16th World Conference on Earthquake, 16WCEE 2017
Santiago Chile, January 9th to 13th 2017
Paper N° 4269 (Abstract ID)
Registration Code: S-C1463010453

EFFECTS OF SOIL-PILE-STRUCTURE INTERACTION ON SEISMIC RESPONSE OF SDOF STRUCTURES

M. G. Durante(1), L. Di Sarno(2), George Mylonakis(3), Colin A. Taylor(4), A. L. Simonelli(5)

(1) Post-Doctoral Research Scholar, Università degli Studi del Sannio, Department of Engineering, Benevento, mgdurante@unisannio.it
(2) Assistant Professor, Università degli Studi del Sannio , Department of Engineering, Benevento, Italy, ldisarno@unisannio.it
(3)Professor, Department of Civil Engineering, University of Bristol, Bristol, UK, g.mylonakis@bristol.ac.uk
(4)Professor, Department of Civil Engineering, University of Bristol, Bristol, UK, colin.taylor@bristol.ac.uk
(5) Associate Professor, Università degli Studi del Sannio, Department of Engineering, Benevento, Italy, alsimone@unisannio.it

Abstract

The interaction between soil, foundation and structure during earthquake shaking is a complex phenomenon in which several mechanisms are involved. Soil-structure interaction (SSI) is formed by two main mechanisms: kinematic and inertial interaction, involving wave scattering and impedance problems, respectively. Theoretical studies in the subject abound in the literature and show that the effects of SSI on the earthquake response of structures involve mainly an elongation in fundamental natural period and a change (usually an increase) in damping. Nonetheless, the experimental validations of such studies are still scarce. Such validations can be efficiently investigated with physical scaled model in 1-g or n-g devices. In the present paper the soil-pile-structure interaction (SPSI) is investigated by utilizing a set of data selected from a comprehensive experimental test program carried out using 1-g shaking table tests. The scaled model adopted in the tests comprises a group of five piles embedded in a bi-layer deposit with or without a single-degree-of-freedom oscillator mounted on the piles, with or without a rigid connection (cap) between them. The present work focused on the response of the scaled model when subjected to both harmonic input motions and the strong motion recorded at Tolmezzo Station during the 1976 Friuli (Italy) earthquake. The experimental outcomes are compared with some theoretical formulations from the literature. It is found that: *(i)* the SPSI effects are, as expected, more evident in the system without a stiff connection between the piles and *(ii)* the theoretical formulae are not able to predict in an accurate manner the above quantities, due to a variety of factors discussed in the paper.

Keywords: Soil-pile-structure interaction; shaking table tests; period elongation

1. Introduction

Soil-pile-structure interaction (SPSI) is a complex phenomenon which is usually split into two simultaneous, yet fundamentally different mechanisms: kinematic interaction (Fig. 1a) and inertial interaction (Fig. 1b).

The kinematic interaction stems from the tendency of the pile to deform in a different manner, mainly due to stiffness mismatch, compared to the surrounding soil. In the scientific community several analytical and numerical studies are available, focusing on the evaluation of this effect notably in correspondence to the interface between soil layers with different mechanical properties [1-4]. The inertial interaction is an additional contribution to the pile loading due to the oscillation of the superstructure.

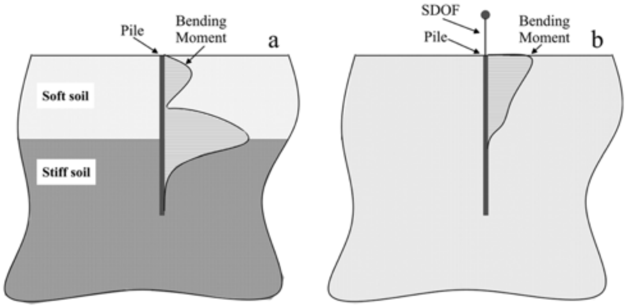

Fig. 1 - (a) Kinematic and (b) inertial bending moments (qualitative patterns) [20]

The combination of these two coexisting yet asynchronous phenomena is not trivial, but the main effects, from a structural point of view, can be summarized in the period elongation and the increase in damping ratio [5-9].

Modern building codes [10-13] provide simplified expressions mainly for the evaluation of the period elongation due to the soil-structure interaction, but the most useful findings are obtained from data collected from real structures or scaled ones, investigated by means of experimental campaigns in n-g or 1-g laboratory devices [14-20].

In this paper the SPSI is investigated by means of a series of high quality 1-g shaking table tests carried out at the Bristol Laboratory for Advanced Dynamics Engineering (BLADE) of the University of Bristol (UK), within the Framework of the Seismic Engineering Research Infrastructures for European Synergies (SERIES), which was funded by the 7th Programme of the European Commission. The scaled model is formed by a group of five piles embedded in a bi-layer deposit. The results presented in this work refer to the response of a Single-Degree-of-Freedom system (SDOF) with different pile configurations (with and without connection at the pile top). In order to better understand the dynamic response, both harmonic and seismic input motions are considered. The experimental results are compared with available theoretical formulations for period elongation and damping ratio.

