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Three-dimensional numerical analysis of the generalized group effect in monitored continuous flight auger pile groups

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Article

Keywords
Group effect
Continuous flight auger pile
Finite element method
Deep foundation
Soil-pile interaction

Abstract

The interaction mechanisms related to the group effect between piles and between pile groups significantly influence the soil-structure interaction process. This interaction causes the superposition of stresses and, in general, makes the pile group settlement different from the settlement of an isolated pile. The objective of the present paper is to evaluate the soil-structure interaction mechanisms of buildings with foundations of monitored continuous flight auger piles (CFA) in a stratified soil mass, with the presence of an intermediate soft soil layer. Hence, it is particularly analyzed the group effect between piles of a group and the group effect between all pile groups from a foundation of a study case instrumented by means of numerical modeling, considering the effect of the soft soil layer. The results show the significant group effect on displacements, showing the increase in settlement due to the overlapping of the tension bulbs of the piles and neighboring pile groups.

1. Introduction

The soil-structure interaction (SSI) is responsible for the redistribution of efforts through structural rebalancing, which occurs with the construction evolution. The study of the processes of soil-structure interaction is important for predicting the behavior of the structure during the construction sequence. The interaction mechanisms related to the group effect between piles and pile groups significantly influence the soil-structure interaction process, more specifically, the pile-soil interaction process. This interaction causes overlap of the tension bulbs and, in general, makes the settlement of the group of piles different from the settlement of an isolated pile.

The group effect, defined by NBR 6122 (ABNT, 2019) as the process of interaction of the various elements that constitute a foundation by transmitting the loads applied to them to the soil, causes the overlap of the tension bulbs and causes the settlement of the group be, in general, different from the settlement of the isolated element. Velloso & Lopes (2010) define the group effect as the perceived difference in load capacity and settlement measured in a group of piles, connected by a pile block, and in an isolated pile, due to the interaction that occurs through the soil.

In the last decades, several studies, with different methodologies, have been dedicated to the analysis of the group effect between piles connected by the same block (Poulos & Mattes, 1971; Randolph & Wroth, 1979; Poulos & Davis, 1980; Poulos & Randolph, 1983; Randolph, 1994; Guo & Randolph, 1999; Poulos, 2006; Sheil & McCabe, 2012; Guo, 2013; Randolph & Reul, 2019; among others). However, the analysis of the generalized group effect, that is, the group effect between all pile groups in the building, is generally disregarded. This is due, in general, to the computational effort required for the analysis of the entire foundation. Therefore, numerical analyzes of the group effect on piles are usually restricted to relatively small groups of piles (Randolph, 1994). However, with the development of technology, the use of the finite element method becomes more efficient and makes it possible to solve more complex problems, such as, for instance, the analysis of problems involving stratified subsoil, with a greater number of piles and pile blocks, enabling a more representative analysis of the performance of the entire building and the generalized group effect.

Therefore, the objective of this work is to evaluate, by means of three-dimensional numerical modeling, the soil-structure interaction mechanisms of a building with a monitored continuous flight auger pile foundation in a stratified subsoil, with the presence of an intermediate soft soil layer. Specifically, the group effect between piles connected by the same block and the group effect between all pile groups in the building of an instrumented case study are analysed. The effect of the soft soil layer is also evaluated.

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2. Case study

The case study consists of a residential building with 19 floors with reinforced concrete structure and sealing masonry in ceramic material, located in the city of Campos dos Goytacazes-RJ, Brazil. The location of the case study is shown in Figure 1. The building consists of 3 garage floors that occupy the entire area of the terrain and the body of the building with 14 type floors and a penthouse, in addition to the water tank, occupying the central area.

The region where the case study is located is marked by the presence of plains of fluvial-marine origin and Cenozoic sedimentary basins, characterized by sub-horizontal surfaces consisting of well-selected sandy or clayey to clayey deposits, with extremely smooth and convergent gradients towards watercourses (Lazaretti et al., 2017).

The elevated part of the municipality presents soils resulting from the weathering of Pre-Cambrian rocks (gneisses and granites) and Tertiary sediments of the Barreiras Formation (Costa et al., 2008).

The investigation and characterization of the soil profile was performed through 8 standard penetration test (SPT) holes.

The foundation used were monitored continuous flight auger-type deep piles, with diameters of 500 mm, under the main body of the building, and of 400 mm, under the extension of the garage area. The monitored pillars and piles are positioned in the body of the building. All piles are 18m long, armed in the first four meters. Therefore, they are settled in a layer of silty clay with sand, which showed a high N_{SPT} value, with an average N_{60} value of approximately 58 blows.

