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ORIGINAL ARTICLE

Numerical analysis of piled rafts with short bored piles

Análise numérica de radier estaqueado com estaca escavada curta

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Abstract: Numerical analysis of the behavior of piled rafts seated on uniform soil with low bearing capacity has been important to support the project design. The calibration of the numerical model with instrumented load test allows usage of the results, in given conditions, in the foundation design of small and medium-sized buildings built on soils with the same mechanical properties analyzed in this paper. In this context, this paper evaluates numerical models, which allow to consider the influence of short bored piles connected to the raft. The models are also assessed using piled rafts concepts. From the results obtained, the load supported by the total shaft resistance is significant for the case of bored piles, and this load is from 14% to 30% higher in the case more flexible or thinner raft. Inserting piles in the rafts reduces settlement and increases overall stiffness. Such effects are amplified in piles with higher slenderness ratios (L/d).

Keywords: piled raft, numerical modeling, bored piles, load sharing, settlement reduction.

Resumo: A análise numérica do comportamento de radiers estaqueados assentes em solo uniforme e de baixa capacidade de suporte tem se mostrado importante para subsidiar a concepção do projeto. A calibração do modelo numérico com uma prova de carga instrumentada permite que os resultados possam ser aplicados, dentro das condições estabelecidas, ao projeto de fundações para edificações de pequeno e médio porte assentes em solos com as mesmas propriedades mecânicas analisadas neste artigo. Nesse sentido, o artigo avalia modelos numéricos, que permitam estudar a influência de estaca curta executada por escavação acoplada ao radier. Os modelos também são avaliados a partir dos conceitos de radier estaqueado. A partir dos resultados obtidos, verifica-se que a carga suportada pela resistência lateral, significativa para o caso de estacas escavadas, é de 14% a 30% maior para radiers mais flexíveis ou com menores espessuras. A introdução de estacas nos radiers promove a redução de recalques e o aumento da rigidez do sistema, tendo seus efeitos ampliados para estacas com esbeltezes (L/d) mais elevadas.

Palavras-chave: radier estaqueado, modelagem numérica, estacas escavadas, distribuição de carga, redução de recalques.

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1 INTRODUCTION

Understanding the behavior of a piled raft foundation leads to the need of analyzing not just the foundation system in each separate element, the piles and the raft, but also the interactions among them over time.

In typical foundation projects, such as pile groups, the cap resistance is neglected in the design, even when the cap is in contact with the soil. Investigations and analytical methods have been developed to consider the soil-structure interaction, enabling to assess the contribution of the raft on the bearing capacity of the system. Sophisticated

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methodologies and the search for refined results have become main points in the field of foundations, due to the decrease of computational costs. In practice, the creation of numerical models that can guide the engineer to an efficient foundation design is a key factor to achieve efficacy of a project.

Among other advantages, numerical modeling enables fast parametric analyses, saving tests and experimentations, even though it does not replace them. Correlations factors can be deduced from the model results, and then combined and calibrated with experimental results.

The foundations considered in this work consist of rafts of varying thicknesses and short bored piles of varying lengths. The concepts and characteristics of each one of these elements are discussed, as well as how they affect the behavior of the piled rafts studied. In addition, features and results are presented in terms of the behavior of the system and their elements separately.

The present work is limited to considering the following hypotheses:

- the soils have constant mechanical characteristics along its depth, since short piles are used;
- the load is applied of loading distributed over the entire raft area; loading takes place at time intervals that do not allow soil consolidation;
- pore pressure and saturation are not considered;
- effects due to suction are implicit in the calibration and validation of the model with experimental results.

The numerical analysis considered elastoplastic constitutive model materials, based on the elastic perfectly plastic behavior with of Mohr-Coulomb failure criterion.

From the analysis of sixteen cases of piled rafts, it was possible to quantify the load distribution between the raft and the pile, as well as to estimate the influence of the piles on reducing settlements, on the variation of the shaft resistance according to the pile depth, on the axial load transfer, on the pile lateral and toe strength portions and on the overall stiffness.

1.1 Previous works

The number of studies on the behavior of piled foundations has increased significantly since the 1950's, strengthening and consolidating the understanding of these systems. Several works have studied the influence of foundation geometry [1]–[4], the contribution of raft-soil contact and load distribution among the elements and their variables [5] and the use of numerical models for analysis of piled rafts [6].

Many authors report several advantages in considering the raft-soil contact, such as reduction and uniformity of settlements (differential and total) and the increase in load capacity [6]–[8]. According to Butterfield and Banerjee [5], the load supported by the raft can range from 20% to 60%, assuming larger values for higher spacing between piles. Experiments reported in Garcia and Albuquerque [4] and numerical studies reported in Garcia [9] considering porous residual soil and piles spacing (s) equal to five times their diameter, shows a contribution of 21% and 36% of the raft-soil contact, respectively. Kuwabara [10], reports study using boundary elements method in cases of piles spacing smaller than ten times their diameter normal spacing and compared pile groups and piled rafts and founding a distribution of 20% to 40% of the total load to the raft.

The parameters involving foundation geometry, number of piles, and materials properties influence the behavior of the foundation [2]. According to Ottaviani [6] and Kuwabara [10], the effect of raft-soil contact influences the load distribution and transfer to the soil, and are affected by in terms of the position of the pile in the raft. Brown and Wiesner [7] highlighted the importance of parameters such as pile slenderness, L/d, relative pile spacing, s/d, relative stiffness between raft and soil, and relative stiffness between pile and soil for a preliminary assessment of the piled foundation design.

Saeedi Azizkandi et al. [11] investigated the load sharing mechanisms in piled rafts using numerical analyses with and without connection of the piles to the raft. The authors reported that the increase in the pile length reflected an increase in the portion of shared load, particularly in rafts with connected piles.

An important aspect in the analysis of piled foundations is related to the raft and how it is designed to be either rigid or flexible. Clancy and Randolph [12] concluded that the behavior of the foundation changed with the increase in raft flexibility when the foundation models have few piles (less than 4 piles). Analyzing the measurements taken at the foundation of the Messeturm building in Frankfurt, Randolph [8] observed that the failure of the piled raft foundation occurred mostly by punching the raft, since the piles prevent the raft from moving with the soil, submitting it to the Ultimate Limit State of the foundation. However, pile rafts must be classified according to their dimensions in order to define the appropriate analysis. Russo and Viggiani [13] categorize piled rafts in two groups, calling "small" rafts those in which rafts do not have sufficient bearing capacity and the piling alone will ensure adequate safety factor, and "large" rafts, which have enough bearing capacity, ensuring a certain share of and requiring the introduction of piles as settlement reducers.

