European Commission

Horizon 2020
European Union funding
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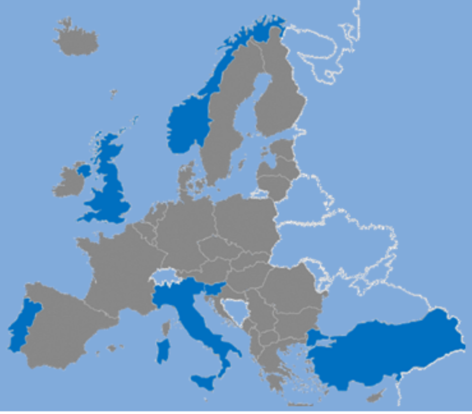
liquefACT



Pavia Workshop - October 9th 2019

ASSESSMENT AND MITIGATION OF LIQUEFACTION POTENTIAL ACROSS EUROPE

A holistic approach to protect structures / infrastructures for improved resilience to earthquake-induced liquefaction disasters

WP4. Comparative Analysis of State of the Art Liquefaction Mitigation Measures

T4.2 – Small scale centrifuge modelling

CENTRIFUGE MODELLING OF SOIL-STRUCTURE INTERACTION IN LIQUEFIABLE GROUND

Vincenzo Fioravante, Jenni Moglie, Sergio Airoldi

ISMGEO

ISTITUTO SPERIMENTALE MODELLI GEOTECNICI

MODELLING

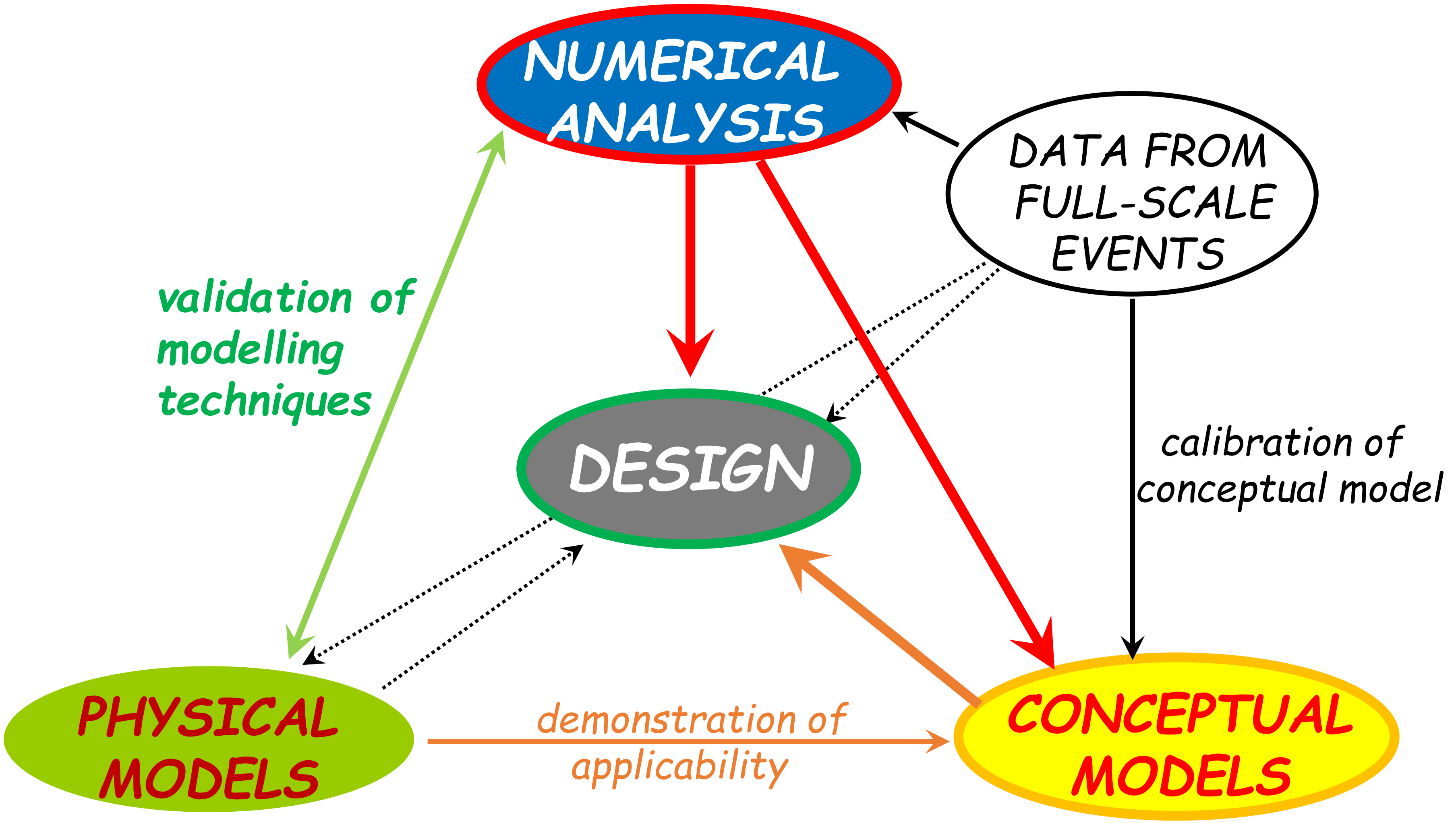
"…almost everything that engineers do is concerned with modelling" (*Muir Wood 2004*)

A model is an appropriate simplification of reality and
engineering is fundamentally concerned with identifying the key features to be accounted in the design and to be modelled, to solve a real problem

MODELLING

- EMPIRICAL ⇨ *inductive models - empiricism*
- PHYSICAL ⇨ *the key features of the real problem are reproduced and tested*
  - Full scale
  - Small scale
- CONCEPTUAL ⇨ *deductive models - rationalism*
  - Theoretical
  - Constitutive
  - Semi-empirical
- NUMERICAL ⇨ *from continuous to discrete*

INTERPLAY OF DIFFERENT ASPECTS OF MODELLING



Randolph & House (2001)

PHYSICAL MODELS

Every experiment can be considered a ***physical model***, directed to ***confirm or develop*** theoretical/empirical assumptions and ***understand mechanisms***

Key features of actual engineering problem (***prototype***) to be analysed are reproduced (***model***) and tested

Full scale models: employed when the behaviour of the prototype is so dependent on the details of actual soil fabric and structure

Small scale models: The key question is concerned with establishing the validity of the models and ensuring a secure way to extrapolate the observations made at small scale to the prototype scale (**scaling laws**)

SIMILARITY IN CENTRIFUGE

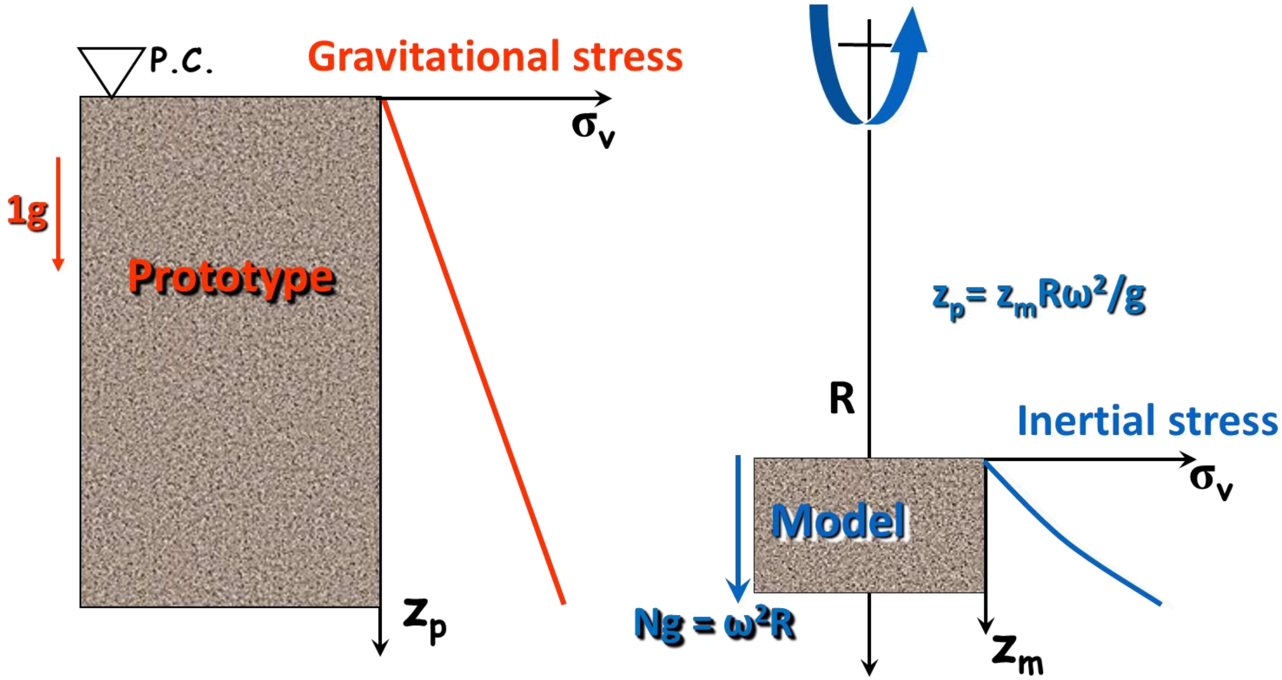
Scaling: $X^* = X_{prototype}/X_{model}$ ⇨ $\sigma^* = z^* \rho^* g^*$

in a accelerated field (centrifuge) $a{*}g = \omega^2 R$

$z^* = N$
$\rho^* = 1$
$g^* = 1/N$

} $\sigma^* = 1$

MODEL with SAME STRESS FIELD as PROTOTYPE



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

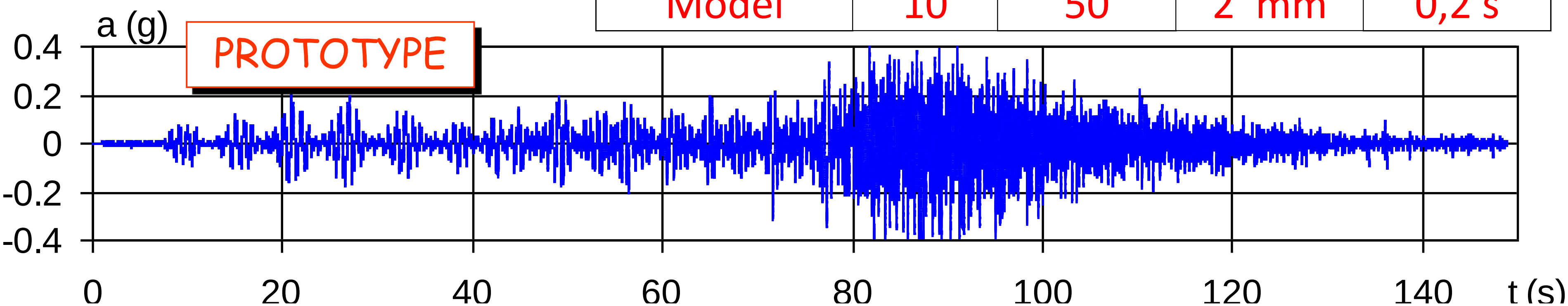
SCALE FACTORS ($x^* = x_{prot}/x_{mod}$)

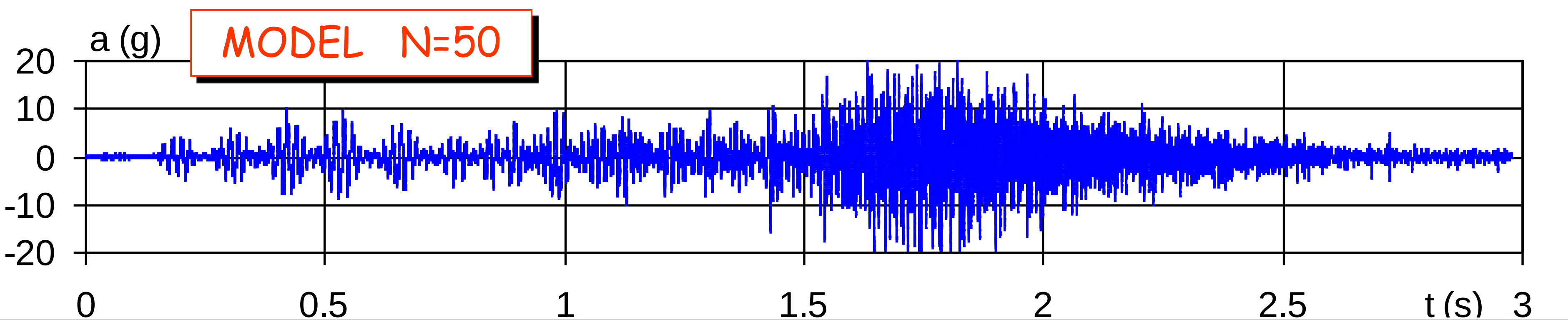
DYNAMIC PHENOMENA IN CENTRIFUGE

linear dimension: $L^* = N$
acceleration: $a^* = N^{-1}$
frequency: $f^* = N^{-1}$
velocity: $v^* = 1$
time (dynamic): $t^* = N$
time (diffusion): $t^* = N^2$
stress: $\sigma^* = 1$
strain: $\varepsilon^* = 1$
fluid dynamic viscosity: $\mu^* = N^{-1}$