The piles considered in the numerical model are located under the main body of the building and are divided, according to the loading level, into peripheral, intermediate and central piles.

Figure 2 shows the stakeout project, the location of instrumented piles, the division of piles into peripheral, intermediate and central piles and the location of SPT holes.

The following soil layers were identified in the SPT: yellow silty clay from 3.7 to 6.4 meters deep, clayey sand from 11.3 to 13.7 m, dark gray peaty clay from 11.3 to 13.7 m and impenetrable hard light gray silty clay from 19.5 to 20.5 m, as shown in Figure 3.

The monitoring of the work, since the first stages of construction, was carried out by Waked (2017) and Prellwitz (2016). Waked (2017) monitored the displacement relative to the pillars of 4 piles, using telltales and strain gauges, and Prellwitz (2016) monitored the settlement of all the pillars of the building, using a monitoring system based on the principle of communicating vessels and the data acquisition was done using photogrammetry.

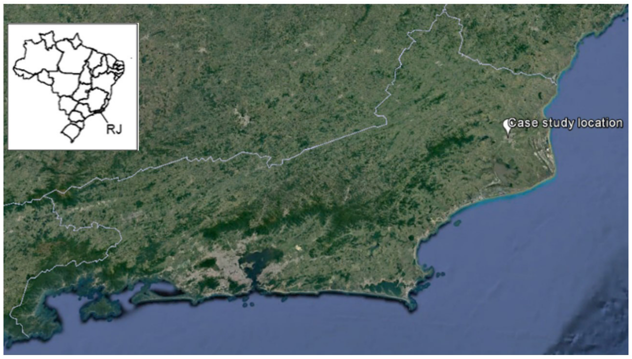


Figure 1. Case study location.

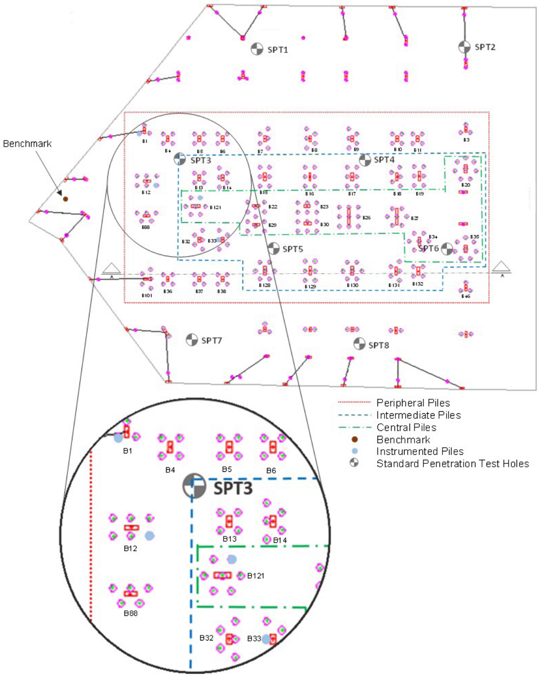


Figure 2. Stakeout project and location of instrumented piles and SPT holes.

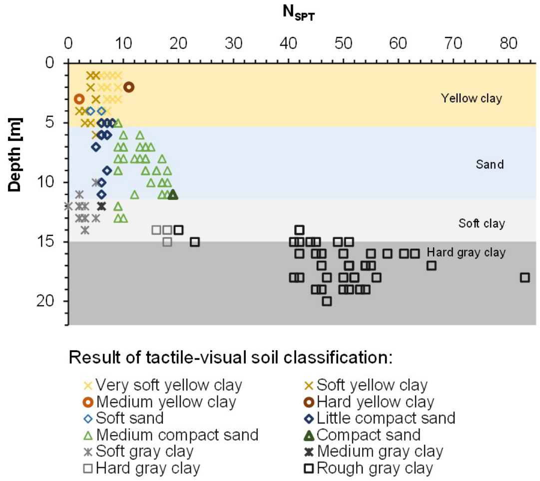


Figure 3. Simplified soil profile and SPT variation.

Table 1. Geometry of the blocks.

