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NUMERICAL SIMULATION OF SOIL-STRUCTURE INTERACTION: A PARAMETRIC STUDY

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Abstract. *Soil Structure Interaction (SSI) is a complex phenomenon that may radically change the earthquake response of structural systems, as consequence of the variation of the natural frequency and the damping ratio. One of the most effective means for evaluating SSI is the use of physical models. In this study the physical model considered is formed by an oscillator founded on a group of piles embedded in a horizontally layered deposit of dry sand. The benchmark experimental campaign was carried out at the Bristol Laboratory for Advanced Dynamics Engineering (BLADE) at the University of Bristol (UK), financed by the Seismic Engineering Research Infrastructures for European Synergies (SERIES). An accurate parametric numerical study is performed and the results are discussed. The study investigates the effects of the dynamic properties of the oscillator on the period elongation and piles response. By means of advanced numerical analyses the outcomes of the present work provide insights into the quantitative evaluation of period elongation and the strength of inertial contribute to the bending moment at the pile head, when the system approaches resonance conditions.*

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1 INTRODUCTION

The complex interaction between soil, foundation and superstructure is usually called Soil-Structure-Interaction (SSI). In dynamic conditions the effects of such interaction may cause significant variations of the system response due to the modification of dynamic properties of both structure and soil as a consequence of the shaking. The main effects of SSI on deep foundations include: (*i*) kinematic bending applied along the piles – even in the absence of a superstructure; (*ii*) the variation between the free-field ground motion and the motion at the pile top, that is at the base of the superstructure. From a structural point of view, SSI causes mainly period elongation and variation of the damping ratio.

An effective way for evaluating SSI is the use of earthquake simulator for testing physical models, and the employment of such results for the validation of numerical models. In this paper the numerical model adopted has been validated by means of 1-g shaking table results from and experimental campaign carried out at the Bristol Laboratory for Advanced Dynamics Engineering (BLADE) at the University of Bristol (UK). This experimental effort was funded by the Seismic Engineering Research Infrastructures for European Synergies (SERIES). In order to investigate the effects of the oscillator properties on the SSI, a parametric analysis has been carried out. The inputs considered have been selected from the recent 2016 and 2017 Central Italy sequence and scaled in frequency at the model size. The configuration considered in the parametric study is formed by an oscillator connected to the central pile. The outcomes of the numerical simulations are presented in terms of period elongation, maximum relative displacement for the oscillator and bending moments for the pile connected to the oscillator and the neighboring pile. The parametric study shows that the resonance of the system soil-foundation, oscillator and input drives the response of all the component of the system.

2 PHYSICAL MODEL

The physical model considered in this work is formed by a Single-Degree-Of-Freedom (SDOF) founded on a pile embedded in a bi-layer deposit. This configuration has been selected among others available from an experimental shaking-table campaign carried out at 3mx3m 1-g shaking table of the Bristol Laboratory for Advanced Dynamics Engineering (BLADE) at the University of Bristol (UK) [1].

2.1 Experimental setup

The physical model (Figure 1) was formed by a group of five piles embedded in a bi-layer of dry Leighton Buzzard (LB) sand fraction E (D_r = 28%, γ_d = 13.63 kN/m^3) for the top layer and a mix of 85% of fraction B and 15% of fraction E (D_r = 41%, γ_d = 17.46 kN/m^3) for the bottom one. The initial stiffness contrast (G_{bottom}/G_{top}), computed experimentally [2], was equal to 3. Piles were formed by an alloy aluminum tube (E = 7e10 Pa) with thickness t = 0.71 mm, outer diameter D = 22.23 mm and length L = 750 mm. The response of the model was monitored using accelerometers, Linear Variable Displacement Transformer (LVDT) and strain gauges. More details about the experimental campaign can be found in Durante et al. [3].

