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ABSTRACT

During earthquakes seismic wave crossing through soft soil can lead to significant curvatures on pile foundations, which in turn lead to significant bending moments. These bending moments are commonly named “kinematic bending moments”, to be distinguished from the “inertial bending moments” due to horizontal forces transferred from superstructures to pile heads. Approaches to carefully evaluate inertial bending moments have been recently developed world-wide; but the evaluation of the kinematic bending moments is still questionable. In this paper a 3D soil-pile FEM system is analysed. The system is subjected to seismic input motions, applied at the base of the system, which represents the conventional bedrock. The FEM analyses lead to the evaluation of the kinematic bending moment distribution along the pile. The pile is embedded in two soil layers, characterised by three different stiffness ratio V_{s2}/V_{s1}. Moreover, five different seismic input motions recorded in Europe in the last 30 years are considered.

INTRODUCTION

The seismic response of pile foundation is the result of a complex soil-pile-superstructure interaction. The analysis of this interaction is more difficult considering the non-linear phenomena occurring in the surrounding soil. The different layers of soil, subjected to seismic waves coming from the bedrock, drag in their motion the piles and the superstructure. Moreover, in comparison with the free-filed condition, the presence of piles change the seismic motion that involves the superstructure.

During the passage of seismic waves in soil, in the pile are generated stress due to deformation of the soil: the
moments caused by this type of interaction are called kinematic moments.

The oscillation of the superstructure, prompted by the seismic motion, causes the development of inertia forces, which in turn determine stresses and deformations in the foundation and soil, with the generation of additional waves at the soil-pile contact. In this case we talk about inertial interaction. The bending moments that are generated in the pile foundation due to the inertia forces coming from the superstructure are called inertial moments.

Until a few years ago, kinematic interaction was neglected and the seismic design of pile foundations and superstructures was based only on the inertial interaction. However, recent studies (Mylonakis [1999]; Maiorano & Aversa [2006]; Cairo & Dente [2007]) have demonstrated the great importance in some cases of kinematic interaction, especially when a pile is embedded in two layers of soil with significantly different stiffnesses. Recently, the EC8 [2003] and the new Italian Technical Regulations, D.M. 14 January 2008, prescribe to take into account both types of interactions for particular situations related to: the soil type, the seismicity of the area, and the importance of structure. The relative importance of these two types of interaction (kinematic and inertial) depends on the characteristics of the: structure, foundation, soil and nature of the seismic waves (AGI [2005]; Maiorano & Aversa [2006] Di Laora et al. [2009]).

Experimental and numerical studies have showed that kinematic interaction assumes considerable importance in case of soft soil, high contrast of stiffness and very rigid piles.

For the sake of computational simplicity, it is preferable to separate the two interaction phenomena and to obtain the response of the soil-pile-superstructure system from the overlap of their single responses. This approach is commonly named “method of substructures” (Gazetas & Mylonakis [1998]). The present paper is devoted to kinematic interaction.

The kinematic interaction has been studied with various models, such as: i) simplified models with the hypothesis that the pile follows the soil motion of in free-field condition (Margason [1975]; Margason & Halloway [1977]; NEHRP [1997]); ii) Winkler models (BDWF), which summarizes the soil-pile interaction, with a system of springs and dampers distributed along the pile and a linear-elastic (Dobry & O'Rourke [1983]; Nikolaou et al. [1995]; Nikolaou et al. [2001]; Castelli et al. [2008]), or non-linear and hysteretic soil behaviour (Conte & Dente, [1988], [1989], Castelli & Maugeri [2007]; Maiorano et a., [2007]; Cairo et al. [2008]); iii) FEM or BEM models (Wu & Finn [1997], Grassi & Massimino [2008], [2009]). In particular, some Winkler models (BDWF) provide fairly simple formulas to be used for determining the maximum kinematic moment at the interface between two soil layers with different stiffnesses (Dobry and O'Rourke [1983]; Nikolaou et al. [1995]; Mylonakis [1999]; Nikolaou et al. [2001]).

