Dynamic analysis of piled foundations in stratified soils by a BEM-FEM model *

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Abstract

In this paper, a 3D BEM-FEM coupling model is used to study the dynamic behavior of piled foundations in elastic layered soils in presence of a rigid bedrock. Piles are modelled by FEM as beams according to the Bernoulli hypothesis, and every layer of the soil is modelled by BEM as a continuum, semi-infinite, isotropic, homogeneous, linear, viscoelastic medium. First, the main points of the model are set out. Then, several results of vertical, horizontal and rocking impedances for single piles and 2×2 pile groups embedded in a stratum resting on a rigid bedrock, are presented. The influence on the dynamic response of stratum depth, soil stiffness and piled foundation configuration is discussed. Finally, the influence of the stratigraphy on the seismic response of a 3×3 pile group is analyzed, together with the pile-to-pile kinematic interaction and the wave-scattering phenomena.

1 Introduction

The steady-state dynamic response of piled foundations in elastic soils has been the subject of much research, in both the kinematic and the forced vibration analyses (see e.g. [1]). For the study of piles and pile groups embedded in a homogeneous half-space, several frequency domain boundary integral formulations in conjunction with the monodimensional Finite Element Method (FEM) have been used by different authors [2, 3, 4, 5]. Linear analyses for non-homogeneous media or layered soils have also been carried out using the same kind of approach [6, 7, 8, 9]. Subsequently, more versatile and rigorous linear numerical models have been developed using the Boundary Element Method (BEM) for both soil and piles [10, 11, 12, 13], but with the disadvantage of a high computational cost.

Although a great deal of this research has been focused on the forced vibration problem, much of it has also dealt with the kinematic response of piled foundations. For instance, parametric studies of the seismic response of single piles and pile groups to Rayleigh waves and to vertically and obliquely incident body waves have been reported in [14, 15, 16, 17].

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On the other hand, due to the fact that piles are commonly used when avoiding shallow soil of low bearing capacity and transferring load to deeper soil or rock of high bearing capacity is needed, a particular case of interest in the dynamic analysis of piles is that of piled foundations embedded in a viscoelastic stratum resting on a rigid bedrock, for both floating and hinged piles. However, not many papers have been reported focusing on this topic [18, 19], though some have dealt with it while studying the pile-soil-structure interaction problem [20, 21, 22, 23].

For this reason, the aim of this paper is to present a method for the dynamic analysis of piles and pile groups and, making use of it, contribute to the topic discussed above by investigating, through parametric studies: *a)* the influence of the presence of a rigid bedrock on the dynamic impedances of piled foundations, and *b)* the influence of the stratigraphy on the seismic response of hinged pile groups. To this end, a BEM-FEM coupling model previously presented by the authors [24] is used to compute time-harmonic dynamic impedances and the seismic response of piled foundations embedded in viscoelastic zoned-homogeneous layered soils. The model has been validated for both the kinematic and the stiffness problems with several results taken from the literature (e.g. [2, 18, 19, 20]), though these comparisons are not presented here for the sake of brevity.

In this approach, and in the line of a previous static model developed in [25, 26, 27], the pile-soil interaction takes place, from the integral equation point of view, through internal forces, as it is assumed that the soil continuity is not altered by the presence of the piles. These are modeled by FEM as beams according to the Bernoulli hypothesis, and every stratum of the soil is modeled by BEM as a continuum, semi-infinite, isotropic, homogeneous, linear, viscoelastic medium. The model not only allows the dynamic analysis of piled foundations embedded in a half-space or in a stratum resting on a rigid bedrock, but also in multilayered soils of generic stratigraphy and topography, including deposits and inclusions.

Firstly, the main points of the BEM-FEM coupling model formulation are set out. Secondly, several results of vertical, horizontal and rocking time-harmonic dynamic impedances of single piles and 2×2 pile groups embedded in a stratum resting on a rigid bedrock, are presented. Different depths of the stratum and three foundation configurations are studied, and the effects associated to these parameters are discussed. Finally, the influence of the stratigraphy on the seismic response of a 3×3 pile group is analyzed. To this end, displacement transfer functions for vertically-incident plane time-harmonic shear waves and response spectra for a particular configuration, under two different strong ground motions, are presented for several soil profiles. Pile-to-pile kinematic interaction and wave-scattering phenomena, are also investigated.

Regarding the impedances study, it is shown that the effect of the presence of the rigid bedrock is vital for the horizontal impedance of single piles and pile groups, and also for the rocking behavior of single piles, while it is almost negligible for the rocking response of pile groups. Regarding the vertical impedances of floating piled foundations, the effect of the bedrock is not important except for frequencies below 1.5 times the fundamental natural frequency of the stratum.

As for the performed seismic analysis, it can be seen that the presence of a soft layer at the top of a stratum yields to rapidly decreasing transfer functions and, consequently, to a weakened seismic response at the pile cap. However, taking into account additional layers with shear wave velocity increasing with depth is of minor importance.

2 Pile-soil interaction model

The behavior of a pile submitted to harmonically varying loads, considering zero internal damping, can be described by the equation

$$\bar{\mathbf{K}}\,\mathbf{u}^p = \mathbf{F}^{ext} + \mathbf{Q}\,\mathbf{q}^p, \tag{1}$$

where $\bar{\mathbf{K}} = \mathbf{K} - \omega^2 \mathbf{M}$, being $\mathbf{K}$ and $\mathbf{M}$ the stiffness and mass matrices of the pile, ω is the circular frequency of excitation, and $\mathbf{u}^p$ the vector of nodal translation and rotation amplitudes along the pile. $\mathbf{F}^{ext}$ includes the forces at the top $\mathbf{F}_{top}$ and the axial force at the tip of the pile $\mathbf{F}_p$, $\mathbf{q}^p$ is the vector of tractions along the pile-soil interface, whereas $\mathbf{Q}$ is the matrix that transforms these nodal traction components to equivalent nodal forces. By means of Eq. (1), piles are modelled as vertical Bernoulli beams by three-node FEM elements on which there are defined 13 degrees of freedom: three lateral displacements on each node, and two rotations on each one of the extreme nodes.

On the other hand, each stratum of the soil is modelled by BEM as a linear, homogeneous, isotropic, viscoelastic, unbounded region. The boundary integral equation for a time-harmonic elastodynamic state defined in a domain Ω_m with boundary Γ^m can be written in a condensed and general form as

$$\mathbf{c}^k \mathbf{u}^k + \int_{\Gamma^m} \mathbf{p}^* \mathbf{u}\, d\Gamma = \int_{\Gamma^m} \mathbf{u}^* \mathbf{p}\, d\Gamma + \int_{\Omega_m} \mathbf{u}^* \mathbf{X}\, d\Omega, \tag{2}$$

where $\mathbf{c}^k$ is the local free term matrix at collocation point 'k', $\mathbf{X}$ are the body forces in the domain Ω_m, $\mathbf{u}$ and $\mathbf{p}$ are the displacement and traction vectors, and $\mathbf{u}^*$ and $\mathbf{p}^*$ are the elastodynamic fundamental solution tensors for a time-harmonic concentrated load at point 'k'. A hysteretic damping model is used for the soil through a complex valued shear modulus μ of the type $\mu = Re[\mu](1 + 2\mathrm{i}\xi)$, being ξ the damping coefficient. Details about BEM formulation can be found in [28].

Generally, body forces $\mathbf{X}$ are considered to be zero in most of elastodynamic problems. Nevertheless, in this approach, from the integral equation point of view, the pile-soil interaction takes place through internal punctual forces placed at the geometric piles tip and through load-lines placed along the piles axis, as it is assumed that the soil continuity is not altered by the presence of the piles. The load-lines within the soil, the tractions along the pile-soil interface acting over the pile and within the soil ($\mathbf{q}^{p_j} = -\mathbf{q}^{s_j}$), and the internal punctual forces F_{p_j} at the tip of the piles, are represented in Fig. 1, where a sketch of the model is shown.

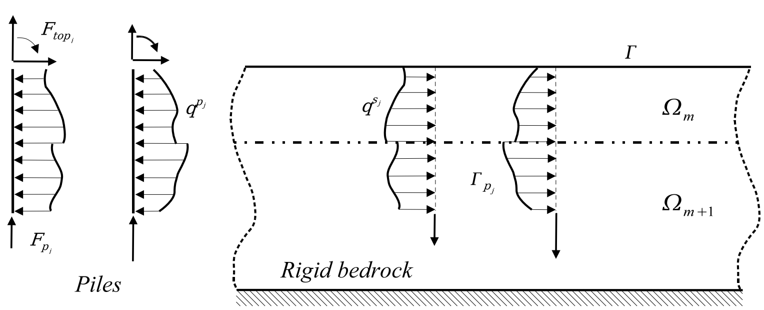

Figure 1: Load-lines representation of two piles embedded in a layered soil.

