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# SEISMIC PILE-SOIL INTERACTION: EXPERIMENTAL RESULTS VS. NUMERICAL SIMULATIONS

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**Abstract.** *The present analytical work discusses the outcomes of a series of 1-g shaking table experimental tests that were carried out to validate numerical models formulated for kinematic and inertial interaction effects on pile-supported systems. Towards this aim, pile models in layered sand deposits were built in the laboratory; such models were subjected to several cyclic tests and an ensemble of earthquake loading. The piles were densely instrumented with accelerometers and strain gauges; therefore, earthquake response, including bending strains along their length, could be measured directly. Different configurations were considered for the shake-table tests; the latter configurations include free-head piles and single-degree-of-freedom (SDOF) systems with short and long caps at foundation level. The experimental data have been assessed accurately to estimate the period elongation of the SDOF structures, if any. Additionally, comparisons between the soil free-field response derived experimentally and advanced numerical simulations are also included. The results of the analyses show that the period elongations of the SDOF structure caused by pile-soil-interactions may be significant, thus affecting the evaluation of structural response under earthquake loading. Implications on the assessment of existing structures and the design of new ones are discussed.*

## 1 INTRODUCTION

Assessing the seismic behaviour of piled foundations is not an easy task, especially in presence of a superstructure. Soil-structure interaction (SSI) for piled foundations may cause: (i) a variation between the free-field ground motion and the corresponding motion at the base of the superstructure, (ii) kinematic bending, axial and shear stresses along the piles even in the absence of a superstructure. The kinematic bending moments may be particularly significant for piles embedded in soft soils closed to the pile head in presence of a rigid cap or in the vicinity of interfaces between layers having high stiffness contrasts.

The present work is aimed at shedding light into different aspects of soil-pile-structure interaction. To this end, it discusses and simulates the results of a series of high-quality shaking table tests on model piles. The experimental test program was performed at the Bristol Laboratory for Advanced Dynamics Engineering (BLADE), within the framework of the Seismic Engineering Research Infrastructures for European Synergies (SERIES). Tests were carried out on different pile group configurations, with and without pile caps and superstructures, subjected to both lateral and vertical earthquake shaking. Single-degree-of-freedom (SDOF) systems were considered to simulate the response of either buildings or bridge piers on piled foundations. The loading conditions include different input motions such as white noise, sine dwells and recorded earthquakes. The tests aimed at investigating various aspects of seismic Soil-Pile-Structure-Interaction (SPSI), including the natural frequency (in both horizontal and vertical direction) of the system, the natural frequency and damping of embedded piles, the horizontal and vertical soil-pile kinematic interaction and foundation-structure interaction. The experimental data have been analyzed accurately to estimate the period elongation of the superstructure, if any. Additionally, comparisons between measured and simulated free-field soil response are included. It is found that the period elongations caused by pile-soil-interactions may be significant thus affecting the evaluation of the structural response of SDOF under earthquake excitation.

The earthquake response of pile groups was investigated through 1-g shaking table tests. Such laboratory tests were aimed at assessing the effects of both kinematic and inertial effects on the piles. The test campaign consisted of two series of tests: preliminary tests, carried out in November 2010, and a more comprehensive series of tests, including earthquake loading, carried out in June 2011. The 6-degree-of-freedom earthquake simulator of BLADE and the equivalent shear beam (ESB) laminar container were utilized to this end [1 - 2]. The ESB consists of 8 rectangular aluminium rings, which are stacked alternately with rubber sections to create a hollow yet flexible box of inner dimensions 1.190 m long by 0.550 m wide and 0.814 m deep [3].

The sample test model consists of five piles embedded in a bi-layer soil (Figure 1a). The piles consist of an alloy aluminium tube (commercial model 6063-T6) and the superstructure is modeled using different masses and two types of columns (aluminum, steel); the principal characteristics of these elements are listed in Table 1.

Accelerometers were used to monitor the accelerations of the shaking table, the shear stack, the soil along a vertical array, the pile heads and the superstructure. The LVDT transducers were employed to monitor the displacements of the pile in the horizontal and vertical direction. To evaluate the bending response along the piles, 8 strain gauge pairs have been attached on the shafts of piles 4 and 5; additionally, 4 strain gauges are placed on the shaft of pile 1 close to the layer interface. 63 data channels were used in total.

A two-layer soil profile was deposited by pluviation. The top layer is made of Leighton Buzzard sand (LB) fraction E, the bottom layer is a mix of LB fractions B and E (85% and 15%, respectively) The LB sand adopted in the tests has been extensively used in the experimental research activity carried out in BLADE. Material data can be found in previous experimental studies [4 -8].