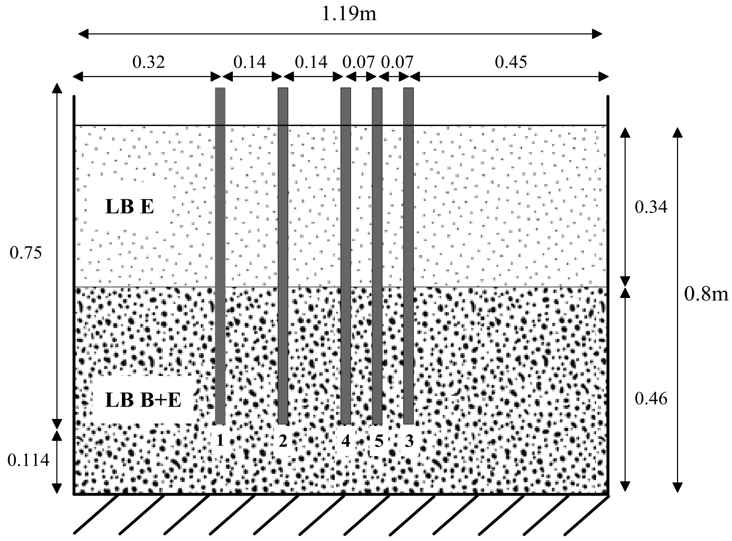

Figure 1: Model details (after Durante et al., 2016)

2.2 Numerical model

Based on the physical model described in the previous section, a numerical model has been developed and implemented in the finite difference element code FLAC2D v.5 [4]. In such numerical model (Figure 2), soil deposit is modeled using a user-defined hysteretic Ramberg-Osgood constitutive model [5]. The two model parameters of the model are obtained fitting the model response with experimental Vucetic and Dobry *G(γ)* and *D(γ)* curves for zero plasticity index [6]. The structural elements are modeled by means of pile (for the foundation) and beam elements (for all the SDOF components) implemented in FLAC2D. Pile elements interact with the soil by means of non-linear normal and shear coupling springs. The normal springs are defined using the Georgiadis et al. [7] analytical method, while the shear springs properties are obtained from the soils properties [4]. More details about the numerical model and its validation against the shaking table results can be found in [8].

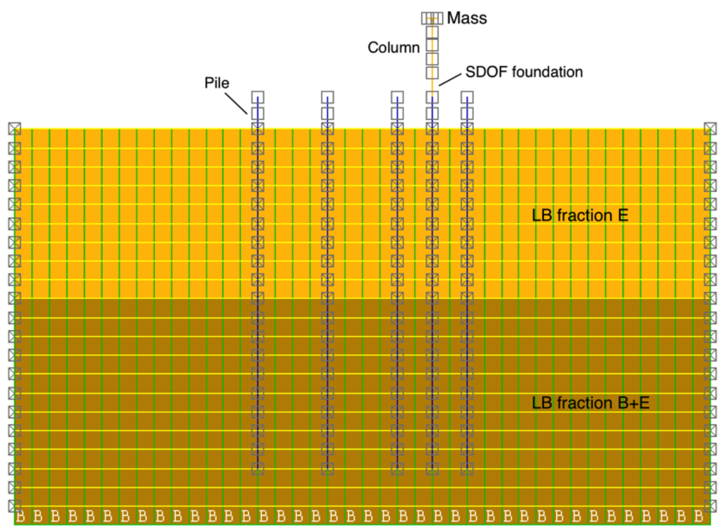

Figure 2: Numerical model (after Durante et al. 2015 [8])

2.3 Parametric analysis

In order to investigate the effects of the dynamic properties of the oscillator on the period elongation and on piles response, a parametric study has been performed. In do doing, two different sections have been considered for the column (SEC1 and SEC2) and seven different masses for a total of eight different oscillators (Table 1). The oscillators are connected to the central pile (Pile 5, Figure 1) and subjected to three scaled ground motion records (Figure 3, Table 2). The latter strong motion records were selected from the recent seismic sequence of Central Italy earthquakes (e.g. [9] among others]. The oscillators have been carefully selected so that the range of variation of the wave parameter ($1/\sigma = f_{fix} \cdot h/V_s$ [10]) is 0.01 – 0.6. The latter mechanical parameter can be considered as a synthetic index of the structure and soil relative stiffness, in which f_{fix} is the theoretical natural frequency of the fixed base oscillator, h is the height of the column and V_s is the shear wave velocity of the deposit in the active length of the pile. It should be noted that SEC1 was assumed equal to the actual section adopted for the oscillators in the experimental campaign. The Scaling Factor (SF) for the ground motions is assumed equal to 12, in accordance with the scaling law adopted in the experimental campaign [11].

