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Dynamic response of piled foundation blocks considering pile-to-pile interaction

Amanda Morais Oliveira and Josué Labaki

School of Mechanical Engineering, University of Campinas, Campinas SP Brazil

Abstract. This article presents a numerical model and case study of the dynamic response of piled foundation blocks. The problem consists of blocks with three different geometries, which are supported by groups of two, three and four piles. Horizontal and vertical time-harmonic loads are applied to the blocks, and their horizontal and vertical responses are computed via a coupled method. The method consists in using finite element discretizations to model the blocks, and the impedance matrix method to model the embedded pile group. Coupling between the two domains is obtained by imposing continuity and equilibrium conditions between pile heads and the discrete nodes of the blocks. The analysis considers the influence of pile length and distance in the response of the system. The results show that, depending on the loading direction, these parameters may have a significant effect on the response of the system, and that pile-to-pile interaction must be modeled properly.
Keywords: soil-structure interaction, piled structures, pile groups, coupled methods

INTRODUCTION

Pile groups are one of the main geotechnical solutions for foundations for heavy structures. The idea is that these relatively stiff bodies embedded in the soil increase locally the stiffness of the soil, making it more able to support the weight of the structure. Designing pile groups to support structures is an ancient branch of engineering (Rathod et al., 2020). The static loading case has been explored even for quite sophisticated types of soil (Ghosh et al., 2012; Zheng et al, 2015). A popular model to represent pile behavior is the Winkler model, which resorts to approximating the response of the pile–soil system by a spring and sometimes a spring-dashpot system. A Pasternak model is an improved version of this idea, in which the shear contact at the pile–soil interface is incorporated (Zhang et al., 2018). Despite the inability of these models to represent the energy exchanged between piles through the soil, they have even been used to model dynamic problems, for the cases in which the piles are far enough from each other that their interaction can be disregarded (Allotey et al., 2008).

Pile group models that take into consideration the energy exchanged by piles typically resort to some boundary element discretization, due to the ability of this type of discretization to model unbounded media. Some examples are the models by Padrón et al. (2007), who resorted to full-boundary discretizations for the soil surface while approximating the piles as one-dimensional bodies, and the model by Maeso et al. (2005), which used full discretization of the entire soil surface and pile–soil interface. Indirect boundary element formulations have also been proposed (Labaki et al., 2021). One such model is the one proposed by Kaynia and Kausel (1991), now know as the impedance matrix method. The method consists in modeling each embedded pile as a one-dimensional beam, and describing their interaction with the soil through their coupling with soil influence functions. This model is able to represent energy exchange between piles and the soil, as well as between piles. The representation of the soil via influence functions for layered half-spaces confines the approximations of the method to the pile–soil interface. Kaynia and Kausel (1991) also included in their paper the case of rigid rafts supported by pile groups.

This paper addresses the problem of the dynamic response of foundation blocks supported by pile groups. The model uses Kaynia and Kausel's (1991) impedance matrix method to describe the response of the pile group. In order to extend their method to consider arbitrarily-shaped elastic bodies supported by the pile group, rather than just rigid rafts, this paper proposes a coupled method using finite element discretizations to model the foundation block. The method is used in this paper to study the influence of pile length and distance in the dynamic response of the block.

PROBLEM STATEMENT

Figure 1 shows the three cases of piled foundation blocks considered in this paper. They differ in their geometry and in the number of piles by which they are supported. All blocks have thickness 0.65 m and all piles have diameter 0.25 m.

All blocks and piles are made of concrete with material properties $E = 25\,\text{GPa}$, $\nu = 0.2$ and $\rho = 2500\,\text{kg/m}^3$, in which E, ν and ρ stand for the elasticity modulus, Poisson ratio, and mass density, respectively. The piles are embedded in a multilayered soil profile consisting of a 1.35 m layer of silty-sandy clay of $E = 12.5\,\text{MPa}$ and $\rho = 1447.5\,\text{kg/m}^3$, resting on top of a 6 m layer of silty sand of $E = 12\,\text{MPa}$ and $\rho = 1529\,\text{kg/m}^3$, resting on top of a 4 m layer of sandy-clayey silt of $E = 11\,\text{MPa}$ and $\rho = 1549.5\,\text{kg/m}^3$, which in turn is supported by an idealized rigid base. All soil layers have Poisson ratio $\nu = 0.4$. All data considered in this study, including blocks and pile group material and geometry and soil profile come from a case study conducted by Garcia and Albuquerque (2019) at a experimental field at the University of Campinas, in Brazil.

