Soils and Rocks

An International Journal of Geotechnical and Geoenvironmental Engineering

www.soilsandrocks.com

ISSN 1980-9743
ISSN-e 2675-5475

Efficiency of single piled raft units with short piles in compressible tropical soils

Marcos Rodrigo Lopes Campos[1], Alisson Filmiano Andrade Lopes[1], Jean Rodrigo Garcia[1#]

Article

Keywords
Piled raft foundations
Single piled raft
Short piles
Load-sharing mechanisms
Lateritic soils

Abstract

This paper presents an experimental investigation on the behavior of single piled raft units installed in unsaturated lateritic soil representative of the Uberlândia region, Minas Gerais, Brazil. Static load tests were performed on circular raft foundations, both isolated and combined with bored piles measuring 4 m and 6 m in length. The load–settlement responses were analyzed to evaluate system stiffness, ultimate bearing capacity, and load-sharing mechanisms between the raft and the pile. The results show that raft contribution becomes more significant when piles are embedded in lower-strength soil layers, leading to substantial increases in overall bearing capacity. The configuration with a 4 m pile exhibited the highest overall system efficiency, with total capacity exceeding the sum of its isolated components by approximately 21%, whereas the 6 m configuration showed capacity essentially equivalent to the combined isolated elements, indicating that its main benefit lies in load redistribution rather than net capacity gain. Overall, the results indicate that the performance of piled raft systems is governed by the interaction between soil, raft, and pile, rather than by pile length alone. The use of short piles combined with raft foundations may represent an efficient solution under the investigated conditions, particularly for compressible tropical soils.

1. Introduction

With the expansion of construction works on compressible soils, piled raft foundations have gained prominence as an effective solution in foundation design, ranging from loose sandy soils to successful applications in soft clay deposits (Lee et al., 2010; Poulos, 2005; Tan et al., 2006). Their performance depends on the interaction between the raft, the soil, and the piles. However, conventional design methods frequently disregard the raft's contribution to the overall bearing capacity of deep foundation systems. Recent studies by Park et al. (2016) and Singh et al. (2024) have highlighted the importance of pile length and diameter on the global behavior of the system. These parameters have a direct impact on pile stiffness and on the interaction between the raft and the surrounding soil, thereby influencing load sharing and the overall structural response. Studies conducted in Brazil have demonstrated the technical feasibility of using piled raft foundations for building construction (Garcia, 2015; Garcia & Albuquerque, 2021, 2019; Lopes, 2023; Lopes & Garcia, 2024; Oliveira, 2022; Oliveira et al., 2022; Pereira, 2025; Pereira et al., 2025; Sales, 2000; Bezerra et al., 2005; Oliveira & Garcia, 2025).

The use of piled raft foundations has become increasingly common in engineering practice since the pioneering studies of Kishida & Meyerhof (1965), Poulos (1968) and Zeevaert (1957). Several investigations have identified numerous advantages associated with these foundations, including reductions in total and differential settlements, increases in bearing capacity, reductions in the number and length of piles, and mitigation of differential settlements and bending moments within the raft (El-Mossallamy & Franke, 1997; Fattah et al., 2015; Lima, 2007; Poulos, 2001; Prakoso & Kulhawy, 2001; Randolph, 1994). This foundation system integrates the load-bearing capacities of the soil, the raft, and the piles into a composite structural system.

Studies by Lee et al. (2015) and Halder & Manna (2022) have shown that pile length is directly related to the ability of piles to transfer loads to deeper and stronger soil layers, while pile diameter influences stiffness and contact area, thereby affecting stress distribution beneath the raft.

Numerous theoretical, experimental, and numerical studies have contributed to the understanding of piled raft behavior in different soil conditions. Previous investigations have addressed bearing capacity and settlement performance (Akinmusuru, 1973; Poulos, 2001; Randolph & Reul, 2003;

[#]Corresponding author. E-mail address: jean.garcia@ufu.br
[1]Universidade Federal de Uberlândia, Faculdade de Engenharia Civil, Uberlândia, MG, Brasil.

Submitted on February 10, 2026; Final Acceptance on June 26, 2026; Discussion open until May 31, 2027.

Editor: Renato P. Cunha

https://doi.org/10.28927/SR.2027.001626

Lee et al., 2015), soil-structure interaction and load-sharing mechanisms (Clancy & Randolph, 1993; Horikoshi & Randolph, 1998; Comodromos et al., 2015; Halder & Manna, 2022), and numerical modeling approaches for foundation analysis (França & Rodrigo, 2023; Garcia & Albuquerque, 2018, 2019, 2021; Freitas Neto et al., 2014; Lopes & Garcia, 2024; Soares et al., 2015). Despite these advances, few studies have specifically isolated the behavior of single piled raft units installed in unsaturated lateritic tropical soils, particularly considering the influence of short pile length on load-sharing mechanisms and overall system efficiency.

In this context, the present study investigates the behavior of single piled raft units composed of circular rafts and short piles with lengths of 4 m and 6 m, constructed in unsaturated lateritic soil in Uberlândia, Minas Gerais, Brazil. While the 4 m pile was entirely embedded in lower-strength soil layers, the 6 m pile reached a more competent layer, allowing the influence of bearing conditions on system efficiency to be evaluated. The study specifically examines how pile length, soil stiffness contrast, and raft-pile interaction influence load-sharing mechanisms, stiffness evolution, and ultimate bearing response in single piled raft systems under representative tropical field conditions. This study provides experimental contributions to the understanding of the influence of pile length increase in different soil layers and of raft-pile interaction on bearing capacity and stress distribution in the soil, aspects that are often simplified in conventional design approaches based on pile-dominated behavior or elastic assumptions that do not explicitly account for raft contribution in short-pile systems.

Although pile length is often considered the main controlling parameter for piled raft performance, this study provides experimental evidence that soil compressibility and strength conditions may exert a more decisive influence on the overall efficiency of single piled raft units. By comparing short piles embedded in different soil strata under controlled field conditions, this research provides direct evidence of how raft participation varies depending on subsoil competence, contributing to improved interpretation of load-sharing mechanisms in tropical soils.

In compressible tropical soils, the use of short piles in piled raft systems presents a distinct design challenge, since near-surface layers commonly exhibit high compressibility, marked heterogeneity, and unsaturated behavior, which may lead to excessive settlements when raft–soil interaction is not adequately considered. In addition, conventional design approaches that neglect the structural contribution of the raft may result in conservative pile lengths and inefficient foundation solutions. Therefore, understanding the load-sharing mechanisms of short piled raft systems is essential for developing more rational and economical foundation designs in tropical soils.

The investigation of single piled raft units is particularly relevant because these systems represent the fundamental load-transfer mechanism that governs the behavior of more complex piled raft foundations. Understanding the interaction between a single pile, the raft, and the surrounding soil provides essential insight into load-sharing mechanisms, stiffness evolution, and bearing response, which form the basis for interpreting group effects in larger foundation systems. In addition, isolated piled raft units have practical application in low-rise and social housing foundations, where simplified and economical foundation solutions are often required.

Compressible tropical soils, particularly unsaturated lateritic deposits, present distinctive geotechnical characteristics that differentiate them from the soft clays and sands commonly discussed in the piled raft literature. These soils often exhibit a metastable structure, pronounced heterogeneity, significant matric suction under natural conditions, and a marked potential for collapse upon wetting, which may substantially alter stiffness, compressibility, and load-transfer mechanisms. As a result, foundation behavior in tropical unsaturated soils may differ significantly from that observed in conventional temperate soil profiles, reinforcing the need for dedicated experimental investigation under representative field conditions.

