KINEMATIC INTERACTION IN PILE FOUNDATIONS

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ABSTRACT :

In this paper the seismic behaviour of single piles embedded in layered soil deposits is evaluated by considering the soil-pile kinematic interaction. The kinematic analysis is performed by using a finite element model for the pile foundation and a Winkler-type medium for the soil. The excitation motion is obtained by means of a one-D propagation analysis of an artificial accelerogram from the bedrock. The analytical model permits calculating the internal forces induced by soil-pile interaction. A comprehensive parametric analysis is carry out by varying the main parameters governing the dynamic response of piles. The influence of the layered soil properties, the bedrock location, the diameter and the bedrock embedment of piles is discussed.

KEYWORDS: dynamics, soil-structure interaction, kinematic interaction, piles, pile foundations.

1. INTRODUCTION

The dynamic response of piles during transient earthquake motions has received large attention in recent years, and several studies have investigated the nature of input ground motion and the mechanism of soil-pile interaction to determine seismic design loads for pile-supported structures. Modern seismic codes have acknowledged these aspects and suggest accounting for soil-structure interaction effects in the foundation and superstructure design (Dezi 2006).

The domain decomposition technique is an approach that can account for soil-foundation-structure interaction and is commonly used in professional engineering and research practices. According to this technique, the soil-structure interaction may be evaluated in two steps: the kinematic and the inertial interaction analyses. In the first step the soil-foundation system (without the superstructure) subjected to the free-field incoming motion is analyzed, obtaining stress resultants along the piles, soil-foundation impedance functions and the foundation input motion. These quantities allow performing the inertial interaction analysis in witch the superstructure is considered on a compliance base characterized by the dynamic impedances of the soil-foundation system and subjected to the foundation-input motion. In the case of pile foundations the kinematic interaction induces stress resultans along the piles that, depending on the stratigraphy, may be of the same magnitude of those induced at the pile head by the inertial interaction. For design purposes the model of beam on Winkler restrains is commonly used to study the pile-soil interaction because of its versatility in accounting for various complicated conditions (Novak, 1974; Flores-Berrones & Whitman, 1982; Makris and Gazetas, 1992; and Kavvadas & Gazetas, 1993).

In this paper the numerical procedure, recently proposed by the authors (Dezi et al. 2007a) to perform kinematic interaction analysis of pile foundations with generic geometry and layered soil profile, is applied to evaluate the seismic behaviour of single piles embedded in layered soil. A finite element model is used for the piles and a Winkler-type medium for the soil. Both the piles and the soil are considered to have a linear behavior. The soil-pile interaction is performed in the frequency domain and the excitation motion is obtained by means of a one-D propagation analysis of artificial accelerograms from the bedrock.

After a brief presentation of the analytical model and its validation, a comprehensive parametric analysis is carried out by considering single piles with fixed-head and by varying the main parameters governing the dynamic response of piles. The influence of the layered soil properties, the bedrock location, the diameter and the bedrock embedment of piles is discussed.

2. SOIL - PILE FOUNDATION INTERACTION ANALYSIS

2.1. Overview of the analytical model

In this section a brief recall of the analytical model developed by the authors to perform soil-foundation dynamic interaction analyses for pile foundations is presented (Dezi et al. 2007a). The procedure allows studying generic pile group geometry in layered soil profile. Piles are modeled as Euler-Bernoulli beams and are assumed to be linearly elastic. Separation and slippage at the soil-pile interface are not accepted, i.e. the pile-soil displacement compatibility is assured. The soil is considered as a Winkler-type medium, constituted by independent infinite layers, and Green functions are introduced to describe soil-pile interaction and interaction among the piles constituting the foundation. The procedure is based on the Lagrange-D'Alembert principle that in the frequency domain provides the following equation:

$$\int_0^L \boldsymbol{K}\mathrm{D}\boldsymbol{u}(\omega;z)\cdot\mathrm{D}\hat{\boldsymbol{u}}(z)dz-\int_0^L \boldsymbol{r}(\omega;z)\cdot\hat{\boldsymbol{u}}(z)dz-\omega^2\int_0^L \boldsymbol{M}\boldsymbol{u}(\omega;z)\cdot\hat{\boldsymbol{u}}(z)dz=0 \quad \forall\hat{\boldsymbol{u}}\neq\boldsymbol{0} \qquad (2.1)$$