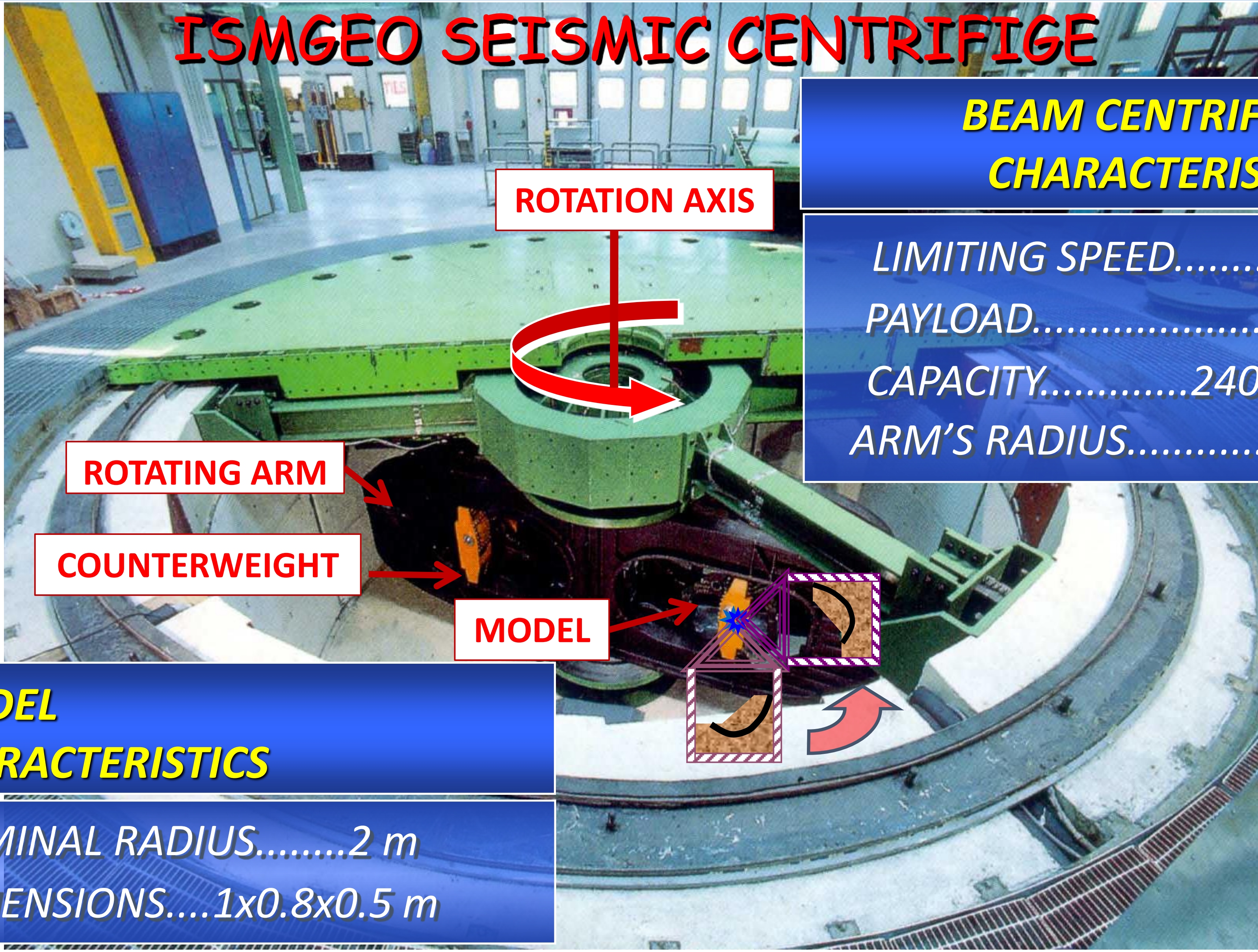
N=50

Heartquake	cycles	f	A	t
Prototype	10	1	0,1 m	10 s
Model	10	50	2 mm	0,2 s





ISMGEO SEISMIC CENTRIFIGE



BEAM CENTRIFUGE CHARACTERISTICS

LIMITING SPEED........600 g

PAYLOAD......................4 kN

CAPACITY............240 g-ton

ARM'S RADIUS..............3 m

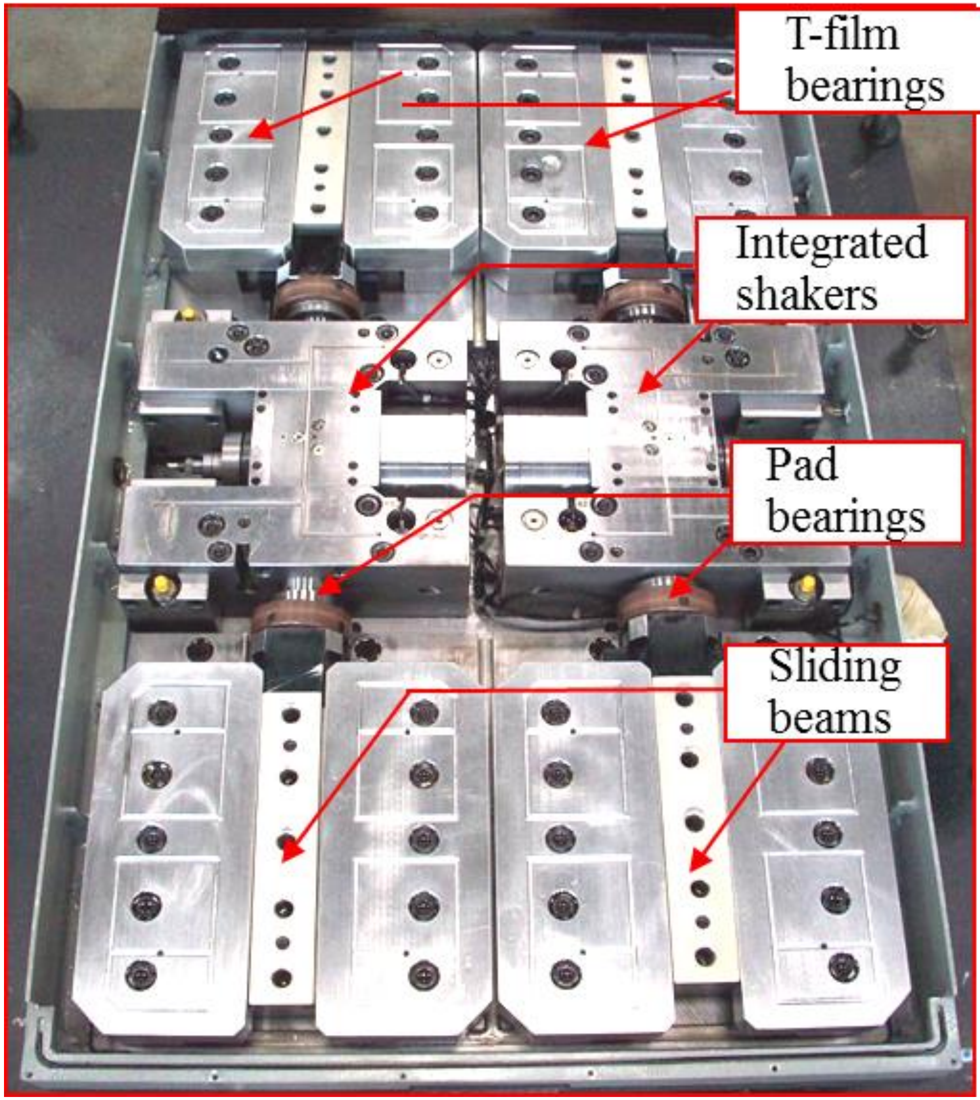
MODEL CHARACTERISTICS

NOMINAL RADIUS........2 m

DIMENSIONS....1x0.8x0.5 m


ISMGEO SEISMIC CENTRIFIGE

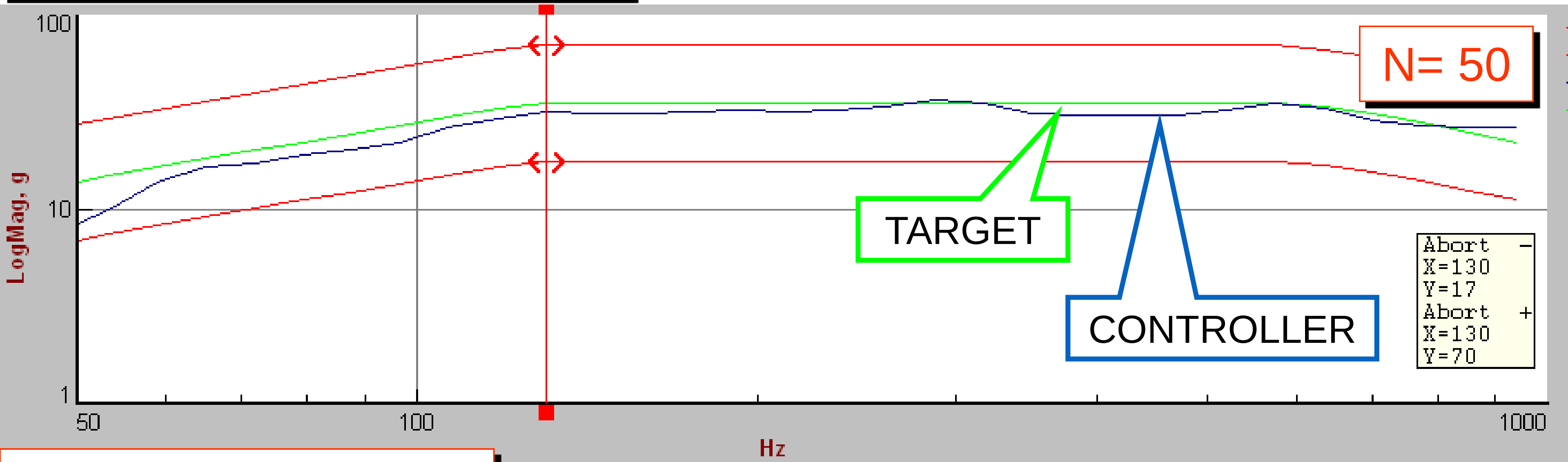
ISMGEO SEISMIC CENTRIFIGE



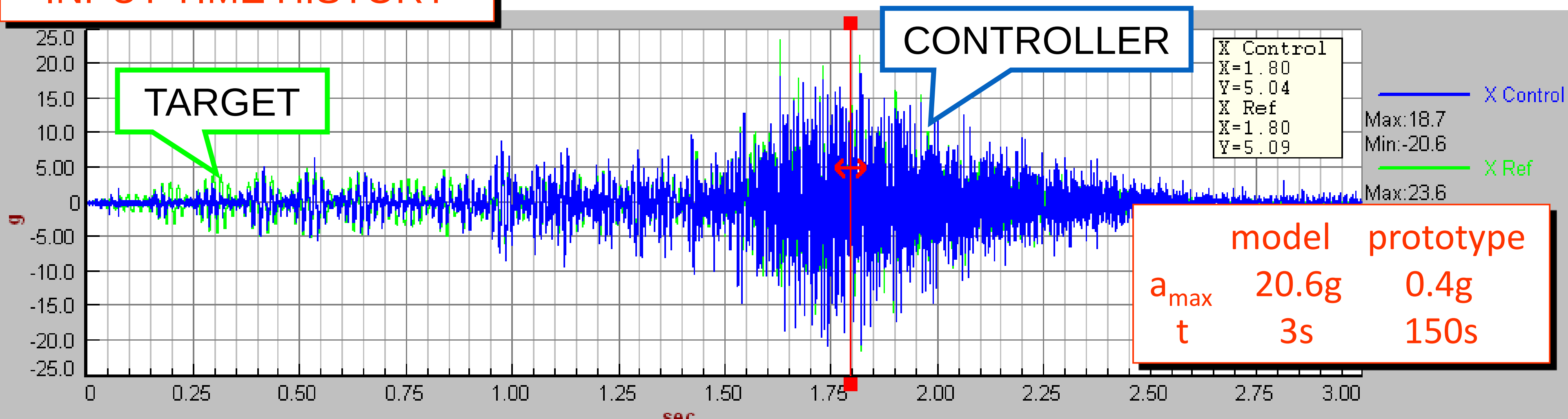
HYDRAULIC SHAKING TABLE INSTALLED ON THE RIGID ARM

one degree of freedom
frequency .... up to 500Hz
100 g centrifuge acceleration
two 50 kN integrated actuators
peak displacement....... +/- 6.35 mm
peak velocity .... 0.9 m/s
moving mass .... 3.50 kN
max acceleration .... 50 g
full load acceleration .... 16 g

INPUT RESPONCE SPECTRUM



INPUT TIME HISTORY



	model	prototype
a_{max}	20.6g	0.4g
t	3s	150s

LIQUEFACT REFERENCE PROTOTYPE

Reference case study for the centrifuge tests:
ground conditions at the sites of San Carlo and Mirabello (where liquefaction occurred in 2012)

PROTOTYPE

- ✓ sandy deposit 15 m deep
- ✓ homogeneous (clean sand or sand with 12% of fine content)
- ✓ or with 1.5 m thick top cap of fine grained soil of lower permeability than the sand
- ✓ ground water table coincident with the soil surface

