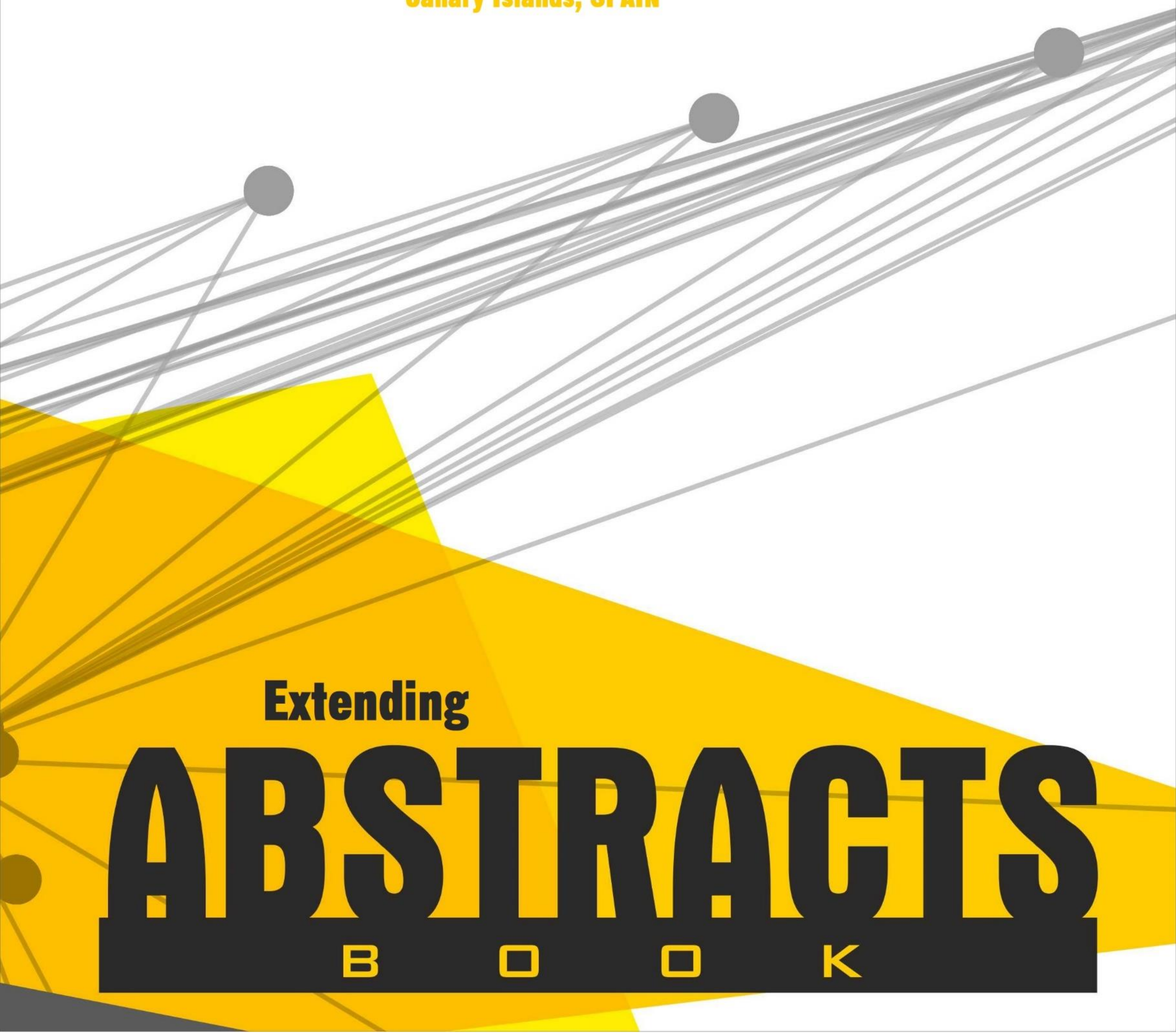

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Pile-to-pile kinematic interaction factors for vertically-incident shear waves

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1. Introduction – When studying the dynamic behaviour of pile group foundations, the total response of the system cannot be computed simply as the addition of the response of each individual pile because of the pile-to-pile interaction effects. This interaction between the piles in the group is produced by the scattered field that the vibration of each pile generates. Pile-to-pile interaction factors [1] are generally used in order to measure these effects and are defined as the response of a 'receiver' pile to the diffracted field generated by a 'source' pile. There is a wide number of works in the literature concerning the interaction factors that are obtained by assuming a prescribed force or displacement at the head of the source pile, i.e. when the source pile is inertially loaded. However, the kinematic counterpart of this problem has received fewer attention. In the work at hand, kinematic pile-to-pile interaction factors are presented by assuming that the source pile is excited by vertically-incident shear waves.