Therefore, the present study aims to quantify the load-sharing mechanisms between raft and pile, evaluate the influence of short pile length on stiffness and bearing capacity, and investigate how soil stratification affects the overall efficiency of single piled raft systems constructed in unsaturated lateritic tropical soil.

2. Material and methods

This section describes the experimental site, the data sources, the tested foundation systems, and the procedures adopted in the load tests.

2.1 Experimental area and subsoil conditions

This study was carried out at the Experimental Field (CEMSF) of the Federal University of Uberlândia (UFU), state of Minas Gerais, Brazil (Figure 1). The site is situated within the Paraná Basin and is underlain by rocks of the São Bento Group, predominantly basic volcanic rocks associated with the Serra Geral Formation, mainly diabase, whose weathering has contributed to the development of the regional lateritic soil profile.

The subsurface profile at the CEMSF is predominantly composed of silty clayey sand, ranging from loose to very dense, underlain by clayey sand. The groundwater table was identified at a depth of 10.5 m. Geotechnical characterization was performed through field tests (SPT and DPL) and laboratory tests (unit weight, grain-size distribution, sedimentation, Atterberg limits, oedometer test, direct shear test, among others), based on previous investigations by Lopes (2023), Oliveira (2022) and Saraiva Júnior (2024), whose results are presented in Figure 2.

The regional climate is characterized by periods of high rainfall interspersed with prolonged dry seasons, defining a tropical climate that directly influences soil formation and behavior.

2.2 Data sources and consistency of the experimental database

In addition to the experimental tests conducted in the present study, complementary data from previous investigations carried out at the same experimental field (Oliveira, 2022; Saraiva Júnior, 2024) were incorporated to support the comparative analyses.

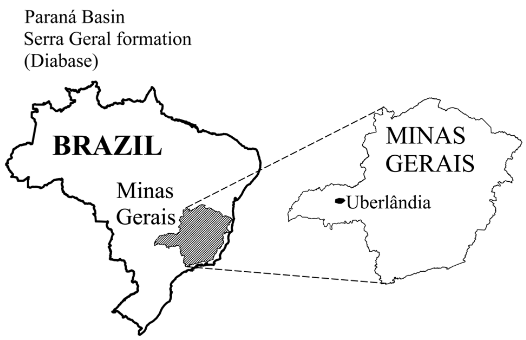

Figure 1. Location of the CEMSF experimental field (Garcia, 2021).

The complementary database also includes static load tests performed on isolated bored piles with lengths of 4 m and 6 m, as well as isolated circular raft foundations with the same geometry adopted in the PRU units (1.0 m diameter and 0.20 m thickness), all executed at the same experimental field under comparable soil and environmental conditions. These reference tests were incorporated to allow direct comparison between isolated foundation behavior and the response of the composite single piled raft units. All tests were conducted at the same site, with comparable soil profiles, groundwater conditions, and seasonal moisture characteristics, as they were carried out during similar periods of the year.

Because the investigations were conducted in a controlled experimental field, the test area remained preserved between campaigns, with no significant site disturbances that could alter the subsurface profile. In addition, dynamic probing light (DPL) tests and soil sampling for natural moisture content determination were performed prior to the 2023 campaign, confirming that the stratigraphic profile and moisture conditions were consistent with those observed during the 2021 testing program.

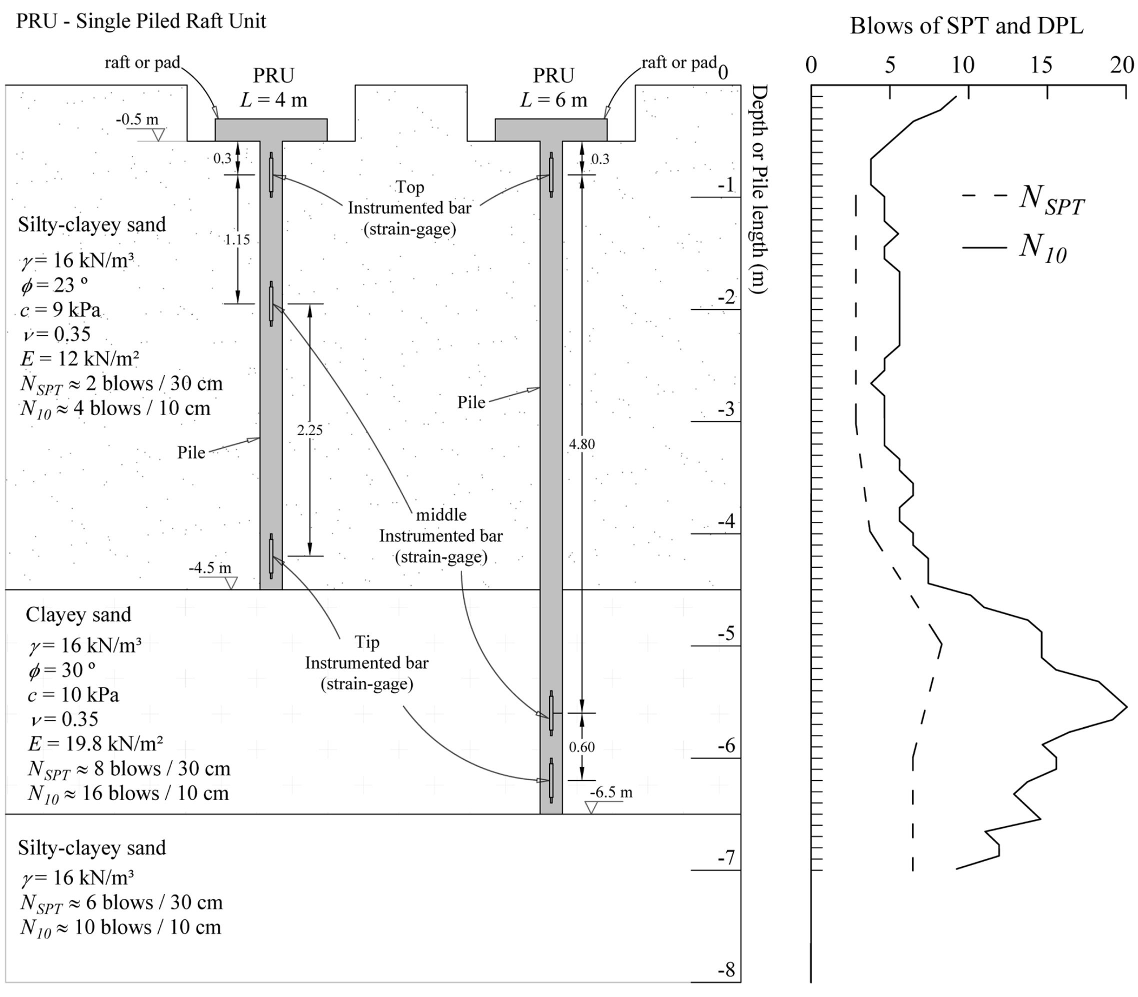

Figure 2. Geotechnical profile of the experimental site and foundation load tests.

The inclusion of these complementary datasets allows for a direct comparison between isolated foundation elements and single piled raft units, enabling a more comprehensive interpretation of load-sharing mechanisms and system efficiency.