Katzenbach and Choudhury [14] recommended evaluating piled rafts at Ultimate Limit State (ULS) and at Service Limit State (SLS), by means modeling that can consider the effects of the interaction among the elements of the foundation. For each limit state, an external check, considering the behavior of the whole foundation, and an internal check, evaluating the elements separately, should be performed and the most unfavorable results used for design. In this context, the use of numerical tools for the analysis of the complexity involved in piled raft foundation is important, as well as its benefits to obtain the appropriate design and to avoiding overdesigning when considering simplified methods. Poulos [15] highlights the importance of considering the effects of interactions among the raft, pile and soil by using structural numerical models in order to avoid under designing the foundation with simplified methods.

Mandolini, Russo and Viggiani [16] and Randolph [8], report evaluating 125 pile load tests with different installation processes. They conclude that the type of installation affects more the load capacity of piles than their axial stiffnesses determined by estimation of the tangent to the curve containing the first three loading points.

The evaluation of the behavior of the elements that form piled rafts is related not only to load capacity and settlement, but also to how the shaft resistance and the toe resistance are mobilized.

Studies performed by Lee et al. [17] on the interaction among elements of piled raft in sands described the load distribution in the pile as a function of the overall displacement, and the established coefficients considering the initial rapid increase of the load on the pile with small displacements that do not considerably increase with larger displacements. These coefficients were later incorporated into the model proposed by Clancy and Randolph [18].

1.2 Some concepts on piled rafts

Katzenbach and Choudhury [14] and Abdel-Azim et al. [19] consider two parameters to distinguish the behavior of piled raft foundations with respect to the pile group and to isolated rafts. In the case of the piled rafts, the coefficient α_{pr} is a correlation related to the characteristic values and is presented as function of a given settlement, s, according to Equations 1 and 2:

$$\alpha_{pr} = \frac{\sum_{j=1}^{m} R_{pile,k,j}(s)}{R_{tot,k}(s)} \tag{1}$$

$$\alpha_s = \frac{s_{pr}}{s_r} \tag{2}$$

Where:

α_{pr} = piled raft coefficient;

α_s = settlement reduction coefficient;

$\sum_{j=1}^{m} R_{pile,k,j}(s)$ = sum of the characteristic pile resistances for a given settlement;

$R_{tot,k}(s)$ = characteristic value of the total resistance for a given settlement;

s_{pr} = settlement of piled raft foundation;

s_r = settlement of a spread foundation.

The α_{pr} values vary between 0 for raft alone and 1 for pile group without raft contribution, as well as the α_s value vary within the range from 0 (piled raft) to 1 (raft alone), as verified by Katzenbach and Choudhury [14], verified the interdependence between the foundation behavior as a function of stress level and settlement (Figure 1).

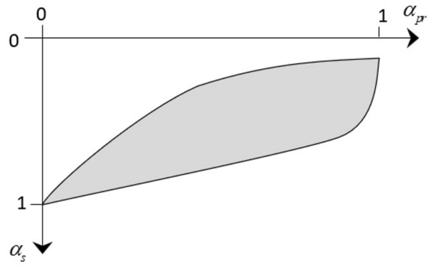

Figure 1. Correlation between settlement reduction coefficient, α_s, and load sharing coefficient α_{pr} of piled raft.

1.3 Effect of rafts on skin friction and axial force

Abdel-Azim et al. [19] analyzed numerically the piled foundations proposed by Katzenbach et al. [20] evaluating the distribution of skin friction along the 30-meter-long pile assessed for settlements, s, equal to 0.5%, 1% and 10% of "d". According to these authors, the best position to obtain the skin friction readings along the shaft interface is at a radial offset of 0.1d from the outer face of the shaft (Figure 2). It is observed that, for the first loading stages, the friction is mobilized to the toe, which has its skin friction exhausted from the sixth loading stage (60% of total load), and then leads to a greater resistance mobilization in a region close to the raft, as previously verified by Fioravante et al. [21].

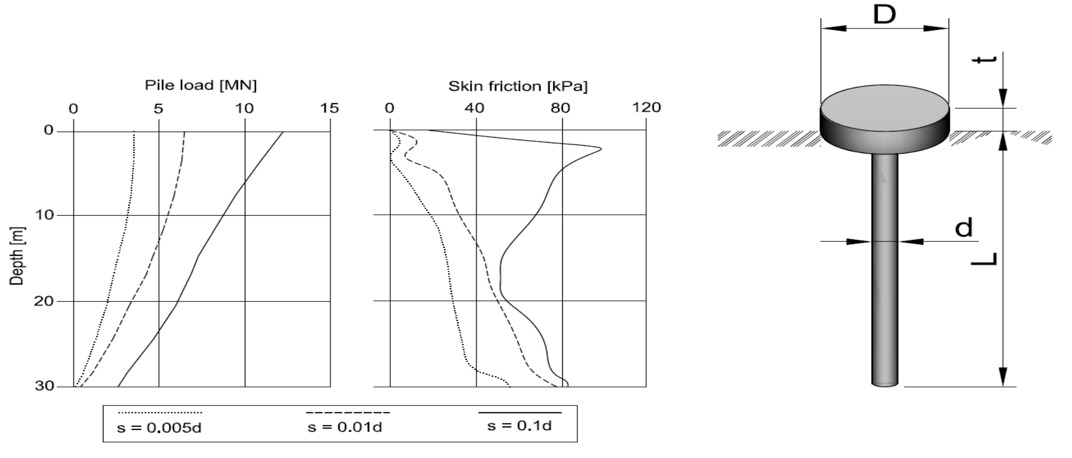

Figure 2. Influence of the pile-raft interaction on axial load transfer and skin friction with depth based on the Frankfurt Clay model (Katzenbach et al. [20]).

1.4 Bored piles

De Cock [22] describes a series of studies carried out by Caputo [23] and reinforced the influence of the pile installation method on soil confinement, and mentioning for example the tendency of the base of bored piles to move in the opposite direction of the excavation, which does not occur with driven piles.

Some studies show that shaft resistance of piles develops before toe resistance because it requires small displacements for mobilization [24], [25]. Through field tests, Garcia [9] observed that shaft resistance mobilization occurs mainly within a range of relative displacement to the pile diameter s/d between 1% and 5%.

