BILINGUAL PUBLISHING GROUP

Journal of Building Material Science

https://journals.bilpubgroup.com/index.php/jbms

ARTICLE

Performance Evaluation of Reinforced Concrete Piled Raft and Pile Cap Foundation Systems through Full-Scale Field Testing

Assad L. Hayal [*] ***, A'amal A. H. Al-Saidi***

Civil Engineering Department, College of Engineering, University of Baghdad, Baghdad 10071, Iraq

ABSTRACT

The use of foundation systems on clayey soils poses serious challenges due to their low shear strength and high compressibility, making the need for appropriate sustainable foundation systems necessary. This study analyzed the structural capacity and the material effectiveness of reinforced concrete piled raft and pile cap foundation systems through full-scale field tests. Tests were carried out using reinforced concrete piles with a square cross-sectional size of 30 cm × 30 cm, and lengths ranging from 8–12 m, along with a reinforced concrete raft fabricated through C30 concrete. The tests were carried out based on the ASTM D1143 method to test the load-settlement relationship and the load-sharing mechanism. The results revealed that the piled raft foundation system performed better in terms of load-bearing capacity and settlements than the conventional pile cap foundation system. For instance, the four-pile piled raft system had a maximum load-carrying capacity of 300–310 kN, which is about 20% higher than the pile cap system with a load-carrying capacity of 250 kN. In the same way, the two-pile system had a maximum load-carrying capacity of 225 kN, and settlements were lower. Raft–pile–soil interaction facilitated the efficiency of load sharing and minimization of the use of extra piles. The research is an important contribution to the development of sustainable foundation engineering as it provides practical evidence through experimentation that pile raft foundations can improve the performance of structures while minimizing the use of construction materials. The results will assist engineers in designing optimum reinforced concrete foundations in clay soils.

Keywords: Clayey Soils; Load–Settlement Behavior; Material Efficiency; Reinforced Concrete; Pile–Raft Foundation; Sustainable Construction

*CORRESPONDING AUTHOR:

Assad L. Hayal, Civil Engineering Department, College of Engineering, University of Baghdad, Baghdad 10071, Iraq;
Email: asaad.hayal2401p@coeng.uobaghdad.edu.iq

ARTICLE INFO

Received: 28 May 2026 | Revised: 2 June 2026 | Accepted: 24 July 2026 | Published Online: 31 August 2026
DOI: https://doi.org/10.30564/jbms.v8i3.13574

CITATION

Hayal, A.L., Al-Saidi, A.A.H., 2026. Performance Evaluation of Reinforced Concrete Piled Raft and Pile Cap Foundation Systems through Full-Scale Field Testing. Journal of Building Material Science. 8(3): 175–190. DOI: https://doi.org/10.30564/jbms.v8i3.13574

1. Introduction

Deep foundations have been widely recognized as an integral part of modern construction practices, especially in cases where the subsurface consists of soils of poor bearing capacity and very high compressibility such as clay soils. Considering the field of building material science and engineering, the relationship between construction materials and geotechnical systems has received increasing recognition in recent years because the performance of construction materials cannot be examined without considering ground conditions under which construction materials are placed. Construction materials like reinforced concrete, which has been considered as one of the most commonly used materials in construction, can be widely seen in foundation constructions owing to its relatively higher compression strength and ability to resist various types of loads [1–3]. The efficient use of reinforced concrete material in foundation systems has remained a problem until now, especially in cases of deep foundations where not only the stability but also geotechnical considerations need to be satisfied. Clay soils having poor shear strength, high compressibility and time-dependency should be treated with deep foundations like pile foundations to satisfy construction and safety requirements [4,5]. Two types of foundations used in such cases include piled raft foundation systems and conventional pile caps.

In recent times, sustainability in the building process has gained a lot of attention in relation to saving resources used during construction. Sustainable construction practice has emphasized the reduction of material use in addition to enhancing their performance. As such, much importance has been placed on foundations that not only ensure stability but also promote the efficient use of construction materials by avoiding wasteful application of reinforced concrete and minimizing the cost of construction and environmental degradation [6–8]. The piled raft foundation involves the combined load-bearing capacity of the raft and the piles together. This foundation contrasts with traditional pile group systems that involve pile caps working essentially as distributors of loads with no involvement in sharing the loads with soil [9–11]. Through the direct interaction between the raft and the underlying soils in the foundation, piled rafts have the capacity to lower the total number of piles, thus optimizing the use of reinforced concrete materials [12–14]. Despite these advantages, piled rafts have yet to be widely adopted in engineering practice owing to uncertainties associated with their load-sharing capabilities and settlement, as well as material effects on their performance.

