SERIES
SEISMIC ENGINEERING RESEARCH INFRASTRUCTURES
FOR EUROPEAN SYNERGIES

SERIES Workshop

"Role of research infrastructures in seismic rehabilitation"

Istanbul, February 8-9, 2012

Experimental investigation of soil-pile-structure seismic interaction

TA project PILESI @ UnivBris

Assessment of Soil-Pile-Structure Seismic Interaction

A.L. Simonelli
University of Sannio, Italy

Università degli Studi del Sannio

L. Di Sarno
M.G. Durante
S. Sica

Università della Calabria

R. Cairo
A. Chidichimo
G. Dente

University of Patras

G. Anoyatis
G. Mylonakis

University of BRISTOL

S. Bhattacharya
M. Dietz
L. Dihoru
C.A. Taylor

CENTRALE PARIS

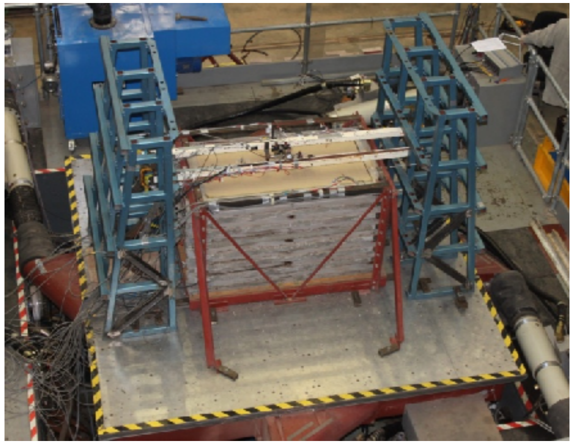
A. Modaressi
L.A. Todo Bom

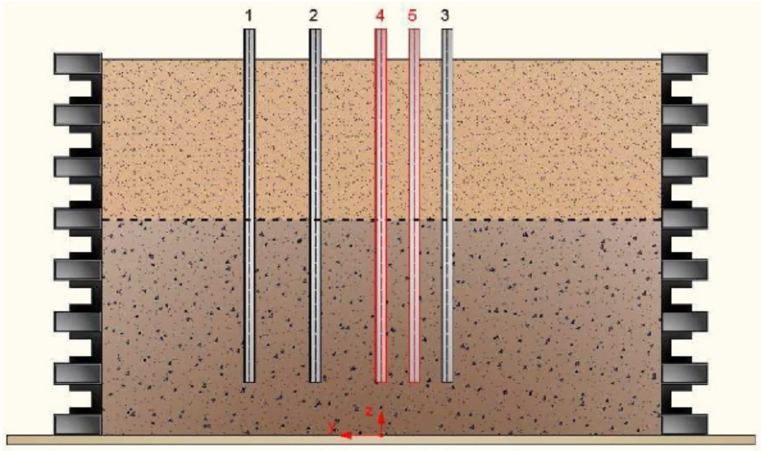
NGI

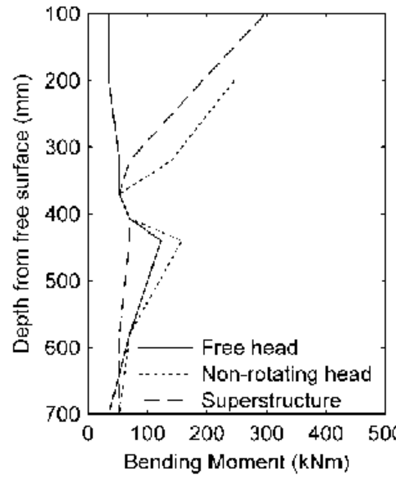
A. Kaynia

PILESI Project (Bristol)

Experimental investigation of soil-pile-structure seismic interaction







Project leader: Prof. A. L. Simonelli (University of Sannio, Italy)

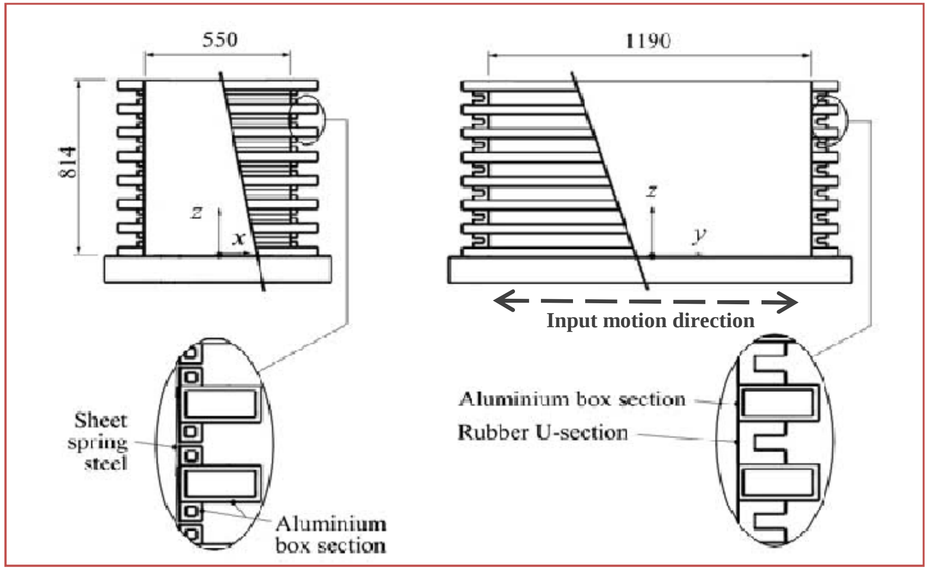
Objectives: To investigate the seismic response of pile groups in layered soils in order to provide a benchmark for numerical-model validation purposes.

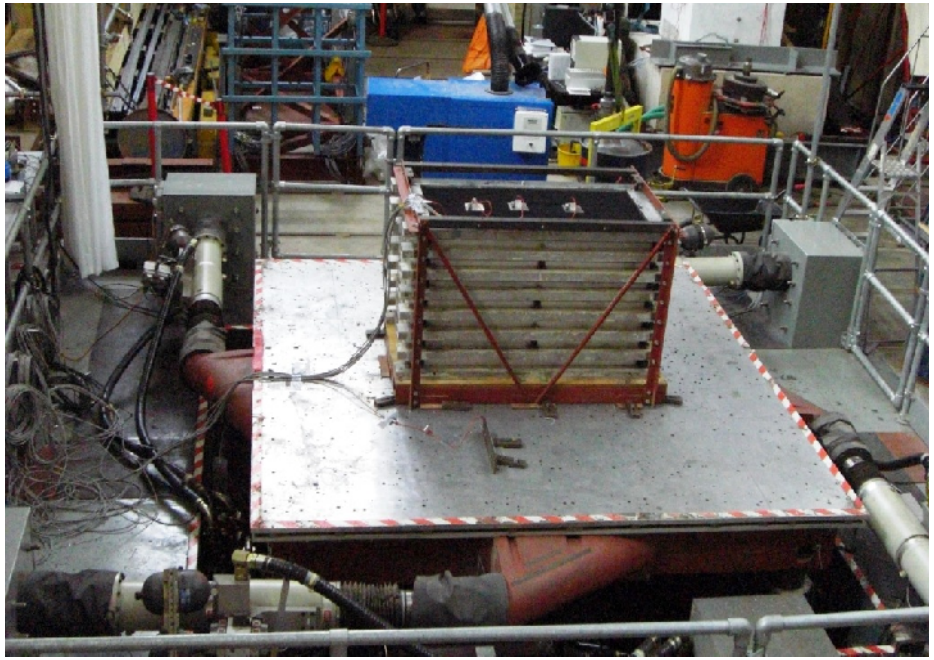
Experimental variables: Pile head fixity, Pile-structure interaction, input motion

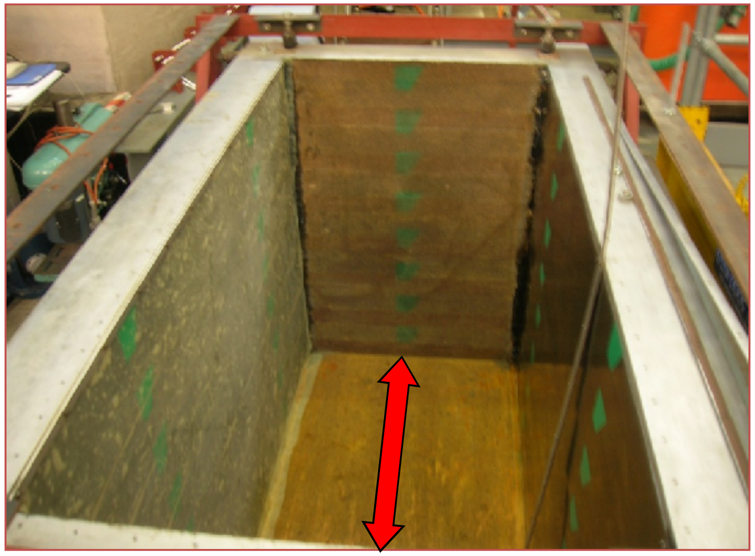
Methodology: **A shear stack is used to apply appropriate boundary conditions**

Controlled Sand Deposition is used to impose a stiffness contrast between upper and lower soil layers.

Bristol SHEAR STACK

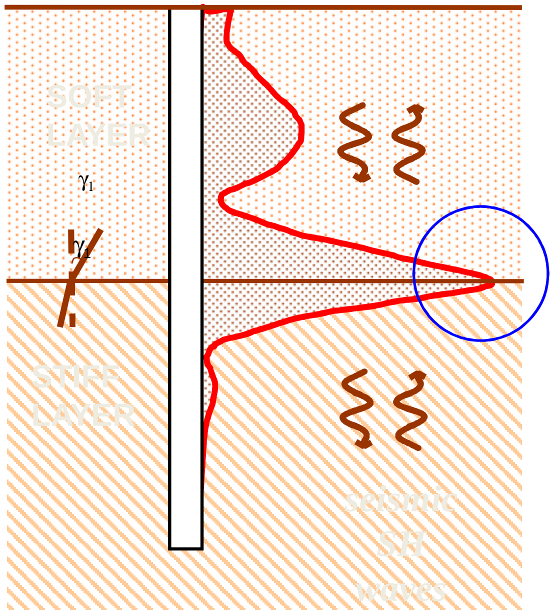






appropriate boundary conditions

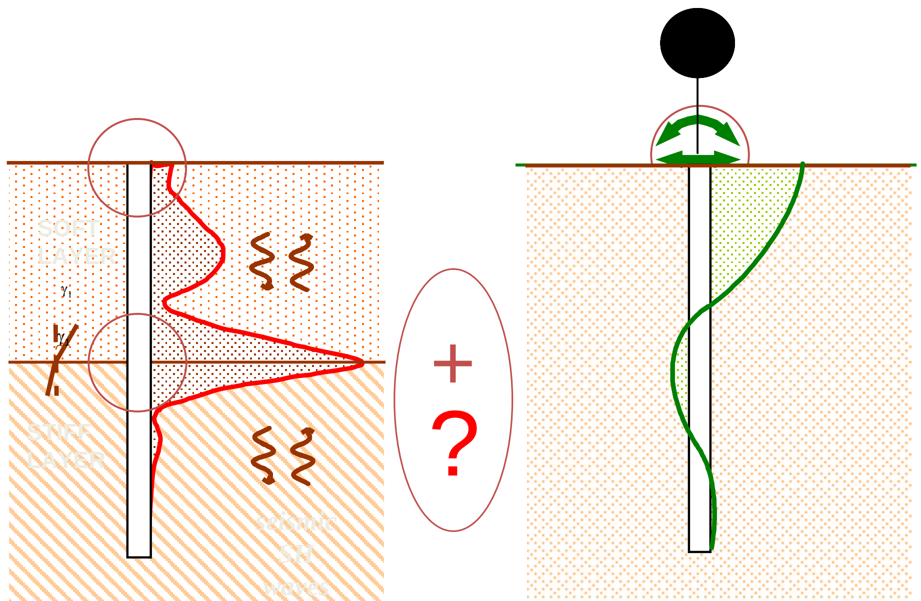
Kinematic pile bending : Theoretical background



Kinematic

Seismic waves through the soil surrounding a pile impose lateral displacements and curvatures on the pile, thereby generating 'kinematic' bending moments even in the absence of a superstructure.

These "kinematic" moments can be quite severe at the interfaces between soft and stiff soil layers.