MODEL

- ✓ geometrical scaling factor N = 50
- ✓ models subjected to a centrifugal acceleration of 50 g, imposed in correspondence of the base of the models

PHYSICAL MODELLING via SEISMIC CENTRIFUGE TESTS

(A) SEISMIC RESPONSE – LIQUEFACTION TRIGGERING

Soils: (1) Ticino sand
(2) Pieve di Cento clean sand
(3) Pieve di Cento sand with 12% Fine Content

miniaturised Cone Penetration Test

Soil Profiles: (1) Homogeneous sand
(2) Two Layers (top with fine material + sand underneath)

Ground Motions: GM 17, 23, 34, 31, 31+

(B) EFFECTIVNESS of MITIGATION TECHNIQUES

1. Vertical DRAINS
2. Horizontal DRAINS
3. Induced Partial Saturation (IPS)

MODELS FREE FIELD STRUCTURE

in HOMOGENEOUS SOIL & TWO LAYERS PROFILE

First series of tests aimed at investigating the liquefaction triggering conditions (reference): reproduction in centrifuge of the liquefaction conditions of a sandy layer in homogeneous (M1) and two layers deposits (M2), in free field and underneath a model structure

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

Second series of tests: effectiveness of vertical and horizontal drains in homogeneous (M1) and two layers (M2) deposits, in free field and underneath a model structure

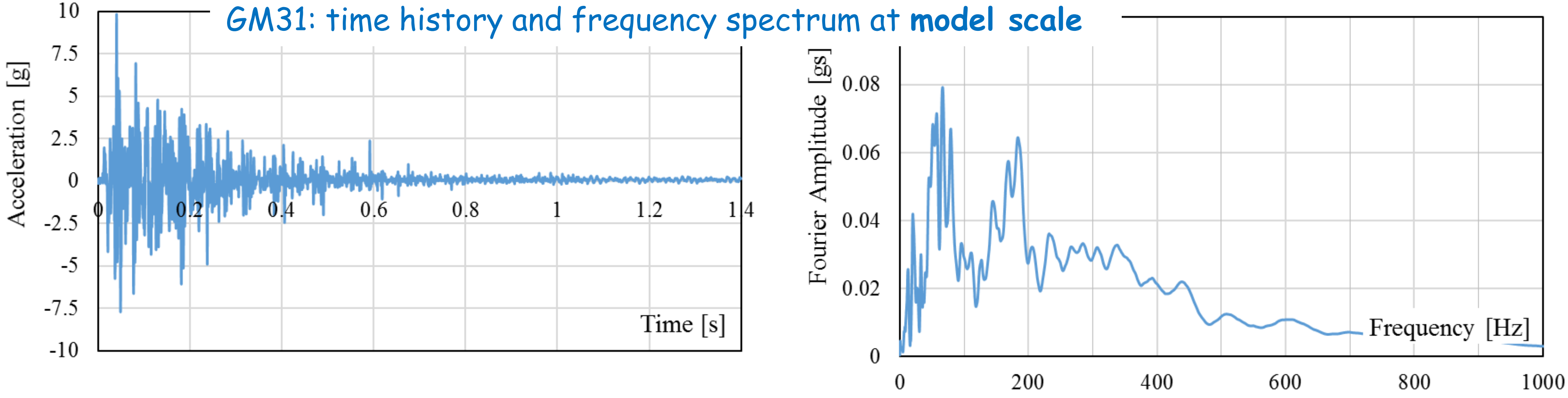
Test number	Model type	Soil	Drains type	Spacing	ID
16	M1	Ticino Sand (S1)	Vertical (VD)	5D	M1_S1_VD1_GM31
17	M1			10D	M1_S1_VD2_GM31
20	M2			5D	M2_S1_VD1_GM31
21	M2			10D	M2_S1_VD2_GM31
24	M1F (with structure)			5D	M1F_S1_VD1_GM31+
26	M2F (with structure)			5D	M2F_S1_VD1_GM31+
18	M1		Horizontal (HD)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

Third series of tests: effectiveness of induced partial saturation (IPS) in homogeneous (M1) and two layers (M2) deposits, in free field and underneath a model structure

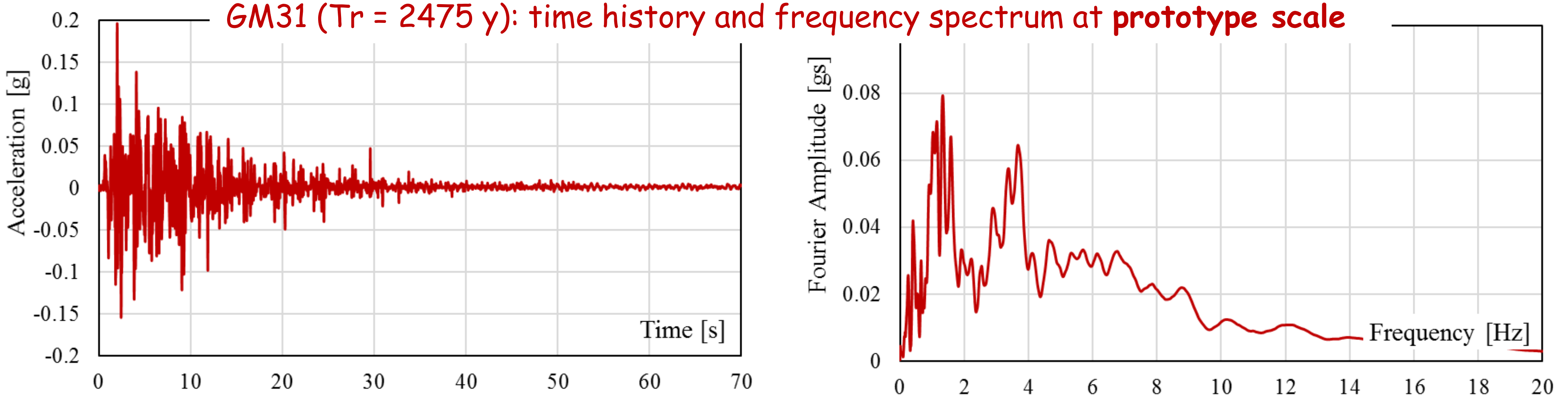
Test number	Model type	Soil	Number of injector	ID
28	M1	Ticino Sand (S1)	1	M1_S1_IPS1_GM31
29			1	M1_S1_IPS1_GM31+
30			4	M1_S1_IPS4_GM31
31			4	M1_S1_IPS4_GM31+
32	M2		1	M2_S1_IPS1_GM31
33			1	M2_S1_IPS1_GM31+
34			4	M2_S1_IPS4_GM31
35			4	M2_S1_IPS4_GM31+
36	M1F (with structure)		4	M1F_S1_IPS4_GM31+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

Four different Ground Motions (corresponding to different seismic hazard levels) have been applied to the models, they have been analytically derived referring to the 2012 Emilia earthquake (northern Italy) by the partners of UNIPV

GM31: time history and frequency spectrum at **model scale**

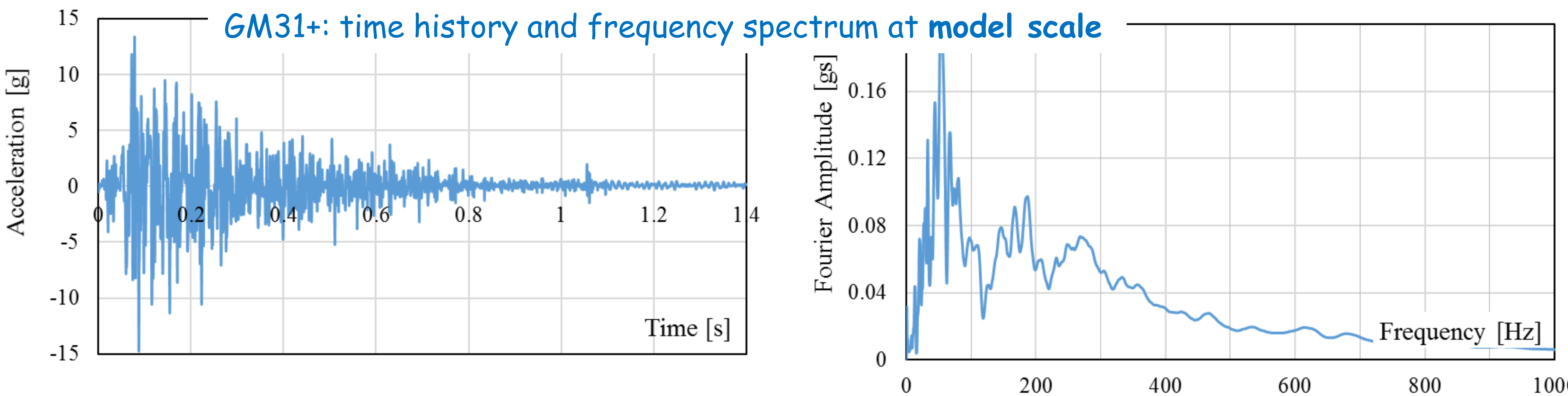


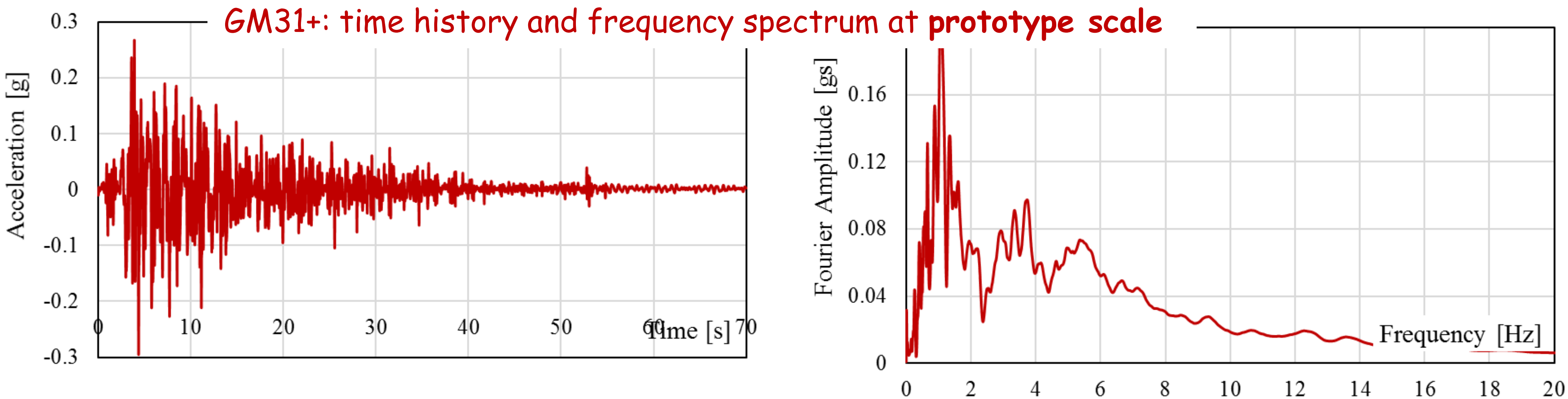
GM31 (Tr = 2475 y): time history and frequency spectrum at **prototype scale**



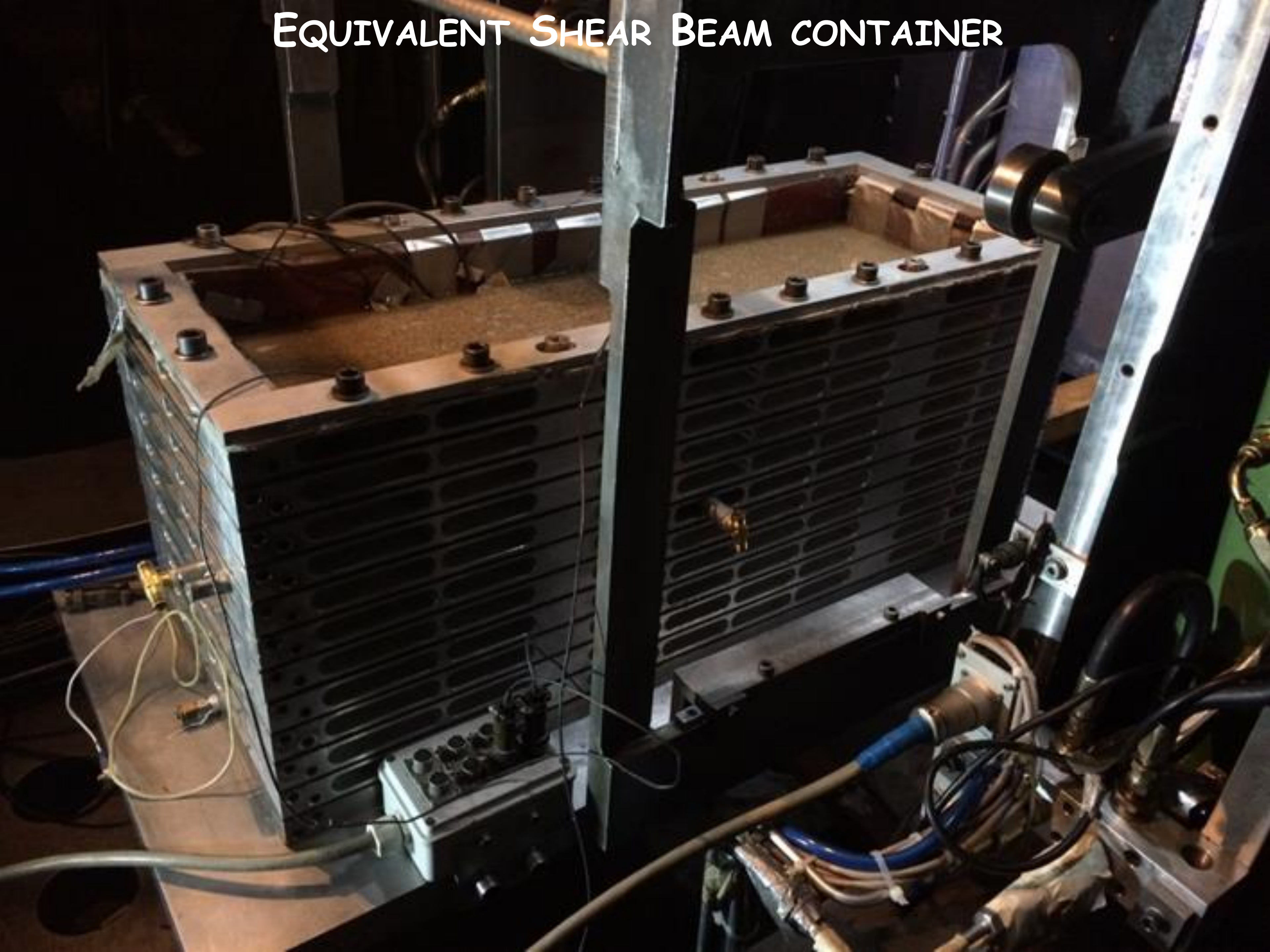
In some cases to achieve liquefaction it was necessary to amplify GM31