where $\hat{\boldsymbol{u}}(z)$ and $\mathrm{D}\hat{\boldsymbol{u}}(z)$ are the vectors of virtual displacement field and relevant strain field respectively, $\boldsymbol{K}$ and $\boldsymbol{M}$ are the stiffness and the mass matrices of the foundation system and $\boldsymbol{r}$ is the vector of the soil reaction forces developing along the pile as a result of the pile-soil-pile interaction. The compatibility condition between the pile and the soil displacements may be expressed by the integral equation

$$\boldsymbol{u}(\omega;\mathrm{z})=\boldsymbol{u}_{\mathrm{ff}}(\omega;\mathrm{z})-\int_0^{\mathrm{L}} \boldsymbol{D}(\omega;\zeta,\mathrm{z})\boldsymbol{r}(\omega;\zeta)\mathrm{d}\zeta \qquad (2.2)$$

in which the soil displacements in correspondence of the pile locations (right hand term) are evaluated by summing the free field motion $\boldsymbol{u}_{ff}$ and the displacements induced by the soil-pile interaction forces. $\boldsymbol{D}(\omega;\zeta,z)$ is a complex valued matrix containing the elastodynamic Green's functions (Wheeler and Sternberg, 1968; Wolf, 1988). Equation (2.2) describes the complex pile-soil-pile dynamic interaction and accounts for the radiation problem which is an important energy dissipation mechanism of the foundation system.
By introducing the Winkler assumption, equation (2.2) remarkably simplifies in

$$\boldsymbol{u}(\omega;z)=\boldsymbol{u}_{ff}(\omega;z)-\hat{\boldsymbol{D}}(\omega;z)\boldsymbol{r}(\omega;z) \qquad (2.3)$$

The solution of the problem is achieved numerically by the finite element method, in the displacement based approach, by dividing each pile into *e* elements and approximating the motion at their interior by interpolating the displacements at the end nodes. Third-order polynomials are adopted for transverse displacements, whereas first-order polynomials are adopted for longitudinal displacements. Five degrees of freedom are thus associated to the *i*-th node of the mesh, namely three translations and two rotations. Further details can be found in Dezi et al. (2007a).
The numerical procedure furnishes the stress resultants along the piles and the displacements at the foundation level due to the kinematic interaction. Furthermore, with the same model the soil-foundation impedance matrix can be computed (Dezi et al. 2007b).

2.2. Model validation

The effectiveness of the model in describing the kinematic response of pile foundations has been investigated with reference to the foundation impedances, the dimensionless displacement response factors and the pile stress resultants. For the sake of brevity, results concerning a single free-head pile are presented here. The pile is embedded in a homogeneous soil deposit having density $\rho_s = 0.7\rho_p$, constant Poisson ratio $\nu = 0.4$ and constant hysteretic damping $\xi =$ 10%. Two E_p/E_s ratios and different pile spacing-diameter ratios were considered. The soil-pile system is excited by vertically propagating harmonic shear waves. In order to make significant comparisons with other models, dimensionless displacement response factors, expressed as the ratio between the motion of the soil-foundation system measured at the pile cap and the free ground surface response, are considered.

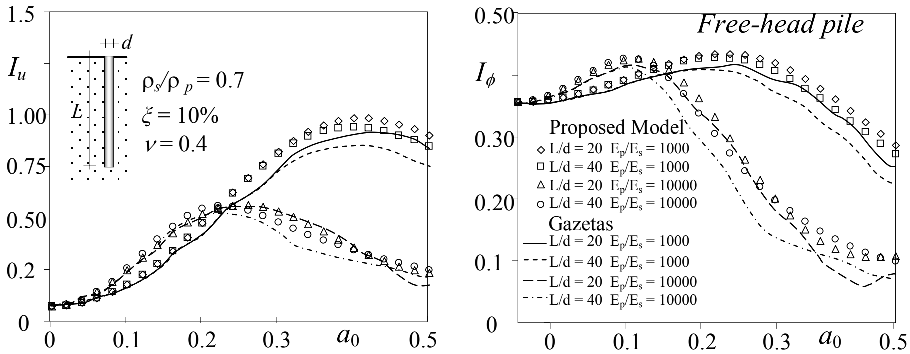


Figure 1 Kinematic response factors I_u and I_ϕ for single free-head pile

Figure 1 shows the comparison between results obtained with the proposed model (dots) and some benchmark data (lines) reported by Fan et al. (1991), in terms of kinematic response factors I_u and I_ϕ versus the non-dimensional frequency factor $a_0 = \omega d/V_s$ where d is the pile diameter and V_s the shear wave velocity.