Kinematic **Inertial**

Overview

Following the early work by Margason & Halloway [1977], theoretical investigations of the problem began in the 1980's [Flores-Berrones & Whitman 1982, Dobry & O'Rourke 1983, Tazoh 1987, Conte & Dente 1989, etc.] and continued into the 1990's and beyond [Novak 1991, Kavvadas & Gazetas 1993, Pender 1993, Mylonakis 2001, Nikolaou et al. 2001, etc.].

In 2005, a systematic research effort was initiated in Italy under the auspicious of the 1th ReLUIS project 2005-2008, which has lead to a number of publications and brilliant research effort on such an issue [Cairo and Dente 2007; Sica et al., 2007-2009-2011; Castelli & Maugeri 2007; Cairo et al. 2008; Di Laora 2009; Maiorano et al. 2009; Moccia 2009; Dezi et al. 2009-2010; etc.].

Many aspects of kinematic pile bending are now better understood, whilst others require further research and remain unsolved.

Unsolved issues on seismic soil-pile interaction

Less research has been carried out on short piles and/or interfaces located close to the pile head.

Lack of simple formulations for assessing kinematic moments at the pile head for non homogeneous soils.

Material nonlinearity and plasticity need to be explored in a more systematic way, despite recent progress.

The effect of the transient nature of the input motion on both kinematic and inertial bending moments along the pile requires further investigation.

Proper summation rule between kinematic and inertial bending moments should be defined.

Notwhitstanding these issues … Code indications

Soil-Pile Kinematic Interaction and EC8

Eurocode 8, prEN 1998-5, December 2003

(3) Analyses to determine the internal forces along the pile, as well as the deflection and rotation at the pile head, shall be based on discrete or continuum models that can realistically (even if approximately) reproduce ....

(6) Bending moments developing due to kinematic interaction shall be computed only when all of the following conditions occur simultaneously:

i. the ground profile is of type D, S1 or S2, and contains consecutive layers of sharply differing stiffness;

ii. the zone is of moderate or high seismicity, i.e. the product $a_g \cdot S$ exceeds 0,10 g , ...

iii. and the supported structure is of importance class III or IV.

(7) Piles should in principle be designed to remain elastic, but may under certain conditions be allowed to develop a plastic hinge at their heads.

Soil-Pile Kinematic Interaction and the Italian Code

Norme Tecniche per le Costruzioni, February 2008 (Italy)

§ 7.11.5.3.2 .... È opportuno che i momenti flettenti dovuti alla interazione cinematica siano valutati per

- le costruzioni di classe d'uso III e IV,
- per sottosuoli di tipo D o peggiori,
- in siti a sismicità media o alta (a_g > 0,25g)
- e in presenza di elevati contrasti di rigidezza al contatto fra strati contigui di terreno.

What is in progress in other European countries ???

RELUIS project 2005-2008: Deep Foundations

(Research Theme 6.4 - Coordinator: A.L. Simonelli)

The main objective of the project is to individuate elements to be introduced in the technical code, regarding the **seismic design of deep foundations**, with particular attention to the effects of kinematic interaction.

Questions (before ReLUIS).... and answers (after ReLUIS)

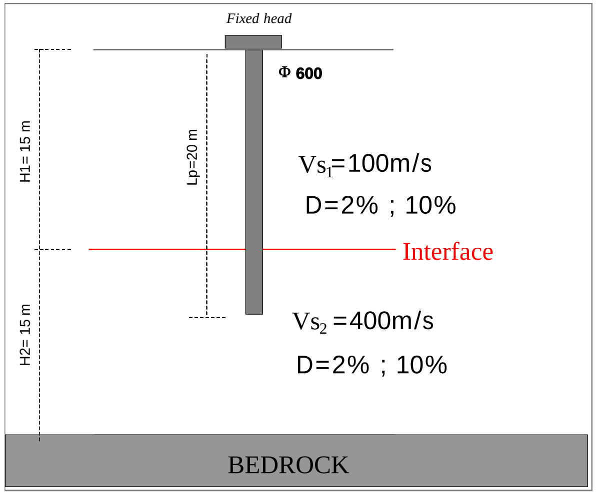
In which cases kinematic interaction should be taken into account ?
(subsoil category, soil layer stiffness contrast, sismicity level)

Which are the factors affecting pile kinematic bending ?
(soil damping, pile-end conditions, soil nonlinearity, wave-forms, etc.)

Which are the analytical tools to evaluate kinematic interaction (in the p.b.d. approach) ?
(from complex dynamic analyses ... to simplified ones ?)

Are the closed-form solutions available in literature effective ?
(Dobry&O'Rourke, 1983; Nikolaou et al., 2001; Mylonakis, 2001)

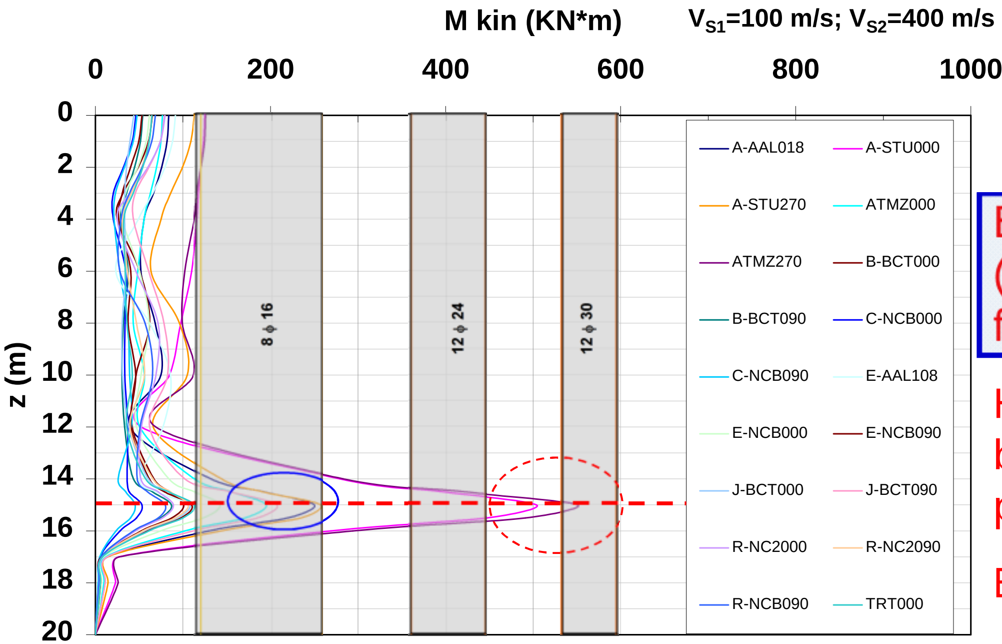
RELUIS project: main numerical results



Subsoil configuration S1

(H1=15m ed H2=15m) $V_{s,30}$=160 m/s - subsoil type D

- BDWF Analysis
- Input motions from SISMA, scaled to the same PGA
- Grey vertical bands represent My for typical pile reinforcement configurations



Bending moments are very high for 2 (over 18) accelerograms and still high for other 4 input motions

Huge effects of dynamic interaction between the input waveform and the pile-soil system

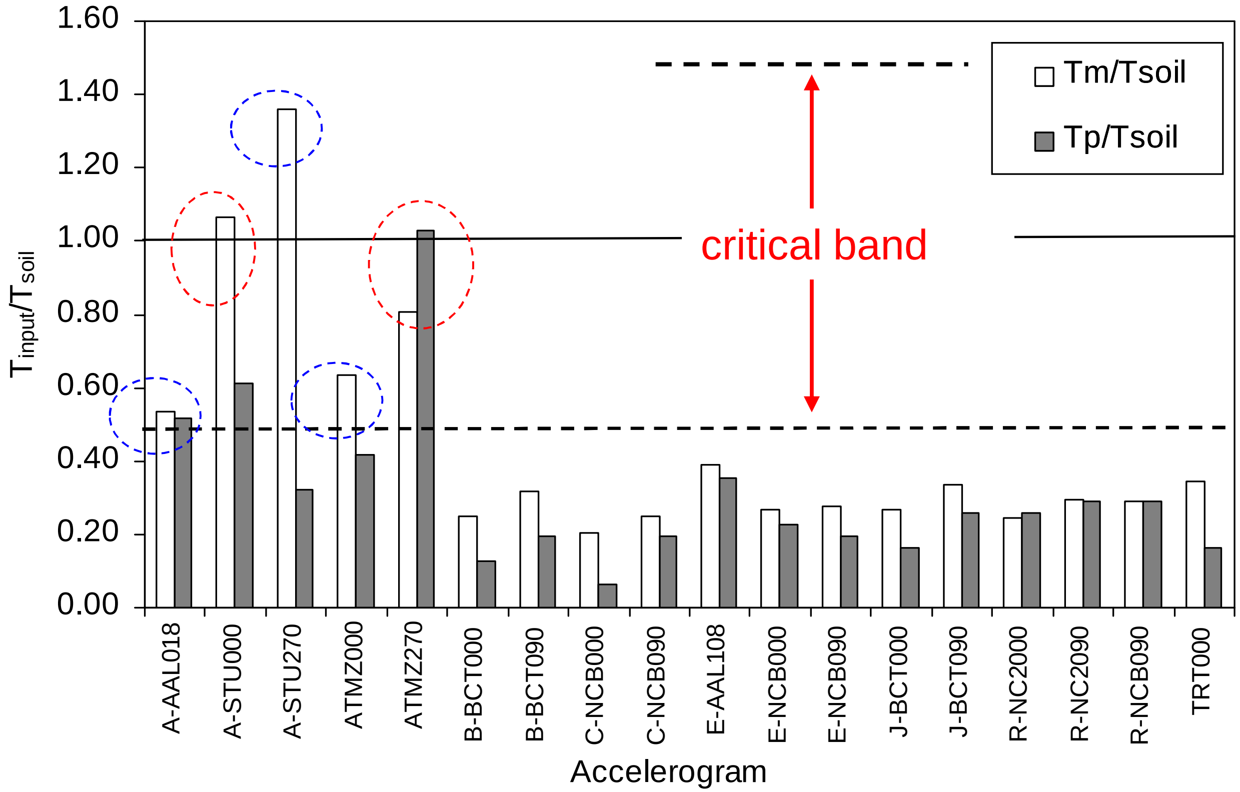
Bending moments can not exceed My

results on www.reluis.it

A simple criterion to investigate waveform-subsoil "coupling" effects

T_{input} → Tm = Mean period of an accelerogram by Rathje et al. (1998) $T_m = \frac{\sum C_i^2 \cdot \left(\frac{1}{f_i}\right)}{\sum C_i^2}$

T_{input} → Tp = predominant period from the acceleration response spectrum (@ damping=5%)



Effect of the ratio between the dominant period of the input motion and the fundamental period of the subsoil S1

A criterion to select significant time-histories from a database

Site susceptibility to significant kinematic effects

If for a given seismic zone the acceleration time-histories are provided (in addition to the peak ground acceleration a_{gR}) a simple criterion to define the "susceptibility of the site with the associated waveforms" to relevant kinematic bending in piles may be established.

$\frac{Tm}{Tsoil}$

- External to the critical band → Susceptibility LOW → Only inertial interaction should be accounted for
- Internal to the critical band → Susceptibility HIGH → Kinematic interaction should be analysed. The analysis tool should be consistent to that adopted in the design

Three alternative "code-oriented" simplified procedures for bending moment evaluation:

1) ***Static approach based on Φ_1*** *(derived from Mylonakis, 2001)*
2) ***Dynamic approach based on Φ_2*** *(derived from Mylonakis, 2001)*
3) ***Dynamic approach based on η*** *(derived from Nikolaou et al., 2001)*

from ***Sica S., Mylonakis G., Simonelli A.L. (2011)***
Soil Dynamics and Earthquake Engineering, Vol. 31

Unsolved issues on seismic soil-pile interaction

Less research has been carried out on short piles and/or interfaces located close to the pile head.

Lack of simple formulations for assessing kinematic moments at the pile head for non homogeneous soils.

Material nonlinearity and plasticity need to be explored in a more systematic way, despite recent progress.

The effect of the transient nature of the input motion on both kinematic and inertial bending moments along the pile requires further investigation.