Block	Hight (z) [m]	Length (x) [m]	Width (y) [m]
B1	1.2	2.05	1.88
B3	1.2	2.05	1.88
B4	1.2	2.05	2.05
B5	1.2	2.05	2.05
B6	1.2	2.05	2.05
B7	1.2	1.88	3.30
B8	1.2	1.88	3.30
B9	1.2	1.88	3.30
B10	1.2	2.05	2.05
B11	1.2	2.05	2.05
B12	1.2	3.30	2.05
B13	1.2	2.05	2.05
B14	1.2	1.88	3.30
B15	1.2	2.05	3.30
B16	1.2	2.05	3.30
B17	1.2	2.05	3.30
B18	1.2	1.88	3.30
B19	1.2	2.05	3.30
B20	1.2	3.05	3.54
B22/29	1.2	3.30	4.55
B23/30	1.2	2.97	4.55
B26	1.2	3.30	3.30
B27	1.2	3.30	2.97
B32	1.2	1.88	3.30
B33	1.2	1.88	3.30
B34	1.2	3.30	2.97
B35	1.2	3.05	3.54
B36	1.2	2.05	2.05
B37	1.2	2.05	2.05
B38	1.2	2.05	2.05
B46	1.2	2.05	1.88
B88	1.2	3.30	1.88
B101	1.2	1.88	3.30
B121	1.2	3.30	2.97
B128	1.2	3.30	2.97
B129	1.2	2.05	3.30
B130	1.2	3.30	2.97
B131	1.2	1.88	3.30
B132	1.2	2.05	2.05

3. Numerical modeling

The analysis of the soil-structure interaction of the case study was carried out from three-dimensional numerical modeling using a software based on the finite element method (FEM), Plaxis 3D.

The piles used in the model are 0.5 m in diameter and 18 m long. The dimensions of the blocks are shown in Table 1.

The soil parameters were validated from parametric retroanalysis in a three-dimensional model based on correlations with the N_{SPT} obtained at the site and based on parameter values suggested by authors such as Décourt (1995), Marangon (2018), Ortigão (2007), Godoy (1972) & Bowles (1997). The validation of soil layer parameters is presented in Leite (2021). The parameters used in numerical modeling are presented in Table 2.

The numerical model developed is presented in Figure 4. The finite element mesh is formed by tetrahedral elements of 10 nodes and has a medium degree of refinement. The number of soil elements is 80,610, and the number of nodes is 119,303.

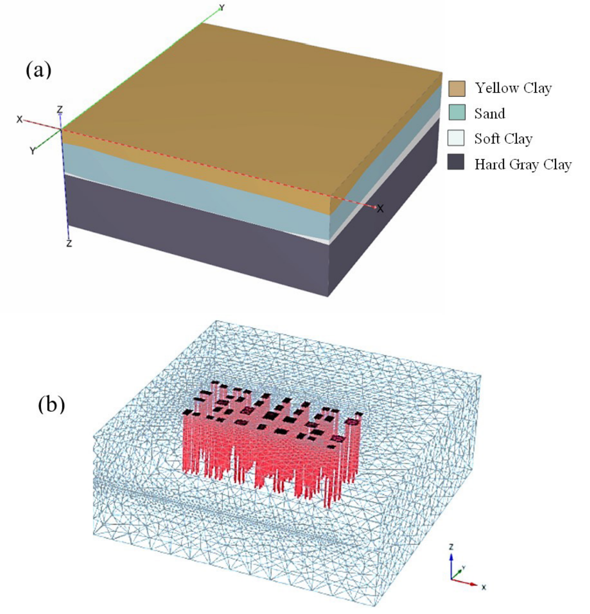


Figure 4. Numerical model (a) of the subsoil and (b) of piles and blocks.

Table 2. Parameters of piles, blocks and soil layers.

	Constitutive model	γ(a) [kN/m^3]	E(b) [GPa]	ν(c)	R_t *max*(d) [kN]	R_{lat} *max*(e) [kN]	c(f) [kPa]	w(g) [m/dia]
Pile	LE	20.7	14.8	0.11	800	1.400	-	-
Block	LE	20.7	148	0.11	-	-	-	-
Yellow clay	LE	17.0	0.023	0.30	-	-	-	0.01
Sand	LE	20.0	0.048	0.40	-	-	-	1.00
Soft gray clay	MC	13.0	0.010	0.40	-	-	25	0.01
Hard gray clay	LE	20.0	0.138	0.40	-	-	-	0.01

(a)Specific weight obtained for pile and block from Maia et al. (2019) and for soil layer from Godoy (1972). (b)Modulus of elasticity obtained for pile and block from Maia et al. (2019) and for soil layers from Décourt correlations (Décourt, 1995). (c)Poisson coefficient values obtained for pile and block from Maia et al. (2019) and for soil layers as suggested by Marangon (2018). (d)Maximum tip resistance achieved by Waked (2017). (e)Maximum lateral resistance achieved by Waked (2017). (f)Cohesion value, as suggested by Marangon (2018). (g)Permeability values suggested by Ortigão (2007).

Sensitivity analyses showed that there was no significant change in the settlement values obtained in the models with the change in the degree of mesh refinement.

The water level was considered with the average depth identified in the soundings, 3.5 m. Therefore, the soil above this depth was configured as dry.