2.3 Numerical convergency

In order to evaluate the effects of the finite element size on the results provided by the proposed numerical model, convergence analyses are performed by considering different finite element lengths L_e, soil profiles and pile group patterns. For the sake of brevity, results concerning only a single pile are discussed here. Analyses are repeated by reducing the finite element size until the convergence is obtained between two consecutive cases. All the analyses are performed assuming an artificial accelerogram as input motion at the outcropping rock. Figure 2 shows the envelopes of stress resultants for a single pile with 1 m diameter. Bending moments vary linearly within the elements whereas shear and axial forces are constant as a consequence of the shape function adopted to interpolate the displacements. Discontinuities of solutions deriving from the displacement based approach of the finite element procedure become no more significant for mesh sizing below 1.0 m. According to the results of this earlier study all the analysis cases are developed by applying a 0.2 m finite element spaced mesh to guarantee satisfactory solution accuracy.

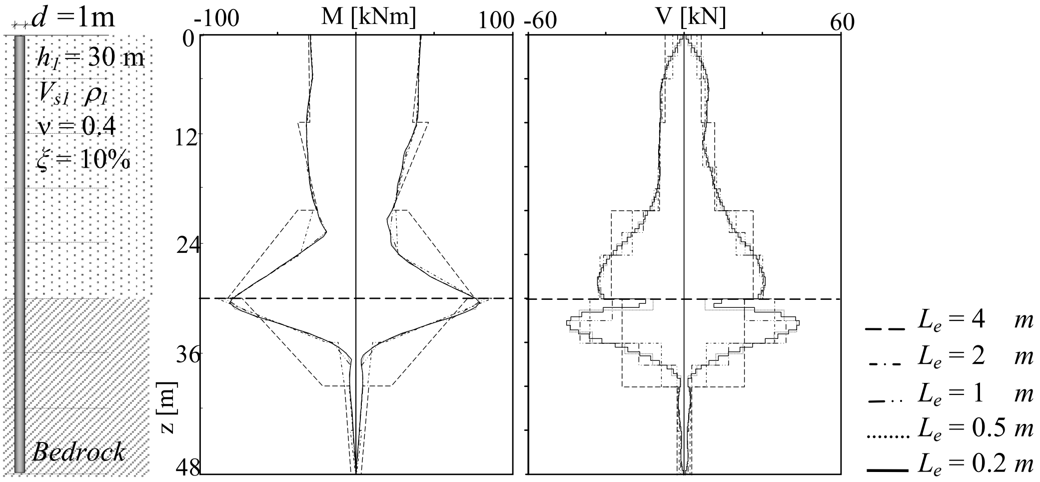


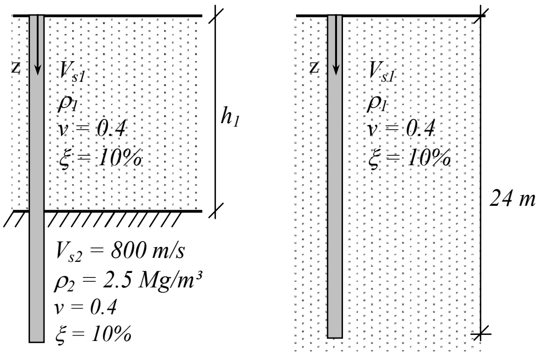
Figure 2 Stress resultants for different finite element sizes

3. PARAMETRIC INVESTIGATION

3.1. Analysis cases

A comprehensive parametric study has been carried out to analyse the effects of kinematic interactions in single piles having restrained rotational degree of freedom at the head. The objective of this study is to examine the influence of the main parameters governing the dynamic response of piles: the pile diameter, the properties of the layered soil (in terms of shear wave velocity) and the bedrock location.