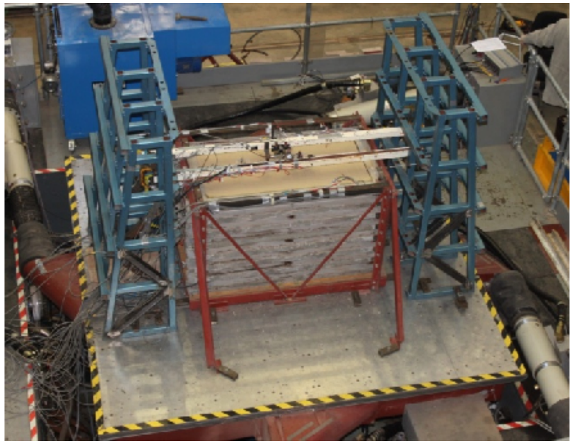
Proper summation rule between kinematic and inertial bending moments should be defined.

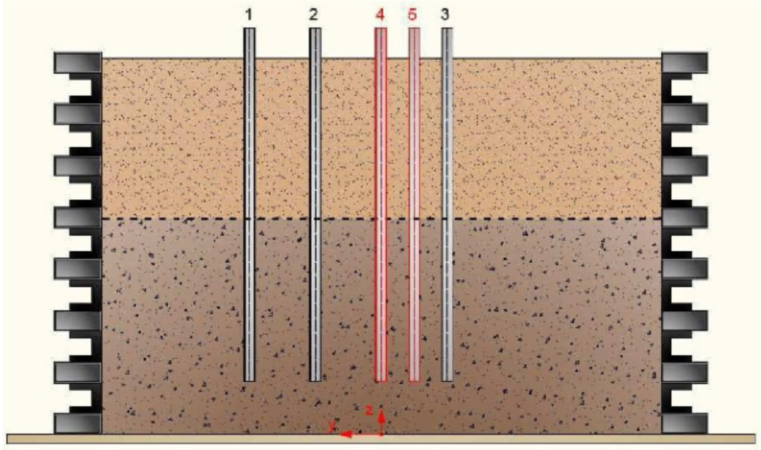
Need of experimental data to validate the huge amount of numerical findings.

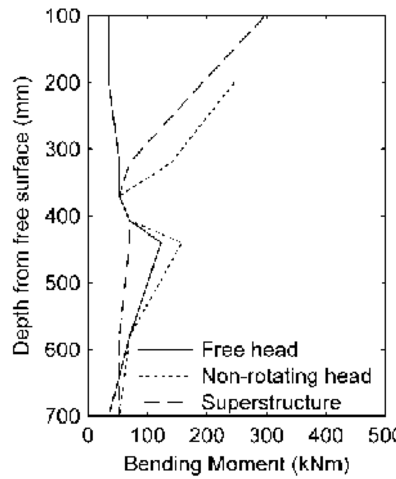
The reliability of existing analytical formulations to predict the inertial and kinematical bending moment along the pile, as a function of the soil and pile properties and the input ground motion characteristics, should be assessed.

PILESI Project (Bristol)

Experimental investigation of soil-pile-structure seismic interaction







Project leader: Prof. A. L. Simonelli (University of Sannio, Italy)

Objectives: To investigate the seismic response of pile groups in layered soils in order to provide a benchmark for numerical-model validation purposes.

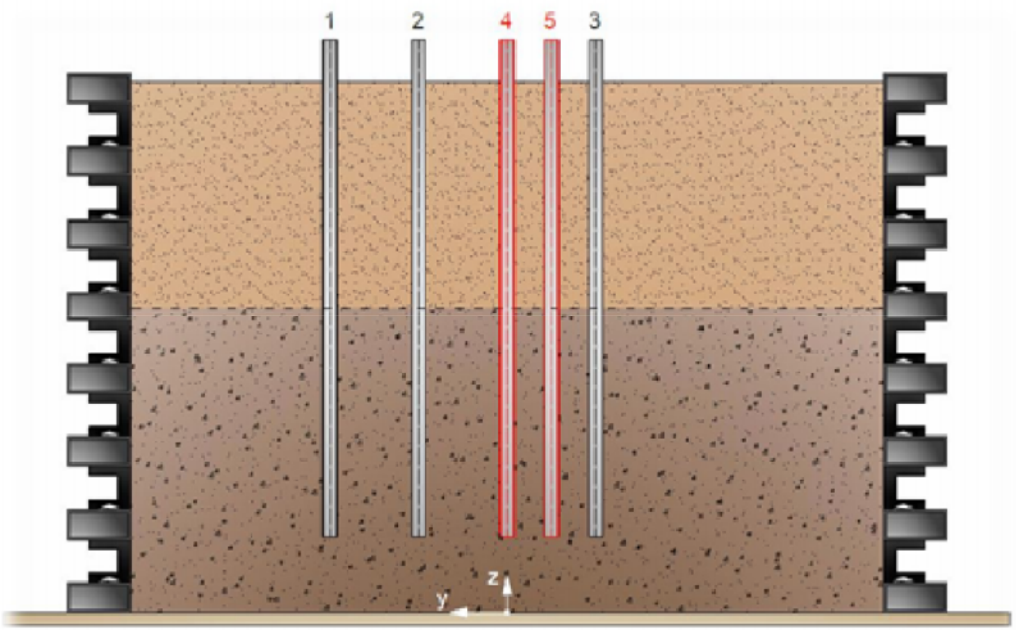
Experimental variables: Pile head fixity, Pile-structure interaction, input motion

Methodology: **A shear stack is used to apply appropriate boundary conditions**

Controlled Sand Deposition is used to impose a stiffness contrast between upper and lower soil layers.

Model details

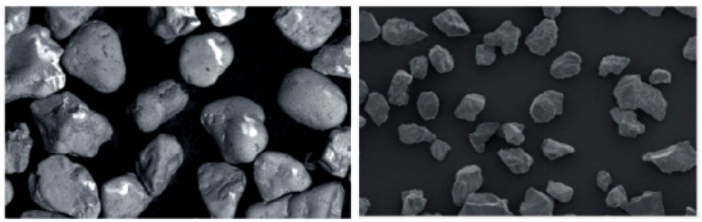
SOIL: Granular 2-layer deposit



Upper layer:
340 mm thick
Leighton Buzzard sand (Fraction E)

Bottom layer:
460 mm thick
Leighton Buzzard
Fraction E + LB-Fraction B

LB-Fraction B



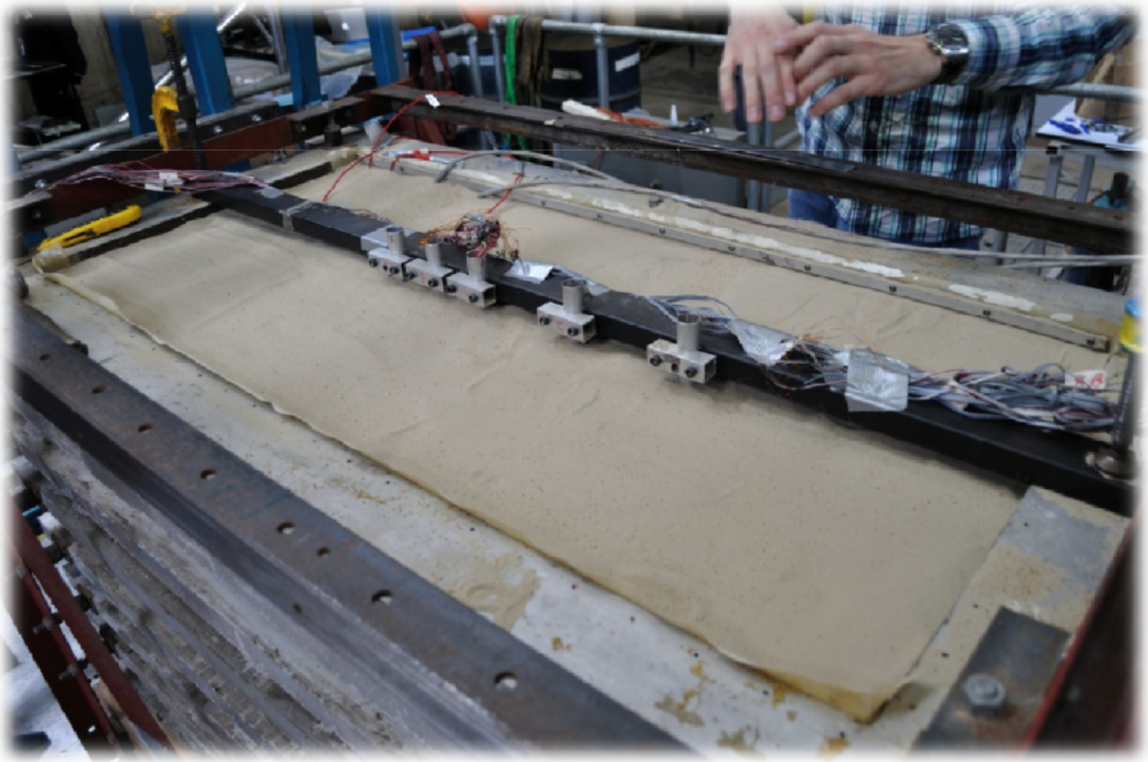
LB-Fraction E

Model details

SOIL DEPOSITION

Model details

SOIL DEPOSITION

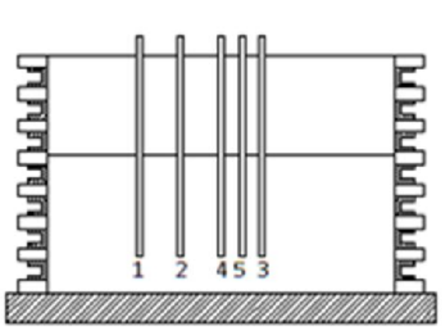


Model details

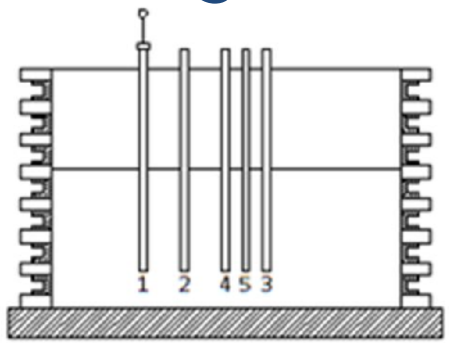
Piles
and
strain gauges

Model configurations

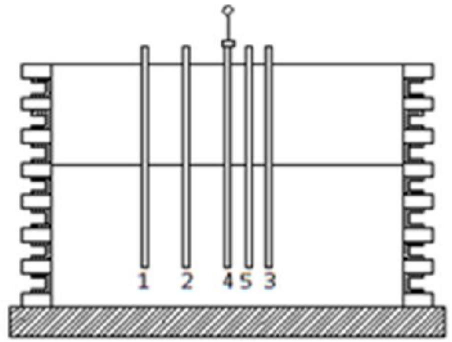
1)



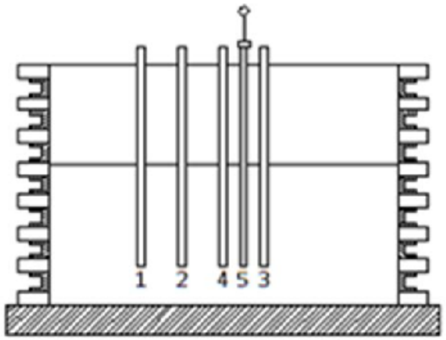
2)



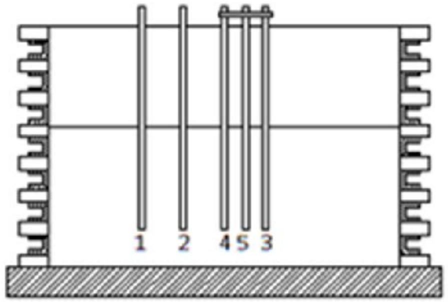
3)



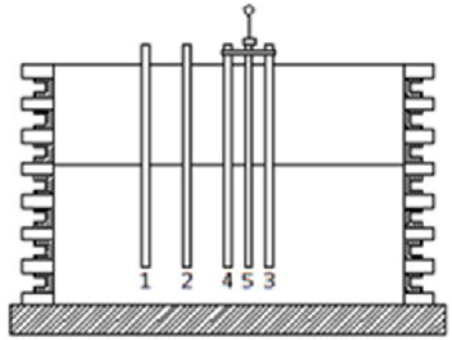
4)



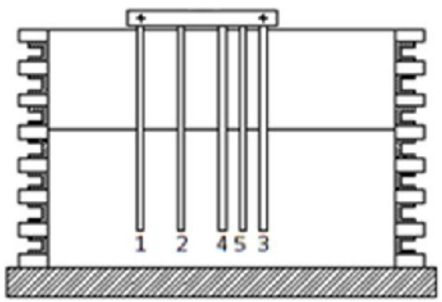
5)



