Combined Piled-Raft Foundations Behavior

Comportamiento De Losas De Cimentación Combinadas Con Pilotes

Authors

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ABSTRACT

Combined pile-raft foundations (CPRFs) have become a prevalent foundation solution in contemporary civil engineering due to the growth in high-rise construction. CPRFs offer advantages such as high load-bearing capacity and reduced settlements. However, their complexity requires thorough investigation to optimize the process via efficient numerical analysis methods. Parameters like pile diameter, length, quantity, and raft thickness, traditionally examined analytically, require comprehensive consideration of interactions, often relying on approximations which lead to uncertainties. This study evaluates CPRF tensile-deformation behavior through parametric investigation using numerical methods to discern the influence of pile diameter, length, quantity, and raft thickness on structural response to vertical and horizontal forces. Findings reveal pile diameter significantly dictates response to horizontal loading, while slenderness ratio governs response to vertical loading, with higher impact at increased values. Increased raft thickness leads to more uniform load distribution among piles and higher bending moments within the raft. These insights deepen understanding of CPRF behavior under various loading conditions, informing optimized design and construction practices in civil engineering.

Keywords: *combined pile-raft foundations, numerical analysis methods, pile diameter, pile length, raft thickness*

RESUMEN

Las losas de cimentación combinadas con pilotes (LCCP) se han convertido en una solución de cimentación predominante en la ingeniería civil contemporánea debido al crecimiento de la construcción de gran altura. Las LCCP ofrecen ventajas como una alta capacidad de carga y asentamientos reducidos. Sin embargo, su complejidad requiere una investigación exhaustiva para optimizar el proceso mediante métodos de análisis numérico eficientes. Parámetros como el diámetro, la longitud, la cantidad y el espesor de la viga del pilote, tradicionalmente examinados analíticamente, requieren una consideración integral de las interacciones, a menudo basándose en aproximaciones que generan incertidumbres. Este estudio evalúa el comportamiento de tensión-deformación del LCCP a través de una investigación paramétrica utilizando métodos numéricos para discernir la influencia del diámetro, la longitud, la cantidad y el espesor de la viga del pilote en la respuesta estructural a las fuerzas verticales y horizontales. Los hallazgos revelan que el diámetro del pilote dicta significativamente la respuesta a la carga horizontal, mientras que la relación de esbeltez gobierna la respuesta a la carga vertical, con mayor impacto a valores mayores. El aumento del espesor de la balsa conduce a una distribución de carga más uniforme entre los pilotes y a mayores momentos de flexión dentro de la balsa. Estos conocimientos profundizan la comprensión del comportamiento del LCCP bajo diversas condiciones de carga, informando prácticas optimizadas de diseño y construcción en ingeniería civil.

Palabras clave*: cimentaciones combinadas de pilotes y balsas, métodos de análisis numérico, diámetro del pilote, longitud del pilote, espesor de la balsa.*

Nota Editorial: Recibido: Febrero 2024 Aceptado: Marzo 2024

1. INTRODUCTION

One of the most significant challenges in combined pile-raft foundations (CPRFs) lies in determining the requisite number of piles for achieving foundation stability, numerous studies have been developed in this sense in recent years [1-14]. The addition of a small number of piles yields a substantial reduction in raft settlement; however, adding more piles results in marginal, nearly insignificant reductions, leading to uneconomical projects. Therefore, optimizing CPRF design necessitates reaching the minimum pile count to achieve settlement within tolerable limits. Incorporating a few piles in the central region of the raft reduces or nullifies differential settlements. In this design approach, piles are positioned centrally within the raft to approximate rigid behavior [15]. Nguyen, et al. [16] demonstrated that placing piles beneath columns significantly reduces soil settlements and bending moments in rafts.