The analysis scenario covers a wide range of possible two-layer soil profiles and allows to investigate the effects of the layer interface on pile bending moments for highly contrasting soil properties and various pile diameters. The soil profile consists of a surface soil layer characterized by a thickness h_1, mass density ρ_1 and a shear wave velocity V_{s1} overlying a rock stratum having mass density $\rho_2 = 2.5$ Mg/m³ and shear wave velocity $V_{s2} = 800$ m/s. Both these layers are supposed to be elastic and characterized by Poisson's ratio $\nu_1 = \nu_2 = 0.4$ and damping $\xi_1 = \xi_2 = 10\%$. Different stratigraphies are considered varying the thickness and the shear wave velocity of the surface layer. Figure 3 shows the generic soil profile and the soil properties selected for the analyses. The pile length is assumed to be 48 m. In any case the piles are considered to have a linear elastic behaviour, a Young's modulus $E_p = 30000$ N/mm² and a mass density $\rho_p = 2.5$ t/m³. By assuming 8 different pile diameters a total number of 120 analyses were derived combining 5 different bedrock location and three different shear wave velocities. Furthermore a set of analysis was performed referring to a homogeneous soil deposit having the same dynamic properties of the deformable layer of the stratigraphies in Figure 3. In this case the pile length is assumed to be 24 m.



V_{s1} [m/s]	ρ_1 [Mg/m^3]
100	1.5
200	1.7
400	2.0

Pile diameter D [mm]	h_1 [m]
200 – 400 – 600 – 800 – 1000 – 1500 - 2000	6 – 12 – 18 – 30 – 42

Figure 3 Analyses schemes: single pile

3.2. Seismic incoming motion

Soil-pile interaction effects are evaluated by means of an analysis procedure consisting in two steps: firstly the free-field motion is obtained in absence of piles; secondly, the free-field motion is applied to the soil-pile system to perform the kinematic soil-pile interaction analysis.

In the first step the seismic input motion along the pile is obtained by means of a one-D local site response analysis where the seismic action at the outcropping rock has to be linearly deconvoluted at the bedrock level and then propagated through the soil profile. In the second step the finite element numerical procedure proposed by the authors is used to study the kinematic soil-pile interaction problem.

The seismic action at the outcropping bedrock is represented by an artificial accelerogram matching the EC8 Type 1 elastic response spectrum for ground type A.

Figure 4 shows the response spectra obtained from the deconvolution analyses for all the investigated soil profiles; each graph refers to a specific soil type and collects results obtained for different thickness h_1 of the deformable layer.

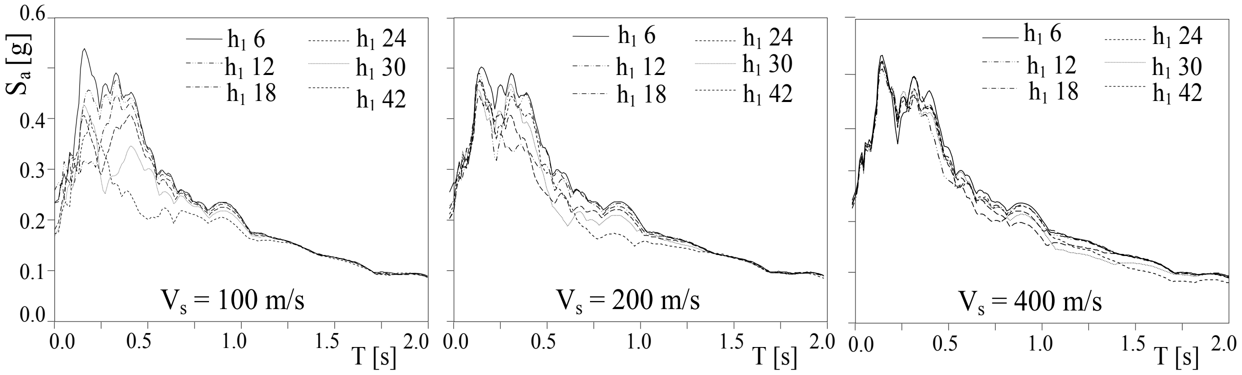


Figure 4 Response spectra obtained for all the investigated soil profiles; each graph refers to a soil type.

3.3. Pile embedment

The effect of the pile embedment into the stiff layer was investigated referring to a single pile of diameter 1 m and different soil profiles characterized by h_1 = 18 m and V_{s1} = 100, 200 and 400 m/s. For each stratigraphy different pile embedments were assumed: 1*d*, 3*d* and 5*d*. Focusing the attention on the behavior at the interface between the two layers, it is important to point out that the same maximum bending moment is achieved for embedment greater that 3*d*, revealing that such length is sufficient to provide the maximum degree of restraint into the stiff layer (Figure 5). In particular the moment envelop along the pile length relevant to the embedment of 3*d* is coincident with the one relevant to the embedment of 5*d* except obviously for the exceeding pile length, where negligible moment values are attained.