Zhang et al. [26] outline three soil situations at the pile toe to explain the mechanism of toe resistance mobilization when there is relative displacement between the pile and the soil. In the first situation (Figure 3a), the soil layer shows a relatively normal resistance. In the second situation (Figure 3b), soil resistance is low, which may be caused by accumulated sediments at the pile base; in the third situation (Figure 3c) the soil under the toe has high resistance. The authors discuss the interaction between the lateral and toe resistance in the three situations with the use of the Mohr-Coulomb's failure criterion.

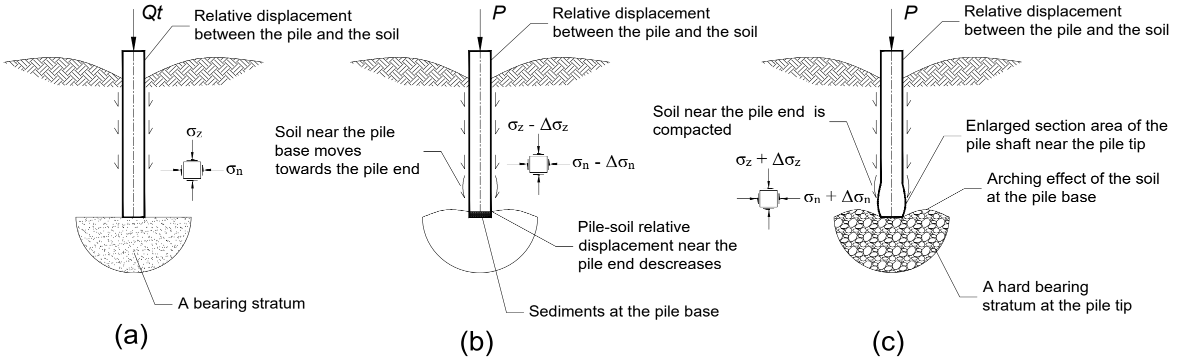

Figure 3. Stress state of soil element near pile end with different soil strengths at pile base (after Zhang et al. [26]).

The piles studied in this article relate to the situation described in Figure 3b, of low resistance soil at the base of the pile, aiming to better represent the behavior of foundations composed by short bored piles, also behaving as friction piles.

2 VALIDATION WITH EXPERIMENTAL STUDY

The material properties were obtained through calibration with experimental results obtained by Garcia [9] in piled cap composed of a short and small diameter bored pile, subjected to axial compression in residual soil. The block geometry (0.60 m x 0.60 m) was adjusted to an equivalent circular geometry, keeping the contact area with the soil to apply axisymmetric numerical modeling with Finite Elements (FEM-2D) by means of the Rocscience RS2 software. The pile used in the model has dimensions of 0.25-m diameter and 5-m length. The numerical model for validation considered non-contact between the side faces of the cap and the soil and included the modeling technique discussed in this work. Hence, the insertion of a region of low resistance soil under the pile toe (Figure 4) to represent the installation method of the pile usually employed in typical foundations.

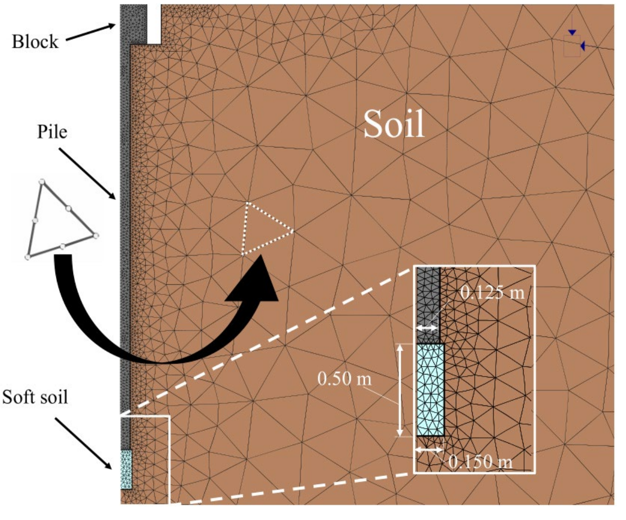

Figure 4. Numerical model for validation and detail of the soft material region inserted below the pile toe and graded mesh type and 6-noded triangle element.

The model was validated by comparing the load *vs.* settlement curve adjustment, both numerical and experimental, described by Garcia [9]. Although the numerical model has not taken into account the variation of soils and properties with the depth considered by Garcia [9], the results of the load-settlement curves (Figure 5) denote optimal adjustment up to the sixth stage of the applied load, in addition to the good agreement in the general behavior of the foundation under the aspect of load distribution, axial load transfer and skin friction. The material parameters obtained with the numerical calibration stage are shown in Table 1.

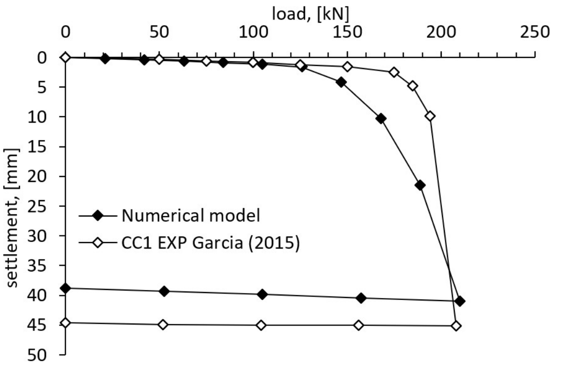

Figure 5. Load-settlement curves of the piled rafts by Garcia [9] versus numerical model.

The parameters were derived from compressive and tensile strengths for mass concrete based on the suggestion given by Ardiaca [27].

Table 1. Mechanical characteristics and materials deformability.

Material	E (MPa)	ν	K_0	γ (kN/m^3)	Model	ϕ (º)	c (kPa)
Soil	30.0	0.33	0.8	15	Elastoplastic	21	22
Soft material	5e-2	0.40	0.8	15	Elastoplastic	3	0
Concrete	30,100	0.20	-	25	Elastic	50	300

Note: E is the Young's modulus; ν is the Poisson's ratio; K_0 is the coefficient of at-rest earth pressure; γ is the unit weight; ϕ is the soil friction angle; c is the cohesion.

3 PARAMETRIC ANALYSIS

The analyses were carried out based on a parametric study, varying the geometric characteristics, such as raft thickness and pile length (Table 2).

Table 2. Details of the piled raft geometries analyzed and their loads.