	Total added mass [g]
SEC1 (3x12mm, h=100mm, E=7e10Pa)	600
	150
	50
SEC2 (20x20mm, h=50mm, E=7e10Pa)	1300
	550
	320
	200
	150

Table 1: Oscillator details

ID	Event	Magnitude	PGA [g]
NRC	24 August 2016 (Norcia Station)	6.1	0.37
CNE	30 October 2016 (Castel Sant’Angelo Station)	6.5	0.29
AQF	18 January 2017 (L’Aquila –V. Aterno –Ferriera Station)	5.5	0.13

Table 2: Ground motions adopted

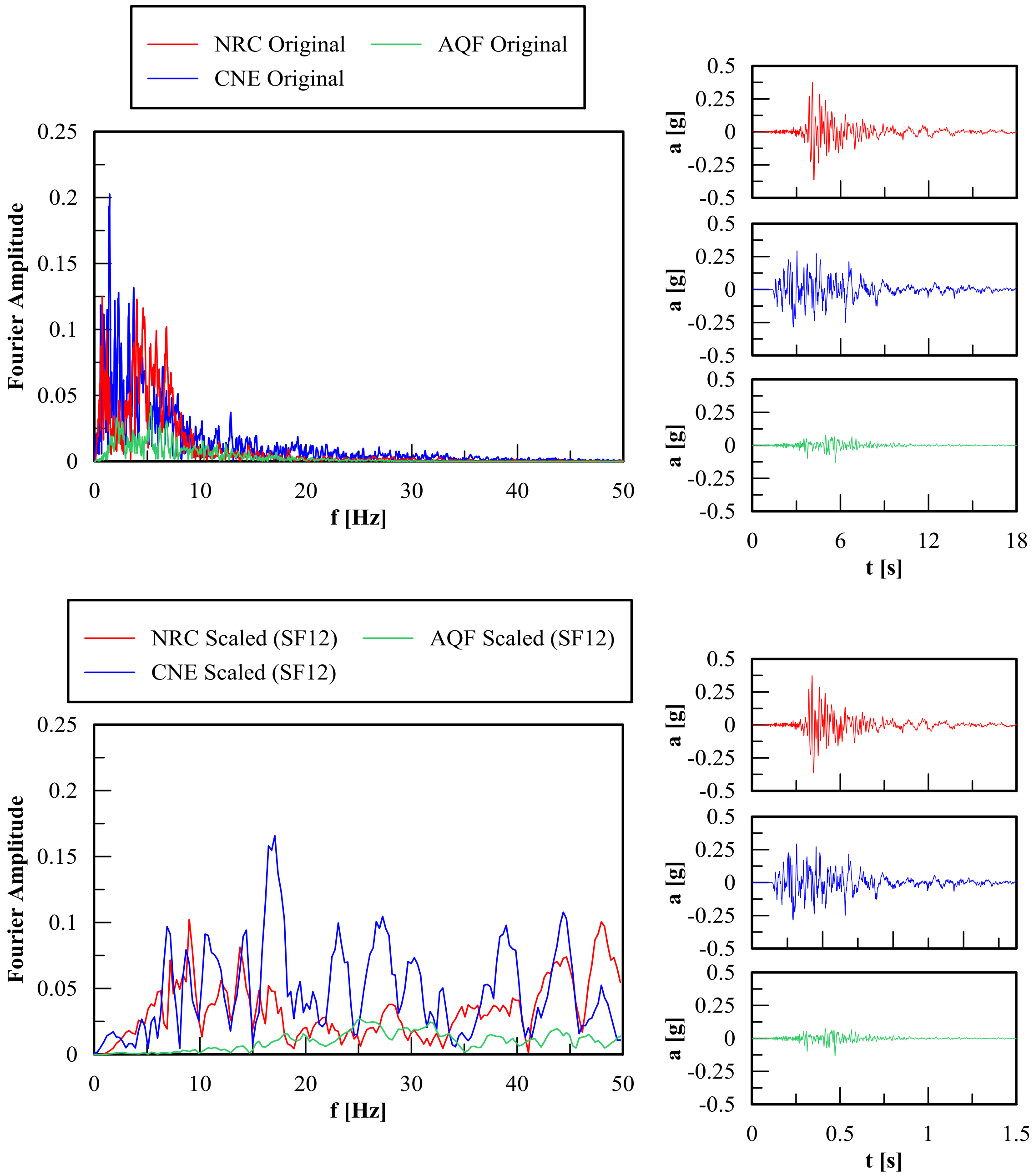

Figure 3: Original and scaled input adopted (FFTs and time series)

3 MAIN RESULTS

The main results obtained from the parametric analyses are discussed. In the following sections the SSI effects are reported in terms of period elongation and piles response.

3.1 Soil-Structure-Interaction effects

In this work, the elongated period of the oscillator (T_{SSI}) is obtained from the Transfer Functions (TFs) computed between the displacements recorded at the top of the oscillator and the one on the free-field surface. The wave parameter is computed considering the shear wave velocity that corresponds to the level of deformation for the ground motion considered.

The variation of the period elongation (T_{SSI}/T_{fix}) with the wave parameter are reported in Figure 4. As expected, the increasing of the period elongation is proportional to the wave parameter with a linear variation. It should be noted that it is possible to fit the data using two different linear