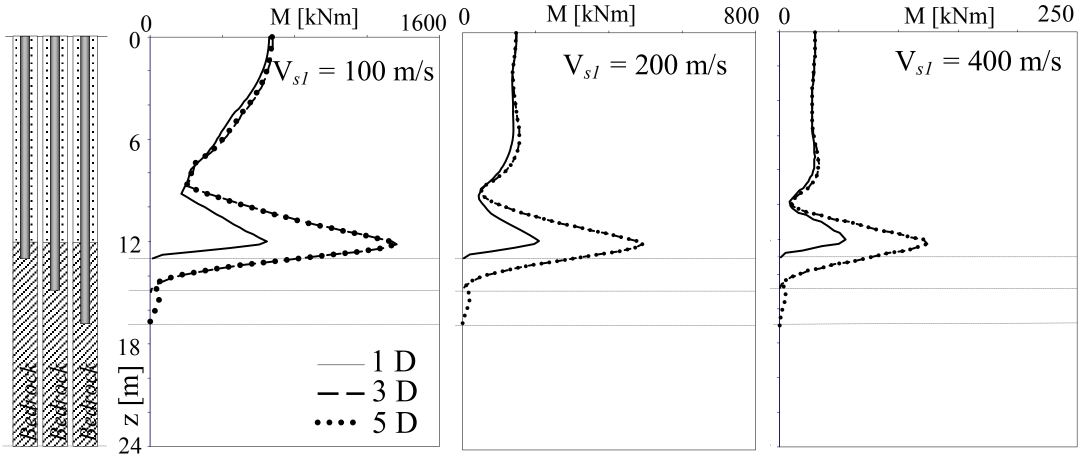


Figure 5 Effect of the embedment into the stiff layer on the bending moment

3.3. Main results

The kinematic interaction analyses, performed in the frequency domain, give the displacements along the piles; by applying the Inverse Fourier Transform results are transformed in the time domain and than stress resultants are calculated. Figure 6 shows results for a selected analysis case, namely the envelopes of bending moments and shear forces as well as the maximum displacements along the pile. These diagrams are obtained for a single pile, fixed head, embedded in a layered soil profile. It is worth noting that the diagram of the maximum bending moments is characterized by a peak value in correspondence of layer interface and by a fairly uniform distribution in the section embedded into the upper layer. The maximum value of the shear force arises in the lover layer nearby the interface. The distribution of displacements achieves the maximum value at the pile head and goes to zero nearby the stiff soil layer. Main considerations are now obtained from the evaluation only of the bending moments envelops since it is one of the most important quantities for seismic design purposes.

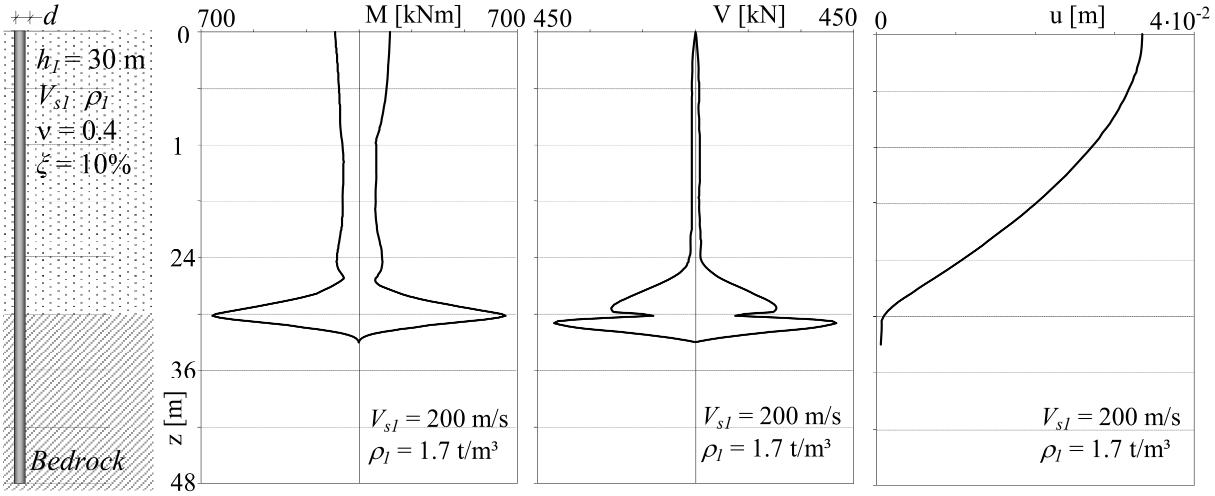


Figure 6 Envelopes of bending moments and shear forces and horizontal displacement along the pile