2. Methodology - The interaction factors are computed through a three-dimensional time-harmonic model for the analysis of pile foundations [2] in which the soil behaviour is modelled through the integral reciprocity theorem and the use of specific Green's functions for the layered half space [3]. On the other hand, piles are considered as Timoshenko's beam finite elements and are treated as load lines acting within the soil, so its presence does not affect the soil continuity. The coupling between pile and soil formulations is done by imposing compatibility and equilibrium conditions in terms of displacements and soil-pile interaction tractions, respectively.

By assuming harmonic displacements and forces, and omitting the term $e^{\mathrm{i}\omega t}$, the finite element system of equations of the piles results in:

$$(\mathbf{K} - \omega^2 \boldsymbol{M})\boldsymbol{u} - \boldsymbol{Q}\boldsymbol{q} = \boldsymbol{F}^{\text{ext}} \qquad (1)$$

where $\boldsymbol{K}, \boldsymbol{M}$ are the stiffness and mass matrices, ω is the angular frequency, $\boldsymbol{u}, \boldsymbol{q}$ are the vectors containing the complex amplitudes of the nodal displacements and soil-pile interaction tractions, $\boldsymbol{Q}$ is the matrix that transform distributed loads into the equivalent nodal forces and $\boldsymbol{F}^{\text{ext}}$ is the vector containing the amplitudes of the external forces acting on the pile due to the boundary conditions (at the pile head or tip).

Regarding the soil equations, the integral expression of the reciprocity theorem [4] in elastodynamics assuming harmonic variables is:

$$\int_{\Gamma} \boldsymbol{p}^{*}\boldsymbol{u}\, d\Gamma + \int_{\Omega} \boldsymbol{b}^{*}\boldsymbol{u}\, d\Omega = \int_{\Gamma} \boldsymbol{p}\boldsymbol{u}^{*}\, d\Gamma + \int_{\Omega} \boldsymbol{b}\boldsymbol{u}^{*}\, d\Omega \qquad (2)$$

where Ω is the domain under study (soil) whose boundaries are denote by Γ (free-surface), $\boldsymbol{u}, \boldsymbol{p}, \boldsymbol{b}$ represent the displacements, tractions and body forces of the problem, and the star index corresponds to the variables of the known fundamental solution required for this formulation. In this work, the Green's functions for the layered half space proposed by Pak and Guzina [2] are used as fundamental solution. These Green's functions represent the response at any point of a horizontally-layered half space to a unitary punctual force applied at each of the three orthogonal directions of the space. Thus, the first integral is cancelled as the used fundamental solution satisfies the zero tractions condition of the free-surface, while the second integral is reduced to the displacements at the collocation point. On the other hand, as no tractions are acting on the free-surface, the third integral is also cancelled. Finally, as mentioned before, the only body forces acting within the soil correspond to the interaction tractions applied at the load lines that represent the piles. With the aforementioned considerations, the integral equation results in:

$$\boldsymbol{u} = \int_{\Gamma_p} \boldsymbol{q}^s \boldsymbol{u}^* \, d\Gamma_p \tag{3}$$

which, after applying the proper discretization of the piles and imposing equilibrium conditions ($\boldsymbol{q}^s = -\boldsymbol{q}$), can be written in matrix form as (see [2] for more details):

$$\boldsymbol{u} + \boldsymbol{G}\boldsymbol{q} = 0 \tag{4}$$

In order to study the pile response to incident planar waves, it is assumed that the total displacement field is obtained as the superposition of the known incident field ($\boldsymbol{u_I}$) and the scattered field produced by the presence of the piles [5]. Noting that the above expression is written in terms of the scattered field, the soil equations can be rewritten in terms of the total displacements of the piles as:

$$\boldsymbol{u} + \boldsymbol{G}\boldsymbol{q} = \boldsymbol{u_I} \tag{5}$$

For the computation of the kinematic interaction factors only the displacements of the incident field corresponding to the source pile are considered.

3. Results and Discussion – Image 1 depicts the definition of the problem that is solved in order to obtain the kinematic interaction factors. The source pile (1) is assumed to be excited by vertically-incident planar shear waves, while the receiver pile (2) only is excited by the scattered field that the presence of the source pile produces. The kinematic interaction factor is then obtained as the ratio between the displacement at pile head of the receiver pile over the one of the source pile (u_2/u_1). In this work, only the case in which the piles are aligned parallel to the direction of the excitation is presented for brevity's sake. However, the situation where the piles are aligned perpendicular to the direction of the excitation has also been studied.