Case	D_r (m)	t (m)	L (m)	d (m)	L/d	t/d	Stress applied (kPa)	Load applied (kN)
1	1.25	0.1	3	0.25	12	0.4	264	324.0
2		0.2		0.25		0.8	284	348.5
3		0.3		0.25		1.2	300	368.2
4		0.4		0.25		1.6	310	380.4
5	1.25	0.1	4	0.25	16	0.4	293	359.6
6		0.2		0.25		0.8	310	380.4
7		0.3		0.25		1.2	328	402.5
8		0.4		0.25		1.6	336	412.3
9	1.25	0.1	5	0.25	20	0.4	320	392.7
10		0.2		0.25		0.8	340	417.2
11		0.3		0.25		1.2	352	432.0
12		0.4		0.25		1.6	370	454.1
13	1.25	0.1	6	0.25	24	0.4	350	429.5
14		0.2		0.25		0.8	371	455.3
15		0.3		0.25		1.2	380	466.3
16		0.4		0.25		1.6	390	478.6

Note: D_r is the raft diameter; t is the raft thickness; L is the pile length; d is the pile diameter; A_{raft} = 1.227m^2.

The geometry of the piled raft cases under consideration has fixed parameters such as raft and pile diameter, and variable parameters such as raft thickness and pile length (Figure 6).

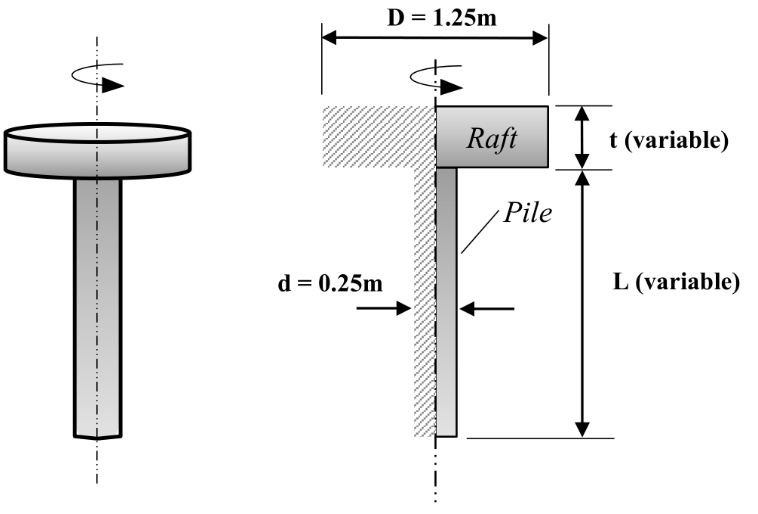

Figure 6. Geometry of the piled raft.

4 NUMERICAL ANALYSIS

The numerical analyses were performed with the aid of Rocscience RS2 software, which enables two-dimensional analyses on geotechnical structures and foundations by means of finite elements by considering, plane strain state or axisymmetric conditions.

The three-dimensional geometry of the foundation was converted into a plane model with axisymmetry around the axis of rotation (Figure 6). For the discretization of the soil mass and the piled raft, elements of the triangular type composed of 6 nodes were used (Figure 5). A graded mesh was adopted, discretized according to the number of dividing elements at the interfaces between the structure and the soil contour, having elements of size at a ratio of 1:70 between the interface around the contact of the structure with the ground and the interior of the soil mass. The number of elements in the models ranged from 4,000 to 6,000; such variation was due to the need for greater discretization inside the piled raft. Therefore, models with thicker rafts and longer piles resulted in a higher number of elements and nodes.

The type of loading chosen in the software was Body Force and Field Stress. It is divided into two stages: first a stress due to the self-weight of the elements is applied considering the horizontal response; then the loading is imposed, according to the stage.

The boundary dimensions were assumed to be about 1.6 times the length of the longest pile (L=6m). Moreover, the lateral boundaries of the model were restrained in the X-direction, and the lower boundary was restrained to move in X and Z-directions.

The dimensions of the low-strength soil element (soft material) were taken with a diameter of 1.2d and height equals to 2 times the diameter of the pile. The choice of extending the width of the region situated at the pile toe beyond the diameter was designed to overcome problems related to stress concentration in zones between different materials, as well as to improve the quality of the mesh in this region.

5 RESULTS AND DISCUSSION

From the methodology presented, an analytical structure was elaborated to briefly represent the steps that compose the present study (Figure 7).

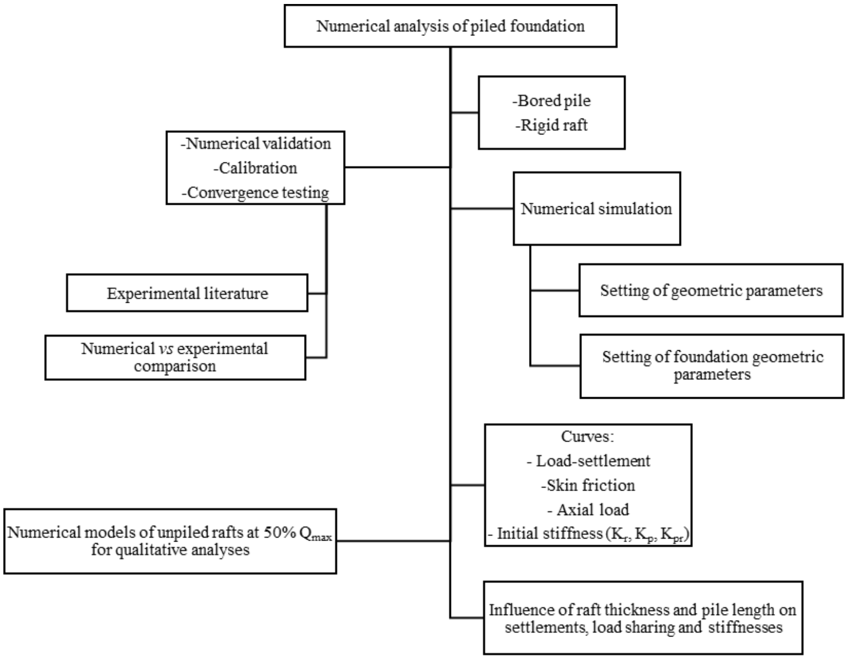

Figure 7. Scheme describing the steps of the present study.

