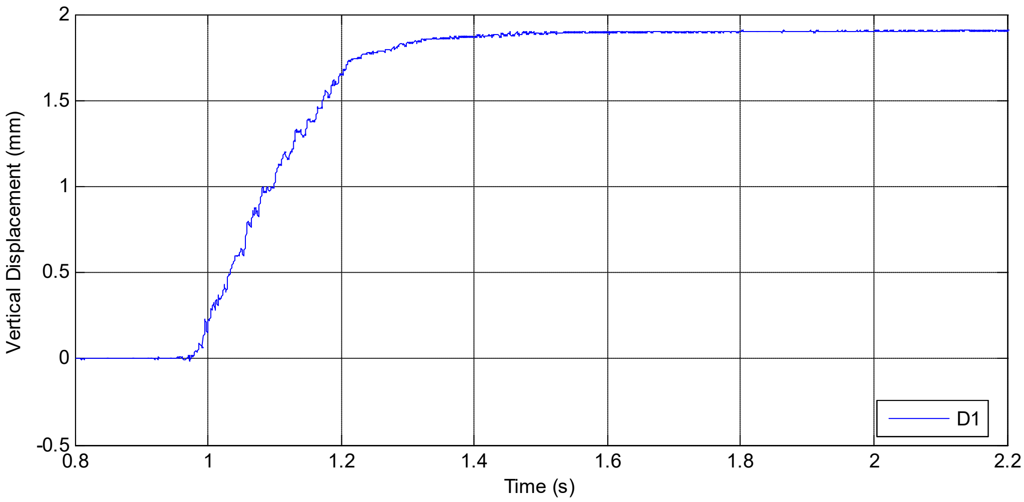
Input motion



Excess pore pressure $\Delta u(t) = u(t) - u_0$ vs. time



Vertical displacements vs. time



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

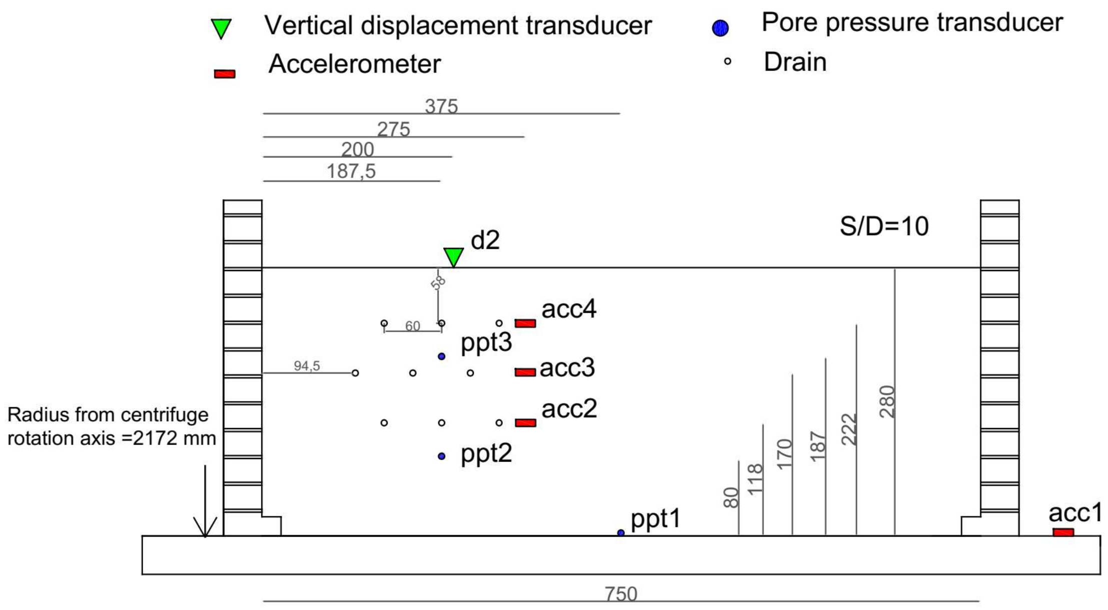
Test 19: M1_S1_HD2_GM31

Model description

The model consists of a homogeneous soil profile of Ticino sand, the ground motion applied was the number 31. Model horizontal drains installed at a spacing of 10 diameters S/D=10.

1 – Reconstruction

Scheme and geometrical dimensions of the model as reconstructed at 1g. The following dimensions refer to model scale.



Ticino sand

Dry density [kN·s²/m⁴]	**1.497**
Relative density [%]	**39.14**
Void ratio [-]	**0.79**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

2 – Equilibrium at centrifuge angular velocity ω= 15.08 rad/s before the shock

Ticino sand, average values

Dry density [kN·s^2/m^4]	**1.543**
Saturated density [kN·s^2/m^4]	**1.971**
Relative density [%]	**54.48**
Void ratio [-]	**0.74**
Degree of saturation [%]	**100.0**

Radii from centrifuge rotation axis

	Radius (mm)
model base	2172.0
free ground surface	1899.4

Pore Pressure Transducer	**Radius (mm)**	**Value before the shock u_0 (kPa)**
ppt3	1990.6	29.7
ppt2	2094.4	85.7
ppt1	2172.0	118.3

Accelerometer	**Radius (mm)**
acc4	1956.6
acc3	2007.1
acc2	2057.5
acc1	2172.0

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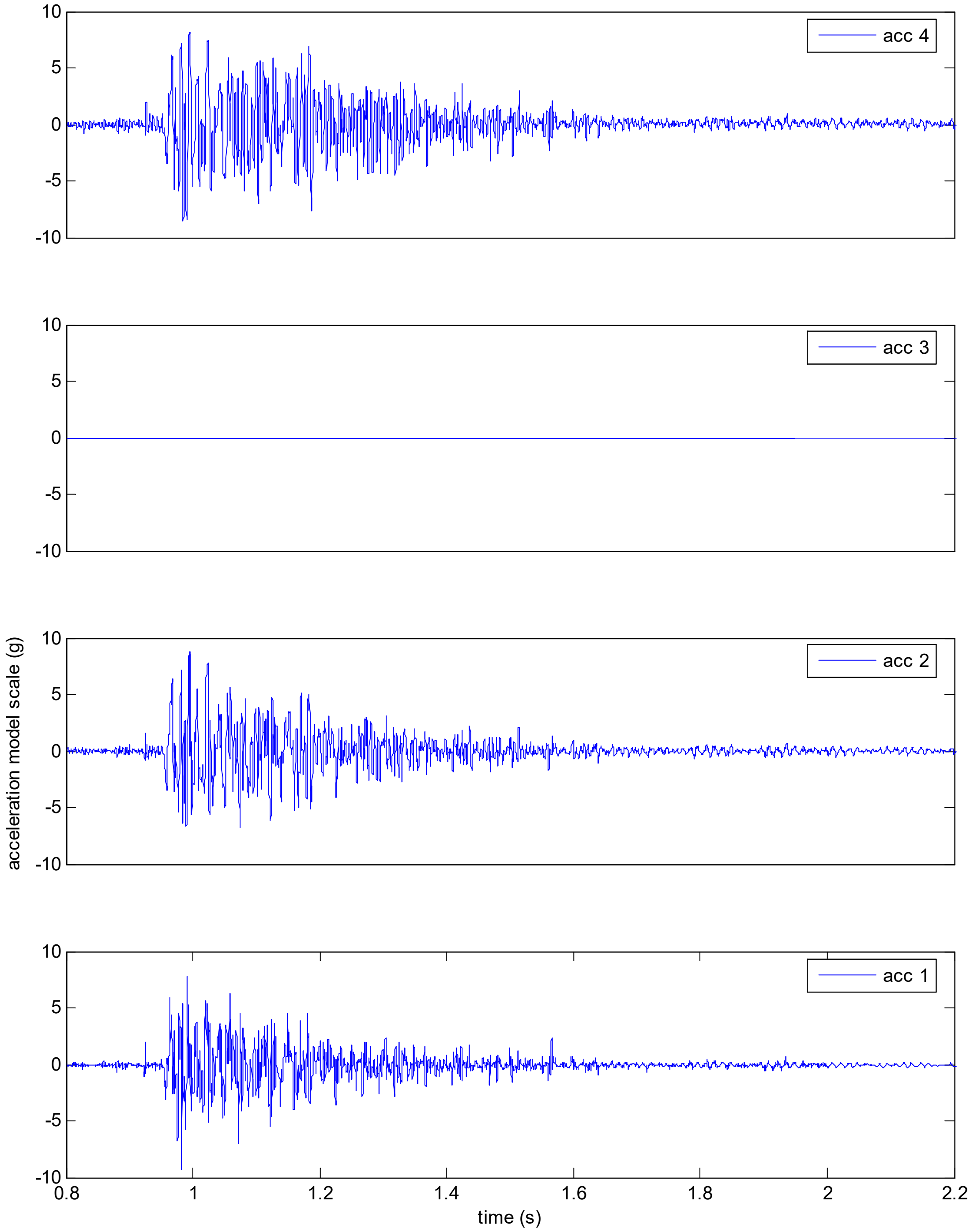
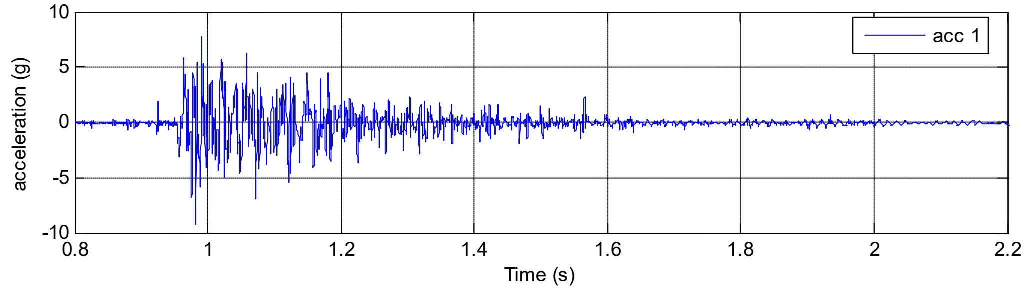
3 – Seismic Excitation

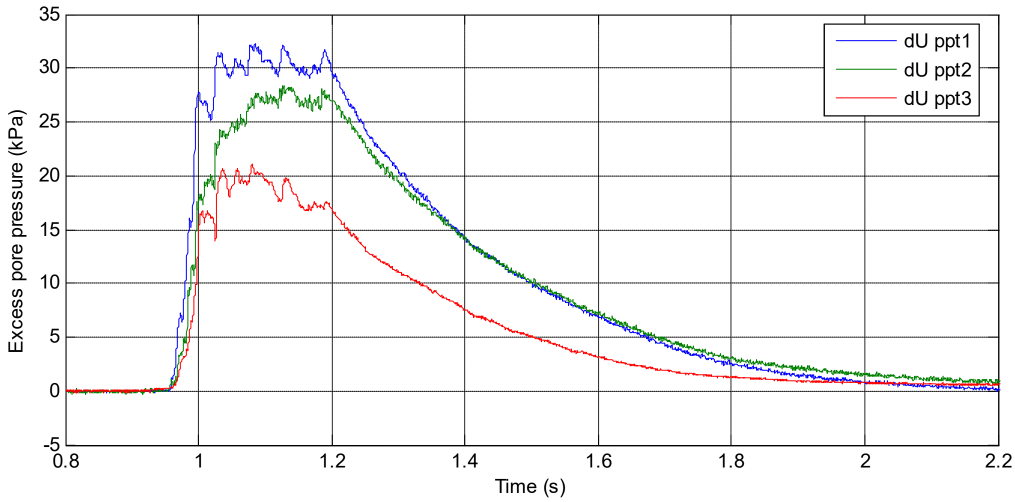
Accelerometers time histories



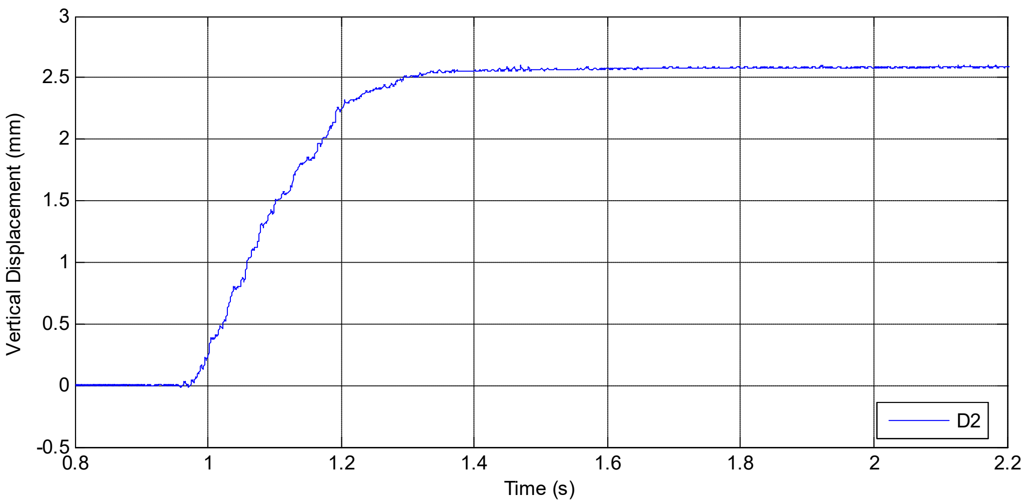
Input motion



Excess pore pressure $\Delta u(t) = u(t) - u_0$ vs. time



Vertical displacements vs. time



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

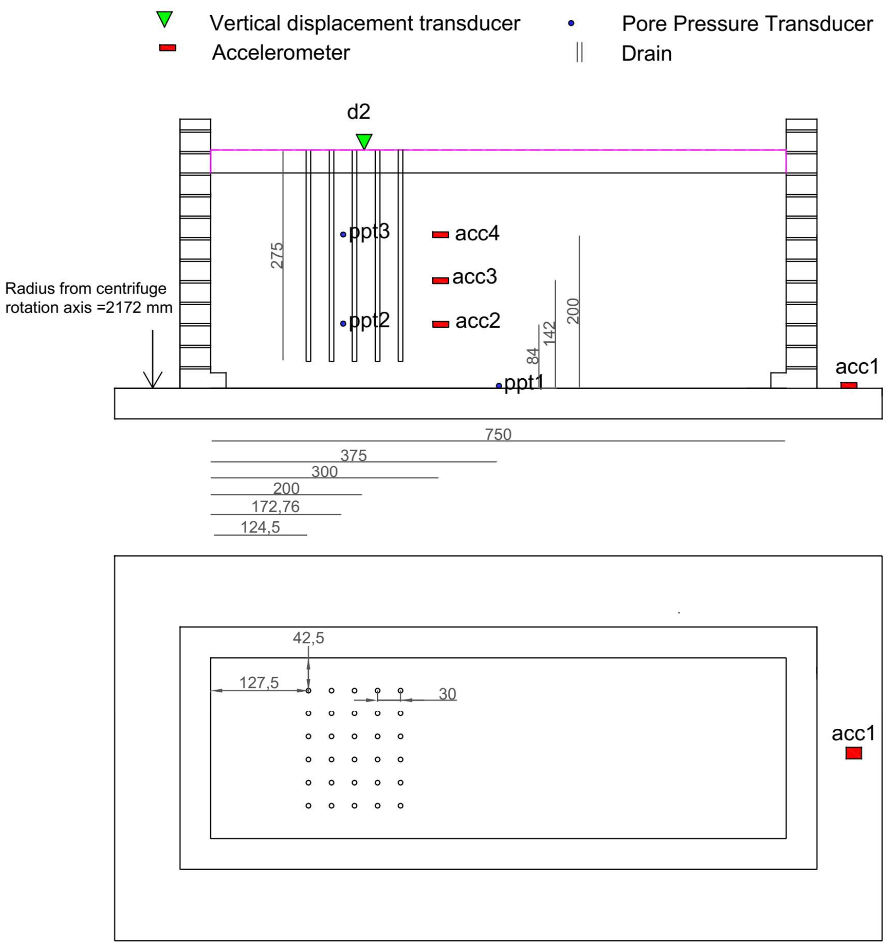
Test 20: M2_S1_VD1_GM31

Model description

The model consists of a two layers soil profile of Ticino sand and Pontida clay, the ground motion applied was the number 31. Model vertical drains installed at a spacing of 5 diameters S/D=5.

1 – Reconstruction

Scheme and geometrical dimensions of the model as reconstructed at 1g. The following dimensions refer to model scale.



Ticino sand

Dry density [kN·s²/m⁴]	**1.514**
Relative density [%]	**44.93**
Void ratio [-]	**0.77**

2 – Equilibrium at centrifuge angular velocity ω= 15.08 rad/s before the shock

Ticino sand, average values

Dry density [kN·s²/m⁴]	**1.545**
Saturated density [kN·s²/m⁴]	**1.966**
Relative density [%]	**55.15**
Void ratio [-]	**0.73**
Degree of saturation [%]	**99.3**

Pontida clay, average value

Mass density [kN·s²/m⁴]	**2.160**

Radii from centrifuge rotation axis

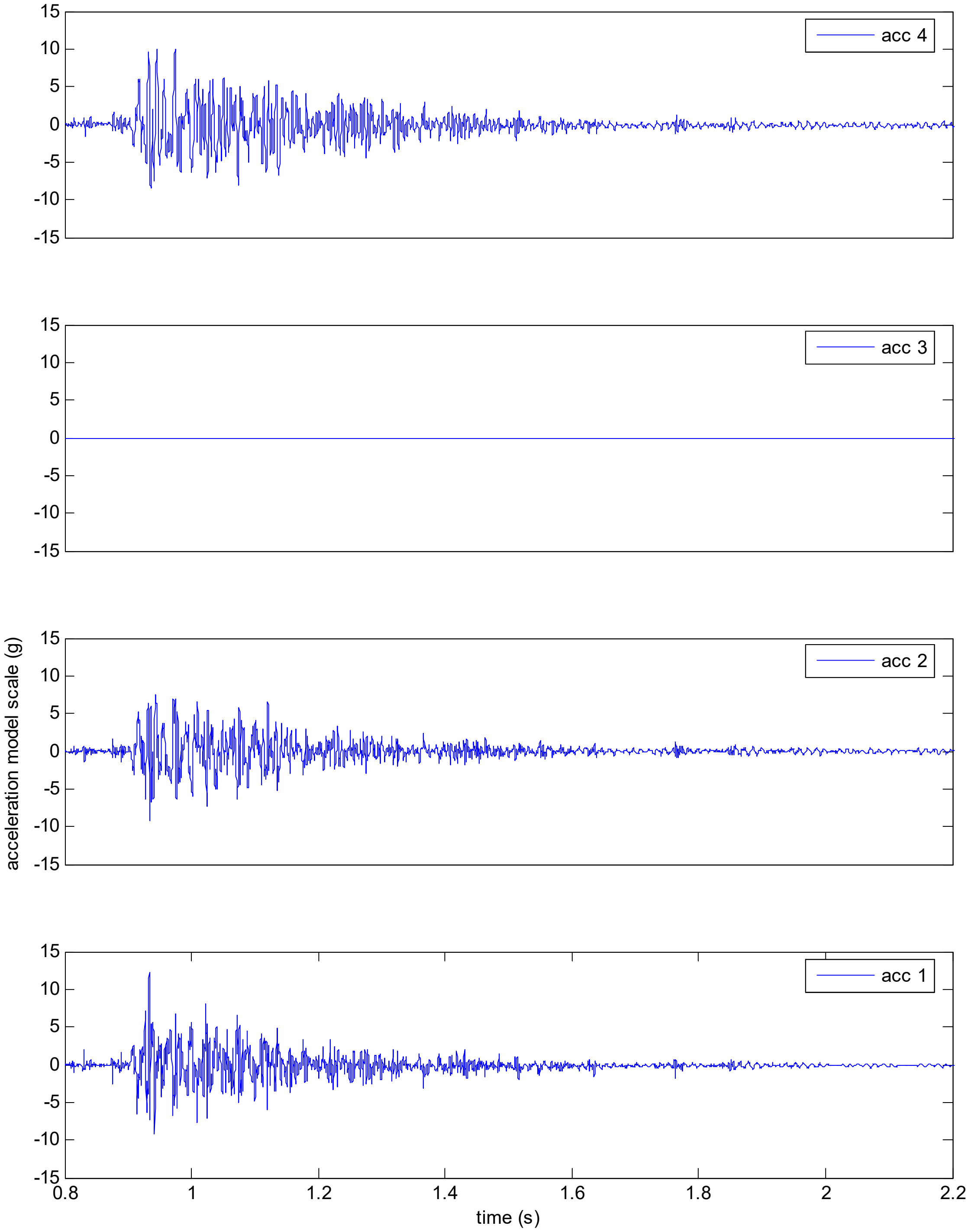
	Radius (mm)
model base	2172.0
free ground surface	1868.0
sand/clay interface	1897.6

Pore Pressure Transducer	**Radius (mm)**	**Value before the shock u_0 (kPa)**
ppt3	1976.0	36.1
ppt2	2089.7	-
ppt1	2172.0	122.1

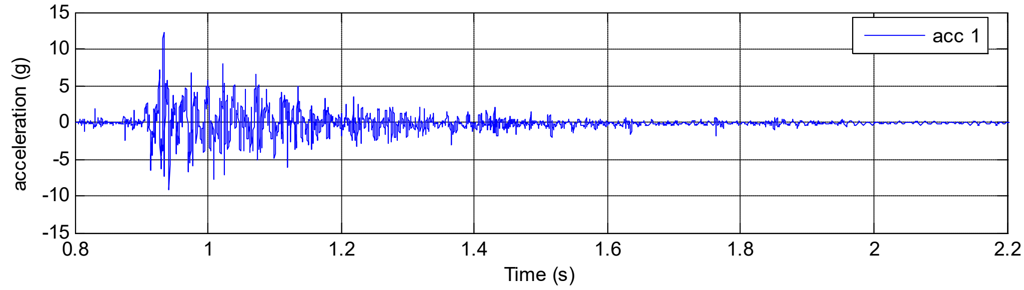
Accelerometer	**Radius (mm)**
acc4	1976.0
acc3	2032.9
acc2	2089.7
acc1	2172.0

3 – Seismic Excitation

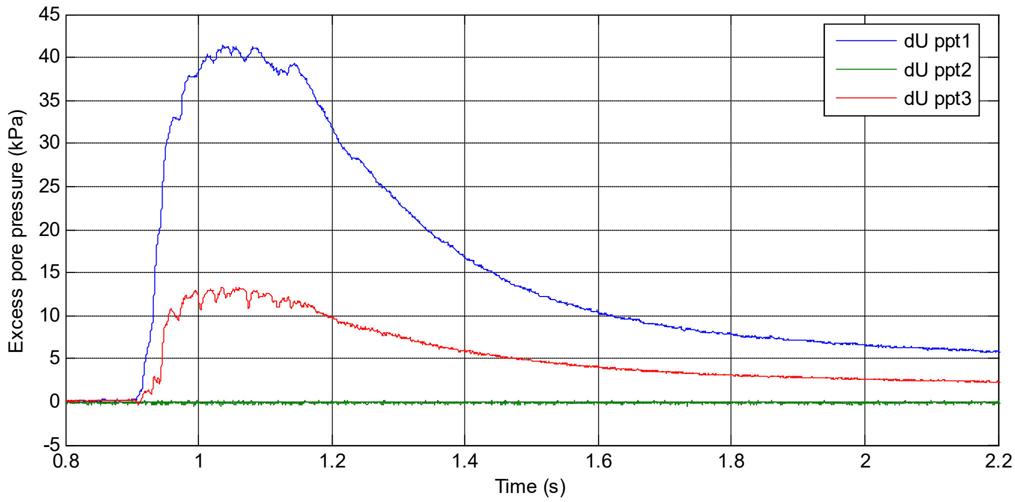
Accelerometers time histories



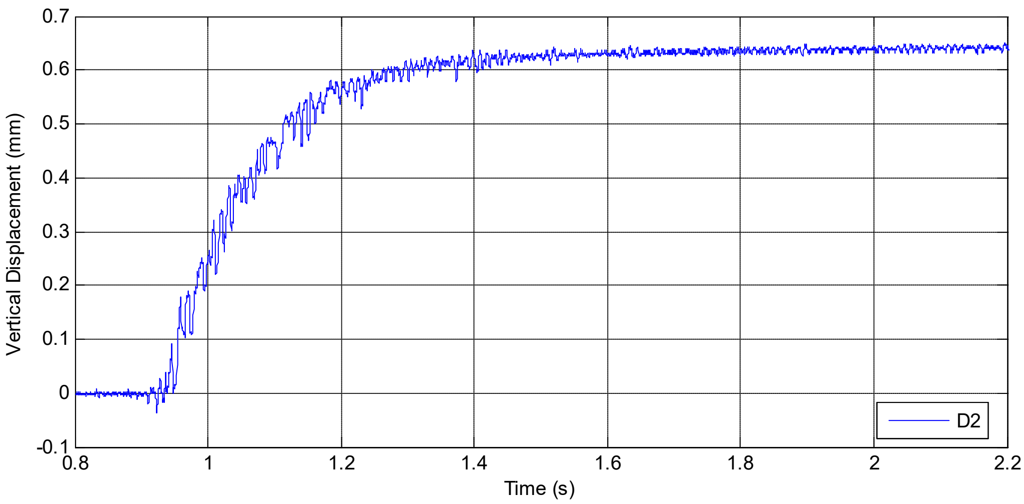
Input motion



Excess pore pressure $\Delta u(t) = u(t) - u_0$ vs. time



Vertical displacements vs. time



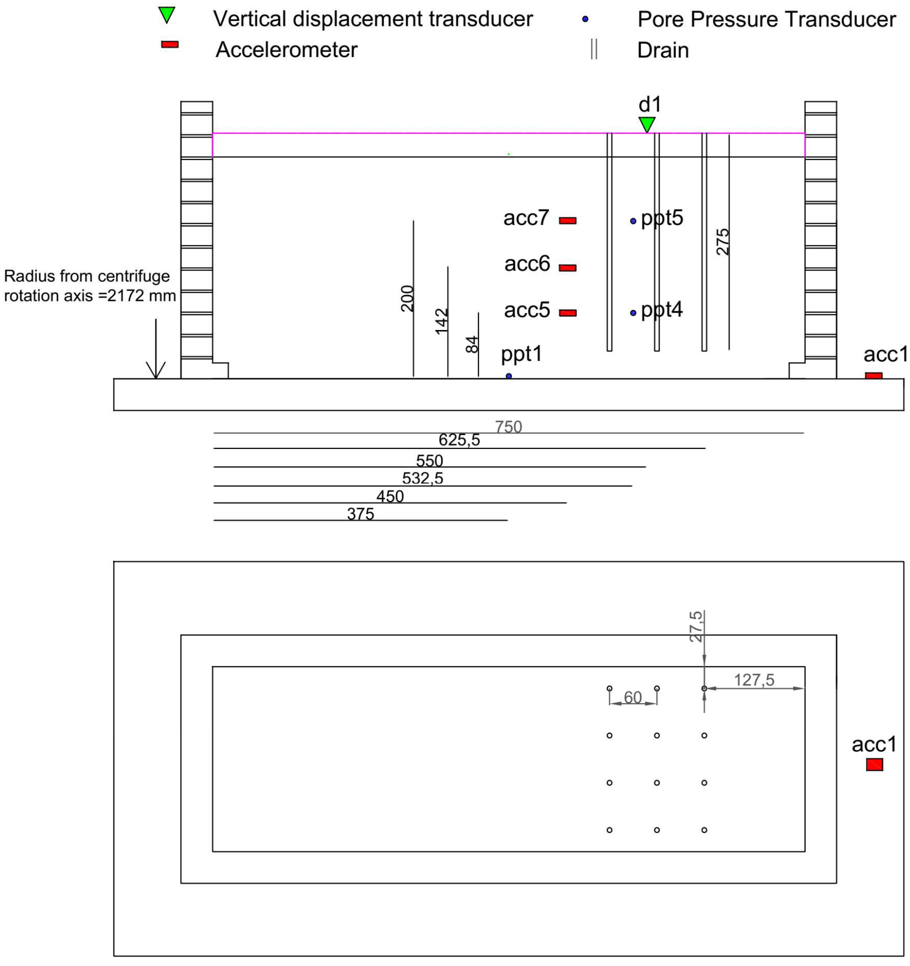
Test 21: M2_S1_VD2_GM31

Model description

The model consists of a two layers soil profile of Ticino sand and Pontida clay, the ground motion applied was the number 31. Model vertical drains installed at a spacing of 10 diameters S/D=10.

1 – Reconstruction

Scheme and geometrical dimensions of the model as reconstructed at 1g. The following dimensions refer to model scale.