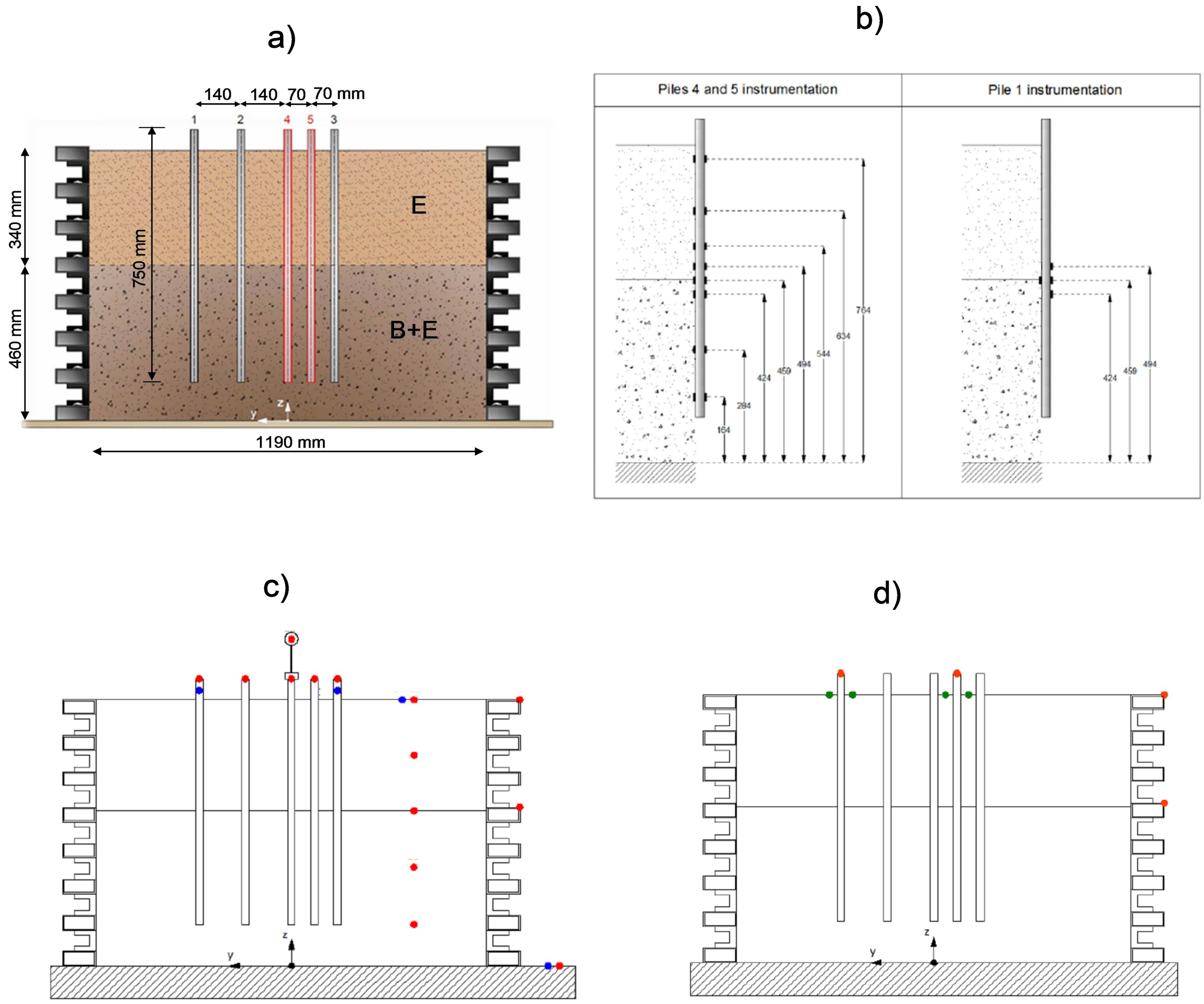



Figure 1. Model setup: (a) subsoil configuration, (b) strain gauge, (c) accelerometer and (d) LVDT location

| Element [type] | Geometrical details [mm] | *Unit weight* [kN/m$^3$] | *Length [mm]* | Young's modulus E [GPa] |
|---|---|---|---|---|
| Pile | $D_e$ = 22.23<br>t = 0.71 | 27 | 750 | 70 |
| Aluminum column | Cross section 3x12 | 27 | 130 (phase I)<br>50 -100<br>(phase II) | 70 |
| Steel column | Cross section 3x12 | 80 | 100<br>(phase II) | 21 |

Table 1. Characteristics of piles and columns

Table 2 outlines the sand index properties obtained from different previous studies, while Table 3 presents physical and mechanical properties of the two soil layers as evaluated from the present sample tests.

| Materials | Type | $G_s$ [Mg/m$^3$] | $e_{min}$ | $e_{max}$ | $D_{10}$ | $D_{50}$ | References |
|---|---|---|---|---|---|---|---|
| LB - fraction E | Sand BS 881-131 | 2.647 | 0.613 | 1.014 | 0.095 | 0.14 | Tan (1990) |
| LB - fraction B | Sand BS 881-132 | 2.647 | 0.486 | 0.78 | | 0.82 | Ling & Dietz (2004) |
| LB - fraction E+B | | 2.647 | 0.289 | 0.614 | | | Moccia (2009) |