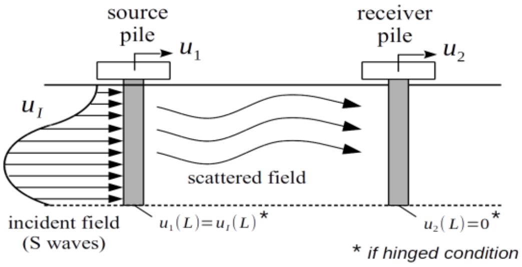


Image 1. Sketch of the problem

Table I. Properties of pile and soil

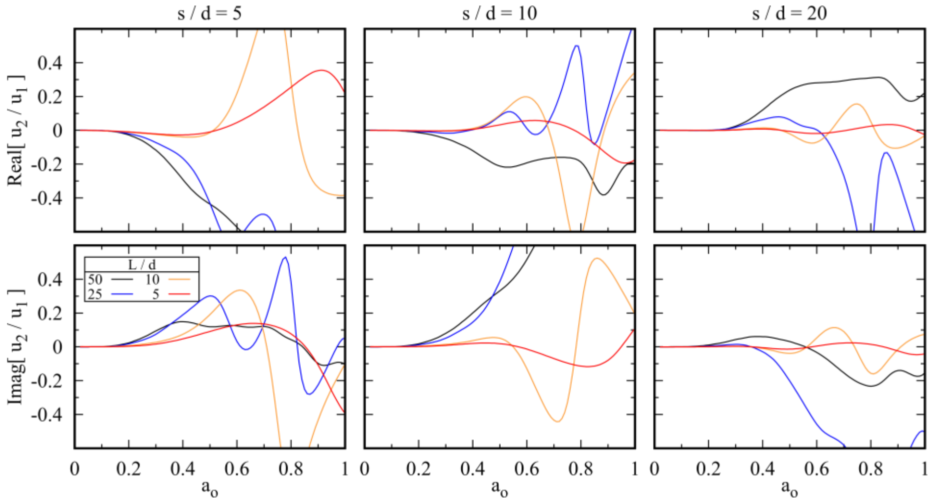
property name	pile	soil
Young's modulus (E)	220 GPa	220 MPa
density (ρ)	2500 kg/m^3	1760 kg/m^3
Poisson's coefficient (ν)	0.2	0.4
damping ratio (β)	0 %	5 %

The material properties assumed for pile and soil are listed in Table I, which corresponds to typical values used in the dynamic analysis of pile foundations ($E_p/E_s = 1000, \rho_s/\rho_p = 0.7$). Two soil profiles will be considered: a homogeneous half space, and a soil layer over an infinitely rigid bedrock. The rotation of the pile head is restricted. On the other hand, the boundary conditions of the pile tip correspond to free-tip or hinged-tip for the homogeneous and layer profiles, respectively. For this last profile, a pile length (L) equal to the layer thickness (H) is assumed.

The influence of different parameters on the interaction effects is analysed along this section: the pile aspect ratio (L/d), the pile separation distance (s/d) and the pile radius to layer thickness ratio (r/H). Note that those parameters are expressed in a dimensionless form. A pile length $L = 15$ m is considered in order to obtain their dimensional magnitudes.

First, Image 2 presents the kinematic interaction factors for the homogeneous profile for different pile aspect ratios and separation distances between the source and receiver pile. Their real and imaginary components are plotted as functions of the dimensionless frequency $a_o = \omega d/c_s$, being c_s the shear wave velocity of the soil. The results show how both the pile aspect ratio and the separation distance have a significant influence on the interaction factors. Generally speaking, the kinematic interaction factors decrease as the pile becomes shorter and the distance between the piles increases. However, the latter effect is not clearly seen for long piles in the high-frequency range. For low frequencies the kinematic interaction vanishes (as expected), and the interaction effects start to appear at smaller frequencies for slender piles. The representation of the interaction factors through their real and imaginary components allows to highlight how the movement of the receiver pile is generally out of phase with the displacements of the source pile.

For slender piles and high frequencies, the kinematic interaction factors seem to significantly increase. In order to explain this effect, it should be considered that the interaction factors represent the ratio between the displacements of the receiver and source piles. Assuming that the movement of the source pile can be approximated to the one of a single pile, the high values of the interaction factors are produced due to the small displacements that the single pile presents at high frequencies (and not because a high oscillation of the receiver pile). This effect is illustrated in Image 3, where the head displacements of the source and receiver piles are plotted in terms of the free-field displacement at surface level (u_{ff}).