The adopted boundary conditions consider the deformations of the massif normally fixed horizontally (X_{min}, X_{max}, Y_{min} and Y_{max}), fully fixed at Z_{min} and free at Z_{max} and the groundwater flow closed at Z_{min} and open in the other directions.

The constitutive model used to represent the elements of piles and blocks was the Linear Elastic (LE), for the soft clay layer the linear elastic perfectly plastic model, called Mohr Coulomb model (MC), was used, the LE model was used for the other soil layers.

The modeling was carried out in several stages, in order to evaluate the effect of the interaction between pile groups. Initially, a model with an isolated pile was simulated, followed by a model with an isolated pile group, connected by the same pile block, the next stages included pile groups located at a radius n times the largest dimension (*B*) of the block considered initially. This evaluation process, increasing the simulated radius in the numerical model, was performed 9 times, 3 starting with peripheral blocks (B1, B6, B12), 3 with intermediate blocks (B15, B33, B129) and 3 with central blocks (B20, B23/30, B27). The location of these blocks is illustrated in Figure 5a. The division of blocks according to the distance to the center of block B129 is shown in Figure 5b.

Figure 6 shows the configuration sequence of the calculated models for the case in which the analysis started with block B129.

All numerical models were configured with and without the soft soil layer, for the analysis of the influence of this layer on the group effect. The soft clay layer was replaced by the layer of greater resistance, hard gray clay, in the models without soft soil.

Only four constructive steps were considered, in order to reduce computational effort and calculation time. The steps adopted are equivalent to approximately 25%, 50%, 75% and 100% of the load calculated for the columns. It is noteworthy that 100% of the loading of each column corresponds to the last constructive stage simulated by Prellwitz (2016), that is, the end of the execution of the sealing masonry.

4. Results and analysis

The results of the numerical simulation, showing the vertical displacements of the soil, with settlement isocurves, of the models with the isolated pile B129c, with the isolated pile group B129 and with the pile groups located at a distance of *2B, 3B, 4B, 5B, 6B, 7B, 8B* and *9B* of the initially analyzed block is shown in Figure 6. The AA cut, shown in Figure 7, passes through the center of the isolated pile E129c. The location of the AA cut in the plan is identified in Figure 2.

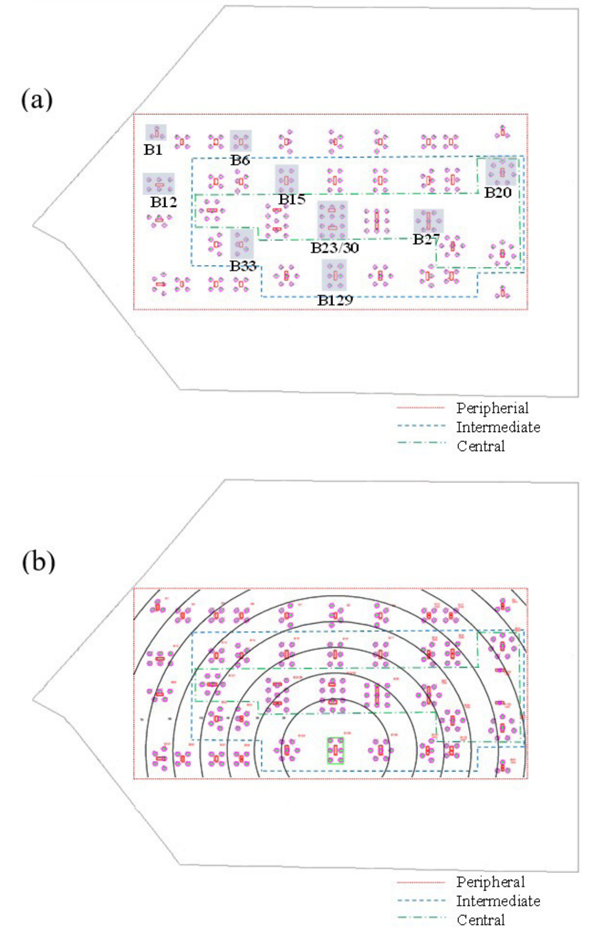


Figure 5. Foundation plan with (a) location of the analyzed blocks and (b) division of the blocks according to the distance to the center of B129.

These results were obtained from models of subsoil with soft soil layer. Figure 8 shows the results of the same test sequence, however, without the soft soil layer.

The comparison between the models with and without soft soil shows the difference in the behavior of the subsoil caused by the soft gray clay layer. In the models with soft soil, there is a change in the vertical displacement pattern of the soil in the depth of the soft gray clay layer, where there is an increase in the volume of displaced soil, presenting a sudden reduction of the displaced soil in the depth of the hard clay layer, located just below the soft clay layer. Furthermore, the level of settlement in numerical models with soft soil was higher than in models without soft soil.