Ticino sand

Dry density [kN·s²/m⁴]	**1.514**
Relative density [%]	**44.93**
Void ratio [-]	**0.77**

2 – Equilibrium at centrifuge angular velocity ω= 15.08 rad/s before the shock

Ticino sand, average values

Dry density [kN·s^2/m^4]	**1.545**
Saturated density [kN·s^2/m^4]	**1.966**
Relative density [%]	**55.15**
Void ratio [-]	**0.73**
Degree of saturation [%]	**99.3**

Pontida clay, average value

Mass density [kN·s^2/m^4]	**2.160**

Radii from centrifuge rotation axis

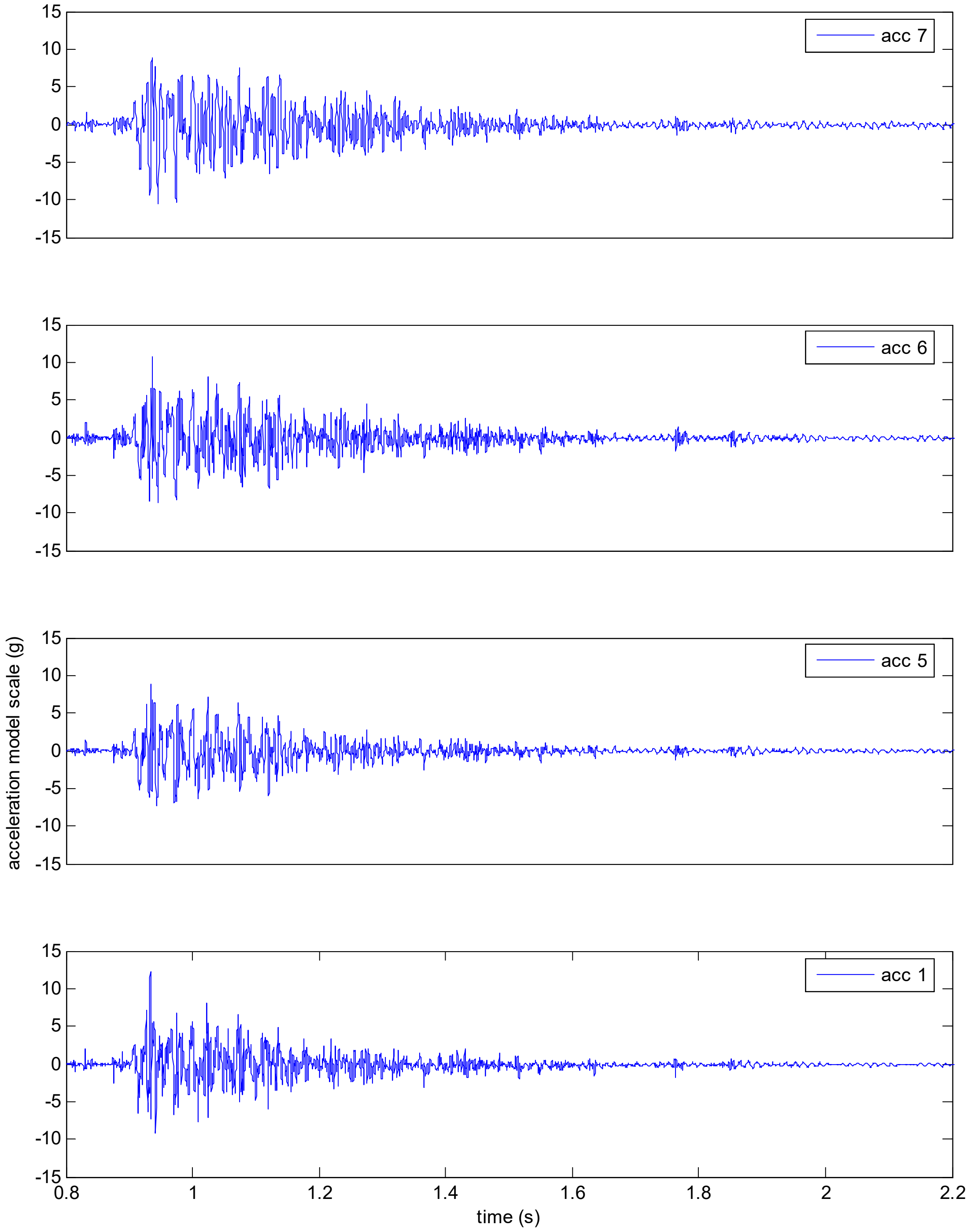
	Radius (mm)
model base	2172.0
free ground surface	1868.0
sand/clay interface	1897.6

Pore Pressure Transducer	**Radius (mm)**	**Value before the shock u_0 (kPa)**
ppt5	1976.0	38.8
ppt4	2089.7	96.8
ppt1	2172.0	122.1

Accelerometer	**Radius (mm)**
acc7	1976.0
acc6	2032.9
acc5	2089.7
acc1	2172.0

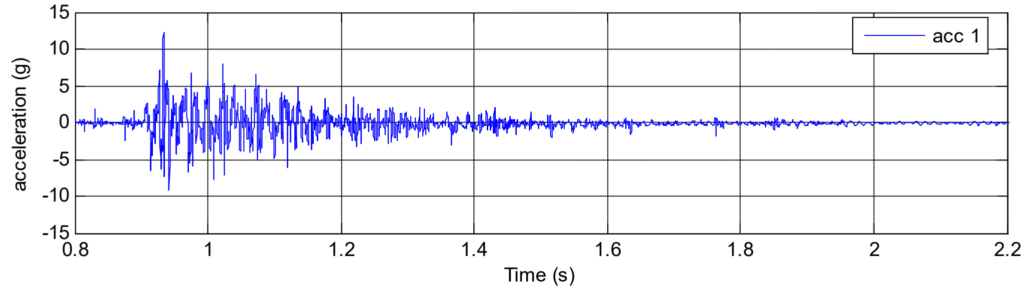
3 – Seismic Excitation

Accelerometers time histories

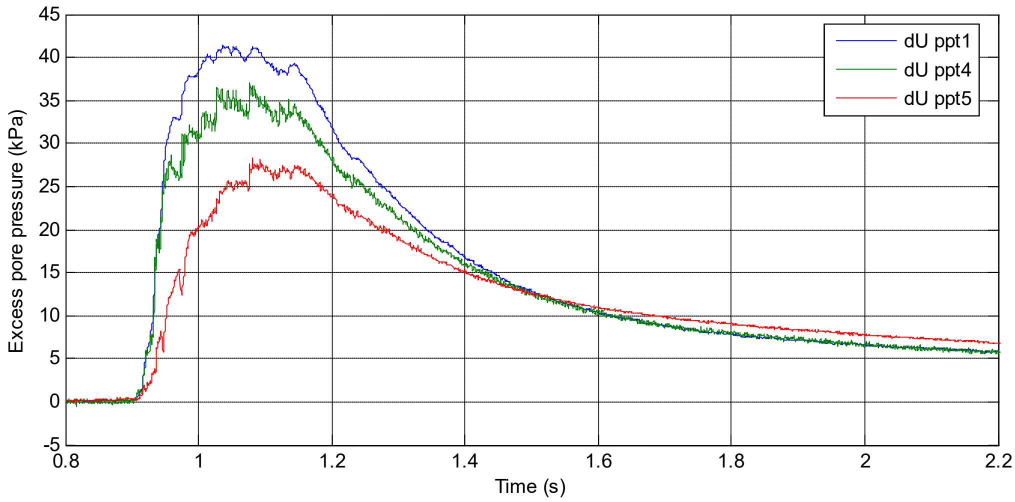


This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

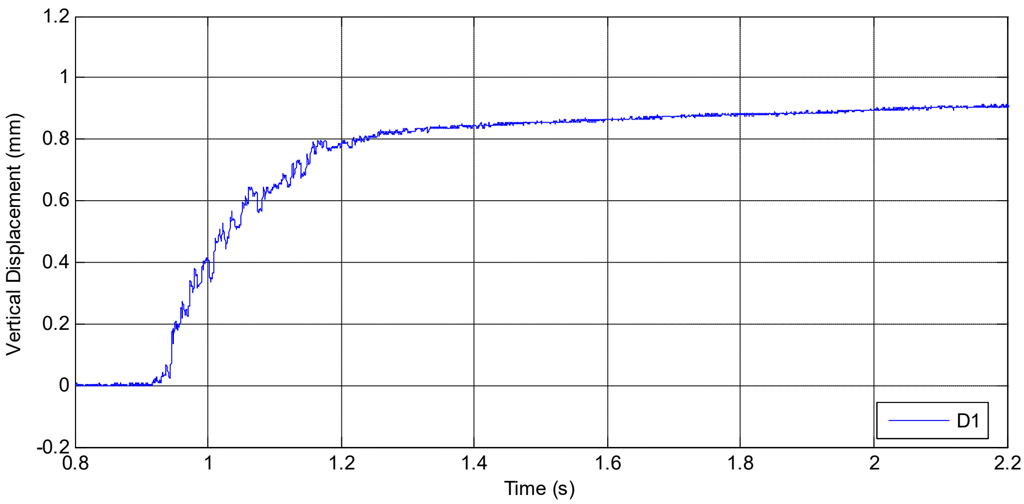
Input motion



Excess pore pressure Δu(t) = u(t) - u_0 vs. time



Vertical displacements vs. time



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

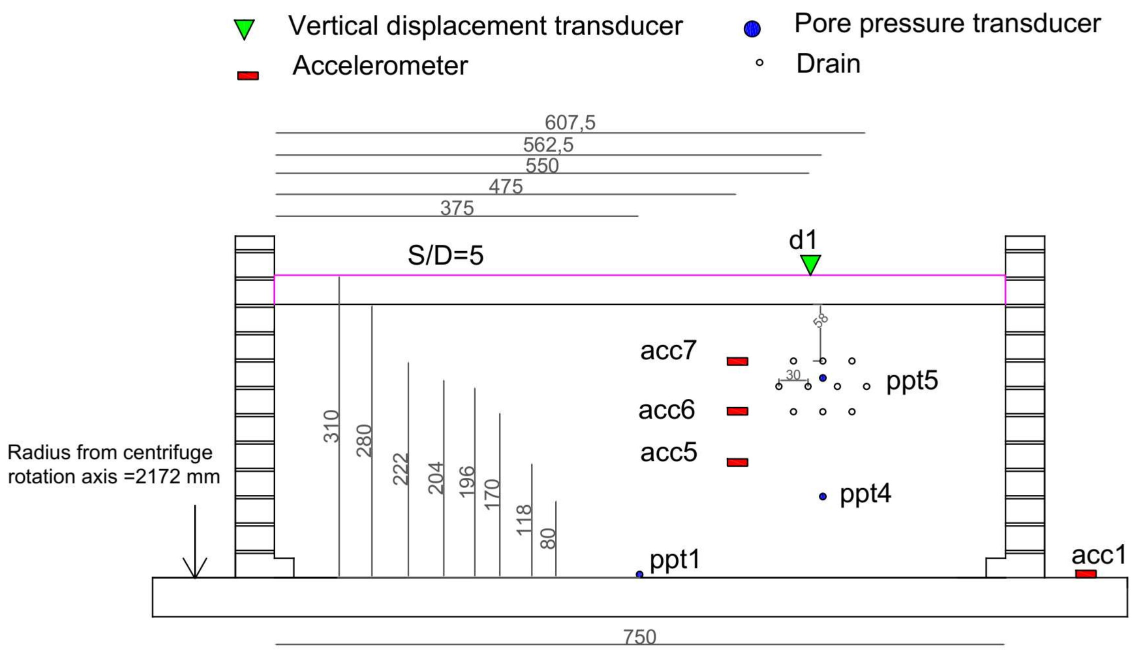
Test 22: M2_S1_HD1_GM31

Model description

The model consists of a two layers soil profile of Ticino sand and Pontida clay, the ground motion applied was the number 31. Model horizontal drains installed at a spacing of 5 diameters S/D=5.

1 – Reconstruction

Scheme and geometrical dimensions of the model as reconstructed at 1g. The following dimensions refer to model scale.



Ticino sand

Dry density [kN·s^2/m^4]	**1.502**
Relative density [%]	**40.97**
Void ratio [-]	**0.78**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

2 – Equilibrium at centrifuge angular velocity ω= 15.08 rad/s before the shock

Ticino sand, average values

Dry density [kN·s²/m⁴]	**1.537**
Saturated density [kN·s²/m⁴]	**1.960**
Relative density [%]	**52.48**
Void ratio [-]	**0.74**
Degree of saturation [%]	**99.1**

Pontida clay, average value

Mass density [kN·s²/m⁴]	**2.160**

Radii from centrifuge rotation axis

	Radius (mm)
model base	2172.0
free ground surface	1868.9
sand/clay interface	1898.3

Pore Pressure Transducer	**Radius (mm)**	**Value before the shock u_0 (kPa)**
ppt5	1972.6	36.7
ppt4	2093.8	110.0
ppt1	2172.0	122.5

Accelerometer	**Radius (mm)**
acc7	1955.0
acc6	2005.8
acc5	2056.7
acc1	2172.0

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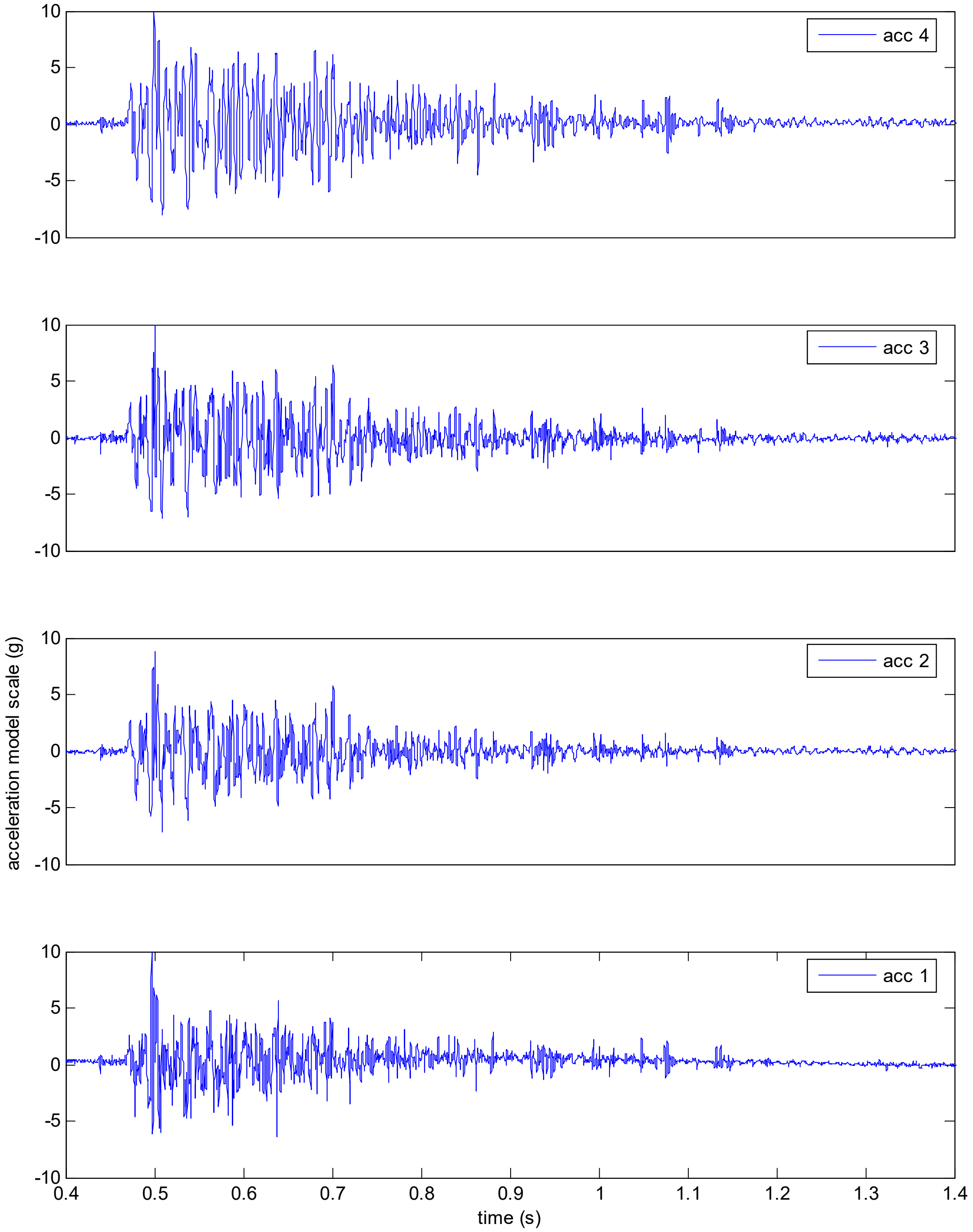
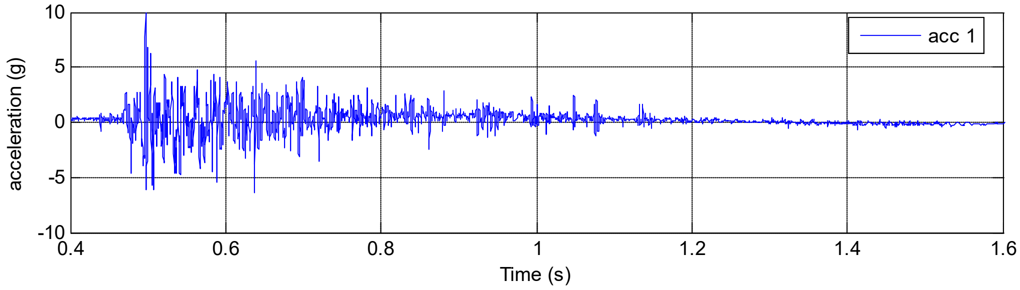
3 – Seismic Excitation

Accelerometers time histories

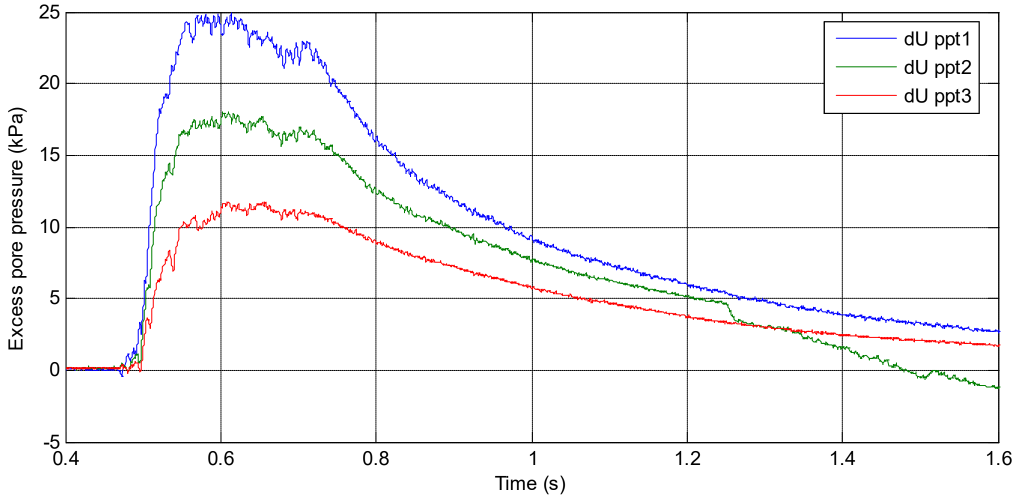


This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

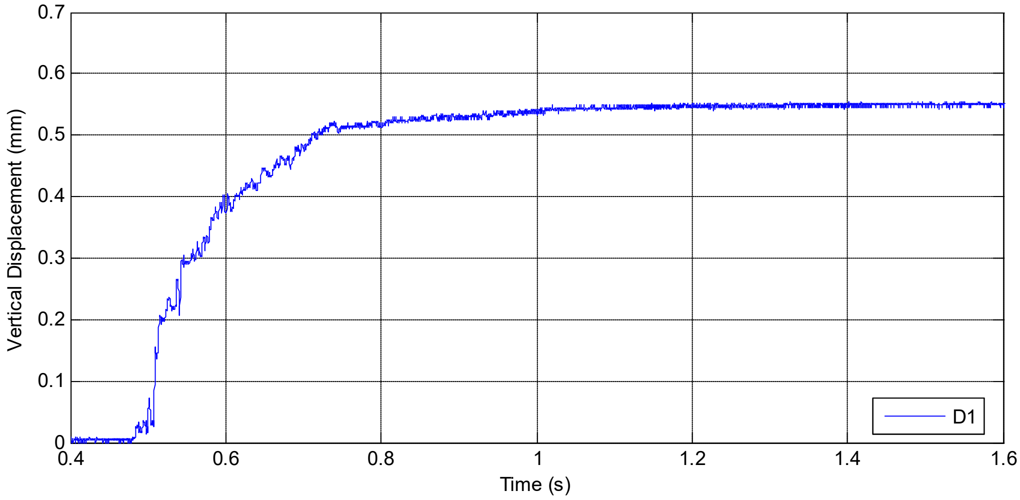
Input motion



Excess pore pressure $\Delta u(t) = u(t) - u_0$ vs. time



Vertical displacements vs. time



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

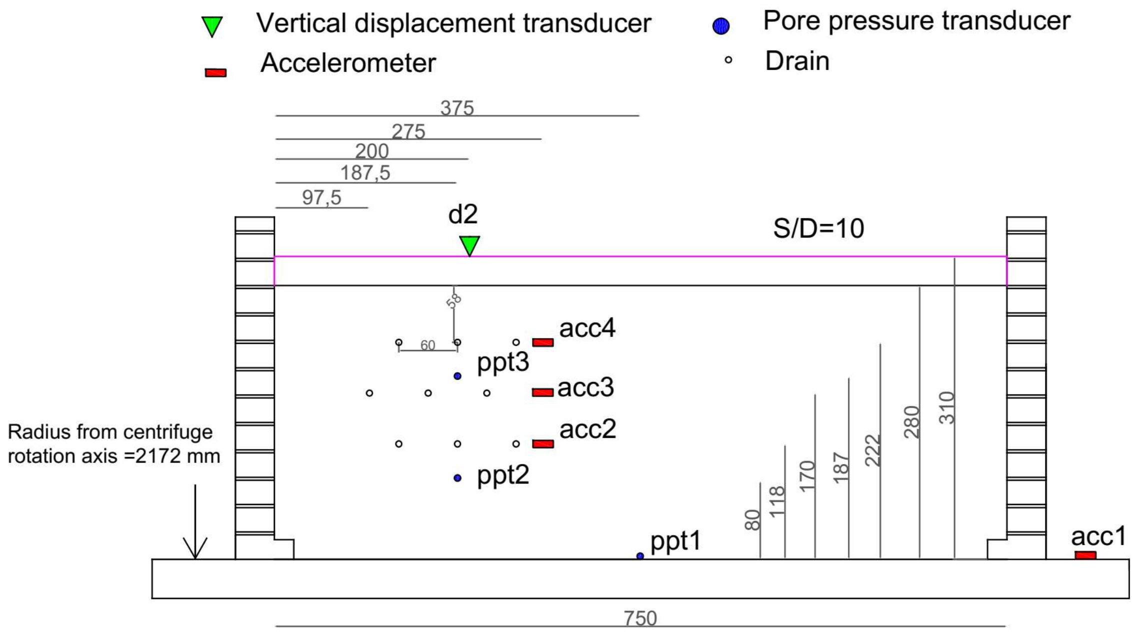
Test 23: M2_S1_HD2_GM31

Model description

The model consists of a two layers soil profile of Ticino sand and Pontida clay, the ground motion applied was the number 31. Model horizontal drains installed at a spacing of 10 diameters S/D=10.

1 – Reconstruction

Scheme and geometrical dimensions of the model as reconstructed at 1g. The following dimensions refer to model scale.



Ticino sand

Dry density [kN·s^2/m^4]	**1.502**
Relative density [%]	**40.97**
Void ratio [-]	**0.78**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

2 – Equilibrium at centrifuge angular velocity ω= 15.08 rad/s before the shock

Ticino sand, average values

Dry density [kN·s^2/m^4]	**1.537**
Saturated density [kN·s^2/m^4]	**1.960**
Relative density [%]	**52.48**
Void ratio [-]	**0.74**
Degree of saturation [%]	**99.1**

Pontida clay, average value

Mass density [kN·s^2/m^4]	**2.160**

Radii from centrifuge rotation axis

	Radius (mm)
model base	2172.0
free ground surface	1868.9
sand/clay interface	1898.3

Pore Pressure Transducer	Radius (mm)	Value before the shock u_0 (kPa)
ppt3	1989.2	47.6
ppt2	2093.8	-
ppt1	2172.0	122.5

Accelerometer	Radius (mm)
acc7	1955.0
acc6	2005.8
acc5	2056.7
acc1	2172.0

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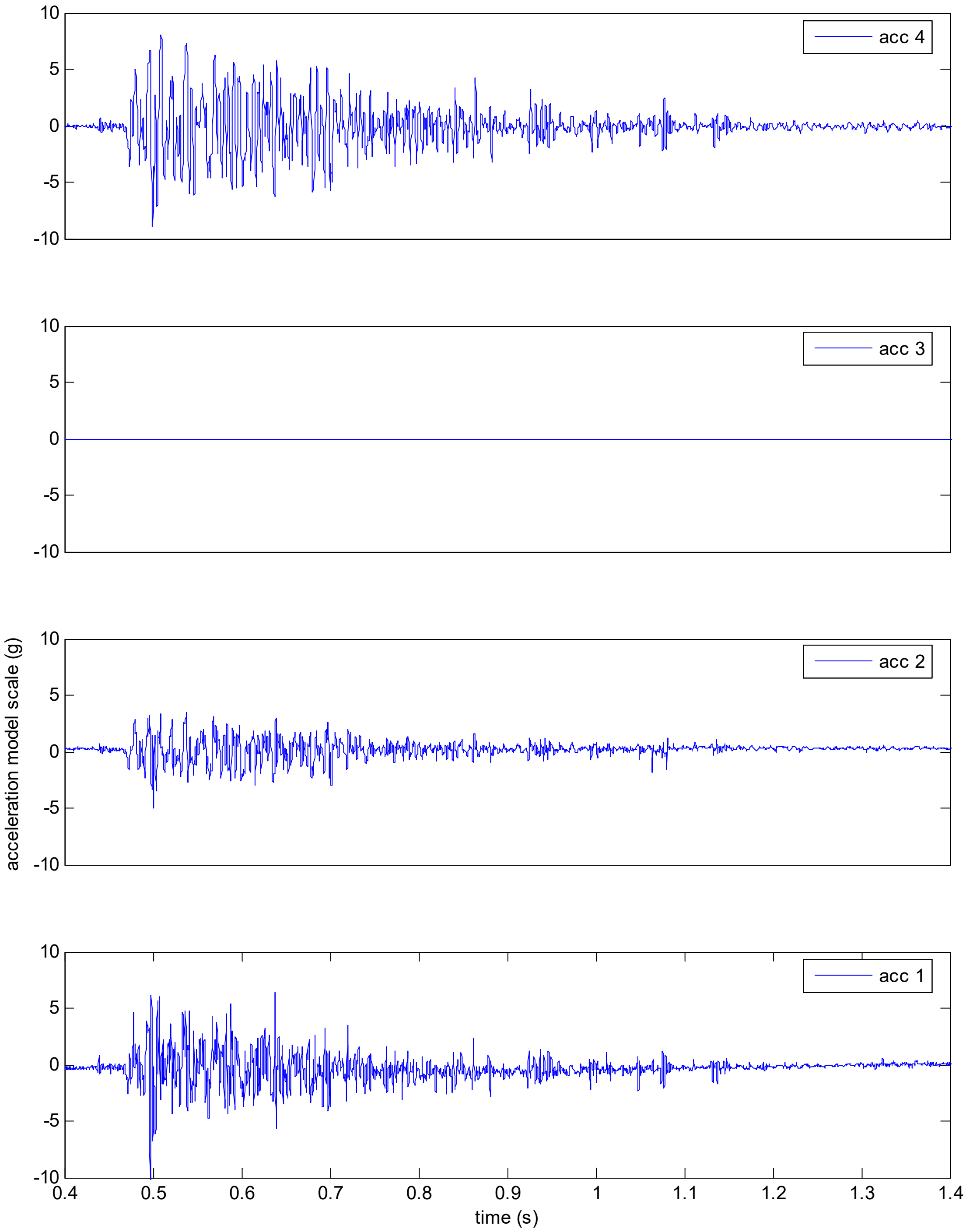
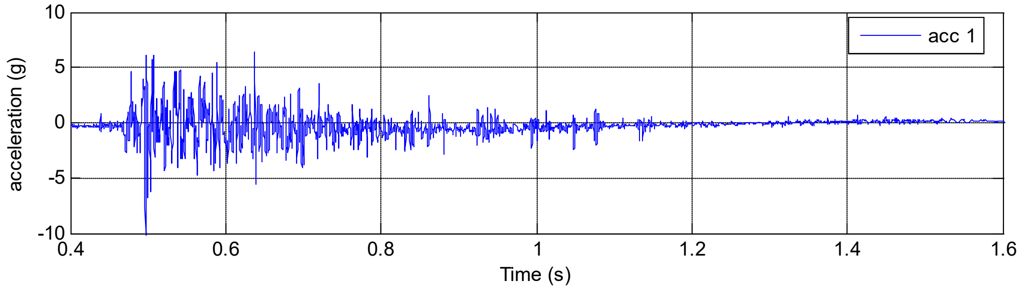
3 – Seismic Excitation

Accelerometers time histories

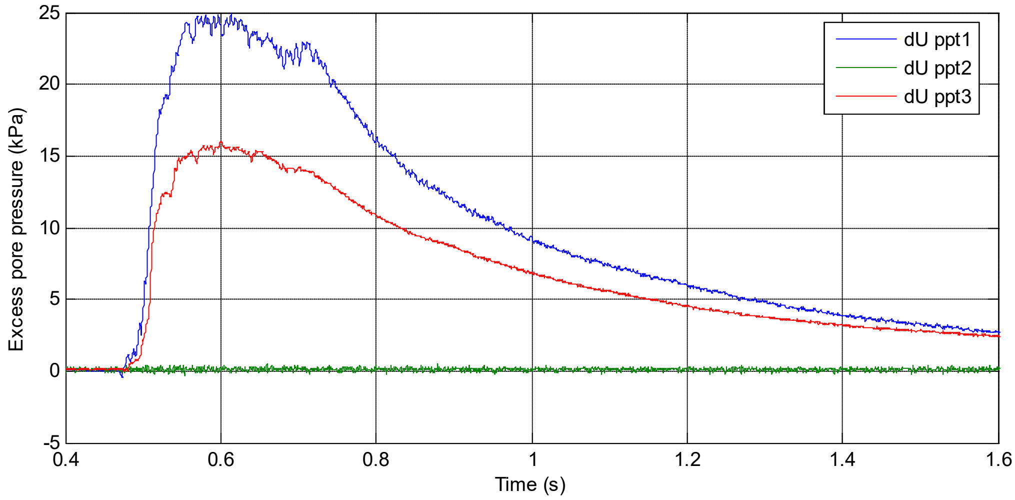


This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

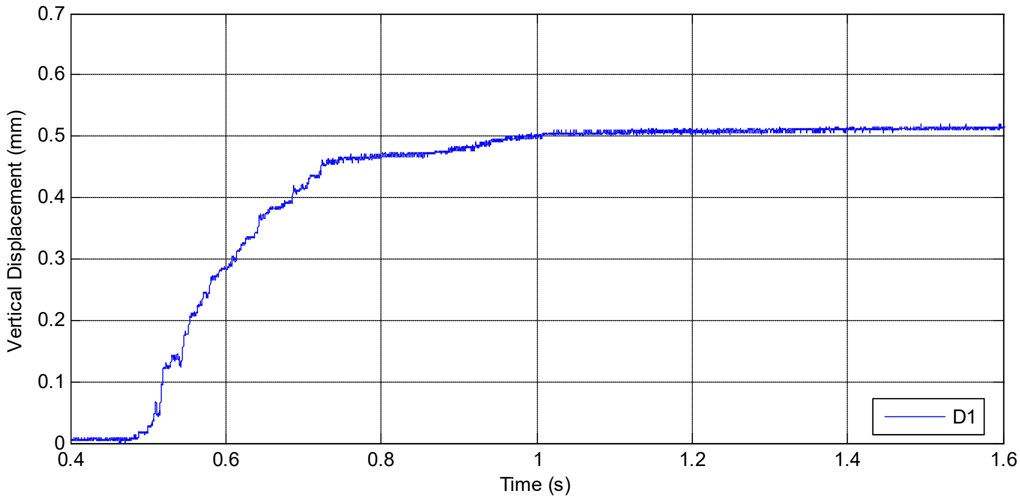
Input motion



Excess pore pressure $\Delta u(t) = u(t) - u_0$ vs. time



Vertical displacements vs. time



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

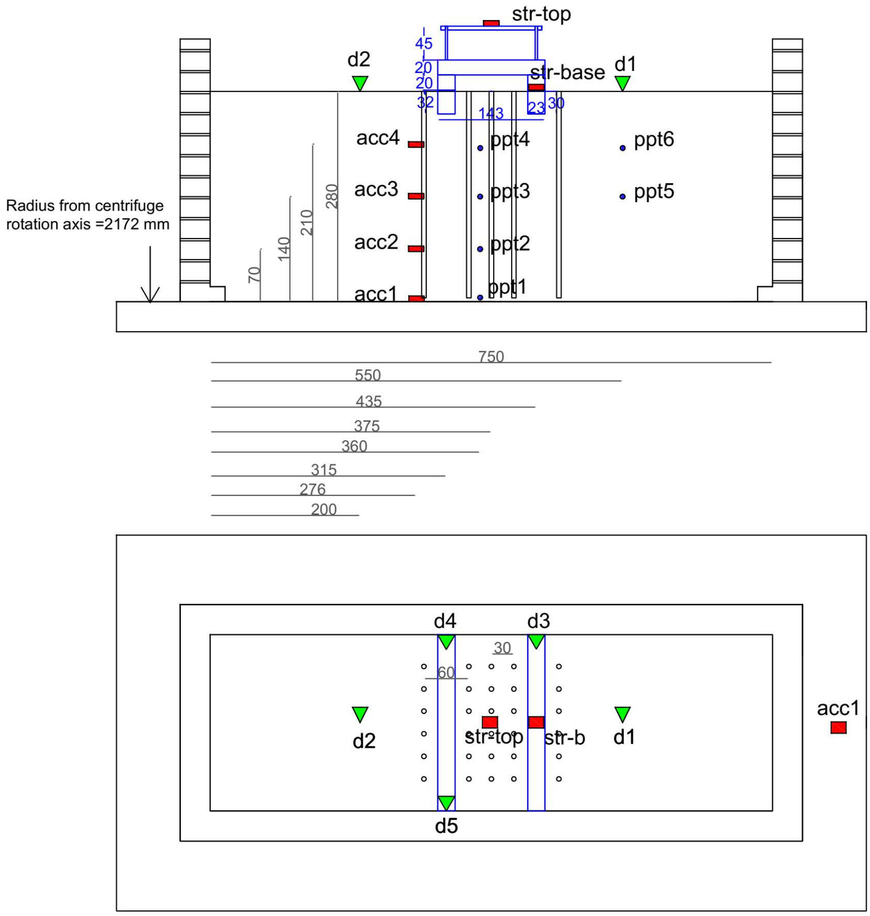
Test 24: M1F_S1_VD1_GM31+

Model description

The model consists of a homogenous soil profile of Ticino sand, with a model structure with shallow foundations. The ground motion applied was the number 31+. Model vertical drains installed at a spacing of 5 diameters S/D=5.