2. Experimental campaign

The dynamic response of the scaled model shown in Fig. 2 has been investigated by means of the six-degree-of-freedom shaking table of the BLADE laboratory. The 1-g shaking table consist of 3 m x3 m cast-aluminum seismic platform powered eight hydraulic actuators. In order to reduce the influence of the soil container on the dynamic response of the model, an equivalent shear beam container (shear-stack) was adopted. The shear-stack is formed by eight rectangular aluminum rings alternated by rubber sections, and the resonant frequency of the empty container is sufficiently different from the values obtained for the container filled with soil material [21].

The sample model (Fig. 2) is formed by 5 aluminum piles embedded in a bi-layer deposit. Each pile was an alloy aluminum tube (thickness 0.71 mm), 750 mm long, with an external diameter of 22.23 mm. The model has been obtained scaling the prototype using well known scaling law [15] based on geometrical similarity, assuming the fundamental scale factor for length (n) equal to 37.5 and equal soil mass densities between model and prototype.

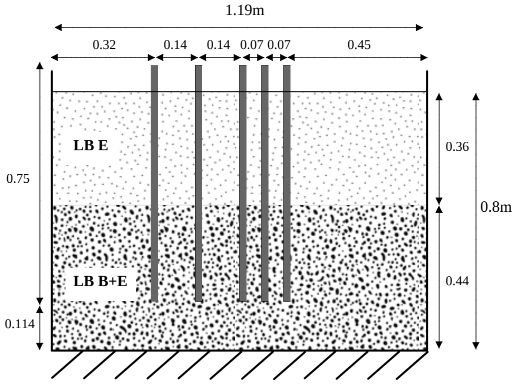

Fig. 2 – Physical model [19]

The bi-layer deposit was formed of dry Leighton Buzzard (LB) sand obtained by pluviation, with the top layer formed by LB sand fraction E and the bottom one by a mix of LB sand fraction B (85%) and fraction E (15%). The main mechanical characteristics of the soil deposit are reported in Table 1.

Table 1 – Soil layer properties [11]

Soil layers	Thickness H [mm]	Dry unit weight γ_d [kN/m^3]		Shear wave velocity V_s [m/s]		V_{s2}/V_{s1}	
		Phase I	Phase II	Phase I	Phase II	Phase I	Phase II
Top LB (E)	340	13.63	13.13	51	54	1.59	1.57
Bottom LB (E+B)	460	17.46	17.92	81	85		

In this work six different kinds of superstructures were considered. The superstructures were formed by the same aluminum column (cross section 3 mm x 12 mm, height 100 mm) with different masses added to its top, to achieve different dynamic properties. The experimental fixed-base frequency and damping ratio of each Single-Degree-of-Freedom (SDOF) are listed in Table 2.

Table 2 – Experimental frequency and damping of fixed-base oscillators

Mass [gr]	Frequency [Hz]	Damping ratio [%]
75	38.0	0.7
125	30.5	1.2
175	26.5	0.9
275	20.5	1.4
475	15.0	1.2
975	10.4	1.5

The whole model was monitored during the experimental campaign with a total of 18 accelerometers (among shaking table, shear-stack, free-field column, pile heads and SDOF), 32 strain-gauges for the evaluation of bending moments and axial forces (eight pairs at different elevations for piles 4 and 5), and eight linear variable displacement transducers in the vertical and horizontal directions (at piles 4 and 5 head).

3. Test results

Typical results of the above experimental campaign are analyzed in this section referring to both harmonic and earthquake input motions. In order to investigate the soil-pile-structure interaction, two different configurations are considered: *(i)* Free Head Pile with oscillator connected to the central pile (FHP+SDOF – Fig. 3a); *(ii)* Short

Cap connection among piles 4,5 and 3 with oscillator connected in correspondence of the central pile (SC+SDOF – Fig. 3b).

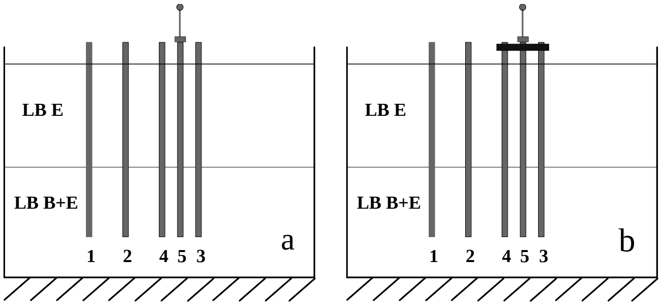

Fig. 3 – Model configuration considered: (a) FHP+SDOF; (b) SC+SDOF [20]

3.1 Sinedwell response

The harmonic input motion considered in this section is a sinusoidal wave characterized by a frequency of 25 Hz and input acceleration equal to 0.09g.