Table 2. LB sand index properties

The shear wave velocity, $V_s$, was derived from white noise tests carried out before corresponding sine dwell and earthquake tests for each stage of the experimental activity. As can be observed from Table 3, the shear wave velocity contrasts between the bottom and top layer are similar for the two stages of tests; the contrast is about 1.6.

| Soil layers | Thickness *H* (mm) | Void ratio *e* | Relative density *Dr* (%) | | Dry unit weight $\gamma_d$ (kN/m$^3$) | | Shear wave velocity *Vs* (m/s) | | $Vs_2/Vs_1$ | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Nov 2010 | June 2011 | Nov 2010 | June 2011 | Nov 2010 | June 2011 | Nov 2010 | June 2011 |
| Top LB(E) | 340 | 0.9 | 28 | 10 | 13.63 | 13.13 | 51 | 54 | 1.59 | 1.57 |
| Bottom LB(E+B) | 460 | 0.48 | 41 | 50 | 17.46 | 17.92 | 81 | 85 | | |

Table 3. Soil layer properties

The testing procedure utilized during the experimental campaign includes both cyclic motions and earthquake records; the input motions are summarized as follows:

- White noise excitation: random noise signal of bandwidth 1-100 Hz and peak ground acceleration varying between 0.01 g and 0.10 g.
- Harmonic excitation: sine dwell acceleration time-histories with amplitudes varying between 0.01g÷0.18g and frequencies varying from 5 to 45 Hz.
- Earthquake excitation: three earthquake records from the Italian database: Tolmezzo (Friuli 1976), Sturno (Irpinia 1980) and Norcia (Umbria-Marche 1997). The earthquake motions were modified by a frequency scaling factor of 5 or 12; acceleration amplitude was varied between 0.043g to 0.577g.

The characteristics of all configurations tested and the number of the tests in the two phases of the experimental tests are summarized in Tables 4 and 5, which refer to Phase I and Phase II, respectively. More than 600 tests were carried out during the two phases; these include 366 tests in Phase I and 248 tests in Phase II. White and sinedwell inputs were considered for the first set of preliminary tests, as also shown in Table 4.

| | Free Head Pile (FHP) | Short Cap (SC) | Short Cap + Single Degree of Freedom on pile 5 (SC+SDOF pile 5) | Free Head Pile + Single Degree of Freedom on pile 5 (FHP+SDOF pile 5) | Free Head Pile + Single Degree of Freedom on pile 4 (FHP+SDOF pile 4) |
|---|---|---|---|---|---|
| White Noise | 4 | 3 | 15 | 12 | 11 |
| Sinedwell | 21 | 15 | 75 | 90 | 90 |

Table 4. Details tests Phase I (total tests: 366)

A comprehensive set of input motions, including vertical white noise, vertical sinedwell, earthquake records, snapback and pullover tests were considered for the Phase II (see Table 5).

| | Free Head Pile (FHP) | Short Cap (SC) | Short Cap + Single Degree of Freedom on pile 5 (SC+SDOF pile 5) | Free Head Pile + Single Degree of Freedom on pile 5 (FHP+SDOF pile 5) | Free Head Pile + Single Degree of Freedom on pile 4 (FHP+SDOF pile 4) | Free Head Pile + Single Degree of Freedom on pile 1 (FHP+SDOF pile 1) | Long Cap (LC) |
|---|---|---|---|---|---|---|---|
| White Noise | 8 | 1 | 9 | 2 | 3 | 3 | 2 |
| Sinedwell | 45 | 1 | 58 | 6 | 26 | 6 | 24 |
| Vertical White Noise | 2 | - | - | - | - | - | - |
| Vertical Sinedwell | 26 | - | - | - | - | - | - |
| Earthquake | 5 | - | 9 | 5 | - | - | - |
| Snapback | 1 | - | - | 5 | - | - | - |
| Pullover | 1 | - | - | - | - | - | - |

Table 5. Details tests Phase II (total tests: 248)

## 2 TEST RESULTS

The outcomes of typical tests of the comprehensive laboratory experimental program carried out on the BLADE shaking table are discussed hereafter, with the specific aim of investigating some particular aspects of seismic SPSI.

### 2.1 Effect of PGA on free-field response

The results reported herein refer to test configuration FHP. Results for sinedwell input motion with frequency of 30 Hz and increasing levels of peak ground acceleration (PGA) applied on the shaking table are reported: 5 tests from PGA=0.008g to 0.069g for the first stage of tests; 6 tests from PGA= 0.016g to 0.105g for the second stage of tests.

In Figure 2 the peak acceleration profiles in the soil (quoted as $a_{max}$) for the two phases are plotted: as expected, free-field response increases with acceleration level. The overall comparison in Figure 2 shows that the profiles of $a_{max}$ exhibit quite similar shapes for both phases of tests. As regards the amount of amplification, it is believed that the effect of loading history on soil properties plays a key role and should be accounted for in a realistic manner in nonlinear numerical simulations.