The results show the significant group effect on the displacements, evidencing the increase in the settlement due to the overlapping of the tension bulbs of sided-placed piles and pile groups. It was observed that this effect occurs for blocks located up to an average radius of five times the largest dimension of the block, becoming relatively unimportant for greater distances. This effect can be observed in Figure 9,

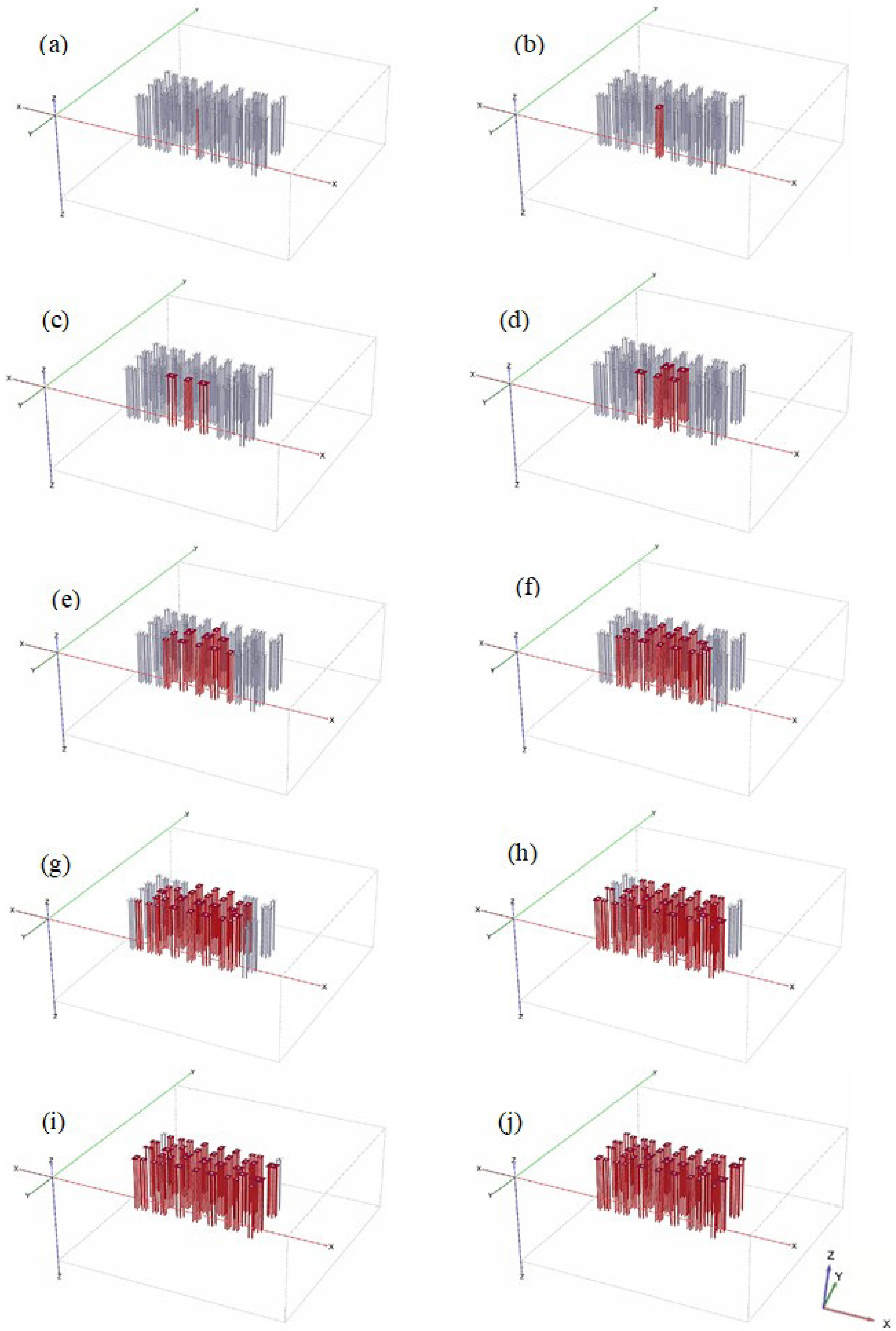


Figure 6. Sequence of numerical models starting with (a) pile E129c, (b) block B129, and blocks located at a distance of (c) 2B, (d) 3B, (e) 4B, (f) 5B, (g) 6B, (h) 7B, (i) 8B and (j) 9B.