SOIL-PILE KINEMATIC INTERCATION: STRATEGY OF ANALYSIS

This paper deals with the problem of a single pile embedded in a soil constituted of two layers of different stiffnesses, resting on an infinitely rigid base (fig. 1). The two layers of soil are considered as linear, elastic, viscous and isotropic materials: the thickness of the two layers are considered uniform in all the analyses, with H_1 = 8 m and H_2 equal to 16 m; at depths of 24 m was assumed the conventional bedrock (rigid base).

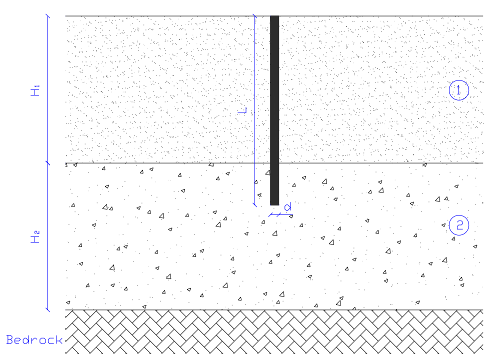

Fig. 1. Reference scheme of a pile embedded into two soil layers of different stiffnesses

The first layer is characterised by: $\rho_1 = 1.73$ kNs^2/m^4, $\upsilon_1 = 0.3$, E_1 = 101300 kPa and V_{S1} = 150 m/s. As regards the second layer of soil three value are assumed for the ratio V_{s2}/V_{s1}. Subsequently three values are assumed for the ratio ρ_2/ρ_1; thus three different soil profiles are considered. Table 1 reports the main soil proprieties.

It is also hypothesized that the head of the pile coincides with soil surface and that the pile has a linear, elastic isotropic behaviour characterized by E_p = 30000000 kPa and a Poisson ratio $\nu = 0.2$.

In order to investigate the role of the seismic input in kinematic interaction of foundation piles, 5 different accelerograms are considered (Table 2 reports some references and the predominant frequencies). The chosen seismic inputs (in terms of acceleration time-histories) were recorded in Europe in the last 30 years, in rock. All the chosen seismic inputs is scaled up to an amplitude equal to 1 m/s^2. The chosen seismic inputs are applied to the FEM model bedrock.

Table 1. Main properties of soil

	Soil profile		
	ST1	ST2	ST3
V_{S2}/V_{S1}	2	3	4
V_{S2} (m/s)	300	450	600
ρ_2/ρ_1	1.1	1.2	1.25
ρ_2 (kN s^2/m^4)	1.91	2.08	2.17
G_2 (kPa)	171560	421101	779817
E_2 (kPa)	446055	1094862	2027523
f_{1t} (Hz)	3	3.8	4.2
f_{2t} (Hz)	6.4	7.8	9.4

Table 2. Characteristics of seismic excitation

Event	Registrations	Date	f_1 (Hz)	f_2 (Hz)
E1	Valnerina	19/09/79	1.35	4.5
E2	Lazio-Abruzzo	07/05/84	2.16	4.7
E3	Etolia (Grecia)	18/05/88	2.90	2.1
E4	Coast of Magion Oros penisnsula (Grecia)	06/08/83	3.82	4.2
E5	Umbria - Marche	03/10/97	7.80	3.1

In order to study the role of the slenderness L/d in kinematic interaction, three piles are taken into account three piles characterised by L = 12, 20 and 24 meters (end-bearing pile); and per each pile different diameters (d = 0.4, 0.5, 0.6, 0.8, 1.0, 1.2 m) are considered.

The problem are studied with a FEM modeling (Grassi and Massimimo 2008, 2009), using the finite element ADINA code (Bathe, 1996) in 3D.

The soil is modelled using "3D solid" elements with 8 nodes while the pile is modelled using "beam" element with 2 nodes (Fig. 2).

Each seismic input motion is applied in terms of horizontal displacement time-history along the "y" direction.