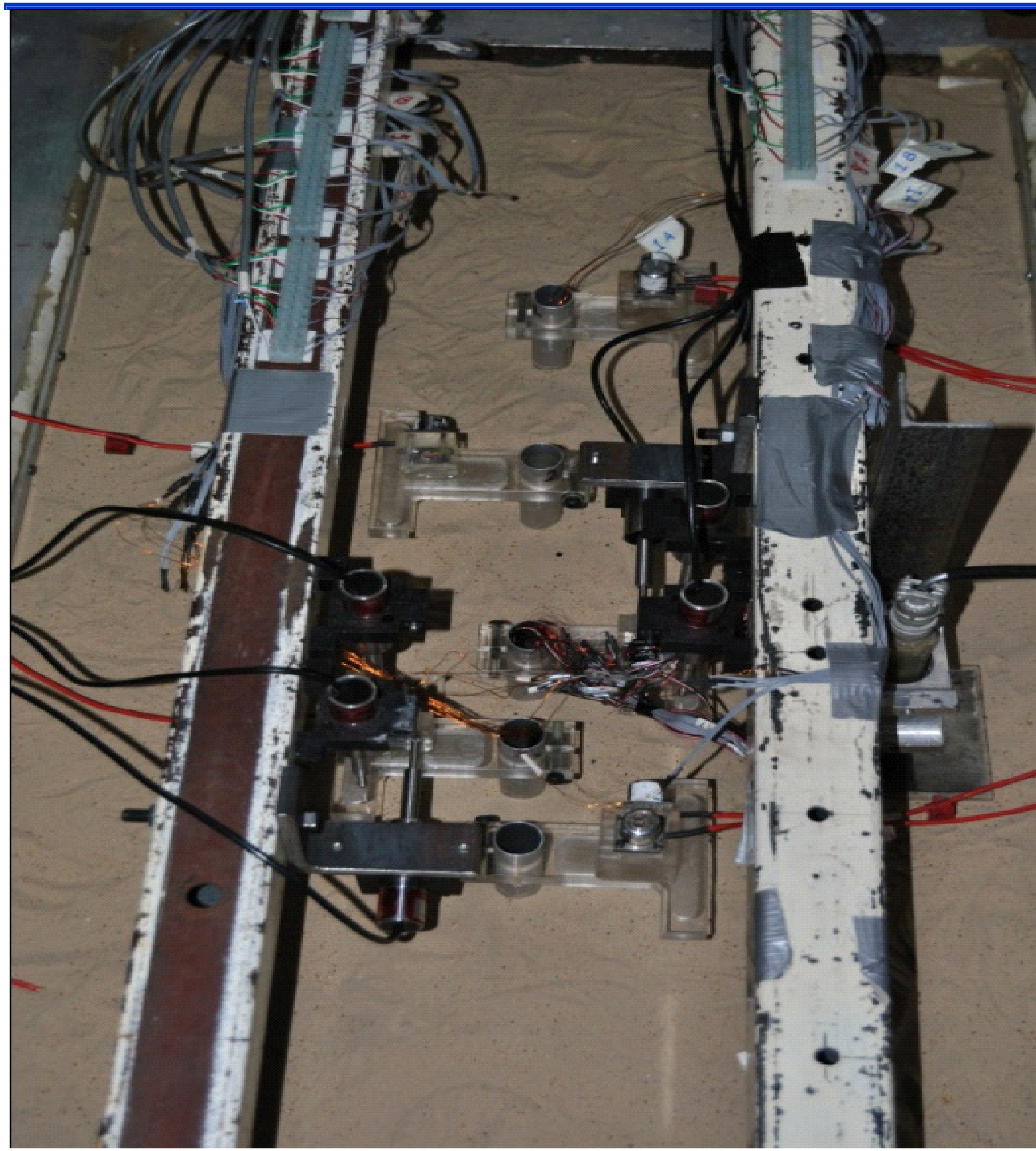
6)



7)

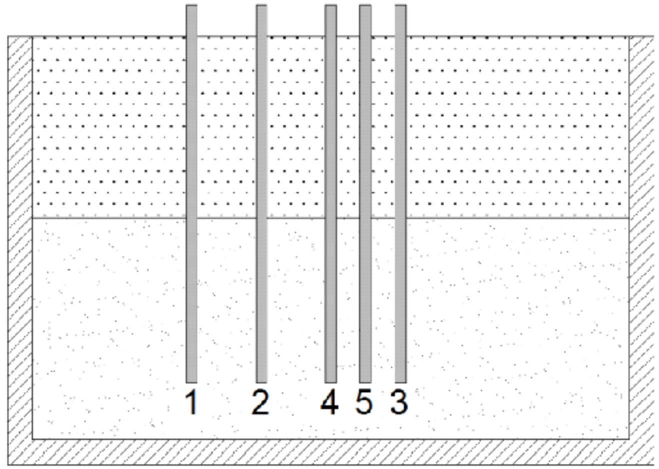


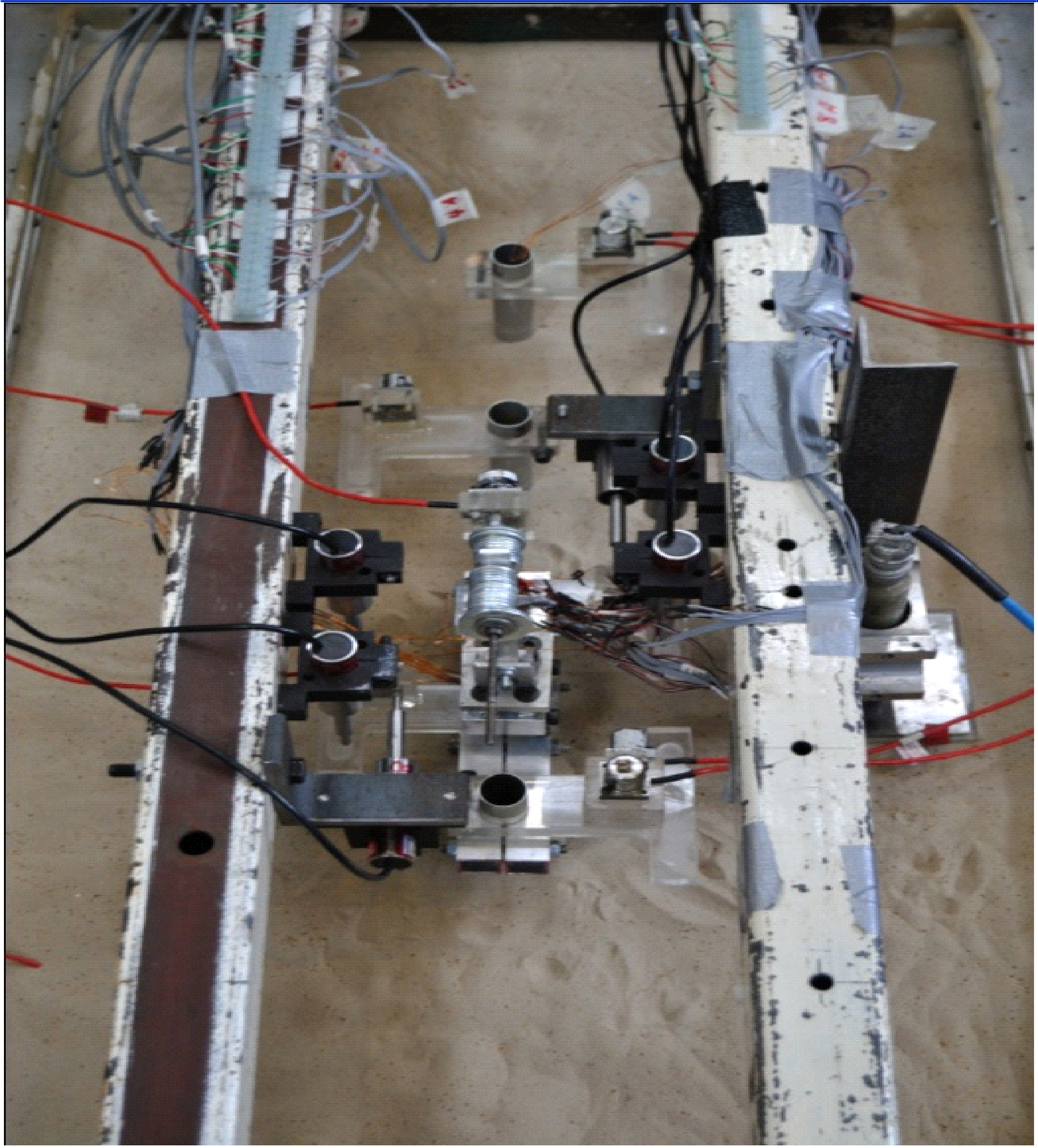
1) **Free head pile**
2) **SDOF on pile 1**
3) **SDOF on pile 4**
4) **SDOF on pile 5**
5) **Short cap connecting piles 3,4,5**
6) **Short cap with SDOF on pile 5**
7) **Long cap from pile 1 to pile 3**