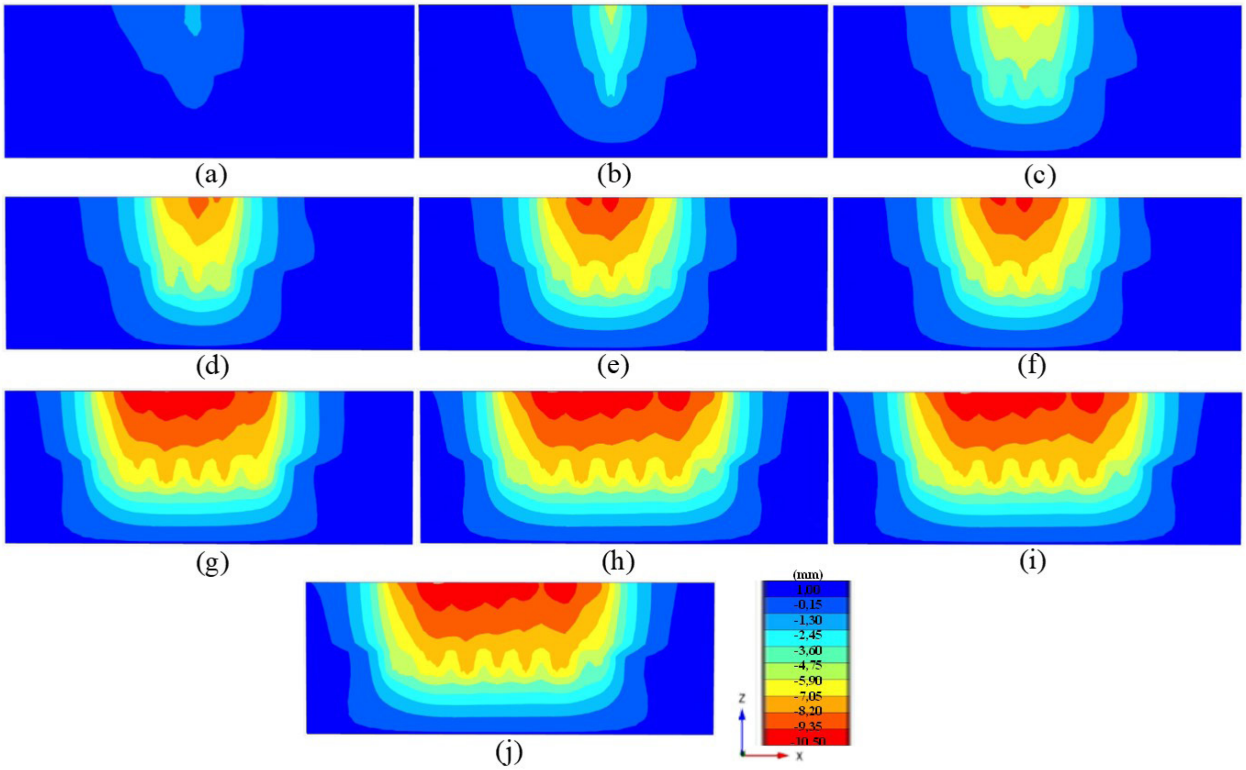


Figure 7. AA cut through the XZ plane showing vertical displacements of the soil in models with soft soil with (a) E129c, (b) B129, and pile groups located at a distance of (c) 2B, (d) 3B, (e) 4B, (f) 5B, (g) 6B, (h) 7B, (i) 8B, and (j) 9B.