Figures 3 and 4 compare experimental data with results of numerical simulations, the latter obtained by linear EERA analyses. Such analyses were carried out by assuming the values of mechanical parameters at low strain level. It is observed that for low values of accelerations (Figures 3a and 4a) there is a close match between the numerical and experimental test results. However, as nonlinearity increases (Figures 3b and 4b) test results tend to diverge from the outcomes of numerical simulations.

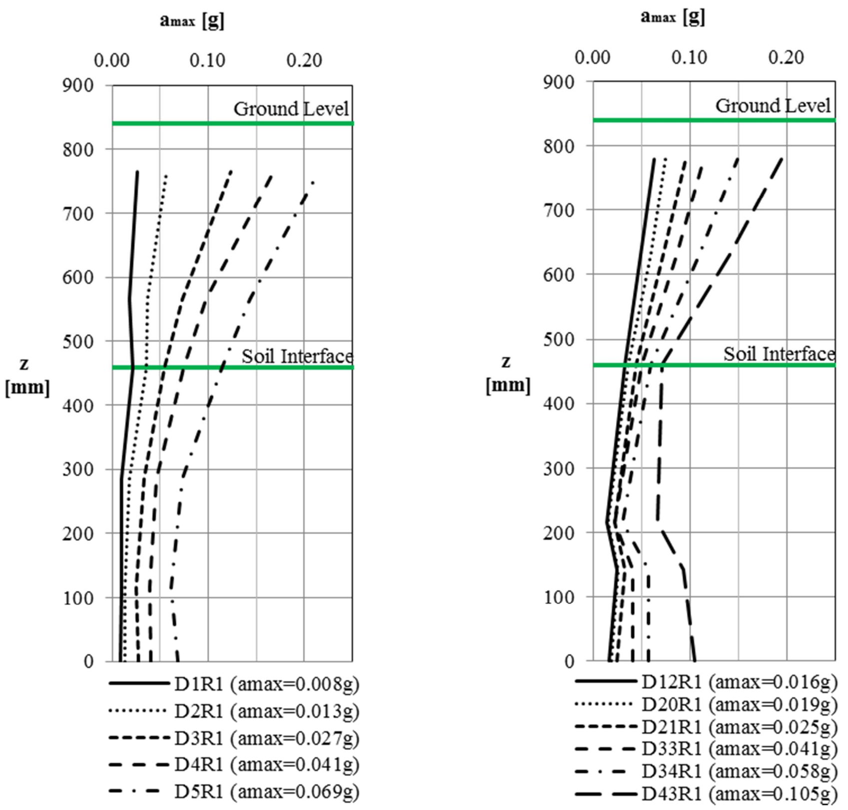



Figure 2. Peak acceleration vs. depth (z) for different amplitudes of input acceleration for Phase I (left) and Phase II (right)