GM31+ was counted as the fifth input motions of the test programme

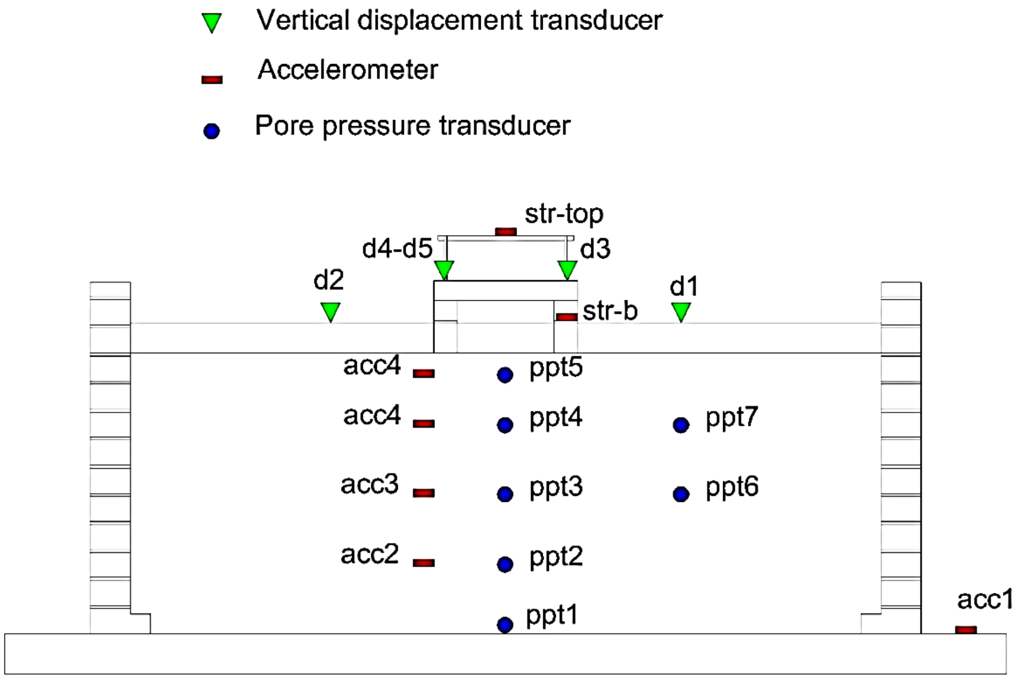


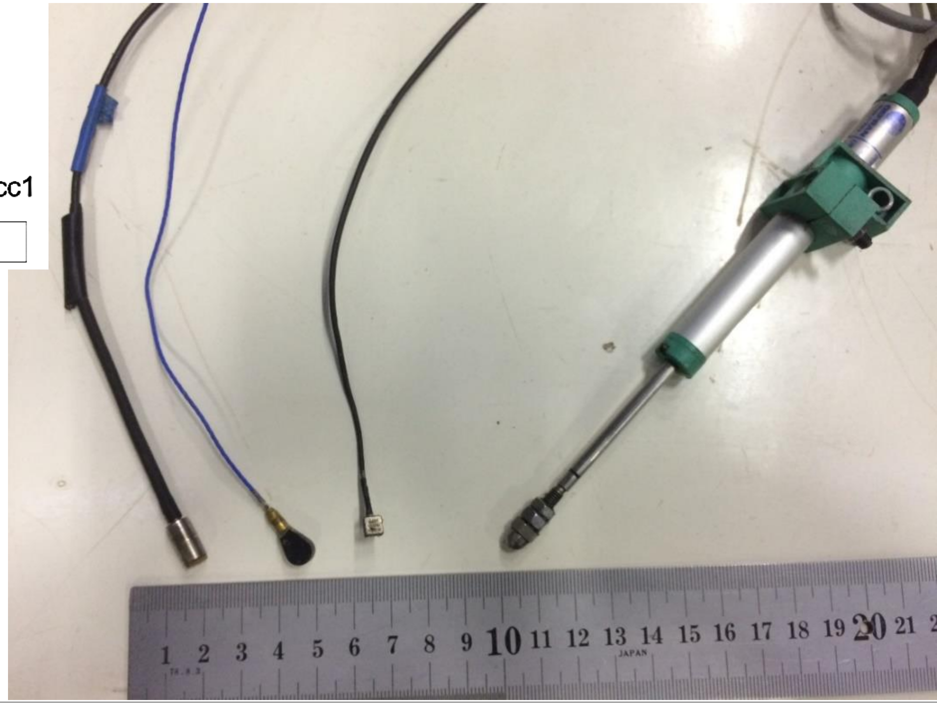


Equivalent Shear Beam container

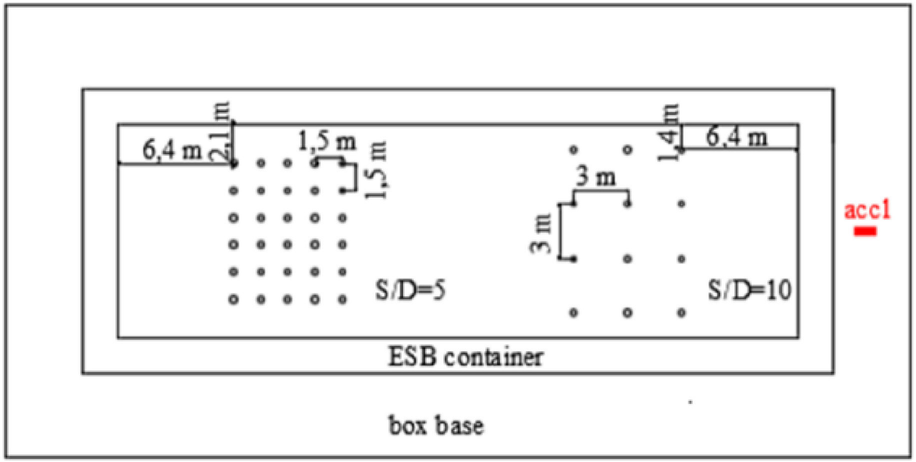


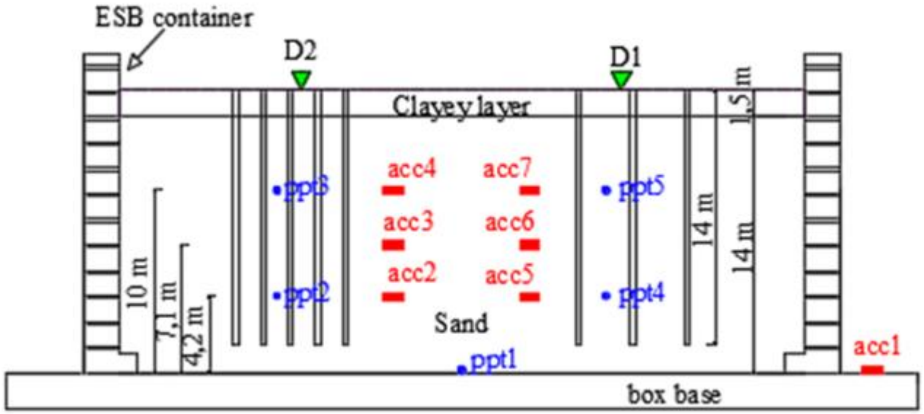
MODEL SCHEME & MINIATURISED TRANSDUCERS





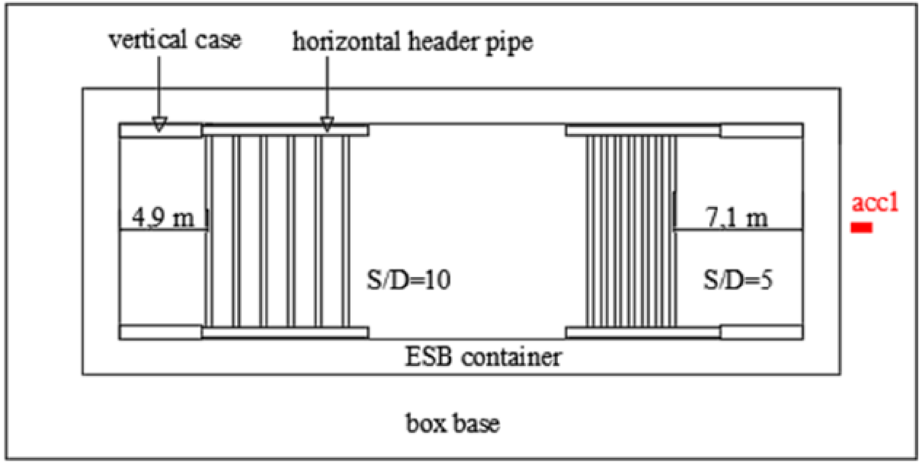
Schemes of vertical and horizontal drains