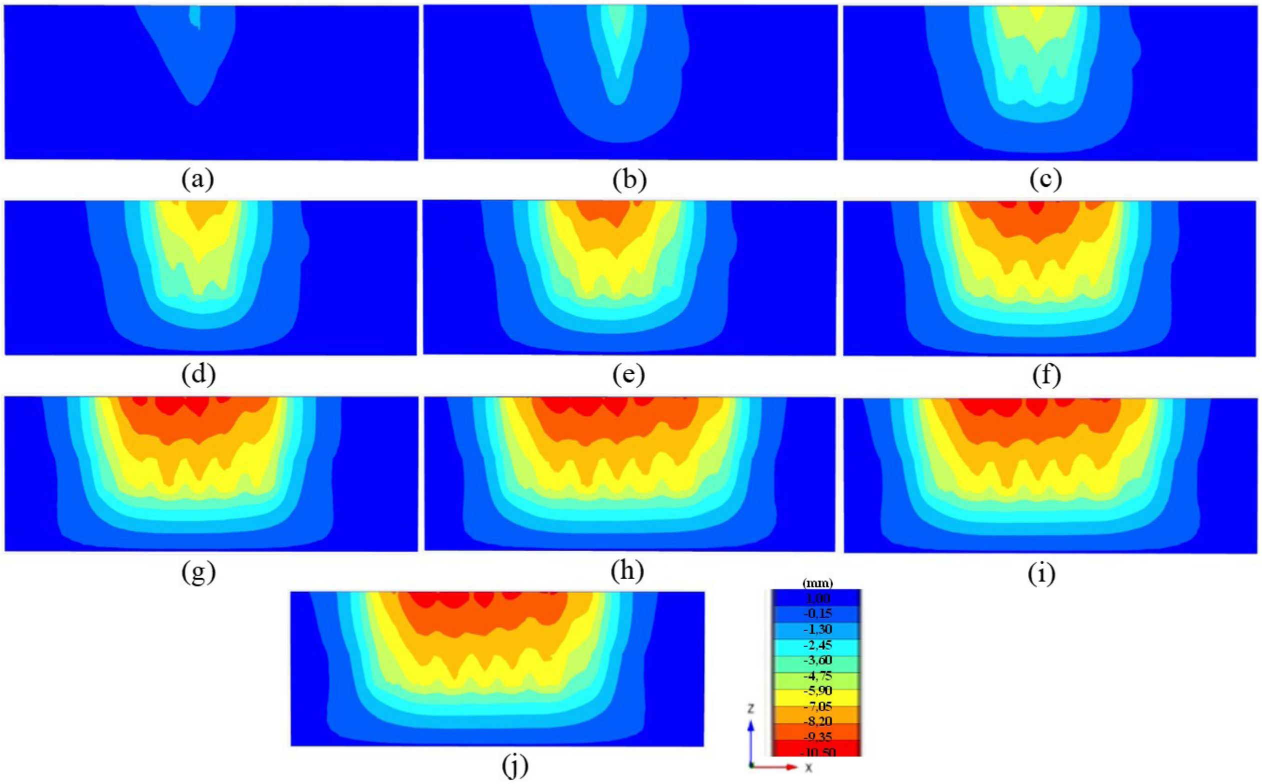
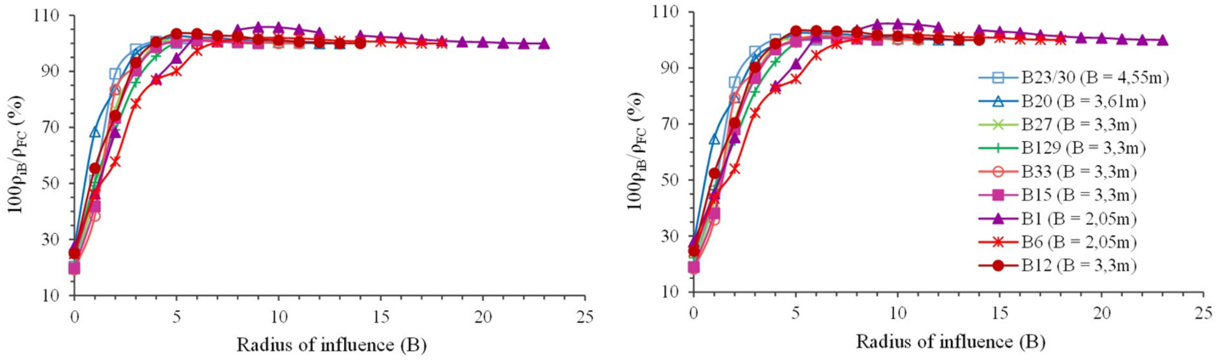


Figure 8. AA cut through the XZ plane showing vertical displacements of the soil in models without soft soil with (a) E129c, (b) B129, and pile groups located at a distance of (c) 2B, (d) 3B, (e) 4B, (f) 5B, (g) 6B, (h) 7B, (i) 8B, and (j) 9B.



(a) (b)

Figure 9. Settlement percentage versus radius of influence curves of models (a) with soft soil layer and (b) without soft soil layer.

which presents the curves of the relationship between the radius of influence (*B*) and the ratio of the block settlement in the model with a certain radius of influence and the block settlement in the model with the complete foundation, with all the foundation elements (ρ_{iB}/ρ_{OC}). There was no significant effect of the presence of soft soil layers in the analysis of the group effect between pile groups.