The effects of the SPSI are evaluated using several types of transfer function (TFs) computed from the ratio between the Fast Fourier Transform (FFT) of the accelerometer responses in different positions. More specifically three kinds of TFs are presented:

- the system response, computed as the ratio between the FFT of the accelerogram at the top of the oscillator and the free-field surface;
- the oscillator response, computed as the ratio between the FFT of the accelerogram at the top of the oscillator and its base, that corresponds to the top of the pile;
- the pile response, computed as the ratio between the FFT of the accelerogram at the top of the pile and the free-field surface.

Fig. 4 shows the TFs for the FHP+SDOF configuration and the fixed base frequency for each oscillator analyzed, compared with the TFs of the piles in the FHP configuration.

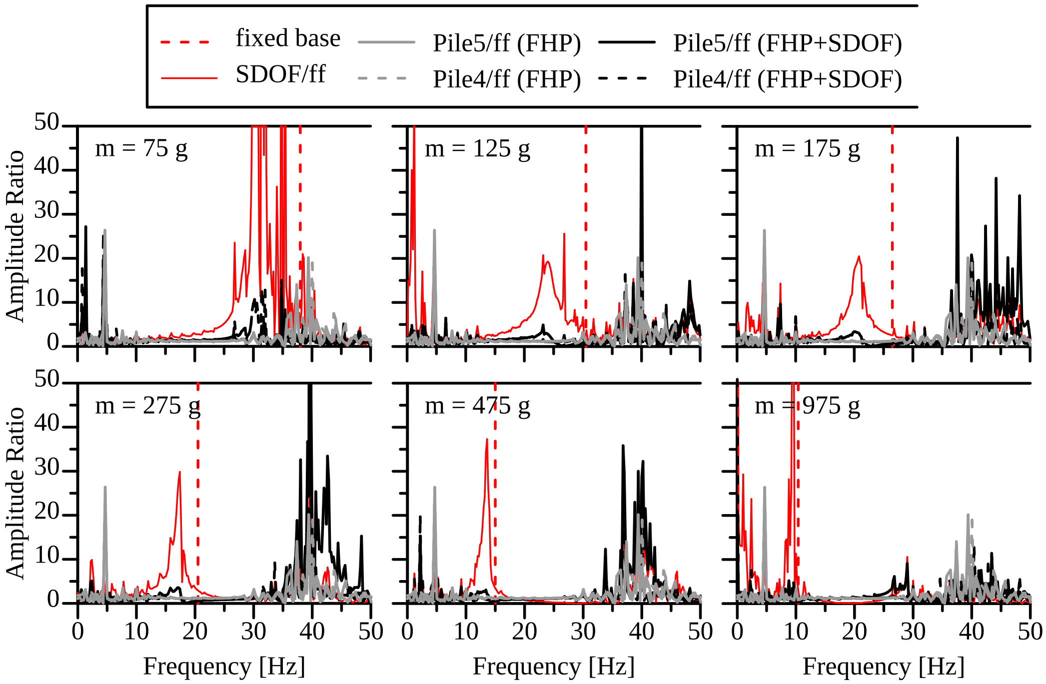

Fig. 4 – Transfer functions for the FHP+SDOF configuration

As expected, due to the different resonance conditions, each oscillator has a different response in terms of both period elongation (T_{SSI}/T_{fix}) and damping ratio (D_{SSI}/D_{fix}), plotted versus the fixed values obtained experimentally (Table 2). To better understand the SPSI in Fig. 5 the results versus the so-called "wave parameter" (Eq. 1), which can be considered an index of the relative stiffness between the structure and the soil [22], are plotted; the shear wave velocity (V_s) considered in the equation is the mean value of the top layer of the deposit in which lies the active length of the pile, evaluated experimentally:

$$\frac{1}{\sigma}=\frac{f_{fix}h}{V_s} \tag{1}$$

The increases of both period elongation and damping ratio with the wave parameters are clear in Fig. 5, and are in accordance with other experimental outcomes [23 - 24]. The damping ratio reported in Fig. 5 is the total one and seems not to be affected by the radiation damping, probably because of the absence of any constraints among the piles. It should be noted that the changes in vibrational characteristics indicated in Fig 5 are not supported by elastodynamic theory, as linear system behaviour should be independent of structural mass [13], and can be attributed to nonlinear effects in the soil due to increasing base shear and overturning moment with increasing mass. In addition, the datapoints indicated in the graphs cannot be connected to form a single curve, as they correspond to different values of the so-called mass ratio (γ) [14].