Then, Eq. (2) can be written as

$$\mathbf{c}^k \mathbf{u}^k + \int_{\Gamma^m} \mathbf{p}^* \mathbf{u}\, d\Gamma = \int_{\Gamma^m} \mathbf{u}^* \mathbf{p}\, d\Gamma + \sum_{j=1}^{n_{ll}^m} \left[\int_{\Gamma_{p_j}^m} \mathbf{u}^* \mathbf{q}^{s_j}\, d\Gamma_{p_j} - \delta_j \boldsymbol{\Upsilon}_k^j F_{p_j} \right], \tag{3}$$

where $\Gamma_{p_j}^m$ is the pile-soil interface along the load-line j within the domain Ω_m; n_{ll}^m is the total number of load-lines in the domain Ω_m; δ_j is equal to one if the load-line j contains the tip of a floating pile and zero otherwise; and $\boldsymbol{\Upsilon}_k^j$ is a three-component vector that represents the contribution of the axial force F_{p_j} at the tip of the j^{th} load-line.

Once all boundaries have been discretized, Eq. (3) can be written for each region for all nodes in Γ^m and $\Gamma^m_{p_j}$ to obtain two matrix equations of the type

$$\mathbf{H}^{ss}\mathbf{u}^s - \mathbf{G}^{ss}\mathbf{p}^s - \sum_{j=1}^{n_{ll}^m} \mathbf{G}^{sp_j}\mathbf{q}^{s_j} + \sum_{j=1}^{n_{ll}^m} \delta_j \boldsymbol{\Upsilon}^{sj} F_{p_j} = 0, \tag{4}$$

and

$$\mathbf{u}^{p_i} + \mathbf{H}^{p_i s}\mathbf{u}^s - \mathbf{G}^{p_i s}\mathbf{p}^s - \sum_{j=1}^{n_{ll}^m} \mathbf{G}^{p_i p_j}\mathbf{q}^{s_j} + \sum_{j=1}^{n_{ll}^m} \delta_j \boldsymbol{\Upsilon}^{p_i j} F_{p_j} = 0, \tag{5}$$

respectively, where $\mathbf{H}$ and $\mathbf{G}$ are coefficient matrices obtained by integration over the elements of the fundamental solution times the corresponding shape functions, $\mathbf{u}^s$ and $\mathbf{p}^s$ are the vectors of nodal displacements and tractions of boundary elements, and $\mathbf{u}^{p_i}$ is the vector of nodal displacements of the load-line i.

A coupled system of equations, of the type

$$\mathbf{A}\{\mathbf{u}^s, \mathbf{p}^s, \mathbf{q}^s, \mathbf{F}_p, \mathbf{u}^p\}^T = \mathbf{B}, \tag{6}$$

representing the layered soil-piles system, can be obtained from Eqs. (1), (4) and (5), where equilibrium and compatibility fully-bonded contact conditions over the different interfaces of the problem have been imposed. $\mathbf{A}$ and $\mathbf{B}$ are the square matrix of coefficients and the known vector respectively, both computed by rearranging the equations and prescribing the known boundary conditions.

In this work, two different kinds of analysis are carried out, each one of them with a different set of boundary conditions, though, in both cases, piles in a group are considered to be fixedly connected to a rigid massless cap (not in contact with the soil) and zero-traction free surface is assumed.

Firstly, dynamic stiffness of piles and pile groups are computed by prescribing forced vibration at the pile cap. Secondly, the seismic response of a piled foundation subject to vertically-incident plane time-harmonic shear waves is analyzed. To this end, the displacement and traction fields in the layered soil are considered as the superposition of two: the uniform viscoelastic layered soil fields $\mathbf{u}_I$ and $\mathbf{p}_I$, whose analytic expression are known; and the scattered wave fields $\mathbf{u}_S$ and $\mathbf{p}_S$, produced by the presence of the piles. Consequently, the total fields are the sum of these two ($\mathbf{u} = \mathbf{u}_I + \mathbf{u}_S,\ \mathbf{p} = \mathbf{p}_I + \mathbf{p}_S$), while it is only in the scattered wave field that the tractions along the pile-soil interface and the forces at the pile tip exist ($\mathbf{q} = \mathbf{q}_S,\ \mathbf{F}_p = (\mathbf{F}_p)_S$). In this case, the above equations are written for the scattered fields in all regions, and then expressed in terms of the total and the incident fields as

$$\mathbf{H}^{ss}\mathbf{u}^s - \mathbf{G}^{ss}\mathbf{p}^s - \sum_{j=1}^{n_{ll}^m} \mathbf{G}^{sp_j}\mathbf{q}^{s_j} + \sum_{j=1}^{n_{ll}^m} \delta_j \boldsymbol{\Upsilon}^{sj} F_{p_j} = \mathbf{H}^{ss}\mathbf{u}^s_I - \mathbf{G}^{ss}\mathbf{p}^s_I \tag{7}$$

and

$$\mathbf{u}^{p_i} + \mathbf{H}^{p_i s}\mathbf{u}^s - \mathbf{G}^{p_i s}\mathbf{p}^s - \sum_{j=1}^{n_{ll}^m} \mathbf{G}^{p_i p_j}\mathbf{q}^{s_j} + \sum_{j=1}^{n_{ll}^m} \delta_j \boldsymbol{\Upsilon}^{p_i j} F_{p_j} = \mathbf{u}^{p_i}_I + \mathbf{H}^{p_i s}\mathbf{u}^s_I - \mathbf{G}^{p_i s}\mathbf{p}^s_I \tag{8}$$

where the right hand terms are known.

Only the main points of the formulation have been presented here. However, more details can be found in Padrón *et al.* [24], where the formulation, focused on pile groups embedded in a half-space, has been presented.

3 Dynamic stiffness of piled foundations in homogeneous strata

The dynamic stiffness matrix K_{ij} of a pile relates the vector of forces (and moments) applied at the pile top to the resulting vector of displacements (and rotations) at the same point. For a group of piles, it is assumed that the pile heads are constrained by a rigid pile-cap, and the foundation stiffness is the addition of the contributions of each pile. Fig. 2 illustrates the approached problem for a usual configuration, where L and d are used to denote the length and diameter of the piles, s refers to the distance between adjacent piles and H denotes the depth of the stratum.

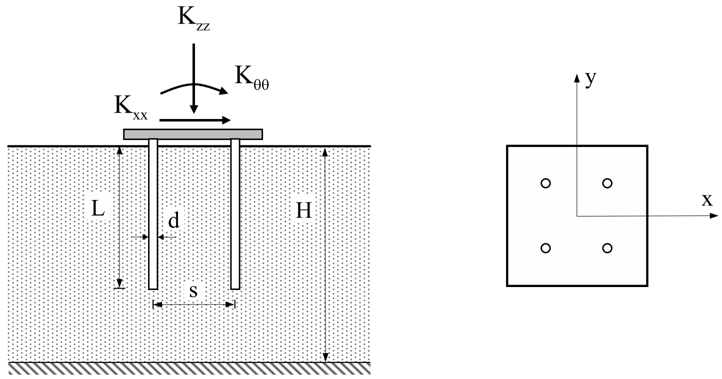

Figure 2: 2x2 pile group embedded in a stratum resting on a rigid bedrock. Problem geometry definition.

The dynamic stiffness terms for a time-harmonic excitation are functions of frequency ω, and they are usually written as

$$K_{ij} = k_{ij} + \mathrm{i} a_o c_{ij}, \tag{9}$$

where k_{ij} and c_{ij} are the frequency dependent dynamic stiffness and damping coefficients, respectively, a_o is the dimensionless frequency

$$a_o = \frac{\omega d}{c_s} \tag{10}$$

and c_s is the soil shear-wave velocity.