Several authors analyze the necessary spacing to eliminate the group effect between piles. Pressley & Poulos (1986) point out that for a group of piles loaded vertically, the spacing of 8 times the diameter (*D*) of the pile results in a failure mechanism characteristic of a single-pile, that is, without group effect. CGS (1992), in a foundation engineering manual, also analyzes the effect of pile spacing and states that, generally, group interaction doesn't need to be considered when pile spacing is greater than 8*D*. Khari et al. (2013) observed that, for a ratio of *S*/*D* greater than 6, the interaction between piles and the group effects are eliminated, considering groups of laterally loaded piles installed in sand. Patrocínio (2018) observed that piles work separately in a group with a ratio *S*/*D* equal to 5. Souri et al. (2020) observed, for piles installed in clay soil, that the group effect on lateral load capacity could be neglected for spacings greater than 5*D*. However, none of these studies analyze the group effect between pile groups.

However, it is noticed that the radius of influence of the group effect between pile groups is of the same order as the radius of influence observed for the group effect between piles of the same pile group. Therefore, it is understood that it is possible to compare the group effect between pile groups to the group effect between piles of the same block. It is understood, therefore, that the pile group behave similarly to the isolated piles, influencing the sided-placed pile groups by overlapping the tension bulbs, causing an increase in the settlement of the adjacent blocks.

It should be noted that the settlement observed in each block in the model simulating the complete foundation was up to approximately 5 times greater than the settlement obtained in the models with isolated piles and up to approximately 3 times greater than the settlement obtained in the models with isolated piles.

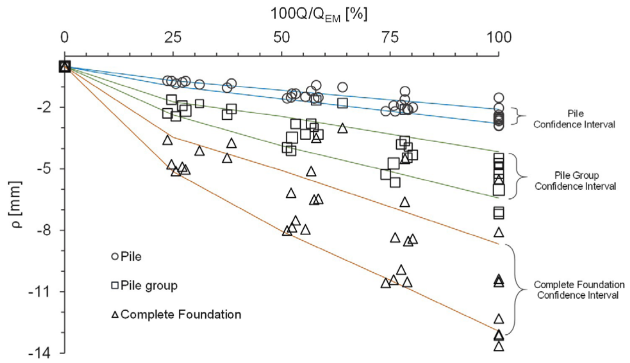


Figure 10. Load-settlement curves of isolated piles, isolated pile groups and the complete foundation.

The group factor (*G*), according to the equation presented by Almeida et al. (2019) and Santos et al. (2019), defined by the relationship between the settlement of the group of piles and the settlement of the isolated pile, was up to approximately 3. That is, the effect of overlapping the stress bulbs of neighboring piles generated a settlement up to approximately 3 times greater in the pile groups compared to the settlement of isolated piles, showing the influence of the group effect on the settlements.

Figure 10 shows the relationship between settlement (ρ) and the percentage ratio between the load in a given construction phase (*Q*) and the estimated load at the end of monitoring (Q_{EM}) obtained in numerical models with isolated piles, isolated blocks and with the complete foundation. The intervals, with 95% confidence, of the load-settlement curves refer to the values obtained in 9 blocks of the models, namely: 3 peripheral (B1, B6, B12), 3 intermediate (B15, B33, B129) and 3 central (B20, B23/30, B27).

5. Conclusion

The group effect between piles and pile groups was analyzed in this research from three-dimensional numerical modeling, using software based on the Finite Element Method. It has been shown that the group effect between pile groups is significant on building behavior. It was observed in numerical models that the group effect between pile groups is similar to the group effect between piles of the same group. This, due to the influence on neighboring pile groups, by overlapping the tension bulbs, resulting in an increase in the settlement of adjacent piles and pile groups. However, this proved to be negligible for pile groups located at a distance greater than 5 times the largest block dimension.

The generalized group effect, in the model with the complete foundation, increased the settlement by up to 3 times, in relation to the settlement of the isolated pile group, and up to 5 times, in relation to the settlement of the isolated pile.

The presence of the soft soil layer generated the vertical displacement of a larger volume of soil and caused higher levels of settlement, however, it did not present a significant influence on the group effect between pile groups.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Lorena da Silva Leite: conceptualization, data curation, formal analysis, investigation, methodology, validation, visualization, writing – original draft. Paulo César de Almeida Maia: conceptualization, data curation, supervision, validation, writing – review and editing. Aldo Durand Farfán: supervision, validation, writing – review and editing.

Data availability

The datasets generated analyzed in the course of the current study are available from the corresponding author upon request.

List of symbols

c	cohesion value
B	largest dimension of the pile block
D	pile diameter
E	modulus of elasticity
Q	load in a given construction phase
Q_{EM}	load at the end of monitoring
R_{lat}	maximum lateral resistance
R_t	maximum tip resistance
S	center-to-center space between piles
w	permeability value
γ	specific weight
ν	Poisson coeficient
ρ	settlement
ρ_{tb}	settlement of the block in a numerical model with a certain radius of influence
ρ_{FC}	settlement of the block in a numerical model with the complete foundation

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