There have been several studies carried out concerning the performance of piled raft foundation systems using experimentation, analytical studies, and numerical analysis. For example, Randolph [15] studied the performance of raft foundations with piles that are connected and not connected, and it was revealed that incorporating piles reduces the settlement of the system. Similarly, Fattah et al. [16] experimented on piled raft foundations in sandy soil conditions, and it was noted that the performance of the foundation was influenced by factors such as pile spacing, number of piles, and dimensions of the raft. Additionally, Yin et al. [17] investigated the influence of pile driving on clayey soils, considering soil displacements and the resulting effect on foundations. Singh et al. [18] analyzed the load-sharing process between the raft and the piles in different soil conditions. Finally, Mukherjee and Borthakur [19] performed field and laboratory tests to determine the load-carrying role played by the raft and piles in foundation systems. Analytical models for predicting load sharing ratios of piled raft structures considering the effects of geometric factors such as pile spacing and pile lengths have been provided by Guo et al. [20]. Finite element modeling has been used by Ahmed et al. [21] to study the efficacy of piled raft foundations in increasing bearing capacity and reducing resource use through appropriately chosen piles. Similarly, the effect of piles' driving on the soil, especially clay, has been investigated by Soomro et al. [22], who observed the requirement of more accurate prediction models for designing and building piled raft systems. It can be seen that these studies have provided significant information about piled raft structures; nevertheless, most of the studies conducted have relied on laboratory-scale tests and computer simulations.

Even though many research works have been published on this topic, a few significant gaps still persist. For instance, while plenty of experiments were done in order to prove one or another assumption, a comprehensive study of piled raft and pile caps' performance compared directly to each other in similar geological and load conditions is lacking. In particular, no research is available on the comparative performance of piled rafts and pile caps in clayey soils. Additionally, an aspect of how reinforcement materials' properties—their stiffness and strength—impact the process of load-sharing and foundation settlements is yet to be examined. Moreover, existing literature mostly revolves around geotechnical issues and does not pay enough attention to material efficiency and sustainability. Finally, the influence of a raft itself on soil properties, and thus, on the total number of piles needed, is unknown, and consequently, the conservative approach to design leads to wastefulness. Therefore, a combined geotechnical and materials perspective is to be taken into account when examining foundation systems' performance.

The motivation behind conducting the current study is the shortcomings in past investigations concerning piled raft foundation systems. Although past research has shown the benefits of piled raft foundation through experiments and numerical analysis, there has not been much research conducted on comparing piled raft and pile cap foundation systems using identical clayey soil in the real world. Also, while the previous research was focused on the geotechnical aspects of piled raft foundations, the aspects of material properties and load sharing, along with material efficiency, have not been studied much. As a result, further field investigation will be needed for optimizing sustainable foundation systems.

As a result of the research gap, the following hypothesis will be tested in the current research:

H1. *Reinforced concrete piled raft foundation system performs better than conventional pile cap foundations when it comes to load-bearing capacity, material efficiency, and settlement control due to the interaction of all three elements.*

The hypothesis will be analyzed by asking the following research questions: (i) How does the load-settlement relationship of piled raft foundations differ from the conventional pile caps under full-scale field conditions? (ii) What is the influence of raft-soil interaction on the improvement of load transfer mechanisms and the bearing capacity? (iii) What is the effect of reinforced concrete properties on structural and material efficiency of the considered foundation types? As such, the objectives of this research are to compare the structural efficiency of the considered foundation types using full-scale experimental field tests; assess their load transfer mechanisms and settlements; evaluate the impact of reinforced concrete properties on the foundation behavior; and establish the most efficient and economically optimized foundation configurations.

The uniqueness of this research stems from the integration of full-scale experimental field testing and analysis of material efficiency of the investigated reinforced concrete foundation system. Contrary to previous research, which was mainly based on laboratory-scale experiments and numerical simulation models, the current research gives experimental insight into the interaction between reinforced concrete components, piles, raft, and clay soil. Furthermore, this study includes a comparison of pile raft and pile cap systems, which is based on the structure and efficiency of materials used, and thus adds some valuable information about sustainable foundation designs and construction processes. The remainder of this paper is outlined as follows. First of all, a review of the literature will be conducted, which is related to the subject matter and includes important findings regarding the piles, raft, and pile cap foundations. After that, a discussion of soil conditions at the site will be provided, thus setting the context for the experimental research of the subject matter. In the fourth part, an outline of the process of conducting the experiments, including the description of the experimental setup and methods used in the course of research, will be provided. In the fifth part, a discussion of the results of the experiments will be presented.