The effects of pile quantity and load application significantly influence maximum settlement, differential settlement, and maximum bending moment. The load application method does not affect the percentage of load borne by the pile group but influences load distribution among them [17]. Pile groups are often designated with uniform lengths; however, this configuration may not be optimal, leading to studies aimed at reducing economic and environmental costs. Elwakil and Azzam [18] suggest that ultimate bearing capacity is directly proportional to pile quantity, and decreasing pile length increases the percentage of load borne by the raft. As the ratio of pile length to diameter (L/d) increases for a given pile count, settlements decrease, but this reduction is minimal for over 20 piles. Friction developed by a CPRF pile significantly exceeds that of an isolated pile or pile group, a critical consideration for design optimization [19].

Pile spacing significantly affects CPRF displacements under horizontal or vertical loading. Increasing spacing can substantially reduce the horizontal load borne by piles [20]. The impact of raft stiffness on behavior under concentrated loads is negligible for maximum settlement and percentage of load absorbed by piles. However, increasing raft thickness reduces differential settlement while increasing the maximum bending moment [17].

Horizontal forces on piles are often much smaller than vertical loads, obviating separate calculations. Under lateral loads, piles experience bending moments and shear forces, with section behavior influencing pile design. Pile lateral displacement is markedly nonlinear, even under relatively low loads; thus, nonlinear behavior must be considered for displacement prediction. Conversely, the maximum bending moment in concrete piles exhibits a near-linear relationship from initial loading to failure.

The lateral displacement of the pile is markedly nonlinear, even for relatively low loads; if a prediction of displacement is critical, the nonlinearity has to be taken into account. On the contrary, the maximum bending moment is linked to the application of lateral loads by a linear relationship; this is an aspect to be taken into account for its structural design. In concrete piles, the non-linearity of the pile material combined with the influence of settlement is compensated, this does not occur in steel piles [21]. The relationship between the load and the maximum bending moment in the pile, on the other hand, is nearly linear from the first loading states to failure.

Lateral loads on piles present a highly complex three-dimensional problem, assessable via the Winkler Model and finite element analysis, which account for nonlinear stress-strain soil behavior, soil variations, pile section variations, and other characteristics. In non-uniform pile arrangements concentrated under columns, the bending moment decreases while horizontal displacement increases [16]. Vertical load influences lateral load effects significantly, with bending moments and horizontal displacements increasing considerably with the vertical force-to-pile length ratio [22].

2. GRAPHICS , TABLES , MATERIALS AND METHODS

In this study, a numerical simulation was employed via a parametric investigation to analyze the behavior of CPRFs under vertical and horizontal loads and their impact on the variables involved in this particular foundation type. To determine the extent of influence exerted by various parameters on CPRF behavior, separate analyses of foundation elements were imperative. Specifically, the evaluation focused solely on the piles. The parameters considered for this investigation are detailed in Table 1, while Table 2 delineates the characteristics of the CPRF models.

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Table 1: Geometric characteristics of isolated pile models

Soil Type	Piles	
	Diameter (m)	Length (m)
Frictional Soil	0.4	5
		10
		20
	0.8	5
		10
		20

These parameters were integral to the numerical simulation aimed at understanding the behavior of isolated piles across various soil conditions and geometries.

Table 2: Geometric characteristics of CPRF models.

Models	Raft Dimensions (m)	Raft Thickness (m)	Pile Diameter (m)	Pile Length (m)	Quantity (units)
LP 4010 0.5	2.1x2.1	0.5	0.4	10	4
LP 4010 1	2.1x2.1	1	0.4	10	4
LP 8010 0.5	3.7x3.7	0.5	0.8	10	4
LP 8010 1	3.7x3.8	1	0.8	10	4

For this study, a linear-elastic model was adopted to represent concrete behavior, consistent with similar studies [23-25]. Concrete is assumed to have a compressive strength of *35 MPa*, an elasticity modulus of *2.35 x 107 kN/m2*, a Poisson's ratio of *0.17*, and a density of *24 kN/m2*.