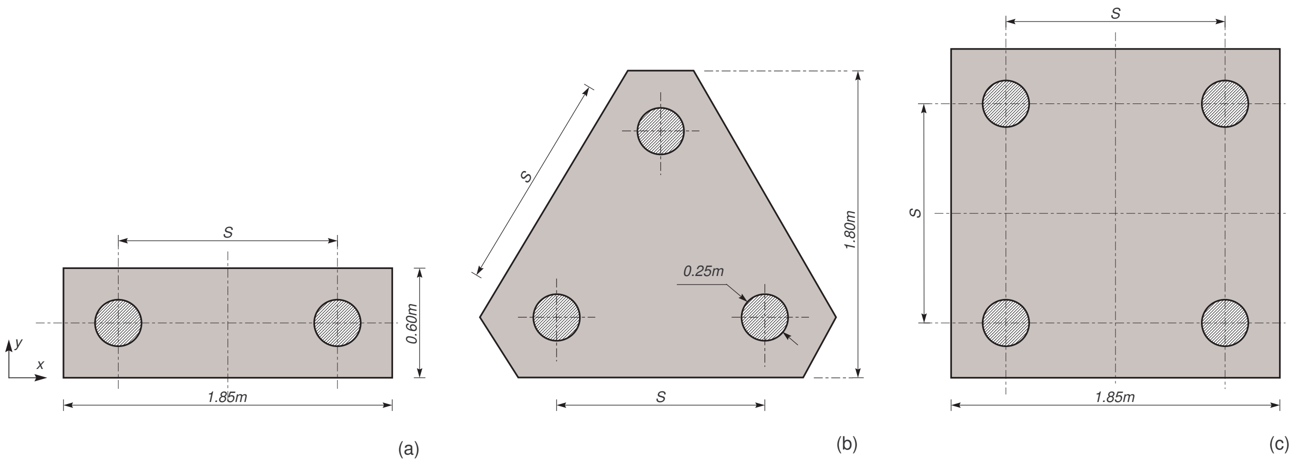

Figure 1 – Dimensions of the piled foundation blocks analyzed in this paper. All blocks have thickness of 0.65 m. Adapted from Garcia and Albuquerque (2019).

NUMERICAL MODEL

This paper uses a coupled method to model the interaction between the foundation blocks and their supporting pile group. The method consists of a classical Finite Element Method (FEM) procedure to describe the response of the blocks as finite structures, together with the impedance matrix method to model the response of the embedded pile group. Coupling between the two systems is obtained by imposing continuity and equilibrium conditions at their interface, which in this model are discrete points where specified nodes of the foundation blocks interact with pile heads.

Three-dimensional, linear-elastic, hexahedral finite elements are used to model the foundation blocks. Each of the 8 nodes of the elements have three displacement degrees of freedom. Stiffness and mass matrices of these elements are given by the classical

$$k_e = \int_{v_e} B^T D B \, dV = \int_{-1}^{1}\int_{-1}^{1}\int_{-1}^{1} B^T D B \det(J)\, d\xi d\eta d\zeta \tag{1}$$

and

$$m_e = \int_{v_e} \rho N^T N \, dV = \int_{-1}^{1}\int_{-1}^{1}\int_{-1}^{1} \rho N^T N \det(J)\, d\xi d\eta d\zeta, \tag{2}$$

in which v_e is the volume of the element, D is the constitutive matrix, J is the Jacobian that relates the (x,y,z) and (ξ,η,ζ) domains, N is the vector of shape functions, and B is the matrix of derivatives of shape functions. These elementary matrices are assembled into the global stiffness amd mass matrices K_g and M_g of the foundation block (Cook, 2007). The dynamic stiffness matrix of the block is defined as

$$\bar{K_b} = K_g - \omega^2 M_g, \tag{3}$$

in which ω is the frequency of excitation. In view of this FEM model of the foundation block, time-harmonic excitation of frequency ω can be applied in any direction anywhere in the block in terms of nodal equivalents (Cook, 2007).