1 – Reconstruction

Scheme and geometrical dimensions of the model as reconstructed at 1g. The following dimensions refer to model scale.



Ticino sand

Dry density [kN·s^2/m^4]	**1.499**
Relative density [%]	**40.01**
Void ratio [-]	**0.79**

2 – Equilibrium at centrifuge angular velocity ω= 15.08 rad/s before the shock

Ticino sand, average values

Dry density [kN·s²/m⁴]	**1.531**
Saturated density [kN·s²/m⁴]	**1.960**
Relative density [%]	**50.61**
Void ratio [-]	**0.75**
Degree of saturation [%]	**99.9**

Radii from centrifuge rotation axis

	Radius (mm)
model base	2172.0
free ground surface	1897.7

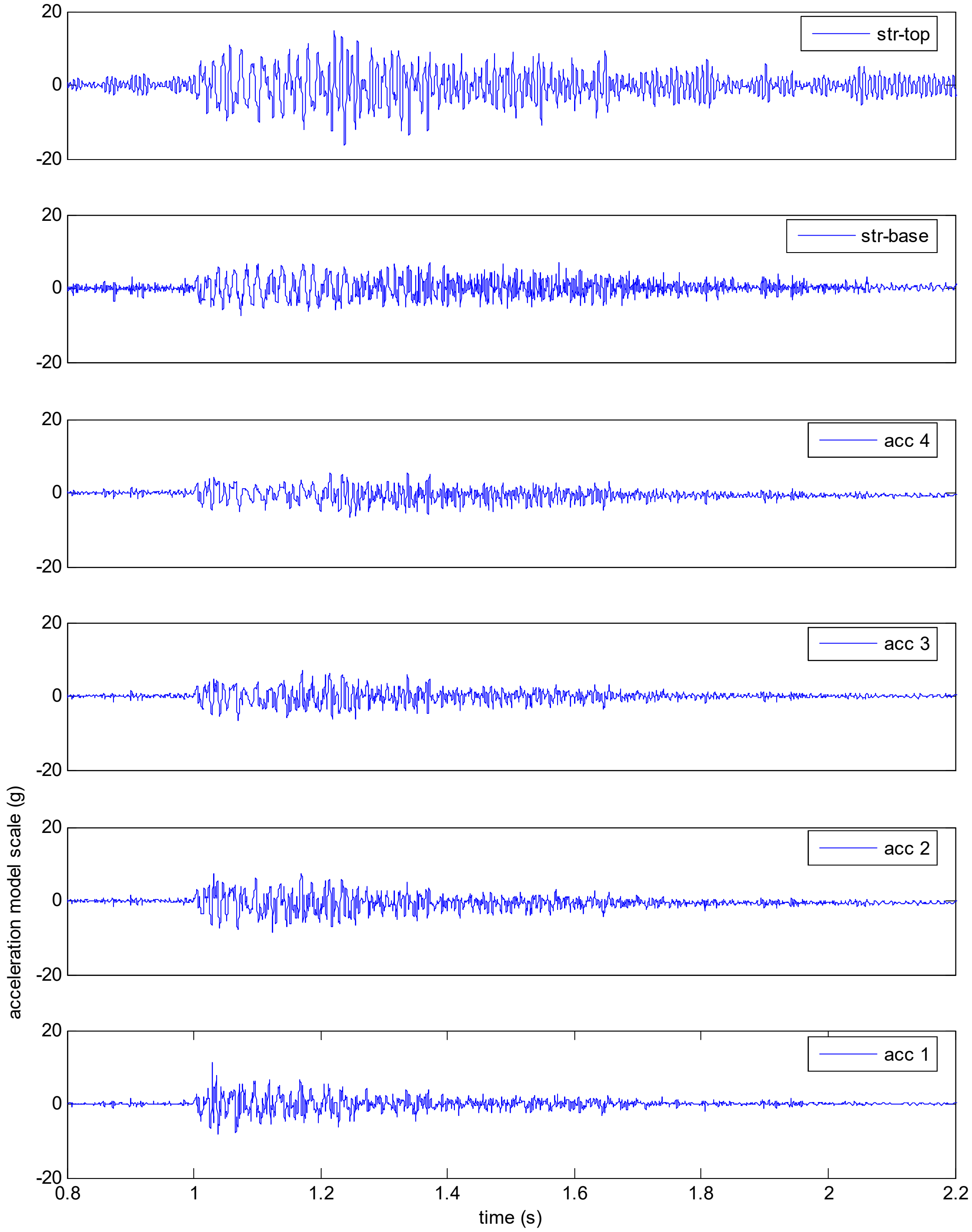
Pore Pressure Transducer	**Radius (mm)**	**Value before the shock u_0 (kPa)**
ppt6	1966.3	25.1
ppt5	2034.9	61.7
ppt4	1966.3	27.3
ppt3	2034.9	53.4
ppt2	2103.4	89.8
ppt1	2172.0	113.7

Accelerometer	**Radius (mm)**
acc4	1966.3
acc3	2034.9
acc2	2103.4
acc1	2172.0

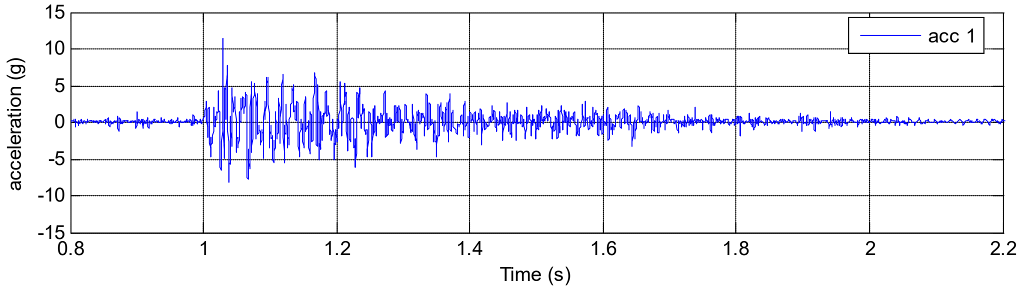
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

3 – Seismic Excitation

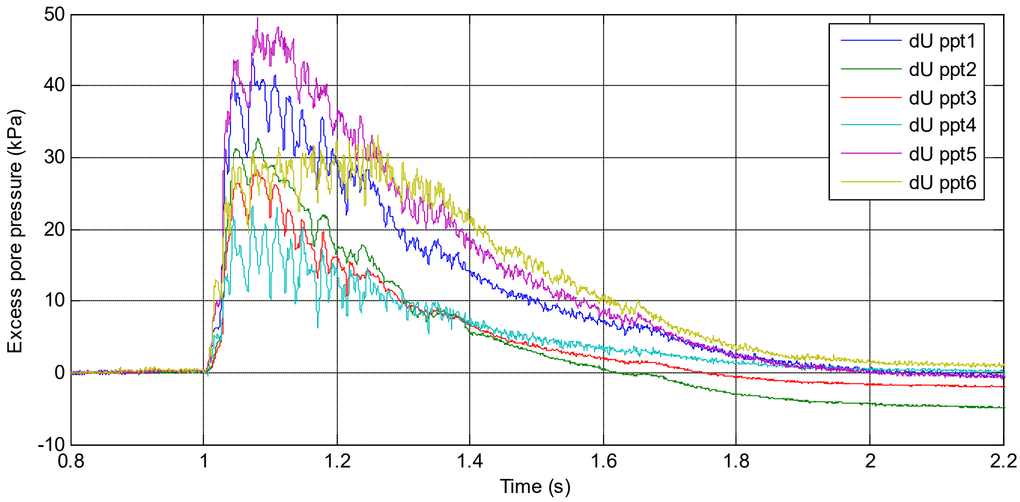
Accelerometers time histories



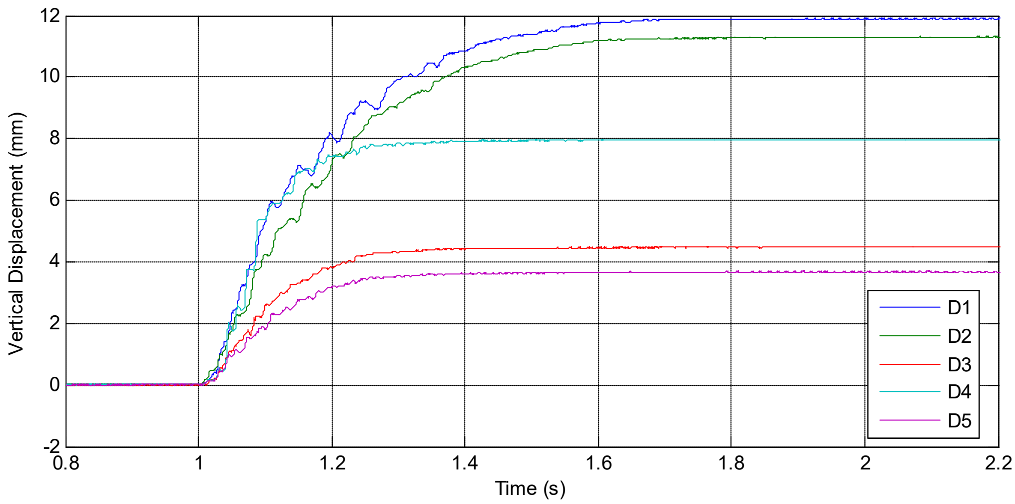
Input motion



Excess pore pressure $\Delta u(t) = u(t) - u_0$ vs. time



Vertical displacements vs. time



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

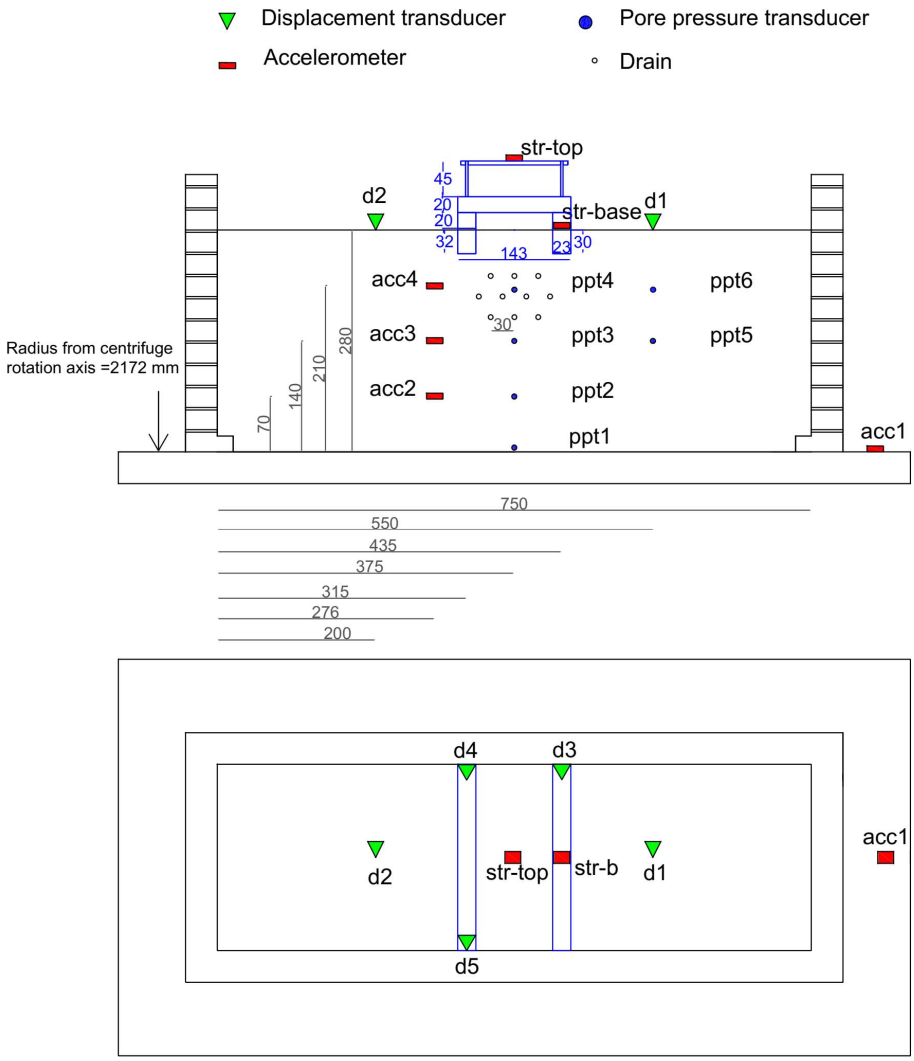
Test 25: M1F_S1_HD1_GM31+

Model description

The model consists of a homogenous soil profile of Ticino sand, with a model structure with shallow foundations. The ground motion applied was the number 31+. Model horizontal drains installed at a spacing of 5 diameters S/D=5.

1 – Reconstruction

Scheme and geometrical dimensions of the model as reconstructed at 1g. The following dimensions refer to model scale.



Ticino sand

Dry density [kN·s^2/m^4]	**1.494**
Relative density [%]	**38.30**
Void ratio [-]	**0.79**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

2 – Equilibrium at centrifuge angular velocity ω= 15.08 rad/s before the shock

Ticino sand, average values

Dry density [kN·s^2/m^4]	**1.533**
Saturated density [kN·s^2/m^4]	**1.957**
Relative density [%]	**51.16**
Void ratio [-]	**0.75**
Degree of saturation [%]	**99.2**

Radii from centrifuge rotation axis

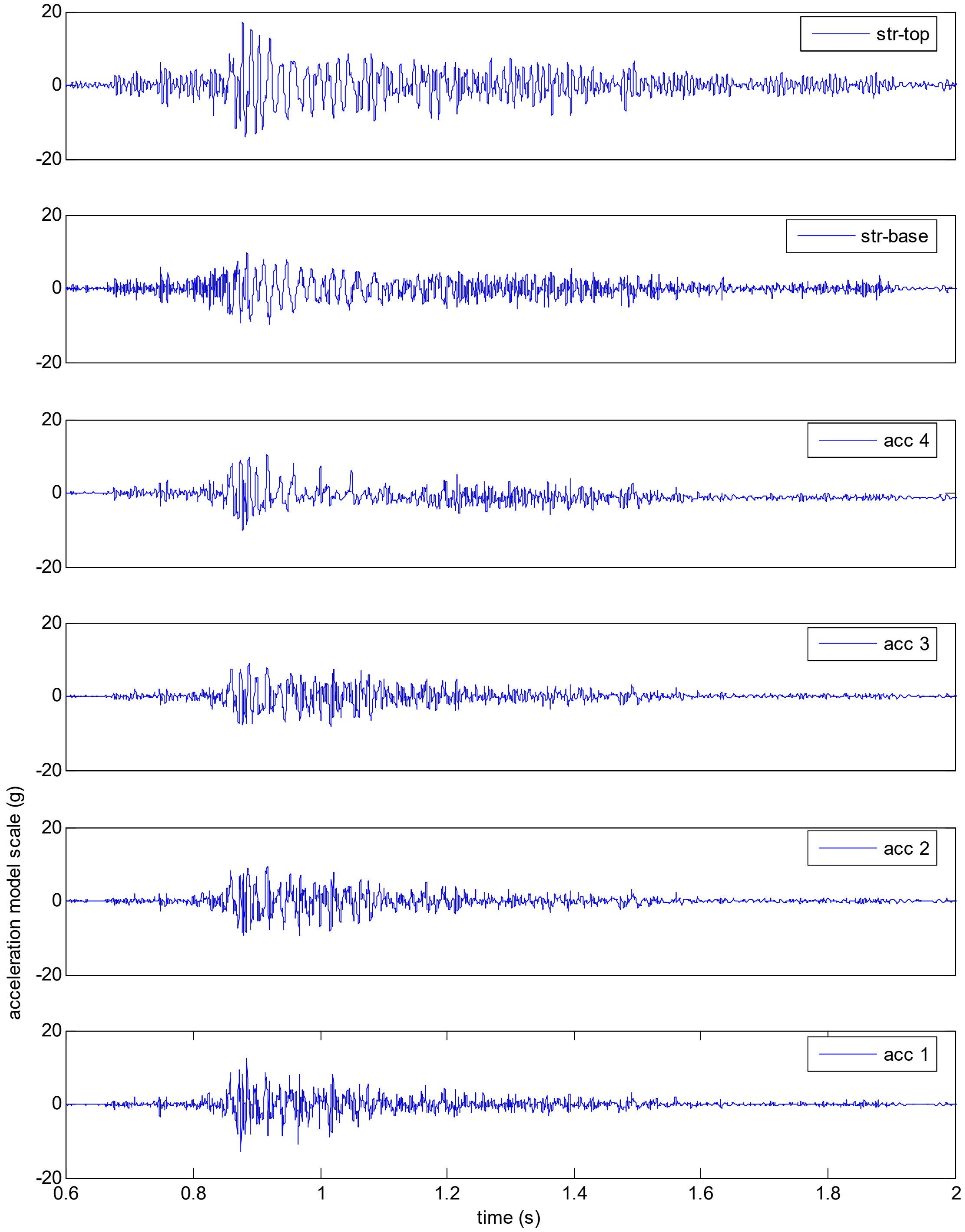
	Radius (mm)
model base	2172.0
free ground surface	1894.2

Pore Pressure Transducer	Radius (mm)	Value before the shock u_0 (kPa)
ppt6	1967.1	26.1
ppt5	2035.4	65.0
ppt4	1967.1	16.9
ppt3	2035.4	55.5
ppt2	2103.7	78.8
ppt1	2172.0	-

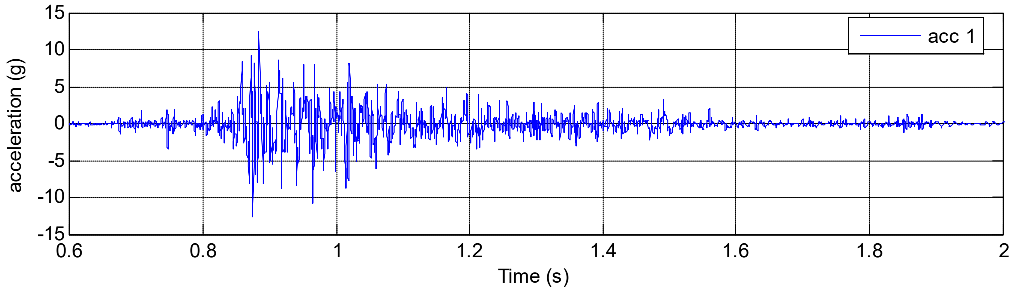
Accelerometer	Radius (mm)
acc4	1967.1
acc3	2035.4
acc2	2103.7
acc1	2172.0

3 – Seismic Excitation

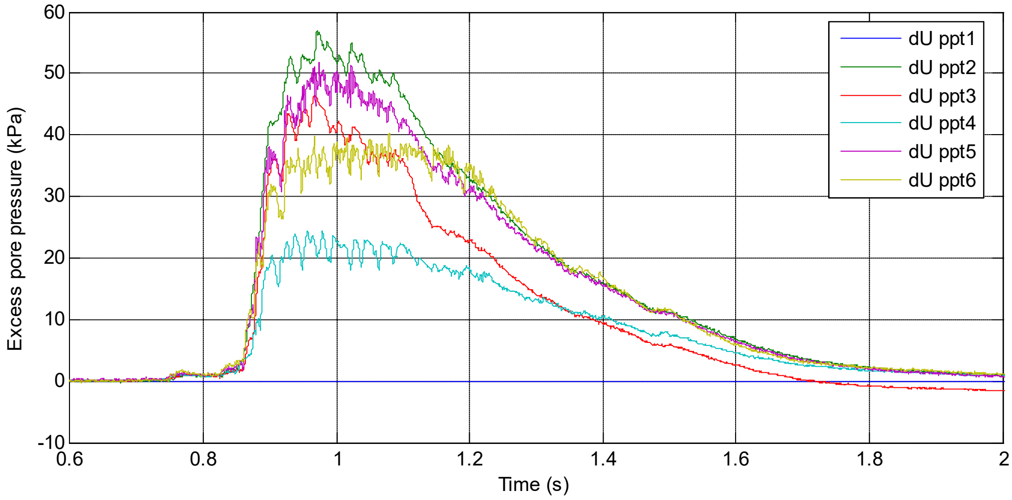
Accelerometers time histories



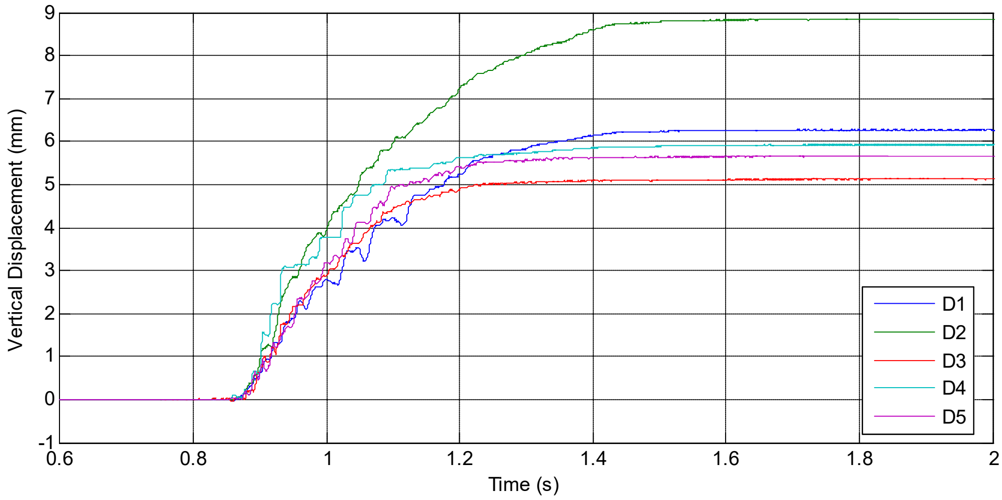
Input motion



Excess pore pressure $\Delta u(t) = u(t) - u_0$ vs. time



Vertical displacements vs. time



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

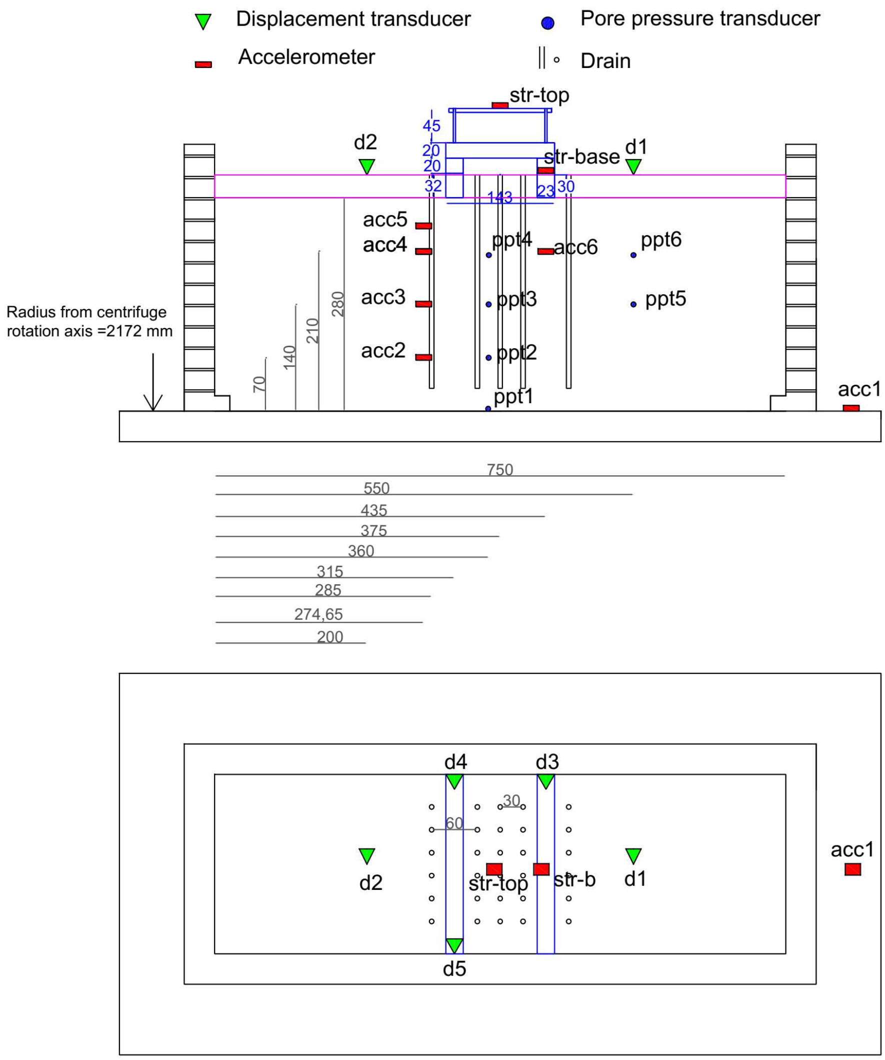
Test 26: M2F_S1_VD1_GM31+

Model description

The model consists of a two layers soil profile of Ticino sand and Pontida clay, with a model structure with shallow foundations. The ground motion applied was the number 31+. Model vertical drains installed at a spacing of 5 diameters S/D=5.

1 – Reconstruction

Scheme and geometrical dimensions of the model as reconstructed at 1g. The following dimensions refer to model scale.