Model configurations

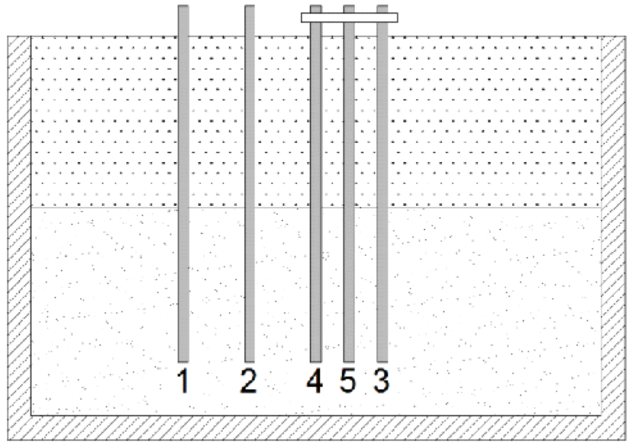
Free Head Pile

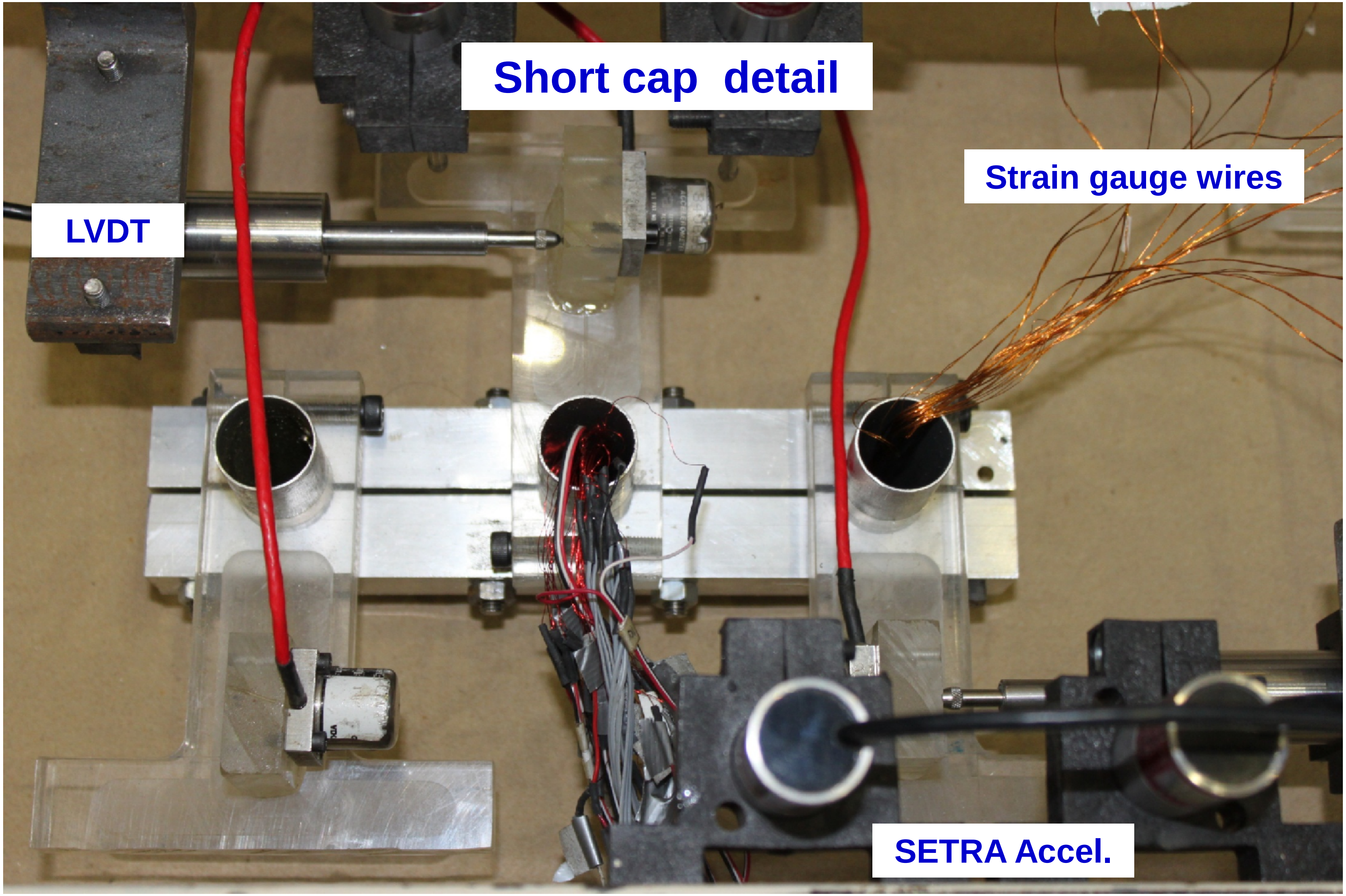


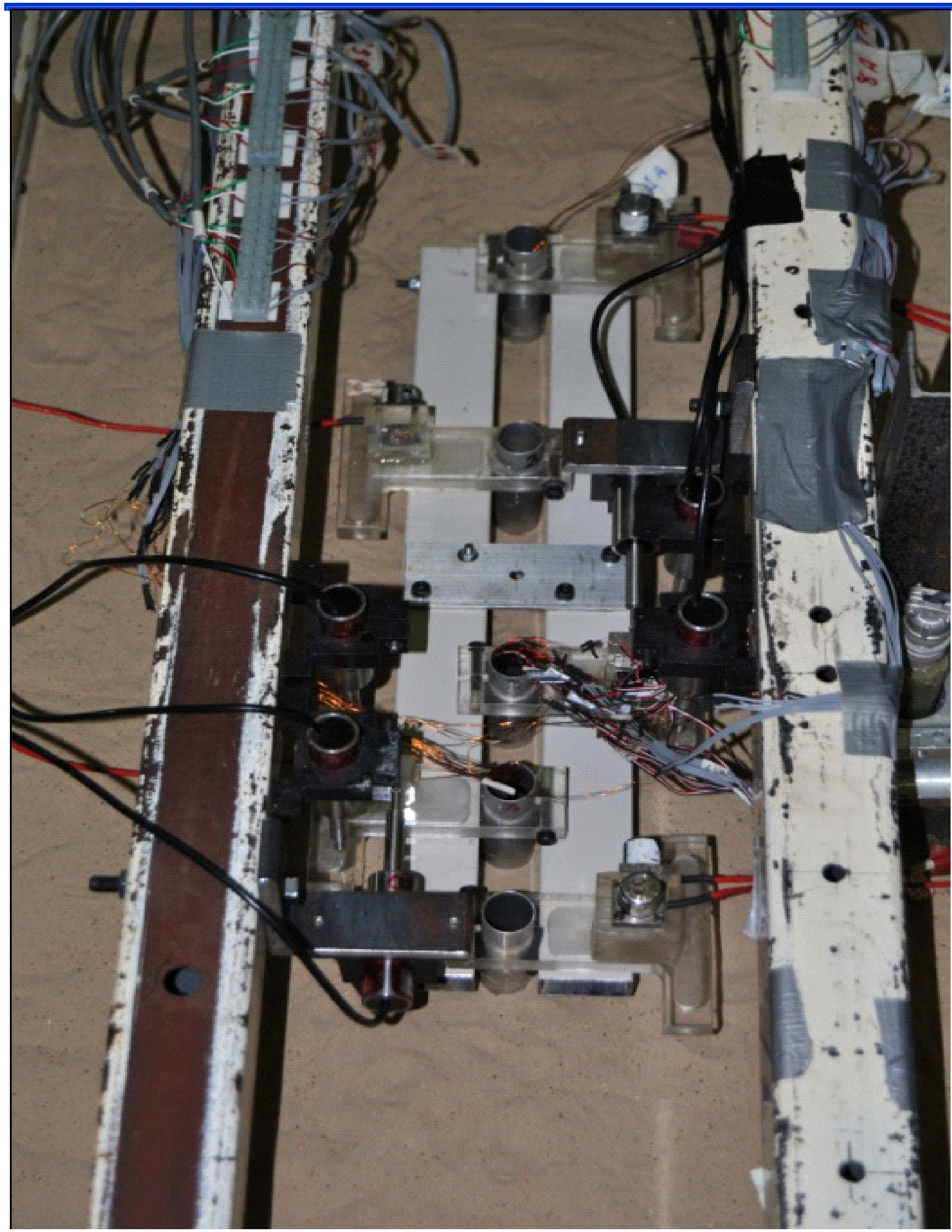


Model configurations

Short cap

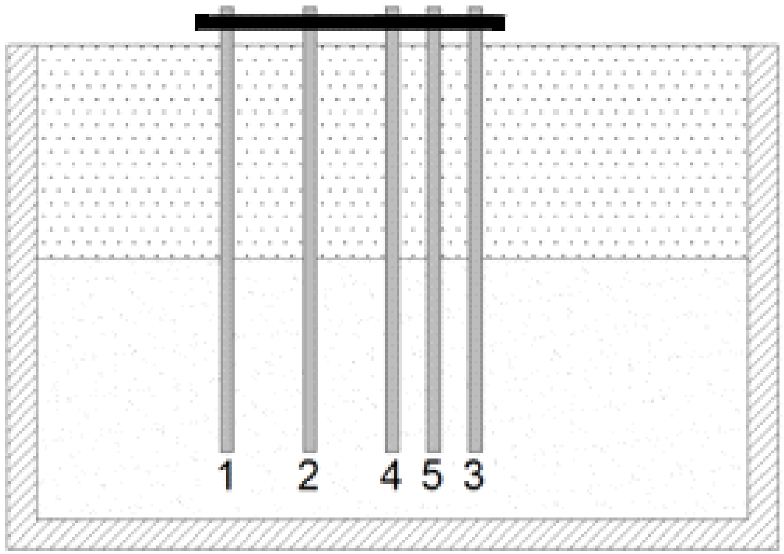


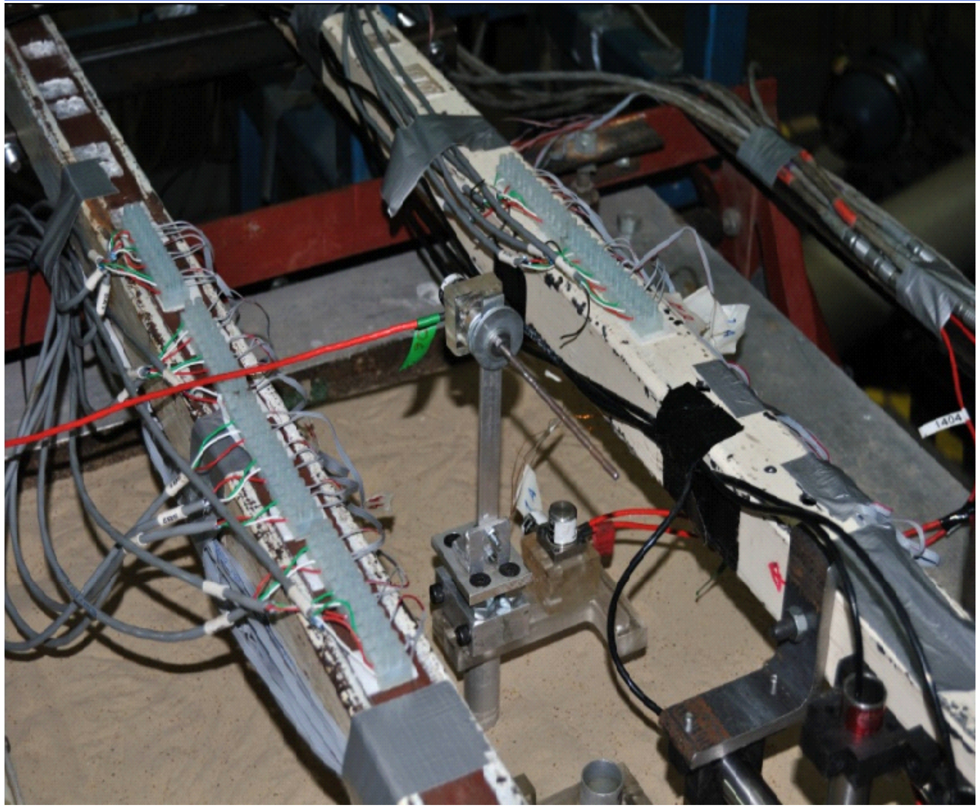

Short cap detail
Strain gauge wires
LVDT
SETRA Accel.