The vertical boundaries are 12 m far from the pile, which is located at the centre of the mesh; the horizontal bottom boundaries are 12 m far from the pile. Furthermore, on the horizontal bottom boundary vertical displacements are not allowable; similarly, on the two vertical boundaries along the "y" direction horizontal displacements in the "x" direction are not allowed. Finally, on the two vertical boundaries along the "x" direction special constrain equations along the "y" direction are imposed. Specifically, each node of one of these boundaries must have the same displacement in “y” direction of its corresponding node in the opposite boundary. Two nodes are considered corresponding nodes if they are part of two opposite vertical boundaries and have the same distance from the horizontal bottom boundary and the same distance from the other two vertical boundaries.

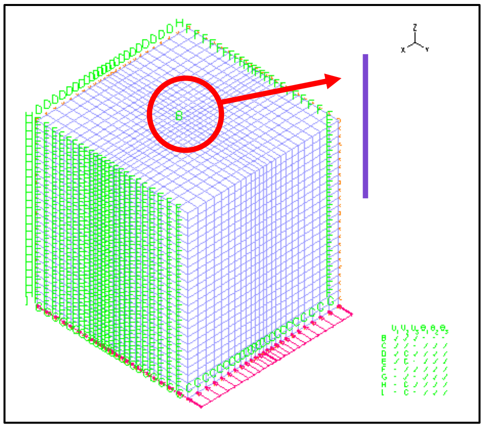

Fig. 2. Adopted FEM model

Whole model is initially subjected to the "mass proportional" command to take into account the unit weight of the involved materials. Then the horizontal bottom boundary is subjected to the horizontal displacement time-history along the “y” direction. This displacement time-history is obtained from the accelerograms, imposing that initial displacement and initial velocity are equal to zero.

Raylight’s method is used to simulated the system damping. More precisely, a damping ratio equal to 3% is assumed for the pile and a damping ratio equal to 5% is assumed for the soil.

RESULT OF PARAMETRIC ANALYSIS

In this paper the main results obtained for the different soil profiles presented, seismic excitations and L/d ratios are presented.

Fig. 3 shows the ”y” horizontal displacements occurring at a generic time considering the ST1 soil profile, the E2 events and L/d=20.

In figs. 4, 5 and 6 the kinematic bending moments along the pile, obtained for the pile of length 12 m and diameter 0.6 m, subjected to all the to seismic events shown in table 2, embedded in the soil profiles ST1 (fig. 4), ST2 (fig. 5) and ST3 (fig. 6), are plotted.

From these figures we can observe that, with the same maximum acceleration of the seismic input, kinematic moments varies considerably under different predominant frequencies of the seismic event.

The greatest bending moments are achieved when the predominant frequencies of the seismic events are similar to the fundamental frequencies of the deposit. Thus, in the case of the soil profile ST1 the event E5 is the most dangerous; while in the case of the soil profiles ST2 and ST3, the event E2 is the most dangerous.