The pile group is modeled with the impedance matrix method proposed by Kaynia and Kausel (1991). The method consists in modeling the embedded piles as one-dimensional finite beam elements, in which nodes longitudinal and transversal displacements and rotations are considered. The interaction between the embedded beam and its surrounding soil is modeled via the superposition of influence functions for the soil part, which correspond to the dynamic displacement response of the soil due to buried cylindrical loads, at the position of each embedded beam element. Continuity and equilibrium conditions are imposed between the beam elements and their corresponding influence functions at discrete sections of the beam. A no-slip continuity condition is imposed, which corresponds to the case in which the piles are perfectly bonded to their surrounding soil throughout their length. This is a reasonable hypothesis in the low-frequency analyses considered in this paper. The coupling following this scheme results in the dynamic stiffness matrix of the embedded pile group, given by

$$\bar{K_p} = \bar{K_e} + \Psi^T \left(F_p + F_s\right)^{-1} \Psi, \tag{4}$$

in which K_e is the dynamic stiffness matrix of the pile group, relating displacements and forces applied at the ends of the piles, $\bar{K_e}$ is the dynamic stiffness matrix of one pile, Ψ is a shape function matrix relating to the model of embedded beam, F_p is the flexibility matrix of a pile with fixed ends, and F_s is the soil flexibility matrix, containing the influence functions for loads applied along the bodies of the piles. In this implementation, F_s is the most computationally demanding task to perform. Soil influence functions are expressed in terms of improper integrals with singular, oscillatory-decaying integrands, the evaluation of which requires special methods (Labaki et al., 2012). For a full description of the terms in Eq. 4, refer to Kaynia and Kausel (1991).

A model of the coupled dynamic interaction between the foundation block and its supporting pile group is obtained by establishing continuity and equilibrium conditions at their interface. In this problem, the interface is the discrete nodes of the finite element mesh of the block that are in contact with the piles. Because of the one-dimensional approximation that is used for the pile, pile heads are simply dimensionless nodes. Continuity is imposed between horizontal and vertical displacements, and equilibrium is imposed between forces only. That is, no continuity of rotation is imposed. These conditions corresponds to the case in which the connection between the block and the pile head is hinged, which limits the application of this model to blocks that are supported by two or more piles. After the incorporation of these conditions, the equation of motion for the piled foundation block can be expressed in the form of the classical

$$\bar{K}u = f, \tag{5}$$

in which f and u express nodal forces and displacements of the finite element mesh of the block, and $\bar{K}$ is the dynamic stiffness matrix of the piled block. Most of $\bar{K}$ is the same as $\bar{K_b}$ from Eq. 3, except for the terms relating to nodes that are connected to pile heads. These terms are modified such that they are the sum of the terms from $\bar{K_b}$ corresponding to the stiffness of the node of the block that is connected to the head of a pile, and the terms from $\bar{K_p}$ from Eq. 4, corresponding to the head of the pile that is connected to that node. Equation 5 can be solved for an arbitrary set of external loads f to obtain the dynamic response u of the piled foundation block.

NUMERICAL RESULTS

This section shows selected numerical results from the analysis of the three piled foundation blocks shown in Fig. 1. The analysis consider horizontal ($x-$direction) and vertical ($z-$direction) loads (F_x and F_z) uniformly distributed on the surface of the blocks. Results are presented in terms of the normalized displacement $U_{ij} = u_{ij}/F_j$, in which i and j ($i, j = x, z$) indicate the direction of displacement and loading, respectively, and of the normalized frequency $a_0 = \omega d/c_s$, in which $d = 0.25\,\mathrm{m}$ is the diameter of the piles and $c_s = 55.8\,\mathrm{m/s}$ is the shear wave speed in the first layer of soil. This paper considers the influence of pile length and distance in the response of the foundation blocks, which are the most significant parameters in their geotechnical design.

Influence of pile length

This section considers the influence of pile length L in the response of the piled foundation blocks. Results are presented in terms of normalized pile lengths $L/d = 10$ and $L/d = 20$. All cases in this section consider pile distance $s = 5d$. Horizontal loading cases are shown in Figs. 2 to 4, while vertical loading cases are show in in Figs. 5 to 7. These results are all shown in the same scale for facilitated comparison.

Figures 2 to 4 show that the length of the piles have negligible influence in the horizontal response of the block, for the cases considered. On the other hand, Figs. 5 to 7 show that there is a significant difference in the vertical response of

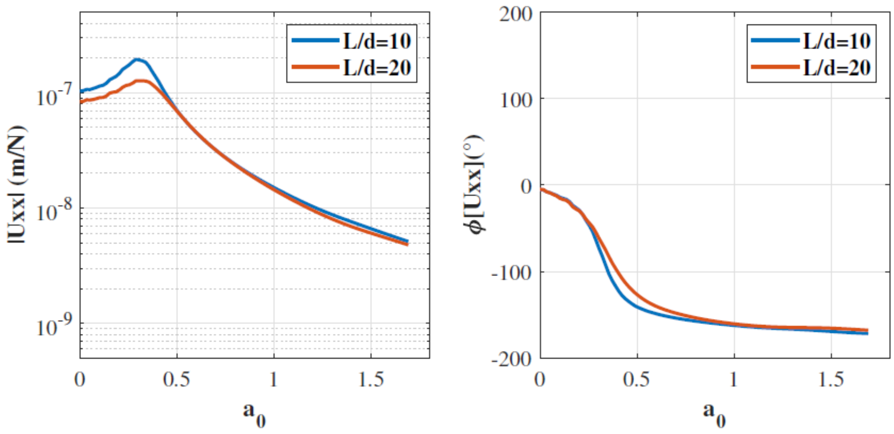

Figure 2 – Influence of pile length in the horizontal response of the foundation block supported by two piles