3.3.1 *Influence of the pile diameter*

Graphs in Figure 7 show the distribution with depth of the maximum amplitude of the bending moments along the pile for some of the considered analysis cases. For the sake of brevity thickness of the surface soil layer equal to 6 and 42 m together with the homogeneous profile are herein presented. Each graph collects results obtained for the different pile diameters and for a constant value of the shear wave velocity V_{s1}. Generally bending moments assume the maximum value at, or very close to, the interface between soil layers, but it is also interesting to see that for low values of the upper layer thickness the maximum value arises at the pile head. Despite the variation of the moment amplitude in each analysis case, it can be observed that all curves have the same shape. In the case of homogeneous soil profile the bending moment distribution is characterized by values increasing from the bottom to the top, without peaks.

The pile diameter affects significantly the amplitude of the bending moments at the pile head and at the interface between layers. The bending moment increases as the pile diameter increases.

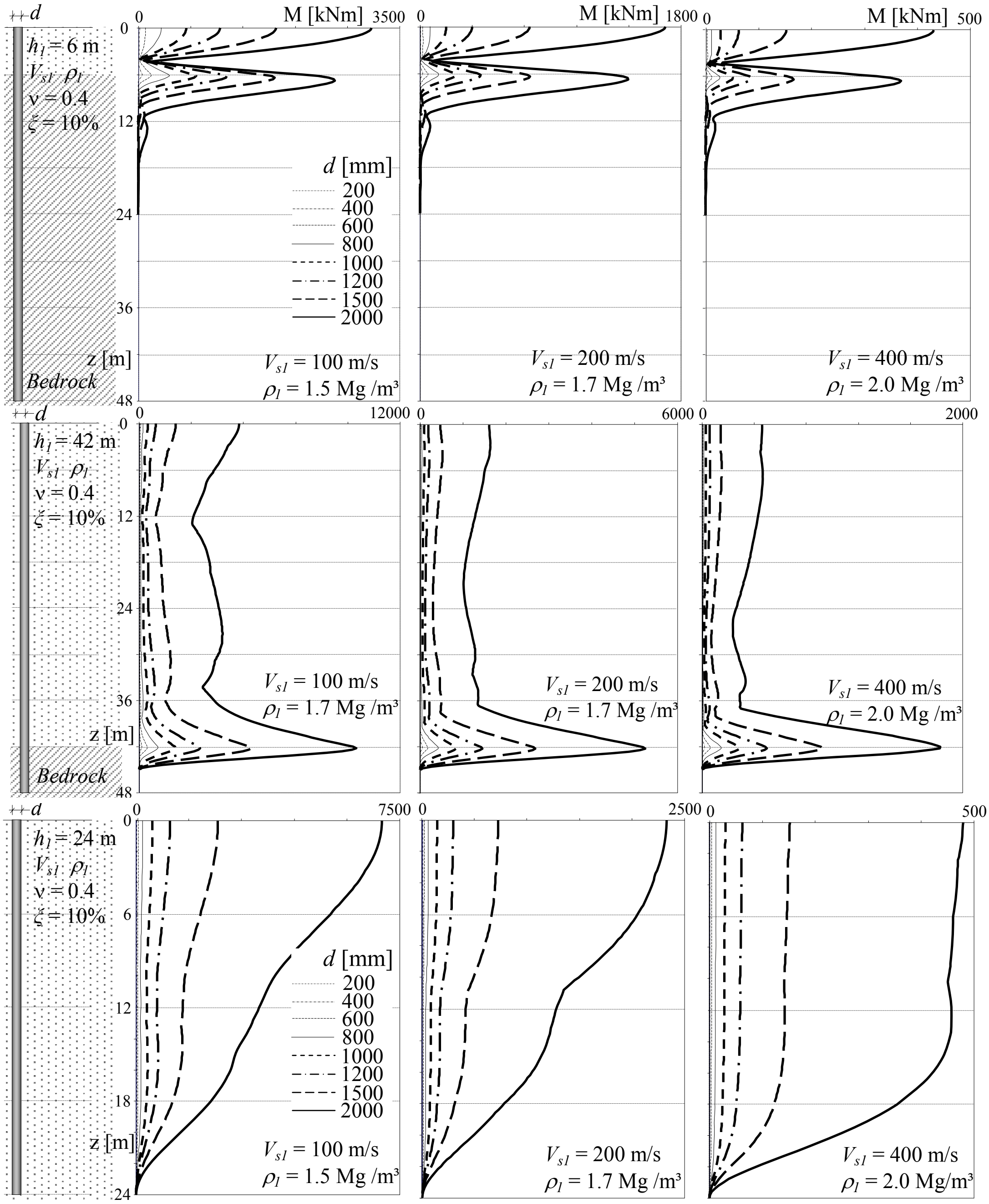


Figure 7 Envelopes of bending moments: h_1 = 6 m, h_1=42 m and homogeneous soil profile.

3.3.2 Influence of the bedrock location