The selected soil model is Mohr-Coulomb, as it best describes tangential and normal stresses and their influence on soil bearing-capacity, aligning with the scope of this work. The homogeneous soil stratum considered here is predominantly granular, characterized by an elastic modulus (*E*) of *5000 kN/m2*, cohesion (*C*) of *10 kN/m2*, an internal friction angle (*Ø*) of *30º*, and a unit weight (*γd*) of *14,15 kN/m3*.

Soil-structure interaction significantly affects the behavior of such foundations [26, 27]. To account for this, interface elements were created [28], allowing for differential displacements between node pairs at the soil-foundation interface. One model slides while the other separates, accounting for interface separations and sliding. The MIDAS GTS NX 2019 program automatically creates the interface throughout the foundation contact area based on soil properties.

Bending moments on the upper and lower faces of Rafts are among the parameters evaluated in this study. To determine their values, Gauging Shell elements are created, extracting mesh parts from the faces of three-dimensional elements to determine internal forces based on face stresses.

Loads are assigned through prescribed displacements, enabling the imposition of a displacement to the model to determine the resulting load. In isolated pile models, vertical displacement was *5 cm* applied punctually perpendicular to the pile's cross-section and *2.54 cm* horizontally. In CPRF models, vertical loads were applied punctually at the Raft center as prescribed displacements (*8 cm*), while horizontal loads were applied punctually at the column edge. Loads were gradually applied in increments to describe the stress-strain behavior for each increment. Soil self-weight, automatically calculated, had to be input in a separate stage per MIDAS GTS NX program requirements. Figure 1 shows the final result of one model (LP 4010 1).

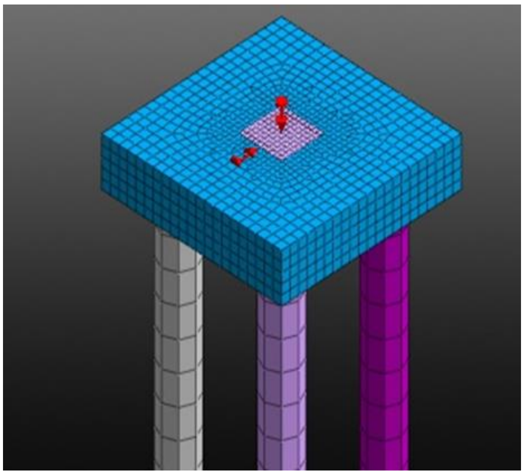

Figure 1: Model LP 4010 1.

Determining the load-bearing capacity and resistance and deformation behavior of CPRFs is a challenge. To achieve this, it is necessary to establish relationships among various influencing parameters, such as the diameter and length of the piles, as well as the thickness of the Raft.

3. RESULTS AND COMMENTS

The stress-strain behavior of individual piles under vertical loading was evaluated, yielding the results depicted in Figure 2.