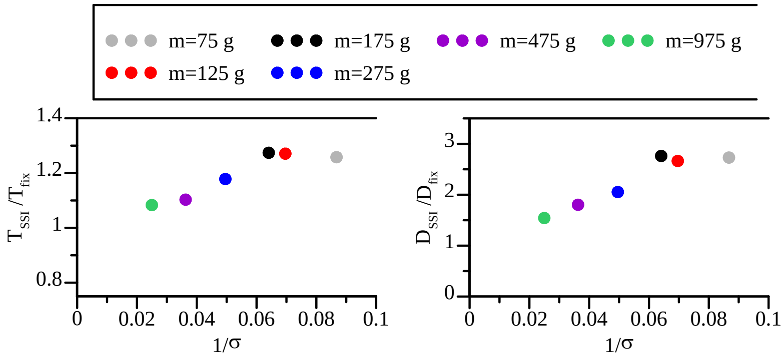

Fig. 5 –Dynamic response of the system: period elongation (left) and damping ratio (right) versus wave parameters for FHP + SDOF configuration

The comparison with the FHP configuration in Fig. 4 shows the effect of the inertial interaction in the kinematic response of the pile. First of all, there is no difference among the TFs of the pile 4 and 5 in the FHP configuration and the TF of pile 4 in the FHP+SDOF configuration. These three TFs are very different from the TF of pile 5 in the FHP+SDOF, due to the effect of the oscillator at the top of the pile, that causes an increase of the TF amplitude until the elongated frequency of the oscillator and a significant decrease right after this frequency. This behavior, which is related to the difference between the Foundation Input Motion (FIM) and the Free-Field Motion (FFM), has been observed in several previous works [25-26], and a series of numerical investigations [27] is aimed at investigating the influence of nonlinearity and ground motion incoherence on pile-soil kinematic interaction. In order to see more clearly the effect of the oscillator on pile response, the left side of Fig. 6 shows the smoothed TFs vs the dimensionless frequency (f/f_{fix}), defined as the ratio between the frequency (the x-axis of the TF) and the fixed base one of each SDOF considered (f_{fix}). Due to the period elongation (reported in the right side of Fig. 6) the decrease after the peak is always less than 1 and the amplitudes that the TFs reach increase with the increase of the period elongation.

Fig. 7 shows the TFs for the SC+SDOF configuration and the fixed base frequency for each oscillator analyzed. Unfortunately, it is not possible to compare the TFs of the piles in the short cap configuration (SC) with the ones in the SC+SDOF, due to problems in data acquisition during SC configuration tests.

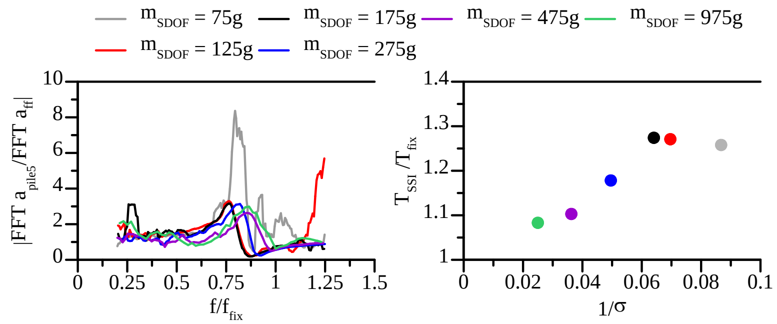

Fig. 6 – Smoothed TFs for pile response (left) and period elongation (right) for FHP+SDOF