Ticino sand

Dry density [kN·s²/m⁴]	**1.498**
Relative density [%]	**39.64**
Void ratio [-]	**0.79**

2 – Equilibrium at centrifuge angular velocity ω= 15.08 rad/s before the shock

Ticino sand, average values

Dry density [kN·s²/m⁴]	**1.522**
Saturated density [kN·s²/m⁴]	**1.953**
Relative density [%]	**47.51**
Void ratio [-]	**0.76**
Degree of saturation [%]	**99.8**

Pontida clay, average value

Mass density [kN·s²/m⁴]	**2.160**

Radii from centrifuge rotation axis

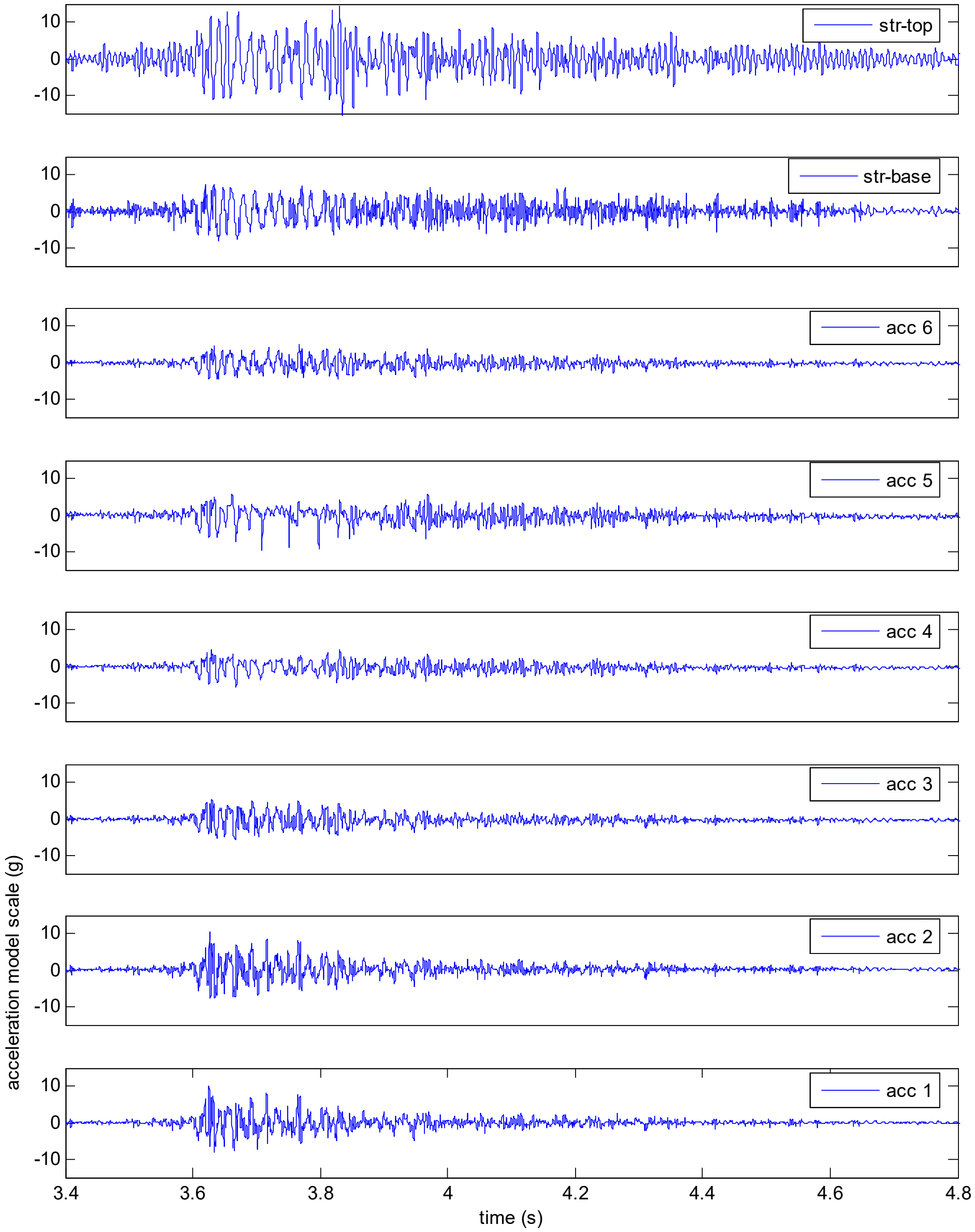
	Radius (mm)
model base	2172.0
free ground surface	1866.3
sand/clay interface	1896.1

Pore Pressure Transducer	**Radius (mm)**	**Value before the shock u_0 (kPa)**
ppt6	1965.2	27.4
ppt5	2034.1	70.7
ppt4	1965.2	42.5
ppt3	2034.1	64.2
ppt2	2103.1	105.4
ppt1	2172.0	136.9

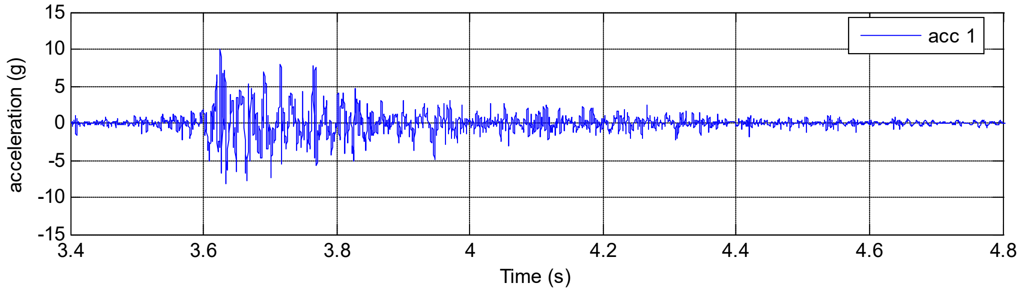
Accelerometer	**Radius (mm)**
acc6	1965.2
acc5	1931.0
acc4	1965.2
acc3	2034.1
acc2	2103.1
acc1	2172.0

3 – Seismic Excitation

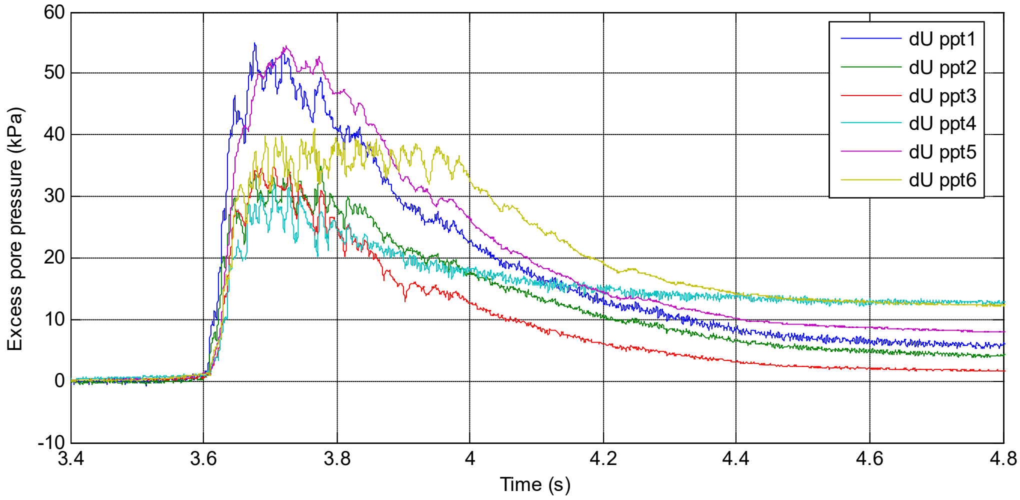
Accelerometers time histories



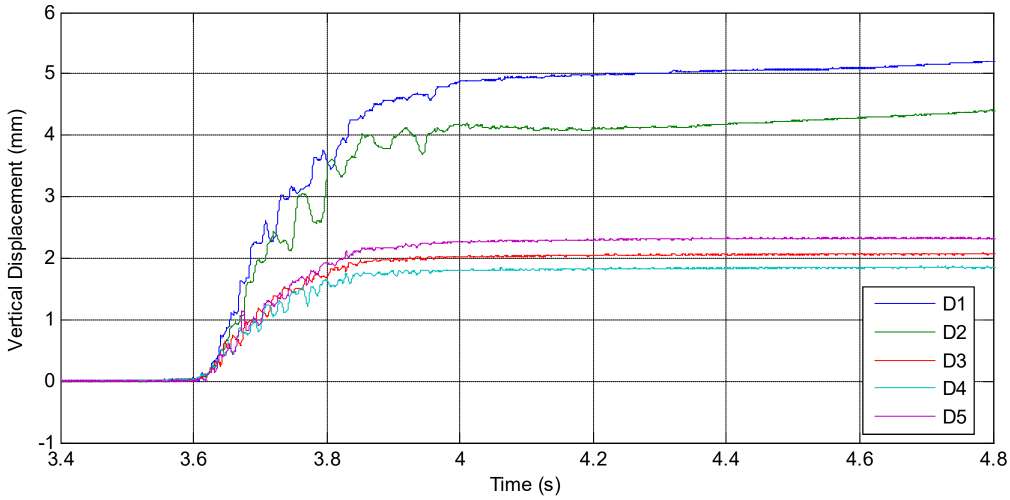
Input motion



Excess pore pressure $\Delta u(t) = u(t) - u_0$ vs. time



Vertical displacements vs. time



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

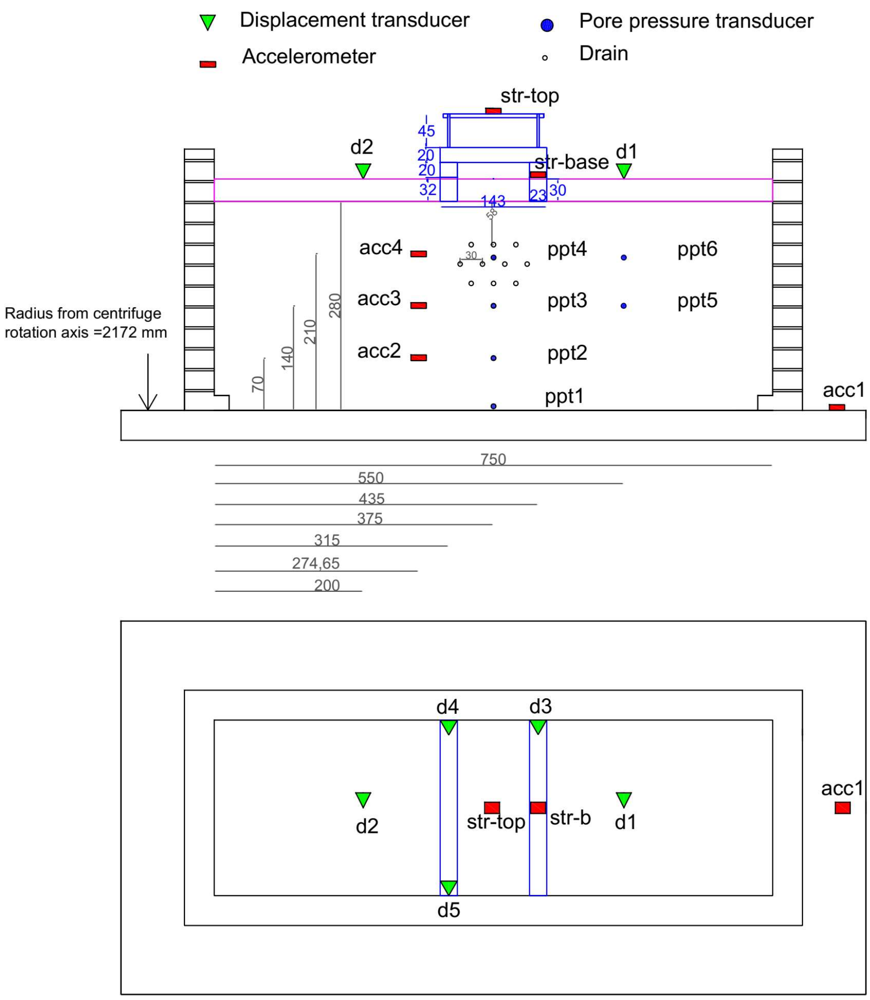
Test 27: M2F_S1_HD1_GM31+

Model description

The model consists of a two layers soil profile of Ticino sand and Pontida clay, with a model structure with shallow foundations. The ground motion applied was the number 31+. Model horizontal drains installed at a spacing of 5 diameters S/D=5.

1 – Reconstruction

Scheme and geometrical dimensions of the model as reconstructed at 1g. The following dimensions refer to model scale.



Ticino sand

Dry density [kN·s^2/m^4]	**1.500**
Relative density [%]	**40.18**
Void ratio [-]	**0.79**

2 – Equilibrium at centrifuge angular velocity ω= 15.08 rad/s before the shock

Ticino sand, average values

Dry density [kN·s^2/m^4]	**1.537**
Saturated density [kN·s^2/m^4]	**1.967**
Relative density [%]	**52.56**
Void ratio [-]	**0.74**
Degree of saturation [%]	**100.0**

Pontida clay, average value

Mass density [kN·s^2/m^4]	**2.160**

Radii from centrifuge rotation axis

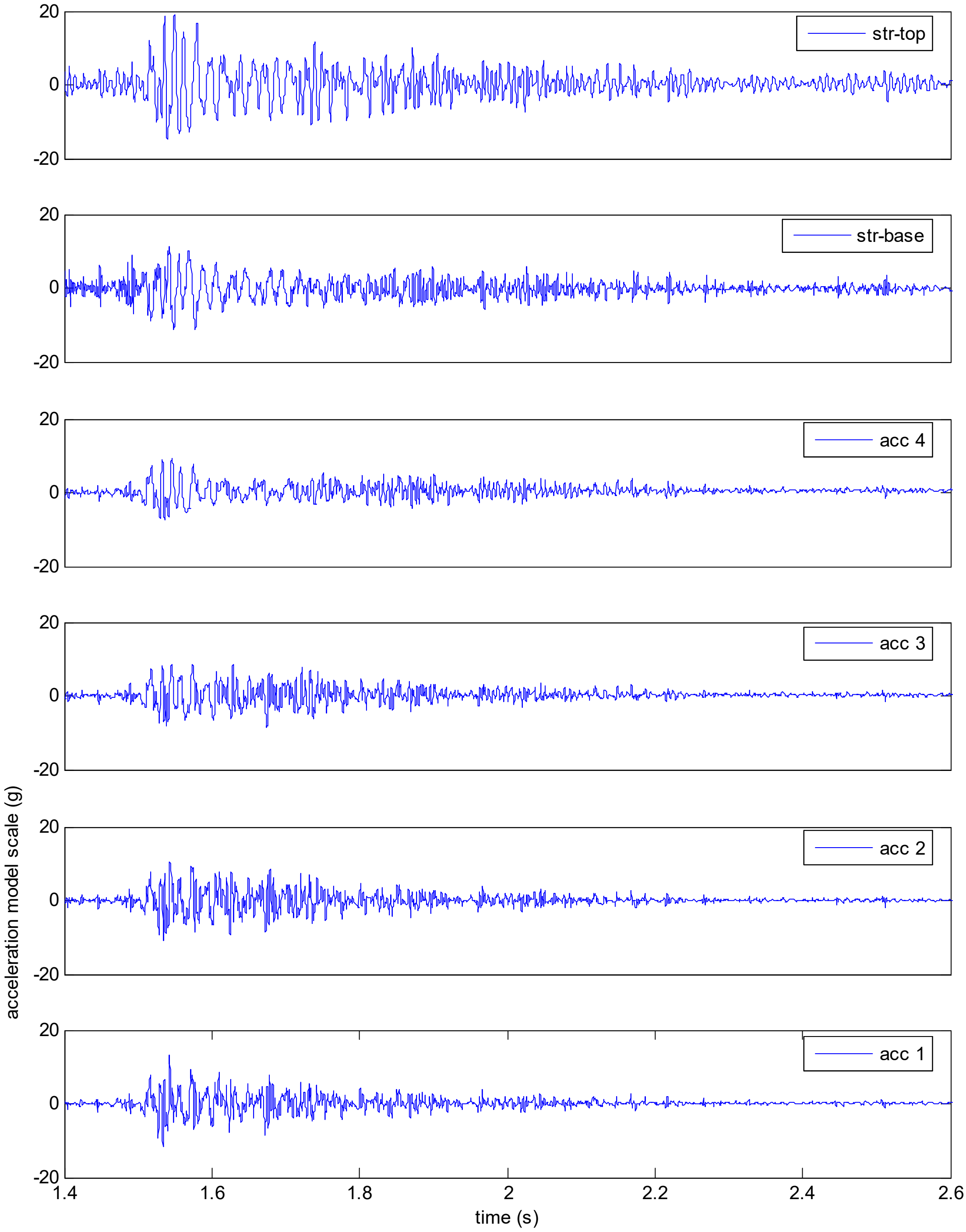
	Radius (mm)
model base	2172.0
free ground surface	1865.6
sand/clay interface	1895.0

Pore Pressure Transducer	**Radius (mm)**	**Value before the shock u_0 (kPa)**
ppt6	1967.0	38.5
ppt5	2035.3	66.7
ppt4	1967.0	35.9
ppt3	2035.3	65.9
ppt2	2103.7	96.0
ppt1	2172.0	122.2

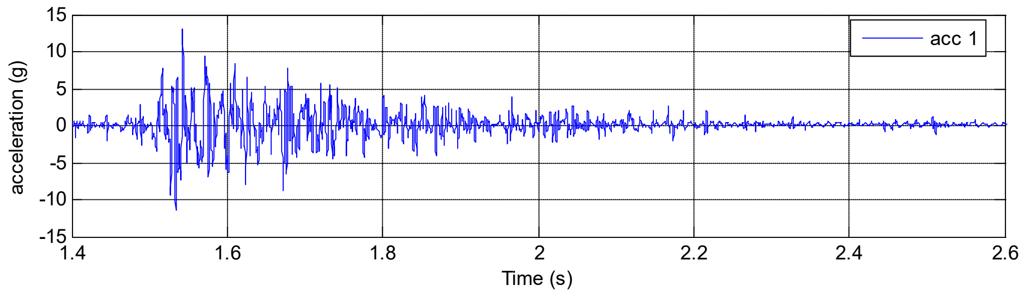
Accelerometer	**Radius (mm)**
acc4	1967.0
acc3	2035.3
acc2	2103.7
acc1	2172.0

3 – Seismic Excitation

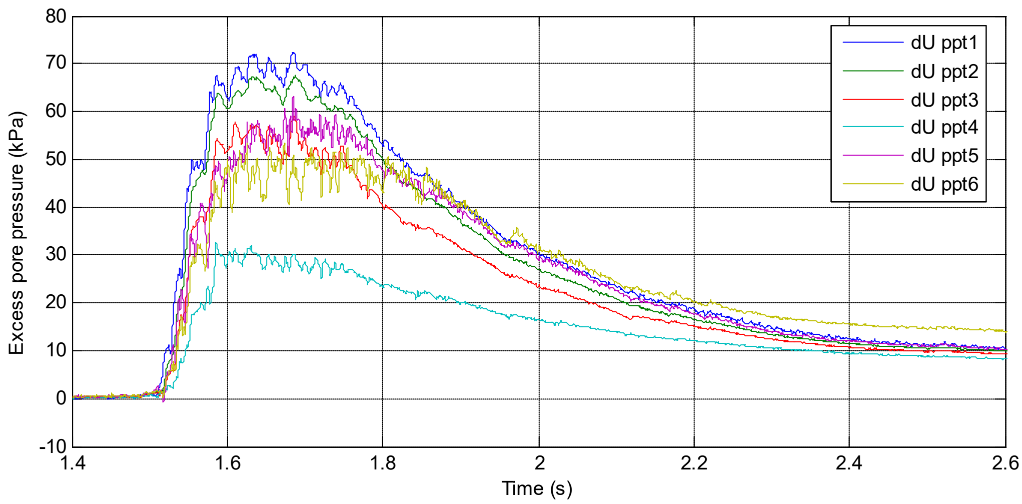
Accelerometers time histories



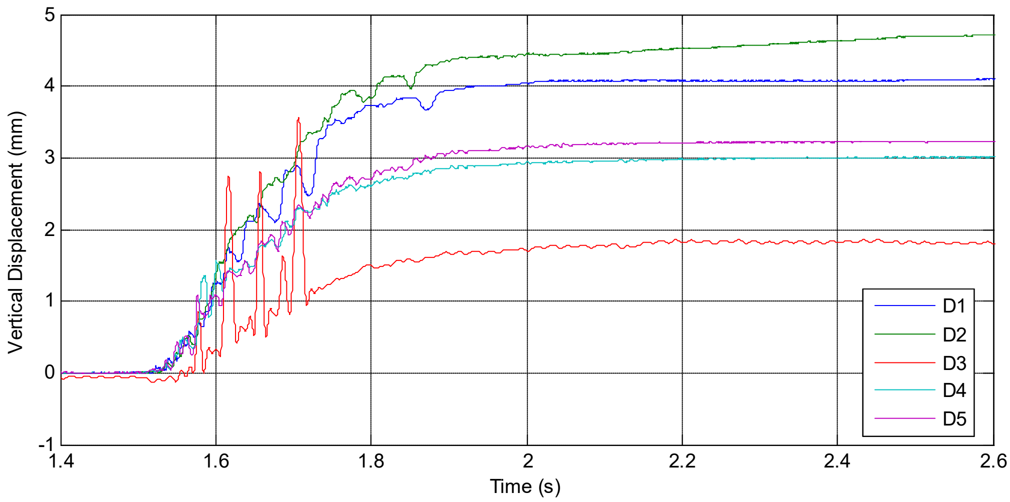
Input motion



Excess pore pressure $\Delta u(t) = u(t) - u_0$ vs. time



Vertical displacements vs. time



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

10.3. Third series of tests

The third series of tests consisted of 10 tests numbered from 28 to 37 as summarised in Table 10. The objective of these tests was to reproduce some of the main features of the liquefaction mitigation technique known as Induced Partial Saturation (IPS). This technique consists of injecting air in liquefiable soil layers to reduce the saturation of the soil, then increasing its resistance in seismic conditions.

The efficacy of IPS was tested both on model type 1 (homogeneous sand) and model type 2 (homogeneous sand topped by a clay layer), in free field conditions or in presence of the simple model structure on shallow foundation. The soil adopted was Ticino sand and the ground motions were GM31 or GM31+.

The test schemes were established with the collaboration of the Partners of UNINA, two test configurations were adopted with one nozzle and four nozzles. The inflight injection system was specifically designed for the LIQUEFACT project.

Experimental targets achieved are:

- Evaluation of excess pore pressures development during the shock and the aftershock dissipation rate of unsaturated soil.
- Evaluation of post liquefaction settlements.
- Production of a consistent set of experimental data which can be used as a benchmark for the numerical simulations and in situ trial activities included in other Tasks of the LIQUEFACT project (e.g. Tasks 4.3, 4.4 and 4.5).

10.3.1. Test summary sheets

The experimental programme list of the third series of tests is reported in Table 13.

The results of each test are summarised in four data sheets. The set of information that can be found is:

Reconstruction:

- Sketch of the model with: (1) sensors ID and positions after deposition (2) position of the injection nozzles (3) model structure position when present (mm at model scale);
- Sand characteristics after deposition (average values of dry density, relative density and void ratio).

Equilibrium at centrifuge angular velocity of 15.08 rad/s, before the shock:

- Soil material characteristics (average value of dry density, saturated density, relative density, void ratio, degree of saturation);
- Position of the (1) free ground surface, (2) model base, (3) sand/clay interface when present, expressed as radius from centrifuge rotation axis;
- Position of PPTs and ACCs expressed as radius from centrifuge rotation axis;
- Pore pressure, u_0 values as measured by the PPTs before the shock;
- Injection parameters: air reservoirs pressure values before, P_{ini}, and after the injection, $P_{fin.}$

Seismic Excitation:

- Time histories measured by the installed miniaturised accelerometers
- Input motion applied by the shaker (ACC1)
- Excess pore pressure [$\Delta u(t) = u(t)-u_0$] versus time measured during the shock by PPTs
- Vertical Displacement of the soil surface vs. time recorded during the shock.

All data are reported at model scale

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

Table 13 Third series of tests

Test number	Test Name	Model Type	Sand	Ground Motion	Number of nozzles	Structure
28	M1_S1_IPS1_GM31	1	1	31	1	-
29	M1_S1_IPS1_GM31+	1	1	31+	1	-
30	M1_S1_IPS4_GM31	1	1	31	4	-
31	M1_S1_IPS4_GM31+	1	1	31+	4	-
32	M2_S1_IPS1_GM31	2	1	31	1	-
33	M2_S1_IPS1_GM31+	2	1	31+	1	-
34	M2_S1_IPS4_GM31	2	1	31	4	-
35	M2_S1_IPS4_GM31+	2	1	31+	4	-
36	M1F_S1_IPS4_GM31+	1	1	31+	4	Yes
37	M1F_S1_IPS4_GM31++	1	1	31++	4	Yes

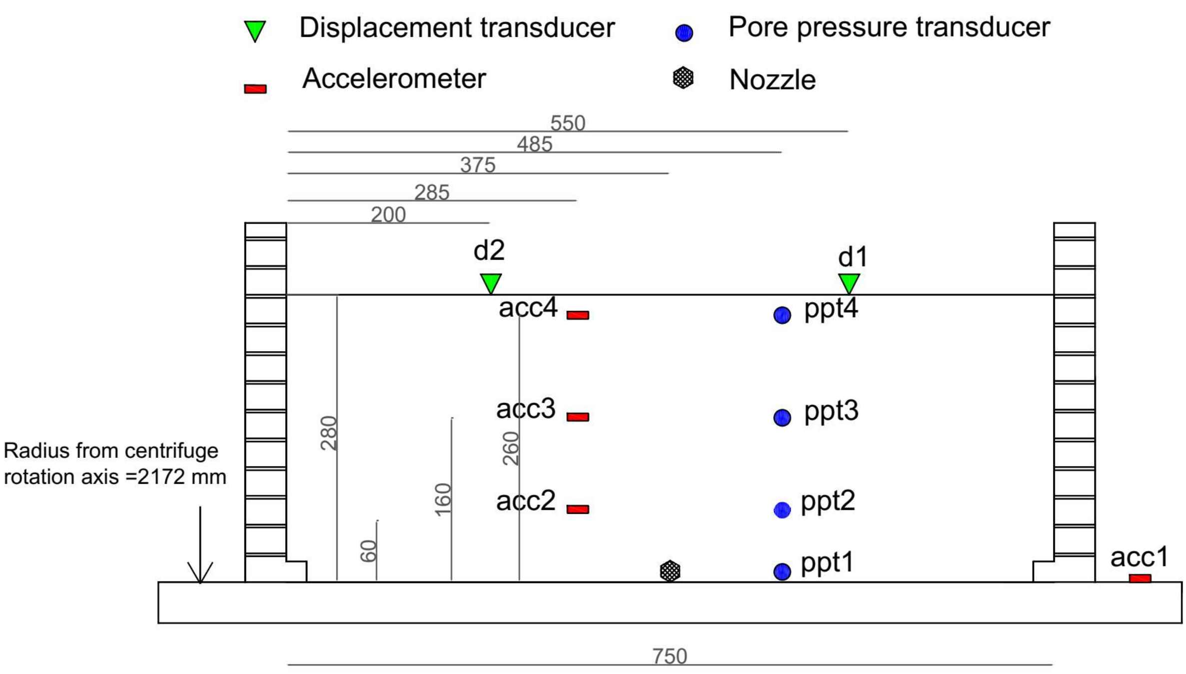
Test 28: M1_S1_IPS1_GM31

Model description

The model consists of a homogenous soil profile of Ticino sand. The ground motion applied was the number 31. Induced Partial Saturation by inflight air injection from one nozzle.

1 – Reconstruction

Scheme and geometrical dimensions of the model as reconstructed at 1g. The following dimensions refer to model scale.