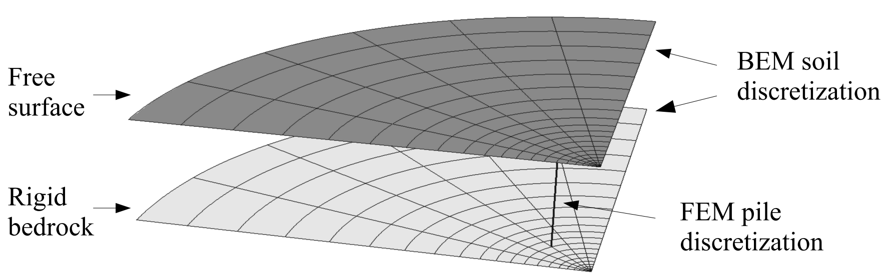

Figure 3: 2x2 pile group and stratum BEM-FEM discretization (only a quarter of the geometry).

Fig. 3 shows a sketch of the discretizations used to obtain the stiffness of different pile groups embedded in a viscoelastic homogeneous stratum resting on a rigid bedrock. As the developed software incorporates symmetry properties, only a quarter of the total geometry of the problem has to be discretized.

In what follows, vertical, horizontal and rocking impedances of different piled foundation configurations are presented. In the case of single piles, the stiffness and damping functions are normalized by the respective static stiffness. As for pile groups, the vertical and horizontal impedance functions are divided by the respective single pile static stiffness ($k^s_{zz_o}$ and $k^s_{xx_o}$) times the number (N) of piles in the group. Finally, the rocking impedances are normalized with respect to the sum of the products of the respective single pile vertical static stiffness ($k^s_{zz_o}$) times the square of the distance to the rotation axis (x_i). All results are plotted versus the dimensionless frequency defined by Eq. (10), and several ratios H/L have been considered.

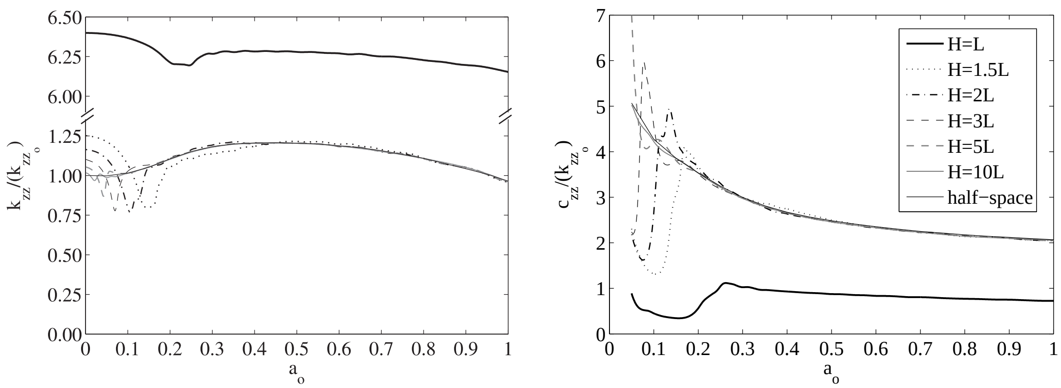

Figure 4: Vertical impedances of a single pile embedded in a homogeneous stratum.

In the first place, vertical impedances of a single pile embedded in a homogeneous stratum of depth H resting on a rigid bedrock are shown in Fig. 4 for ratios between stratum depth and pile length of $H/L = 1$ (hinged pile), 1.5, 2, 3, 5 and 10, together with the response for the half-space. It is assumed that the stratum properties are: internal damping coefficient $\beta_s = 0.05$ and Poisson ratio $\nu_s = 0.4$. The ratio between densities is $\rho_s/\rho_p = 0.7$, the aspect ratio of the pile is $L/d = 15$, and the pile/soil modulus ratio is $E_p/E_s = 10^3$.

As can be seen from the figures, the presence of a rigid bedrock below a floating pile has a strong influence on the impedances in the frequency band from the static value to approximately 1.5 times the dimensionless fundamental natural frequency of the stratum in compression-extension mode. Above this frequency, stiffness and damping coefficient are coincident with those of a floating pile in a half-space, which reveals that the main damping mechanism at intermediate and high frequencies is the energy dissipation through surface waves for both the half-space and the stratum. Below the first natural frequency, the damping coefficients are far lower than the ones corresponding to the floating pile in a half-space, because there cannot be surface waves in a stratum at low frequencies and, thus, the energy is confined in it. As expected, the static value of the vertical stiffness of a hinged pile is much higher than the corresponding to a floating pile. More precisely, it is 5.1 times higher than the corresponding to a floating pile embedded in a stratum of depth $H = 1.5L$. On the other hand, the fundamental natural frequency of the system related to the compression-extension mode is clearly highlighted in each case. Note that the influence of the presence of the rigid bedrock is still noticeable for a stratum depth five times the pile length, while it is hardly significant when the stratum depth is ten times the pile length.

Horizontal and rocking impedances of a single pile embedded in a homogeneous stratum of depth H resting on a rigid bedrock are shown in Figs. 5 and 6 respectively. The characteristics of piles and soils for these and further cases are the ones defined above and, for the sake of clarity, only results for ratios between stratum depth and pile length of $H/L = 1$ (hinged pile), 1.5 and 2, together with the response for the half-space, are presented. The range of interest in each stiffness figure has been enlarged, and the natural frequencies to which every peak is associated have been labeled for the horizontal cases.

In this case, the resonance effects are associated to both the shear and compression-extension modes. The influence of the presence of the rigid bedrock is significant approximately until the second natural frequency related to the shear mode. In this range, the impedances fluctuate about the half-space solution for both the stiffness and the damping coefficients. As for the latter, they are small at low frequencies as discussed above. For higher frequencies, the impedance behavior is similar to the one corresponding to a pile embedded in a half-space.

Vertical and horizontal impedances of a 2×2 pile group embedded in a homogeneous stratum of depth H resting on a rigid bedrock are shown in Figs. 7 and 8, respectively. Ratios between pile separation and diameter of $s/d = 2$, 5 and 10 are presented. For scale reasons, the peaks associated to the stratum natural frequencies do not appear very clearly in the figures, but their magnitudes are proportional to those of the single pile case, and even increase with the ratio s/d. Besides, the vertical impedances at intermediate and high frequencies are equivalent to those of a floating pile group embedded in a half-space. However, the group effect is predominant over the influence of the presence of the rigid bedrock. On the other hand, for the horizontal case, the influence of the rigid bedrock is relatively much more important, even though the group effect is still predominant. The impedances fluctuate about the half-space solution, and the amplitude of this fluctuation increases with the ratio s/d.

Table 1 presents the comparison between the values of dimensionless natural frequencies obtained with the presented coupling model and those analytically computed for an undamped stratum. Only the values obtained for the horizontal impedance of a pile group with a ratio $s/d = 10$ are presented. As can be seen, the proposed method predicts adequately the actual fundamental frequencies.

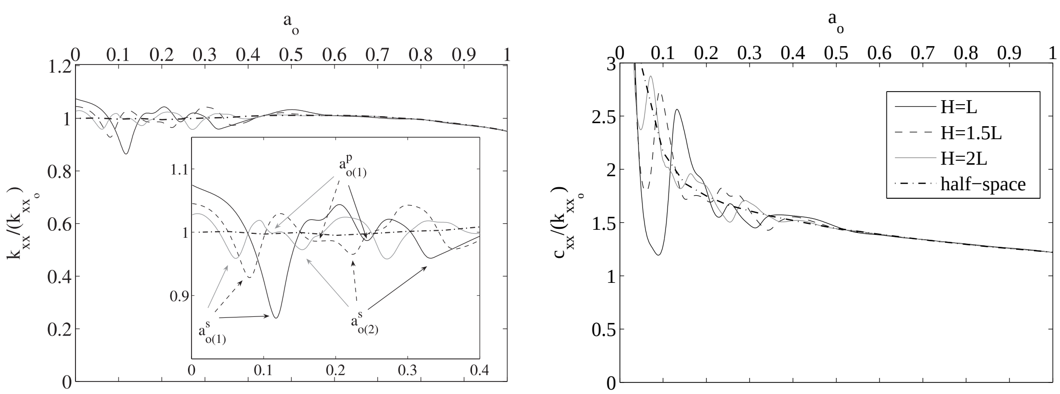

Figure 5: Horizontal impedances of a single pile embedded in a homogeneous stratum.