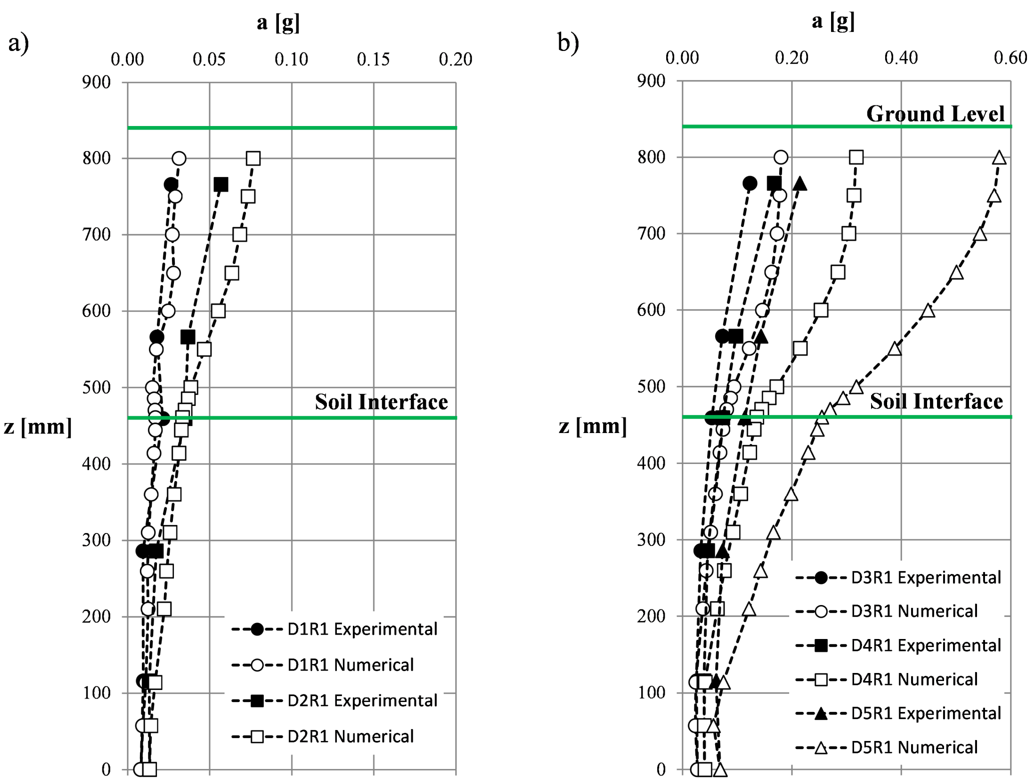



Figure 3. Comparison between experimental and numerical results for Phase I

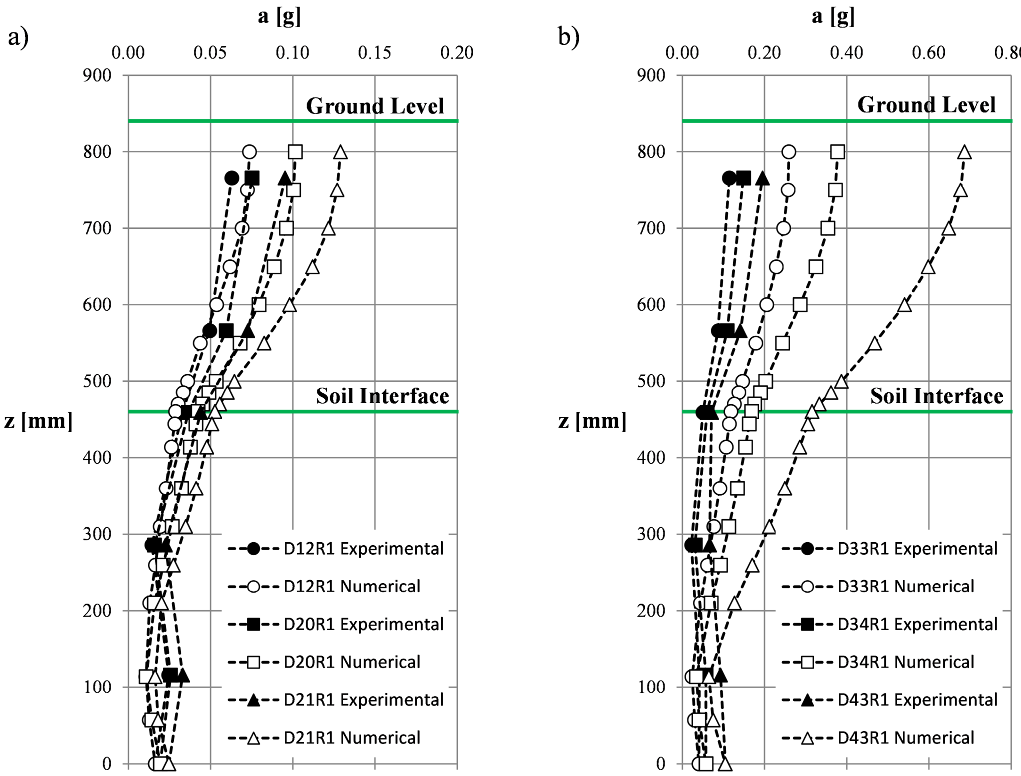



Figure 4. Comparison between experimental and numerical results for Phase II

## 2.2 Soil-structure interaction effects

In order to investigate the effects of soil-structure interaction on the natural period of vibration of the sample SDOF oscillators, fifteen tests were carried out on different system configurations. Such tests were aimed at assessing the effects on the global system response of following factors:

- amplitude of input excitation;
- stiffness and mass of the attached SDOF oscillators.

The superstructure considered consists of an aluminium column of 3mmx12mm rectangular cross section, 130mm long and 15gr mass. Different natural periods were specified by adding masses on the column top (always placed in a symmetrical way with respect to the column). Preliminary white noise tests were conducted in order to determine the "fixed base" frequency of the oscillator, by fixing it directly on the shaking table. The test results for the different oscillators are outlined in Table 6.

The response of the oscillator placed on the short-cap configuration (SC+SDOF) is examined hereafter. The aim is the evaluation of the period shifting of the whole system (soil, pile and superstructure). Additionally, white noise excitations were utilised for evaluating the influence of input motion amplitude on system response. The amplitude of such excitations varied between 0.02g and 0.09g, as listed in Table 7.