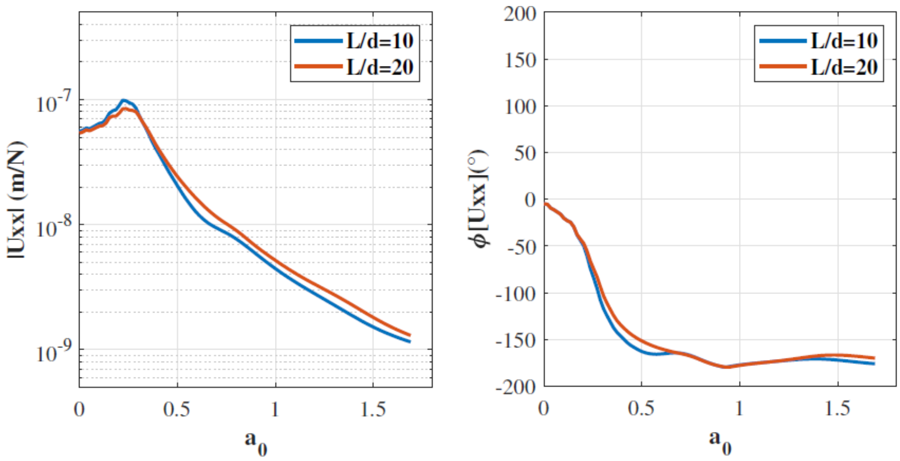

Figure 3 – Influence of pile length in the horizontal response of the foundation block supported by three piles

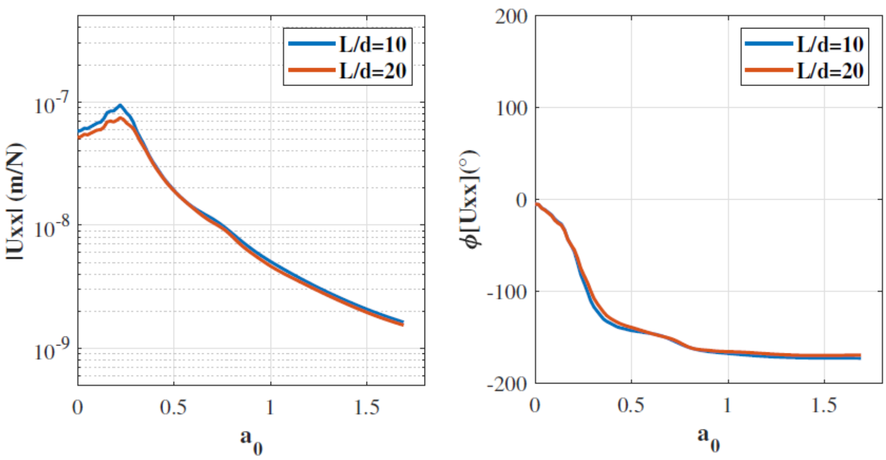

Figure 4 – Influence of pile length in the horizontal response of the foundation block supported by four piles

the block whether shorter or longer piles are included. This difference in behavior in the horizontal and vertical responses can be explained by the fact that the horizontal excitation of the block mainly mobilizes the flexural response of the piles,