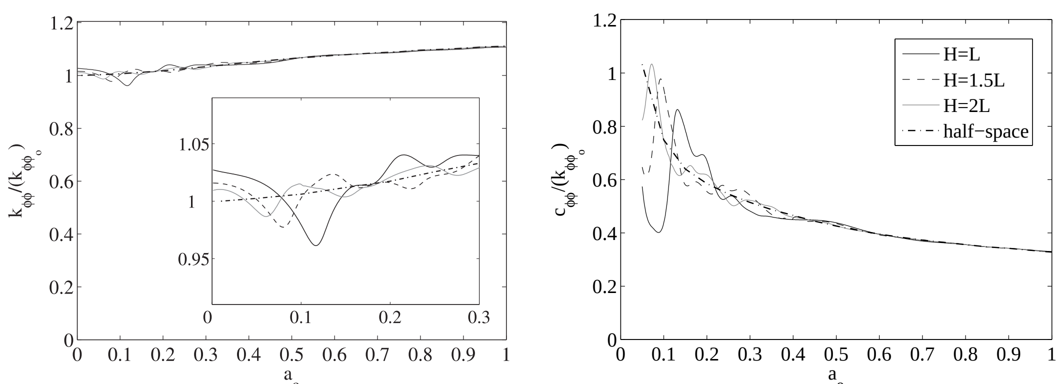

Figure 6: Rocking impedances of a single pile embedded in a homogeneous stratum.

	Stratum natural frequencies in			
	shear mode		compression-extension mode	
	$a^{s}_{o(1)}$	$a^{s}_{o(2)}$	$a^{p}_{o(1)}$	**H/L**
Undamped stratum	0.11	0.31	0.26	1
Pile group-soil system	0.12	0.33	0.25	
Undamped stratum	0.07	0.21	0.17	1.5
Pile group-soil system	0.09	0.23	0.17	
Undamped stratum	0.05	0.16	0.13	2
Pile group-soil system	0.07	0.16	0.12	

Table 1: Comparison between natural frequencies for an undamped stratum and for a 2×2 pile group-stratum system. $s/d = 10$.

Finally, rocking impedances of a 2×2 pile group embedded in a homogeneous stratum on a rigid bedrock are shown in Fig. 9. Only the ratio s/d =10, for which the influence of the rigid bedrock is stronger, has been displayed in order to illustrate the fact that the rocking impedances of pile groups are little influenced by the presence of the bedrock.

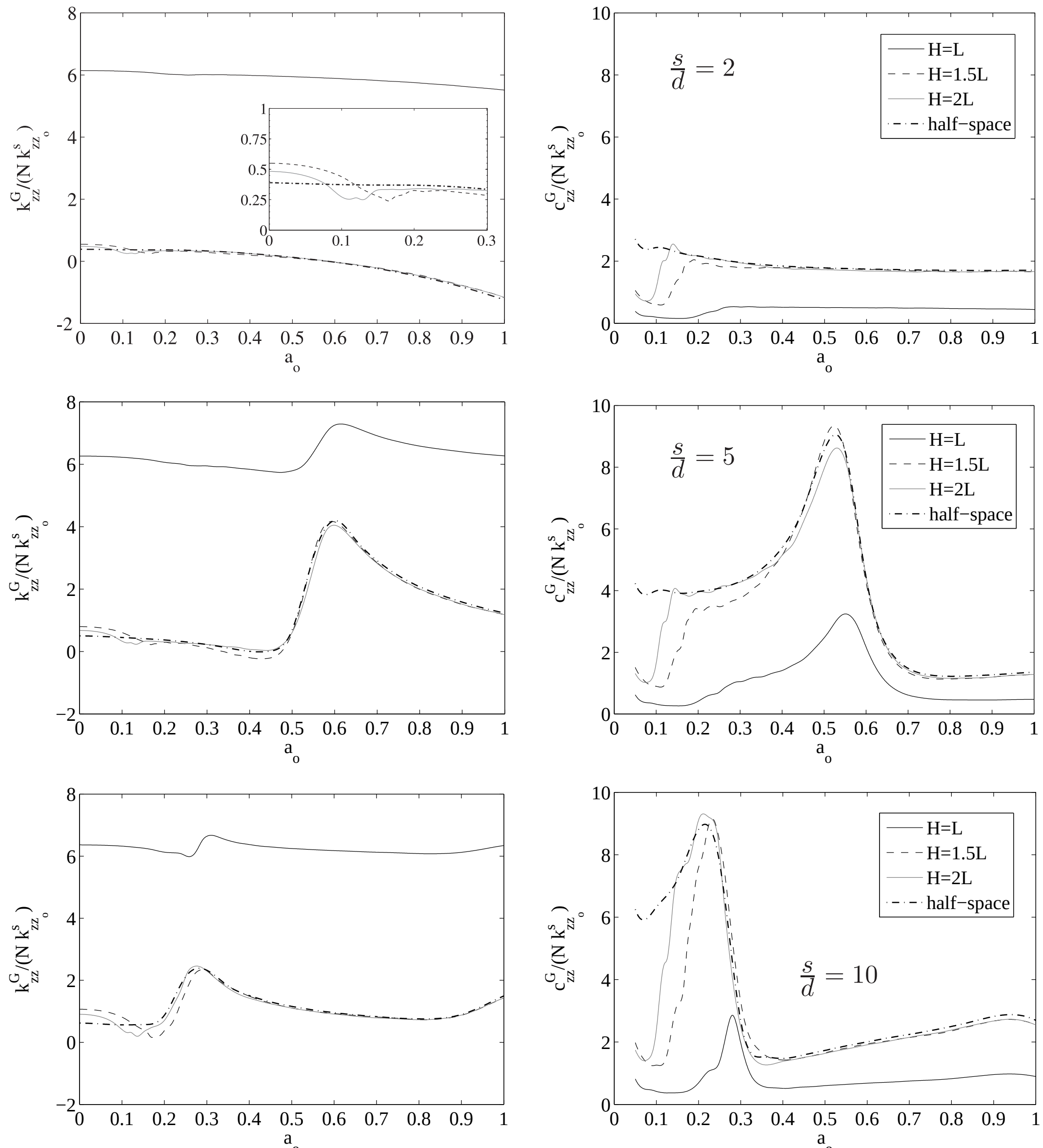

Figure 7: Vertical impedances of a 2x2 pile group embedded in a homogeneous stratum. s/d=2, 5 and 10 (from top to bottom).