Model configurations

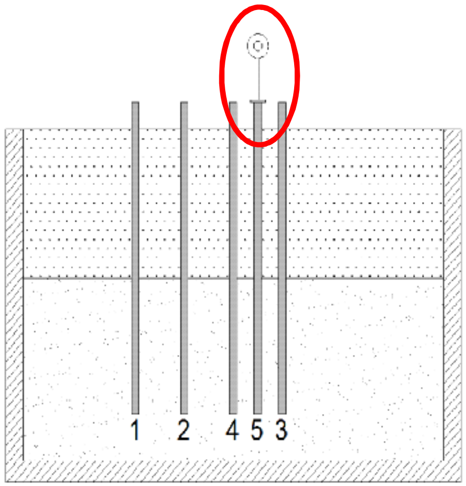
Large cap

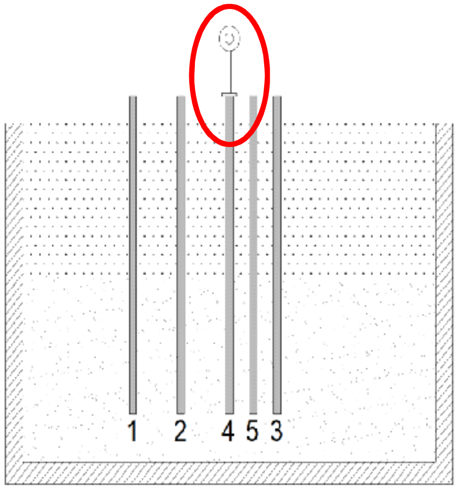


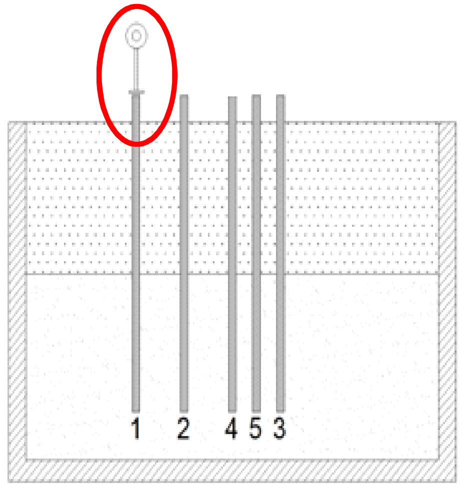


Model configurations With SDOF

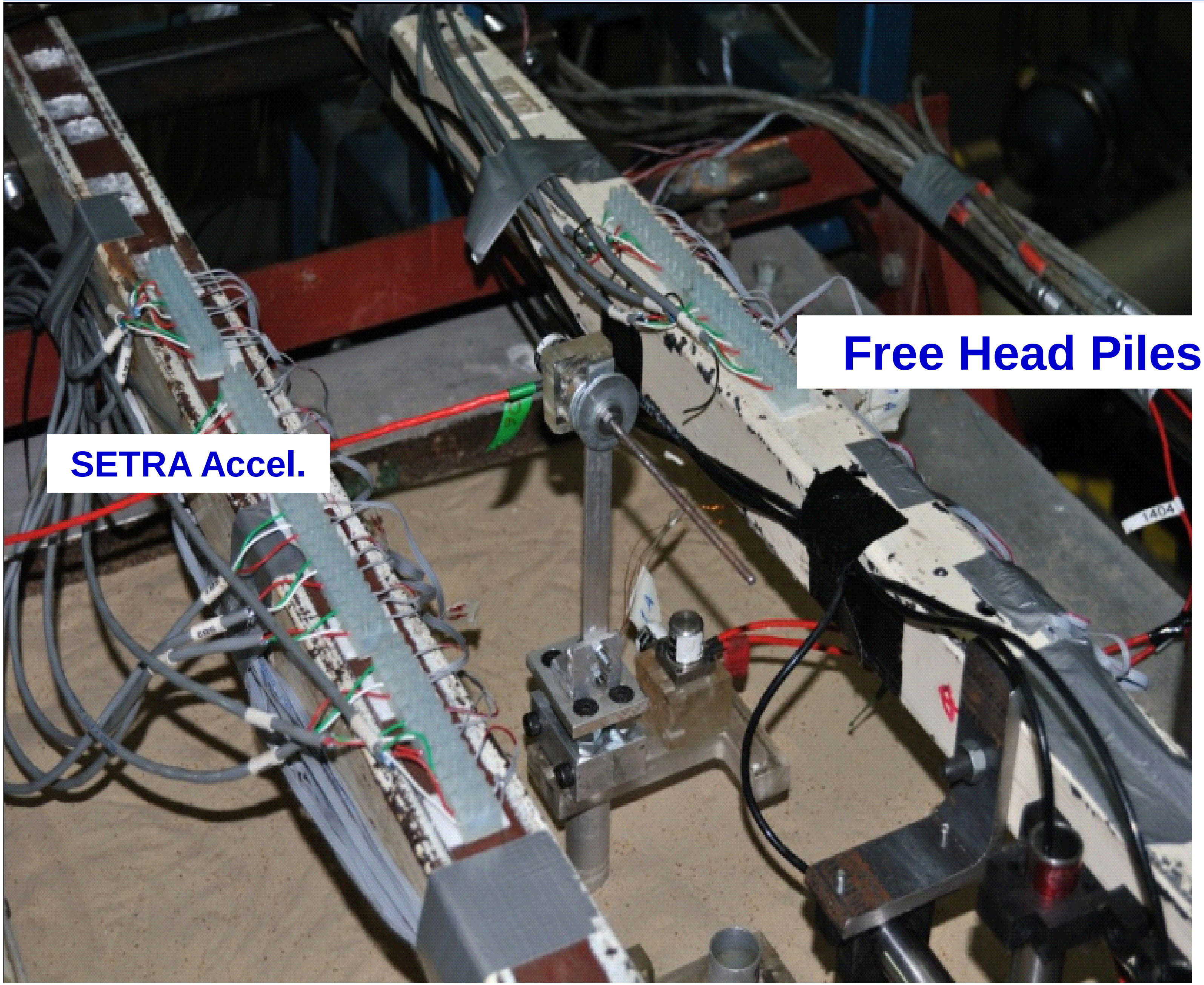
Free Head Piles + SDOF

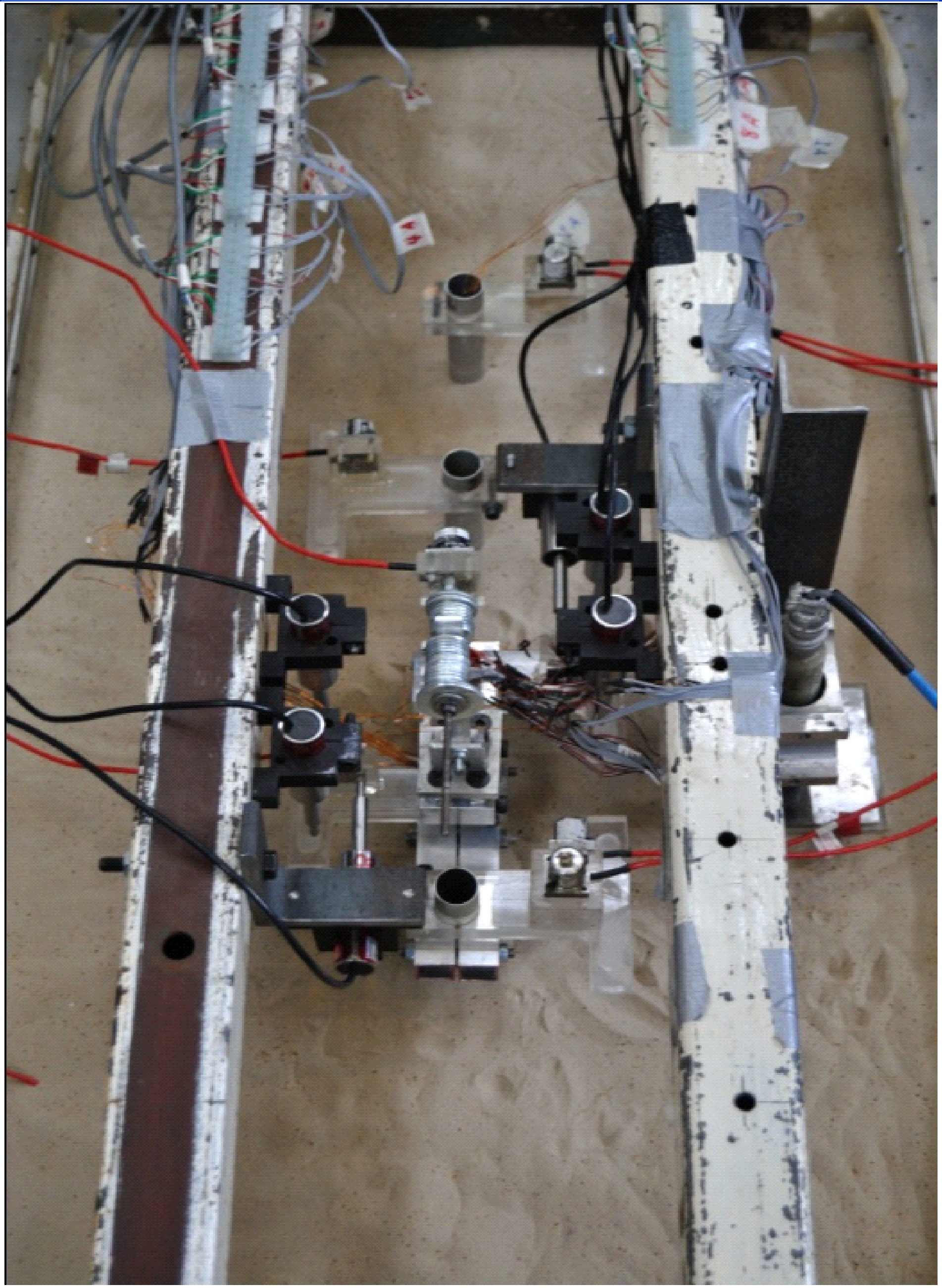






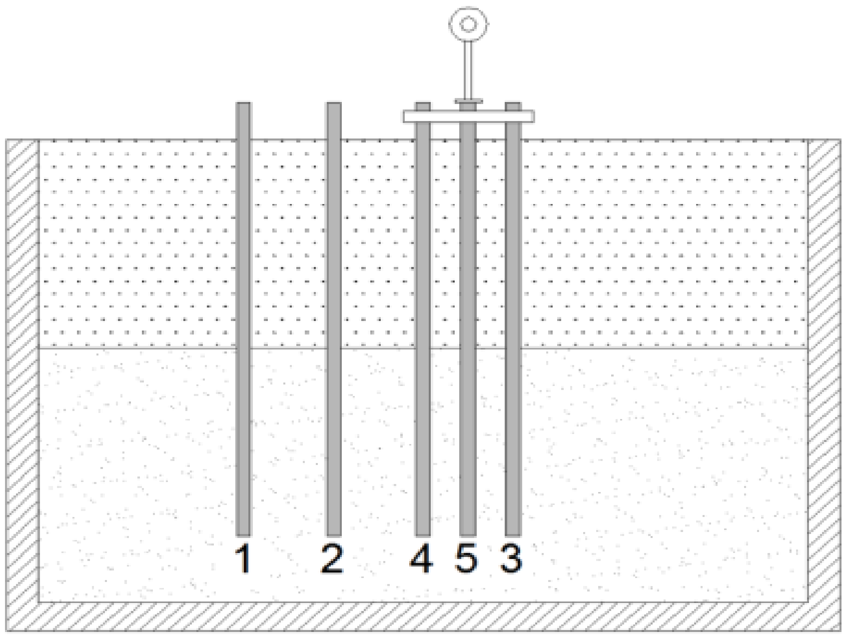
Free Head Piles + SDOF





Model configurations With SDOF

Short cap + SDOF



Test objectives

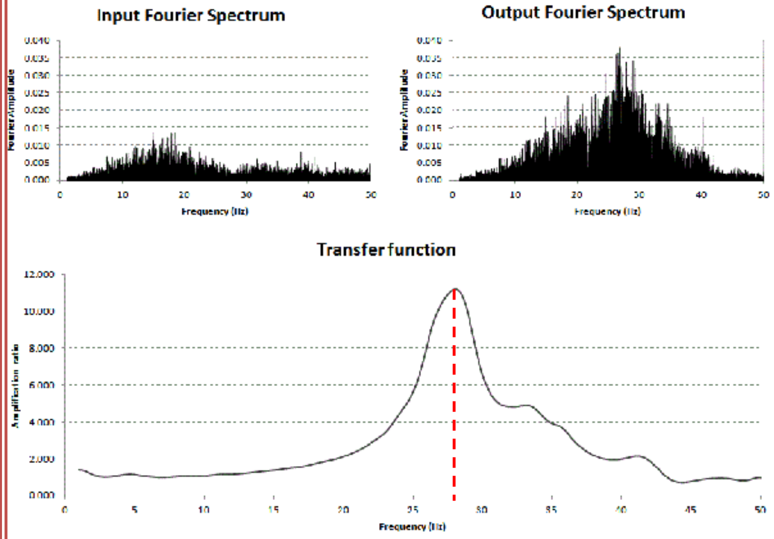
test - input motion		***objective***
Horizontal white noise test	*White noise signals applied on the vibrating table along y direction*	Horizontal natural frequency of the system; Shear stack influence on the system motion
Horizontal sinedwel		ematic interaction factors
Vertical white noise		l frequency of the system
Vertical sinedwell t		atic interaction factors
Static impedance test (Pul	*measure pile head deflection at two points*	components of stiffness matrix
Dynamic impedance test	*Horizontal motion applied to the shacking table. The shear stack is arranged in configuration LC*	Kvv, Krr, Krv components of stiffness matrix
Snapback test	*Traction and quick release applied on pile 5 head*	Natural frequency and damping of the embedded pile
Earthquake tests	*Frequency scaled seismic motions applied on the shaking table*	Observe the behavior under seismic motion

total no. of tests :

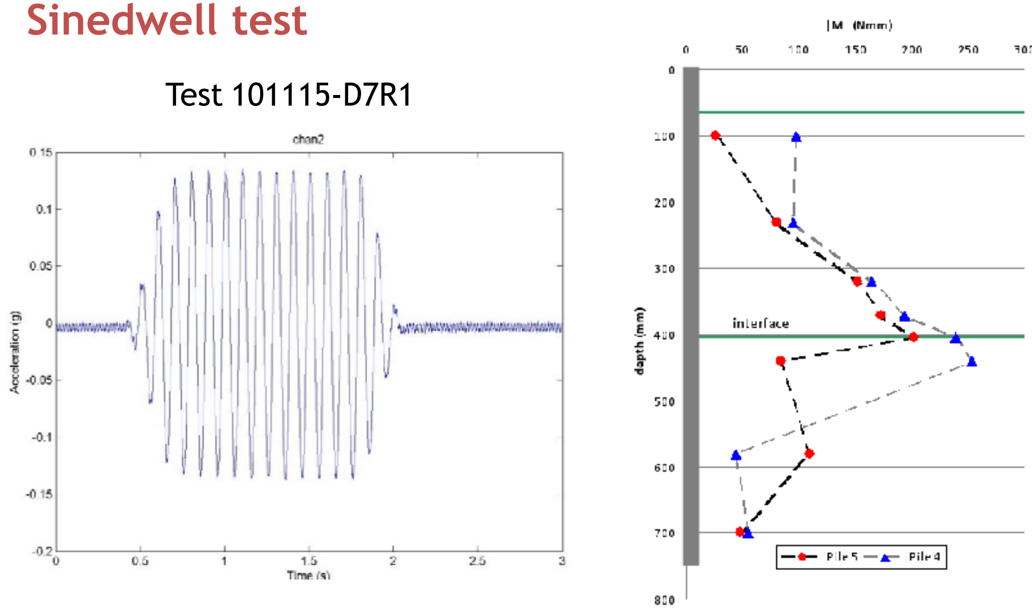
about 600 !