Ticino sand

Dry density [kN·s^2/m^4]	**1.487**
Relative density [%]	**35.76**
Void ratio [-]	**0.80**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

2 – Equilibrium at centrifuge angular velocity ω= 15.08 rad/s before the shock

Ticino sand, average values

Dry density [kN·s²/m⁴]	**1.508**
Saturated density [kN·s²/m⁴]	**1.944**
Relative density [%]	**42.97**
Void ratio [-]	**0.78**
Degree of saturation [%]	**99.6**

Radii from centrifuge rotation axis

	Radius (mm)
model base	2172.0
free ground surface	1890.9

Pore Pressure Transducer	Radius (mm)	Value before the shock u_0 (kPa)
ppt4	1915.6	-
ppt3	2014.2	48.3
ppt2	2112.8	89.2
ppt1	2172.0	127.6

Accelerometer	Radius (mm)
acc4	1915.6
acc3	2014.2
acc2	2112.8
acc1	2172.0

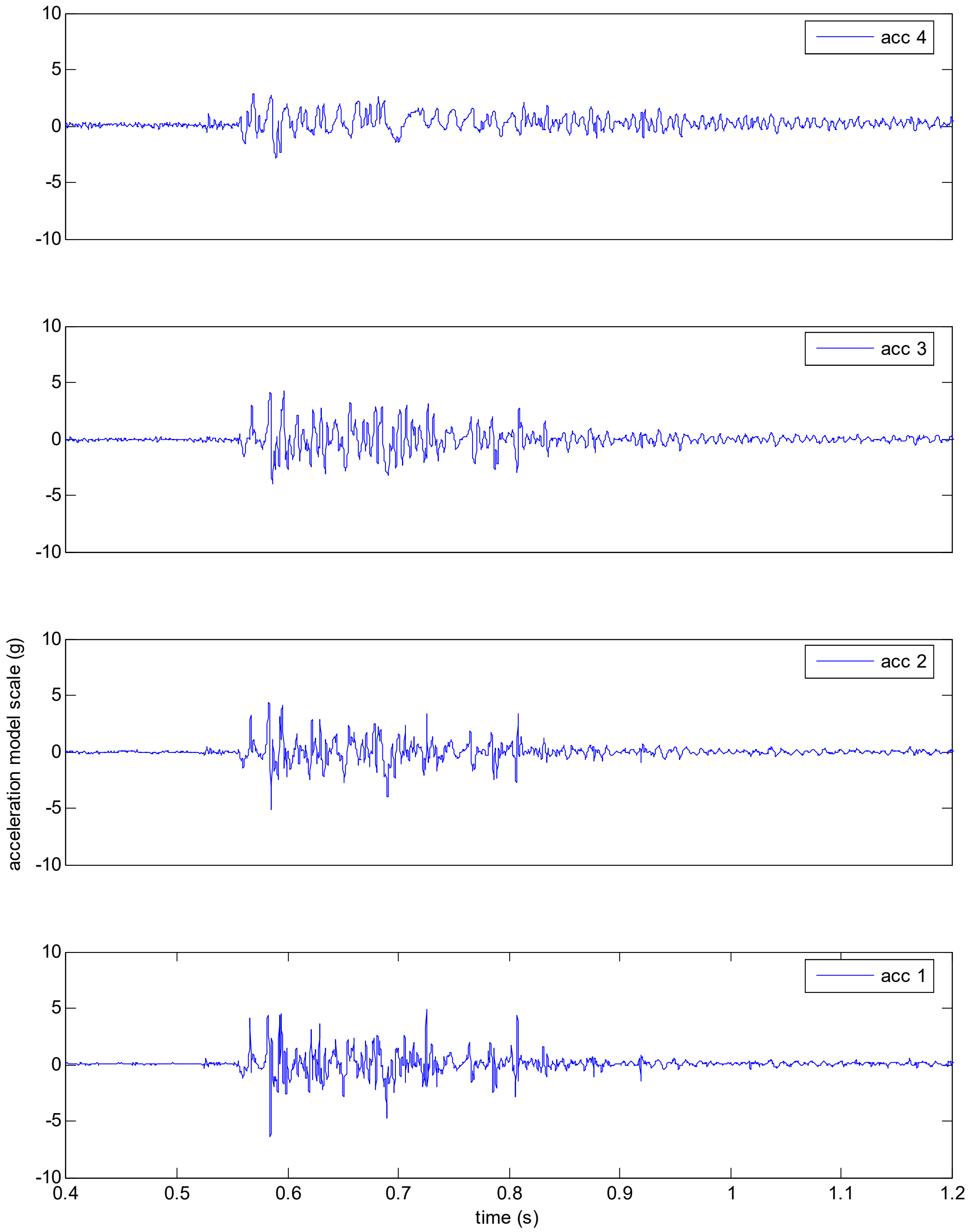
Injection parameters

P_{ini}= 135 kPa P_{fin}= 124 kPa

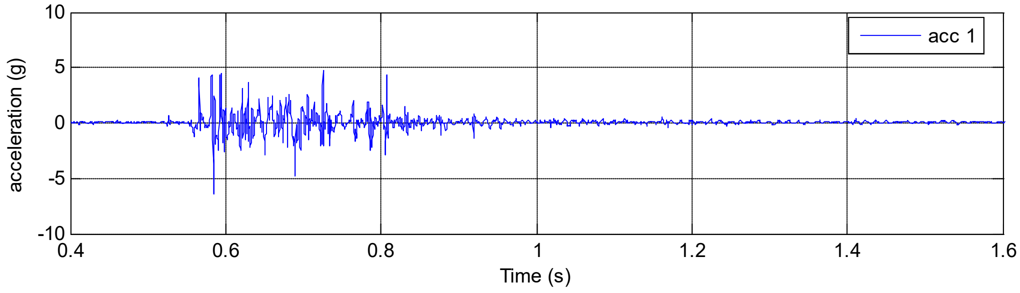
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

3 – Seismic Excitation

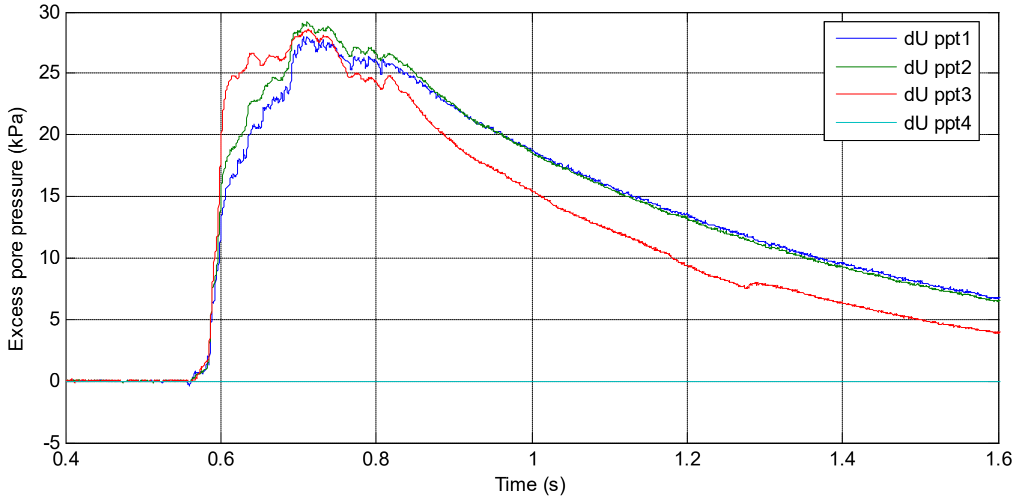
Accelerometers time histories



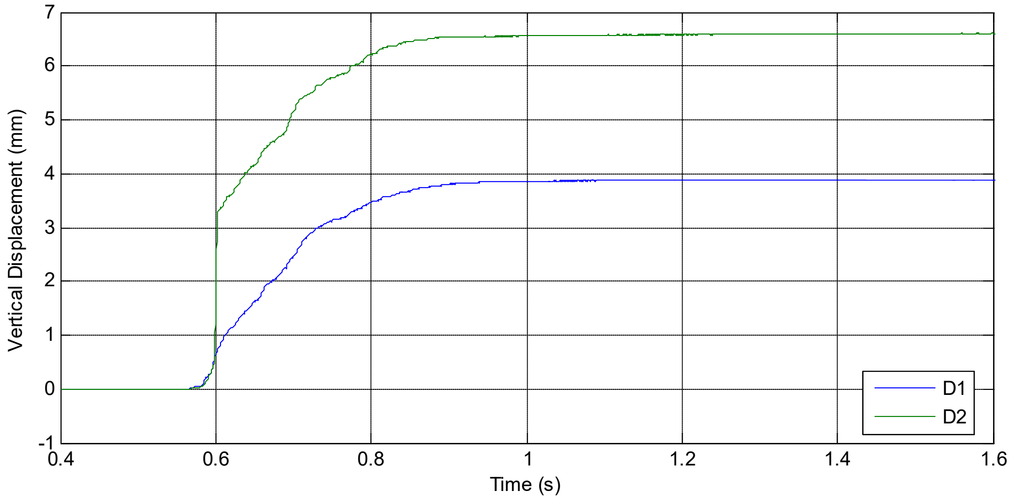
Input motion



Excess pore pressure $\Delta u(t) = u(t) - u_0$ vs. time



Vertical displacements vs. time



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

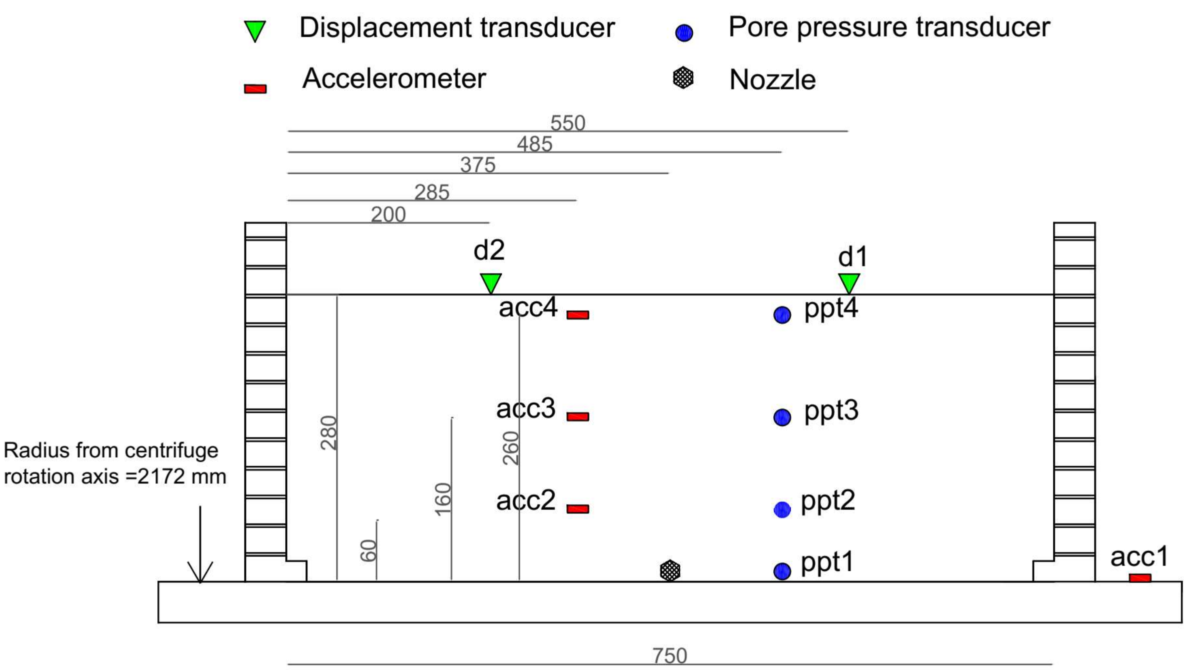
Test 29: M1_S1_IPS1_GM31+

Model description

The model consists of a homogenous soil profile of Ticino sand. The ground motion applied was the number 31+. Induced Partial Saturation by inflight air injection from one nozzle.

1 – Reconstruction

Scheme and geometrical dimensions of the model as reconstructed at 1g. The following dimensions refer to model scale.



Ticino sand

Dry density [kN·s^2/m^4]	**1.487**
Relative density [%]	**35.76**
Void ratio [-]	**0.80**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

2 – Equilibrium at centrifuge angular velocity ω= 15.08 rad/s before the shock

Ticino sand, average values

Dry soil density [kN·s^2/m^4]	**1.532**
Saturated soil density [kN·s^2/m^4]	**1.959**
Relative density [%]	**50.99**
Initial void ratio [-]	**0.75**
Degree of saturation [%]	**99.6**

Radii from centrifuge rotation axis

	Radius (mm)
model base	2172.0
free ground surface	1895.3

Pore Pressure Transducer	Radius (mm)	Value before the shock u_0 (kPa)
ppt4	1919.6	-
ppt3	2016.7	47.3
ppt2	2113.7	88.8
ppt1	2172.0	126.9

Accelerometer	Radius (mm)
acc4	1919.6
acc3	2016.7
acc2	2113.7
acc1	2172.0

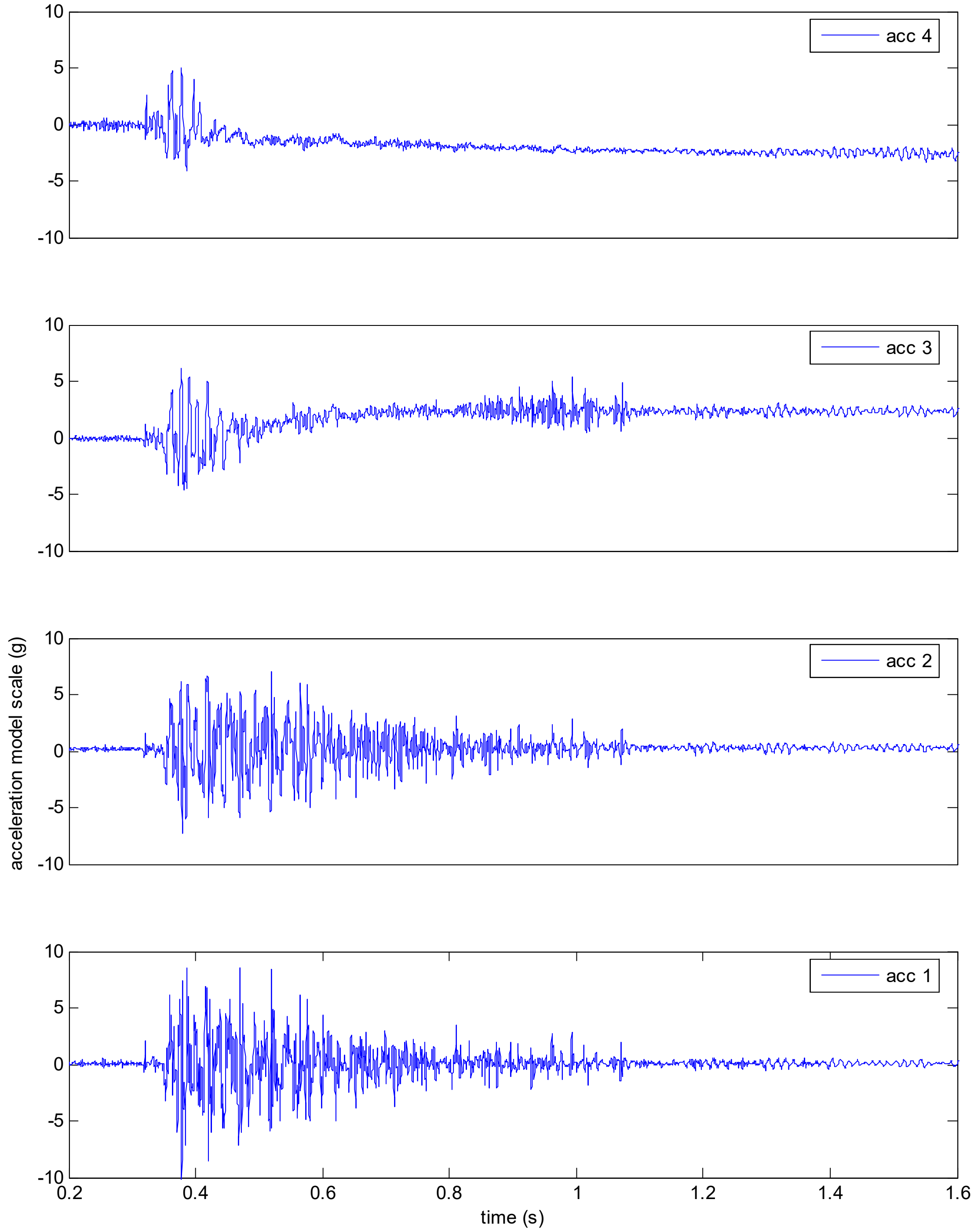
Injection parameters

P_{ini}= 135 kPa P_{fin}= 124 kPa

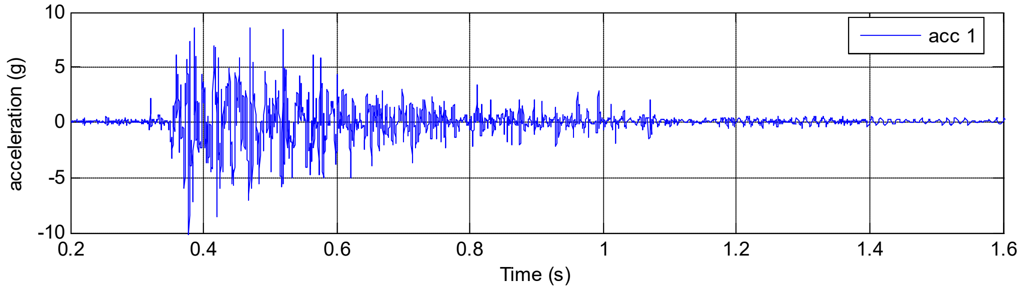
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

3 – Seismic Excitation

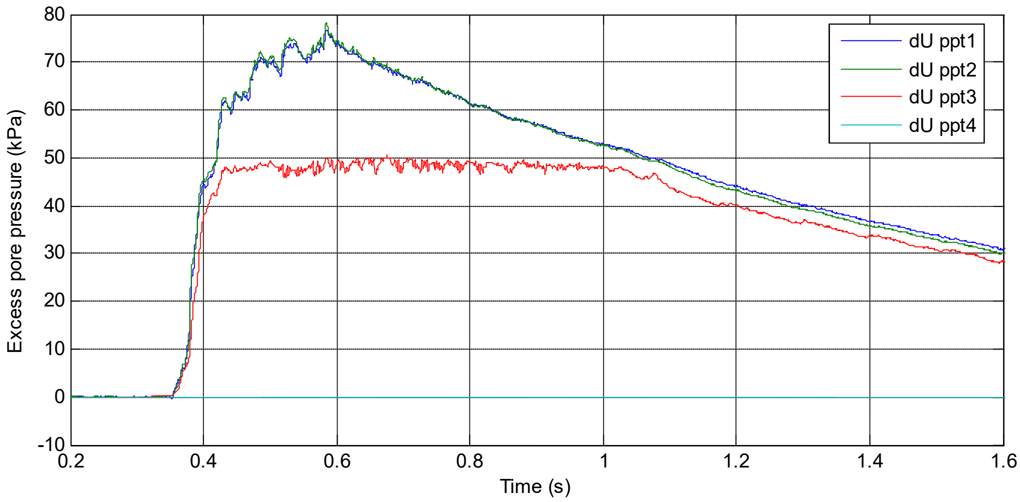
Accelerometers time histories



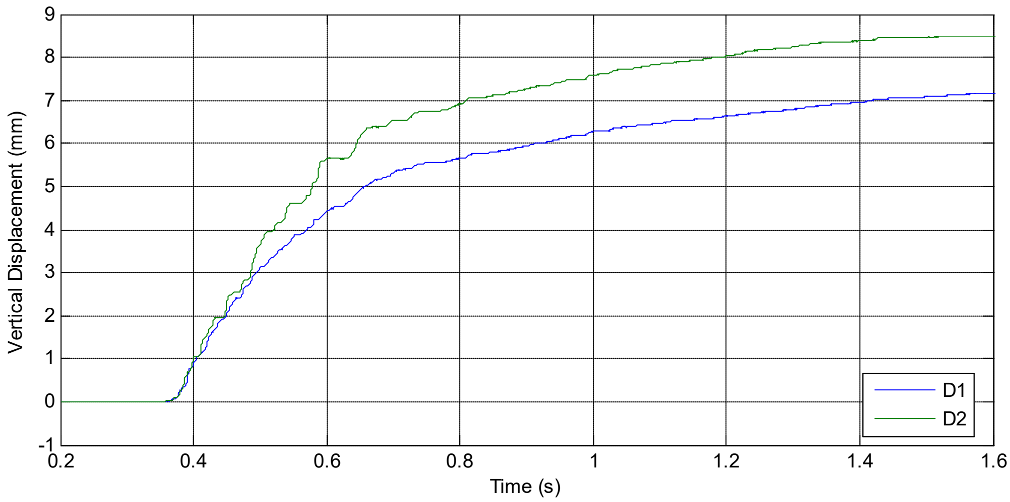
Input motion



Excess pore pressure $\Delta u(t) = u(t) - u_0$ vs. time



Vertical displacements vs. time



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

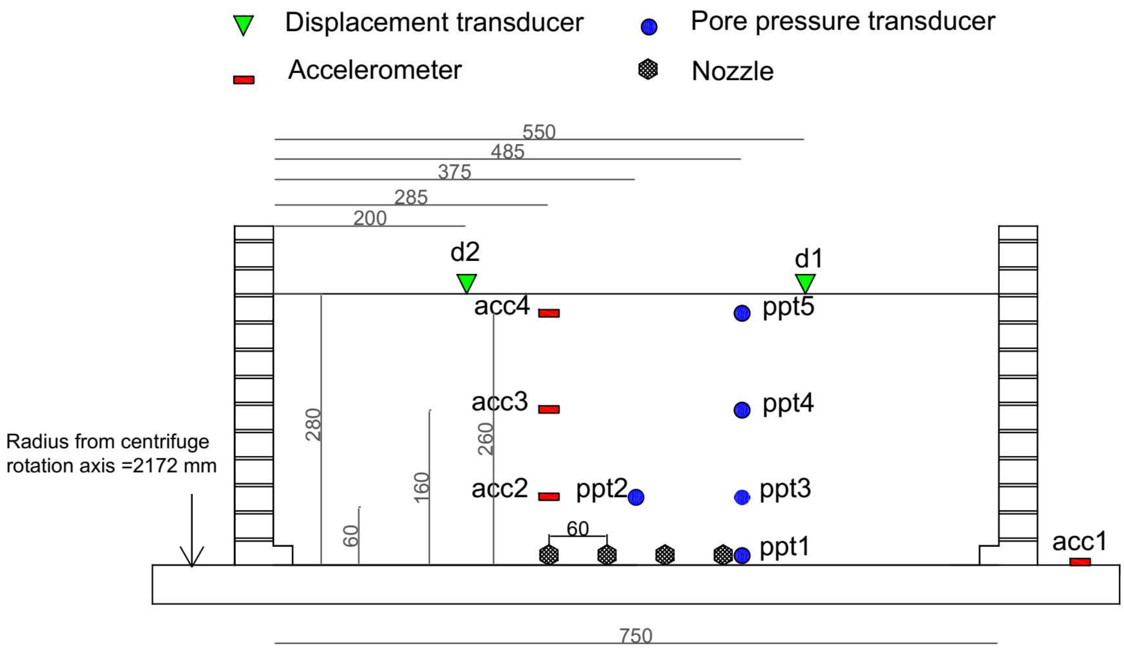
Test 30: M1_S1_IPS4_GM31

Model description

The model consists of a homogenous soil profile of Ticino sand. The ground motion applied was the number 31. Induced Partial Saturation by inflight air injection from four nozzles.

1 – Reconstruction

Scheme and geometrical dimensions of the model as reconstructed at 1g. The following dimensions refer to model scale.



Ticino sand

Dry density [kN·s^2/m^4]	**1.514**
Relative density [%]	**44.93**
Void ratio [-]	**0.77**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

2 – Equilibrium at centrifuge angular velocity ω= 15.08 rad/s before the shock

Ticino sand, average values

Dry density [kN·s²/m⁴]	**1.537**
Saturated density [kN·s²/m⁴]	**1.963**
Relative density [%]	**52.37**
Void ratio [-]	**0.74**
Degree of saturation [%]	**99.9**

Radii from centrifuge rotation axis

	Radius (mm)
model base	2172.0
free ground surface	1896.1

Pore Pressure Transducer	**Radius (mm)**	**Value before the shock u_0 (kPa)**
ppt5	1915.8	10.5
ppt4	2014.3	55.9
ppt3	2112.9	89.7
ppt2	2112.9	93.0
ppt1	2172.0	127.6

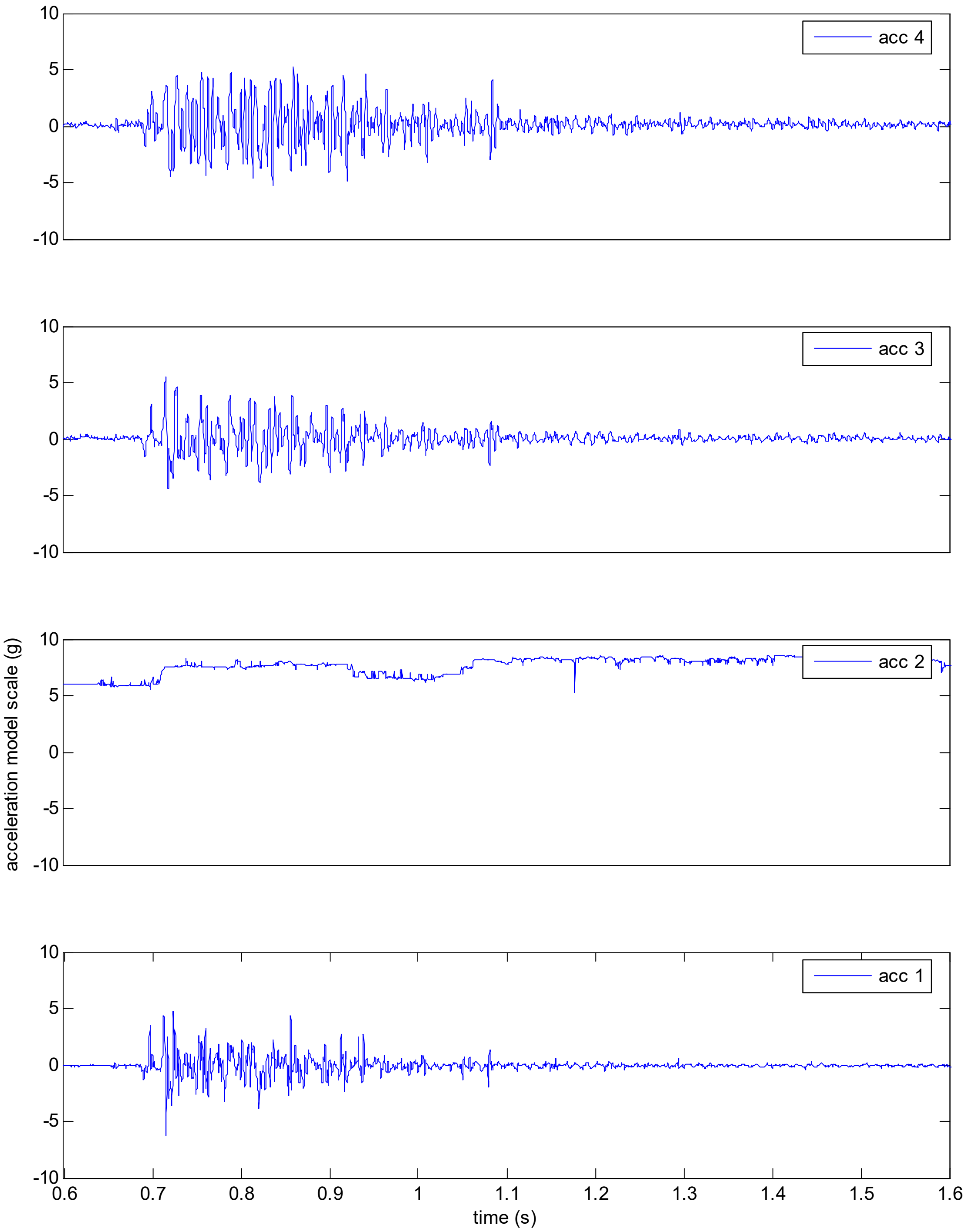
Accelerometer	**Radius (mm)**
acc4	1915.8
acc3	2014.3
acc2	2112.9
acc1	2172.0

Injection parameters

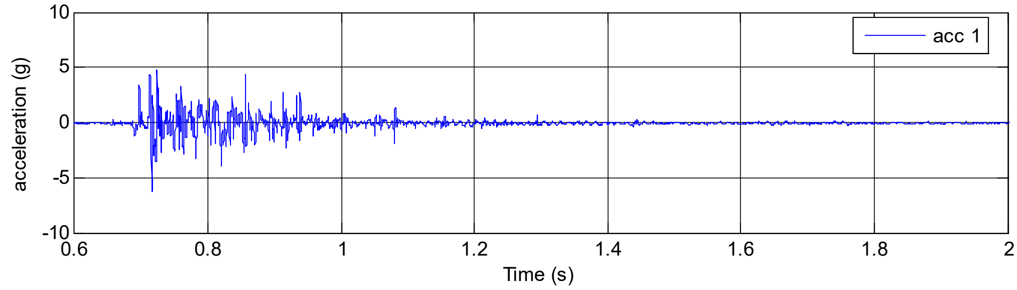
P_{ini}= 131 kPa P_{fin}= 122 kPa

3 – Seismic Excitation

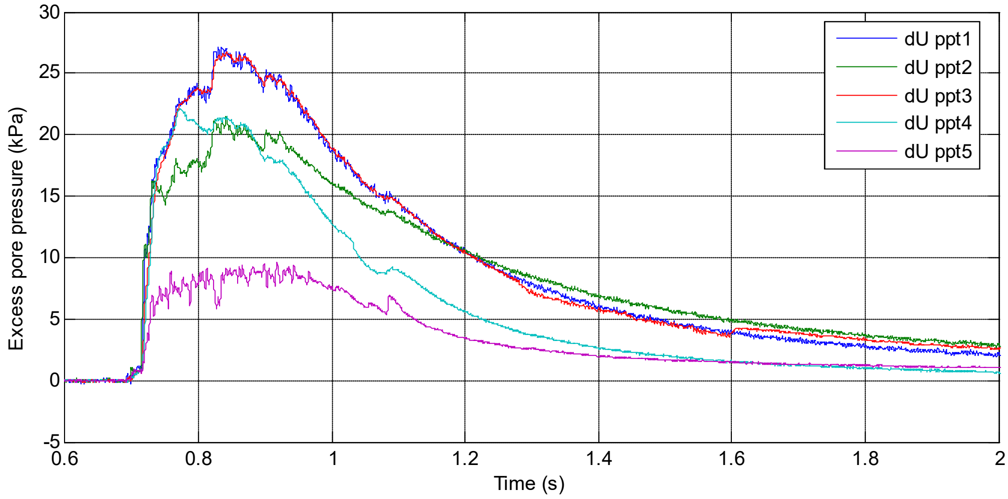
Accelerometers time histories



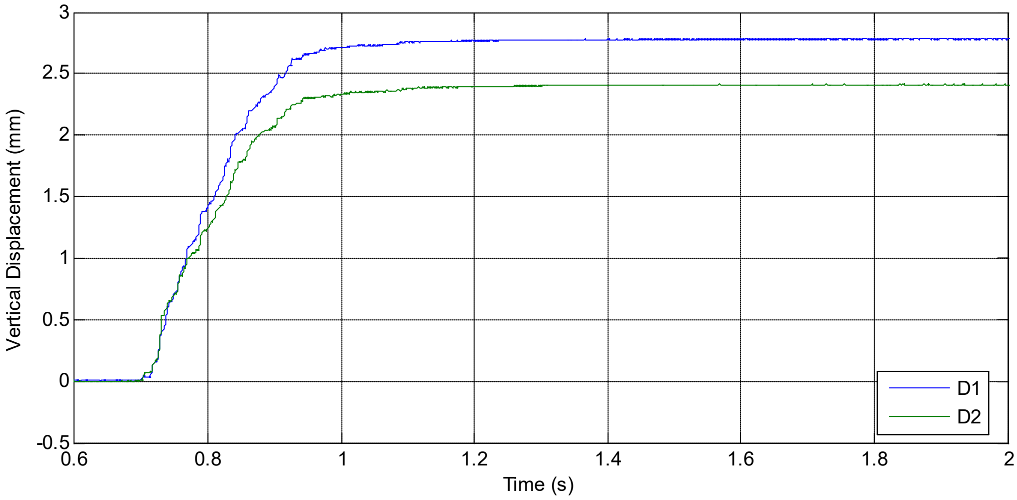
Input motion



Excess pore pressure $\Delta u(t) = u(t) - u_0$ vs. time



Vertical displacements vs. time



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

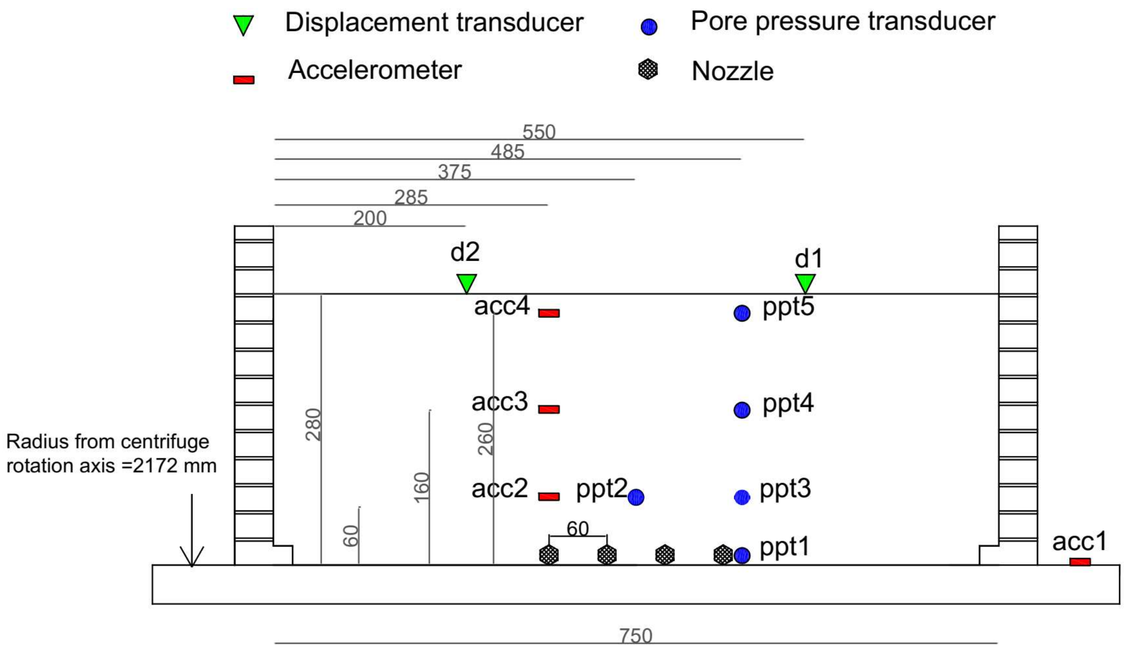
Test 31: M1_S1_IPS4_GM31+

Model description

The model consists of a homogenous soil profile of Ticino sand. The ground motion applied was the number 31+. Induced Partial Saturation by inflight air injection from four nozzles.