5.1 Load settlement curves

The load versus displacement responses of each foundation under analysis were obtained from the application of a 10-stage series, with 10% increments up to the maximum load (Table 2). Unloading was performed in a 4-stage series, with 25% decreases of the maximum test load until total unloading (Figure 8 to Figure 23).

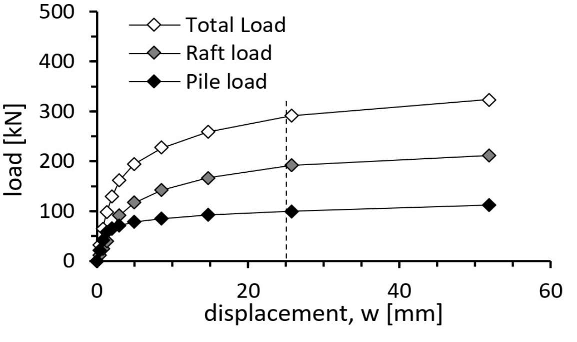

Figure 8. Load-settlement curve for case 1 - L=3m; t=0.1m

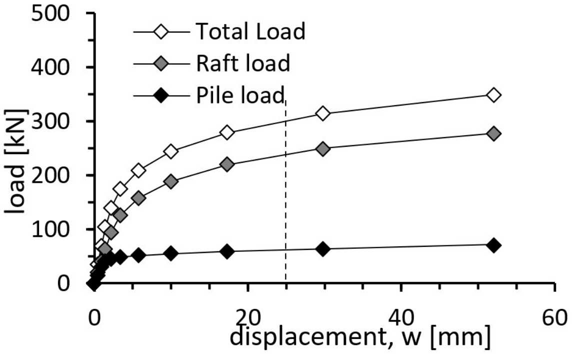

Figure 9. Load-settlement curves for case 2 - L=3m; t=0.2m

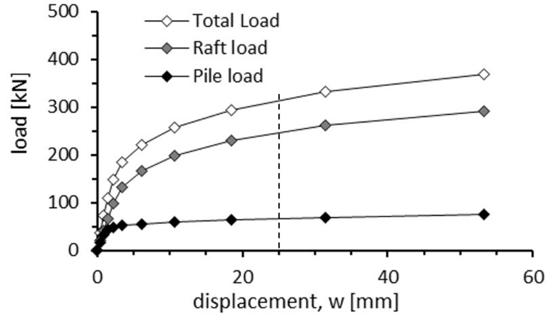

Figure 10. Load-settlement curves for case 3 - L=3m; t=0.3m

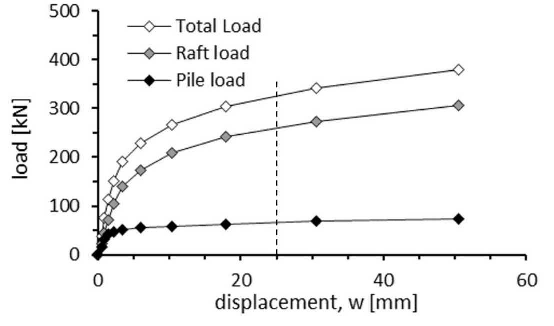

Figure 11. Load-settlement curves for case 4 - L=3m; t=0.4m

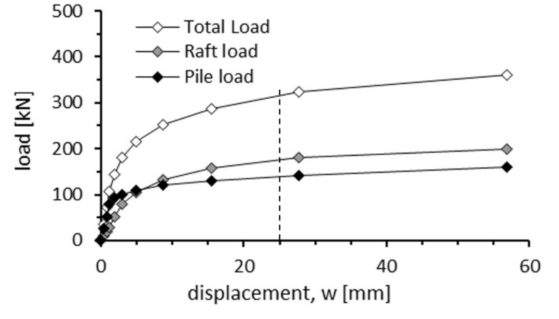

Figure 12. Load-settlement curves for case 8 - L=4m; t=0.1m

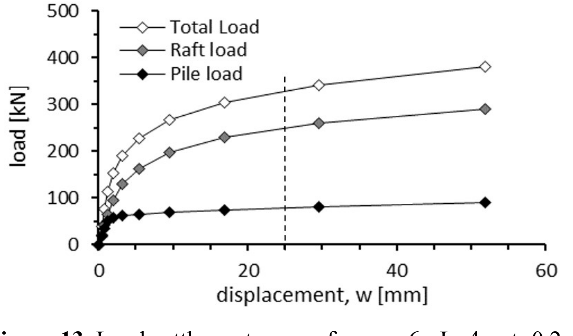

Figure 13. Load-settlement curves for case 6 - L=4m; t=0.2m

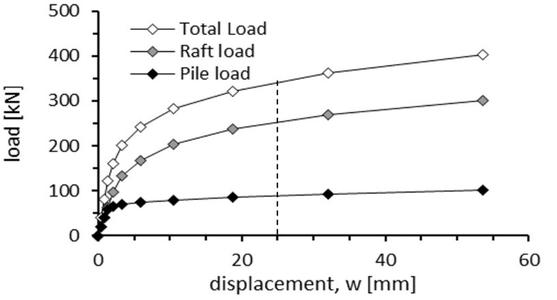

Figure 14. Load-settlement curves for case 7 - L=4m; t=0.3m

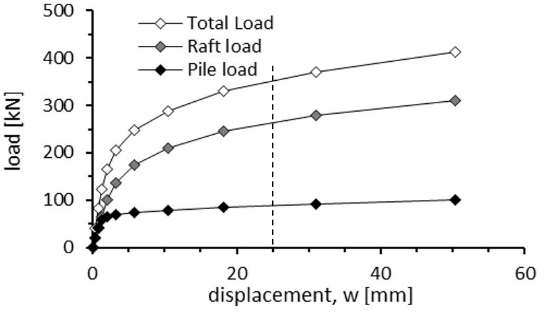

Figure 15. Load-settlement curves for case 8 - L=4m; t=0.4m

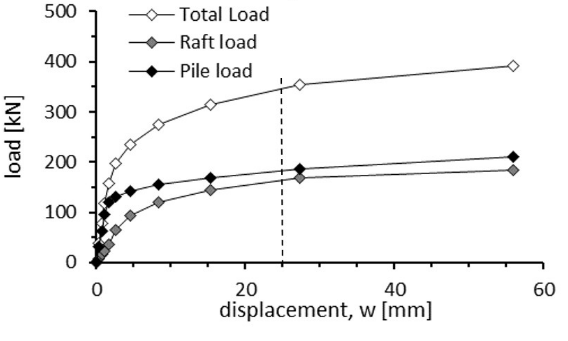

Figure 16. Load-settlement curve for case 9 - L=5m; t=0.1m

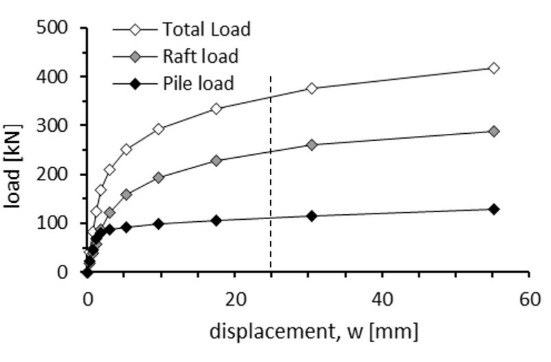

Figure 17. Load-settlement curves for case 10 - L=5m; t=0.2m

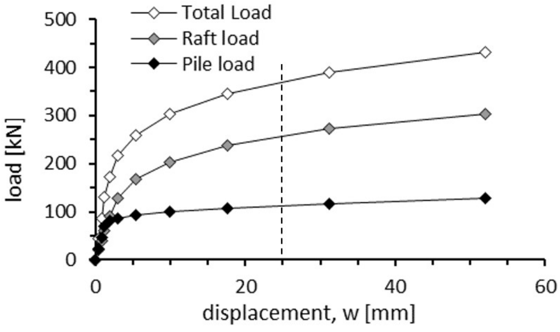

Figure 18. Load-settlement curves for case 11 - L=5m; t=0.3m

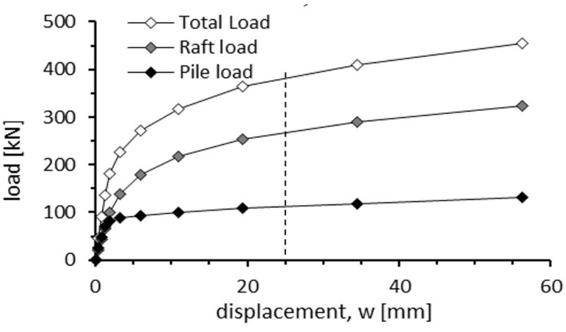