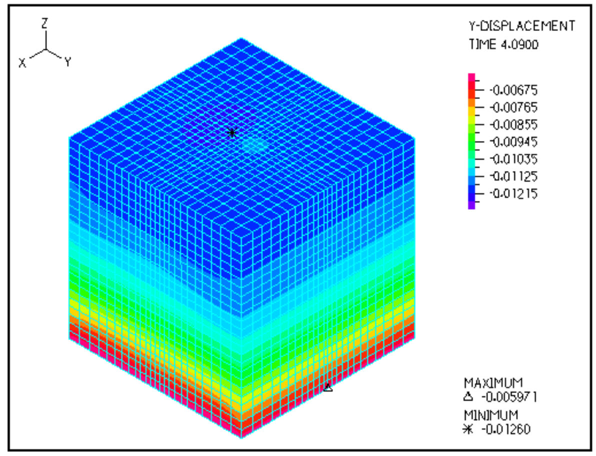

Fig. 3. Horizontal displacement along the input motion direction

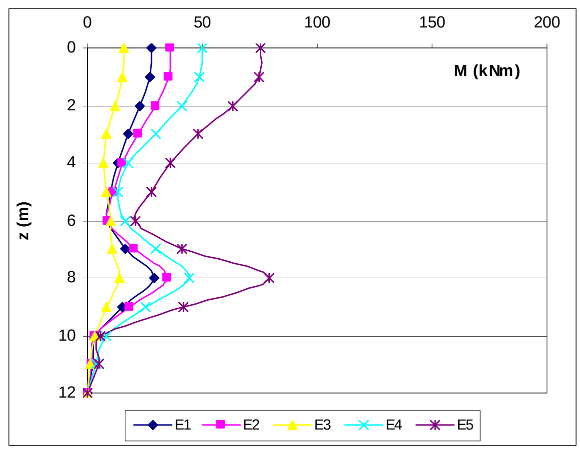

Fig. 4. Kinematic moments along the pile (L =12 m, d =0.6 m) embedded in the soil profile ST1

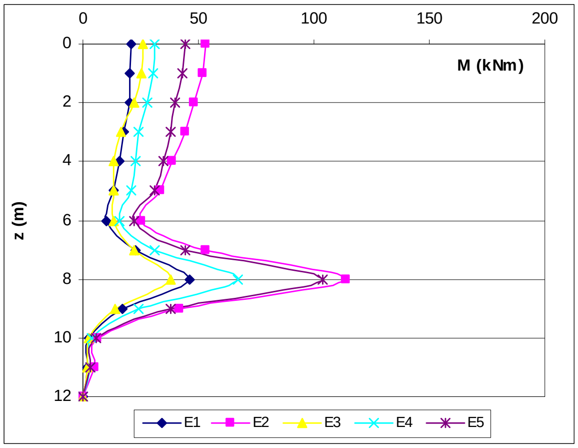

Fig. 5. Kinematic moments along the pile (L =12 m, d =0.6 m) embedded in the soil profile ST2

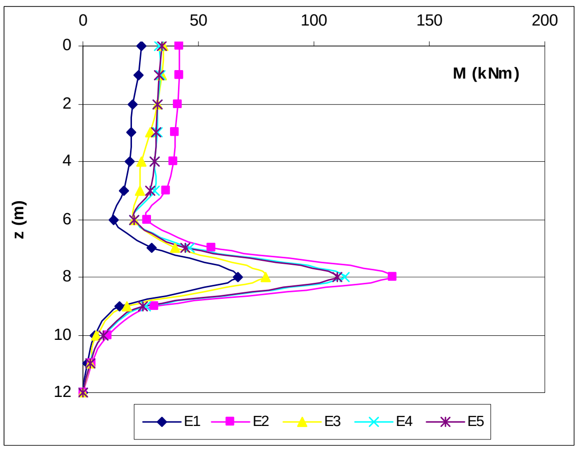

Fig. 6. Kinematic moments along the pile (L =12 m, d =0.6 m) embedded in the soil profile ST3

Furthermore, the results of figures 4, 5 and 6 confirm that the moment at the interface between two layers with different stiffnesses increases with the ratio V_{s2}/V_{s1} increasing. While, whatever the frequency of the event may be, the moment at the pile head tends to decreases with the increase of V_{s2}/V_{s1}. From figure 4, finally, it can seen that if $V_{s2}/V_{s1} = 2$ (soil profile ST1) in some cases the moment at the head is comparable with that at the interface between the two layers of soil; while, in the case $V_{s2}/V_{s1} = 3$ (soil profile ST2) and $V_{s2}/V_{s1} = 4$ (soil profile ST3) the highest moment is always at the interface between the two layers of soil. Considering also inertial interaction this result assumes a significant value.

Similar results are found for other values of L and d.

Table 3 also shows the values of the moment at the interface between the two layers of soil, for the pile embedded in the 3 soil profiles of table 1 and subjected to the 5 earthquakes of table 2. The percentage difference between the bending moments obtained for V_{s2}/V_{s1}=2, 3 e 4 and those obtained for V_{s2}/V_{s1}=1 (homogenous soil) also is reported. Very significant differences are found for the soil profiles ST2 and ST3.