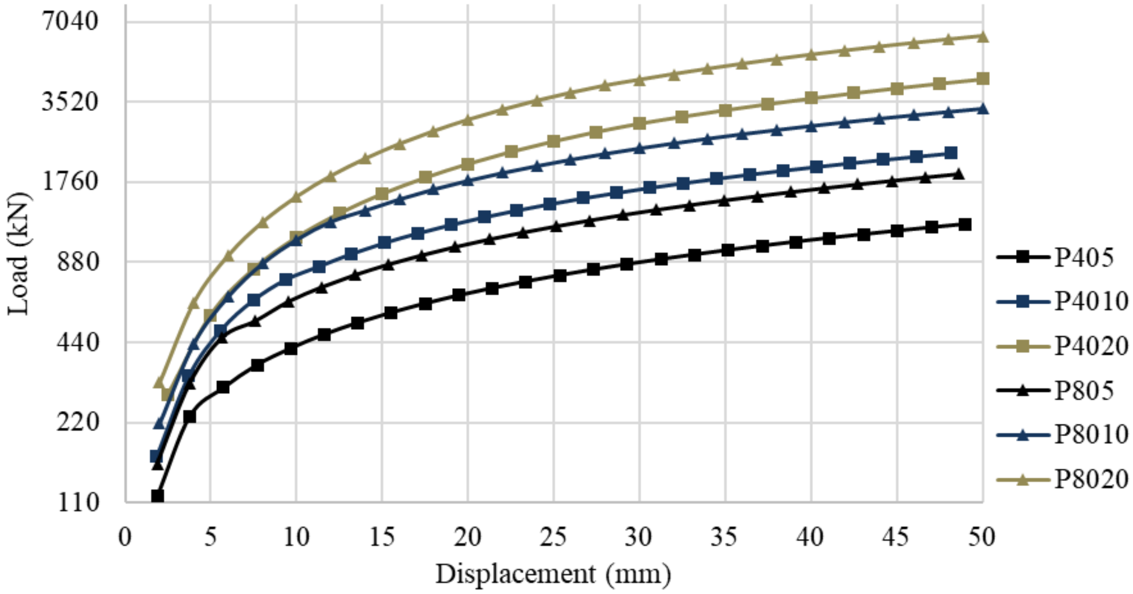

Figure 2: Stress-Strain Characteristics of Individual Piles under Vertical Loads.

From Figure 2, it is evident that increasing the length of the piles under vertical loading results in a proportional increase in the load required to induce the same settlement value in the soil. This relationship stems from the expanded contact area between the soil and the pile, consequently enhancing the foundation's bearing capacity. Moreover, it is a well-established fact that the settlement of piles diminishes as their diameter increases. In this parametric investigation, various isolated piles with differing diameters were designed, confirming the decrease in settlement values with increasing diameters.
The ultimate vertical load-bearing capacity of the isolated pile was determined using the NBR 6122/2010 method, with the results summarized in Table 3.

Table 3: Ultimate vertical load-bearing capacity in individual piles.

Model	**Slenderness Ratio (L/D)**	**Vertical Load-Bearing Capacity (kN)**	**Difference ($\%$)**
P 405	12.5	500	0
P 4010	25	1200	58.3
P 4020	50	4600	73.9
P 805	6.25	1200	0
P 8010	12.5	2300	47.8
P 8020	25	5100	54.9

The ultimate vertical load-bearing capacity increases with both the length and diameter of the pile. Moreover, for the same slenderness ratio, the ultimate vertical load-bearing capacity escalates with the diameter of the piles. The differences obtained in the load capacity between the shorter piles (5m) and the rest (10 and 20m) were significant, with values greater than 45% in all cases, regardless of the diameter of the piles.

Additionally, the determination of the ultimate horizontal load-bearing capacity was predicated on the load that induces a lateral displacement of $2.54\ cm$, with the results illustrated in Figure 3.