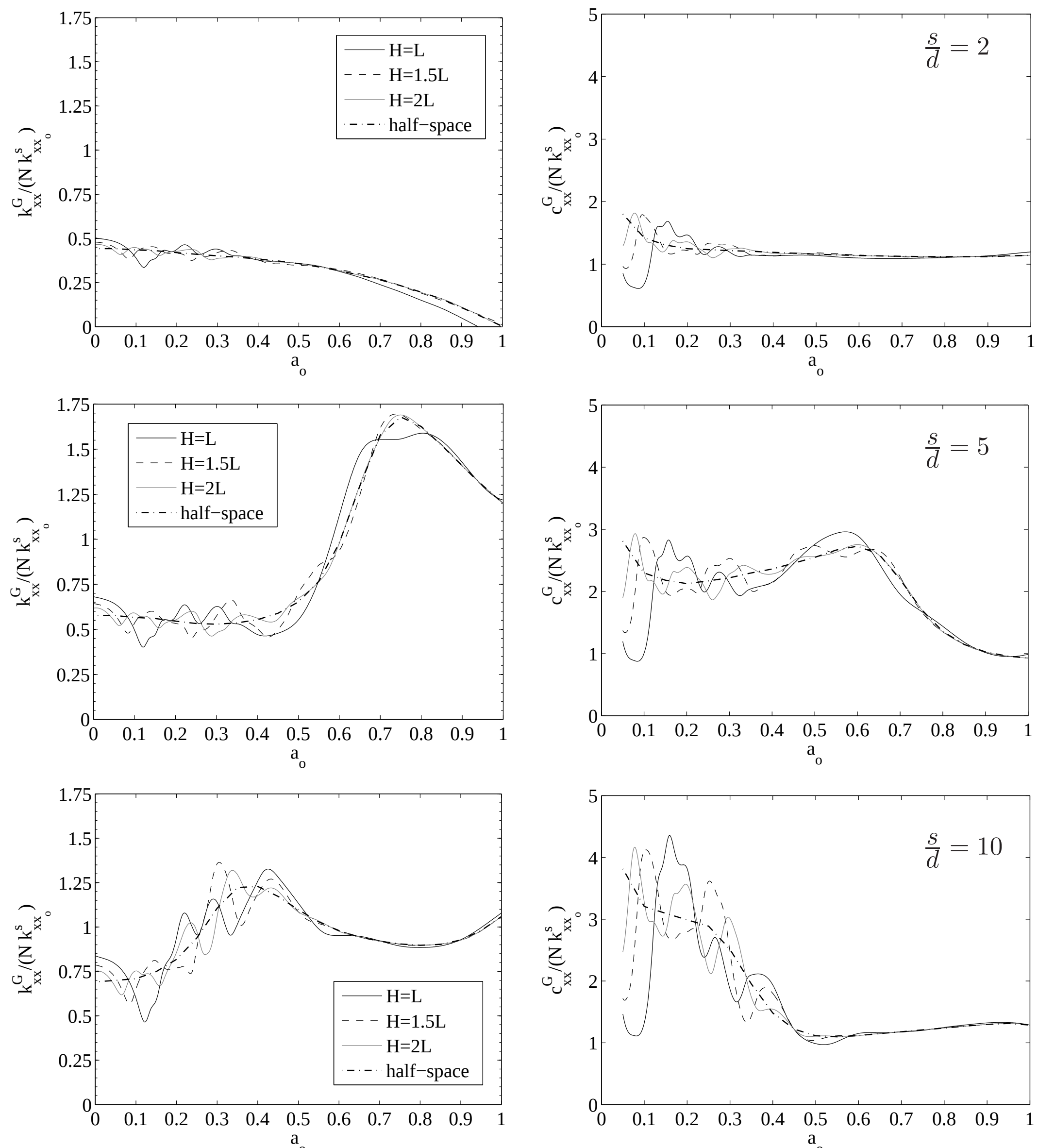

Figure 8: Horizontal impedances of a 2x2 pile group embedded in a homogeneous stratum. s/d=2, 5 and 10 (from top to bottom).

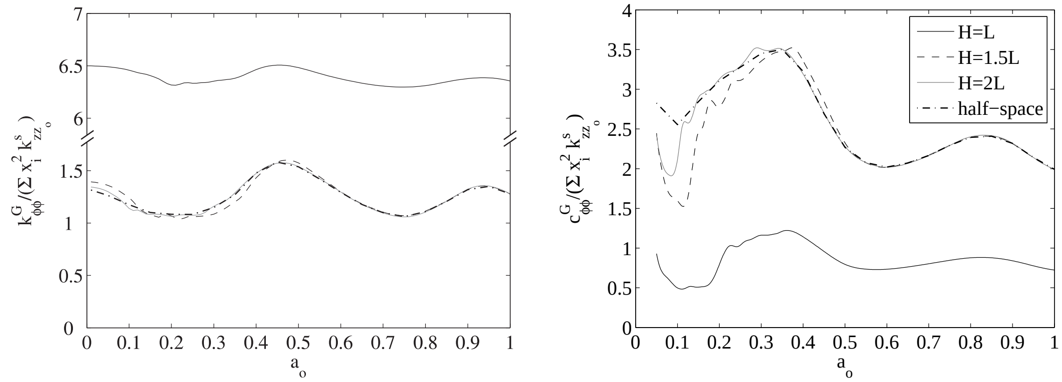

Figure 9: Rocking impedances of a 2x2 pile group embedded in a homogeneous stratum. s/d=10.

4 Seismic response of pile groups to vertically-incident shear waves

The influence of the stratigraphy on the seismic behavior of a piled foundation is studied in this section. To this end, the seismic response of a hinged pile group under vertically-incident plane S-waves is analyzed. The cases included in this experiment are sketched in Fig. 10. Three different layered soils resting on a rigid bedrock, formed by up to four different layers with shear wave velocity increasing with depth, are considered. Besides, two limiting cases corresponding to homogeneous profiles with the properties of the softest and stiffest layers, respectively, as well as the half-space case, are also taken into account. The properties of the stiffest layer are taken as those of a reference soil. As it is well known that the number of piles is not a significant parameter in the horizontal seismic response of piled foundations (see e.g. [16]), only the case of a square 3×3 hinged pile group is presented.

The non-dimensional properties of the reference soil (with shear wave velocity c_s) and pile group are: internal damping coefficient of the soil $\beta_s = 0.05$, Poisson ratio of the soil $\nu_s = 0.4$, ratio between densities $\rho_s/\rho_p = 0.7$, pile/soil modulus ratio $E_p/E_s = 10^2$, aspect ratio of the piles $L/d = 15$, ratio between stratum depth and pile length $H/L = 1$ (hinged piles), and ratio between pile separation and diameter $s/d = 10$. Damping coefficient, Poisson ratio and density are kept constant for all layers.

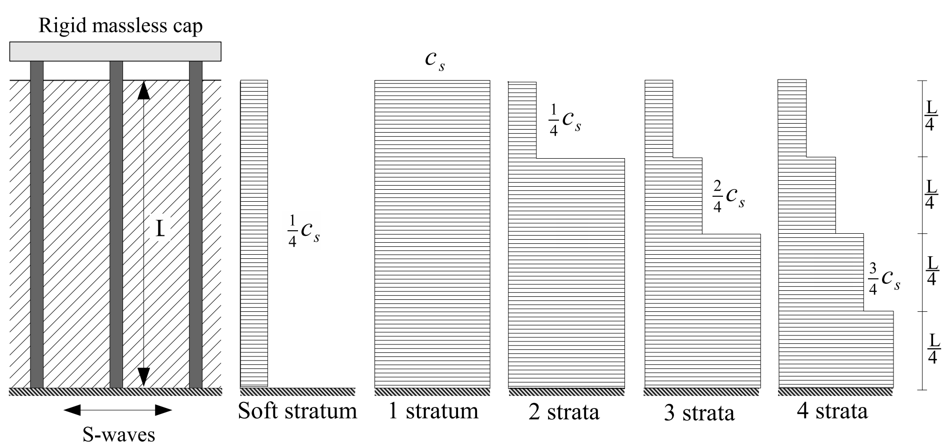

Figure 10: Sketch of studied soil profiles.

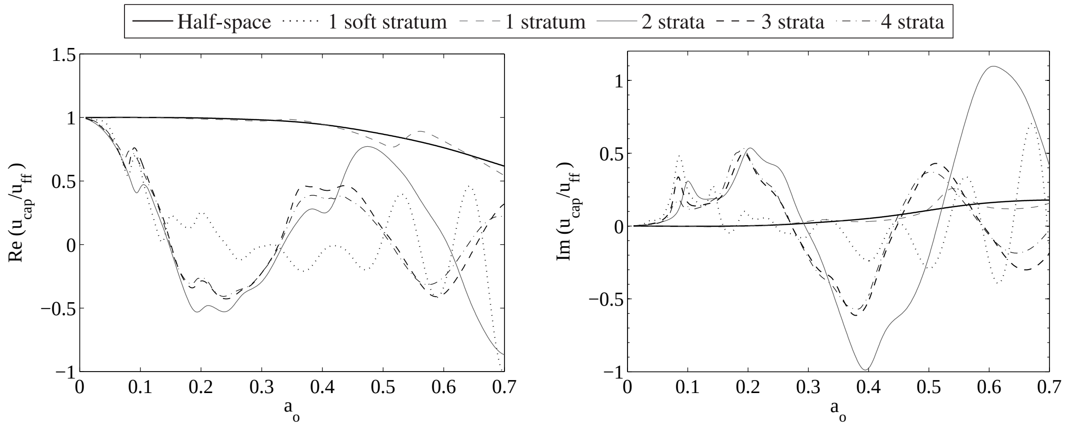

Figure 11: Time-harmonic displacement transfer functions at the pile cap.

The first step is obtaining the time-harmonic transfer functions relating horizontal displacement amplitudes at the pile cap (u_{cap}) to the free field surface horizontal displacement (u_{ff}), for vertically-incident plane time-harmonic S-waves. Real and imaginary parts of these transfer functions are presented in Fig. 11 for the six profiles defined above, being a_o referred to the stiffest soil for all cases. Comparing reference soil one-stratum and two-strata cases, it can be seen that taking into account a soft layer atop yields to much more rapidly decreasing transfer functions (as highlighted before, for instance, in [16, 20]), while the addition of intermediate shear wave velocity layers in between does not alter significantly the response up to $a_o = 0.4$ with respect to the two-strata profile. Also, the difference between the transfer functions for the half-space and the stratum are rather small, only noticeable at the stratum natural frequencies.