1 – Reconstruction

Scheme and geometrical dimensions of the model as reconstructed at 1g. The following dimensions refer to model scale.



Ticino sand

Dry density [kN·s^2/m^4]	**1.514**
Relative density [%]	**44.93**
Void ratio [-]	**0.77**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

2 – Equilibrium at centrifuge angular velocity ω= 15.08 rad/s before the shock

Ticino sand, average values

Dry density [kN·s^2/m^4]	**1.552**
Saturated density [kN·s^2/m^4]	**1.972**
Relative density [%]	**57.17**
Void ratio [-]	**0.73**
Degree of saturation [%]	**99.9**

Radii from centrifuge rotation axis

	Radius (mm)
model base	2172.0
free ground surface	1898.7

Pore Pressure Transducer	**Radius (mm)**	**Value before the shock u_0 (kPa)**
ppt5	1924.2	11.2
ppt4	2010.8	55.2
ppt3	2113.4	90.0
ppt2	2113.4	92.5
ppt1	2172.0	127.3

Accelerometer	**Radius (mm)**
acc4	1924.2
acc3	2010.8
acc2	2113.4
acc1	2172.0

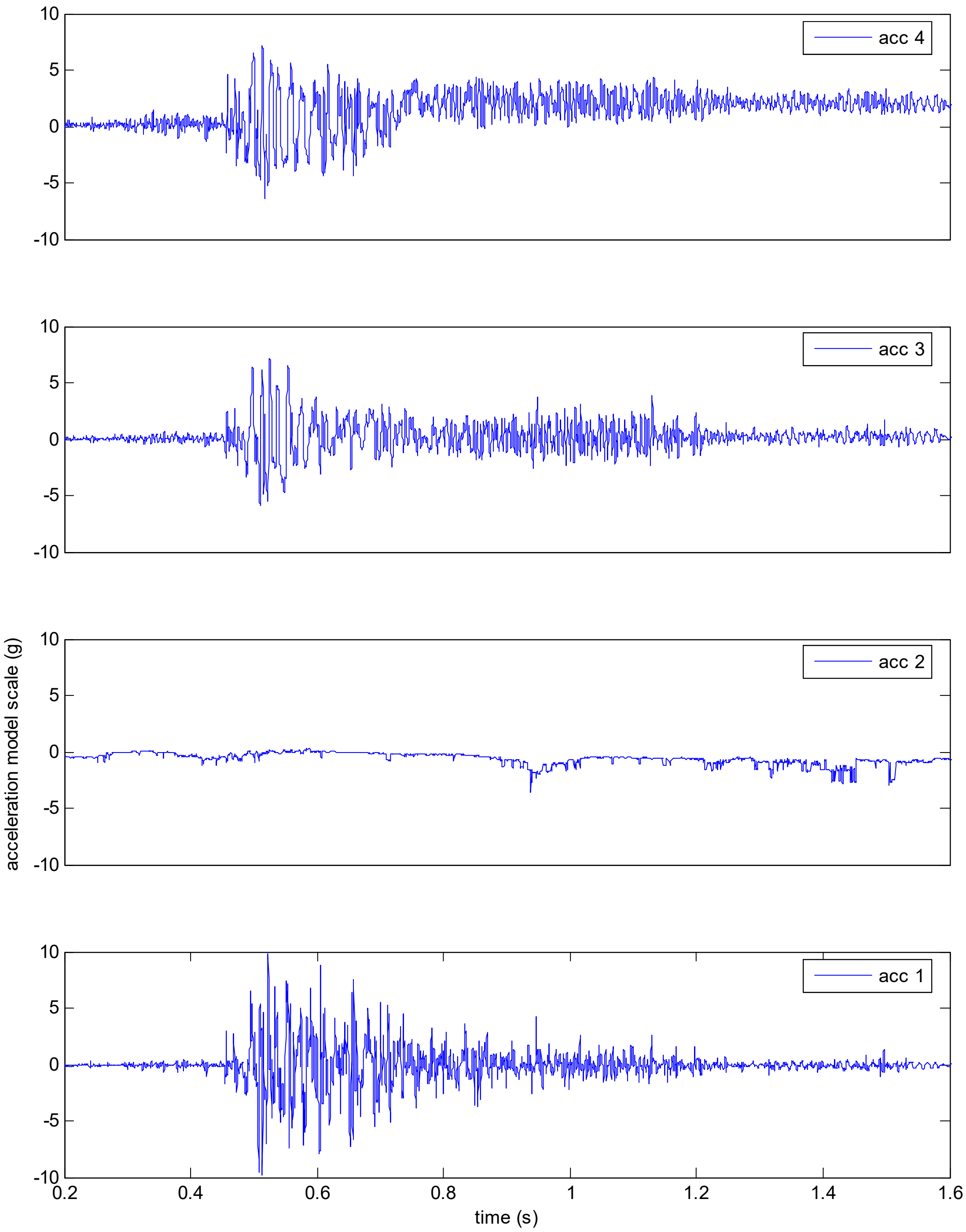
Injection parameters

P_{ini}= 131 kPa P_{fin}= 122 kPa

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

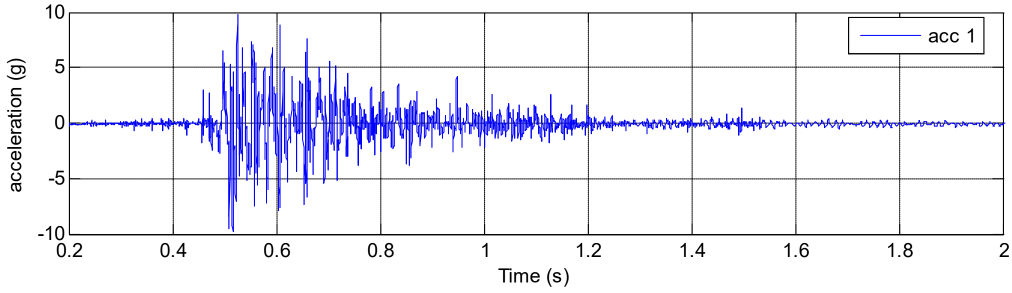
3 – Seismic Excitation

Accelerometers time histories

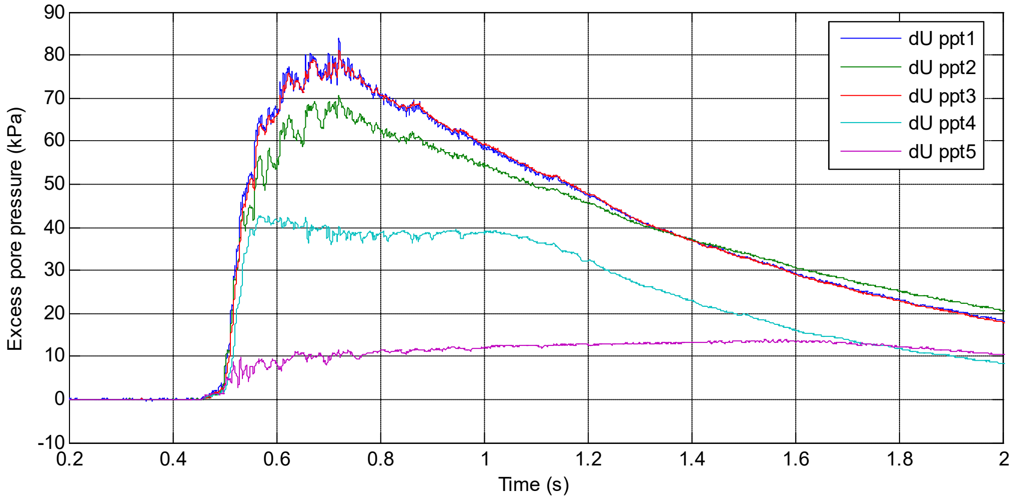


This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

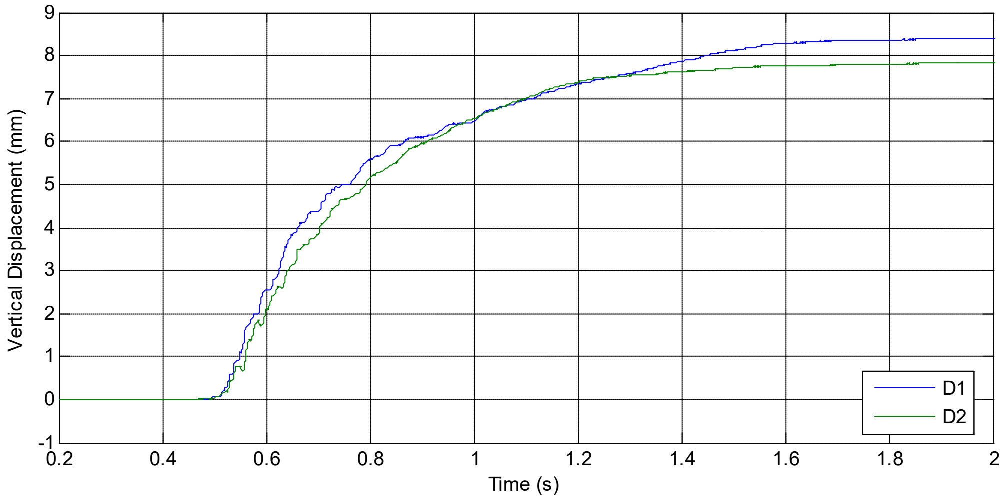
Input motion



Excess pore pressure $\Delta u(t) = u(t) - u_0$ vs. time



Vertical displacements vs. time



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

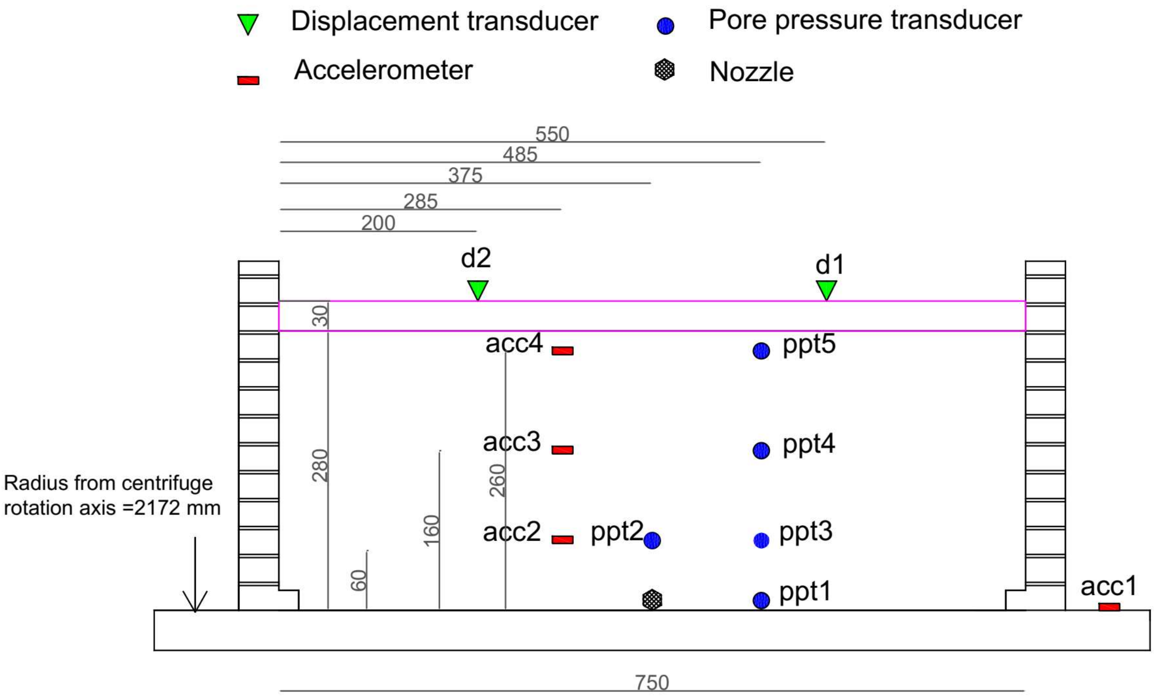
Test 32: M2_S1_IPS1_GM31

Model description

The model consists of a two layers soil profile composed of Ticino sand and Pontida clay. The ground motion applied was the number 31. Induced Partial Saturation by inflight air injection from one nozzle.

1 – Reconstruction

Scheme and geometrical dimensions of the model as reconstructed at 1g. The following dimensions refer to model scale.



Ticino sand

Dry density [kN·s^2/m^4]	**1.487**
Relative density [%]	**35.76**
Void ratio [-]	**0.80**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

2 – Equilibrium at centrifuge angular velocity ω= 15.08 rad/s before the shock

Ticino sand, average values

Dry density [kN·s²/m⁴]	**1.503**
Saturated density [kN·s²/m⁴]	**1.941**
Relative density [%]	**41.32**
Void ratio [-]	**0.78**
Degree of saturation [%]	**99.6**

Pontida clay, average value

Mass density [kN·s²/m⁴]	**2.160**

Radii from centrifuge rotation axis

	Radius (mm)
model base	2172.0
free ground surface	1860.3
sand/clay interface	1890.0

Pore Pressure Transducer	Radius (mm)	Value before the shock u_0 (kPa)
ppt5	1914.8	16.0
ppt4	2013.7	62.1
ppt3	2112.6	96.9
ppt2	2112.6	94.1
ppt1	2172.0	122.2

Accelerometer	Radius (mm)
acc4	1914.8
acc3	2013.7
acc2	2112.6
acc1	2172.0

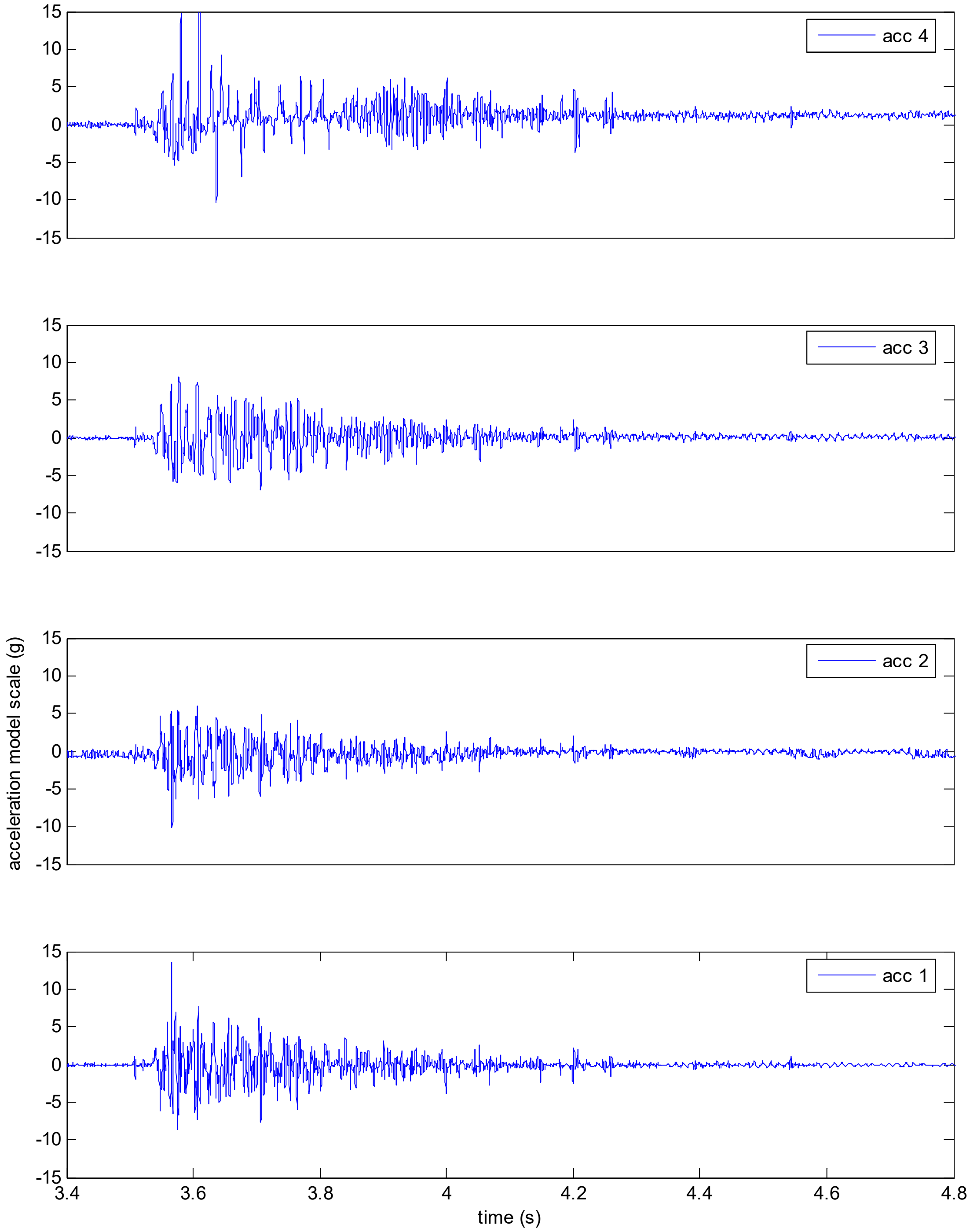
Injection parameters

P_{ini}= 143 kPa P_{fin}= 122 kPa

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

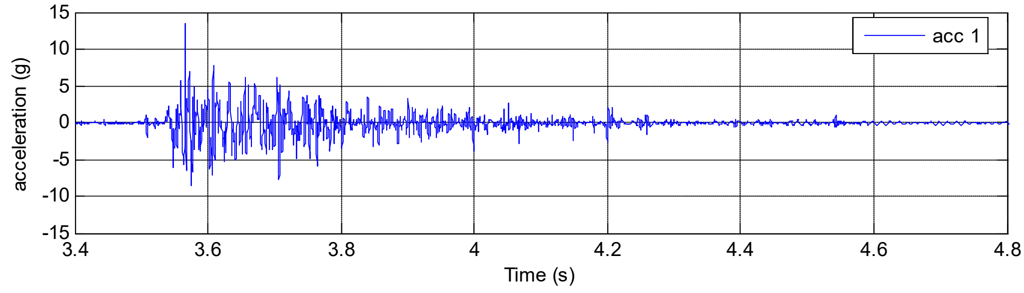
3 – Seismic Excitation

Accelerometers time histories

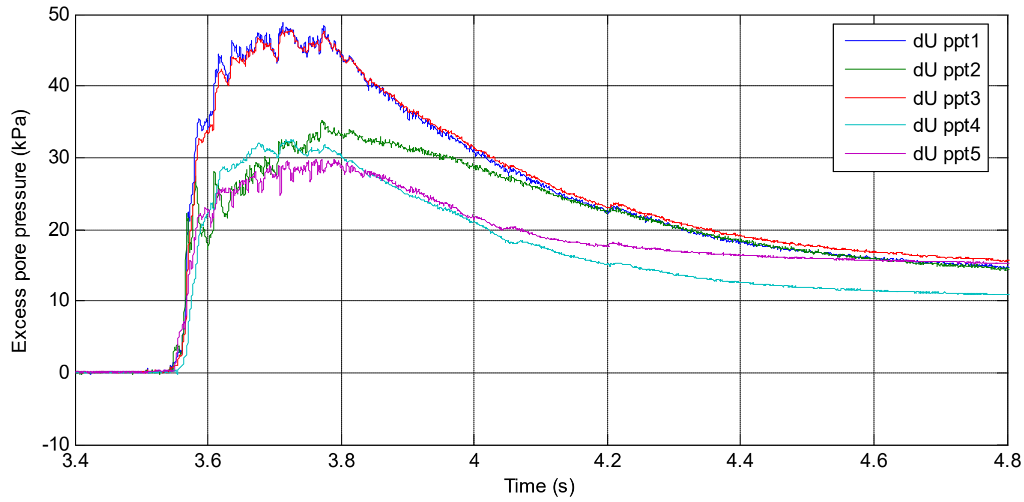


This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

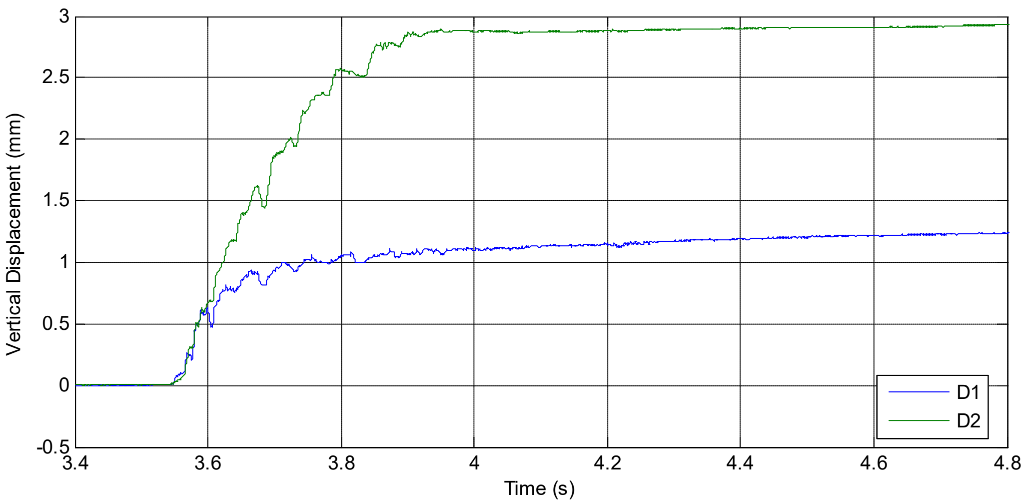
Input motion



Excess pore pressure $\Delta u(t) = u(t) - u_0$ vs. time



Vertical displacements vs. time



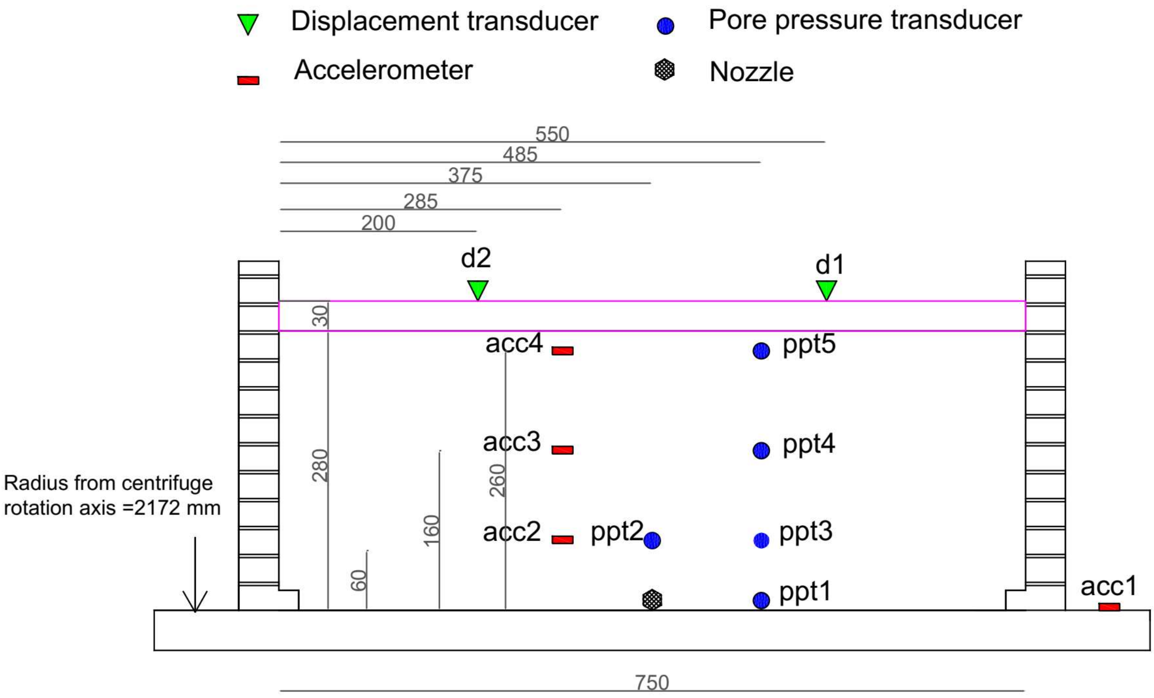
Test 33: M2_S1_IPS1_GM31+

Model description

The model consists of a two layers soil profile composed of Ticino sand and Pontida clay. The ground motion applied was the number 31+. Induced Partial Saturation by inflight air injection from one nozzle.

1 – Reconstruction

Scheme and geometrical dimensions of the model as reconstructed at 1g. The following dimensions refer to model scale.



Ticino sand

Dry density [kN·s²/m⁴]	**1.487**
Relative density [%]	**35.76**
Void ratio [-]	**0.80**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

2 – Equilibrium at centrifuge angular velocity ω= 15.08 rad/s before the shock

Ticino sand, average values

Dry density [kN·s²/m⁴]	**1.503**
Saturated density [kN·s²/m⁴]	**1.941**
Relative density [%]	**41.32**
Void ratio [-]	**0.78**
Degree of saturation [%]	**99.6**

Pontida clay, average value

Mass density [kN·s²/m⁴]	**2.160**

Radii from centrifuge rotation axis

	Radius (mm)
model base	2172.0
free ground surface	1864.1
sand clay interface	1893.5

Pore Pressure Transducer	**Radius (mm)**	**Value before the shock u_0 (kPa)**
ppt5	1917.9	16.9
ppt4	2015.6	62.1
ppt3	2113.4	97.7
ppt2	2113.4	92.9
ppt1	2172.0	122.8

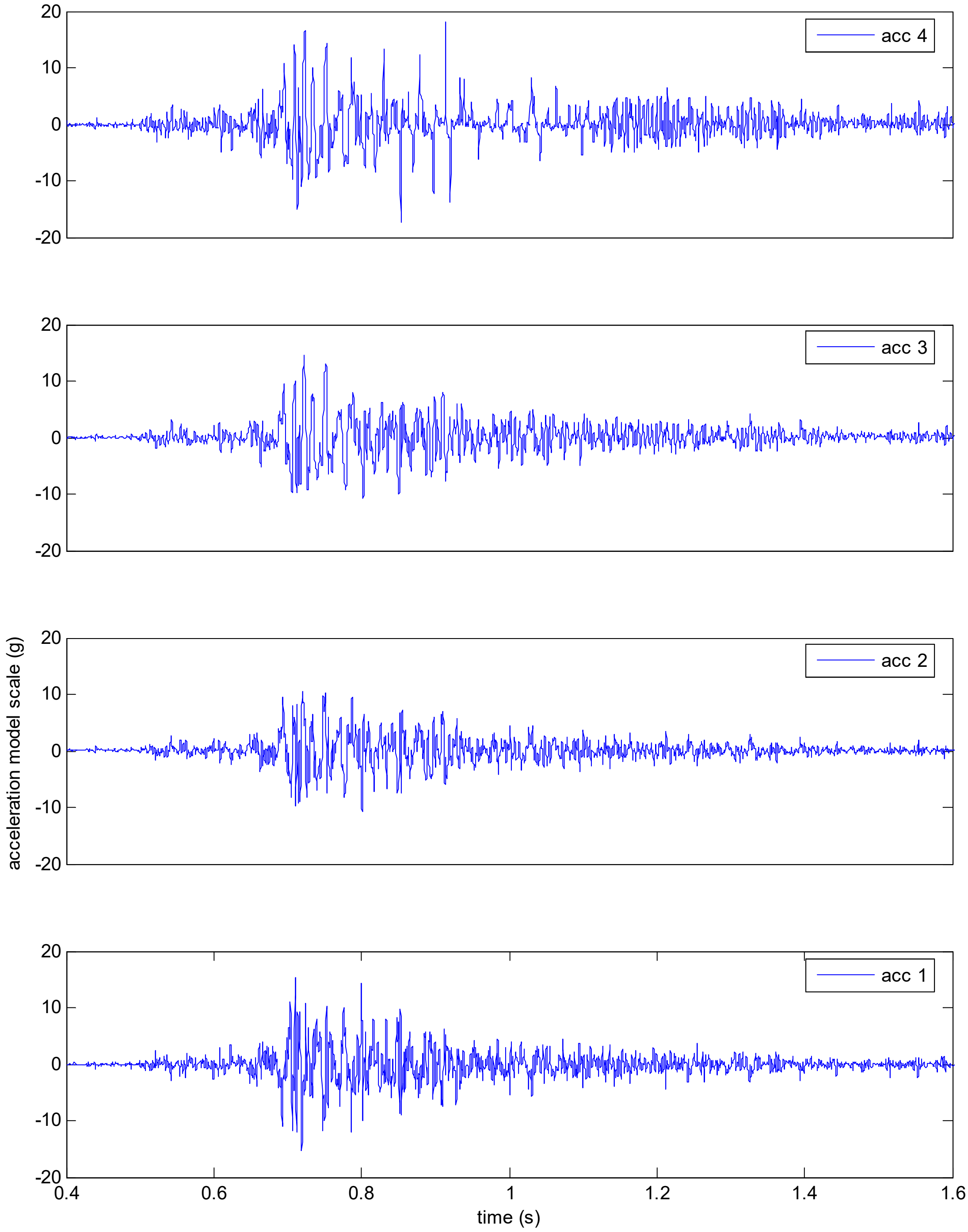
Accelerometer	**Radius (mm)**
acc4	1917.9
acc3	2015.6
acc2	2113.4
acc1	2172.0