Table 3. Kinematic moments at the soil layer interface: comparison with the case $V_{s2}/V_{s1} = 1$

	Soil profiles					
	ST1		ST2		ST3	
	M (kPa)	variation	M (kPa)	variation	M (kPa)	variation
E1	29	26%	46	100%	67	191%
E2	34.9	6%	114	245%	134	306%
E3	79	216%	104	316%	110	340%
E4	44	69%	67	158%	113	335%
E5	14	22%	38	230%	79	587%

Figure 7 shows the horizontal displacements along the pile embedded in the soil profile ST1 and subjected to the 5 seismic events. While in figure 8 the comparison between the horizontal displacements of the soil in free field and the pile horizontal displacements for the event E2 are reported. The horizontal displacement curve of the soil in free field present a cusp at the interface between the two layers of soil, clearly identifying the soil layer interface; while the pile horizontal displacement curve shows a clear continuity.

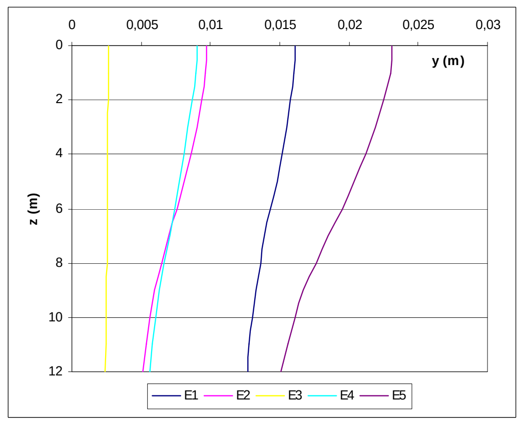

Fig. 7. Horizontal displacement along the pile (L=12 m, d=0.6 m) embedded in ST1

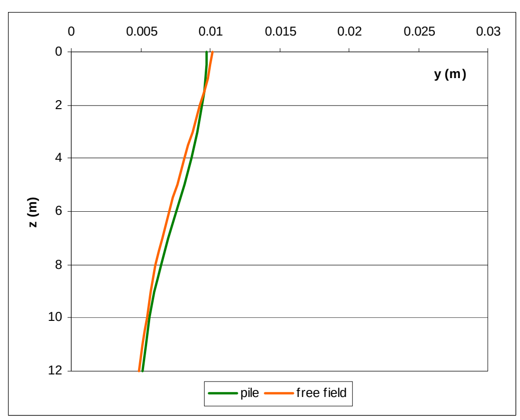

Fig. 8. Comparison between horizontal displacement of the pile embedded in ST1 and the free field motion (event E2)

Finally, the main results, obtained varying the length L and diameter d of the pile (i.e., the slenderness L/d) and maintain fixed the seismic excitation (E2), are reported.

In particular, table 4 shows the kinematic moments obtained at the top of the pile (z = 0 m) and at interface between the two soil layers (z = 8 m) for a pile of diameter 0.6 m and length respectively equal to 12, 20 and 24 m, for the soil profiles ST1, ST2 and ST3. The results show that the length of the pile does not have influence on the kinematic moments.

Table 4. Kinematic moments for different value of pile length for the analysis ST1-E2, ST2-E2 and ST3-E2

Stratigraphics	L (m)	$M_{z=0}$ (kPa)	$M_{z=8}$ (kPa)
ST1	12	36.0	34.9
	20	36.2	35.0
	24	36.0	34.8
ST2	12	53.0	114.0
	20	53.2	115.0
	24	53.0	114.7
ST3	12	42.0	134.0
	20	43.4	134.2
	24	43.3	134.1