It is emphasized that only datasets obtained under comparable boundary conditions, testing procedures, and instrumentation approaches were considered in the analyses.

This approach ensures the consistency and reliability of the comparative analyses presented in this study.

2.3 Test foundations and instrumentation

The test foundations are single piled raft units (PRUs), according to the definition proposed by Clancy & Randolph (1993). Each PRU consists of a circular raft measuring 1.0 m in diameter and 0.20 m in thickness (Figure 2). The selected thickness follows the standard adopted for isolated raft foundations used in constructions associated with Brazilian Federal Government Social Housing Programs.

The deep foundation element consists of a bored pile constructed without stabilizing fluid, with a length of 6 m and a diameter of 0.25 m. This selection is supported by the extensive adoption of this type of foundation in residential buildings in the Uberlândia region and in many other parts of Brazil.

In the present study, the pile length is 6 m (Campos, 2025), whereas in the study by Oliveira (2022) the pile length was 4 m.

The tests performed in the present study refer to the PRU with a 6 m pile, while the 4 m configuration corresponds to data obtained from Oliveira (2022).

All other dimensions of the single piled raft unit are identical to those adopted by Oliveira (2022), allowing for a direct comparison between the results. The static load tests were carried out at the same experimental field, but in different years, always in August, ensuring similar climatic conditions and in situ moisture contents. The tests were conducted in August 2021 and 2023 for single piled raft units with pile lengths of 4 and 6 meters, respectively.

The pile and raft were constructed using the same concrete mix, with a unit weight of 25 kN/m^3 and a Young's modulus of 23.5 GPa. Static load tests were performed after a minimum curing period of 28 days, ensuring adequate development of concrete mechanical properties prior to loading. The adoption of the same concrete characteristics for both structural elements provides consistency in stiffness evaluation and in the interpretation of load-sharing mechanisms within the foundation system.

The piles of the tested foundations were instrumented along their length using reinforcing bars equipped with electrical resistance strain gauges at three levels, as shown in Figure 2. This instrumentation enabled the analysis of load sharing and load transfer mechanisms within the single piled raft units.

The instrumentation levels were not uniformly spaced along the pile length because the experimental program aimed to capture the load-transfer behavior near the pile tip. Since the tested elements were short bored piles, greater attention was given to the lower portion of the pile, where tip resistance and shaft resistance interaction were expected to have a relevant influence on the overall pile response.

At each instrumented level, the axial load in the pile was obtained from the measured microstrains recorded by the electrical resistance strain gauges. The measured strains were converted into axial force using the pile Young's modulus and the cross-sectional area of the pile. Thus, the axial load was calculated directly for each instrumented section, rather than extrapolated from another elevation. The pile Young's modulus was obtained from a reference section of an isolated instrumented pile, where the surrounding soil had been excavated to eliminate the influence of shaft friction.

The adopted Young's modulus was based on reference sections of previously instrumented isolated piles tested at the same experimental field by other authors (Oliveira, 2022; Saraiva Júnior, 2024), constructed with the same concrete mix, similar curing conditions, and equivalent construction procedures. Therefore, the adopted modulus is considered representative for interpreting pile stiffness in the present study.

2.4 Test procedures

The test foundations investigated in this study, as well as those tested by other authors, were designed in accordance with Brazilian standards ABNT NBR 6122:2022 (ABNT, 2022) and ABNT NBR 6118:2014 (ABNT, 2014).

This research was developed in five main stages, encompassing foundation execution and load testing. Initially, the bored pile was constructed following local geotechnical conditions. Subsequently, instrumented bars with strain gauges were prepared and positioned within the pile reinforcement, allowing monitoring of load transfer along the pile length (Figure 3).

After this stage, excavation and reinforcement of the raft were carried out, ensuring the proper structural configuration of the foundation (Figure 3). Finally, a slow static load test (SLT) was performed in accordance with current technical standards (Figure 4), enabling analysis of the load–settlement behavior of the foundation and contributing to the understanding of the structural performance of the single piled raft unit.

The foundations were subjected to slow maintained static load tests to assess their behavior under small displacements, as they were later used in complementary research involving soil flooding. Therefore, the foundations were not loaded to failure in order to preserve their structural integrity.

Accordingly, the present study sought to investigate the response of these foundations under small vertical displacements, with the purpose of examining their performance under stress levels below the soil preconsolidation pressure.

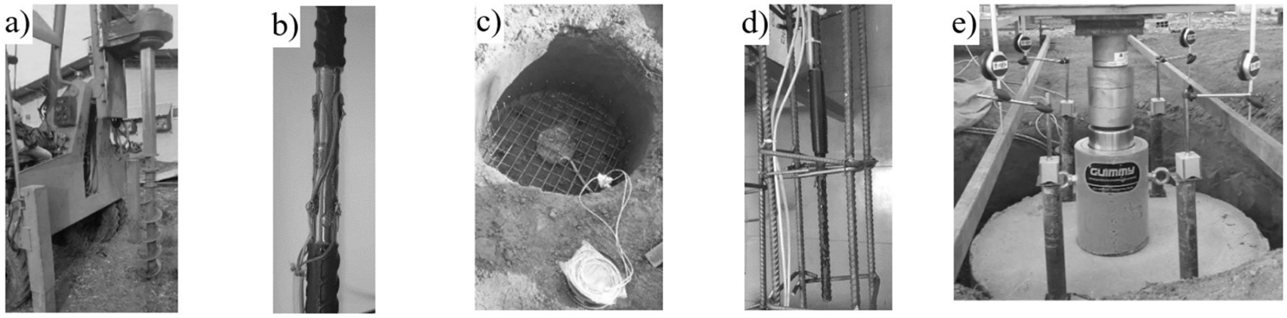

Figure 3. Research stages: a) pile drilling; b) instrumented bar with strain gauges; c) positioning of the bar in the pile reinforcement cage; d) excavation and construction of the footing or raft; e) static load test.