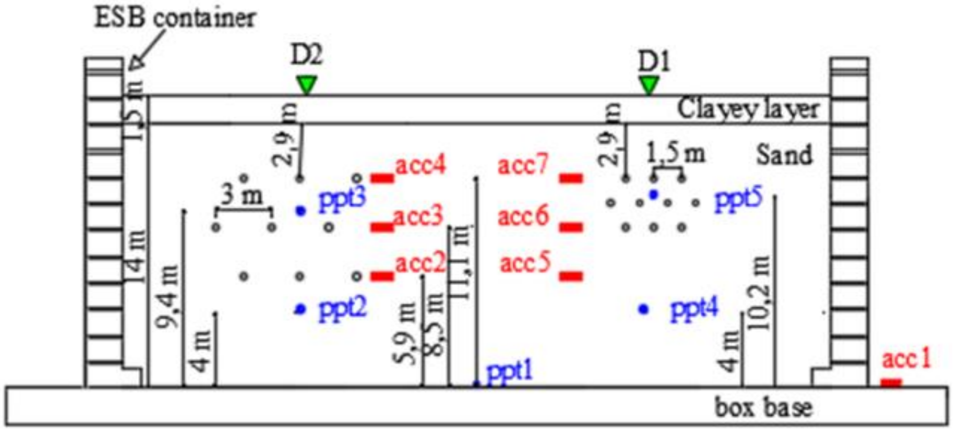


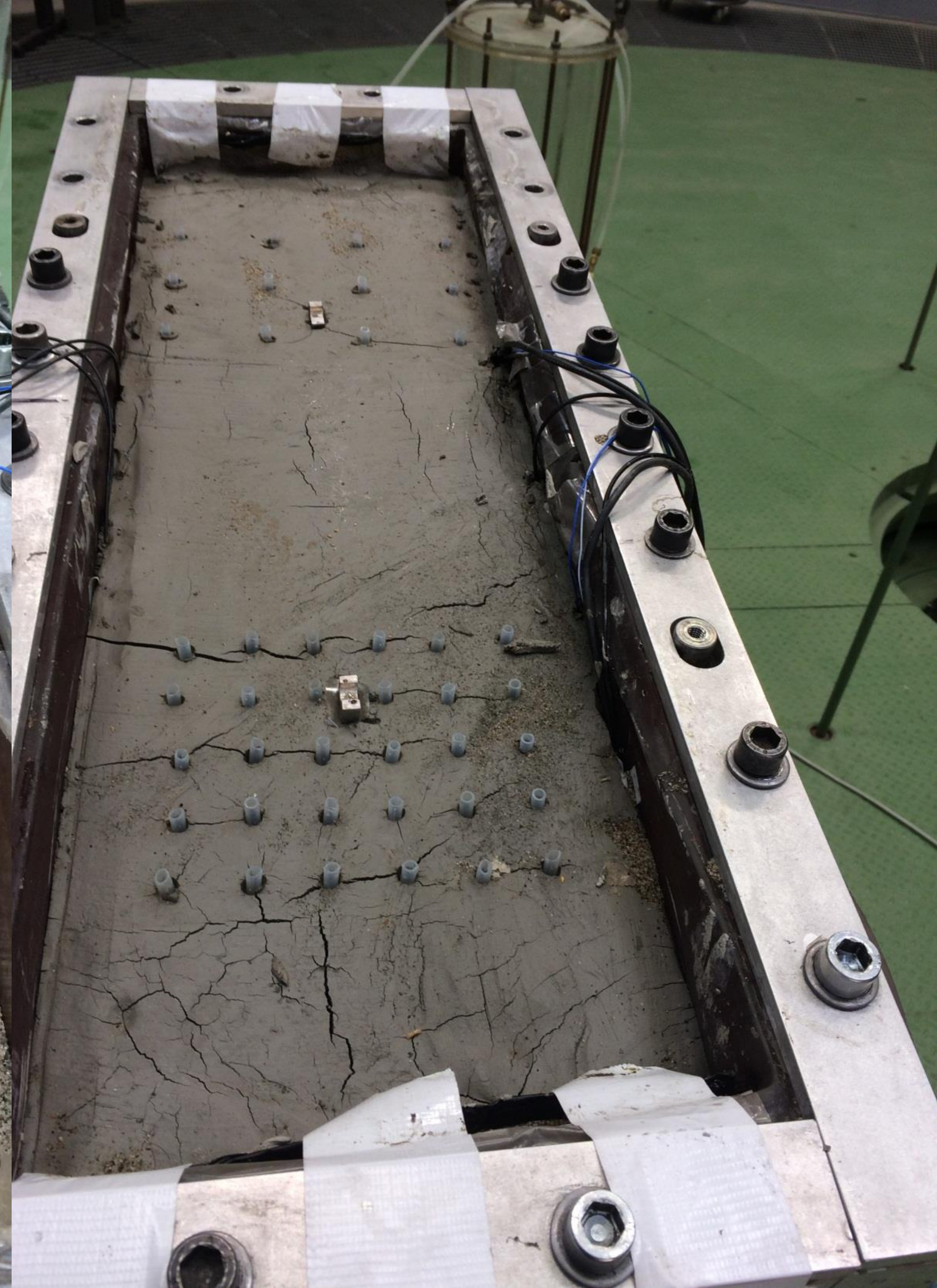


Layout

cross section

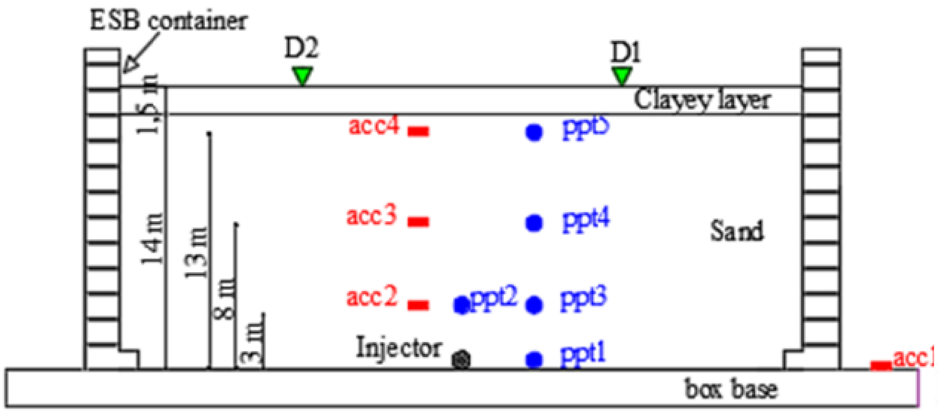




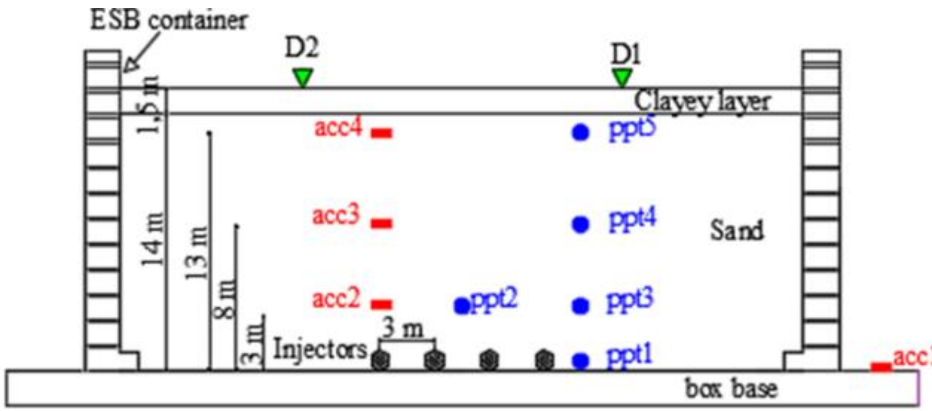



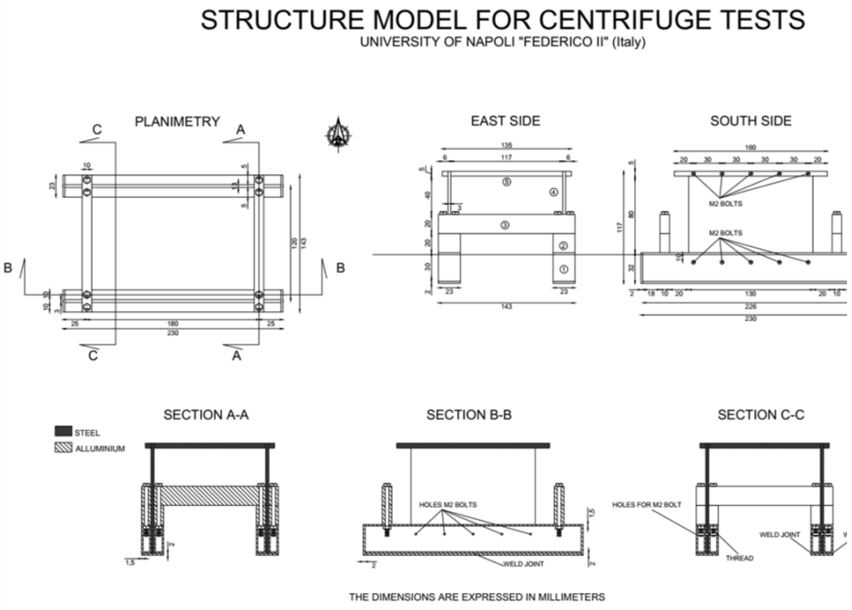
Schemes of IPS

1 nozzle

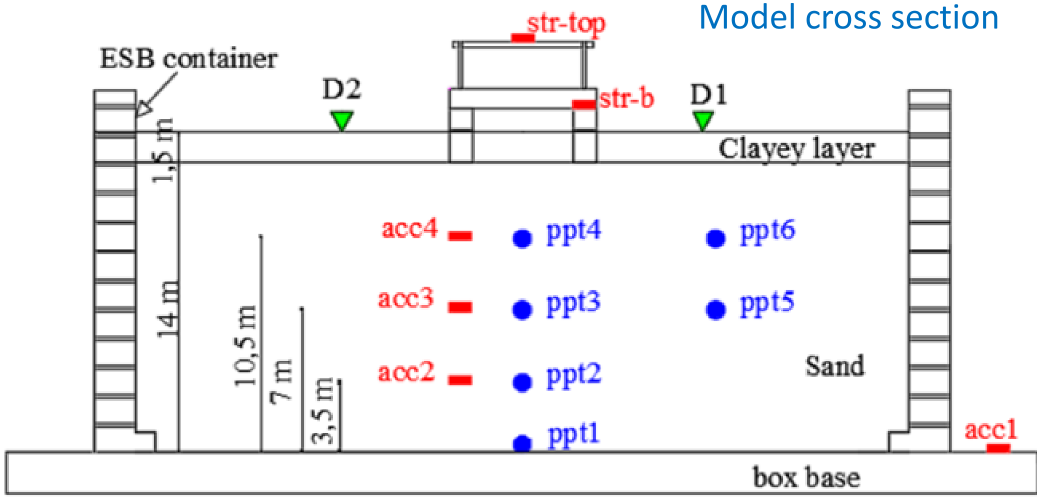


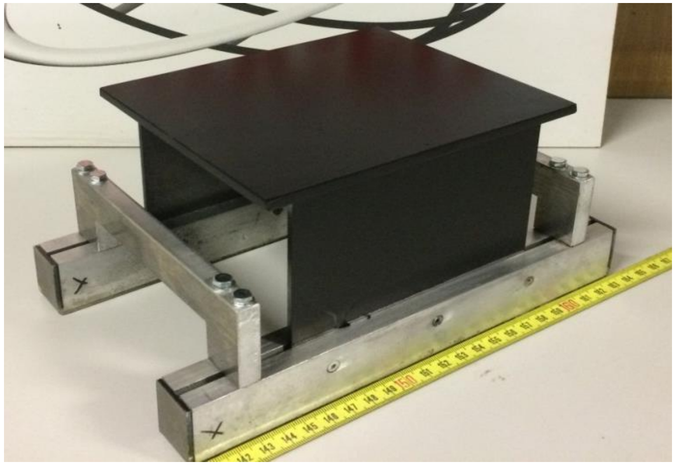
4 nozzles



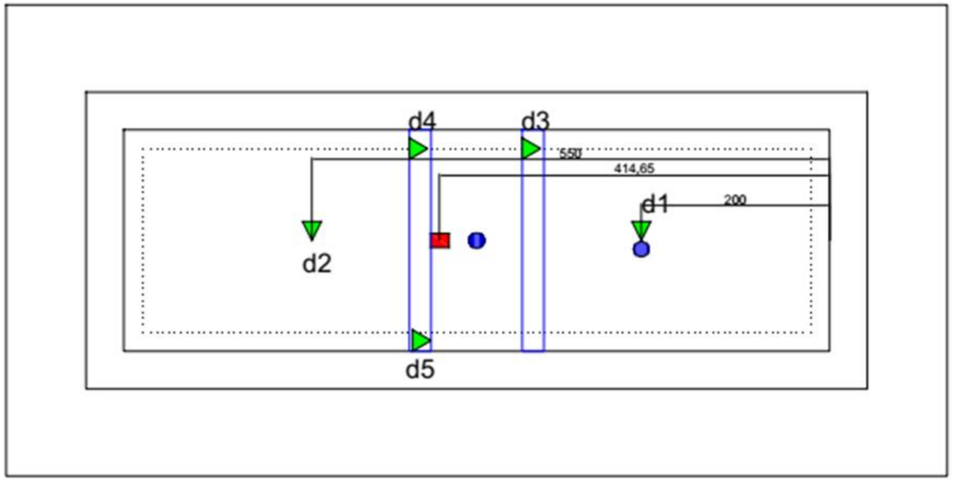


Model cross section



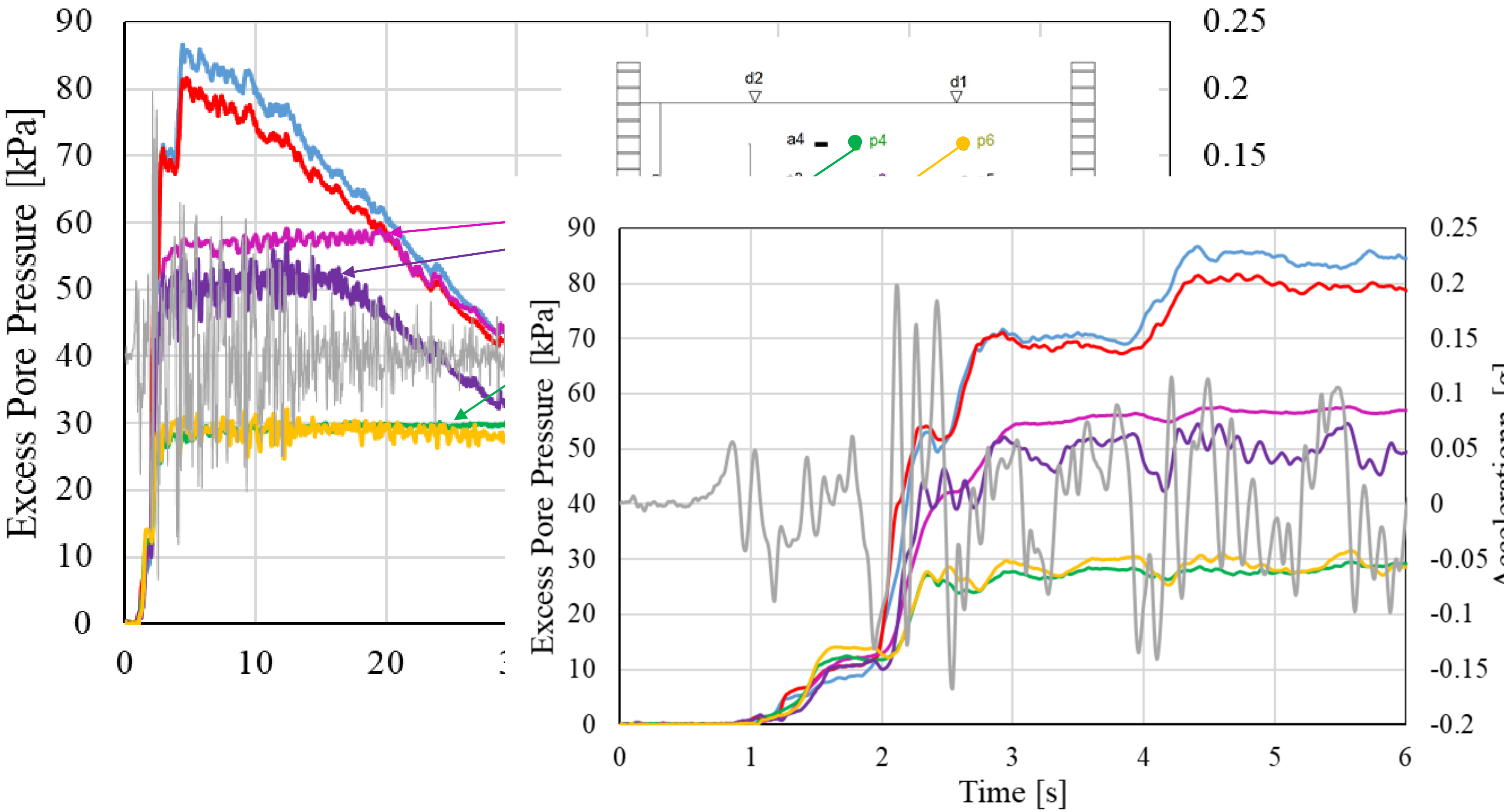