Firstly, transfer functions (TFs) between the oscillator and its base (or the top of the pile 5) and between the oscillator and the shaking table were computed. These TFs allow estimating the fundamental frequencies of the whole system and its sub-assemblage. Figure 5 displays the plots of such TFs for the input motion with PGA≈ 0.02g, computed with reference to the SDOF base (Figure 5a) and the shaking table (Figure 5b). The natural frequencies are close to the "fixed base" ones, as expected. The experimental outcomes confirm that the frequency decreases as the mass increases. The amplitude of the TFs relative to the shaking table is significantly higher (Figure 5b).

| Total added mass [g] | Added mass constituent parts | Fixed base frequency [Hz] |
|---|---|---|
| 75 | Mass-fixing arrangement and accelerometer | 38.0 |
| 125 | Mass-fixing arrangement and accelerometer + 50g | 30.5 |
| 175 | Mass-fixing arrangement and accelerometer + 2 x 50g | 26.5 |
| 275 | Mass-fixing arrangement and accelerometer + 4 x 50g | 20.5 |
| 475 | Mass-fixing arrangement and accelerometer + 8 x 50g | 15.0 |
| 975 | Mass-fixing arrangement and accelerometer + 2 x 50g + 4 x·200g | 10.0 |

Table 6. Results of tests carried out for identifying the fixed-base frequency of the different oscillators

| Application order | SIGNAL TYPE | CODE | FREQUENCY [Hz] | AMPLITUDE [g] |
|---|---|---|---|---|
| 1 | White noise | X1R1 | 0.1-100 | ~ 0.02 |
| 2 | White noise | X2R1 | 0.1-100 | ~ 0.04 |
| 3 | White noise | X3R1 | 0.1-100 | 0.07÷0.09 |

Table 7. Input motion selected for the tests on the SDOF system

In order to investigate the effects of SSPSI on SDOF response, the shifting of the SDOF fundamental frequencies (and periods) with respect to the SDOF fixed-base configuration has been evaluated. The values for three white noise excitations and different masses are summarized in Table 8.

| **mass** | **Transfer** | **a ~ 0.02g** | | | | **a ~ 0.04g** | | | | **a = (0.07÷0.09)g** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **[grams]** | **function** | **f [Hz]** | **$T_{SSI}$ [s]** | **ΔT [s]** | **ΔT [%]** | **f [Hz]** | **$T_{SSI}$ [s]** | **ΔT [s]** | **ΔT [%]** | **f [Hz]** | **$T_{SSI}$ [s]** | **ΔT [s]** | **ΔT [%]** |
| **125** | SDOF-S.T. | 29.2 | 0.034 | 0.001 | 4.539 | 28.996 | 0.034 | 0.002 | 5.187 | 29.002 | 0.034 | 0.002 | 5.167 |
| | SDOF-P.H. | 29.8 | 0.034 | 0.001 | 2.488 | 29.799 | 0.034 | 0.001 | 2.353 | 29.776 | 0.034 | 0.001 | 2.430 |
| **175** | SDOF-S.T. | 25.2 | 0.040 | 0.002 | 5.014 | 24.724 | 0.040 | 0.003 | 7.184 | 24.511 | 0.041 | 0.003 | 8.117 |
| | SDOF-P.H. | 25.0 | 0.040 | 0.002 | 6.195 | 25.117 | 0.040 | 0.002 | 5.507 | 25.167 | 0.040 | 0.002 | 5.295 |
| **275** | SDOF-S.T. | 20.4 | 0.049 | 0.000 | 0.540 | 20.379 | 0.049 | 0.000 | 0.596 | 20.238 | 0.049 | 0.001 | 1.294 |
| | SDOF-P.H. | 19.9 | 0.050 | 0.001 | 3.037 | 19.817 | 0.050 | 0.002 | 3.445 | 19.812 | 0.050 | 0.002 | 3.475 |
| **475** | SDOF-S.T. | 14.7 | 0.068 | 0.001 | 1.749 | 14.883 | 0.067 | 0.001 | 0.784 | 14.888 | 0.067 | 0.001 | 0.746 |
| | SDOF-P.H. | 14.5 | 0.069 | 0.002 | 3.323 | 14.557 | 0.069 | 0.002 | 3.024 | 14.473 | 0.069 | 0.002 | 3.619 |
| **975** | SDOF-S.T. | 10.0 | 0.100 | 0.000 | 0.000 | 10.060 | 0.099 | 0.000 | 0.000 | 10.043 | 0.100 | 0.000 | 0.000 |
| | SDOF-P.H. | 9.9 | 0.101 | 0.001 | 1.641 | 9.897 | 0.101 | 0.001 | 1.545 | 9.841 | 0.102 | 0.002 | 2.404 |

Table 8. Input Period shifting for the sample systems. Keys: S.T. shaking table; P.H. Pile head; $\Delta T=T_{SSI}-T_{fix}$; $\Delta T[\%]=(\Delta T/T_{fix})\times 100$