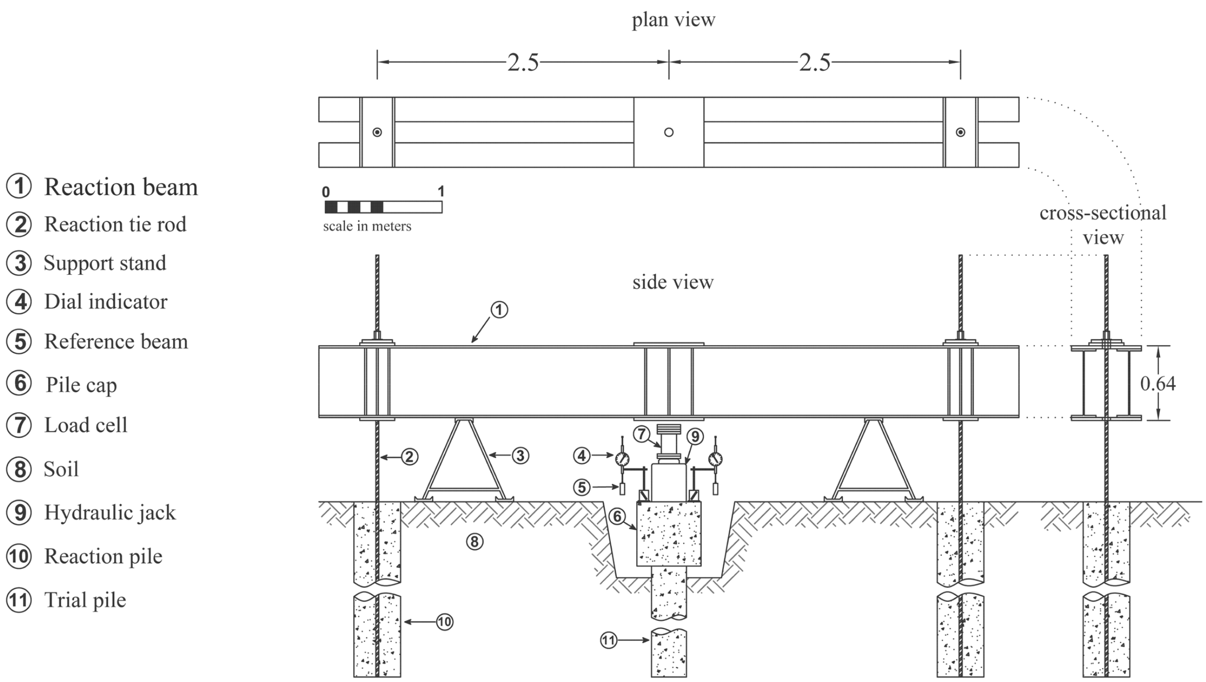

Figure 4. Schematic of the static load test on a composite foundation system (Garcia, 2021).

Static load tests were performed under slow maintained loading conditions in accordance with ABNT NBR 16903:2020 (ABNT, 2020). Load was applied in equal successive increments not exceeding 20% of the predicted working load of the test foundation. Each loading stage was maintained until displacement stabilization was achieved, with a minimum duration of 30 minutes. Stabilization was defined when the difference between two consecutive displacement readings did not exceed 5% of the displacement increment for that loading stage. Displacement readings were recorded at 5, 10, 15, and 30 minutes after load application, with additional readings at 15-minute intervals when stabilization was not reached within the initial period. This procedure is consistent with the slow maintained load testing principles commonly adopted in international static pile load testing practice, such as ASTM D1143 (ASTM, 2020).

3. Results and discussion

The load-settlement curves obtained from the static load tests allowed the determination of the corresponding load-displacement relationships for each single piled raft unit (PRU) with pile lengths of 4 m and 6 m, as well as for the corresponding isolated foundation elements, namely the circular raft (shallow element) and the bored pile (deep element), which were used as reference systems for comparison. Analysis of these curves indicates that the combined raft-pile system exhibited enhanced bearing performance, highlighting the beneficial interaction between the foundation components.

For the shallow element (raft), a similar load-settlement response was observed in both PRU configurations, regardless of the associated pile length. For example, a settlement of 5 mm corresponded to an applied load of approximately 50 kN in both cases (Figures 5 and 6). This indicates that the raft response remained relatively consistent, while differences in overall system behavior were primarily associated with the contribution of the pile and its interaction with the surrounding soil profile.

In addition, comparisons among the tested foundations were performed using normalized settlements and loads, revealing a similar behavioral trend for the PRUs (Figure 7).

When analyzing the normalized load parameter ($s \cdot d \cdot Ep/P$) as a function of normalized settlement (s/D), it is observed that the normalized load parameter increases with increasing normalized settlement, while foundation stiffness (P/s) progressively decreases (Figure 8 and Figure 9). For small settlement values, stiffness is high, the normalized load parameter remains below 100, and stiffness values exceed 50 kN/mm. Conversely, as settlement increases, foundation stiffness decreases, remaining below 25 kN/mm, corresponding to an average reduction of approximately 50% relative to the initial loading stage (Figure 9).

In the present study, foundation stiffness was evaluated using the secant stiffness parameter (P/s), defined as the ratio between the applied load (P) and the corresponding measured settlement (s) at each loading stage. In addition, normalized parameters were adopted following Randolph (1994), where the term $s \cdot d \cdot E_p/P$ represents a dimensionless indicator of relative foundation flexibility, allowing comparison between tested systems with different geometric and stiffness characteristics.

Analysis of stiffness behavior (P/s) as a function of normalized load by loading stages shows that the PRUs exhibit high initial stiffness values, which progressively decrease up to the maximum applied test load (Figure 10).

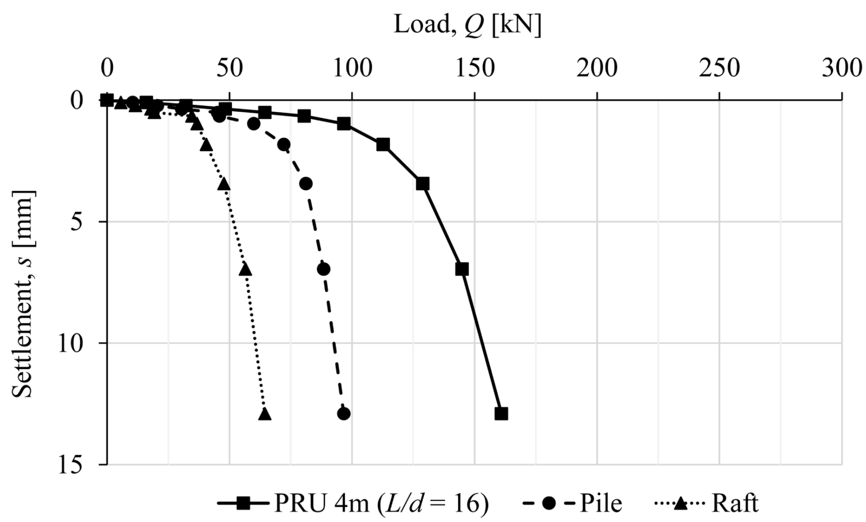

Figure 5. Load-settlement curves for PRU pile of 4 m.

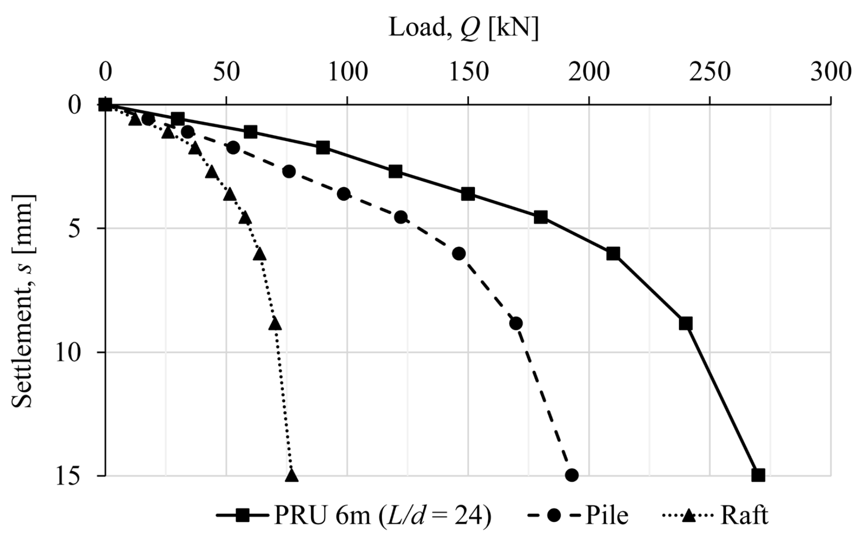

Figure 6. Load-settlement curves for PRU pile of 6 m.