A phenomenon that can be studied here, in reference to the difference between homogeneous and stratified strata transfer functions, is the horizontal deformation of the free surface. Assuming S-waves acting along direction y, Fig. 12 shows, for the one-layer and two-layer profiles, and several frequencies, the real part of the horizontal displacements of points on the free surface placed along axis y and x, for horizontal coordinates from 12 to 82 times the diameter of the piles. It can be seen that the perturbation generated by the presence of the piles on the incident field is much more stronger, both in amplitude and extension, when a soft soil stratum exists atop, which is related to the more rapidly varying transfer function of this case. Obviously, the magnitude and shape of this perturbation is function of the wave length in the soil. In all cases, the perturbation is not significant at distances from the foundation axis higher than $70d$.

On the other hand, Fig. 13 presents the distributions of incident field and central pile displacements along depth for the four-layer soil profile. Non-dimensional frequencies $a_o = 0.09$, 0.20 and 0.30 are shown. It can be seen that the pile is able to keep approximately to the incident field within the deep layers, where the wave length is long enough. In the upper layers, on the contrary, where wave lengths are shorter, the pile is not flexible enough so as to follow the free field ground motion, which causes the difference between pile cap and free field surface motions. Additionally, Fig. 14 compares the deformed shapes of all piles in the 3×3 pile group, and also of a fixed head single pile (no rotations allowed), for the four-layer soil profile. It can be seen that, for a certain non-dimensional frequency, all deformed shapes are very close one to another. Thus, there seems to be no significant pile-to-pile interaction effects under seismic excitation in the problem at hand. However, as this is only shown for this particular case, general conclusions would need of further studies.

Acceleration time-histories and response spectra can now be obtained for particular cases. The chosen problem, whose parameters are summarized in Table 2, is that of a group of concrete piles

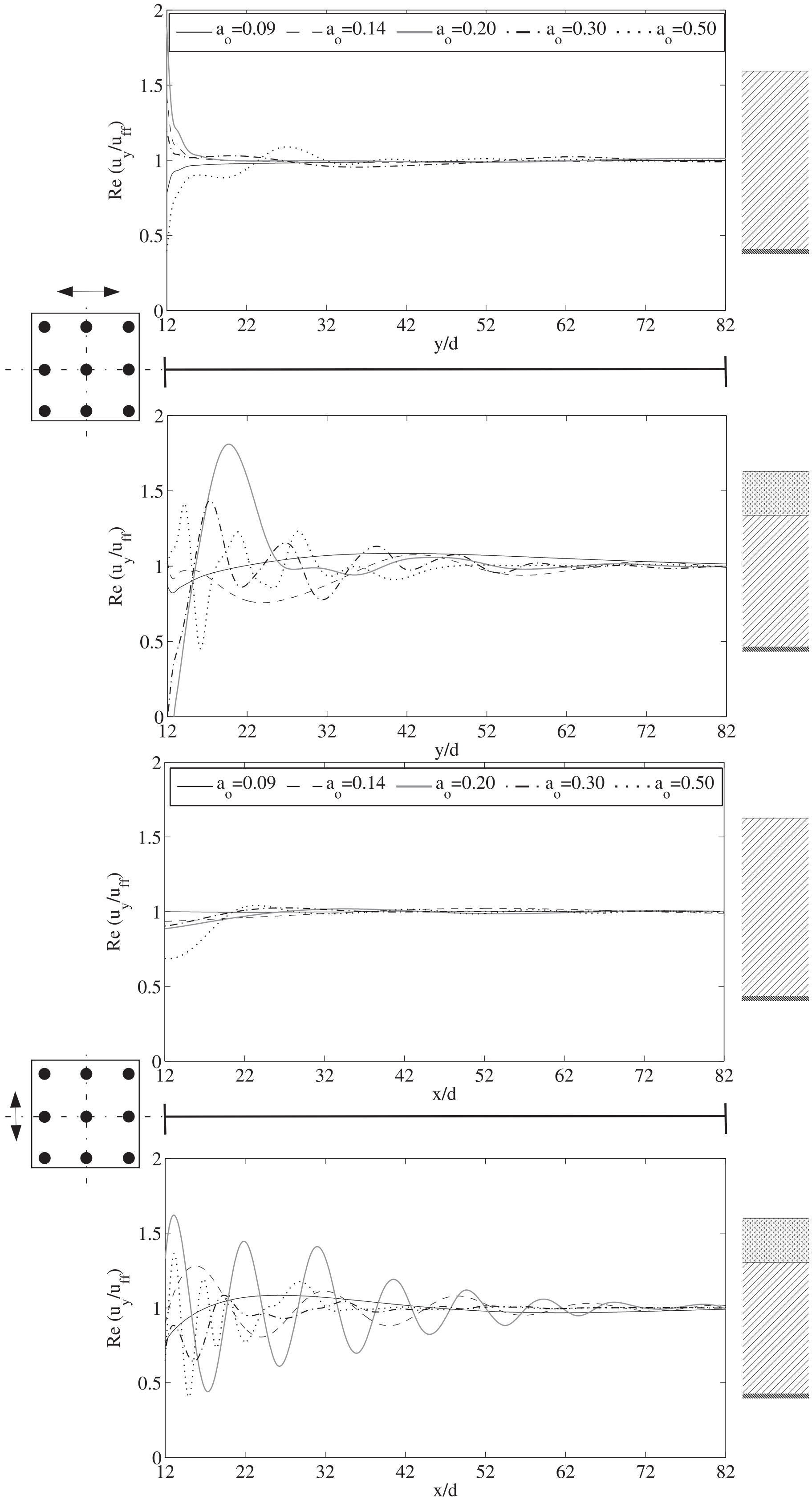

Figure 12: Horizontal deformation of free surface.

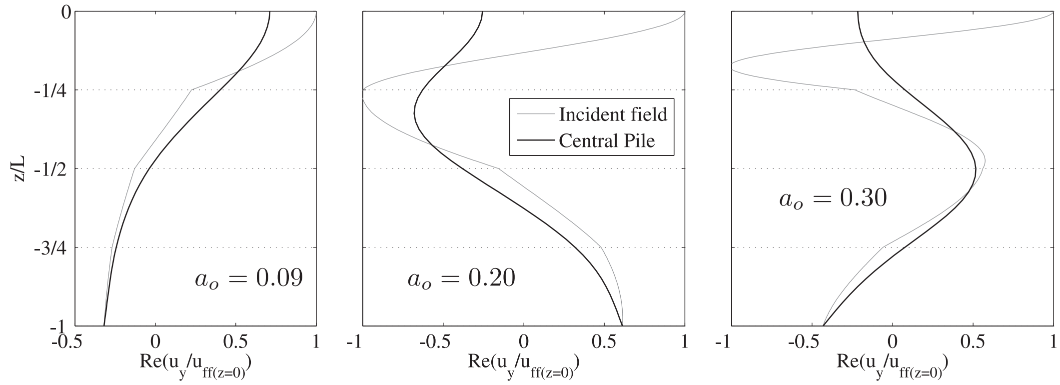

Figure 13: Distributions of incident field and central pile displacements along depth for the four-layer soil profile.

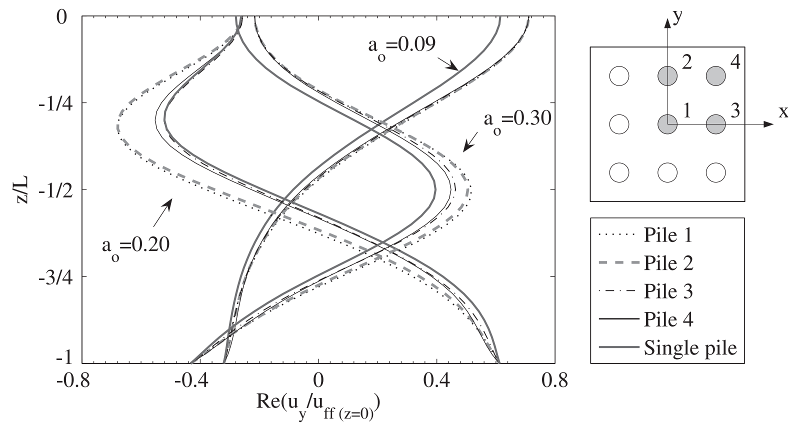

Figure 14: Comparison of deformed shapes of all piles in the group, and of a single pile, for the four-layer soil profile.

of diameter $d = 1.0$ m., being worth noting that the resulting properties for the softest layer correspond to the case of a considerably soft soil. The system is subjected to the two following simulated earthquakes, specified at the free surface:

- The N-S component recorded at the Imperial Valley Irrigation District substation in El Centro, California, during the Imperial Valley, California, earthquake of May 18, 1940.
- The S50W component recorded at Bonds Corner substation in El Centro, California, during the Imperial Valley, California, earthquake of October 15, 1979.