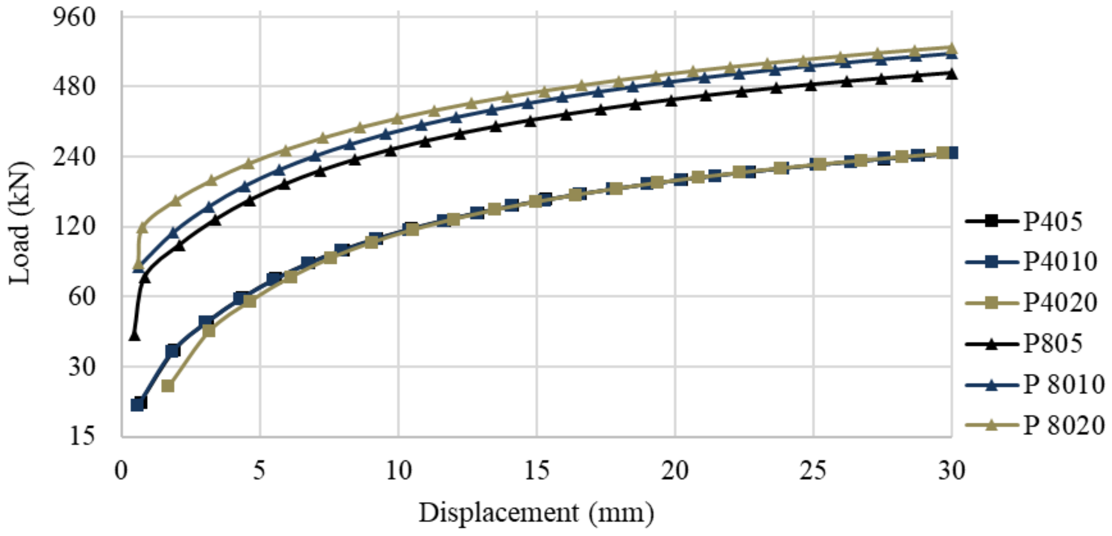

Figure 3: Stress-Strain Behavior of Individual Piles under Horizontal Loads.

The pile length does not significantly impact the ultimate horizontal load-bearing capacity. However, with an increase in diameter, the load-bearing capacity increases considerably. The results of the ultimate horizontal load-bearing capacity and its variation concerning pile length are presented in Table 4.

Table 4: *Values of horizontal load-bearing capacity for 40 cm diameter piles.*

Model	Slenderness Ratio (L/D)	Ultimate Horizontal Load-Bearing Capacity (kN)	Differenc e (%)
P 405	12.5	221	0
P 4010	25	222	0.45
P 4020	50	223	0.44
P 805	6.25	490	0
P 8010	12.5	591	17
P 8020	25	625	5

For $40\ cm$ diameter piles, the difference in horizontal load-bearing capacity is practically negligible with increasing length, the differences between the load capacity of the shorter piles (5m) and the longer piles. In the case of $80\ cm$ diameter piles, although the difference compared to $40\ cm$ piles is slightly more pronounced, their contribution to the ultimate horizontal load-bearing capacity remains relatively low. This reaffirms that pile length does not significantly influence the ultimate horizontal load-bearing capacity of the piles.

Combined Rafts with piles stand out as one of the most common foundation solutions for tall buildings. Despite decades of research, uncertainties persist regarding their design and performance due to the complex load transfer mechanism between the structure and the soil, which is influenced by various factors. Numerical methods offer precise modeling capabilities for such foundations, enabling predictions of their behavior under diverse loading scenarios.

In the models of combined Rafts with piles, a uniform pile length of 10 meters was maintained throughout, with the supporting soil remaining consistent. The only variables considered were the diameters of the piles ($40\ cm$ and $80\ cm$) and the heights of the pile caps ($50\ cm$ and $100\ cm$). Figure 4 illustrates the stress-strain response under vertical loads.