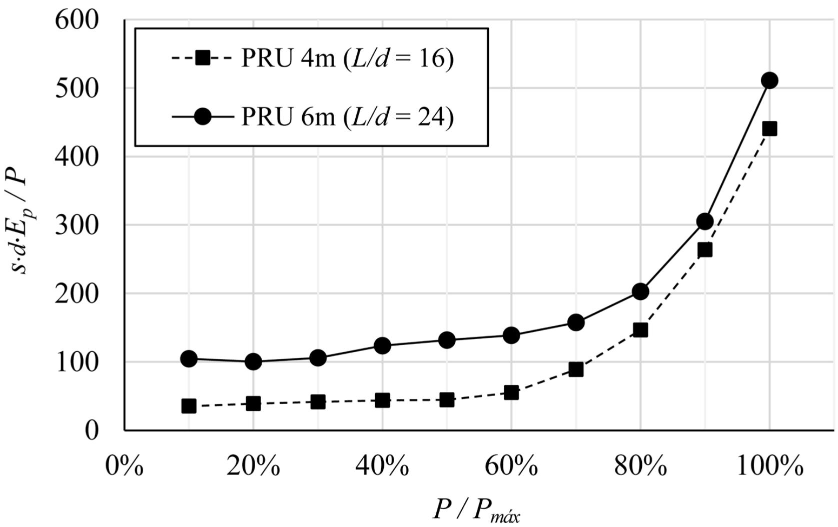

Figure 7. Normalized load and settlement curves for the analyzed foundations.

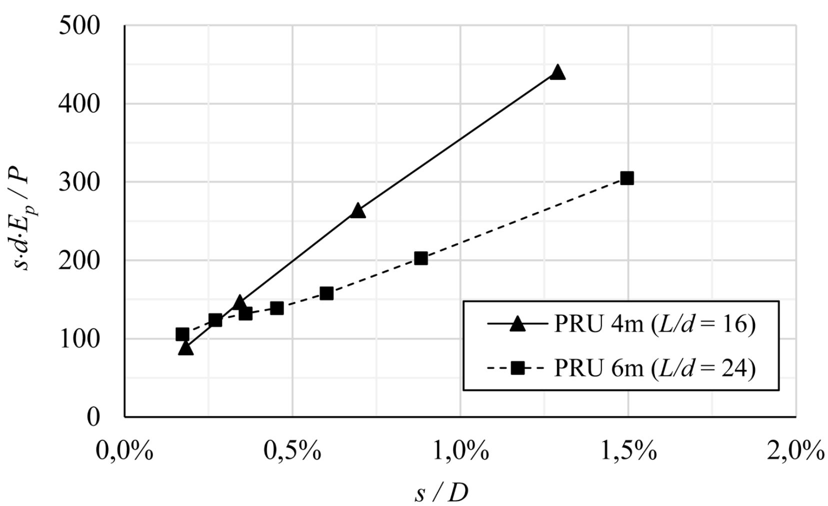

Figure 8. Normalized settlement as a function of load and raft diameter.

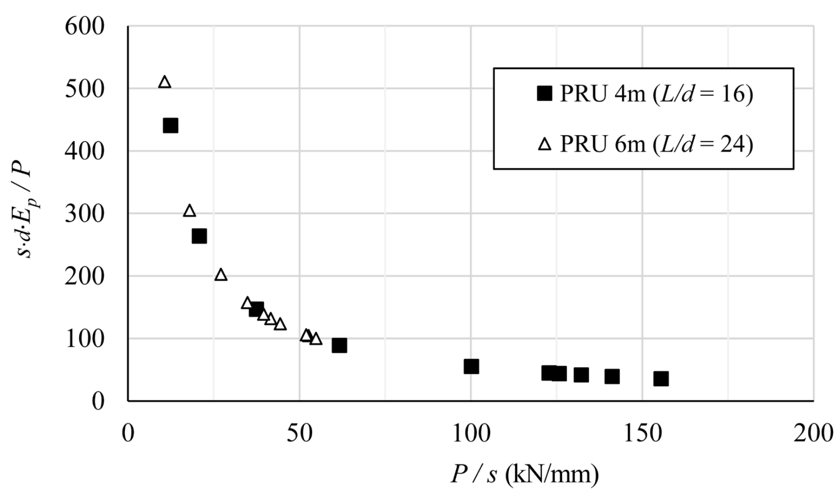

Figure 9. Normalized settlement as a function of stiffness for all foundations.

This effect is more pronounced for the PRU with a 4 m pile, which presents significantly higher initial stiffness compared to the 6 m pile PRU. In addition, stiffness by loading stage undergoes a marked reduction, decreasing from approximately 25 kN/mm at 80% of the maximum load to about 12 kN/mm at the final loading stage.

When analyzing separately the foundation elements composing the PRUs, a similar behavior is observed for the rafts of the PRUs, namely a reduction in stiffness as the foundation is loaded. When the stiffness of the isolated raft is compared with that of the rafts within the PRUs, the isolated raft consistently shows the lowest stiffness throughout all stages of loading.

It is observed that the stiffness of the single piled raft units presents high values at the initial stages of loading and progressively decreases as settlement increases, indicating that the initial response of the system is not representative of its overall behavior throughout the loading process.

The discrepancy between the isolated raft and the PRU rafts decreases significantly only near the maximum applied load (Figure 11). Moreover, the inclusion of the pile enhances the overall performance of the raft within the foundation system by increasing stiffness and, consequently, reducing settlement for a given load when compared with the isolated raft (without pile).

The same trend of stiffness reduction with increasing load was observed for the piles of all single piled raft units, as shown in Figure 12.

The load distribution among the tested foundation elements and the corresponding load fractions absorbed by each component are presented in Table 1. Isolated elements considered in this analysis were obtained from previous studies conducted at the same experimental field (Oliveira, 2022; Saraiva Júnior, 2024), ensuring consistency in soil conditions and testing procedures. Table 1 summarizes both isolated elements and PRU configurations, allowing direct comparison of efficiency gains under the investigated conditions.

For comparative purposes, the ultimate load (Q_{ult}) adopted in this study corresponds to the load associated with a settlement equal to 5% of the pile diameter (12.5 mm), a displacement-based criterion commonly used in foundation performance assessment when clear plunging failure is not reached during testing. This approach provides a consistent basis for comparing the bearing response and efficiency of the investigated foundation systems under equivalent serviceability-related displacement conditions.

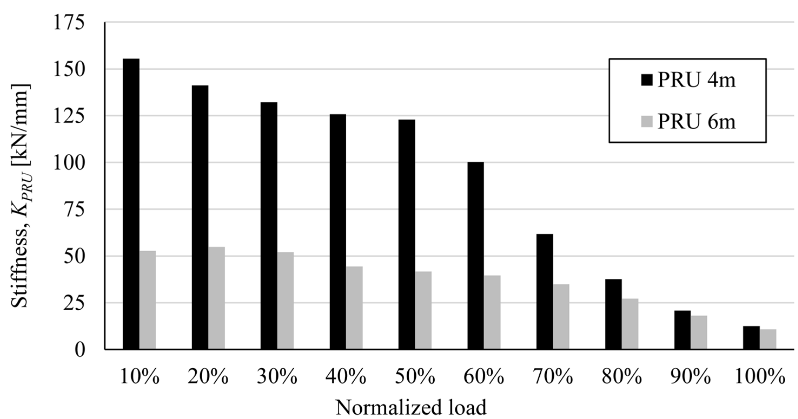

Figure 10. Normalized load–settlement curves for the analyzed foundations.