Typical results

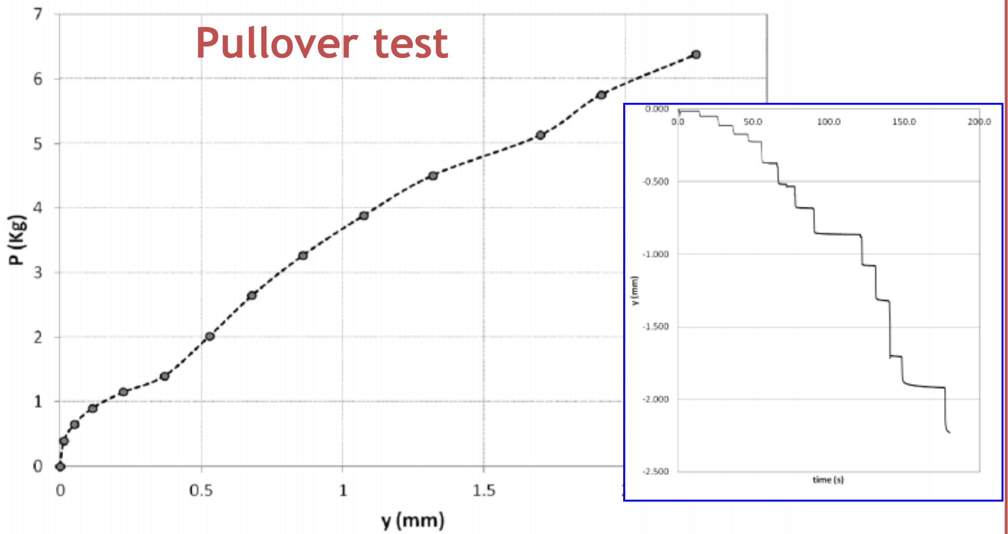
White noise test



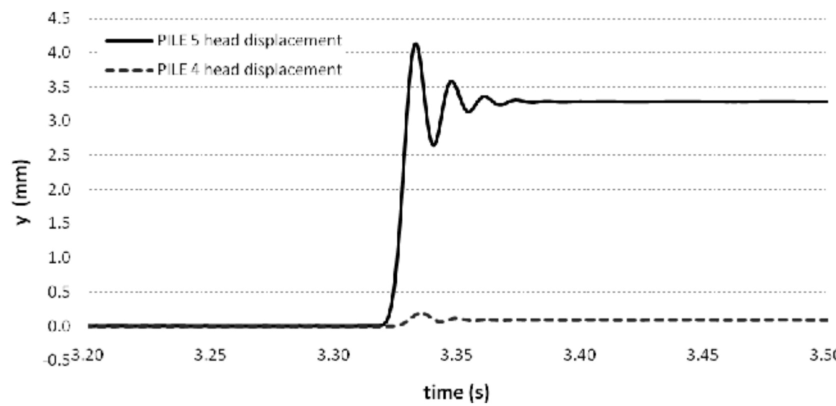
Sinedwell test



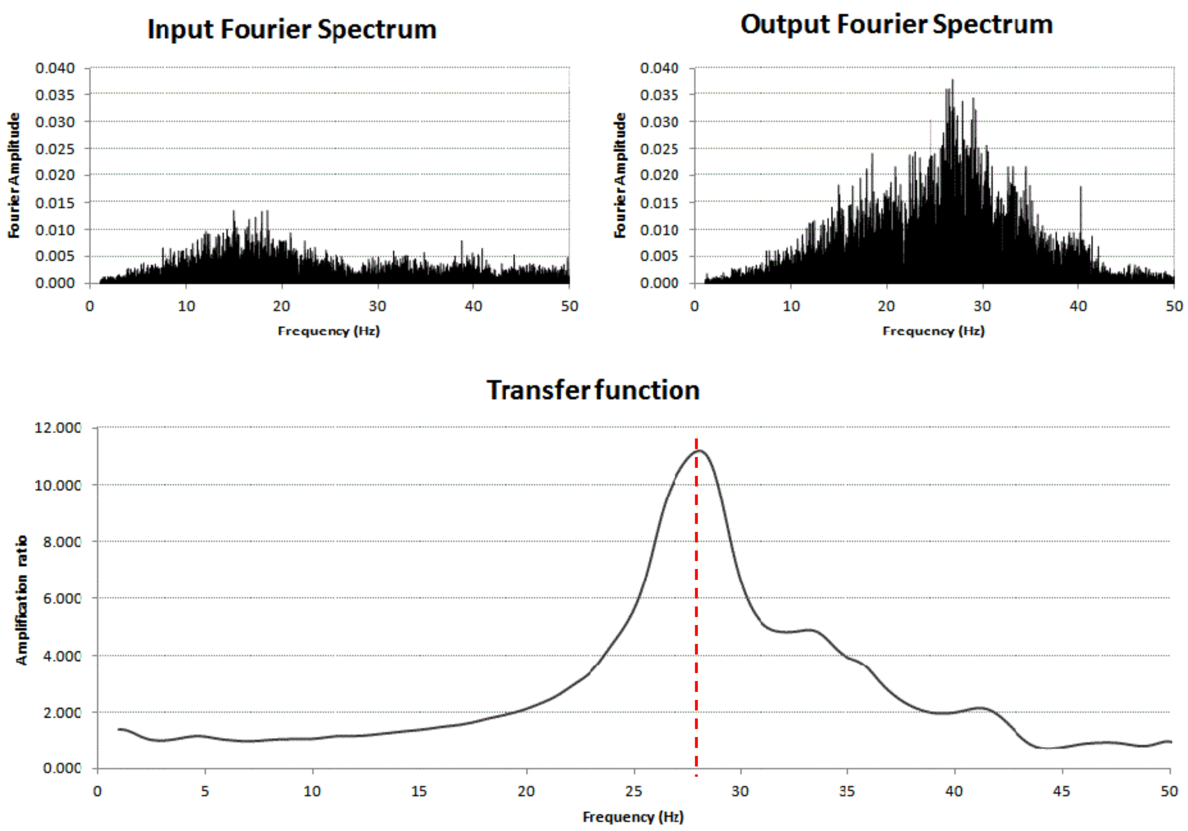
Pullover test



Snapback test



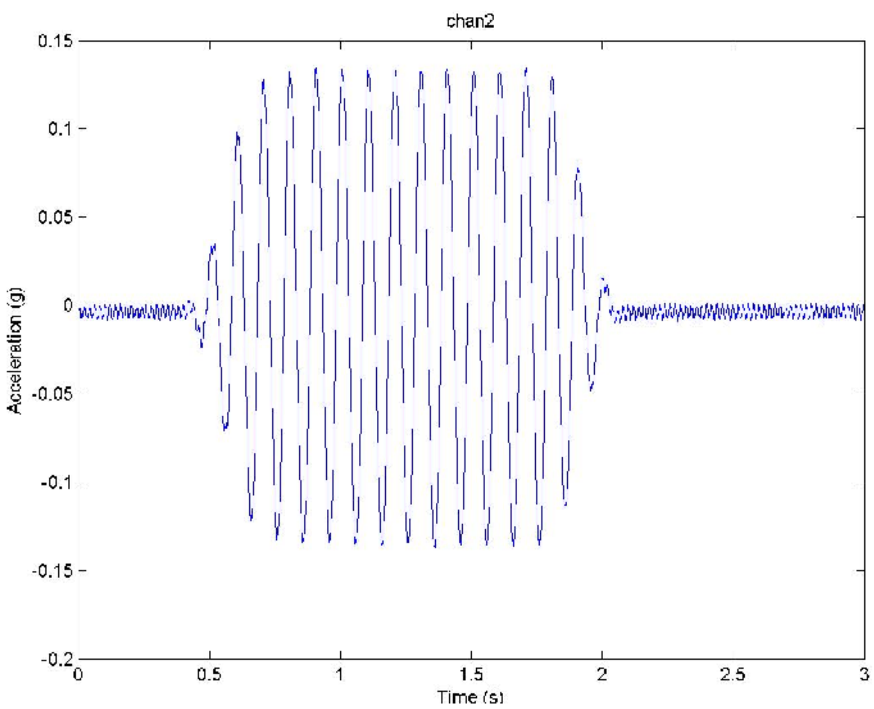
White noise test

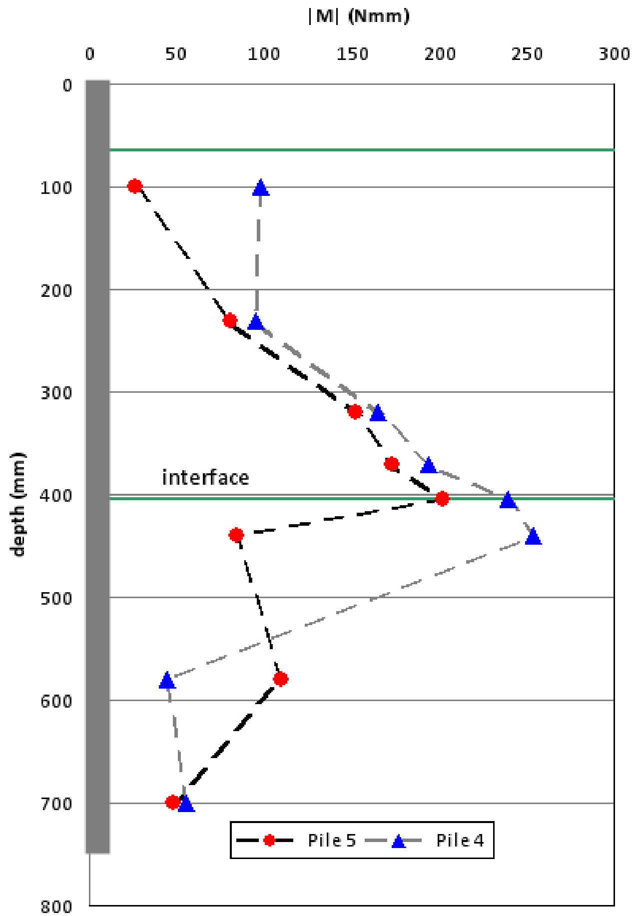


Horizontal natural frequency of the system

Sinedwell test

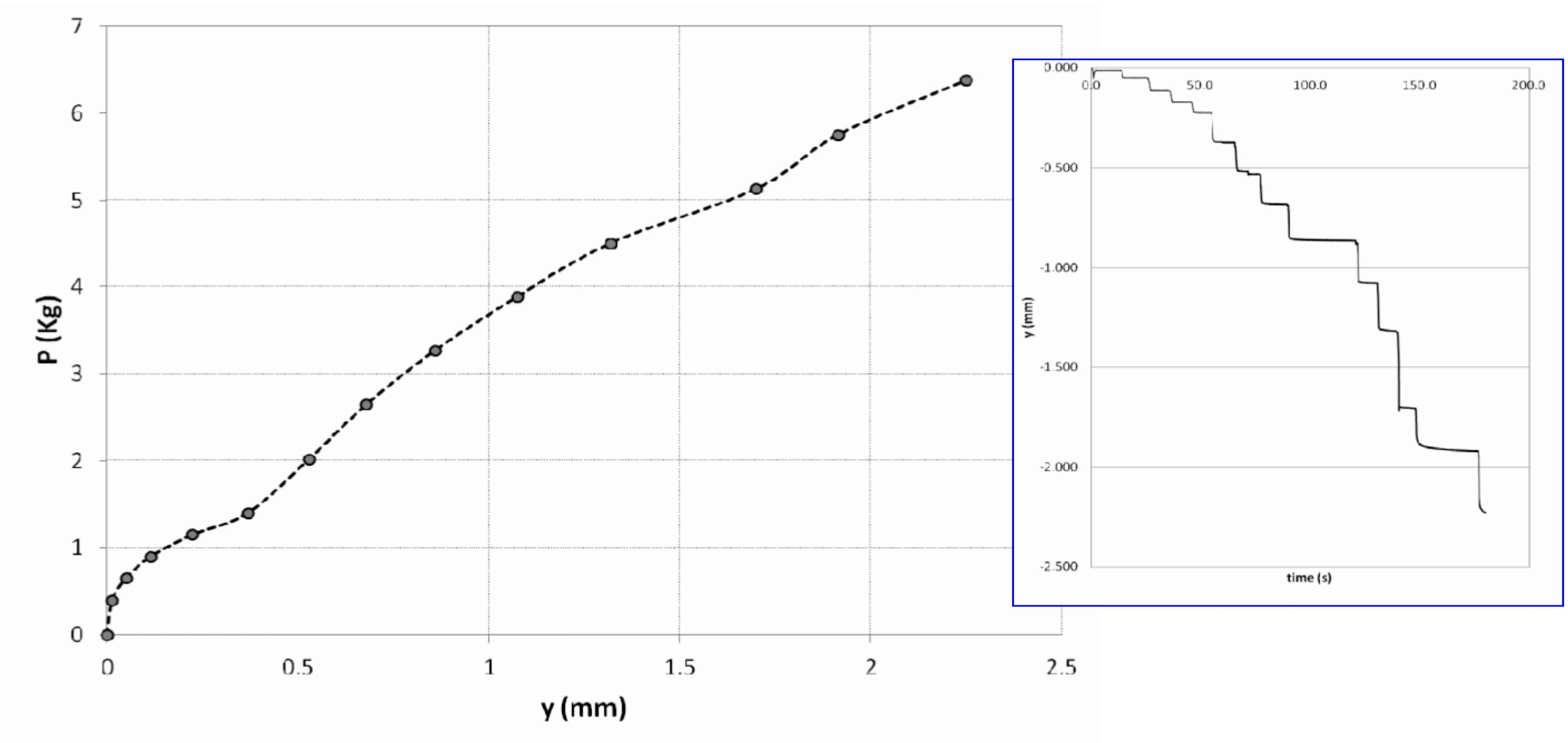
Test 101115-D7R1





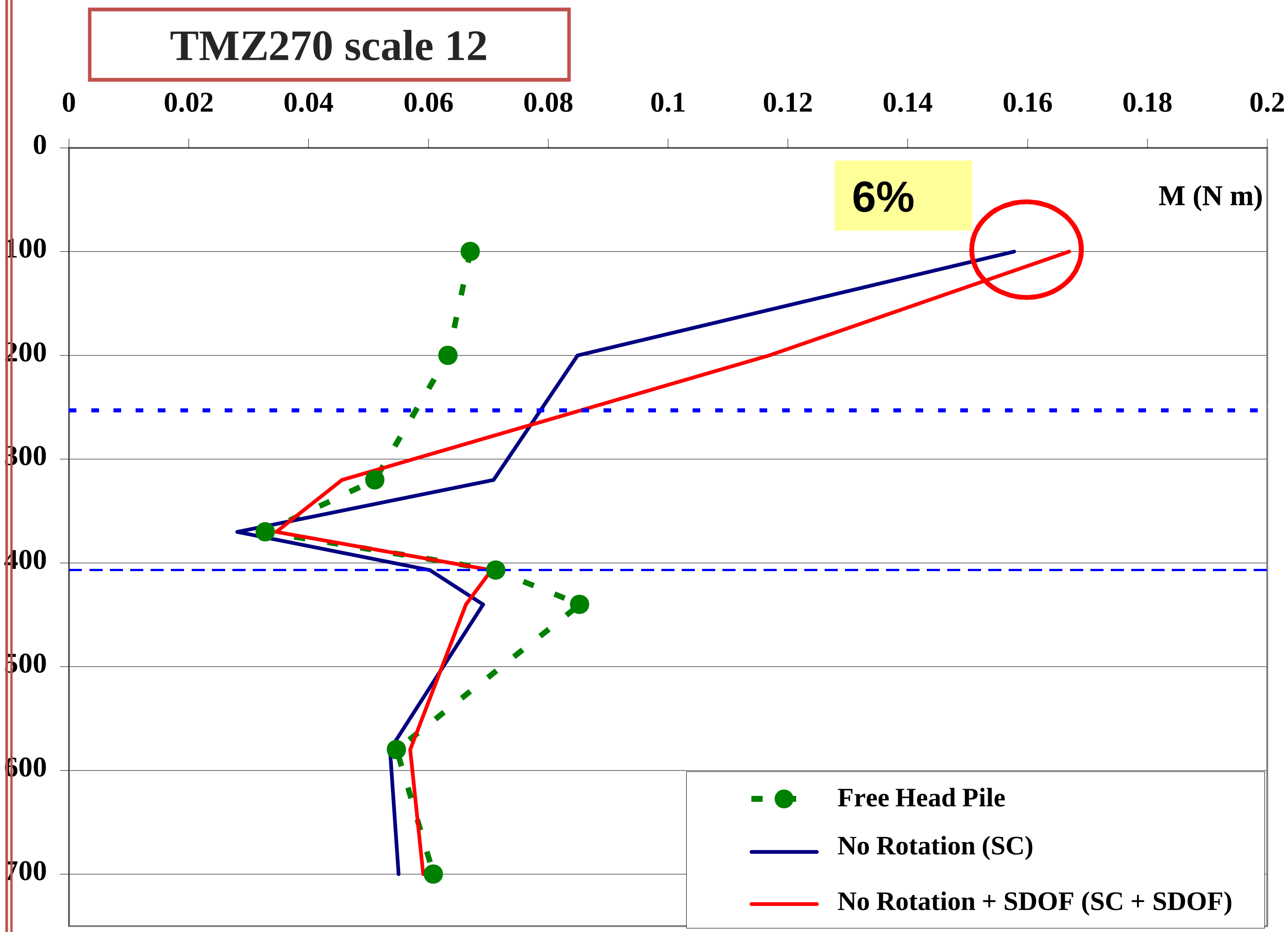
Horizontal kinematic interaction

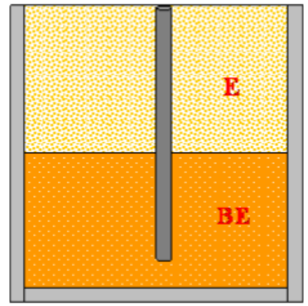