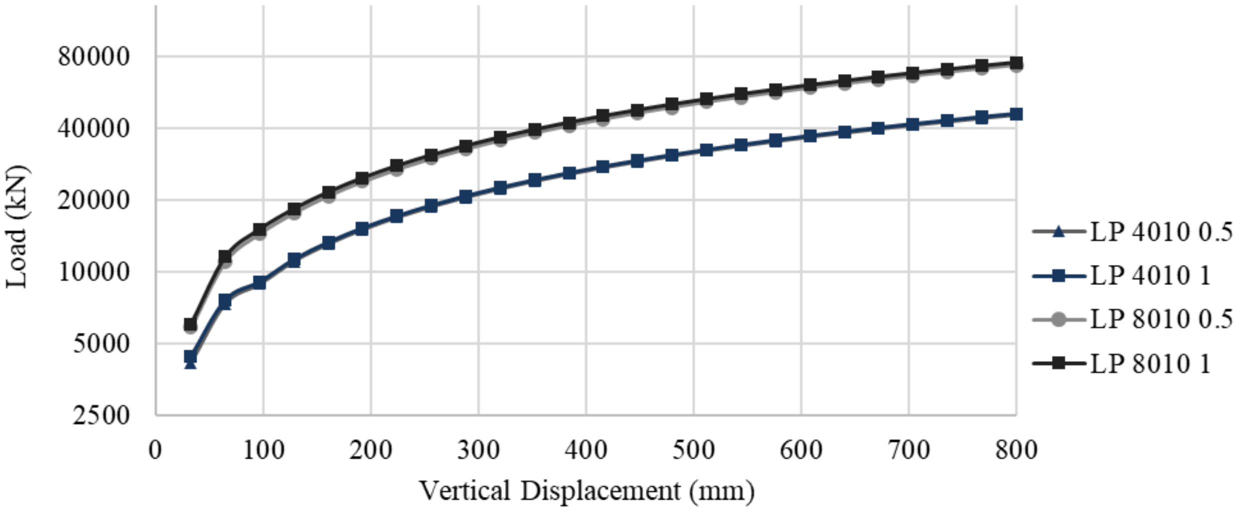

Figure 4: Stress-strain behavior of CPRF under vertical loads.

According to Figure 4, it is evident that, for the same raft thickness, the one with a pile diameter of $80\ cm$ exhibits greater resistance. This is because the increased contact area between the soil and the surface of the piles reduces pressures at the pile tips, thereby enhancing their load-bearing capacity under vertical loads. The raft thickness is a crucial variable, as it contributes to the horizontal load-bearing capacity of the foundation system.

The results obtained indicate that increasing the raft thickness by $50\ cm$ does not affect the ultimate vertical load-bearing capacity of the foundation. This is attributed to the fact that small-sized pile caps do not significantly contribute to the vertical load-bearing capacity.

Additionally, the stress-strain behavior under horizontal loads was evaluated while maintaining a constant raft thickness. This allowed for the assessment of the influence of pile diameter on the horizontal load-bearing capacity and the behavior of the combined Rafts with piles. The results of these models are presented in Figure 5

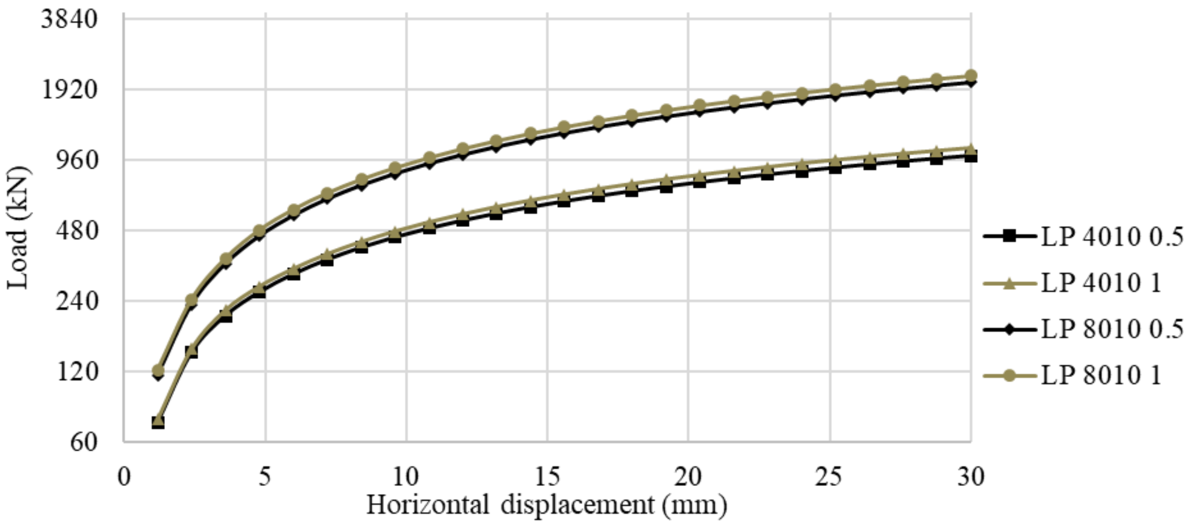

Figure 5: Stress-strain behavior of CPRF under horizontal loads.