equations, one for each group of oscillator considered in this study (SEC1 and SEC2, Table 1). The linear equation for SEC1 is the same that was obtained experimentally in [3], while the equation for SEC2 is characterized by the same slope but different constant term. This outcome suggests that, if it is assumed a linear trend between T_{SSI}/T_{fix} and $1/\sigma$, the slope of the equation is affected by the soil-foundation system, while the constant term is influenced by the column characteristics. This aspect is still under investigation and it will further discussed in future publications.

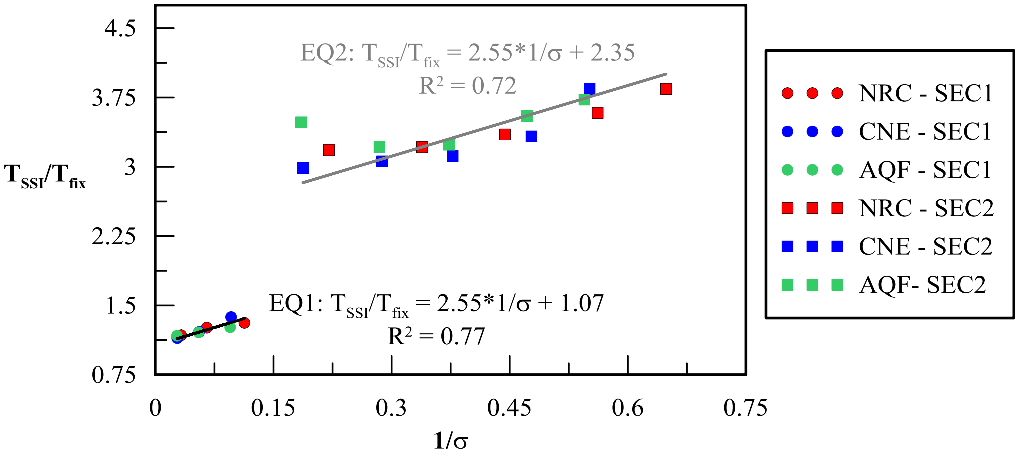

Figure 4: Period elongation versus wave parameter

Figure 5 shows the variation of the maximum relative displacement of the oscillator, computed as the difference in the time domain between the response at the top and the base of the oscillator, with the wave parameter. The relative displacement increases with the wave parameter with a different slope for each input. The strong motion that generates the most rapid increasing of the relative displacement with the wave parameter is CNE, which possesses the intermediate value of PGA. The observed behavior is related to the frequency content of the input (Figure 3): the high intensity around the soil deposit frequency (around 30 Hz) induces effects of resonance that affect the oscillator response.