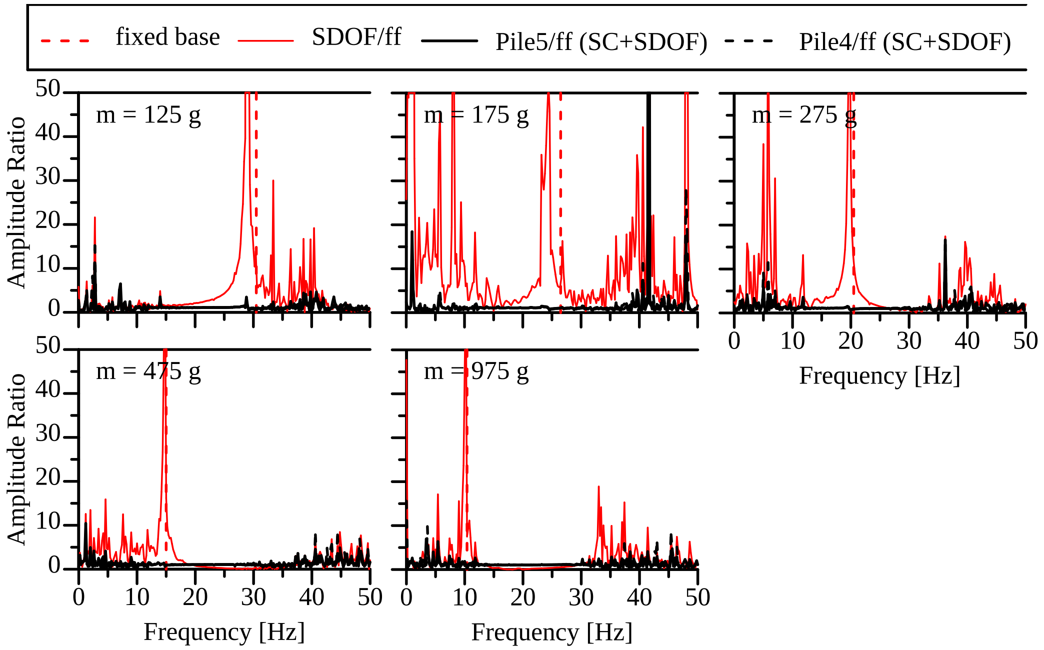

Fig. 7 – Transfer functions for the SC+SDOF configuration

As illustrated for the FHP+SDOF configuration, Fig. 8 shows the variation of the period elongation and the damping ratio with respect to the wave parameter. Due to the connection among piles, the period elongation is almost negligible for this configuration; as a matter of fact, the cap connection tends to replicate the fixed base condition. The effects of pile connection are clear also in terms of damping ratio response: the radiation damping generates, in the majority of the analyzed cases, a decrease of the damping ratio compared to the fixed one ($D_{SSI}/D_{fix} < 1$).

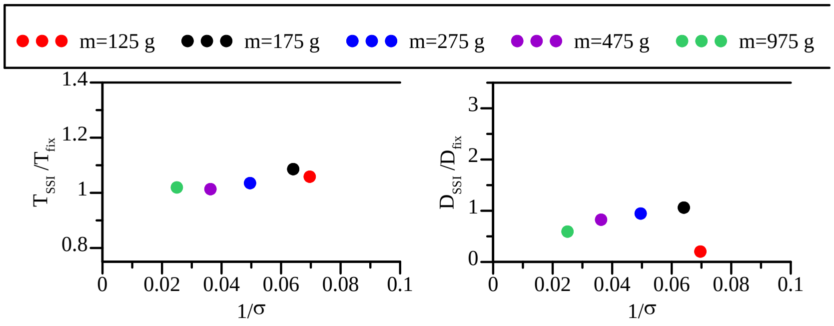

Fig. 8 – Dynamic response of the system: period elongation (left) and damping ratio (right) versus wave parameters for SC+SDOF configuration

Fig. 9 shows the smoothed TFs for pile 4 and 5 response versus the frequency divided by the fixed base frequency of each oscillator: the decrease in terms of amplitude (Fig. 9 – left) is almost one for all the cases, due to the negligible period elongation (Fig. 9 – right). Furthermore, the cap connection causes almost the same response in both the monitored piles.

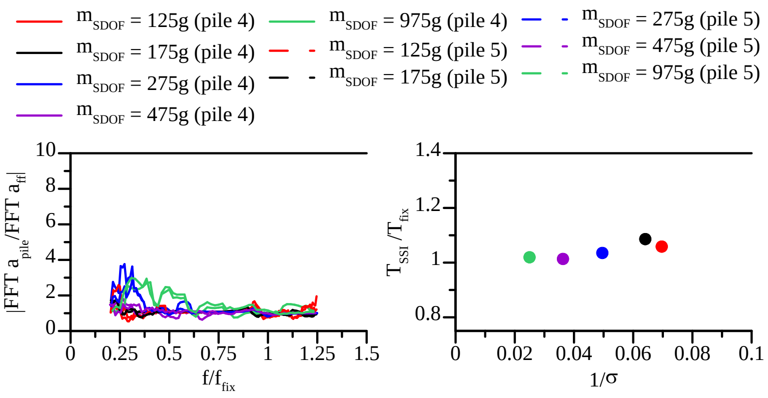

Fig. 9 – Smoothed TFs for pile response (left) and period elongation (right) for SC+SDOF

3.2 Earthquake response

The input motion considered in this section is the accelerogram recorded at the Tolmezzo Station (A270) during the 1976 Friuli (Italy) earthquake. A scaling factor (SF) of 12 has been adopted to ensure that the model is tested in the optimal frequencies range of the shaking table (i.e. 0-50 Hz). The maximum acceleration of this input is around 0.1g.

The oscillator considered in this section is characterized by an aluminum column 100 mm in length with a mass at the top equal to 150 gr. The fixed base characteristics of this oscillator, obtained experimentally, are f_{fix}= 27.02 Hz and D_{fix}= 0.59 %.

In Fig. 11 the TFs of the two configurations considered (FHP+SDOF dashed line, SC+SDOF continuous line) are reported, together with the fixed base frequency of the oscillator.