Layout



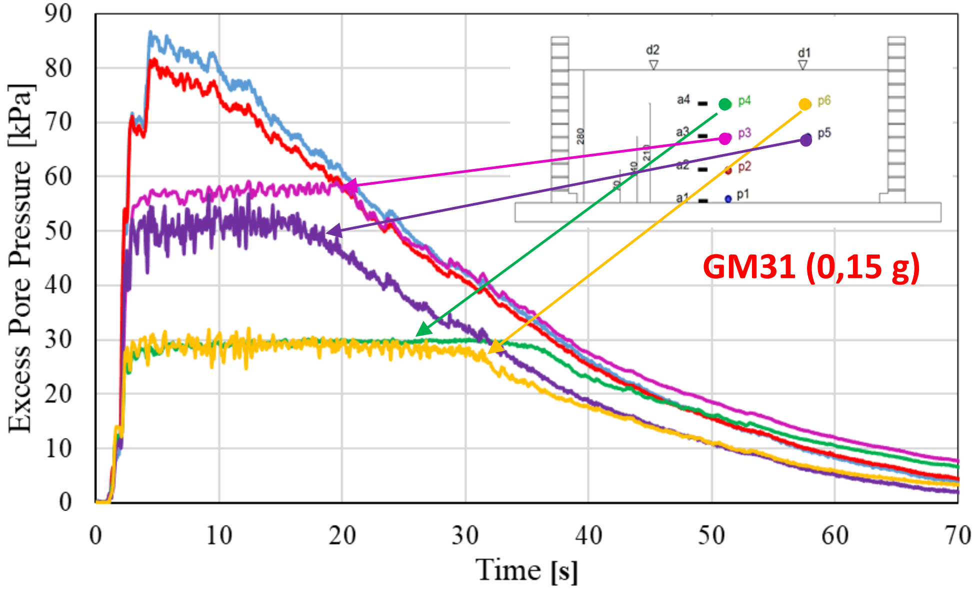
OBSERVED MECHANISMS

1. HOW THE EXCESS PORE PRESSURE INCREASES



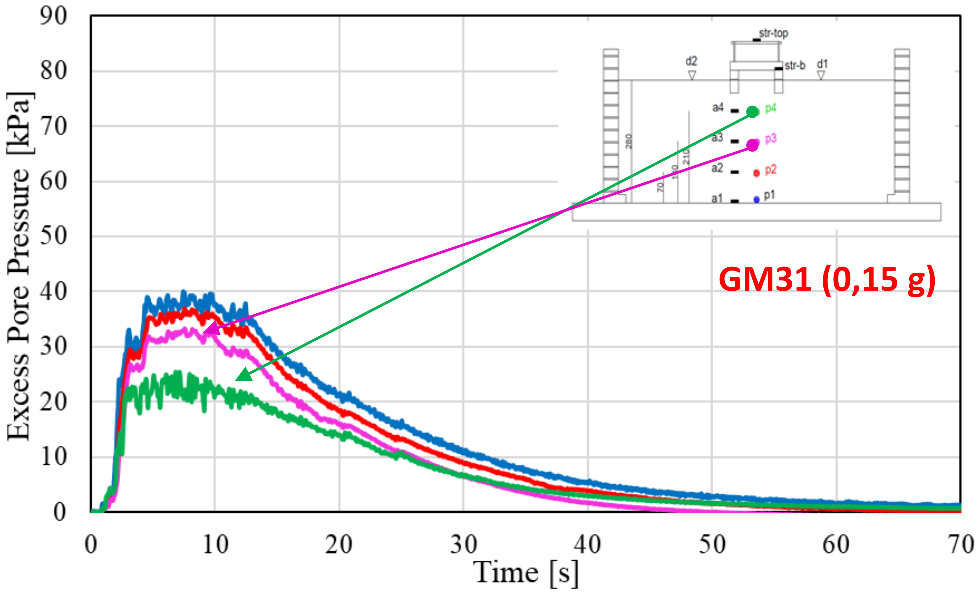
2. LIQUEFACTION TRIGERRING UNDERNEATH STRUCTURE

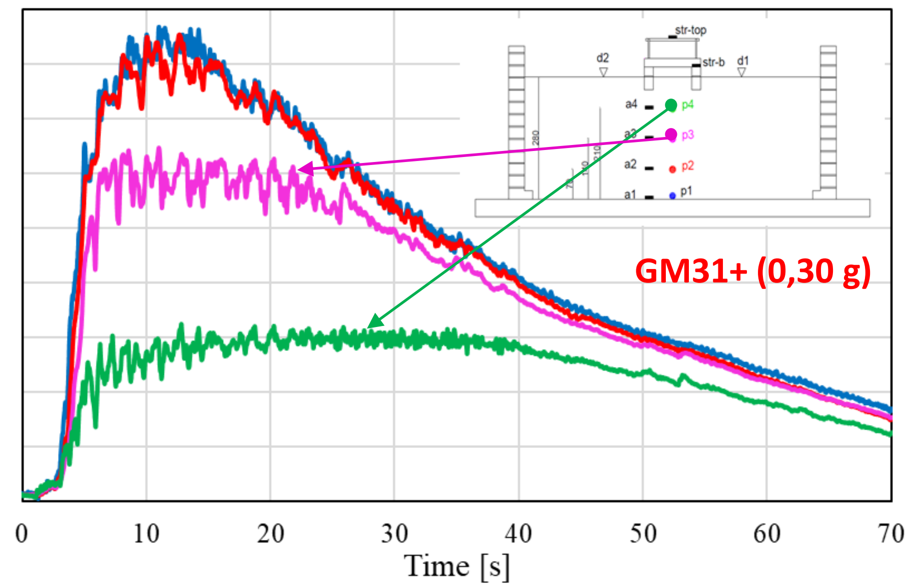
EXCESS PORE PRESSURE



free field – homogeneous soil

structure on homogeneous soil

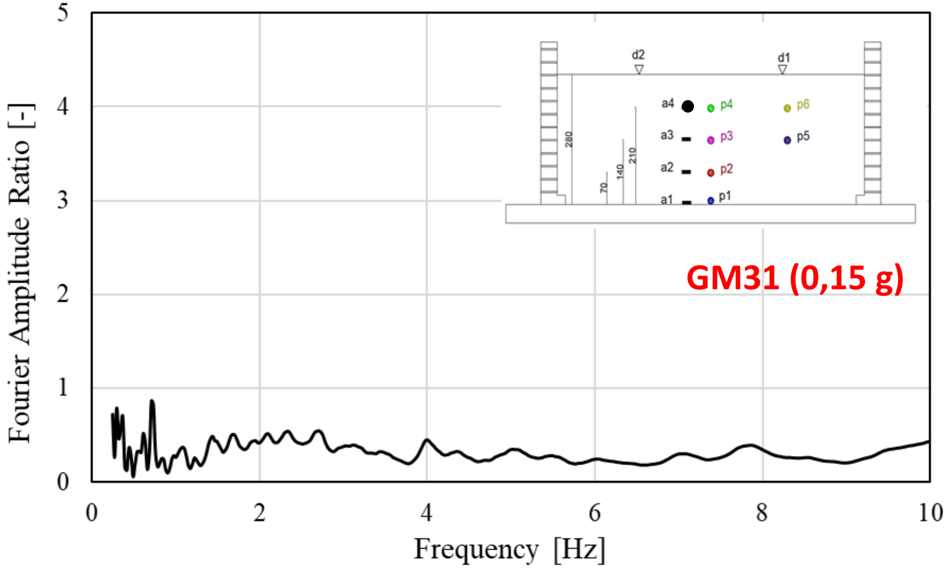




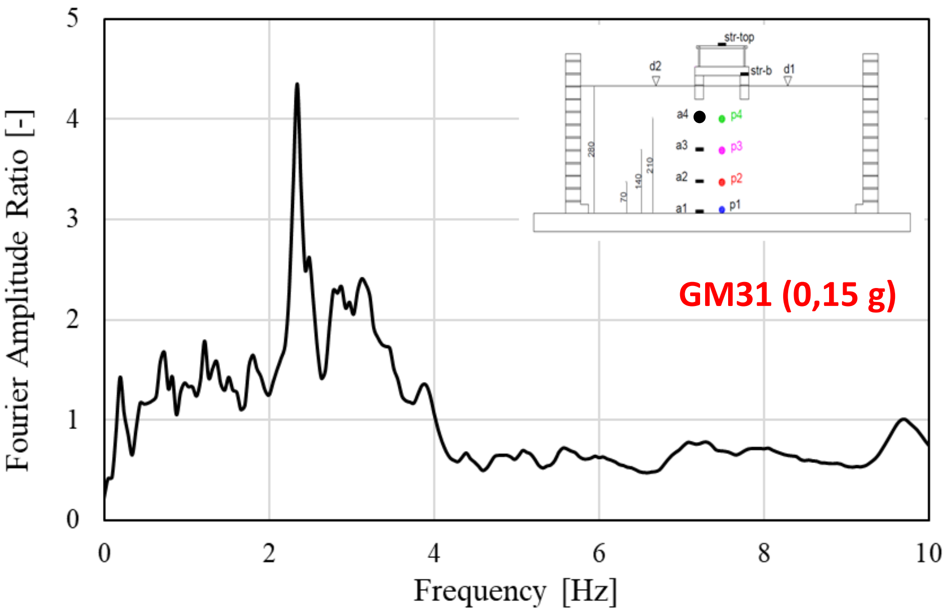
2. LIQUEFACTION TRIGERRING UNDERNEATH STRUCTURE