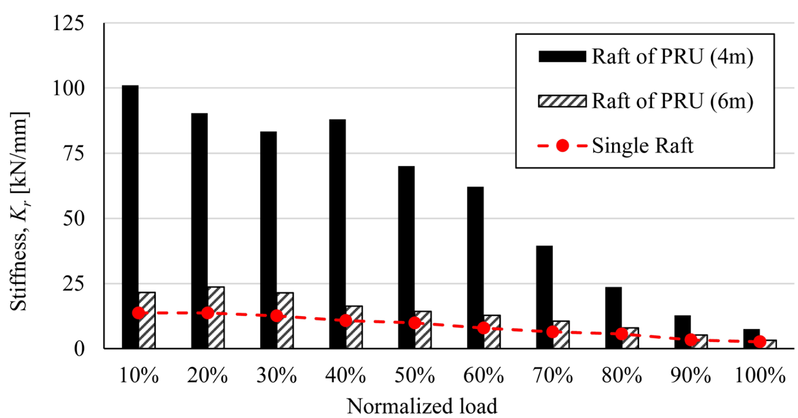

Figure 11. Normalized settlement curves for the analyzed foundations.

This behavior can be explained by the interaction between soil stiffness contrast, load-transfer mechanisms, and stress redistribution within the foundation system. In the 4 m configuration, the pile tip remains embedded in a lower-strength and more compressible soil layer, which limits the mobilization of end-bearing resistance and reduces the overall stiffness of the deep element. As a result, a greater portion of the applied load is redistributed through shaft friction and direct raft-soil contact, leading to increased raft participation in the overall load-sharing mechanism. In addition, the larger deformation of the surrounding soil mass promotes greater interaction between the stress bulbs generated beneath the raft and around the pile shaft, enhancing the coupled response of the piled raft unit. In contrast, in the 6 m configuration, the pile tip reaches a stiffer layer, allowing greater mobilization of tip resistance and reducing the relative contribution of the raft to the system response.

When comparing these results with isolated pile tests of the same diameter and length obtained from these previous investigations, it is observed that the isolated 4 m pile exhibited lower stiffness than the corresponding pile combined with the raft (1 m diameter), with stiffness values becoming similar at approximately 80% of the total applied load. In contrast, the isolated 6 m pile reached this equivalence earlier, at about 60% of the maximum load (Figure 12).

For the PRU with a 6 m pile, the presence of the raft resulted in a reduction in the load fraction absorbed by the pile when compared to the isolated pile. This behavior is associated with soil deformation beneath the raft and interaction within the stress bulb of the system. This configuration exhibited a 30% increase in ultimate load relative to the isolated pile of equal diameter and length.

In contrast, the PRU with a 4 m pile showed a significantly higher efficiency, with a 129% increase relative to the isolated pile capacity. This difference in performance is primarily associated with the soil conditions in which each pile is embedded. The 6 m pile reaches a more competent soil layer, allowing it to mobilize a larger portion of the load independently. As a result, the relative contribution of the raft becomes less significant.

Conversely, the 4 m pile is entirely embedded in lower-strength soil layers, where the pile alone is less efficient in mobilizing load. Under these conditions, the raft plays a dominant role in load redistribution, leading to a substantial increase in overall system efficiency. This behavior highlights the importance of soil stiffness and strength in controlling load-sharing mechanisms between raft and pile.

The raft component of the PRU with a 6 m pile exhibited a 19% increase in capacity compared to the corresponding isolated raft, whereas the pile component showed a 7% reduction relative to the isolated pile.

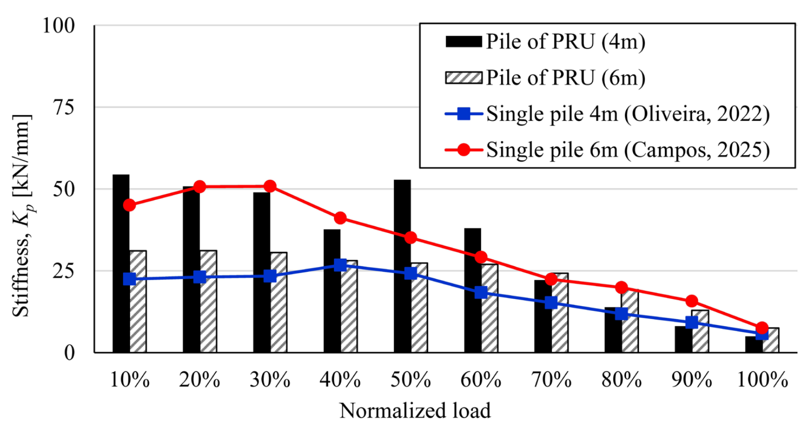

Figure 12. Normalized load–settlement curves for the analyzed foundations.

Table 1. Ultimate load, load-sharing, and efficiency indicators of single piled raft units.

Parameter	PRU 4 m (kN)	PRU 6 m (kN)	PRU 4 m (%)	PRU 6 m (%)
Single raft (isolated)	62	62	-	-
Single pile (isolated)	70	198	-	-
Pile component within PRU	96	184	-	-
Raft component within PRU	64	74	-	-
Total PRU capacity	160	258	-	-
Pile contribution	-	-	60	71
Raft contribution	-	-	40	29
Pile efficiency ratio (Pile in PRU / isolated pile)	-	-	137	93
Raft efficiency ratio (Raft in PRU / isolated raft)	-	-	103	119

Legend: see List of Symbols.

This behavior is associated with stress redistribution within the soil mass beneath the raft, which modifies load transfer along the deeper pile. In contrast, for the 4 m configuration, both the raft and pile components exhibited higher mobilized loads than their isolated counterparts, reflecting stronger raft participation and enhanced pile–raft interaction in the more compressible upper soil layers. When evaluated as a whole, the PRU with a 4 m pile reached 160 kN, exceeding the sum of its isolated components (132 kN) by approximately 21%, indicating positive system interaction. In contrast, the 6 m configuration reached 258 kN, essentially matching the combined isolated capacity (260 kN), indicating that its main benefit lies in load redistribution rather than net bearing capacity gain.

The results demonstrate that the efficiency of piled raft systems depends not only on pile length but also on the interaction between soil conditions and foundation geometry.

It should be noted that the results presented in this study are based on full-scale field tests conducted under specific geotechnical and environmental conditions. As with any field investigation, some degree of variability is inherently associated with soil heterogeneity, instrumentation accuracy, and local construction effects. Although these factors may influence the absolute measured response, the comparative trends observed between the investigated foundation configurations are considered consistent, since all tests were conducted under controlled conditions within the same experimental field, using comparable construction procedures, instrumentation, and testing protocols.

It should be noted that the adoption of a displacement-based criterion emphasizes comparative structural performance under equivalent settlement conditions, rather than a classical geotechnical failure condition associated with plunging behavior.

The observed load-sharing behavior is broadly consistent with the conceptual framework proposed in previous piled raft studies, in which system response is governed by the relative stiffness between raft, pile, and supporting soil, as well as by the progressive mobilization of shaft and tip resistance (Clancy & Randolph, 1993; Horikoshi & Randolph, 1998; Poulos, 2001). However, the present results also highlight the distinctive influence of unsaturated lateritic tropical soils, where soil compressibility, stiffness contrast between layers, and suction-controlled mechanical behavior significantly affect raft participation and overall system efficiency. In this sense, the experimental findings contribute to refining current understanding of piled raft performance under tropical geotechnical conditions.