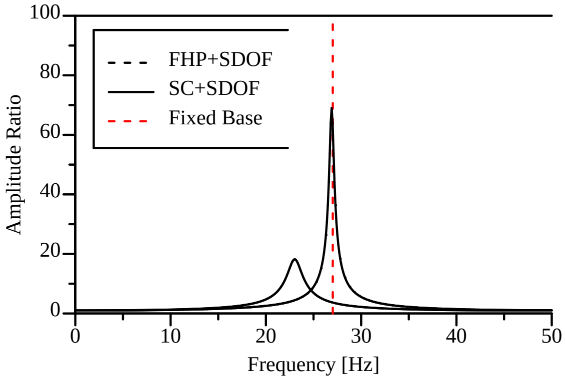

Fig. 10 – Transfer functions for FHP+SDOF and SC+SDOF configurations for the scaled Tolmezzo record (Friuli 1976, SF12)

As expected, the type of configuration generates a significant difference in the system response, in both period elongation and damping ratio (Table 3). The SC+SDOF configuration generates results very similar to the fixed base ones: this is more evident in terms of the period elongation than the damping ratio. In contrast, the effects of the SPSI are important in the FHP+SDOF configuration.

Table 3 – Seismic response of the system in FHP+SDOF and SC+SDOF configurations

	T_{SSI}/T_{fix}	D_{SSI}/D_{fix}
FHP+SDOF	1.170	5.247
SC+SDOF	1.004	1.255

3.3 Experimental vs Theoretical

In this section the experimental results in terms of period elongation are compared with several analytical solutions proposed in literature [28-32]. In order to have a general behavior of the system analyzed, additional results obtained in the same experimental campaign and published by the Authors are considered [20]. In particular, the latter results refer to White-Noise input motion, that excites the system with a range of frequency from 0 to 100 Hz with a constant amplitude.

Fig. 11 shows the comparison between the experimental results and the literature formulas for the cases considered. First of all, it is necessary to underline that the experimental data are slightly different for the three kinds of input motion, for both configurations: the harmonic input (i.e. White-Noise and Sinedwell) generates period elongation of the system bigger than the Earthquake one. Fig. 11 reports also the analytical formulae by Gazetas [31] and Kumar and Prakash [32] for the single pile response. The discrepancies observed are due to the elastodynamic theory that does not account for non linear behaviour of the soil, which is evident in the experimental tests. Other classical calculations were also carried out but they are not reported herein for sake of brevity [28-30].

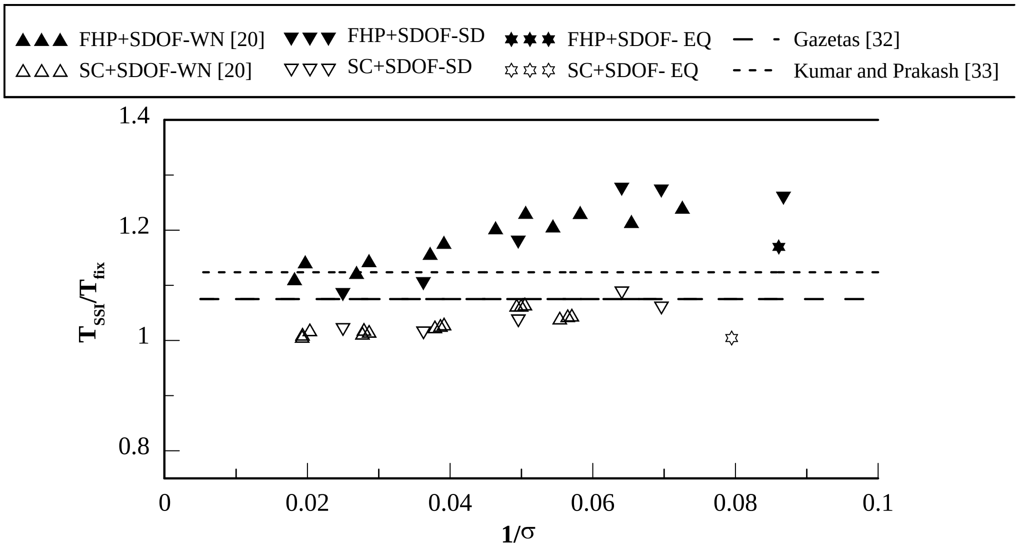

Fig. 11 – Experimental and theoretical period elongation for FHP+SDOF and SC+SDOF configurations for White-Noise (WN), Sinedwell (SD) and Earthquake (EQ) input motions

4. Conclusions

The paper reports on selected results from a comprehensive experimental campaign carried out at the Bristol Laboratory for Advanced Dynamic Engineering (BLADE) of the University of Bristol, within the Framework of the Seismic Engineering Research Infrastructures for European Synergies (SERIES).