Figure 19. Load-settlement curves for case 12 - L=5m; t=0.4m

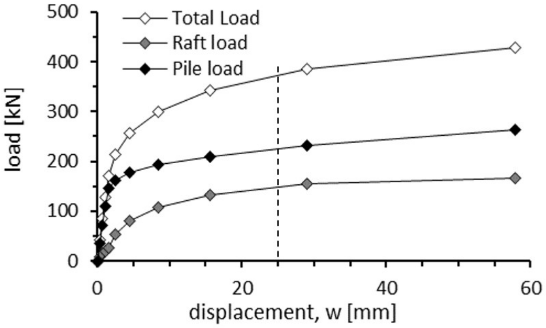

Figure 20. Load-settlement curves for case 13 - L=6m; t=0.1m

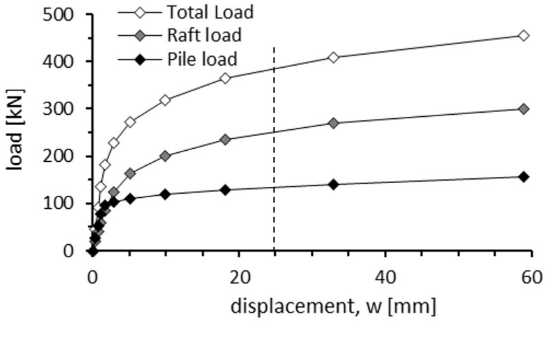

Figure 21. Load-settlement curves for case 14 - L=6m; t=0.2m

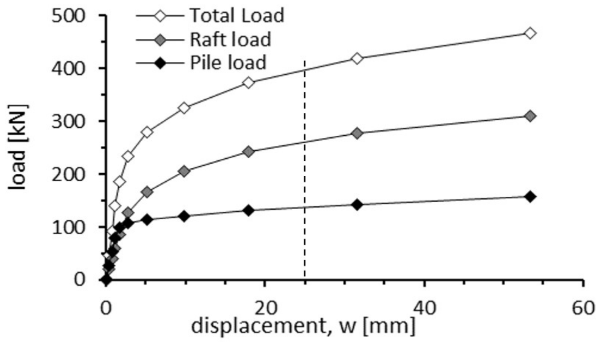

Figure 22. Load-settlement curves for case 15 - L=6m; t=0.3m

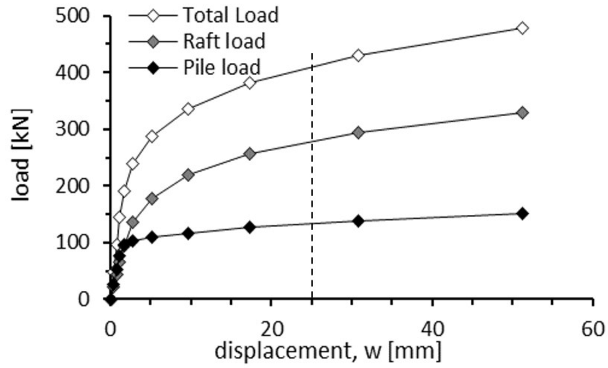

Figure 23. Load-settlement curves for case 16 - L=6m; t=0.4m

The maximum test loads were established for each piled raft to obtain approximately 50 mm of displacement, conventionalizing the geotechnical "failure" of the foundation by one of the limit states. As a failure criterion for ultimate resistance, according to the recommendations from the British Standard BS 8004:2015 [28], the displacement assumed was of 10% of the pile diameter or 25 mm.

The load settlement curves show a greater pile share in the load capacity of the foundation system for 0.10-m thick rafts. The contribution of the pile is reduced for rafts with thickness of 0.20 m or more. On the other hand, in all cases analyzed, the participation of the raft-soil contact is preponderant in comparison to the pile participation. Such evidence can be attributed to the high raft contribution area in the overall bearing capacity. The following curves are basically distinguished by the characteristics of the raft-soil stiffness, i.e., for rafts considered flexible (0.10 m in height) and rigid (> 0.20 m).