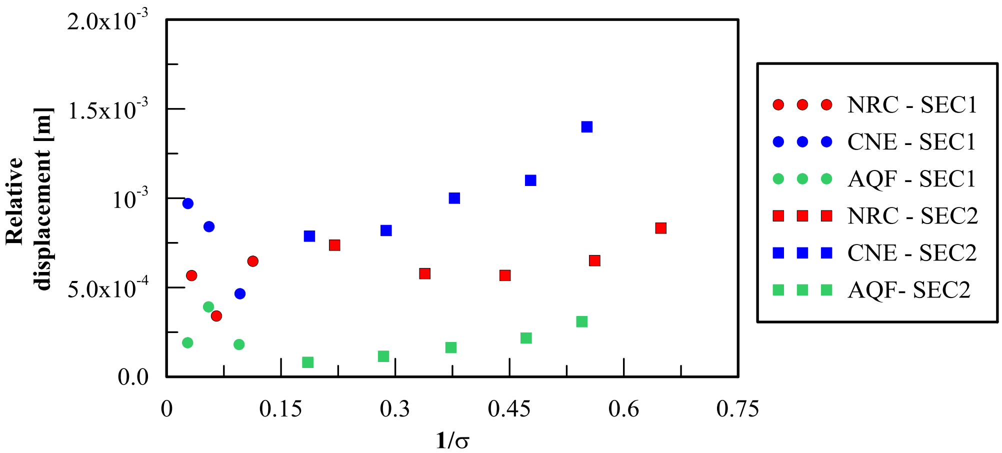

Figure 5: Oscillator elative displacement versus wave parameter

3.2 Geotechnical response

The effects of the SSI on piles response are presented in this section with reference to the pile directly connected to the oscillator (Pile 5, Figure 1) and the lateral pile not connected to the oscillator (Pile 4, Figure 1) but within the area of influence of pile 5 (the ratio between the spacing among the piles for the small group (s) and the pile diameter (D) is around 3).

Soil response in the free-field condition for all the configurations is reported in Figure 6 in terms of absolute maximum acceleration along the depth. The soil response is function only of the input considered and so the kinematic interaction on the piles is not changing with the oscillator.

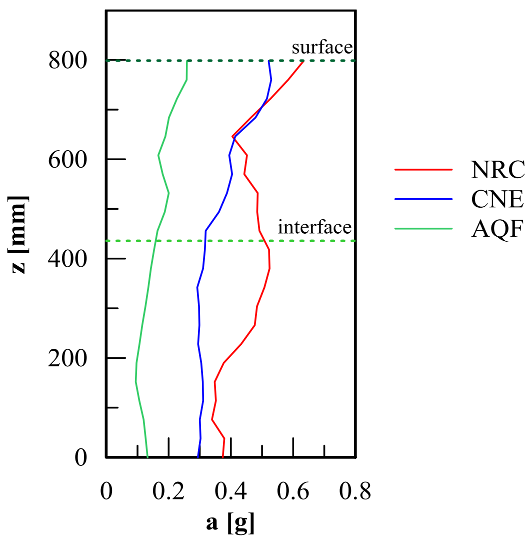

Figure 6: Envelope of absolute acceleration versus depth for the selected ground motions

Figure 7 shows the envelope of the absolute bending moments along depth for Piles 4 and 5 for the configuration considered together with the pure piles kinematic response (Free Head Pile configuration without oscillator – FHP). Figure 7a shows that despite Pile 4 is not connected to the oscillator, its response is changing with the configuration considered, due to the short distance to the oscillator (s/D=3). As a result, Pile 4 experiences either an increasing or decreasing of the response respect to the pure kinematic response (FHP response) depending to the oscillator considered. This phenomenon is related to the complex combination of resonance effects with soil non-linearity and for this reason it is not trivial to provide a general rule able to predict such response. This aspect requires further investigations. However, it is worth noticing that in both piles analyzed the response after the pile active length (that falls in the first layer of the deposit) results not affected by the inertial interaction at the pile head.