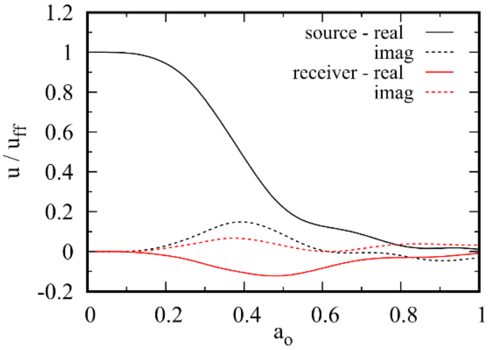


Image 3. Head displacements of the source and receiver piles. L/d=25, s/d=5, homogeneous soil

Image 4 shows the kinematic interaction factors now assuming the profile of the soil layer over the rigid bedrock. As the soil resonance effects dominate the response of the piles in this configuration, the influence of the ratio between the pile radius and the layer thickness r/H is studied instead of the one of the pile aspect ratio. In addition to this, the results are now plotted against the frequency expressed in terms of the soil layer fundamental frequency $\omega_g = \pi c_s/(2H)$. Attending to the results, the resonance effects are clearly seen in the interaction factors: once the frequency of the excitation reaches the fundamental frequency of the soil layer, the interaction between the piles becomes evident. For frequencies below the resonance, only the real part of the interaction factors is nonzero and its negative sign indicates that the displacements of the receiver pile oppose to the ones of the active pile. Regarding the effects of the radius-thickness ratio, as it becomes higher (i.e. shorter piles with respect to the layer height), the pile-to-pile kinematic interaction is magnified, while for very slender piles ($r/H < 0.04$) virtually no interaction is found around the fundamental frequency of the soil. On the other hand, as the pile separation distance increases, the kinematic interaction factors are reduced. This effect of the separation distance is more evident for this layer profile than for the case of the homogeneous half space.

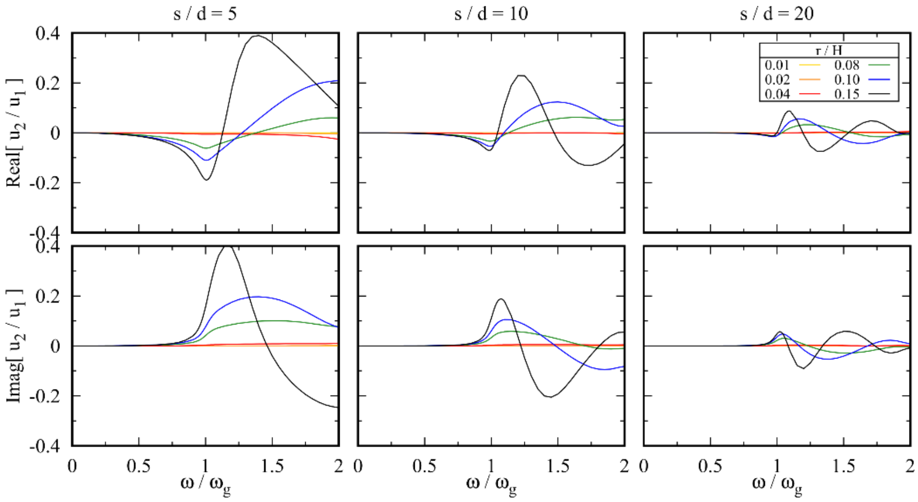


Image 4. Kinematic interaction factors for the soil layer over a rigid bedrock

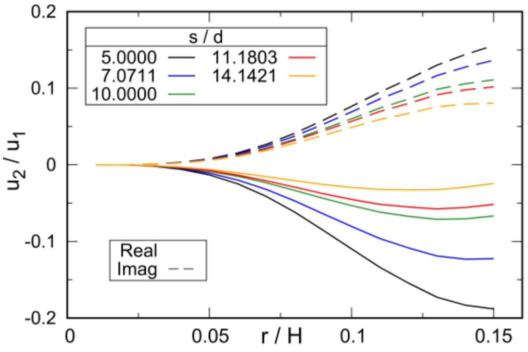


Image 5. Kinematic interaction factors at the fundamental frequency of the soil layer

In order to further illustrate the influence of the two studied parameters on the kinematic interaction factors for the soil layer, Image 5 displays their values at the fundamental frequency of the profile. A smooth increment of the interaction factors with the radius-thickness ratio is found, saturating their values at the higher studied value. On the other hand, an exponentially decreasing relation with the separation distance is found for the kinematic interaction factors when plotted against this parameter.

4. Conclusions - The obtained results can be used to better understand the interaction effects between piles subjected to seismic loads, e.g. the negative real values of the interaction factors explain why the kinematic response of pile groups at medium-low frequencies is smaller than the one of a single pile. The pile-to-pile kinematic interaction factors can be also used as a numerical tool in order to incorporate the group effects into simplified models, such as beam-on-dynamic-Winkler-foundation, through a superposition method [6,7].

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