5.2 Influence of raft thickness on shaft resistance of piles

The effect of raft thickness on the portion of total load supported by total shaft resistance of piles (Figure 24). The 0.10-m thick rafts influenced positively the mobilization of skin friction, compared to models with 0.20 m, 0.30 m, 0.40 m thicknesses: differences between 14% and 30% can be seen. In addition, with increasing loads, rafts thicker than 0.10 m led to minor load sharing by the pile due to little toe resistance and to greater participation of the raft. During the loading test with piled rafts instrumented and described by Garcia [9], the values measured for total toe resistance were around 6% of the total load applied to the foundation, even at displacement levels of approximately 20% of the pile diameter. In all cases, the axial load reaching the pile toe was less than 2% of the total load, even for large relative displacements, close to 20% of the pile diameter (50 mm). The behavior of the piles compares to that of floating piles, which orient their resistance predominantly to the shaft. Such values imply that the model represents adequately a short bored pile of small diameter inserted in uniform soil.

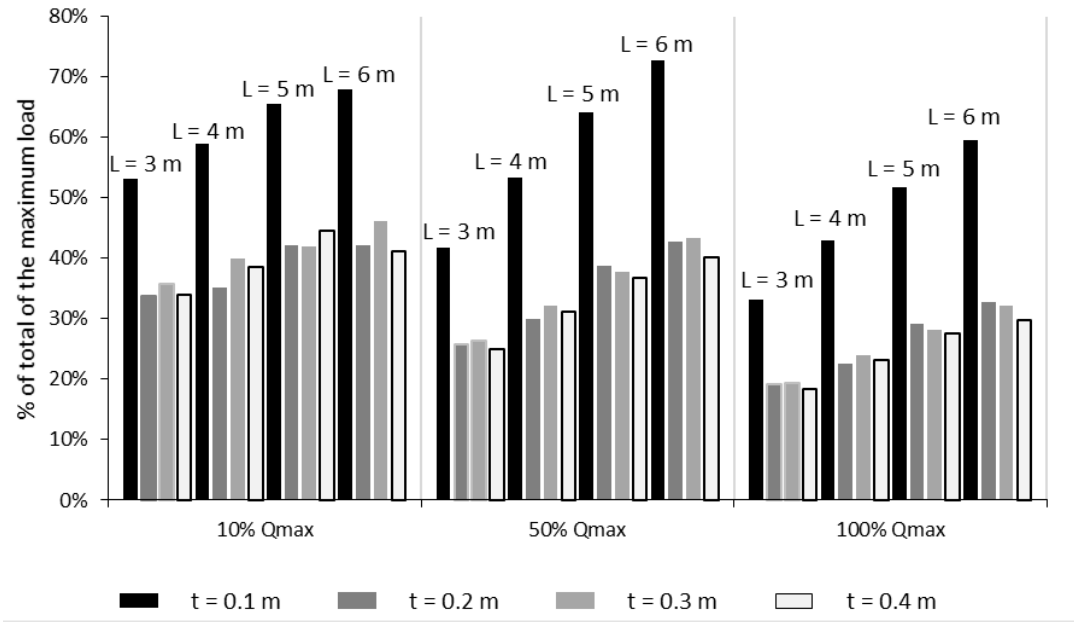

Figure 24. Portion of the maximum load taken by the total shaft resistance.

6 RESPONSE AND BEHAVIOR ANALYSES

The choice of geometric parameters to evaluate the interaction among the soil, raft and pile is based on previous works in the literature on piled foundations, among which, those of Poulos and Davis [2], Kuwabara [10] and Clancy and Randolph [18].

The behavior analyses regarding relative stiffness were established with respect to the pile slenderness ratio (L/d), and the ratio between raft thickness and pile diameter (t/d). Based on the parametric characteristics and properties of the mechanical behavior of foundations under analysis, this work seeks to correlate the favorable features to the appropriate design elaboration, supporting premises for a qualitative evaluation for conception and predesign of foundation elements of superstructures.

6.1 Initial Stiffnesses of Piled Rafts

For the 16 cases analyzed, the stiffness of piled rafts foundations ($K_{piled\ raft}$) and their elements (K_{pile} e K_{raft}) were calculated by means of the loading and displacement values obtained in the first stages (i.e., up to 50% of the maximum load of a given foundation (Q_{max}), and therefore, the structural elements exhibit a linear elastic behavior and they have a good potential to be used in practical applications.

The increase in raft thickness for a constant diameter (t/d) does not influence the increase in stiffness of the piled raft unit, which remains almost constant for the same pile slenderness ratio (Figure 25a). On the other hand, for a higher pile slenderness ratio, there is an increase in relative stiffness of the piled rafts under analysis, showing that the isolated stiffness of the pile (Figure 25b) is directly related to its slenderness ratio (L/d). The raft stiffness is small for flexible rafts (t/d = 0.4), but it remains almost constant for rafts considered as rigid (t/d ≥ 0.8) (Figure 25c). The models with 0.1-m thick rafts (t/d = 0.4) allow greater pile response, since the surface element has lower capacity to restrain displacements due to its lower stiffness.

When analyzing the influence of the use of longer piles connected to thicker rafts, it was found that piled raft stiffness is predominantly influenced by pile stiffness and its slenderness ratio (Figures 25 and 26). For rafts considered rigid (t/d ≥ 0.8), the raft response is practically uniform for different values of pile slenderness (L/d), while the contribution to pile stiffness and overall stiffness is linearly increasing. Distinct behavior is observed for rafts considered flexible (t/d= 0.4), in which raft stiffness (K_r) decreases linearly with increasing ratio L/d This is explained by the increasing pile stiffness (K_p), as seen in Figure 26b and Figure 26c.