Graphs in Figure 8 show the kinematic bending moments arising along the pile of 1 m diameter for all the considered soil profiles. Each graph refers to a shear wave velocity Vs_1 and collects results obtained for different values of h_1. The bending moment at the layer interface increases with the depth of the bedrock whereas the bending moment at the pile head increases as h_1 decreases expecially in soft soil deposits (V_{s1}=100 m/s).

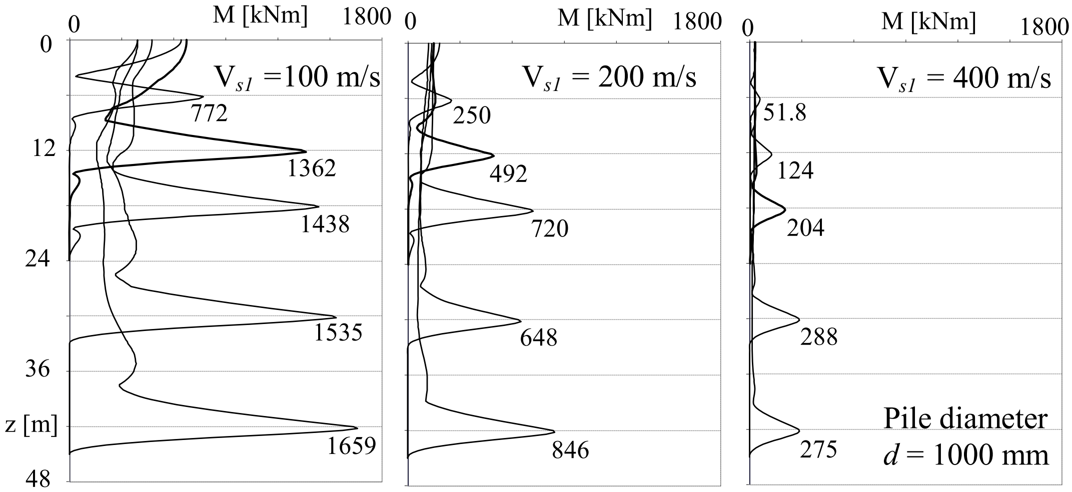


Figure 8 Envelopes of bending moment for d=1000 mm, V_{s1}=100, 200, 400m/s and h_1=6, 12, 18, 30, 42m.

3.3.3 Influence of the soil properties

To better understand the effect of the stiffness contrast between the two layers on the maximum bending moment, five shear wave velocities for the upper soil layer are considered (V_{s1}= 100, 150, 200, 300 and 400 m/s). The graphs of Figure 9 show the bending moment distributions obtained for three pile diameters and a constant value of the bedrock location h_1. As expected, the bending moments increase as the shear wave velocity V_{s1} decreases.

Finally Figure 10 shows the maximum kinematic bending moments at the pile head and at the layer interface, normalized with respect to the corresponding bending moments obtained for V_{s1} = 400 m/s, versus the shear wave velocity of the upper soil layer. The graphs refer to three pile diameters (400, 1000 and 1200mm). It is worth noticing that the graphs are superimposed and the normalized bending moments sharply decrease as the shear wave velocity increases.