In the displayed models, it is noticeable that there are increases in the load-bearing capacity of the combined Rafts with piles as the diameter of the piles increases. According to the results, a $100\ \%$ increase in pile diameter leads to approximately a $50\ \%$ increase in the load-bearing capacity of the combined rafts with piles. The raft thickness is a crucial variable, and understanding its contribution to horizontal loading can be economically advantageous for the foundation.

Moreover, the effect of raft thickness on the combined rafts with piles positively contributes to the horizontal load-bearing capacity. In both experiments, there is a slight increase in the load-bearing capacity of the combined Rafts with piles. In both cases, the increase in horizontal load-bearing capacity was modest, with values of $7\,\%$ and $6\,\%$ in the combined rafts with piles with pile diameters of $40\,cm$ and $80\,cm$, respectively. Despite this, it contributes to the load-bearing capacity, being a factor to consider in the design, primarily due to the friction generated on the adjacent faces and the passive soil pressure on the frontal face.

To determine the influence that the vertical load has on the horizontal load capacity, an LCCP was modeled with vertical load and horizontal load applied simultaneously and another only with horizontal load in the LCCP model with piles of $40\ cm$ diameter, and raft thickness of 1m, then the results are shown in Figure 6.

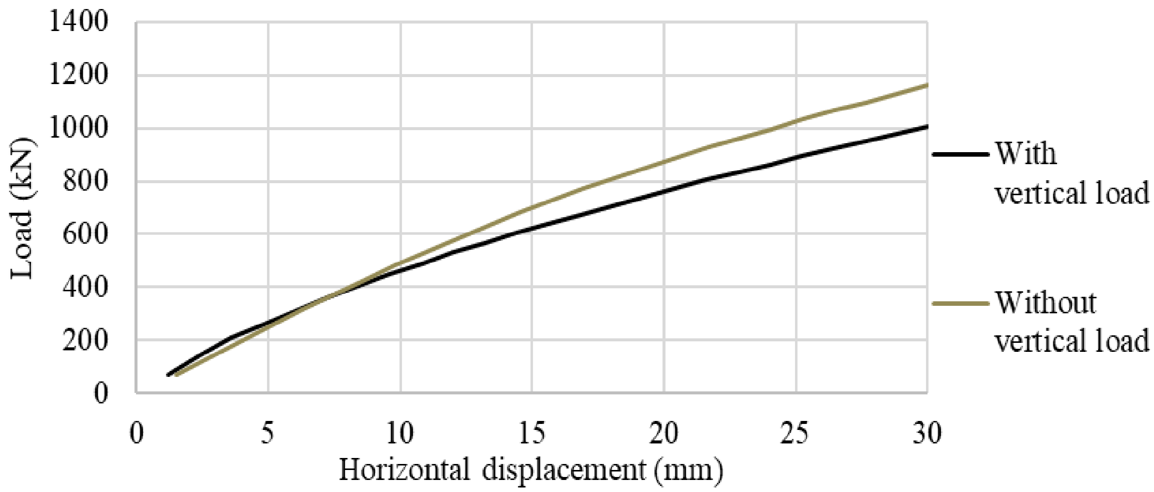

Figure 6: CPRF behavior under horizontal and vertical load.

The application of vertical loads induces an increase in the horizontal load-bearing capacity of the foundation, underscoring the importance of considering its impact in the design phase. The combined effect of vertical and horizontal loads resulted in an approximate $14\,\%$ enhancement in the horizontal load-bearing capacity. Therefore, when devising such foundations, accounting for this factor is imperative to ensure optimal design.

The influence of the raft thickness of the combined rafts with piles (LCCP) on the flexural moments of the rafts of models LP 8010 0.5 and LP 8010 1, with a vertical load applied value of $3000\ kN$ at the center of the Raft, was assessed. Figure 7 depicts the values of these moments in the X-direction.