Soil	**Piles**	**Pile group**
$c_s = 239\ m/s$	$E_p = 2.76 \cdot 10^{10}\ N/m^2$	$s/d = 10$
$\rho_s = 1750\ kg/m^3$	$\rho_p = 2500\ kg/m^3$	$L/d = 15$
$\nu_s = 0.4$	$d = 1\ m$	$H/L = 1$

Table 2: Reference soil, pile and pile group properties.

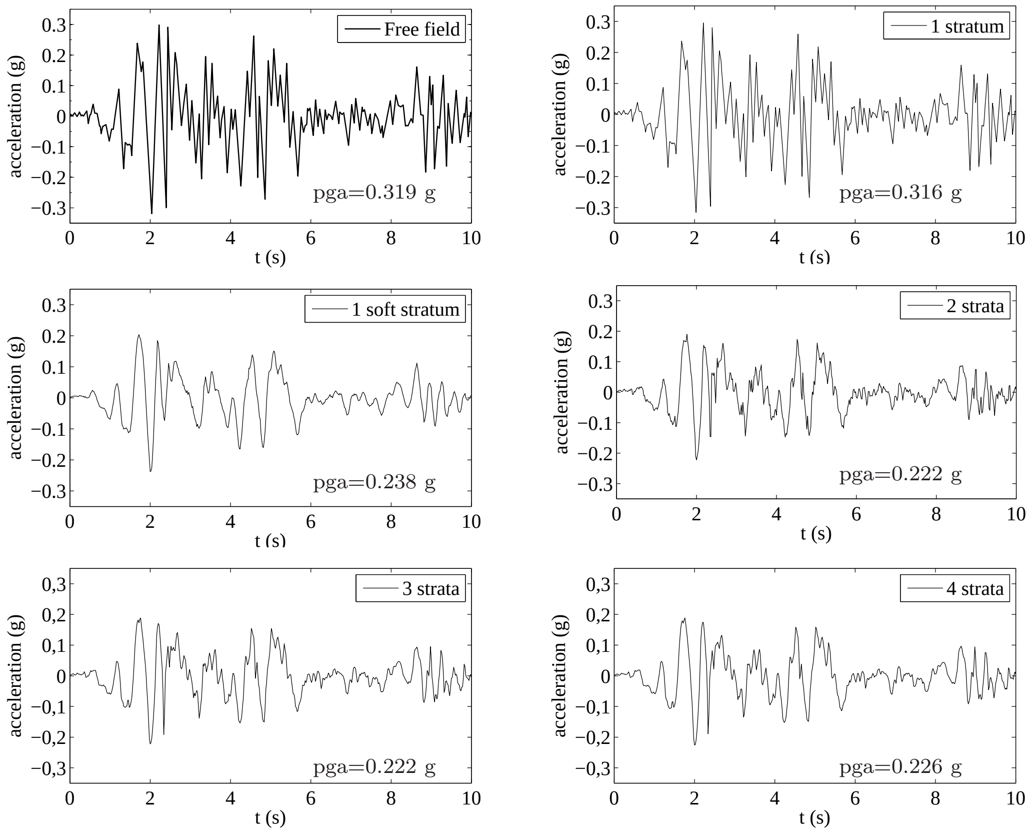

Figure 15: Response acceleration histories for El Centro (1940) earthquake specified at the free surface.

Figs. 15–18 show the acceleration time-histories and response spectra ($\xi = 5\%$), for both earthquake ground motions, all of them measured at the pile-cap. As expected in view of the transfer functions presented above, it can be seen that the response of the piled foundation embedded in a half-space or in a stratum, both with the reference soil properties, are almost coincident with the excitation. As for the rest of cases, the acceleration response spectra values are significantly smaller in the range of periods shown in Figs. 16 and 18. However, there is not a clear tendency between the response spectra for the different profiles as for to say that the more layers considered, the more conservative estimate, neither the contrary. For instance, for periods below 0.2 seconds, the response for the soft stratum is the lowest one, while between 0.25 and 0.4 seconds, it is the two-strata profile whose values are the smallest.

Up to now, the same seismic excitation has been specified at the free surface for all soil profiles, but it is also worth investigating the system behavior when the seismic input is specified at the bedrock. In this case, different amplification phenomena due to the soil stratigraphy take place in each profile, as can be seen if Fig. 19, which presents the free field and pile cap acceleration response spectra ($\xi = 5\%$) obtained when El Centro (1940) earthquake is specified at the bedrock. Indeed, the strong ground motion, measured at the free surface, is significantly amplified, especially at frequencies near the strata natural frequencies. However, the attenuating effect of the piled foundation seen before, is also evident in this case. As expected, reference soil one-stratum free field and pile cap response spectra are again almost coincident, but as for the rest of cases, the presence of the piles always leads to smaller responses.

Since further parametric studies should be carried out with a greater variety of profiles, including

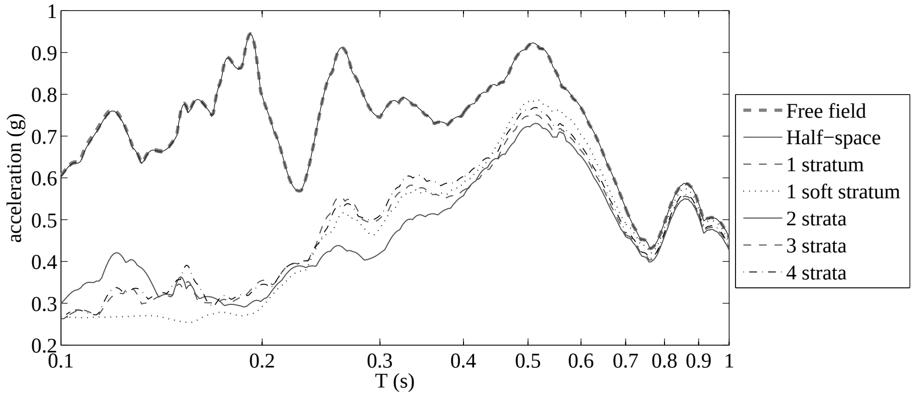

Figure 16: 5 per cent-damped acceleration response spectra for El Centro (1940) earthquake specified at the free surface.

parameters such as densities, damping coefficients and Poisson ratios, conclusions from this study may not be generalized. On the other hand, only the horizontal response has been treated here but, depending on the problem, the rocking behavior could also be an important parameter.

5 Conclusions

In this paper, a BEM-FEM coupling model previously presented by the authors has been used to compute dynamic impedances and kinematic response of piled foundations embedded in viscoelastic homogeneous strata resting on a rigid bedrock. This way, the two first steps of the substructuring method are performed.

Piles have been modelled by FEM as beams according to the Bernoulli hypothesis, and strata have been modelled by BEM as continuum, semi-infinite, isotropic, homogeneous, linear, viscoelastic media. The model not only allows the dynamic analysis of piled foundations embedded in a half-space or in a stratum resting on a rigid bedrock, but also in multilayered soils of generic stratigraphy, including deposits and inclusions. Any kind of geometry can be modelled by boundary discretizations, thus, more complex stratigraphies and topographies than those reported in this paper can be analyzed.

Firstly, several results of vertical, horizontal and rocking impedances for single piles and three different configurations of 2×2 pile groups embedded in a stratum have been presented. Several depths of the stratum have also been studied. From the analysis of these results, the following conclusions can be drawn:

- The pile-soil system presents peaks associated to the stratum natural frequencies that the numerical model is able to predict adequately.
- The vertical impedance functions of a piled foundation embedded in strata of the analyzed depths are equivalent to those embedded in a half-space at frequencies above 1.5 times the fundamental natural frequency of the stratum in the compression-extension mode. Besides, the foundation vertical behavior is only influenced by this natural frequency.
- The influence of the stratum depth over the horizontal impedance functions of a piled foundation is significant over a broader band of frequencies. Thus, several peaks associated to both the shear and the compression-extension modes appear in the foundation response.