In order to study the main effects of the Soil-Pile-Structure Interaction (SPSI), different pile-structure configurations in a bi-layer soil deposit were tested on a 3 m x 3 m 1-g shaking table device. In this study the main variables considered are the following:

- type of foundation: *(i)* single pile foundation, the so-called Free-Head-Pile (FHP) configuration; *(ii)* pile group configuration, the so-called Short-Cap (SC) configuration, where the group is formed by three piles;
- dynamic characteristics of the Single-Degree-Of-Freedom (SDOF) oscillator connected to the foundation, obtained using the same column but different masses at its top;
- input motion: harmonic excitations and scaled recorded accelerogram from the Friuli 1976 Earthquake (Italy).

The main goal of this paper has been to investigate how the above listed variables can modify the SPSI looking at the period elongation and the damping ratio. These properties have been evaluated using the fixed base properties which were obtained experimentally, fixing the oscillator directly on the shaking table.

The results in terms of both period elongation and damping ratio indicate that:

- for all the input motions considered, significantly higher SPSI effects are recorded for the oscillator with the single pile foundation (FHP+SDOF), as compared to those with the pile group foundation (SC+SDOF);
- for similar values of input amplitude, the harmonic excitations generate higher SPSI effects than the transient earthquake records in both configurations.

The comparison of the measured period elongation with the analytical formulae available in literature, based on linear theory, is problematic as, on one hand, the experimental results for different oscillation masses cannot form continuous curves (i.e. each dot refers to a different γ parameter) and are affected by nonlinear phenomena; on the other hand, the analytical formulae suffer from various issues including dimensionality and arbitrary treatment of coupling stiffness terms.

Furthermore, it has been found that the inertial interaction affects the pure kinematic response at the pile head in both the configurations, causing a decrease in Foundation Input Motion (FIM) that, beyond the natural frequency of the system, becomes dramatically lower than the Free-Field Motion (FFM).

5. Acknowledgements

The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007–2013) under grant agreement no. 227887, SERIES.

The financial support provided by the ReLUIS (TaskMT2) project funded by the Italian Civil Protection (Agreement No. AQDPC/ReLUIS 2014–2018) is also appreciated.

The authors would like to acknowledge all the contributors to the SERIES TA4 project, namely: Dr. Matthew Dietz and Dr. Luiza Dihoru from University of Bristol, Prof Subhamoy Bhattacharya from University of Surrey (formerly at University of Bristol), Dr Stefania Sica from University of Sannio, Prof. Gianni Dente, Dr. Roberto Cairo and Dr. Andrea Chidichimo from University of Calabria, Prof. Arezou Modaressi and Dr. Luìs A. Todo Bom from Ecole Centrale Paris, Prof. Amir M. Kaynia from Norwegian University of Science and Technology and Dr. George Anoyatis from University of California Irvine (formerly at University of Patras).

References

[1] Mylonakis G. (2001): Simplified model for seismic pile bending at soil layer interfaces. *Soils and Foundations*, 41:47–58.

[2] Nikolaou S, Mylonakis G, Gazetas G, Tazoh T. (2001): Kinematic pile bending during earthquakes: analysis and field measurements. *Géotechnique*, 51(5):425–440.

[3] Cairo R, Dente G. (2007): Kinematic interaction analysis of piles in layered soils. *14th European Conference on Soil Mechanics and Geotechnical Engineering, ISSMGE-ERTC 12 Workshop Geotechnical Aspects of EC8*, Madrid (Spain), Pàtron Editore, Bologna, cd-rom, paper n. 13.

[4] Padron LA, Aznarez JJ, Maero O. (2008): Dynamic analysis of piled foundations in stratified soils by a BEM-FEM model. *Soil Dynamics and Earthquake Engineering*, 5:333–346.

[5] Gazetas G, Fan K, Tazoh T, Shimizu K, Kavvadas M, Makris N. (1992): Seismic Pile-Group-Structure Interaction piles under dynamic loads. Geotech. Spec. Publ. No. 34 ASCE, p 56–93.

[6] Pender M. (1993): Seismic pile foundation design analysis. *Bulletin of the New Zealand National Society for Earthquake Engineering*, 26(1):49–160.

[7] Mylonakis G, Nikolaou A, Gazetas G. (1997): Soil-pile-bridge seismic interaction: kinematic and inertial effects. Part I: soft soil, *Earthquake engineering and structural dynamics*; 26:337–359.

[8] Gazetas G, Mylonakis G. (1998): Seismic soil–structure interaction: New evidence and emerging issues. *Geot. Earthq. Engng & Soil Dynamics III, Geo-Institute ASCE Conference*, Seattle, Dakoulas P, Yegian MK, Holtz RD (eds), Vol II, 1119–1174

[9] Chau KT, Shen CY, Guo X. (2009): Non-linear seismic soil-pile-structure interaction: shaking table tests and FEM analyses. *Soil Dynamics and Earthquake Engineering*, 29:300–310.