Injection parameters

P_{ini}= 131 kPa P_{fin}= 122 kPa

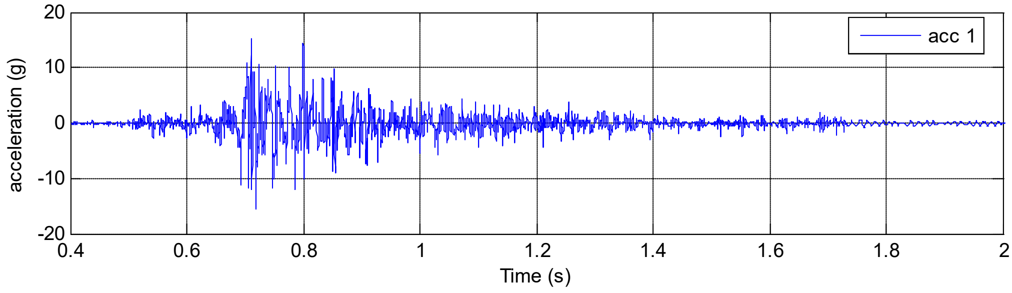
3 – Seismic Excitation

Accelerometers time histories

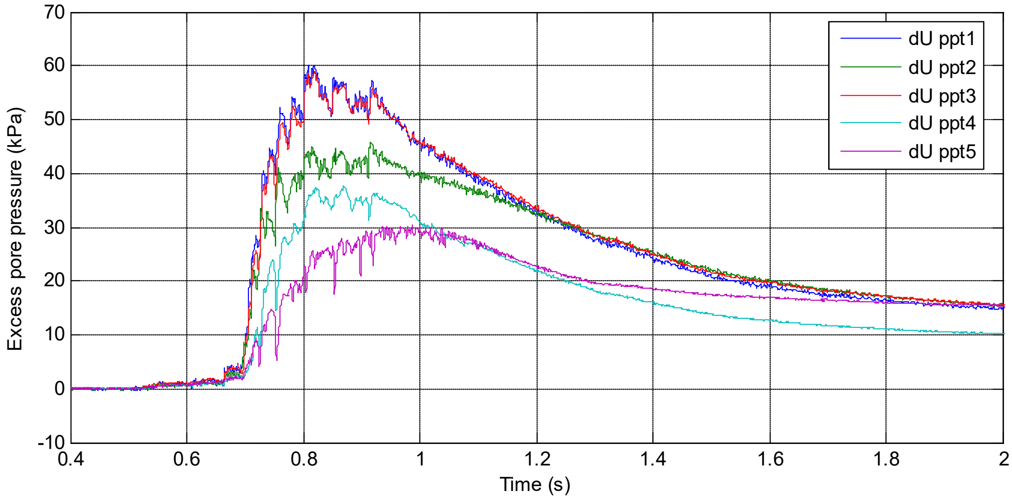


This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

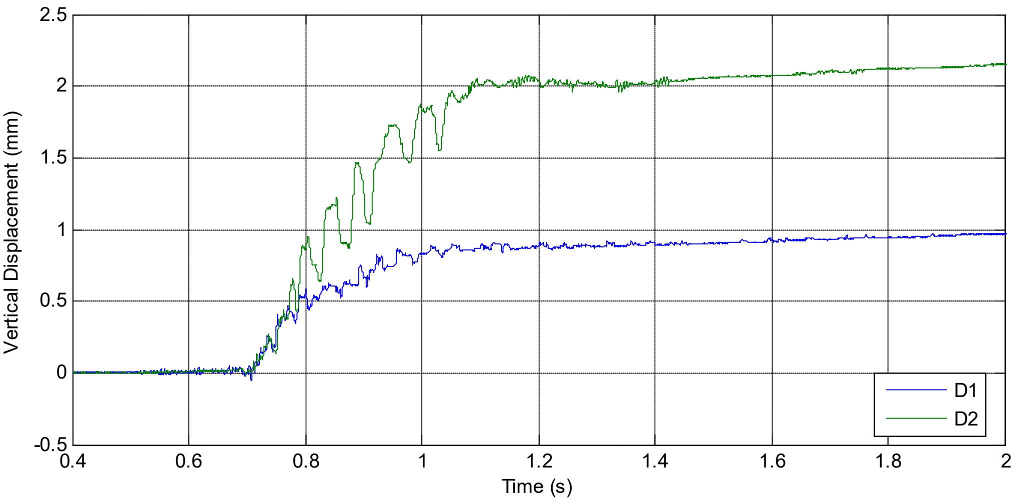
Input motion



Excess pore pressure $\Delta u(t) = u(t) - u_0$ vs. time



Vertical displacements vs. time



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

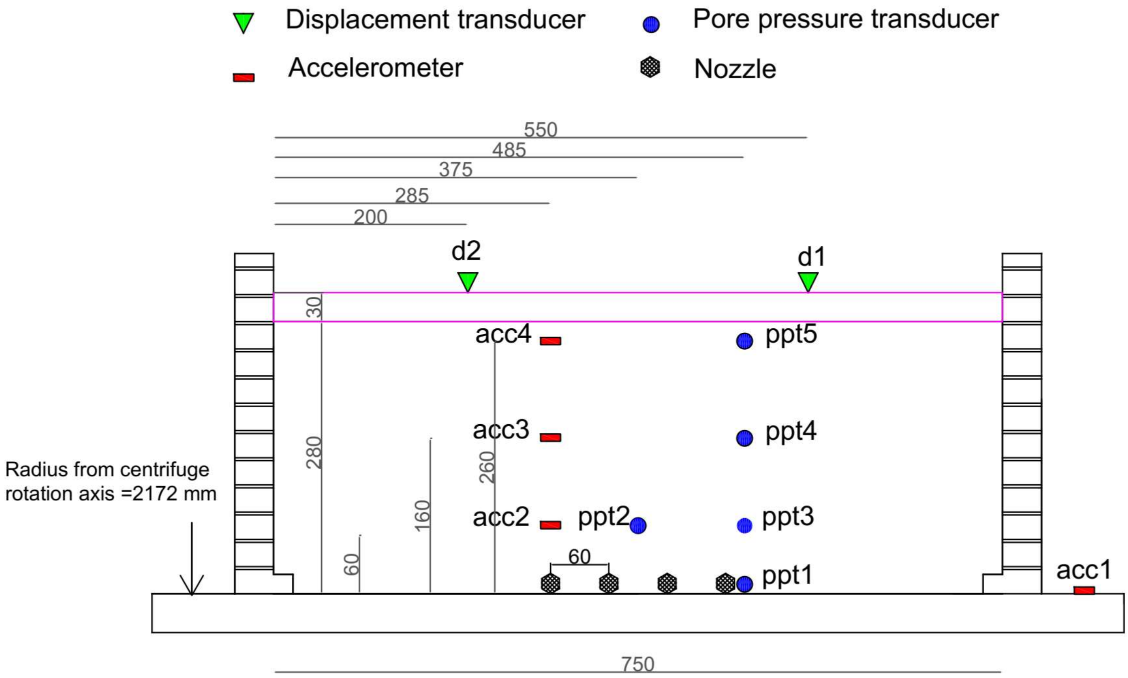
Test 34: M2_S1_IPS4_GM31

Model description

The model consists of a two layers soil profile composed of Ticino sand and Pontida clay. The ground motion applied was the number 31. Induced Partial Saturation by inflight air injection from four nozzles.

1 – Reconstruction

Scheme and geometrical dimensions of the model as reconstructed at 1g. The following dimensions refer to model scale.



Ticino sand

Dry density [kN·s^2/m^4]	**1.498**
Relative density [%]	**39.43**
Void ratio [-]	**0.79**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

2 – Equilibrium at centrifuge angular velocity ω= 15.08 rad/s before the shock

Ticino sand, average values

Dry density [kN·s²/m⁴]	**1.521**
Saturated density [kN·s²/m⁴]	**1.952**
Relative density [%]	**47.19**
Void ratio [-]	**0.76**
Degree of saturation [%]	**99.6**

Pontida clay, average value

Mass density [kN·s²/m⁴]	**2.160**

Radii from centrifuge rotation axis

	Radius (mm)
model base	2172.0
free ground surface	1863.7
sand clay interface	1893.2

Pore Pressure Transducer	Radius (mm)	Value before the shock u_0 (kPa)
ppt5	1915.9	20.0
ppt4	2014.4	60.8
ppt3	2112.9	85.9
ppt2	2112.9	92.3
ppt1	2172.0	132.0

Accelerometer	Radius (mm)
acc4	1915.9
acc3	2014.4
acc2	2112.9
acc1	2172.0

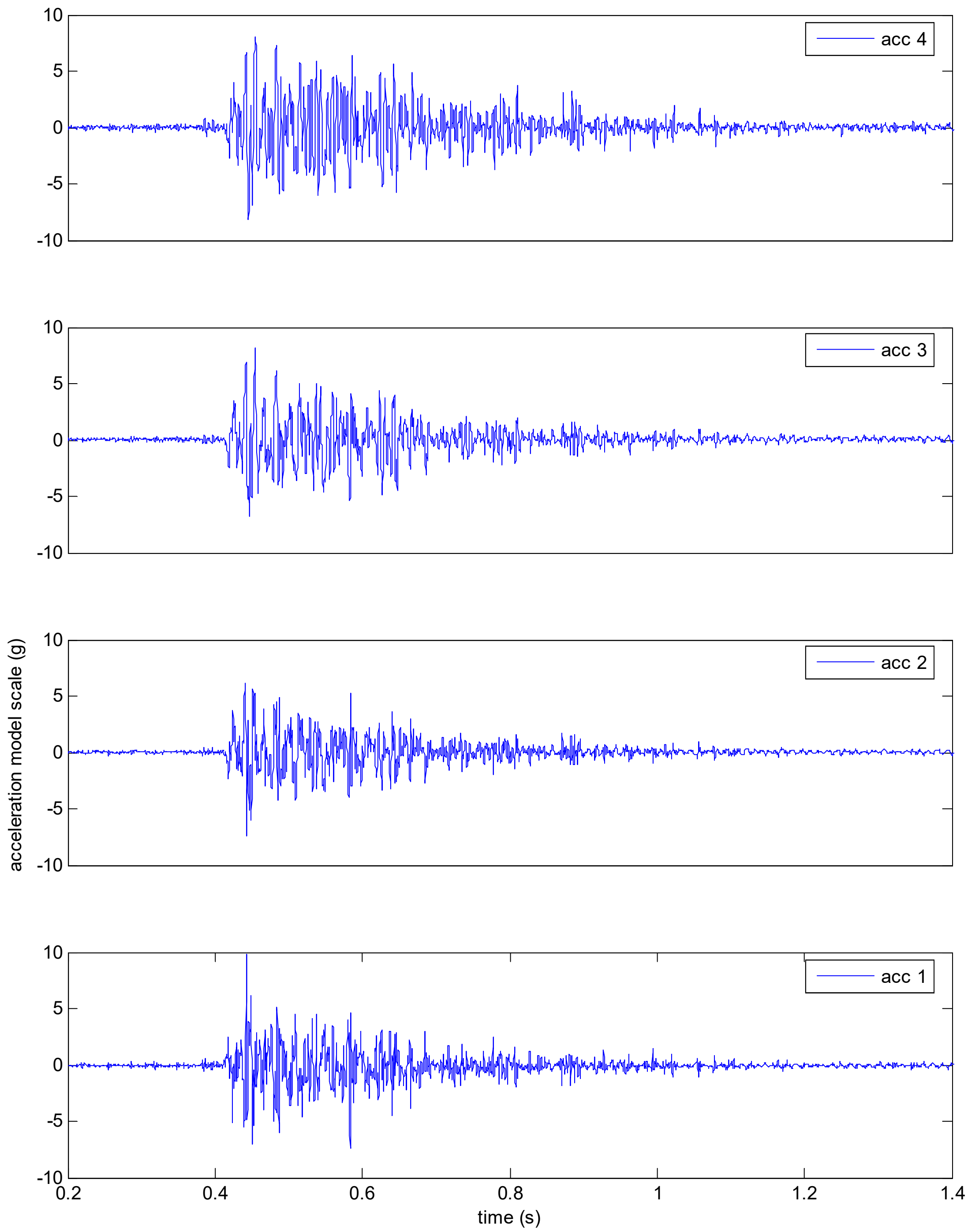
Injection parameters

P_{ini}= 138 kPa P_{fin}= 132 kPa

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

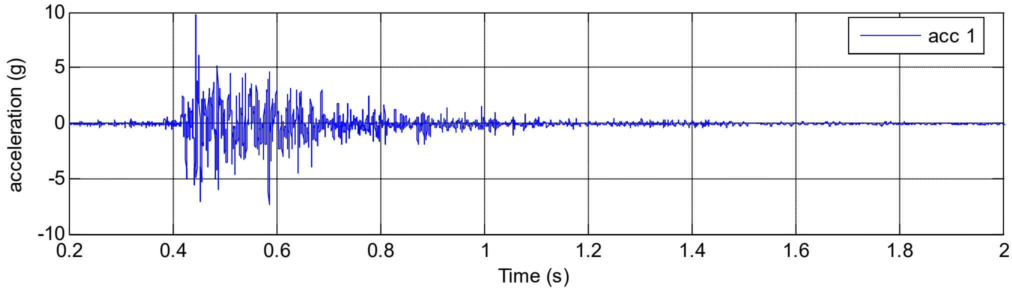
3 – Seismic Excitation

Accelerometers time histories

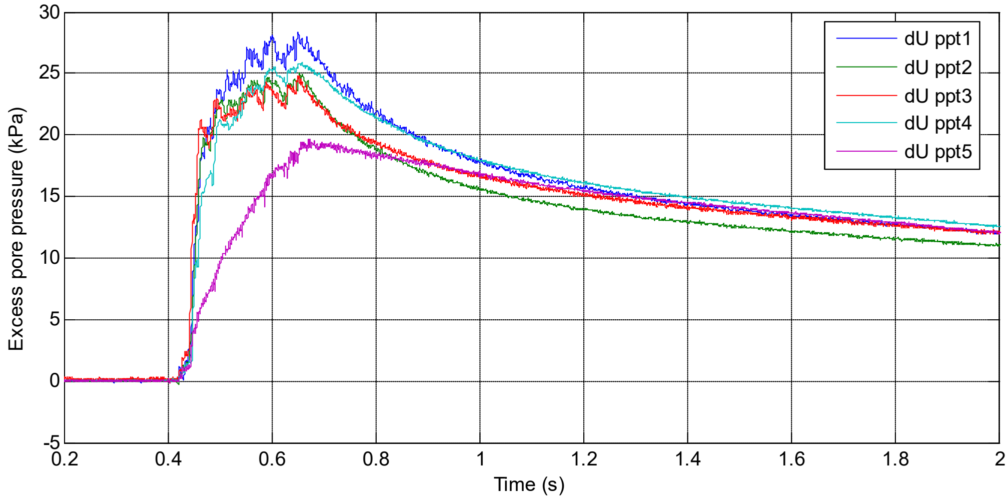


This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

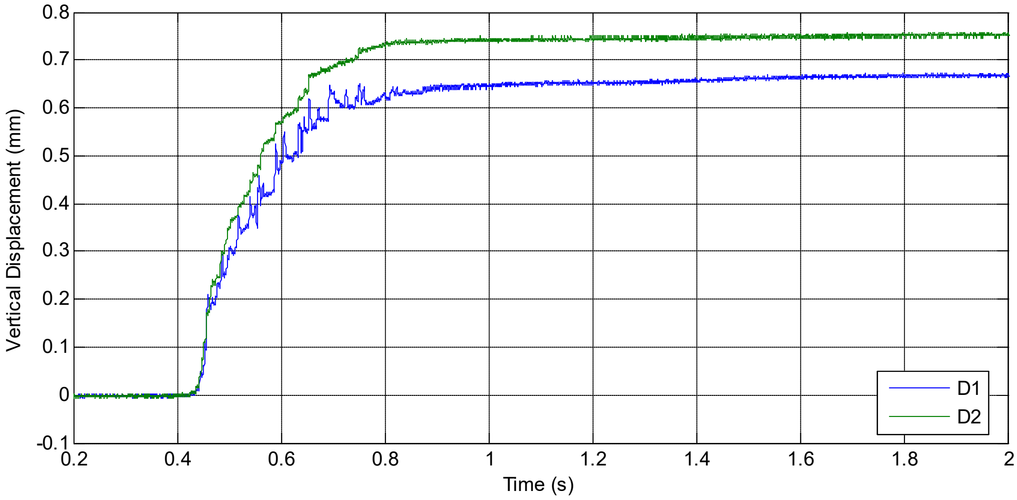
Input motion



Excess pore pressure $\Delta u(t) = u(t) - u_0$ vs. time



Vertical displacements vs. time



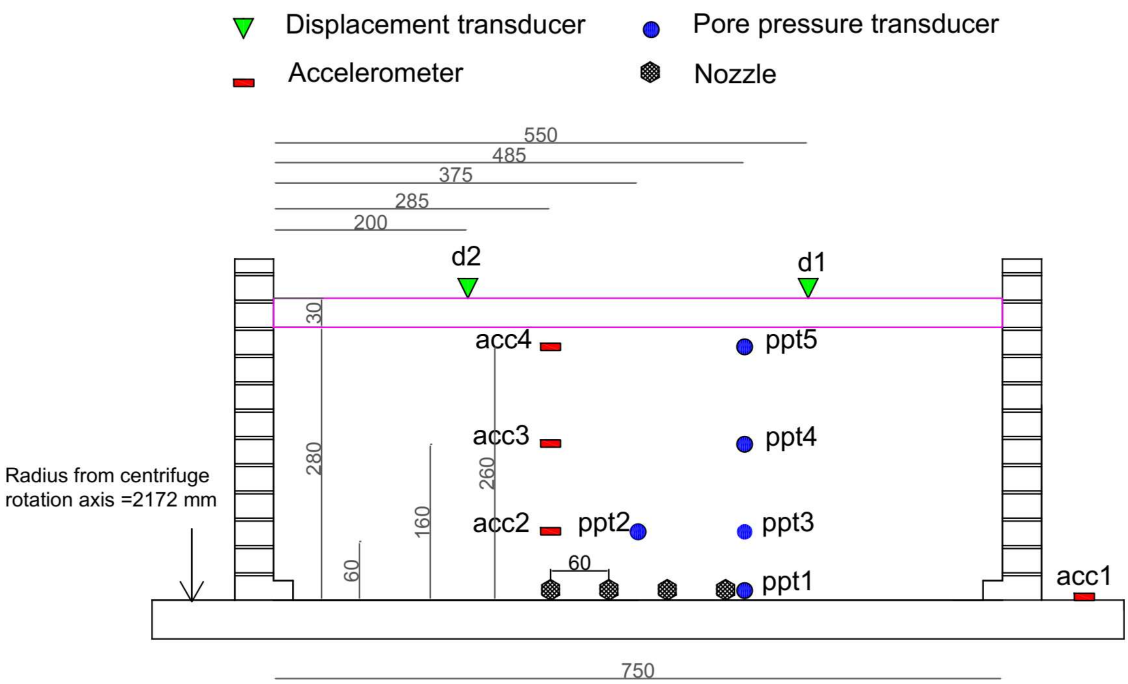
Test 35: M2_S1_IPS4_GM31+

Model description

The model consists of a two layers soil profile composed of Ticino sand and Pontida clay. The ground motion applied was the number 31+. Induced Partial Saturation by inflight air injection from four nozzles.

1 – Reconstruction

Scheme and geometrical dimensions of the model as reconstructed at 1g. The following dimensions refer to model scale.



Ticino sand

Dry density [kN·s²/m⁴]	**1.498**
Relative density [%]	**39.43**
Void ratio [-]	**0.79**

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2 – Equilibrium at centrifuge angular velocity ω= 15.08 rad/s before the shock

Ticino sand, average values

Dry density [kN·s²/m⁴]	**1.525**
Saturated density [kN·s²/m⁴]	**1.954**
Relative density [%]	**48.48**
Void ratio [-]	**0.76**
Degree of saturation [%]	**99.6**

Pontida clay, average value

Mass density [kN·s²/m⁴]	**2.160**

Radii from centrifuge rotation axis

	Radius (mm)
model base	2172.0
free ground surface	1864.5
sand clay interface	1893.9

Pore Pressure Transducer	**Radius (mm)**	**Value before the shock u_0 (kPa)**
ppt5	1916.5	20.0
ppt4	2014.8	61.3
ppt3	2113.0	85.7
ppt2	2113.0	92.6
ppt1	2172.0	132.2

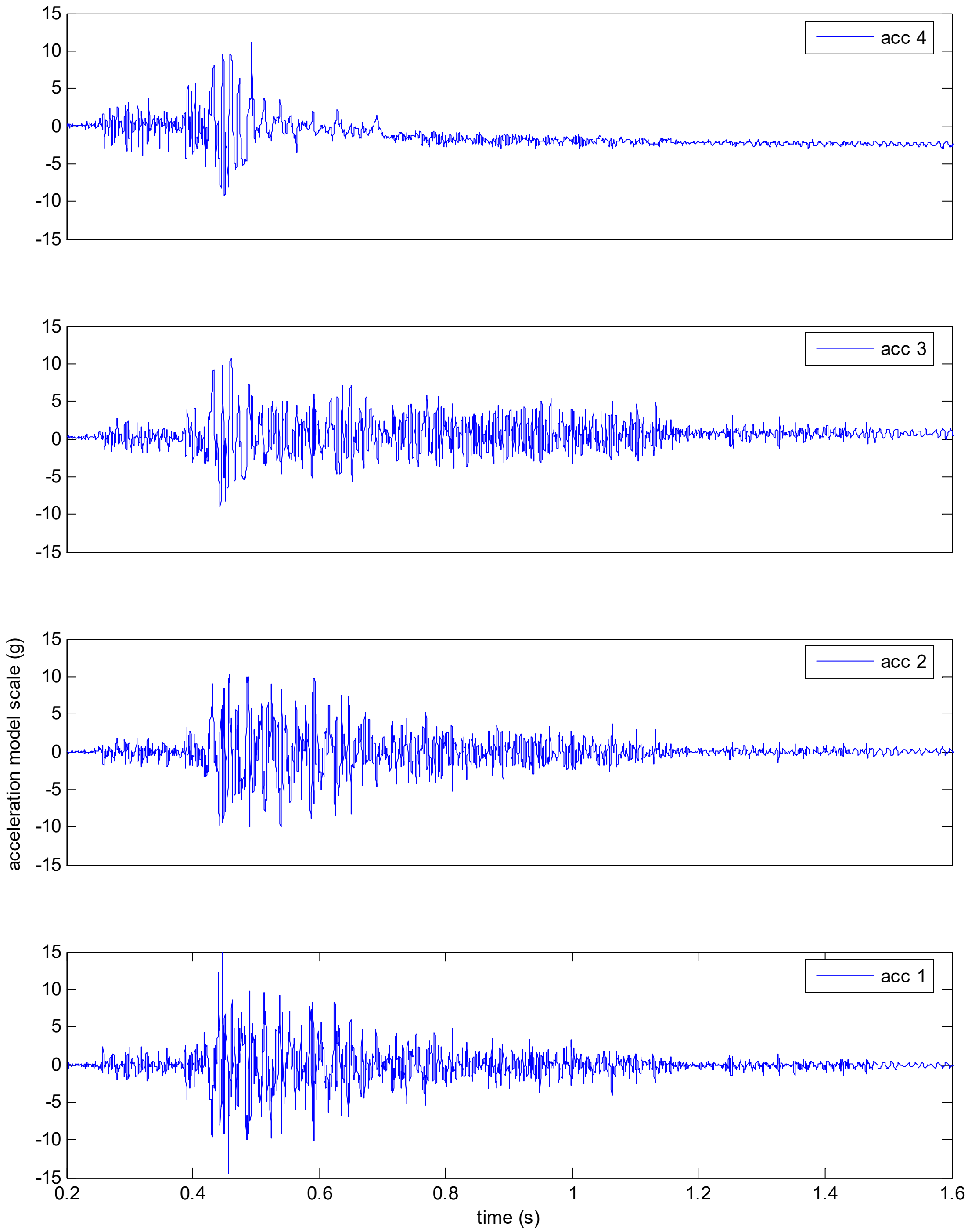
Accelerometer	**Radius (mm)**
acc4	1916.5
acc3	2014.8
acc2	2113.0
acc1	2172.0

Injection parameters

P_{ini}= 138 kPa P_{fin}= 132 kPa

3 – Seismic Excitation

Accelerometers time histories



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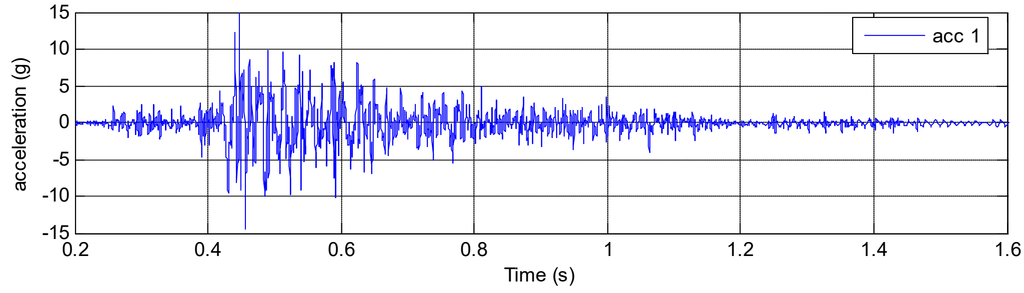
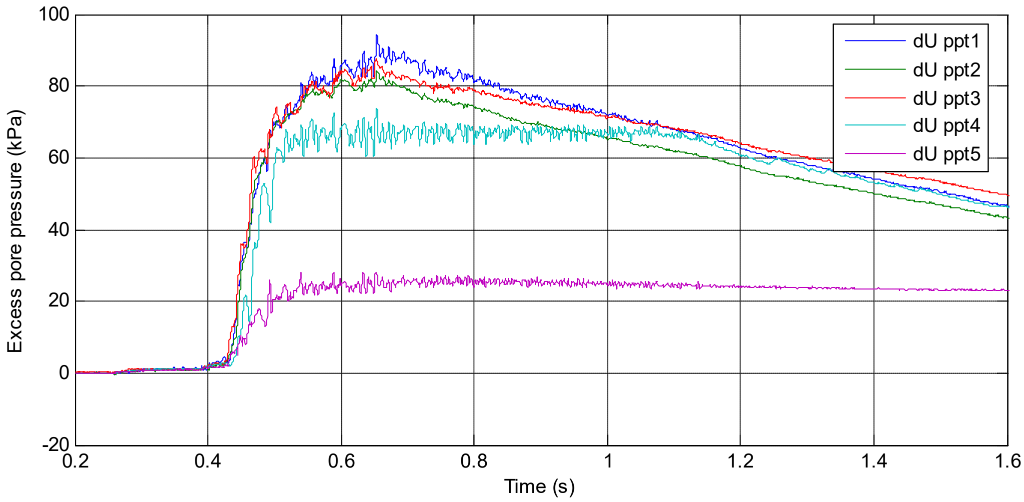
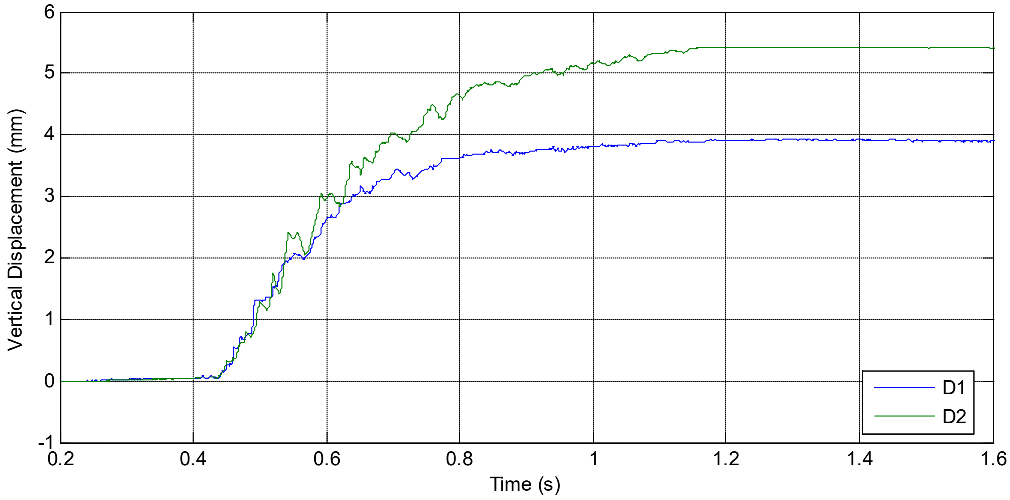
Input motion



Excess pore pressure $\Delta u(t) = u(t) - u_0$ vs. time



Vertical displacements vs. time



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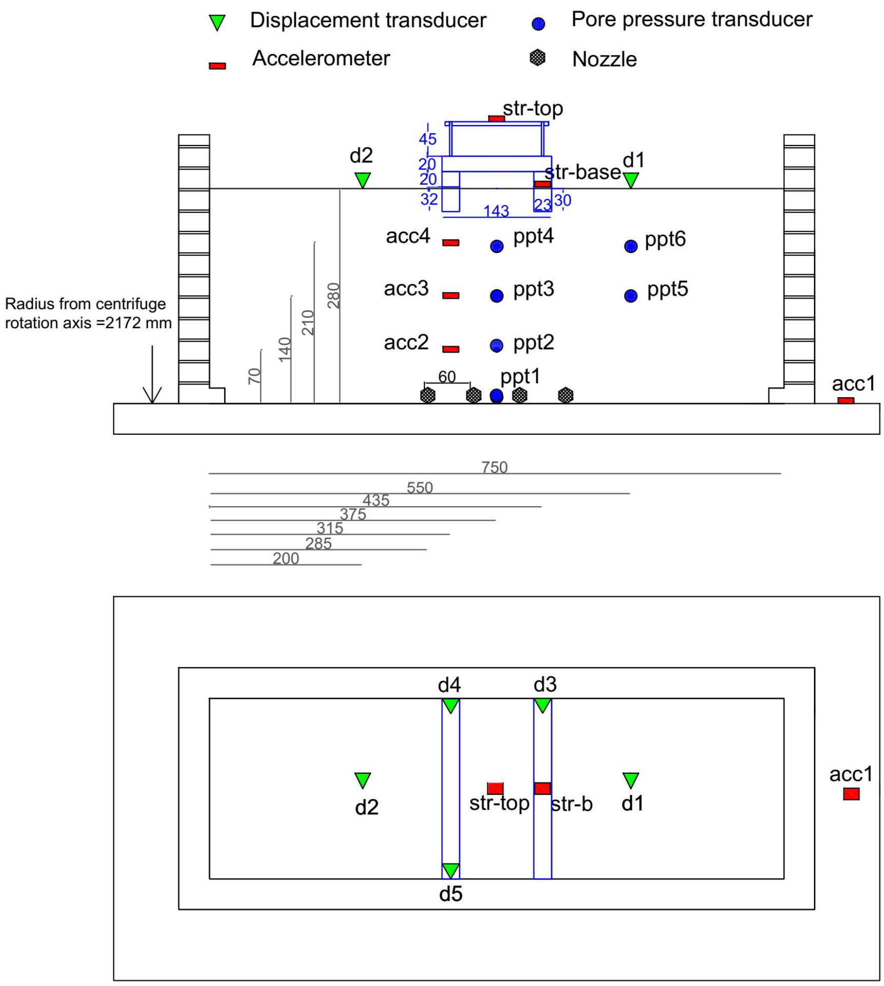
Test 36: M1F_S1_IPS4_GM31+

Model description

The model consists of a homogenous soil profile of Ticino sand, with a model structure with shallow foundations. The ground motion applied was the number 31+. Induced Partial Saturation by inflight air injection from four nozzles.