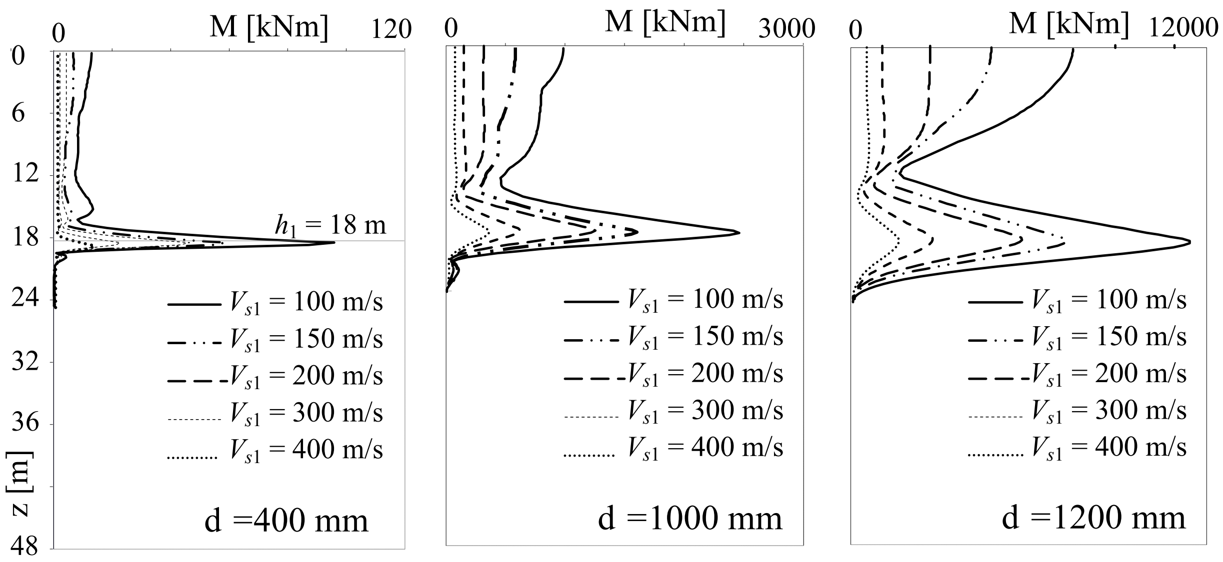


Figure 9 Envelopes of bending moments for d = 400, 1000 and 1200 mm and for different soil V_{s1}

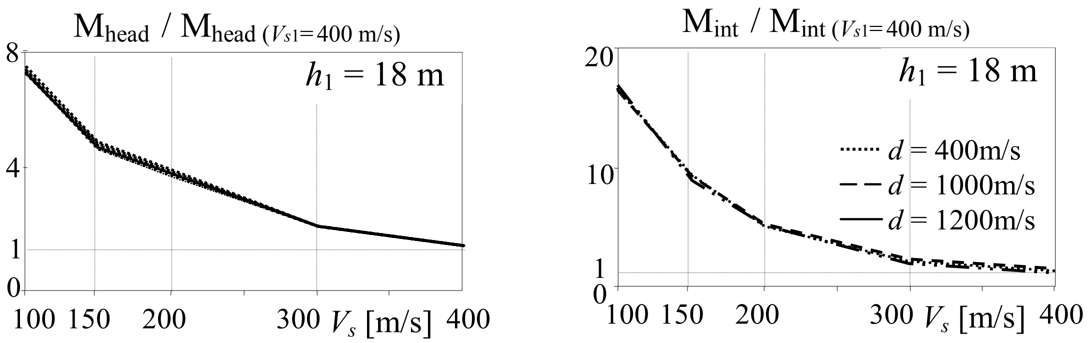


Figure 10 Normalized bending moments at pile head and at layer interface

4. CONCLUSIONS

Kinematic interaction analysis of single piles embedded in layered soil deposits has been performed by using a finite element model for the pile foundation and a Winkler-type medium for the soil. A numerical procedure proposed by the authors has been applied to obtain the stress resultants and the displacements along piles induced by soil-pile interaction.

The seismic incoming motion along the pile has been evaluated by means of a one-D local site response analysis and by considering artificial accelerograms as input at the outcropping rock.

The parametric study allows drawing the following conclusions:

- the embedment of 3d into the stiff layer is the minimum length providing the maximum degree of restraint at the lower end of the pile;
- the peak values of the bending moment at the soil layer interface increases with the pile diameter and the thickness of the superficial soil layer as well as with the stiffness contrast between layers;
- for small values of the superficial soil layer thickness, the maximum bending moment arises at the pile head instead of at the layer interface;
- the bending moment at pile head and at layer interface sharply reduce as the shear wave velocity increases.

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