2. Materials and Methods

Experimental investigations of this research were intended to analyze structural performance and material efficiency of reinforced concrete pile-raft and pile cap foundation systems under full-scale field testing, taking into account the following factors related to soil properties, constructional elements, and testing procedures. This research was executed on the test site that is dominated by clay soil. To obtain the detailed subsurface profile and determine foundation design, the Cone Penetration Testing (CPT) procedure was employed at the site. The CPT data were used to characterize the subsurface conditions and to determine appropriate pile dimensions and embedment depths for the experimental program. The interpretation procedure followed the recommendations of ASTM D5778 and established geotechnical design principles for pile-supported foundation systems [23]. Meanwhile, the layers located beneath these layers have relatively low stiffness, so it is appropriate to use piles having lengths equal to 8–12 m. Thus, these results could be taken into account when calculating pile embedment depths.

In connection with the construction materials of the experimental project, it should be pointed out that the reinforced concrete items were primarily applied, which include, in particular, the piles, raft foundation (in situ), and pile caps. In particular, the piles were designed with a square cross-section of 30 × 30 cm and fabricated from the grade C30 concrete possessing a compression strength of about 43 MPa, established in the laboratory in accordance with ASTM C39. The yield strength of the reinforcement bars was specified at 420 MPa. The selection of the concrete material can be explained by the wide application of grade C30 concrete in foundation engineering projects, providing an optimal balance of strength, durability, and economy. Raft and pile cap components were fabricated with a size of 2 m × 2 m and a depth of 0.4 m, allowing for proper flexural stiffness to transfer the applied loads and establish a good interaction with the underlying soil mass. The material properties and foundation configurations used in the experimental program are summarized in **Table 1**. The details of testing standards, equipment, and procedures adopted for full-scale evaluation are presented in **Table 2**. The sequence of steps followed during the experiment, namely the preparation of the foundation, positioning of the test beam, instrumentation and loading, are illustrated in **Figure 1**.

Different configurations of the foundation were used in the experiments to allow for comprehensive comparison of results. They included the single pile rafted foundation, two piles rafted foundation, four piles rafted foundation, and their respective pile cap foundation, where the pile configuration was similar for each configuration. In the rafted foundation case, the raft was allowed to be in contact with the soil surface to permit the involvement of the soil in the load-carrying capacity, while in the case of the pile cap, the cap was located about 0.5 m above the ground surface. This was important in assessing the load-carrying capacity of the raft itself, and the effect of the soil structure interaction on the performance of the foundation. The similarity in the pile configuration, including diameter, spacing, and material properties, facilitated this comparison.

Table 1. Material properties and geometric configuration of reinforced concrete foundation systems used in the study.

Parameter	Specification
Concrete grade	C30
Compressive strength	43 MPa
Reinforcement yield Strength	420 MPa
Pile cross-section	30 × 30 cm
Pile length	8–12 m
Raft dimensions	2 m × 2 m
Raft thickness	0.4 m
Pile arrangement	Single, 2-pile (2 × 1), 4-pile (2 × 2)
Foundation types	Piled raft, pile cap
Cap elevation Pile cap system	0.5 m above ground

Table 2. Experimental standards, equipment, and procedures adopted for full-scale foundation testing.

Component	Description
Soil investigation method	Cone Penetration Test (CPT)
CPT standard	ASTM D5778
Concrete testing standard	ASTM C39
Load testing standard	ASTM D1143
Loading system	Hydraulic jack with reaction frame
Measurement devices	Dial gauges/displacement transducers
Loading method	Incremental static loading
Settlement recording	At each load increment until stabilization
Ultimate load determination	Tangent intersection method
Test condition	Full-scale field testing in clayey soil