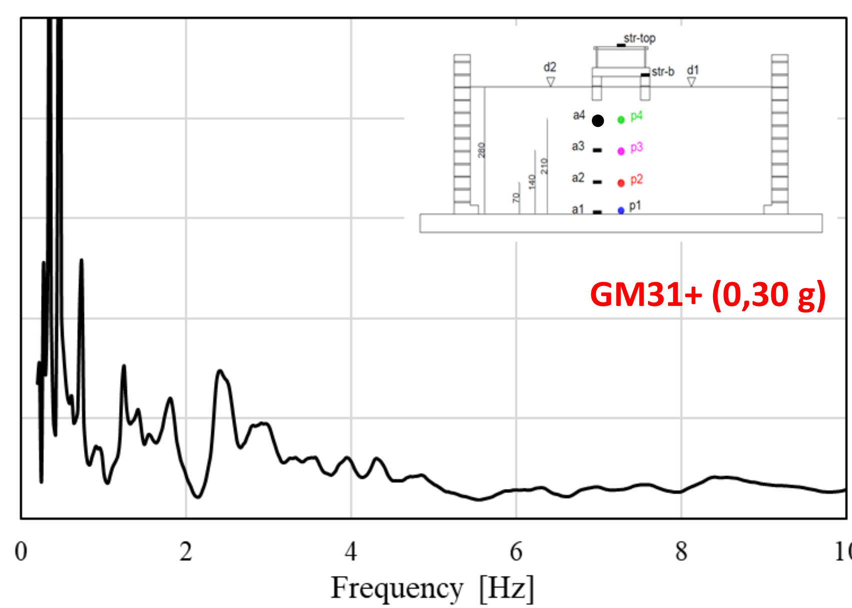
FOURIER AMPLITUDE RATIO a4/a_base

free field - homogeneous soil



structure on homogeneous soil



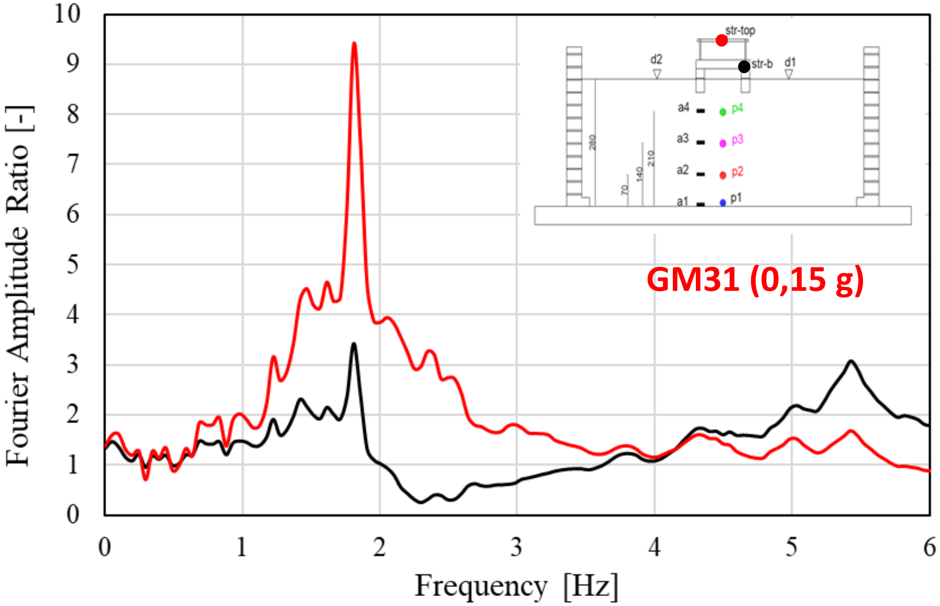


3. BEHAVIOUR OF THE STRUCTURE IN LIQUEFIED SOIL

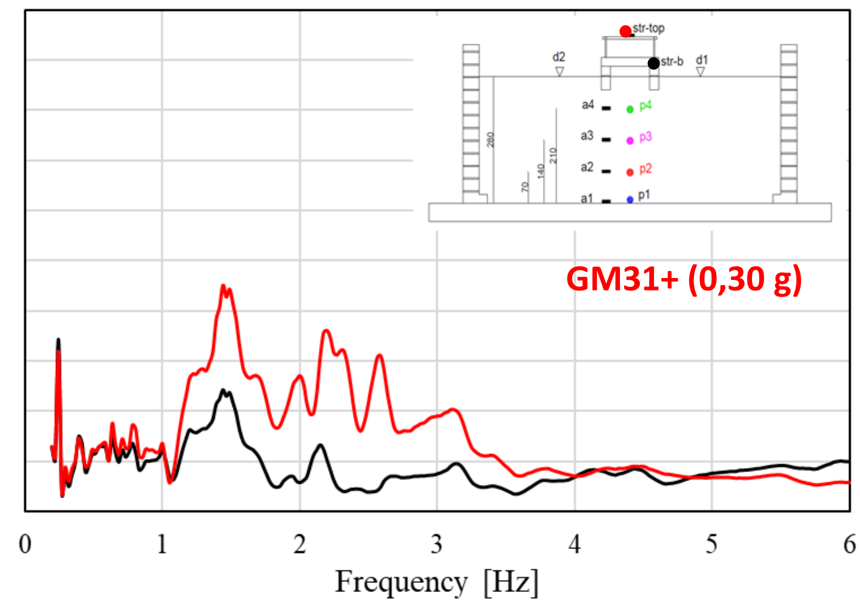
FOURIER AMPLITUDE RATIO OF STR-TOP AND STR-B NORMALIZED TO a4

homogeneous soil

NO LIQUEFACTION



LIQUEFACTION

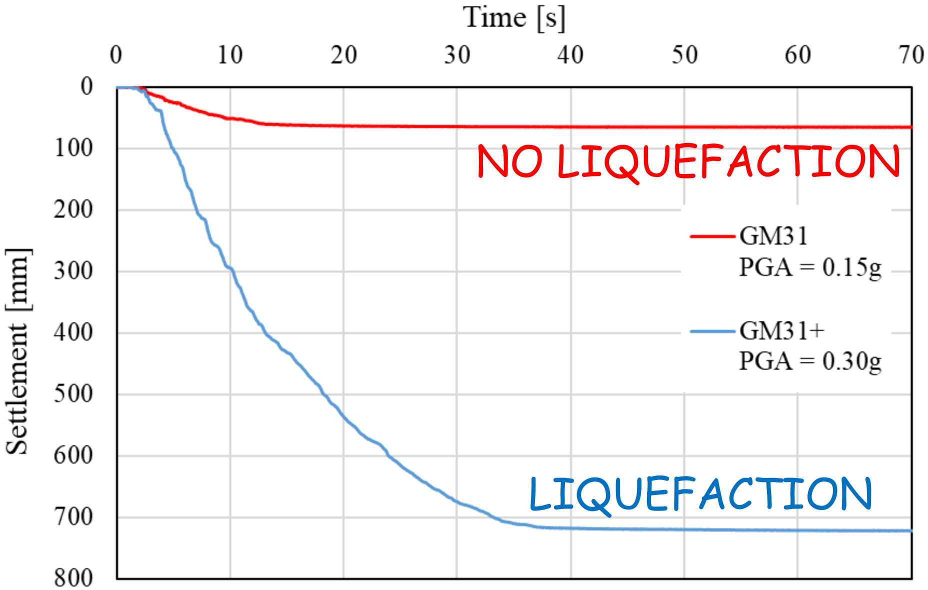


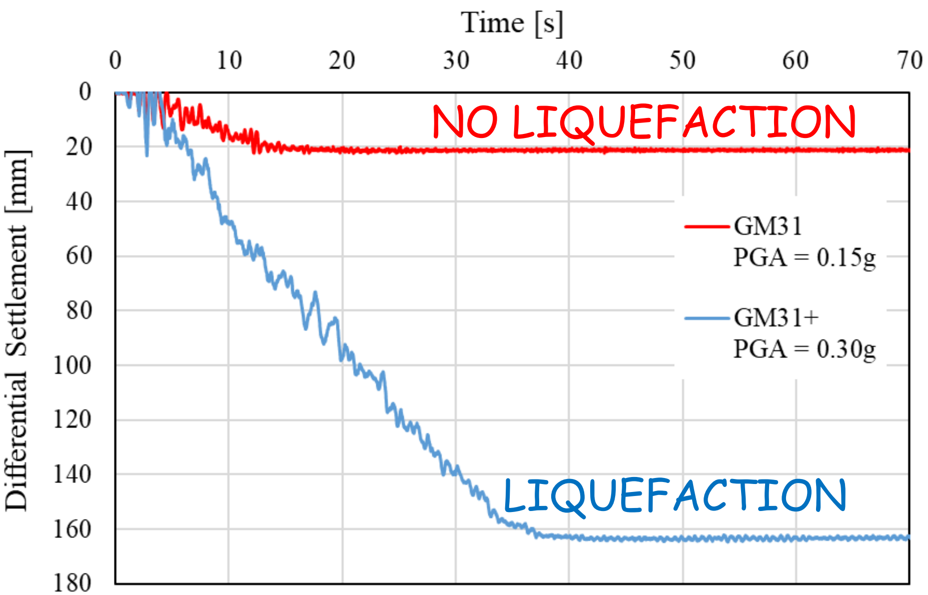
3. BEHAVIOUR OF THE STRUCTURE IN LIQUEFIED SOIL

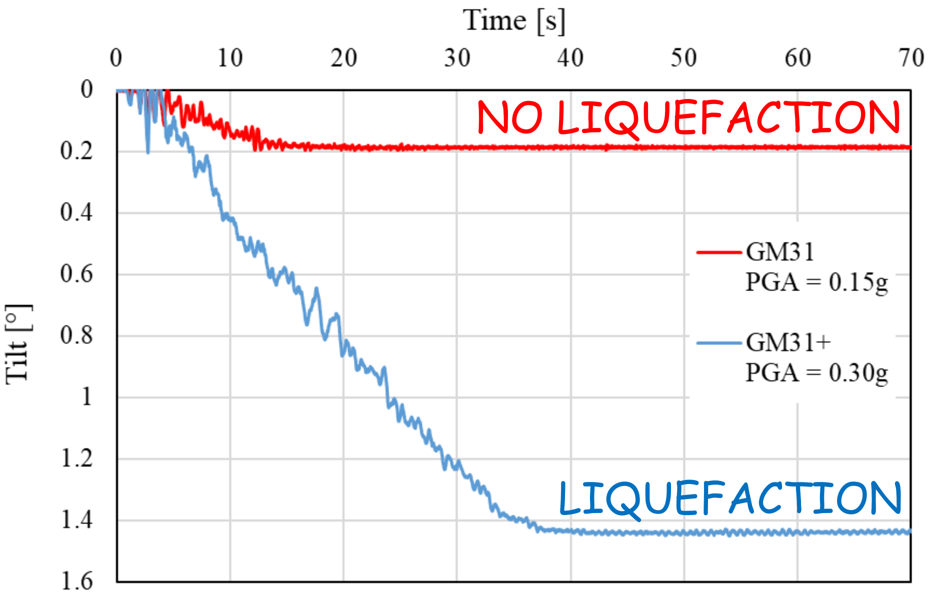
STRUCTURE SETTLEMENTS

homogeneous soil

input	s [mm]	Δs [mm]	tilt [°]	Liquefaction occurrence
GM31 (0,15 g)	65	20	0.2	no
GM31+ (0,30 g)	720	164	1.4	yes