Pullover test

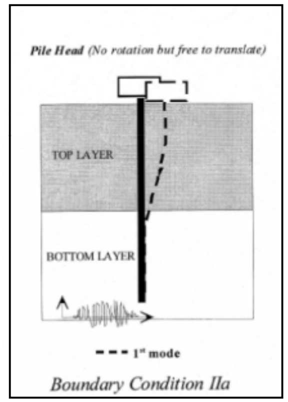


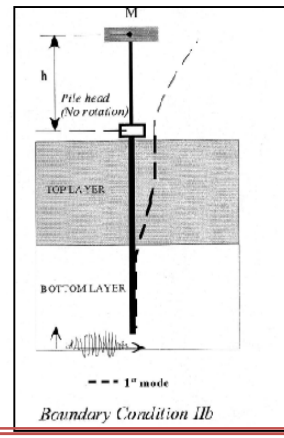
Static impedance test

Kinematic and Inertial bending moments

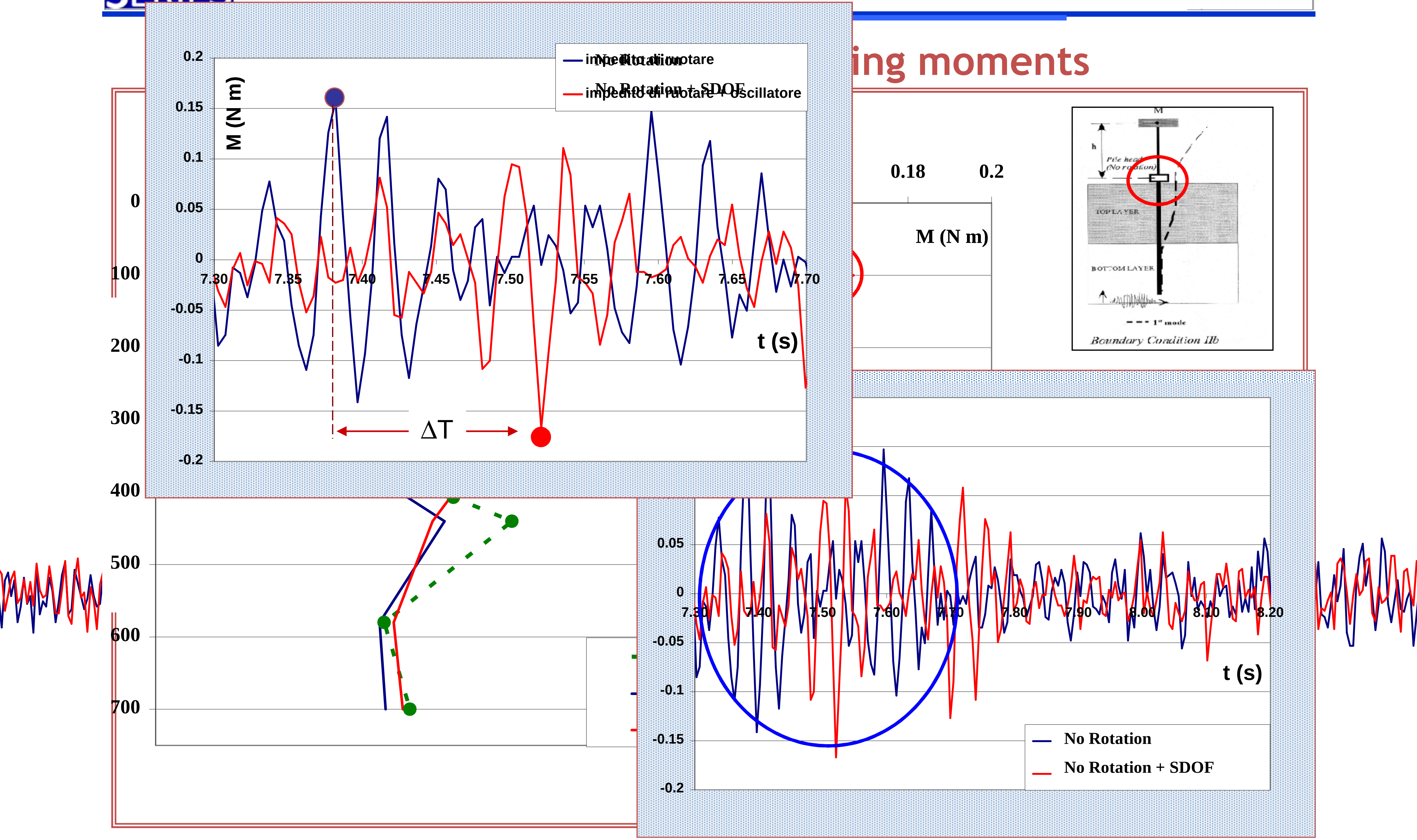




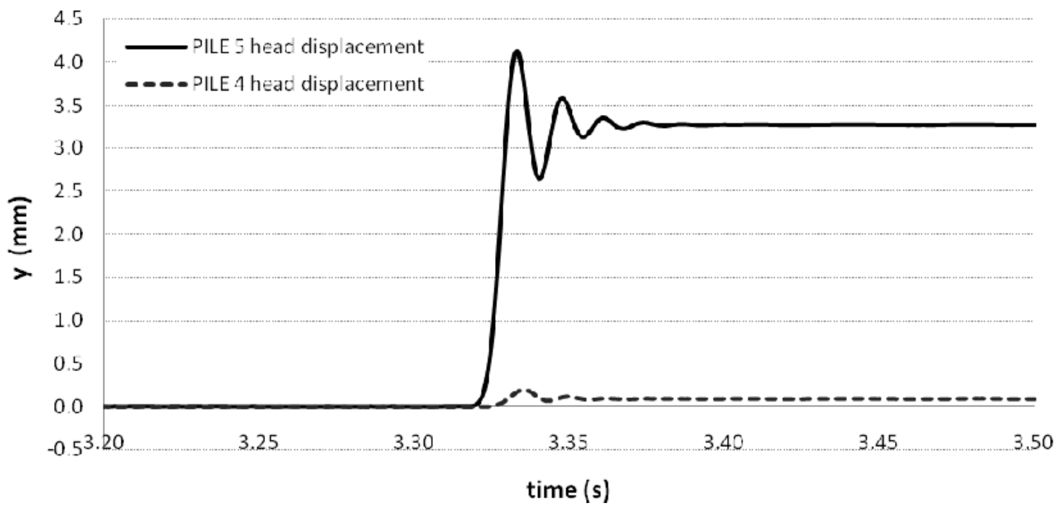




...ing moments


M (N m)
t (s)
No Rotation
No Rotation + SDOF
impedito di ruotare
impedito di ruotare + oscillatore
ΔT
Pile head (No rotation)
TOP LAYER
BOTTOM LAYER
1st mode
Boundary Condition IIb

Snapback test



Natural frequency and damping of the embedded pile

Thank you

for

your attention