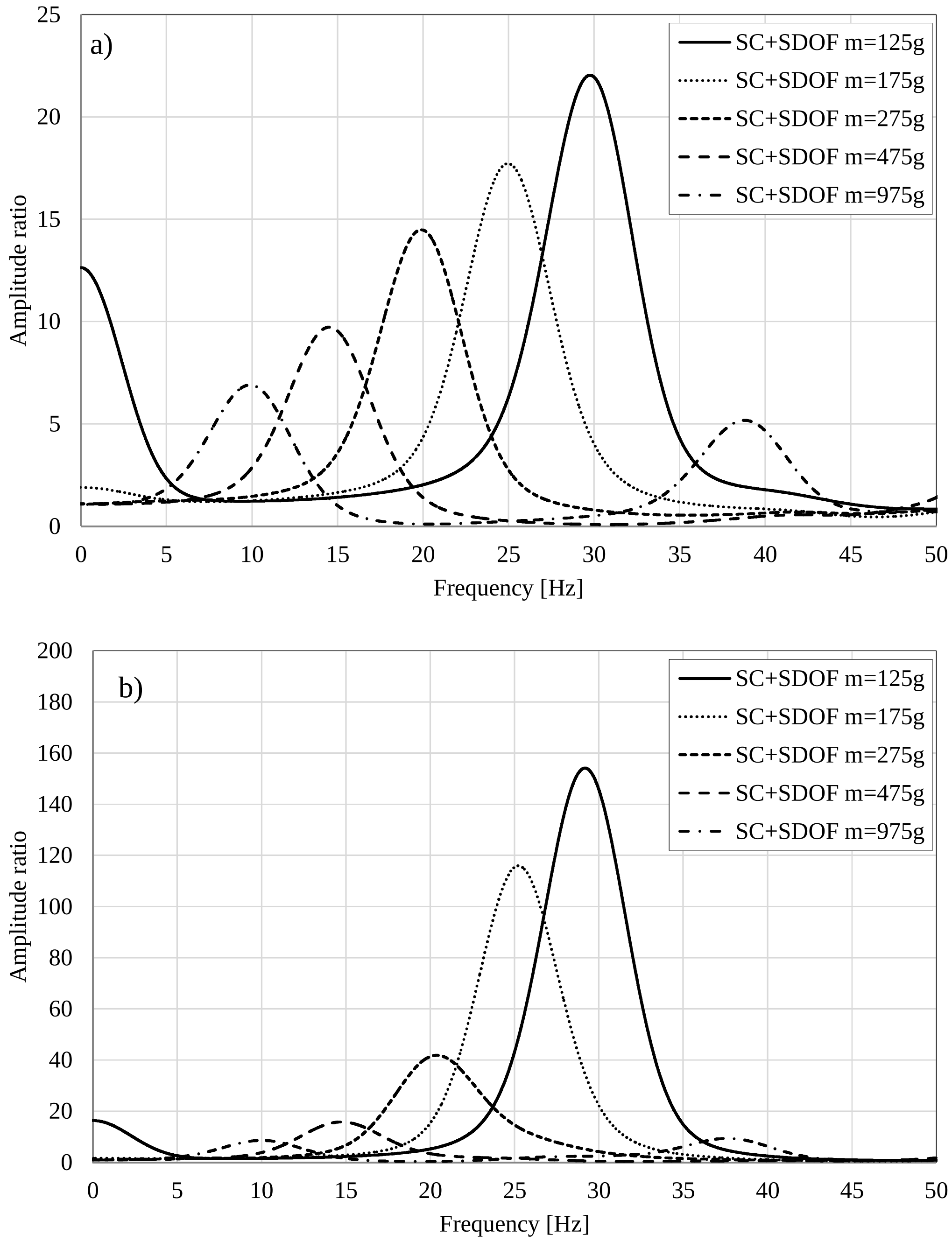



Figure 5. Transfer function between the oscillator and its base (a) and the oscillator and the shaking table (b) (white noise motion with PGA≈ 0.02g)

According to the fundamentals of the SSI theory, the ratio $T_{SSI}/T_{fix}$ does not vary with structural (SDOF) mass. This statement is corroborated by the experimental results shown in Figure 6, where the ratio $T_{SSI}/T_{fix}$ has been plotted against the mass of the SDOF for different system configurations (SC and FHP with SDOF on pile 4 or 5) and peak acceleration at the shaking table (a=0.021g and 0.046g). The assessment of the slight variability of the experimental data with respect to mass values is still under investigation. The results in Figure 6 also show that, at the model scale, period elongation due to SSI is modest, yet not insignificant.

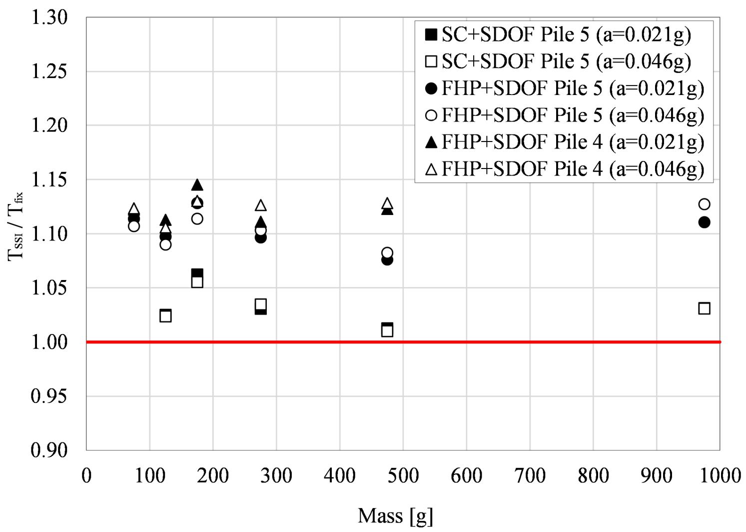



Figure 6. Ratio $T_{SSI}/T_{fix}$ against the mass of the SDOF for different system configuration and peak input acceleration