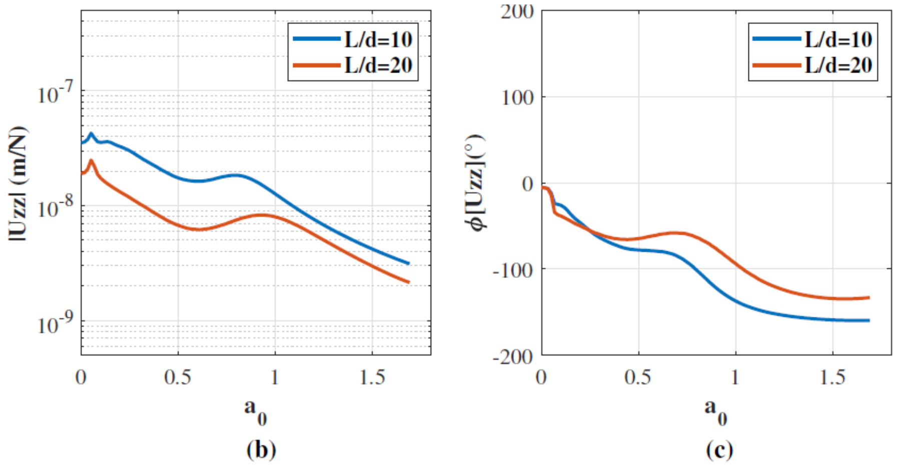

Figure 5 – Influence of pile length in the vertical response of the foundation block supported by two piles

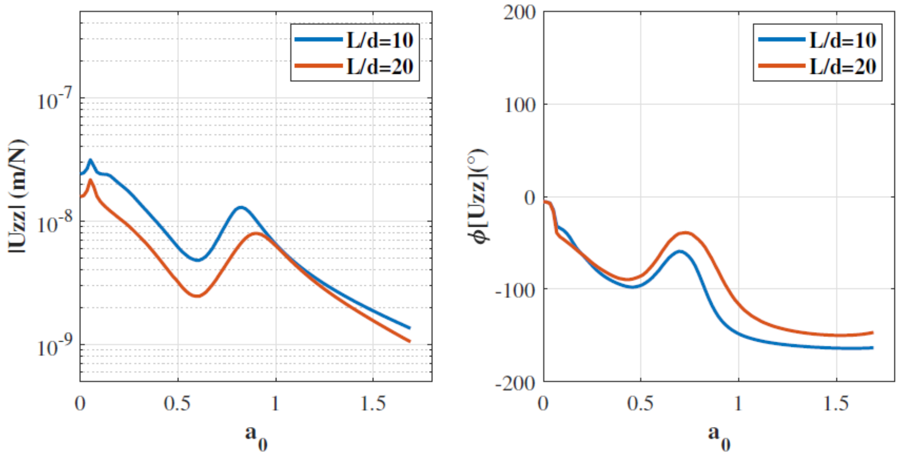

Figure 6 – Influence of pile length in the vertical response of the foundation block supported by three piles

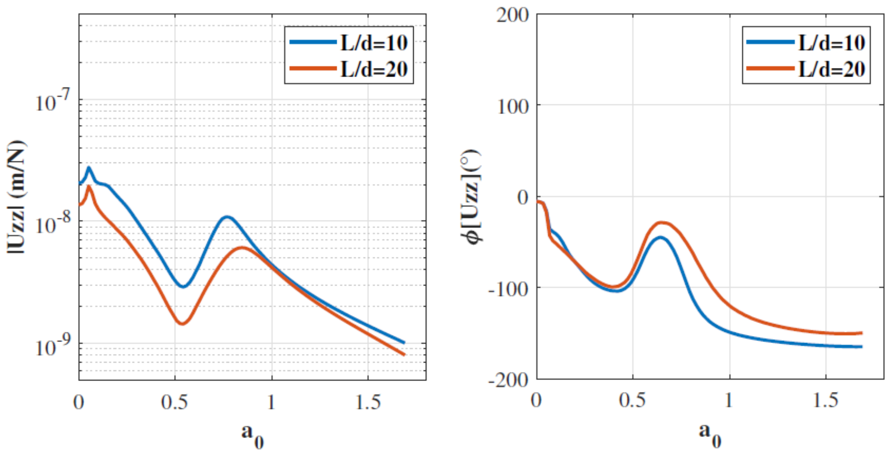

Figure 7 – Influence of pile length in the vertical response of the foundation block supported by four piles

which quickly becomes very stiff at larger depths within the soil. In the horizontal direction, the most flexible part of the piles are their very top, near the soil surface. Figures 2 to 4 indicate that piles longer than $L/d = 10$ provide no extra stiffness to the system in the horizontal direction. On the other hand, Figs. 5 to 7 show that adding length to the piles after $L/d = 10$ is still able to provide a significant modification of its vertical response. In all three cases, this modification has been one of attenuation of the magnitude of vibration of the blocks.

Influence of pile distance

This section considers the influence of pile distance s in the response of the piled foundation blocks (see Fig. 1). Results are presented in terms of normalized pile lengths $s/d = 3$ and $s/d = 5$. These values were chosen because in engineering design practice they correspond to the cases in which pile-to-pile interaction can typically be disregarded $(s/d > 3)$ or not $(s/d \leq 3)$ (Garcia and Albuquerque, 2019). All cases in this section consider pile length $L = 10d$. Horizontal loading cases are shown in Figs. 8 to 10, while vertical loading cases are show in in Figs. 11 to 13.