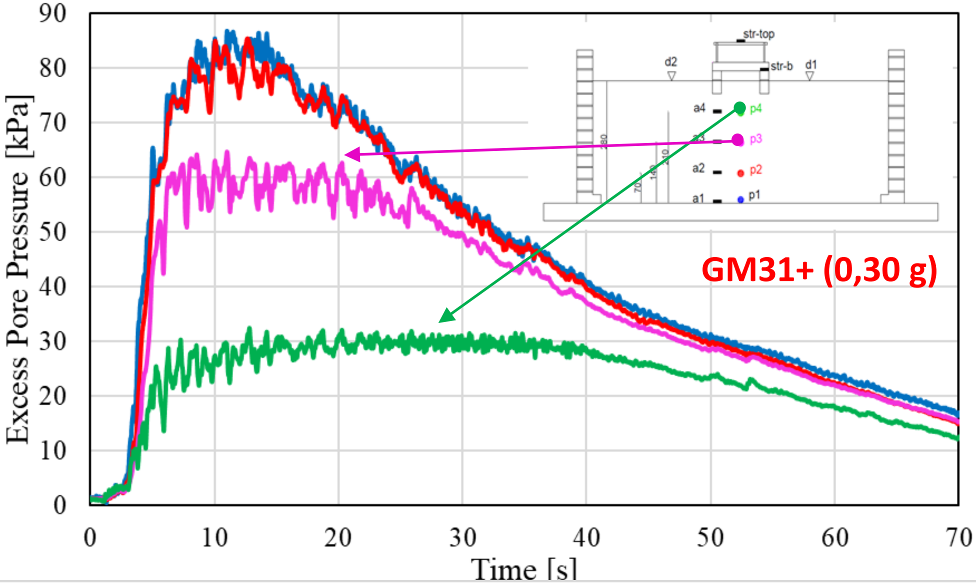


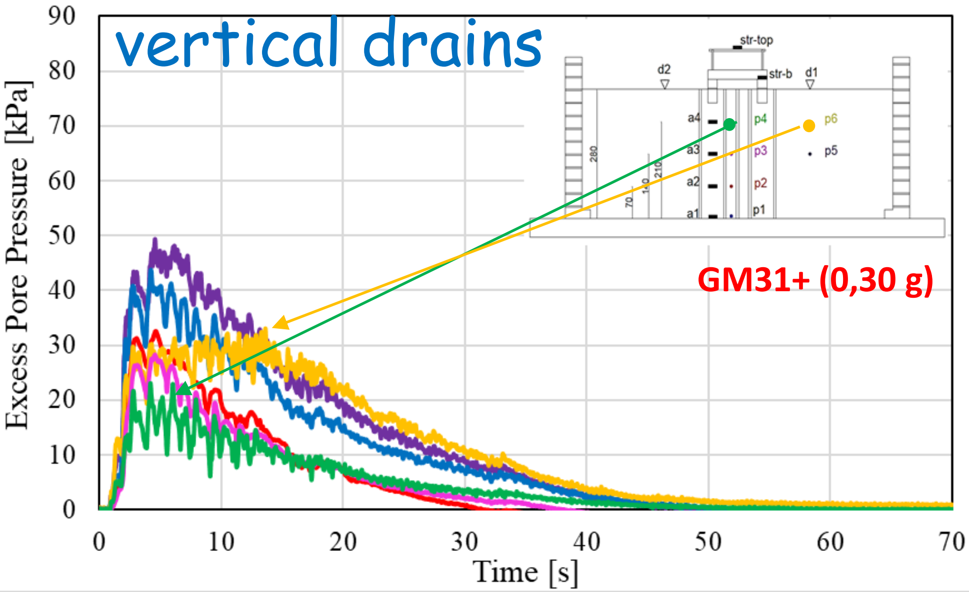


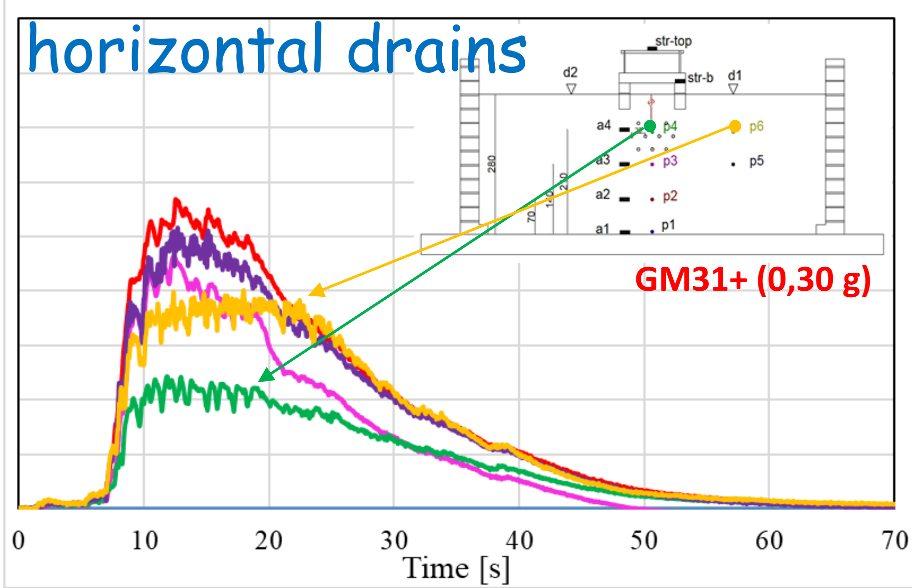


4. EFFECTIVNESS OF MITIGATION TECHNIQUES UNDER STRUCTURE

EXCESS PORE PRESSURE



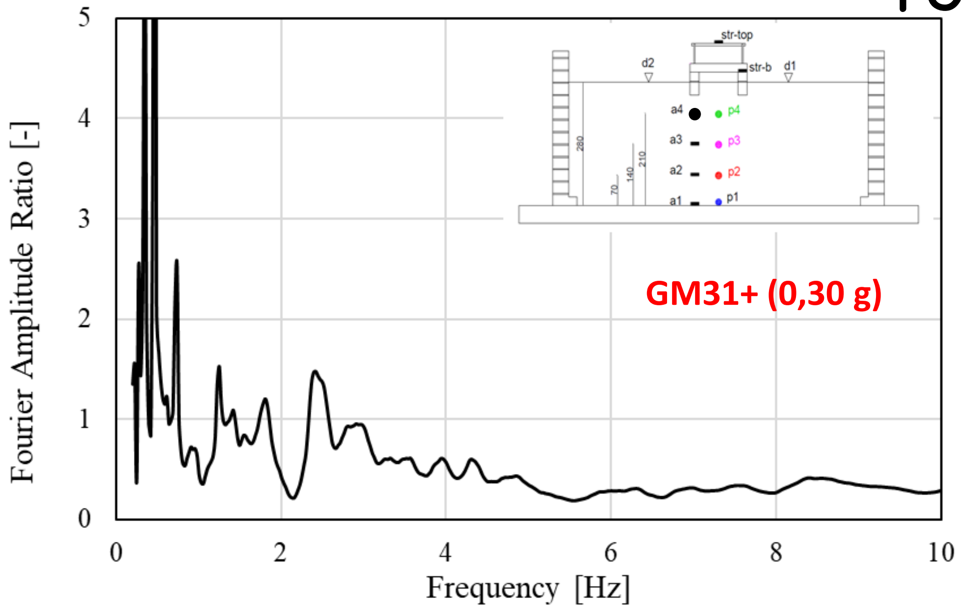




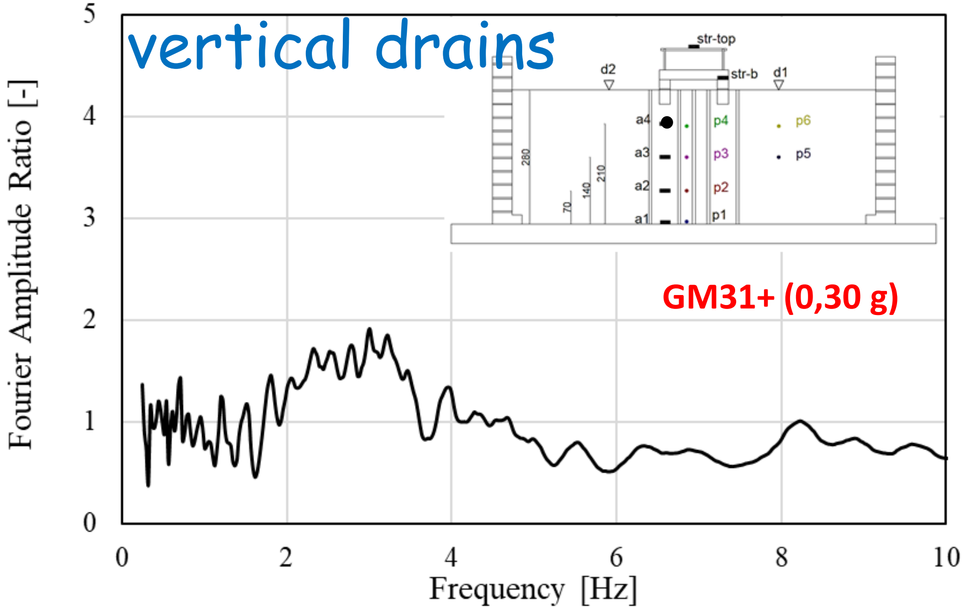
4. EFFECTIVNESS OF MITIGATION TECHNIQUES UNDER STRUCTURE

FOURIER AMPLITUDE RATIO a4/a_base

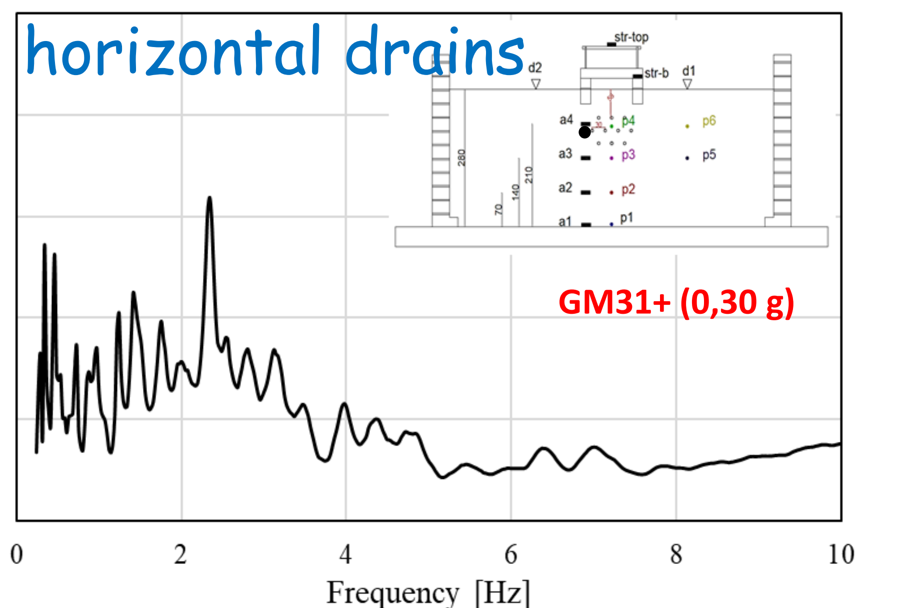
NON treated liquefied soil



vertical drains



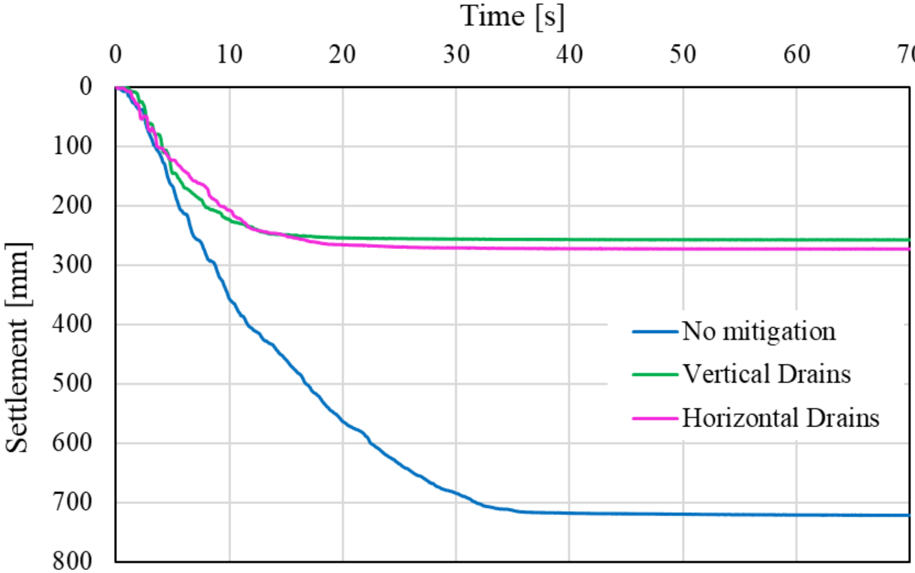
horizontal drains

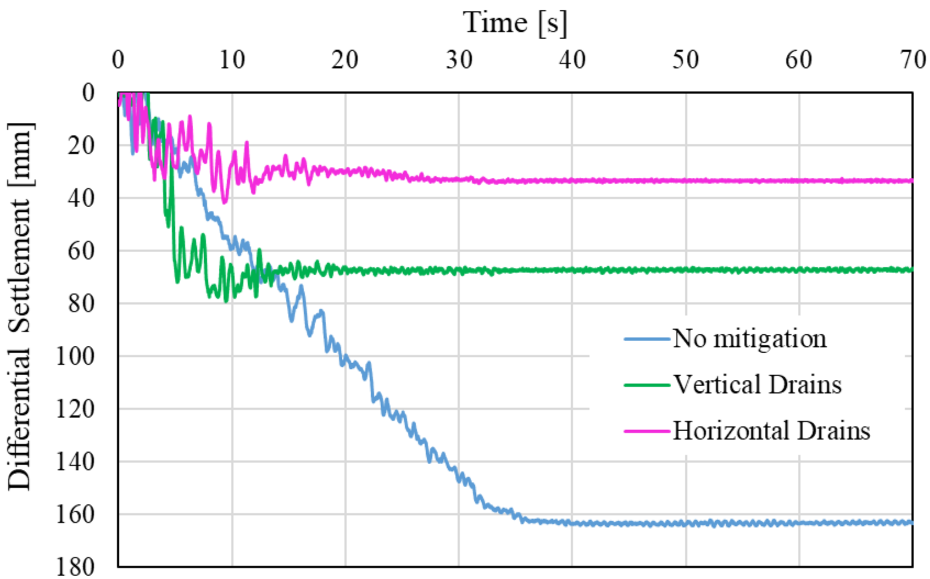


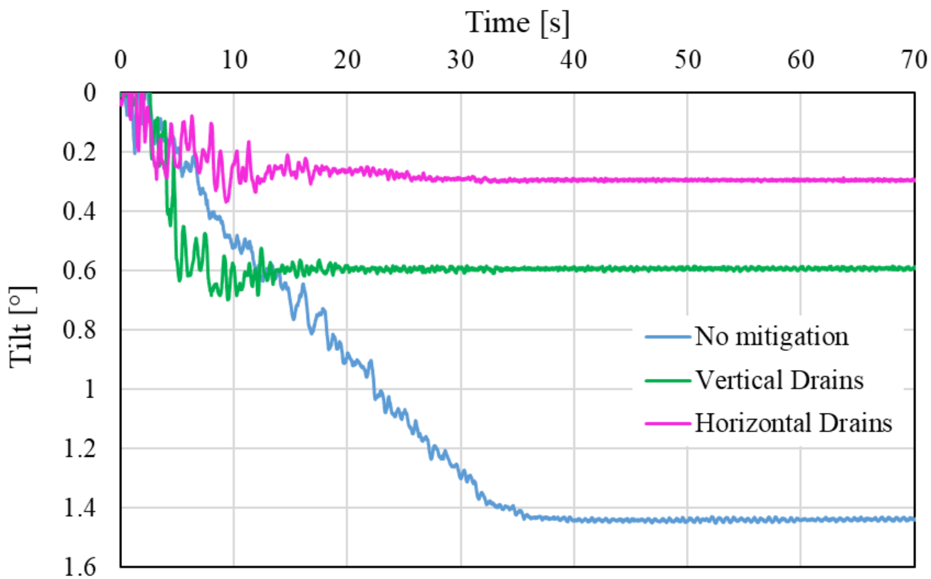
4. STRUCTURE BEHAVIOUR IN HOMOGENEOUS SOIL

STRUCTURE SETTLEMENTS

input	s [mm]	Δs [mm]	tilt [°]	Drains	Liquefaction occurrence
GM31+ (0,30 g)	720	164	1.4	no	yes
GM31+ (0,30 g)	257	67	0.6	vertical	no
GM31+ (0,30 g)	273	33	0.3	horizontal	no







1. The centrifuge tests highlighted the dependency of the pore pressure build-up on the number of cycles and shear stress applied when an irregular excitation is applied
2. The stress field due to the presence of structures reduces the liquefaction susceptibility
3. A liquefied layer acts as a damper on the structure but induces large settlement and rotation
4. If the soil doesn't liquefy settlement and rotation are smaller but the seismic actions transmitted to the structure are much higher
5. Vertical and horizontal drains reduces the pore-pressure build up, the excess pore pressure dissipation is faster; settlement and rotation of the structure are mitigated but the energy transmitted to the structure is larger
6. Physical modelling highlights mechanisms and validates conceptual models; the results allows parametric studies via numerical modelling simulations

"I più benedetti denari che si spendono da chi vuol fabbricare sono i modegli"
Michelangelo Buonarroti (XVI century)

"The money best spent by those who wish to build is that spent to make models"