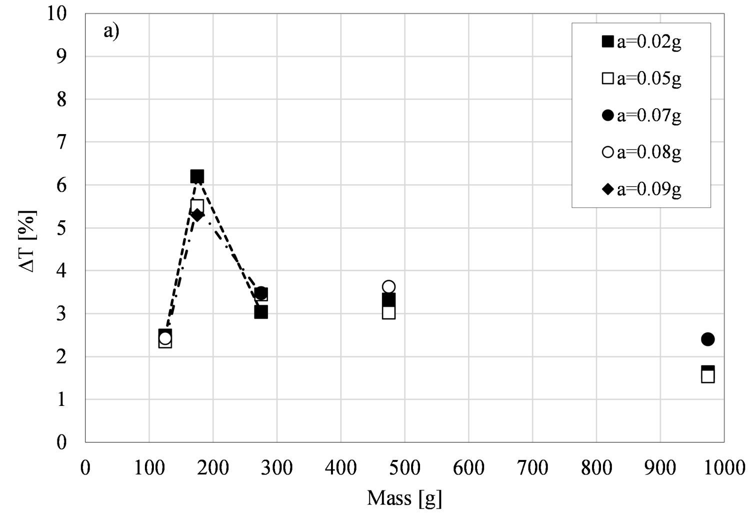
The period shift ΔT [%], expressed as a percentage of $T_{fix}$, is represented in Figure 7 against the mass of the SDOF. The plot provided in figure 7 shows a clear dependence on the SDOF mass. The maximum period shift ΔT [%] corresponds to the mass of 175grams, due to a resonance occurring between the fundamental frequencies of the SDOF ($f_{SDOF}$=26.5 Hz) and of the soil ($f_{soil}$=22÷28 Hz).

The sample tests show that the period shift ΔT [%] of the SDOFs with SSPSI varies between 1% and 8% at the model scale. Further analyses still on-going are investigating on SSPSI effects on full-scale systems.

## 3 CONCLUDING REMARKS

The present work has discussed the outcomes of a series of 1-g shaking table tests that were carried out to validate numerical models formulated for kinematic and inertial interaction effects on pile-supported systems. The results of the laboratory tests and numerical simulations conducted on well-calibrated models have indicated that:

- From a purely linear site response analyses, it is observed that for low values of accelerations there is a close match between measured and predicted values; However, as nonlinearity increases the outcomes of numerical simulations tend to diverge from test results, thus highlighting the need for a more suitable modelling of soil behaviour;
- The experimental outcomes indicate that the frequency of the single-degree-of-freedom (SDOF) system in the short cap configuration decreases as the mass increases. The amplitude of TFs relative to the shaking table is significantly higher than TFs relative to the base of the SDOF. This finding contradicts fundamental (linear) SSI theory and can thus be attributed to nonlinear soil effects near the pile head.



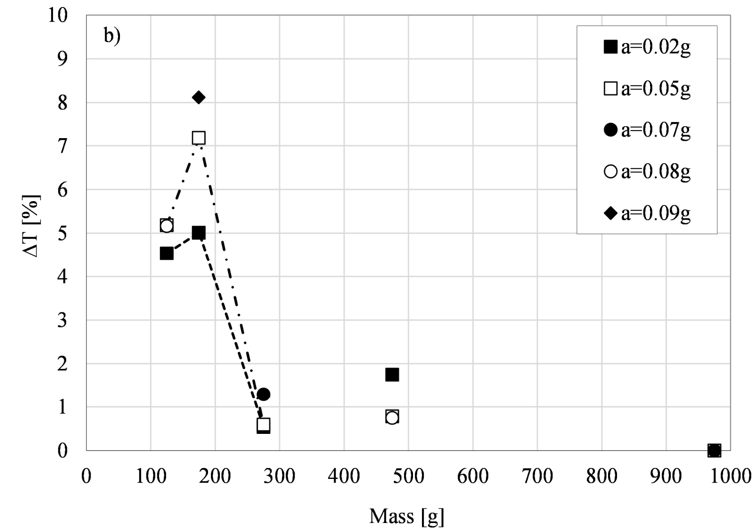




Figure 7. Period shift ΔT [%] vs. the SDOF mass, obtained by TFs between: a) SDOF and Pile Head; b) SDOF and Shaking Table

Further investigations are ongoing to derive the variation, if any, of the equivalent viscous structural damping of the SDOF systems with soilstructure-interaction effects. Design implications will be derived from the assessment of the prototype response of the single piles and group of piles, with or without caps.

## Acknowledgments

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