Figure 9 shows the influence of the diameter d on kinematic moments at the top of the pile; while figure 10 refers to the interface between the two layers of soil. From Figure 9 we see that per each ratio V_{s2}/V_{s1}, the increase of the pile diameter, leads in general, to an increase of the moment at the pile head and at the interface between the two layers of soil. However, with regard to the head of the pile, for values of L/d > 20 the ratio V_{s2}/V_{s1} does not have a significant influence. For the moment at the interface, for V_{s2}/V_{s1} is equal to 2, the increase of the kinematic moment with the decreasing pile slenderness, is contained, while for V_{s2}/V_{s1} greater than 2 this increase is more significant. So, for example, for L/d = 15 the moment at the interface obtained for $V_{s2}/V_{s1} = 3$ is approximately equal to 300% of what you get for $V_{s2}/V_{s1} = 2$. Thus, the combination of high contrast in soil stiffness and low slenderness of the pile increases significantly the kinematic moment at the soil layer interface. Finally, the moment at the interface increase with the ratio V_{s2}/V_{s1}, while at the top it has its maximum value for $V_{s2}/V_{s1} = 3$ and then decreases for $V_{s2}/V_{s1} > 3$.

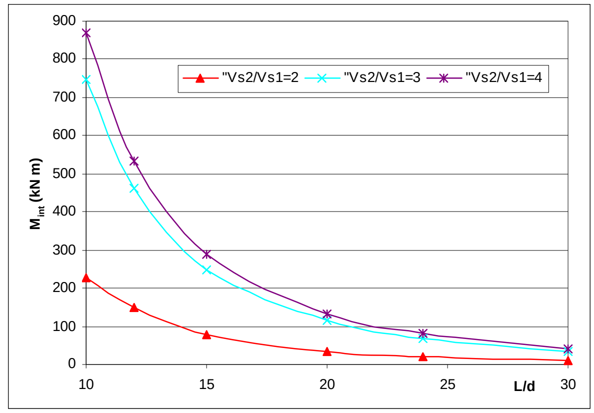

Fig. 9. Kinematic moments at the top of the pile, for different values of d and V_{s2}/V_{s1}, subjected to E2 event.

CONCLUSION

Bending moments on foundation piles due to soil-pile kinematic interaction can cause severe damage on pile. This paper presents a parametric analysis on a single pile with a 3-D FEM approach: the soil is modelled with “3D solid” elements while the pile with "beam" element.

The pile is supposed to be embedded into two soil layers, characterised by different stiffnesses and subjected to different seismic excitation (five accelerograms scaled to 1 m/s^2 and with different frequencies are considered).

The presented numerical results confirm the importance of contrast in stiffness between soil layers in witch the pile is embedded. The increase of contrast stiffnesses significantly increases the bending moment at the interface between the two layers of soil.

For constant peak ground acceleration, the bending moment on the pile changes greatly with the frequency of the seismic excitation: the highest values are found for the predominant frequencies of the seismic event very close to the fundamental frequencies of the deposits.

The soil horizontal displacement distribution with the depth in free-field condition is generally different from the pile horizontal displacement distribution with the depth. Furthermore, the soil horizontal displacement distribution with the depth presents a cusp at the soil layer interface; while the pile horizontal displacement distribution with the depth does not present any significant cusp.

The study on the effect of slenderness (L / d) shows that the variation of the pile diameter has a significant impact on the bending moment at the soil layer interface, especially for high value of the ratio V_{s2}/V_{s1}. The only length of the pile does not seem to be a significant parameter.

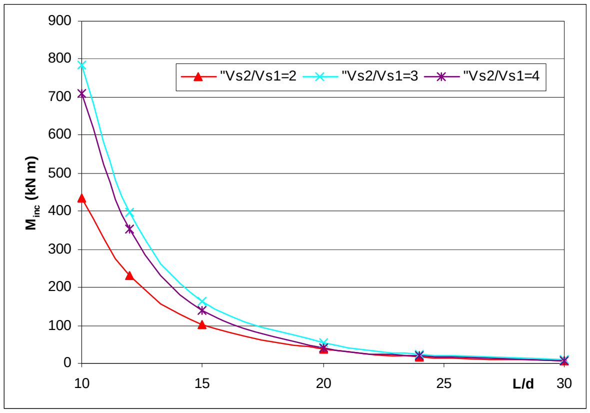

Fig. 10. Kinematic moments at the soil layer interface, for different values of d and V_{s2}/V_{s1}, subjected to E2 event

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