Figures 8 and 9 show the envelope of the absolute bending moments along depth for Piles 4 and 5 for the configuration considered together with the pure piles kinematic response for the records CNE and AQF, respectively. When considering CNE, the response of Pile 4 (Figure 8a) seems to be affected by the inertial effects of the oscillator only in the top part of it, but it is not able to affect the kinematic response at the interface between the two layers as it happens for the motion AQF (Figure 9a). The response of Pile 5 (Figures 7b, 8b and 9b) shows that: (*i*) the inertial contribution to the pile response is dissipated at different depths for the different motion but always within the first layer; and (*ii*) the oscillator that generates higher inertial effects is different for each ground motion because of the combination between the dynamic properties of oscillators and ground motions.

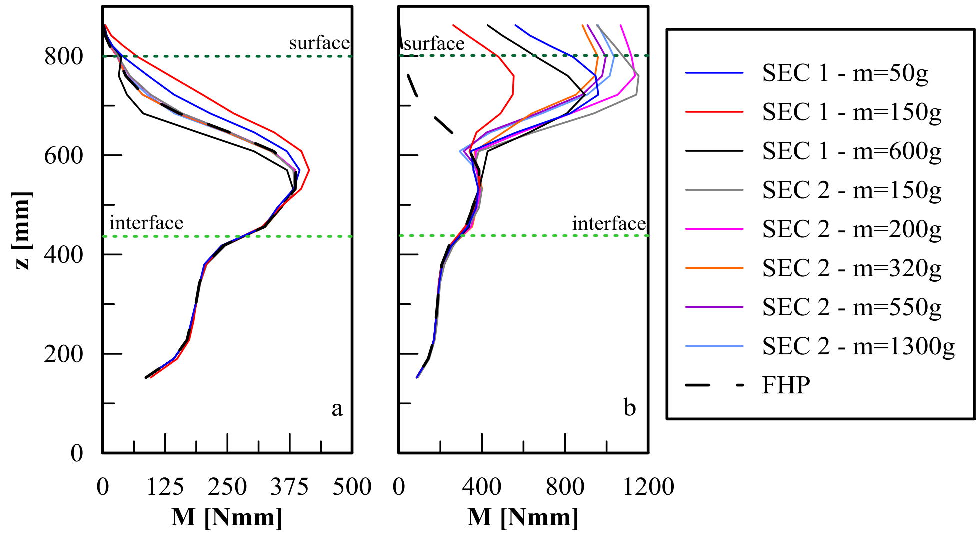

Figure 7: Envelope of bending moment along Piles 4 (a) and 5 (b) for NRC ground motion

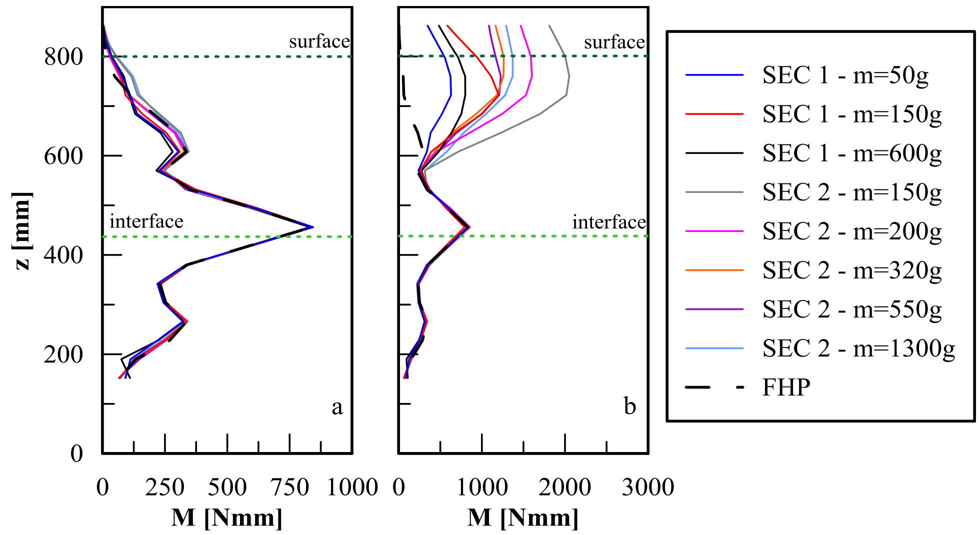

Figure 8: Envelope of bending moment along Piles 4 (a) and 5 (b) for CNE ground motion