1 – Reconstruction

Scheme and geometrical dimensions of the model as reconstructed at 1g. The following dimensions refer to model scale.



Ticino sand

Dry density [kN·s²/m⁴]	**1.499**
Relative density [%]	**40.01**
Void ratio [-]	**0.79**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

2 – Equilibrium at centrifuge angular velocity ω= 15.08 rad/s before the shock

Ticino sand, average values

Dry density [kN·s^2/m^4]	**1.547**
Saturated density [kN·s^2/m^4]	**1.971**
Relative density [%]	**55.83**
Void ratio [-]	**0.73**
Degree of saturation [%]	**100.0**

Radii from centrifuge rotation axis

	Radius (mm)
model base	2172.0
free ground surface	1900.2

Pore Pressure Transducer	**Radius (mm)**	**Value before the shock u_0 (kPa)**
ppt6	1968.1	21.5
ppt5	2036.1	51.2
ppt4	1968.1	19.8
ppt3	2036.1	49.9
ppt2	2104.0	80.1
ppt1	2172.0	113.4

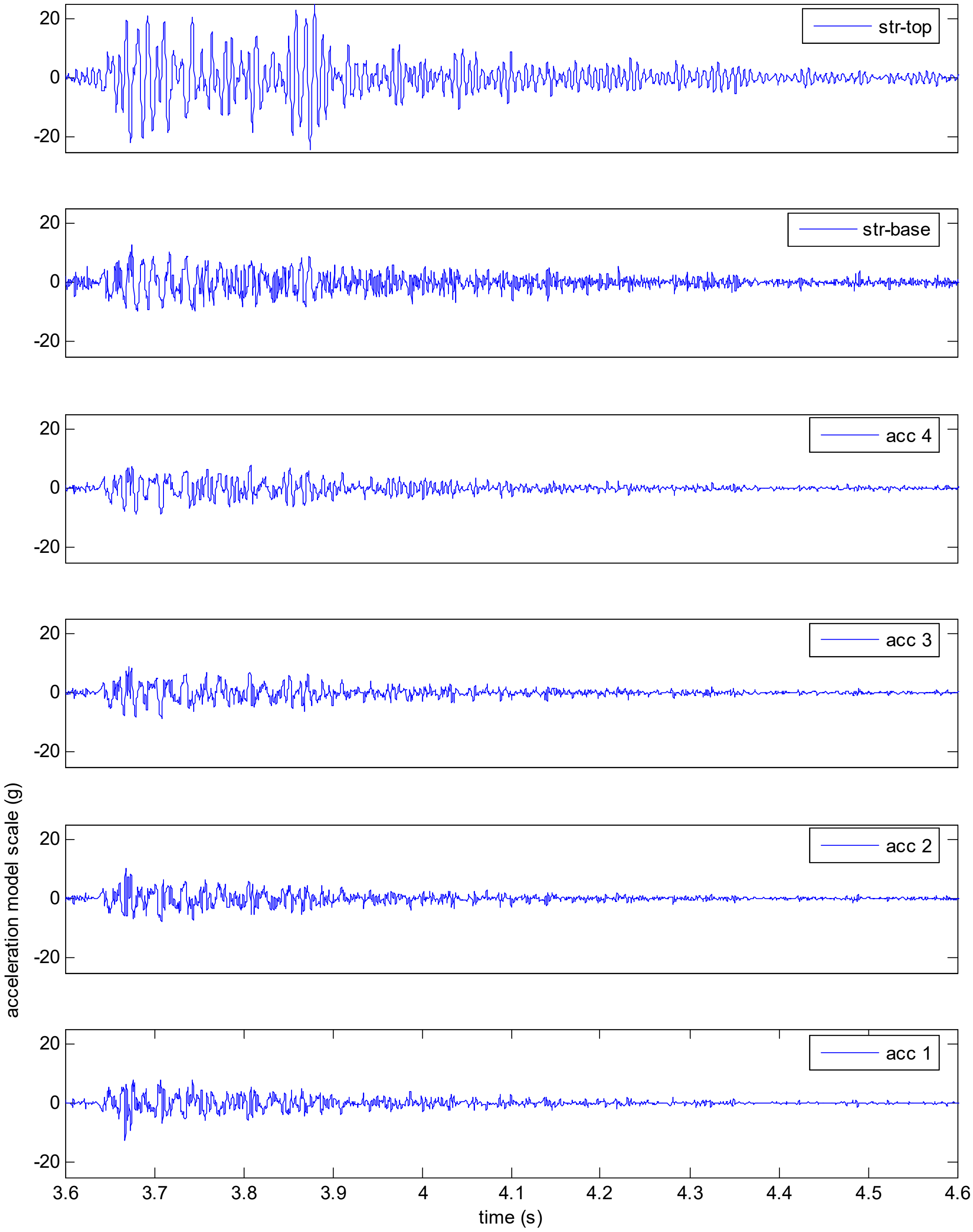
Accelerometer	**Radius (mm)**
acc4	1968.1
acc3	2036.1
acc2	2104.0
acc1	2172.0

Injection parameters

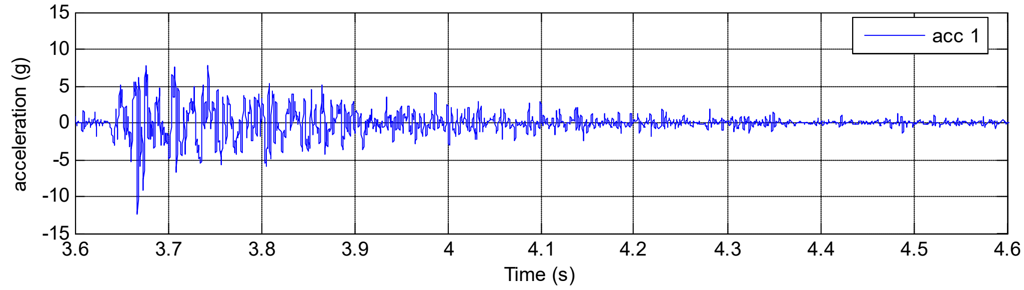
P_{ini}= 154 kPa P_{fin}= 121 kPa

3 – Seismic Excitation

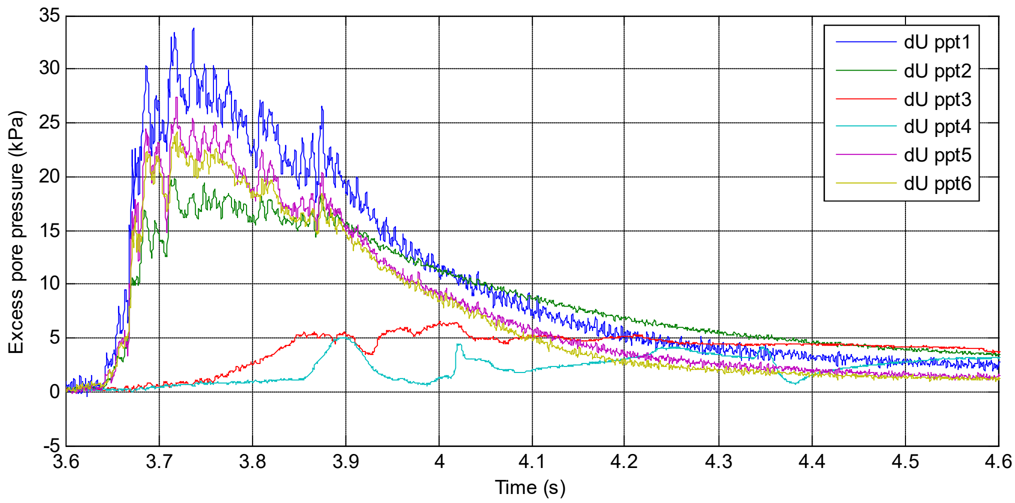
Accelerometers time histories



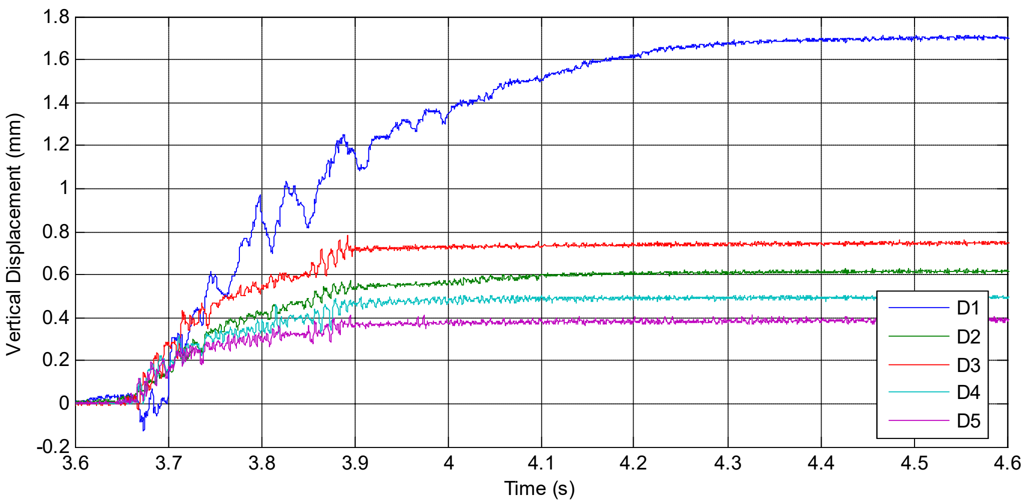
Input motion



Excess pore pressure $\Delta u(t) = u(t) - u_0$ vs. time



Vertical displacements vs. time



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

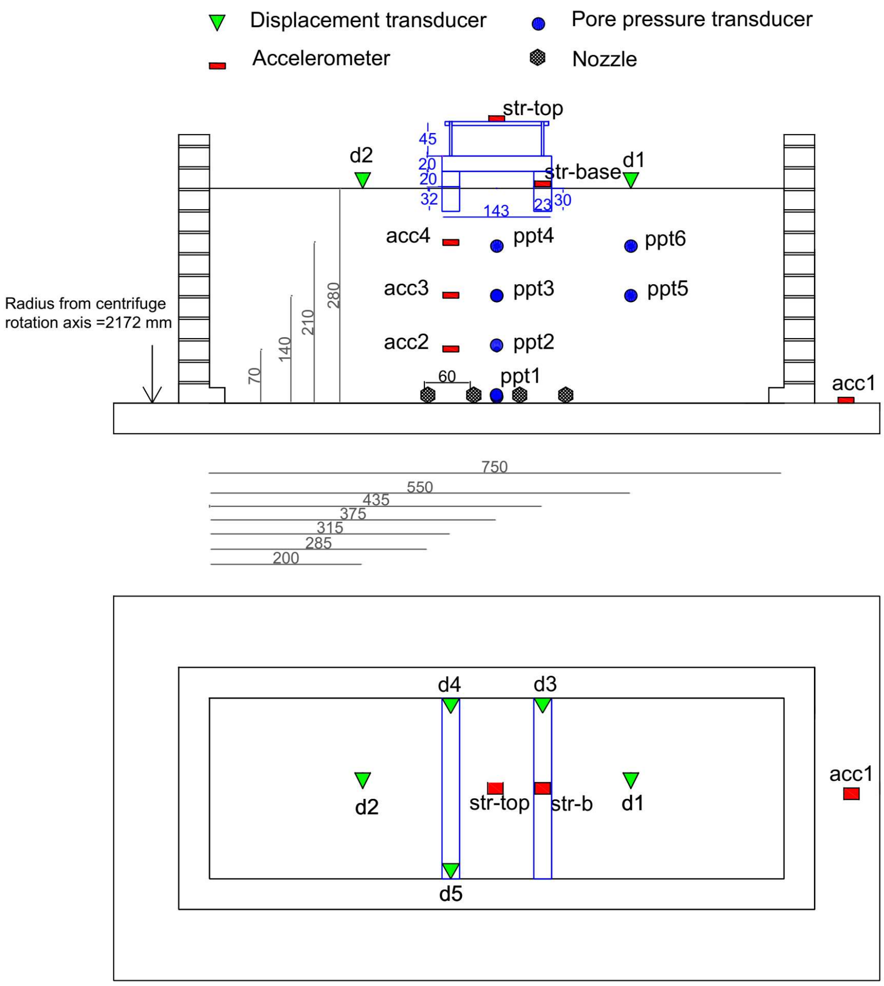
Test 37: M1F_S1_IPS4_GM31++

Model description

The model consists of a homogenous soil profile of Ticino sand, with a model structure with shallow foundations. The ground motion applied was the number 31++. Induced Partial Saturation by inflight air injection from four nozzles.

1 – Reconstruction

Scheme and geometrical dimensions of the model as reconstructed at 1g. The following dimensions refer to model scale.



Ticino Sand

Dry density [kN·s^2/m^4]	**1.499**
Relative density [%]	**40.01**
Void ratio [-]	**0.79**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 700748

2 – Equilibrium at centrifuge angular velocity ω= 15.08 rad/s before the shock

Ticino sand, average values

Dry density [kN·s^2/m^4]	**1.552**
Saturated density [kN·s^2/m^4]	**1.974**
Relative density [%]	**57.34**
Void ratio [-]	**0.73**
Degree of saturation [%]	**100.0**

Radii from centrifuge rotation axis

	Radius (mm)
model base	2172.0
free ground surface	1901.4

Pore Pressure Transducer	**Radius (mm)**	**Value before the shock u_0 (kPa)**
ppt6	1969.0	21.7
ppt5	2036.7	51.2
ppt4	1969.0	20.0
ppt3	2036.7	50.0
ppt2	2104.3	80.5
ppt1	2172.0	113.8

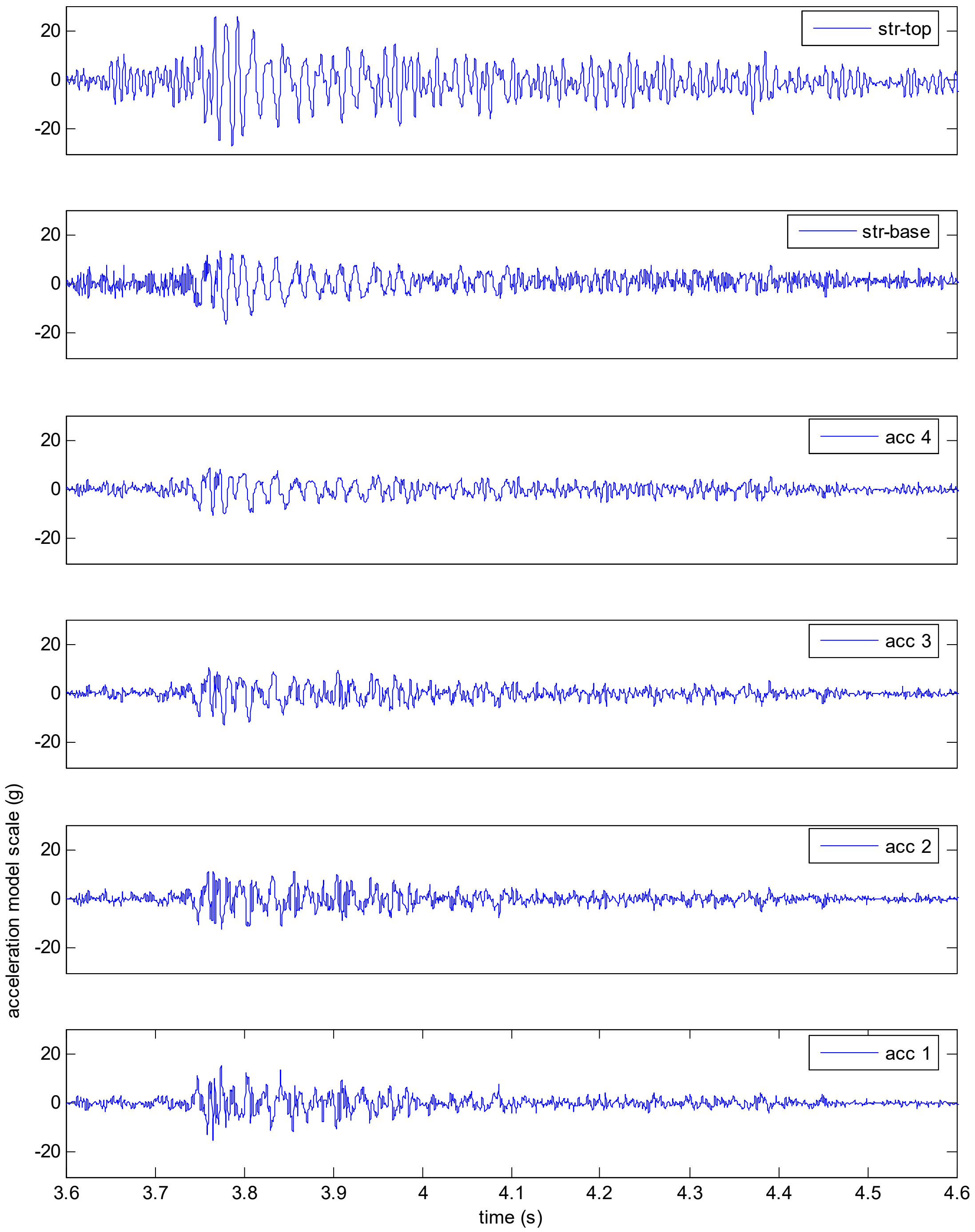
Accelerometer	**Radius (mm)**
acc4	1969.0
acc3	2036.7
acc2	2104.3
acc1	2172.0

Injection parameters

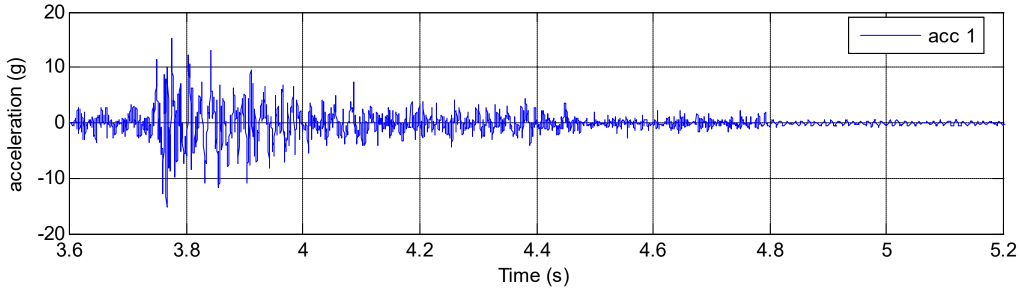
P_{ini}= 154 kPa P_{fin}= 121 kPa

3 – Seismic Excitation

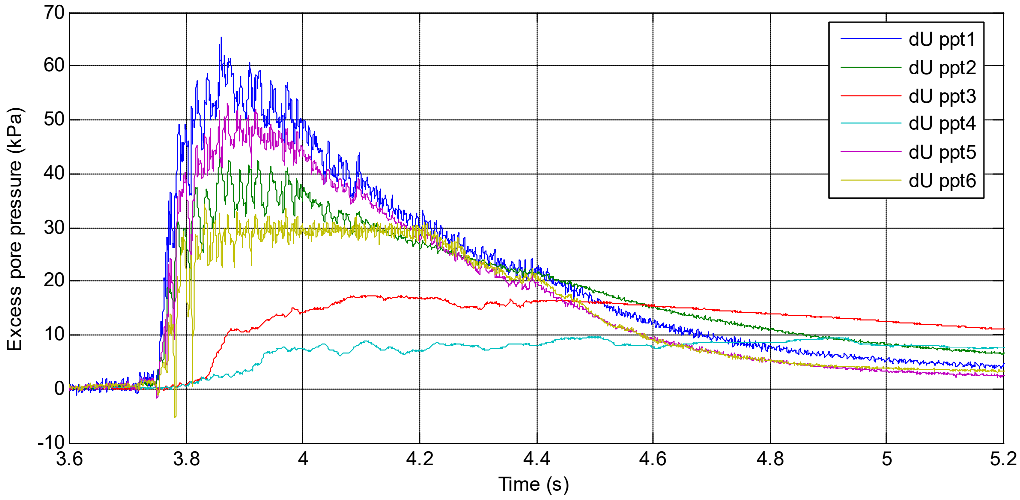
Accelerometers time histories



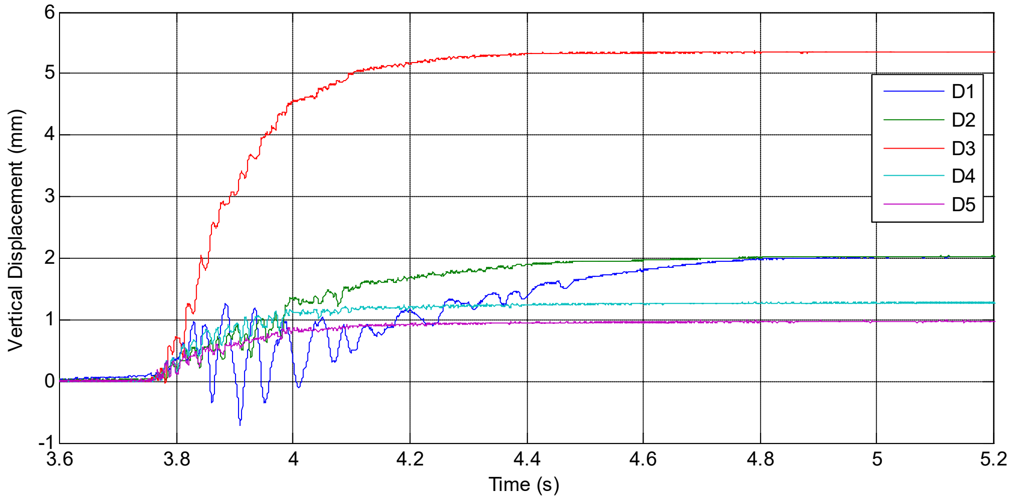
Input motion



Excess pore pressure $\Delta u(t) = u(t) - u_0$ vs. time



Vertical displacements vs. time



11. References

Airoldi, S., Fioravante, V., Giretti, D. (2016). The ISMGEO Seismic Geotechnical Centrifuge. In Proceedings of the 3rd European conference on Physical Modelling in Geotechnics, Nantes, France, 185-190

Allard, M.A. and Schenkeveld (1994). The Delft Geotechnics model pore fluid. Centrifuge 94, Leung, Lee & Tan (eds), Balkema, Rotterdam

Baldi, G., Belloni, G., Maggioni, W. (1988). The ISMES Geotechnical Centrifuge. In Centrifuge 88, Paris, Corté J. F. Ed., Balkema, Rotterdam, 45-48

Bertalot, D. (2013). "Seismic behaviour of shallow foundations on layered liquefiable soils" Ph.D. Thesis, University of Dundee, United Kingdom

Brennan, A. J. (2003). "Vertical drains as a countermeasure to earthquakeinducedsoil liquefaction." Ph.D. Thesis, Cambridge University, United Kingdom.

Brennan, A. J., Madabhushi, S. P. G., and Houghton, N. E. (2006). Comparing laminar and equivalent shear beam (ESB) containers for dynamic centrifuge modelling. Proc. 6th Int. Conf. on Physical Modelling in Geotechnics 06, Vol. 1, Balkema, Rotterdam, The Nertherlands, 171-176

Bolton, M.D., Gui, M. W., Garnier, J., Corte, J. F., Bagge, G., Laue, J. & Renzi, R. (1999). Centrifuge Cone Penetration Tests in Sand. Geotechnique, Vol. 49, No. 4, pp. 543-552.

Calabrese L, Martelli L, Severi P. (2012) Stratigrafia dell'area interessata dai fenomeni di liquefazione durante il terremoto dell'Emilia (Maggio 2012). Proceedings of the 31th GNGTS, November 20-22, Potenza, pp 119-125.

Campbell, D.J., Cheney, J.A. and Kutter, B.L. (1991). "Boundary effects in dynamic centrifuge model tests", Proceedings of Centrifuge 91, 441-448, University of Colorado, Boulder, Colorado.

Derkx, F., Thorel, L., Chazelas, J. L., Escoffier, S., Rault, G., Buttigieg, S., (2006). Dynamic tests and simulation of earthquakes in the LCPC's centrifuge. Physical Modelling in Geotechnics – 6th ICPMG '06 – Ng, Zhang & Wang (eds), Taylor & Francis Group, London, pp. 181-186

Fioravante, V. and Jamiolkowski, M (2005). Physical modelling of piled rafts. Soil structure interaction: Calculation methods and Engineering Practice. International Geotechnical Conference. Saint Petersburg. May 2005. Pp 89, 95

Fioravante, V. & Giretti, D. Unidirectional cyclic resistance of Ticino and Toyoura sands from centrifuge cone penetration tests. Acta Geotech. (2016) 11: 953. https://doi.org/10.1007/s11440-015-0419-3

Garnier, J., C. Gaudin, S.M. Springman, P.J. Cullingan, D. Goodings, D. Konig, B. Kutter, R. Phillips, M.F. Randolph and L. Thorel. IJPMG, Vol. 3 (2007)

Giretti, D. and Fioravante, V. (2017). A correlation to evaluate cyclic resistance from CPT applied to a case history. Bull Earthquake Eng, DOI 10.1007/s10518-016-0057-7

Hardin, B. O. and Drnevich, V. P. (1972). "Shear modulus and damping in soils: measurement and parameter effects." Journal of Soil Mechanics and Foundations Division, ASCE, 98(6), 603-624.

Imamura, S., Hagiwara, T., Nomoto, T. (1998). Nishimatsu dynamic geotechnical centrifuge facility. Centrifuge 98, Tokyo, Kimura, Kusakabe & Takemura (eds), Balkema, Rotterdam, pp. 19-24

Lee, S. H., Choo, Y. W., and Kim, D. S. (2013). "Performance of an equivalent shear beam (ESB) model container for dynamic geotechnical centrifuge tests." Soil Dynamics and Earthquake Engineering, 44, 102-114.

Ma, X. F., He, Z. M, Zhu, H. H, Lin, M., 2006. Development of a new geotechnical centrifuge at Tongji University in Shanghai. Physical Modelling in Geotechnics – 6th ICPMG '06 – Ng, Zhang & Wang (eds), Taylor & Francis Group, London, 151-156

Matsuo, O., Tsutsumi, T., Kondoh, K., Tamoto, S. (1998). The dynamic geotechnical centrifuge at PWRI. Centrifuge 98, Tokyo, Kimura, Kusakabe & Takemura (eds), Balkema, Rotterdam, pp. 25-30

Ohta, Y, and N Goto (1978). Empirical shear wave velocity equations in terms of characteristic soil indexes, Earthq.Eng. Struct. Dyn., 6:167–187.

PEER (2012) "Guidelines for Estimation of Shear Wave Velocity Profiles" PEER Guidelines. 2012/08, December 2012.

Santos, J.A., Gomes Correia, A., Modaressi, A., LopezCaballero, F., & Gomes, R. (2003). "Validation of an elasto-plastic model to predict secant shear modulus of natural soils by experimental results" Deformation Characteristics of Geomaterials, Vol. 1, Di Benedetto et al., Eds., Swets & Zeitlinger, Lisse: 1057-1061.

Schofield, A.N. (1980). Cambridge Geotechnical Centrifuge Operations. Geotechnique, Vol. 24, No. 4, pp. 227-268.

Seed, H. B., and Idriss, I. M. (1971). "Simplified procedure for evaluating soil liquefaction potential." Journal of Soil Mechanics and Foundations Division, ASCE, 97(9), 1249-1273

Seed, HB, RT Wong, IM Idriss, and K Tokimatsu (1986). Moduli and damping factors for dynamic analyses of cohesionless soils, J. Geotech. Eng., 112(11):1016–1032.

Shen, C. K., Li, X. S., Ng, C. W. W., Van Laak, P. A., Kutter, B. L., Cappel, K., Tauscher, R. C. (1998). Development of a geotechnical centrifuge in Hong Kong. Centrifuge 98, Tokyo, Kimura, Kusakabe & Takemura (eds), Balkema, Rotterdam, pp. 13-18

Steedman, R. S., and Sharp, M. (2001). "Liquefaction of deep saturated sands under high effective confining stress." Proceedings of the 4th International Conference on Recent Advances in Geotechnical Engineering, Lisbon, 21- 28.

Steedman, R. S., Ledbetter, R. H., and Hynes, M. E. (2000). "The inuence of high confining stress on the cyclic behavior of saturated sand." ASCE Geotechnical Special Publication No.107, 35-57.

Van Laak, P. A., Adalier, K., Dobry, R., Elgamal, A. W. (1998). Design of RPI's large servohydraulic centrifuge shaker. Centrifuge 98, Tokyo, Kimura, Kusakabe & Takemura (eds), Balkema, Rotterdam, pp. 105-110

Teymur, B., and Madabhushi, S. P. G. (2003). "Experimental study of boundary effects in dynamic centrifuge modelling." Geotechnique, 53(7), 655-663.

Zeng, X., and Schofield, A. N. (1996). "Design and performance of an Equivalent Shear Beam (ESB) model container for earthquake centrifuge modelling." Geotechnique, 46(1), 83-102