[10] Federal Emergency Management Agency (2000): Prestandard and Commentary for the Seismic Rehabilitation of Buildings, *FEMA Document No. 356*, Washington D.C., USA.

[11] Eurocode 8 (2004): Design of structures for earthquake resistance, Part 5: foundations, retaining structures and geotechnical aspects, *CEN E.C. for standardization*, Bruxelles.

[12] Federal Emergency Management Agency (2005): Improvement of Nonlinear static analysis procedures, *FEMA Document No. 440*, Washington, D.C. USA.

[13] NIST (2012): Soil–structure interaction for building structures. National Institute of Standards and Technology, U.S. Department of Commerce, Washington D.C. Project Technical Committee: Stewart JP (Chair), Crouse CB, Hutchinson T, Lizundia B, Naeim F, Ostadan F., *Report No. NIST GCR* 12-917-21.

[14] Meymand PJ (1998). Shaking table scale model tests of nonlinear soil-pile-superstructure interaction in soft clay. PhD Thesis, *University of California*, Berkeley.

[15] Muir Wood D, Crewe A, Taylor CA. (2002): Shaking table testing of geotechnical models. *IJPMG - International Journal of Physical Modelling in Geotechnics*, 1:01–13.

[16] Pitilakis D, Dietz M, Wood DM, Clouteau D, Modaressi A. (2008): Numerical simulation of dynamic soil–structure interaction in shaking table testing. *Soil Dynamics and Earthquake Engineering*, 28:453–467.

[17] Moccia F. (2009): Seismic soil pile interaction: experimental evidence. PhD Thesis, *Universita' degli Studi di Napoli Federico II*, Napoli.

[18] Chidichimo A, Cairo R, Dente G, Taylor C, Mylonakis G. 1-g experimental investigation of bi-layer soil response and kinematic pile bending. Soil Dyn Earthq Eng 2014; 67: 219–32.

[19] Durante MG. (2015): Experimental and numerical assessment of dynamic soil–pile–structure interaction. Ph.D. Thesis, *Universita' degli Studi di Napoli Federico II*, Napoli.

[20] Durante M. G., Di Sarno L., Taylor C. A., Mylonakis G., Simonelli A. L. (2016): Soil-pile-structure interaction: experimental outcomes from shaking table tests. *Earthquake Engineering and Structural Dynamics*, DOI: 10.1002/eqe.2694.

[21] Crewe AJ, Lings ML, Taylor CA, Yeung AK, Andrighetto R. (1995): Development of a large flexible shear stack for testing dry sand and simple direct foundations on a shaking table. *Elnashai, editor. European seismic design practice.* Rotterdam: Balkema.

[22] Veletsos AS. (1977): Dynamics of structure-foundation systems. *Structural and geotechnical mechanics*. Englewood Cliffs, NJ: Prentice-Hall; 333–61.

[23] Ciampoli M, Pinto PE. (1995): Effects of soils–structure interaction on inelastic seismic response of bridge piers. *Journal of Structural Engineering, ASCE*; 121(5):806–814.

[24] Stewart JP, Fenves GL, Seed RB. (1999): Seismic soil–structure interaction in buildings. I: Analytical methods. *Geotechnical and Geological Engineering ASCE*; 125(1):26–37.

[25] Kim S., and Stewart JP.(2003): Kinematic soil-structure interaction from strong motion recordings . *J. Geotech. And Geoenviron. Eng.*, 129 (4), 323-335.

[26] Givens MJ, Mikami A, Kashima T, and Stewart JP. (2012): Kinematic Soil-Structure Interaction Effects from Building and Free-Field Seismic Arrays in Japan. *Proc. 9th International Conf. on Urban Earthquake Engin./4th Asia Conf. on Earthquake Eng*, Tokyo Institute of Technology, Tokyo, Japan.

[27] Turner BJ, Brandenberg SJ, Stewart JP (2015): Influence of Kinematic SSI on Foundation Input Motions for Pile-Supported Bridges. *6th International Conference on Earthquake Geotechnical Engineering*, Christchurch, New Zealand.

[28] Jennings PC, Bielak J. (1973): Dynamics of building–soil interaction. *Bull SeismolSoc Am*, 63(1):9–48.

[29] Veletsos AS, Nair VVD. (1975): Seismic interaction of structures on hysteretic foundations. *J StructDiv*, 101(1): 109–29.

[30] Wolf JP. (1985): Soil–structure interaction. New Jersey, USA: *Prentice Hall*.

[31] Gazetas G. (1996): Soil dynamics and earthquake engineering –case studies. Athens: *Simeon publications*.

[32] Kumar S, Prakash S. (2004): Estimation of fundamental period for structures supported on pile foundations. *Geo-tech Geol Eng*, 22: 375–89.