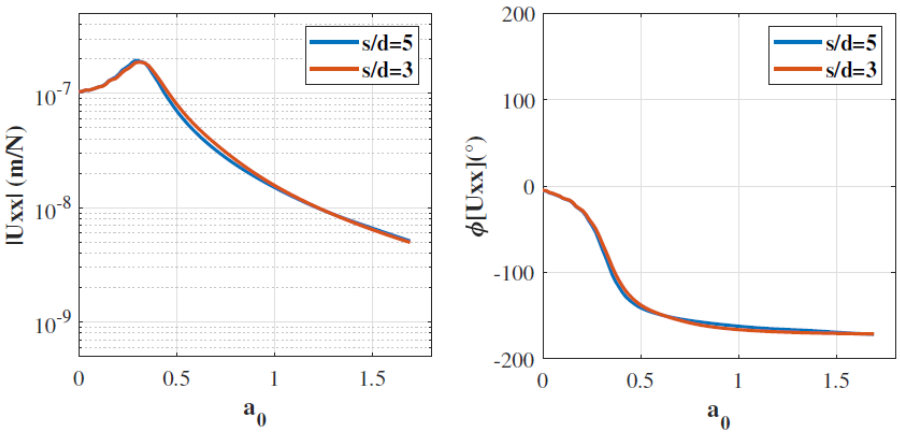

Figure 8 – Influence of pile distance in the horizontal response of the foundation block supported by two piles

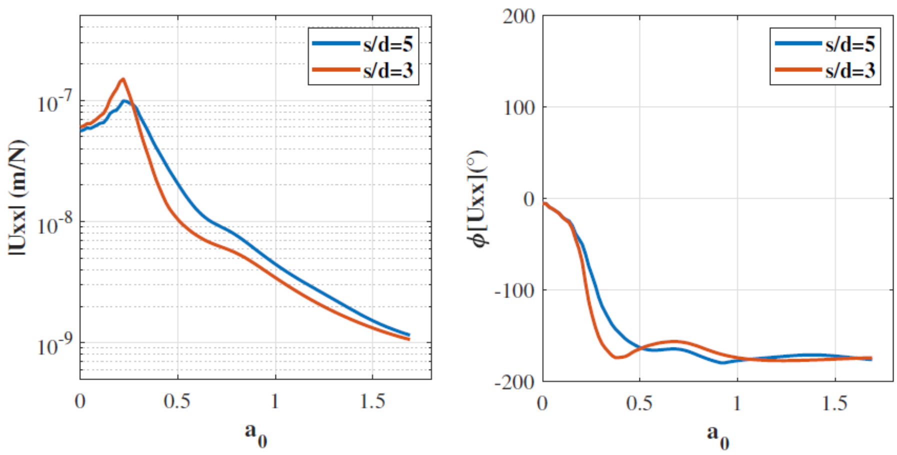

Figure 9 – Influence of pile distance in the horizontal response of the foundation block supported by three piles

Figures 8 to 10 show that pile distance has a marginal effect in the horizontal response of the foundation block. Once again, this is explained by the fact that the horizontal response of the block comprises the mobilization of flexural modes of the piles, the main motion of which is confided to the region immediately surrounding the pile heads. The vertical response of the system, however, is more strongly affected by pile distance. Figures 11 to 13 show that whether pile distance results in attenuation or increase in amplitude of motion of the system depends on the frequency of excitation. This shows that the proximity of the piles non only affects the static response of the bulb of pressure under the foundation block, which is widely known in the literature (Poulos and Davis, 1980), but that the vibration modes of the system are also strongly affected by their coupled interaction. This indicates that the widely used Winkler/Pasternak approximations