It is also important to recognize that the mechanical response observed in the present study is influenced by the unsaturated condition of the lateritic tropical soil. Under natural moisture conditions, matric suction contributes to increased apparent cohesion and stiffness of the soil skeleton, which may enhance shaft resistance, improve raft-soil contact response, and increase the overall stiffness of the piled raft system. Consequently, seasonal variations in moisture content and suction may modulate soil–structure interaction and load-transfer mechanisms in tropical environments, highlighting the importance of considering hydro-mechanical effects in the interpretation and design of foundation systems constructed in unsaturated tropical soils.

4. Conclusion

The following conclusions are directly supported by the experimental results obtained in this study. This study experimentally investigated the behavior of single piled raft units constructed in unsaturated lateritic soil, focusing on the influence of pile length on load-sharing mechanisms, stiffness, and bearing capacity. The results indicate that the structural response of piled raft systems is governed by the interaction between raft, pile, and soil, rather than by pile length alone, particularly due to the influence of soil stiffness and compressibility on load-sharing mechanisms.

Increasing pile length significantly enhanced the individual bearing capacity of the isolated pile. However, the results indicate that the overall efficiency of the piled raft system is strongly influenced by the strength and compressibility of the surrounding soil. The single piled raft unit with a 4 m pile, entirely embedded in lower-strength soil, showed substantially greater efficiency, with ultimate load gains markedly higher than those observed for the 6 m configuration. These findings indicate that raft participation tends to become more pronounced when piles are installed in weaker soil layers under the investigated conditions.

For the 6 m configuration, although the load fraction mobilized by the pile within the composite system was lower than that of the isolated pile, the total bearing capacity of the piled raft remained higher due to the contribution of the raft. This behavior highlights the importance of considering stress redistribution and soil deformation beneath the raft when evaluating piled raft performance.

Stiffness was highest during the initial loading stages and progressively decreased with increasing settlement, reflecting the nonlinear response of the soil–foundation system. In all cases, the raft–pile interaction improved overall system stiffness when compared with the isolated elements.

From a practical perspective, the results suggest that single piled raft units incorporating short piles may represent an efficient foundation alternative for compressible tropical soils, provided that local stratigraphy and hydro-mechanical soil conditions are properly considered in design. The findings reported herein are based on specific soil conditions and foundation configurations, and extrapolation to other geotechnical scenarios should be made with caution.

Acknowledgements

This study received financial support from the Coordination for the Improvement of Higher Education Personnel (CAPES) under funding code 001; the National Council for Scientific and Technological Development (CNPq, Process 404634/2021-4); the Research Support Foundation of the State of Minas Gerais (FAPEMIG, APQ-00335-21); and the Federal University of Uberlândia (UFU).

Declaration of interest

The authors declare that they have no conflicts of interest. All co-authors have reviewed and approved the manuscript, and no financial interests are associated with this work.

Authors' contributions

Marcos Rodrigo Lopes Campos: conceptualization, data curation, investigation, methodology, visualization, writing – original draft. Alisson Filmiano Andrade Lopes: data curation, investigation, methodology, validation, writing – original draft. Jean Rodrigo Garcia: conceptualization, formal analysis, methodology, supervision, validation, writing – review & editing.

Data availability

Part or all of the data, models, or code supporting the results of this study may be obtained from the corresponding author upon reasonable request.

Declaration of use of generative artificial intelligence

This manuscript was prepared with the assistance of generative artificial intelligence (GenAI), specifically ChatGPT (OpenAI), with the aim of improving the clarity of scientific writing, refining the language, and supporting text revision during manuscript preparation. The entire process of using this tool was supervised, reviewed, and when necessary edited by the authors. The authors assume full responsibility for the content of the publication that involved the aid of GenAI.

List of symbols and abbreviations

D	pile diameter
s	settlement
s/D	normalized settlement
$s \cdot d \cdot E_p/P$	normalized load parameter
D	raft diameter
E_p	Young's modulus of the pile material
L	pile length
L/D	pile slenderness ratio
P	applied load
P/s	foundation stiffness
Q_{ult}	ultimate load corresponding to a settlement of 12.5 mm

References

ABNT NBR 6118. (2014). *Design of concrete structures*. ABNT - Associação Brasileira de Normas Técnicas, Rio de Janeiro, RJ (in Portuguese).

ABNT NBR 16903. (2020). *Soil—Static load test on deep foundation*. ABNT - Brazilian Association of Technical Standards, Rio de Janeiro, RJ (in Portuguese).

ABNT NBR 6122. (2022). *Design and construction of foundations*. ABNT - Associação Brasileira de Normas Técnicas, Rio de Janeiro, RJ (in Portuguese).

ASTM D1143/D1143M-20. (2020). *Standard Test Methods for Deep Foundation Elements Under Static Axial Compressive Load*. ASTM International, West Conshohocken, PA, USA.

Akinmusuru, J.O. (1973). *The influence of a pile cap on the bearing capacity of piles in sand* (M. Eng. Thesis). Ahmadu Bello University.

Bezerra, J.E., Cunha, R.P., & Sales, M.M. (2005). Optimization concepts for the design of piled raft foundation systems Optimisation concepts pour le projet de fondation en Radier sur piex. In *Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering* (pp. 1947-1950). Millpress Science Publishers/IOS Press. https://doi.org/10.3233/978-1-61499-656-9-1947.

Campos, M. (2025). *Influência do comprimento de estacas instrumentadas no comportamento de sapatas de fundação* [Master's dissertation]. Universidade Federal de Uberlândia. https://doi.org/10.14393/ufu.di.2025.5570.

Clancy, P., & Randolph, M.F. (1993). An approximate analysis procedure for piled raft foundations. *International Journal for Numerical and Analytical Methods in Geomechanics*, 17(12), 849-869. https://doi.org/10.1002/nag.1610171203.

Comodromos, E.M., Papadopoulou, M.C., & Laloui, L. (2015). Contribution to the design methodologies of piled raft foundations under combined loadings. *Canadian Geotechnical Journal*, 53(4), 559-577. https://doi.org/10.1139/cgj-2015-0251.

Freitas Neto, O., Cunha, R.P., Santos, O.F., Albuquerque, P.J.R., & Garcia, J.R. (2014). Comparison of numerical methods for piled raft foundations. *Advanced Materials Research*, https://doi.org/10.4028/www.scientific.net/AMR.838-841.334.

El-Mossallamy, Y., & Franke, E. (1997). Piled rafts: numerical modelling to simulate the behaviour of piled raft foundations. In J.A. Hemsley (Ed.), *Design applications of raft foundations*. Darmstadt Germany: Selbstverlag.

Fattah, M.Y., Yousif, M.A., & Al-Tameemi, S.M.K. (2015). Effect of pile group geometry on bearing capacity of piled raft foundations. *Structural Engineering and Mechanics*, 54(5), 829-853. https://doi.org/10.12989/sem.2015.54.5.829.

França, A.G., & Rodrigo, G.J. (2023). Influence of pile cap–ground contact geometry on the behavior of piled foundations. *Arabian Journal for Science and Engineering*, 48(10), 14029-14041. https://doi.org/10.1007/s13369-023-08091-2.

Garcia, J.R. (2015). *Análise experimental e numérica de radiers estaqueados executados em solo da região de Campinas/SP* [Doctoral thesis]. Universidade Estadual de Campinas. https://doi.org/10.47749/T/UNICAMP.2015.952125.