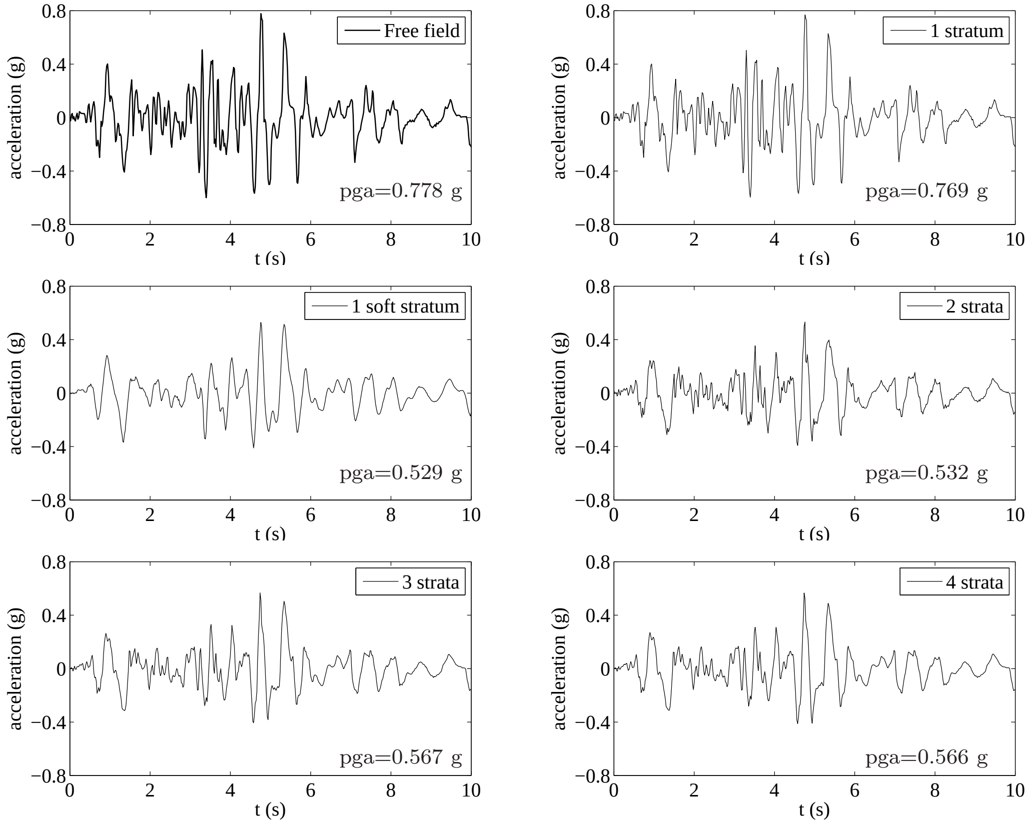

Figure 17: Response acceleration histories for El Centro (1979) earthquake specified at the free surface.

- This influence is even more evident in the damping functions, which at low frequencies are much smaller than the corresponding to the half-space. On the contrary, their values are similar at higher frequencies, which reveals that the main damping mechanism at intermediate and high frequencies is the energy dissipation through surface waves for both the half-space and the strata.
- The influence of the presence of the rigid bedrock is still noticeable for a stratum depth five times the pile length.
- The group effect is predominant over the influence of the presence of the rigid bedrock, especially in vertical and rocking impedances, in which the peaks associated to the natural frequencies of the stratum are of small magnitude. However, the effects of the presence of the bedrock on the horizontal behavior are stronger and become apparent along a broader frequency band. In all cases, the influence of the rigid bedrock increases with the ratio s/d.
- The rocking behavior is the less influenced by the presence of a rigid bedrock.

Also, additional experiments (not shown here for the sake of brevity) that have been carried out in order to investigate the role of the ratio E_p/E_s, show that the frequency band in which the foundation response is influenced by the rigid bedrock broadens with the increase of the soil stiffness. Also, a larger number of natural frequencies of the stratum in both the shear and the compression-extension modes become evident for the horizontal and rocking cases as the soil stiffness increases. At the same time, the group effect becomes more evident as the ratio E_p/E_s turns higher.

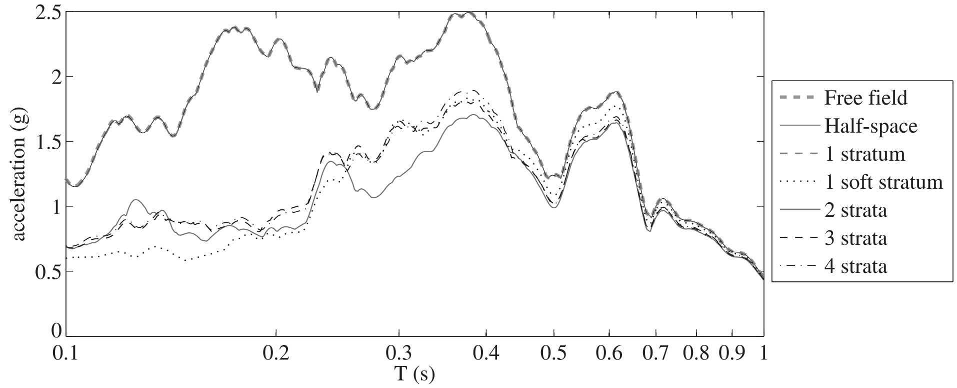

Figure 18: 5 per cent-damped acceleration response spectra for El Centro (1979) earthquake specified at the free surface.

Secondly, the seismic response of a square 3×3 hinged pile group embedded in different soil profiles and under vertically-incident plane time-harmonic shear waves and two different strong ground motions, have been studied. General conclusions cannot be drawn without more and deeper analysis in the subject but, as for the presented case, it has been shown that:

- the presence of a soft layer atop the soil yields to much more rapidly decreasing displacement transfer functions than those corresponding to foundations in the reference homogeneous soil. In fact, two different trends are clearly defined, depending on whether the soft layer is considered or not.
- the addition of further intermediate shear wave velocity layers in between is of minor importance.
- the incident field at the free surface is perturbed by the presence of the piled foundation, being the magnitude of this perturbation larger when a soft layer exists atop. The maximum value of this perturbation is of similar order in both the direction of motions induced by the S-waves and its perpendicular.
- pile-to-pile interaction under seismic excitation is almost nonexistent.
- piled foundations embedded in the non-homogeneous soil profiles studied here filter out a great part of the harmonic components of the seismic input, in such a way that the resulting acceleration response spectra are significantly lower than those corresponding to the free field.
- the simplification of the soil profile to just one stratum or to a half-space would lead to over- or underestimating, depending on the chosen properties, the excitation at the base of a superstructure in a substructuring analysis.
- these conclusions are valid for earthquake motions specified at both the free surface or at the bedrock.

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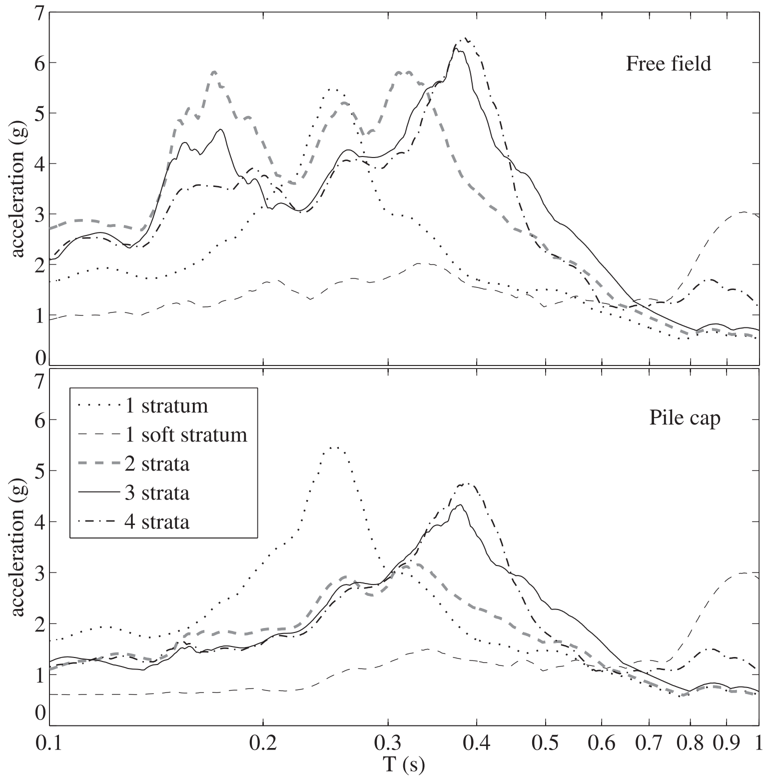

Figure 19: 5 per cent-damped acceleration response spectra for El Centro (1940) earthquake, specified at the bedrock.

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