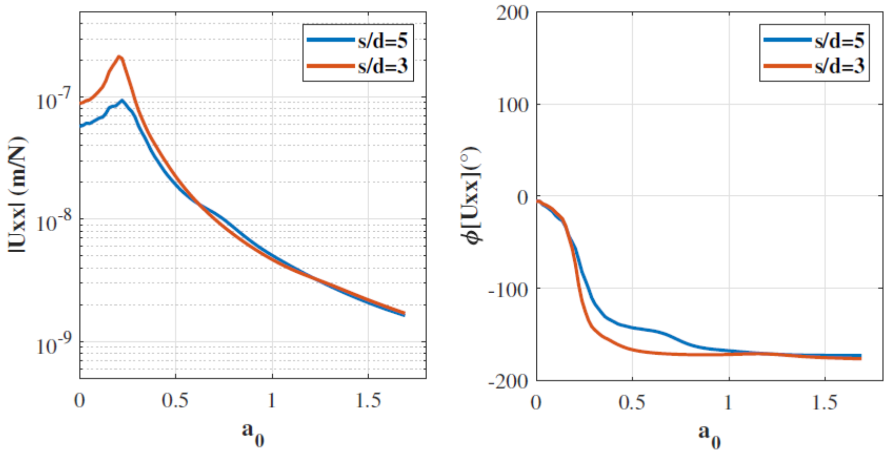

Figure 10 – Influence of pile distance in the horizontal response of the foundation block supported by four piles

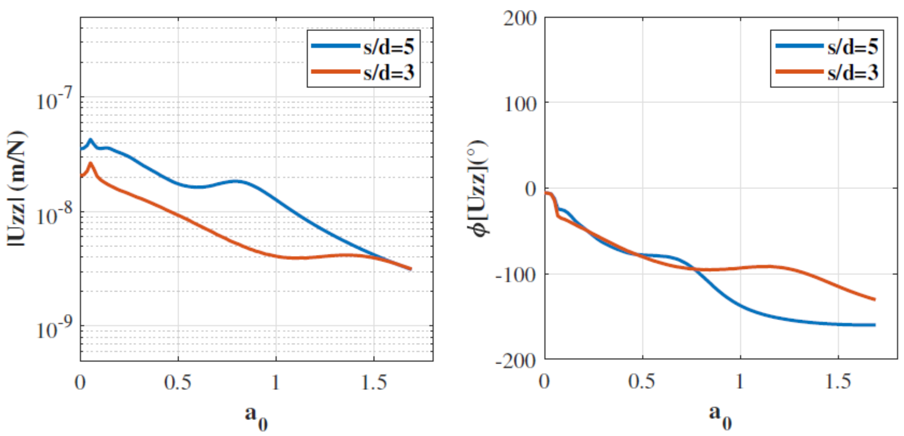

Figure 11 – Influence of pile distance in the vertical response of the foundation block supported by two piles

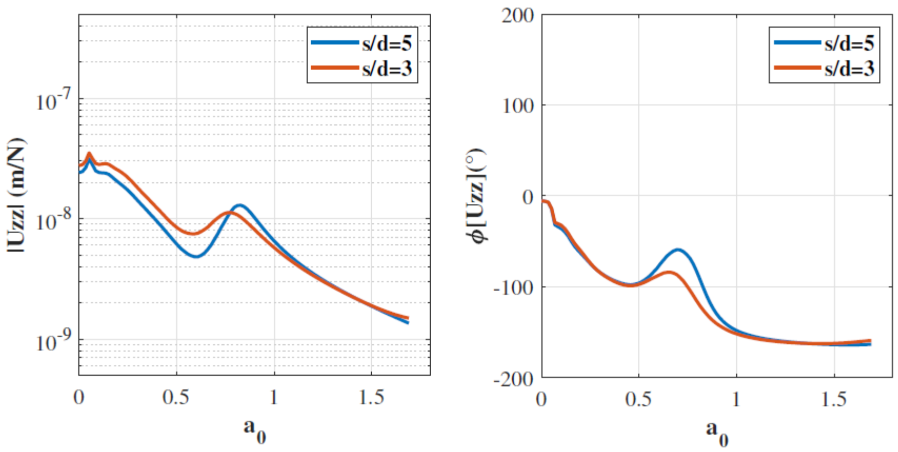

Figure 12 – Influence of pile distance in the vertical response of the foundation block supported by three piles

for the response of pile groups (e.g. Wang et al., 2014), which are unable to model pile-soil-pile interaction properly, are inadequate to address this problem. This vouches for the importance of the use of fully-coupled models like the one presented in this paper.