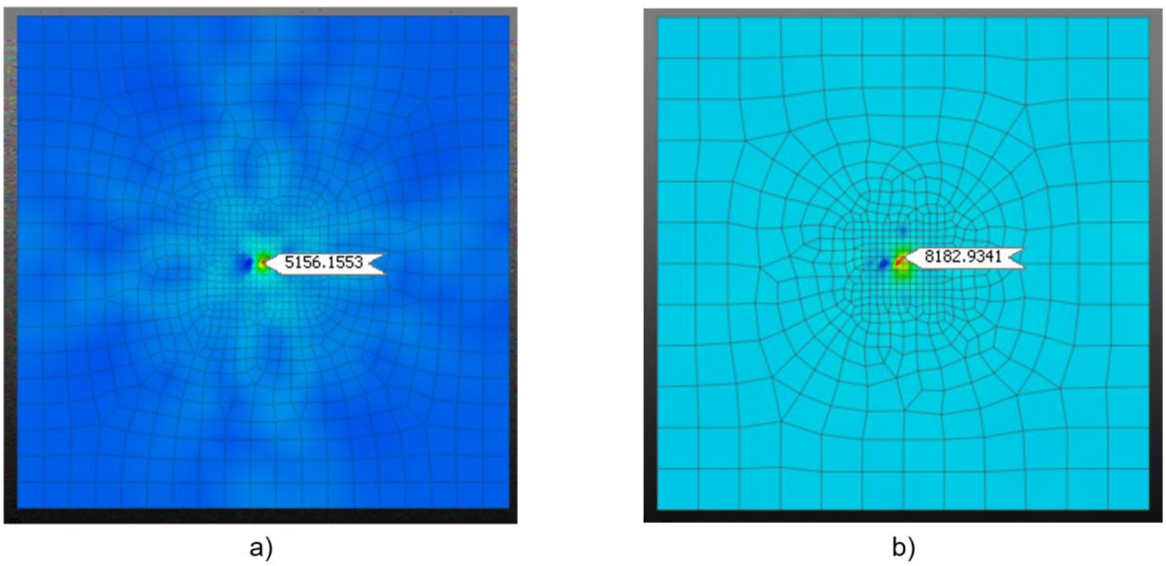

Figure 7: Bending moment in rafts a) LP 8010 0.5 and b) LP 8010 1.

An increase of 50 cm in the Raft thickness results in a 36% increment in bending moments, attributed to the increased rigidity of the Raft.

The equitable distribution of load on piles serves as an indicator of the raft or cap's rigidity. Determining the load borne by each pile in a group requires knowledge of the reactions at their heads, influenced by the displacement imposed on the numerical model of the pile group.

Table 5 summarizes the values of loads per pile for the studied pile groups, presenting their relationship with the applied vertical load corresponding to the imposed displacement.

Table 5: Load Distribution per Pile.

CPRF model	Reactions (kN)					Applied Load (kN)	Difference (%)
	P1	P2	P3	P4	Σ		
LP 4010 0.5	11423	10956	11053	11075	44506	45600	2.4
LP 4010 1	11143	11026	10971	11131	44271	45975	3.7
LP 8010 0.5	16984	16971	16851	16938	67744	73415	7.7
LP 8010 1	17661	17588	17463	17731	70442	75256	6.4

Considering a rigid head and articulated piles at their junctions, numerical results indicate that under this assumption, axial load is evenly distributed among each pile in the group. To consider soil-pile, pile-pile, pile-raft, and raft-soil interactions, the use of numerical simulation is mandatory to accurately determine the load distribution on each pile, as reflected in the results shown in Table 5.

4. CONCLUSIONS

The findings of this study underscore the significant influence of pile diameter and length on their vertical load-bearing capacity, emphasizing the need to consider soil interaction by including interface elements in the numerical model. Pile diameter emerges as the key variable determining horizontal load-bearing capacity, both individually and in groups, while flexural moments are closely related to the thickness of the Raft or head that connects the piles as a unit. The distribution of load among piles within a group is influenced by the complex interaction among all foundation system elements, as well as their properties and geometry. These results highlight the importance of employing advanced computational tools to conduct precise evaluations, avoiding the simplifications inherent in conventional analytical formulations.

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