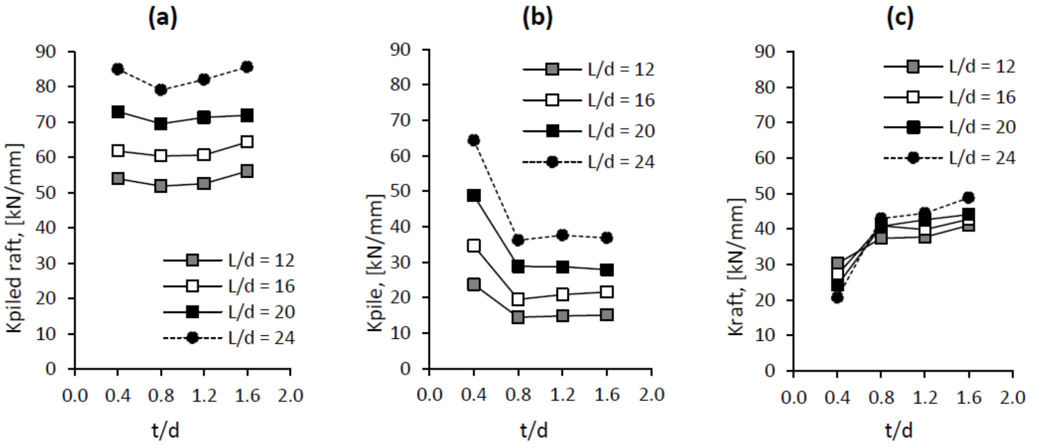

Figure 25. Effect of t/d ratio on piled raft, pile and raft responses

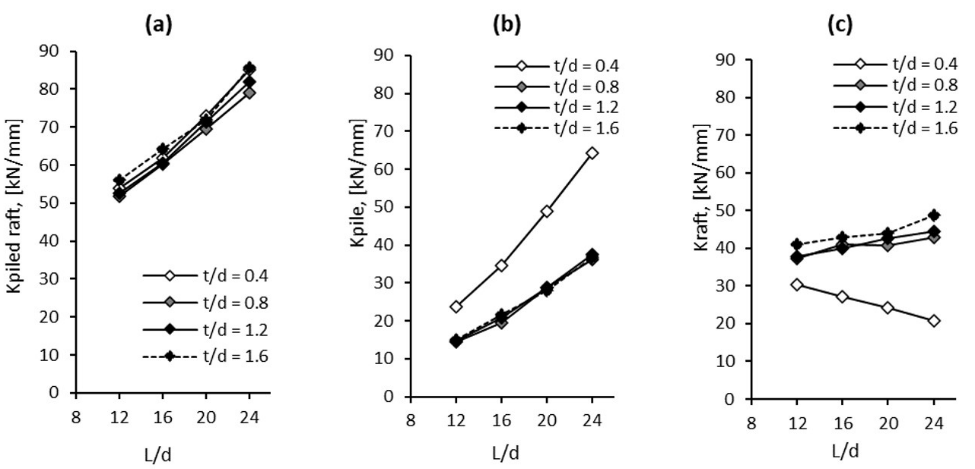

Figure 26. Effect of L/d ratio on piled raft, pile and raft responses.

6.2 Settlement Reduction and Load Sharing

A comparison of the effects of using piles combined with rafts shows that rafts of heights equal to 0.1 m are more sensitive to distribution of loads among the foundation elements, thus increasing the load portion supported by the piles.

Based on the analyses carried out and considering the reduced settlement in the piled foundation (Figure 27), it is verified that increasing raft thickness has little influence on the reduction of its total settlement (s_{pr}), when compared to those of unpiled rafts (s_r). The insertion of piles in the raft and the increase in pile length leads to a significant reduction of the total settlement of the piled raft, for all thicknesses analyzed.

The load sharing in the analyzed models increases with the increase of raft thickness, whose values varied from 28% to 45% (Table 3) for the cases of rigid rafts ($t \geq 0.2$ m). On other hand, based on the average of the coefficient α_s values, the total settlements presented 44% to 78% reduction when compared to isolated rafts, showing the efficiency of the pile insertion. In the cases analyzed in this work, the piles were positioned at the point of occurrence of the greatest displacement, i.e., the central region of the raft.

The results above agree with the propositions given in De Sanctis et al. [29] about what occurs in "small rafts" where the ratio is D/L <1. According to the classification of these authors, a "small" isolated raft does not have enough bearing capacity to support the total load, thus requiring the insertion of piles to ensure reduced settlement. It also improves the bearing capacity of the system. In this case, differential settlement is not essential for rafts considered as rigid since the raft in this situation has enough flexural stiffness.

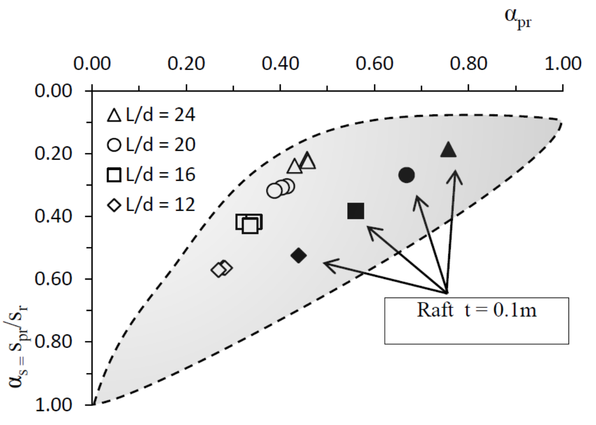

Figure 27. Evaluation of settlement reduction and load sharing for the piled rafts (at 50% of Q_{max}).

Table 3. Results from the evaluation of the piled raft units.

L/d	α_{pr} (t=0.1m)	$\overline{X}(\alpha_{pr})$ (t=0.2m;0.3m;0.4m)	Increasing % in the pile load $\Delta\alpha_{pr}$ (%)	Total settlement reduction
12	0.44	0.28	16%	44%
16	0.56	0.33	23%	59%
20	0.67	0.40	27%	70%
24	0.76	0.45	31%	78%

Note: d = 0.25m; α_{pr} =piled raft coefficient; $\overline{X}(\alpha_{pr})$ average of the values

7 CONCLUSIONS

The determination of parameters through numerical validation of experimental tests is an important tool to study the behavior of piled foundations, since it is possible to assess the interaction between the elements, by means of an appropriate modeling. A careful check is required during the modeling to verify if the conditions observed in the field can be implemented in the numerical model.

For a t/d ratio equal to or higher than 0.8 (t = 0.2 m), there is no increase in the overall initial response, although it is possible to reach a load sharing on the pile equal to 28% to 45% of the total applied load and a 44% to 78% reduction in piled raft settlements compared to those of unpiled rafts.

The pile length has a greater influence on the initial stiffness of the piled raft than the raft thickness. Models with 0.10 m raft thickness positively modified the axial response of the pile, and from the thickness of 0.20m, the models uniformed their behaviors, meaning more distant from the "flexible" raft condition pointed out by Clancy and Randolph [12].

The results of the present study showed good agreement with key points emphasized by El-Mossallamy, Lutz and Duerrwang [30] regarding the confinement caused by raft-soil contact that increases the stress in the region near the top of the pile, and also on the effects of interaction between the elements, for example the load sharing, that has been shown to be dependent on the level of loading.

The results here reported are valid for application under conditions similar to those conducted by this research, and therefore, it cannot be considered a generalized approach.

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