Garcia, J.R. (2021). *Projeto de pesquisa: Otimização de fundações em construções populares em solo da região de Uberlândia/MG - APQ-00335-21* (No. FAPEMIG/DAP no. 37964078/2021). Uberlândia.

Garcia, J.R., & Albuquerque, P.J.R. (2018). Influence of relative stiffness on the behavior of piled raft foundations. *Acta Scientiarum. Technology*, 40(1), 35209. https://doi.org/10.4025/actascitechnol.v40i1.35209.

Garcia, J.R., & Albuquerque, P.J.R. (2019). Analysis of the contribution of the block-soil contact in piled foundations. *Latin American Journal of Solids and Structures*, 16(6), 1-22. https://doi.org/10.1590/1679-78255565.

Garcia, J.R., & Albuquerque, P.J.R. (2021). Numerical analysis of the influence of block geometry on the behavior of piled foundations. *RIEM - Revista IBRACON de Estruturas e Materiais*, 14(1), e14107. https://doi.org/10.1590/s1983-41952021000100007.

Halder, P., & Manna, B. (2022). Performance evaluation of piled rafts in sand based on load-sharing mechanism using finite element model. *International Journal of Geotechnical Engineering*, 16(5), 574-591. https://doi.org/10.1080/19386362.2020.1729297.

Horikoshi, K., & Randolph, M.F. (1998). A contribution to optimum design of piled rafts. *Geotechnique*, 48(3), 301-317. https://doi.org/10.1680/geot.1998.48.3.301.

Kishida, H., & Meyerhof, G.G. (1965). Bearing capacity of pile groups under eccentric loads in sands. In *Proceedings of the 6th International Conference on Soil Mechanics and Foundation Engineering* (Vol. 2, pp. 270-274). Montreal, Canada.

Lee, J., Kim, Y., & Jeong, S. (2010). Three-dimensional analysis of bearing behavior of piled raft on soft clay. *Computers and Geotechnics*, 37(1-2), 103-114. https://doi.org/10.1016/j.compgeo.2009.07.009.

Lee, J., Park, D., Park, D., & Park, K. (2015). Estimation of load-sharing ratios for piled rafts in sands that includes interaction effects. *Computers and Geotechnics*, 63, 306-314. https://doi.org/10.1016/j.compgeo.2014.10.014.

Lima, B.S. (2007). *Otimização de fundações estaqueadas*. Universidade de Brasília.

Lopes, A.F.A. (2023). *Análise experimental e numérica de radier estaqueado isolado com uma estaca em solo tropical na condição in situ* [Master's dissertation]. Universidade Federal de Uberlândia. https://doi.org/10.14393/ufu.di.2023.487.

Lopes, A.F.A., & Garcia, J.R. (2024). Experimental and numerical analysis of single piled raft unit in unconventional soil. *Geomechanics and Geoengineering*, 20(2), 345-356. https://doi.org/10.1080/17486025.2024.2402060.

Oliveira, E. (2022). *Análise experimental e numérica do comportamento de sapata estaqueada em solo tropical*. Uberlândia: FECIV. https://doi.org/10.14393/ufu.di.2022.5055.

Oliveira, E.A.S., & Garcia, J.R. (2025). Numerical and experimental analysis of shallow foundations on tropical climate soil using Mohr-Coulomb cap model. *Soils and Rocks*, 48(2), e2025004724. https://doi.org/10.28927/SR.2025.004724.

Oliveira, E.A.S., Justino, M.O., & Garcia, J.R. (2022). Numerical analysis of piled rafts with short bored piles. *RIEM - Revista IBRACON de Estruturas e Materiais*, 15(4), e15408. https://doi.org/10.1590/s1983-41952022000400008.

Park, D., Park, D., & Lee, J. (2016). Analyzing load response and load sharing behavior of piled rafts installed with driven piles in sands. *Computers and Geotechnics*, 78, 62-71. https://doi.org/10.1016/j.compgeo.2016.05.008.

Pereira, B. (2025). *Análise experimental e numérica do comportamento de radier estaqueado isolado pré-carregado sob condição inundada* [Master's dissertation]. Universidade Federal de Uberlândia. https://doi.org/10.14393/ufu.di.2025.61.

Pereira, B.E., Lopes, A.F.A., & Garcia, J.R. (2025). Impact of flooding on the bearing capacity of a preloaded single piled raft in collapsible soils. *International Journal of Geotechnical Engineering*, 19(10), 896-910. https://doi.org/10.1080/19386362.2025.2561012.

Poulos, H.G. (1968). Analysis of the settlement of piles groups. *Geotechnique*, 18(4), 449-471. https://doi.org/10.1680/geot.1968.18.4.449.

Poulos, H.G. (2001). Piled raft foundations: design and applications. *Geotechnique*, 51(2), 95-113. https://doi.org/10.1680/geot.2001.51.2.95.

Poulos, H.G. (2005). Piled raft and compensated piled raft foundations for soft soil sites. In C. Vipulanandan, & F. C. Townsend (Eds.), *Advances in designing and testing deep foundations* (pp. 214-235). American Society of Civil Engineers, Reston, VA. https://doi.org/10.1061/40772(170)2.

Prakoso, W.A., & Kulhawy, F.H. (2001). Contribution to piled raft foundation design. *Journal of Geotechnical and Geoenvironmental Engineering*, 127(1), 17-24. https://doi.org/10.1061/(ASCE)1090-0241(2001)127:1(17).

Randolph, M.F. (1994). Design methods for pile groups and piled rafts. In *Proceedings of the 13th International Conference on Soil Mechanics and Foundation Engineering* (Vol. 5, pp. 61-82). New Delhi, India.

Randolph, M.F., & Reul, O. (2003). Piled rafts in overconsolidated clay: comparison of in situ measurements and numerical analyses. *Geotechnique*, 53(3), 301-315. https://doi.org/10.1680/geot.2003.53.3.301.

Sales, M.M. (2000). *Behavior analysis of piled rafts*. Universidade de Brasília.

Saraiva Júnior, R. (2024). *Análise experimental e numérica do comportamento de estacas curtas instrumentadas em solo de Uberlândia (MG)*. Universidade Federal de Uberlândia. https://doi.org/10.14393/ufu.di.2024.5246.

Singh, G.G., Tiwari, R.P., & Kumar, V. (2024). Evaluating parametric influences on load-sharing behaviour of piled raft foundations. *National Academy Science Letters*, https://doi.org/10.1007/s40009-024-01540-y.

Soares, W.C., Coutinho, R.Q., & Cunha, R.P. (2015). Piled raft with hollow auger piles founded in a Brazilian granular deposit. *Canadian Geotechnical Journal*, 52(8), 1005-1022. https://doi.org/10.1139/cgj-2014-0087.

Tan, Y.C., Cheah, S.W., & Taha, M.R. (2006). Methodology for design of piled raft for 5-story buildings on very soft clay. In R.L. Parsons, L. Zhang, W.D. Guo, K.K. Phoon, & M. Yang. *Foundation analysis and design* (pp. 226-233). American Society of Civil Engineers. https://doi.org/10.1061/40865(197)29.

Zeevaert, L. (1957). Compensated friction-pile foundation to reduce the settlement of buildings on highly compressible volcanic clay of Mexico City. In *Proceedings of the 4th International Conference on Soil Mechanics and Foundation Engineering*. London. ISSMGE. https://doi.org/10.1680/geot.1972.22.1.95.