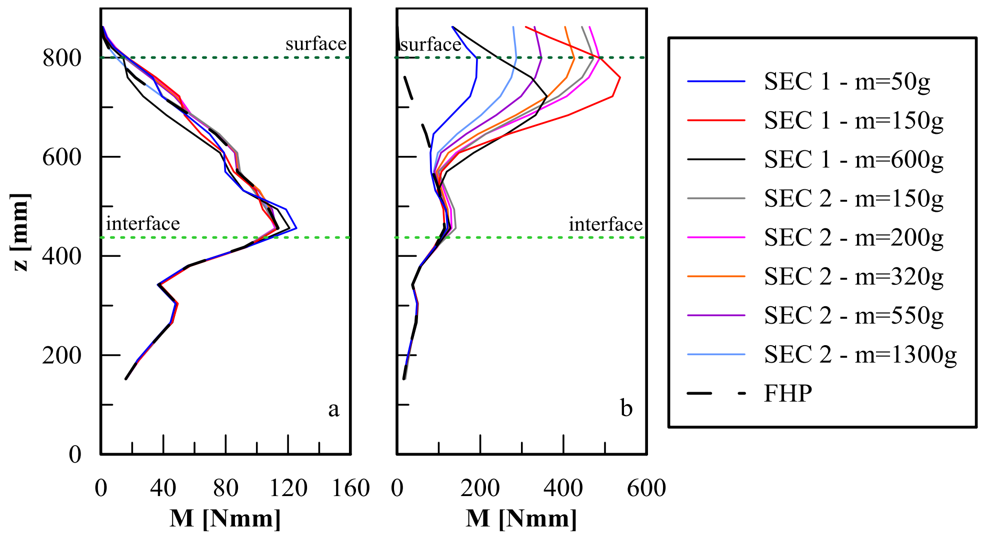

Figure 9: Envelope of bending moment along Piles 4 (a) and 5 (b) for AQF ground motion

4 CONCLUSIONS

A parametric analysis was performed by means of an advance two-dimensional model in the finite difference element code FLAC2D. The numerical model was based on a physical model tested on the shaking table of the BLADE laboratory at the University of Bristol. The physical model was formed by a group of five piles embedded in a bi-layer with several oscillators connected to the central pile. The numerical model accounts for hysteretic constitutive model for the soil and non linear connection between piles and soil. Three different scaled ground motion from the recent central Italy earthquake sequence were selected as input in the numerical model. The main outcomes of this work are:

- The numerical results of the Soil-Structure-Interaction in terms of T_{SSI}/T_{fix} and $1/\sigma$ are in good agreement with the experimental results;
- For the evaluation of the Soil-Structure-Interaction, the relation between T_{SSI}/T_{fix} and $1/\sigma$ can be considered linear for each group of section considered. The equations obtained from the fitting of the numerical results show that the slope coefficient of the equation is affected by the soil-foundation system, while the constant term is influenced by the column characteristics;
- The relative displacement of the oscillator increases with the wave parameter with a different slope for each ground motion, with the maximum response for the input with a significant frequency content around the natural frequency of the deposit;
- For Pile 4 the comparison between the FHP configuration with the configuration with the oscillator shows that the inertial effect affects its response for a depth that is related to the ground motion considered but always within the active length of the pile (first layer);
- For Pile 5 the inertial effects caused by the oscillators are dissipated at different depths for each ground motion (within the first layer) and the resonance mechanisms activated for each test generates different responses in terms of bending moment at the pile head.

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