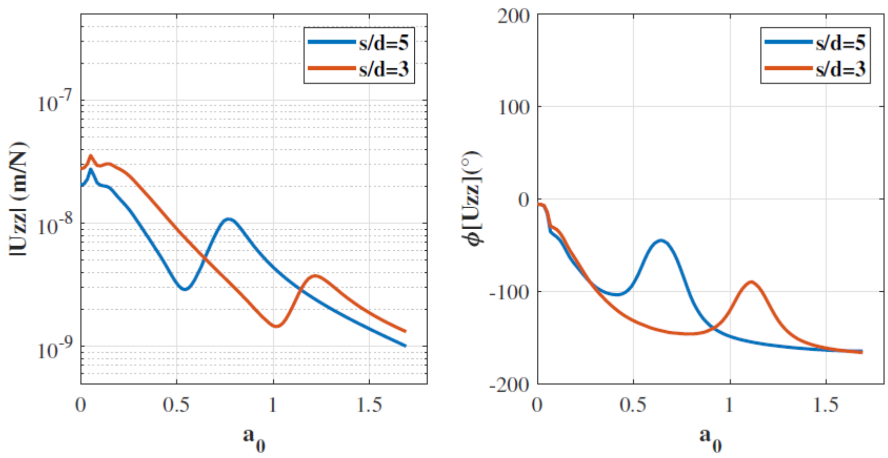

Figure 13 – Influence of pile distance in the vertical response of the foundation block supported by four piles

CONCLUSIONS

This paper presented a study of the dynamic response of piled foundation blocks. A model of the coupled response between the blocks and their supporting pile groups were obtained via a combination of a finite element discretization for the foundation block and an impedance matrix scheme for the pile group. The paper considered the influence of pile length and distance in the horizontal and vertical responses of the piled blocks, which are two important variables in geotechnical engineering design. The results showed that these variables have mostly negligible influence on the horizontal response of the blocks, due to their mobilization of the piles being confined to the surroundings of the pile heads, and that these variables have a more significant effect on the vertical response of the blocks, due to their mobilization of the piles being more evenly spread throughout the bulk of the soil. These results vouch for the importance of conducting these analyses with fully-coupled models like the one presented in this paper, which accurately accounts for the energy exchanged between the various parts of the system.

REFERENCES

Allotey, N. and El Naggar, M.H., 2008. "Generalized dynamic Winkler model for nonlinear soil–structure interaction analysis". Canadian Geotechnical Journal, 45(4), pp.560-573.

Cook, R.D., 2007. "Concepts and applications of finite element analysis". John Wiley & sons.

Garcia, J.R. and Albuquerque, P.J.R.D., 2019. "Analysis of the contribution of the block-soil contact in piled foundations". Latin American Journal of Solids and Structures, 16.

Ghosh, B., Mian, J. and Lubkowski, Z., 2012. "Design of piles in liquefiable soil: A review of design codes and methodologies". In 15th World Conference on Earthquake Engineering (Vol. 28, pp. 22746-22755).

Kaynia, A.M. and Kausel, E., 1991. "Dynamics of piles and pile groups in layered soil media". Soil Dynamics and Earthquake Engineering, 10(8), pp.386-401.

Labaki, J., Barros, P.L. and Mesquita, E., 2021. "A model of the time-harmonic torsional response of piled plates using an IBEM-FEM coupling". Engineering Analysis with Boundary Elements, 125, pp.241-249.

Labaki, J., Romanini, E. and Mesquita, E., 2012. "Stationary dynamic displacement solutions for a rectangular load applied within a 3d viscoelastic isotropic full space—part II: implementation, validation, and numerical results". Mathematical Problems in Engineering, 2012.

Maeso, O., Aznarez, J.J. and García, F., 2005. "Dynamic impedances of piles and groups of piles in saturated soils". Computers & structures, 83(10-11), pp.769-782.

Padrón, L.A., Aznárez, J.J. and Maeso, O., 2007. "BEM–FEM coupling model for the dynamic analysis of piles and pile groups". Engineering Analysis with Boundary Elements, 31(6), pp.473-484.

Poulos, H.G. and Davis, E.H., 1980. "Pile foundation analysis and design" (Vol. 397). New York: Wiley.

Rathod, D., Krishnanunni, K.T. and Nigitha, D., 2020. "A review on conventional and innovative pile system for offshore wind turbines". Geotechnical and Geological Engineering, 38(4), pp.3385-3402.

Wang, J., Zhou, D. and Liu, W., 2014. “Horizontal impedance of pile groups considering shear behavior of multilayered soils”. Soils and Foundations, 54(5), pp.927-937.

Zhang, Z., Huang, M., Xu, C., Jiang, Y. and Wang, W., 2018. “Simplified solution for tunnel-soil-pile interaction in Pasternak’s foundation model”. Tunnelling and Underground Space Technology, 78, pp.146-158.

Zheng, C., Kouretzis, G.P., Sloan, S.W., Liu, H. and Ding, X., 2015. “Vertical vibration of an elastic pile embedded in poroelastic soil”. Soil Dynamics and Earthquake Engineering, 77, pp.177-181.

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