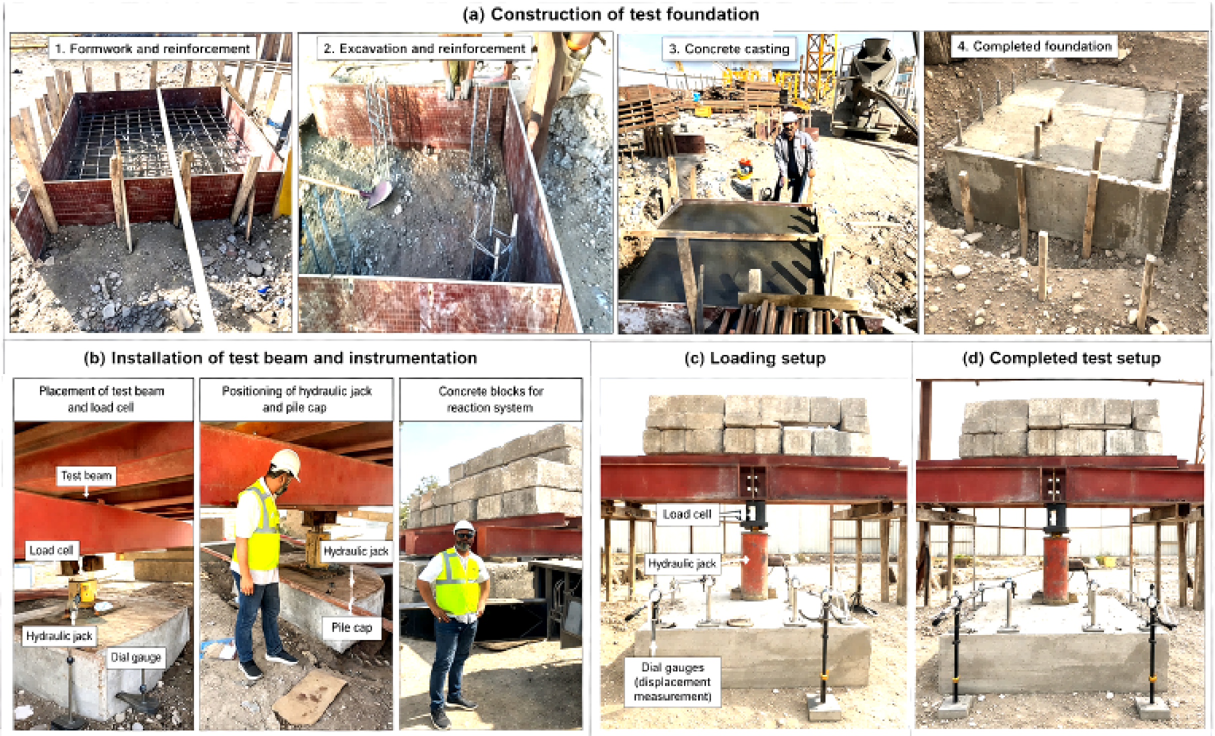

Figure 1. Experimental program: (**a**) Construction of reinforced concrete test foundation showing formwork, reinforcement, and casting stages; (**b**) Installation of test beam, hydraulic jack, load cell, and dial gauges for displacement measurement; (**c**) Loading setup with reaction system using concrete blocks; (**d**) Completed full-scale test arrangement for static load testing.

The major testing method used in the present investigation was the static load test, performed following the standard ASTM D1143 protocol, which has been established as the most suitable technique for assessing the load-settlement relationship and ultimate bearing capacity of deep foundations. The test setup included a hydraulic jack system for applying loads on the footing and also a reaction frame system/kentledge system to resist the applied loads. Loads were applied in an incremental manner, and the settlements were measured by means of extremely sensitive dial gauges/displacement transducers located in suitable positions in the footing. The load application technique adopted in the testing was the maintained load method, which involved maintaining the applied load up to a certain point when the settlements reached stability. The significance of the maintained load test was more pronounced in clay soils due to consolidation effects. The entire process of the experiment, as well as the test configuration classification into pile cap, single pile, and piled raft systems, is shown in **Figure 2**.

Load-settlement data were continuously collected throughout testing to obtain typical graphs for each foundation system. From these graphs, critical stages of the behavior of foundations have been identified such as elastic behavior stage, transition from elastic behavior to non-linear behavior stage, and plastic yielding till the collapse of the foundation. The ultimate load capacity of foundation was obtained through the tangent intersection method, which includes drawing a tangent line to the initial linear region as well as a tangent line to the non-linear region of the load-settlement graph; the intersection point between both lines is then projected on the load axis. This method was adopted since it is appropriate to determine the ultimate load of gradual failure cases which are usually encountered in clayey soils.

Apart from performing the load tests, construction procedures were also taken into consideration to make sure that the models used during experimentation would simulate real-life conditions as closely as possible. Pile installation was done through proper driving techniques considering the site conditions in order to allow sufficient penetration into the target bearing strata. The driving technique would be properly controlled to meet refusal criteria representing sufficient end-bearing capacity. Castings for the raft and pile caps were also conducted in accordance with conventional construction practices to produce concrete that had satisfactory material properties. The reinforcement provided at the interface between piles and raft in the piled raft foundations was designed to provide proper load transfer and structure continuity, which would enable the development of composite action.

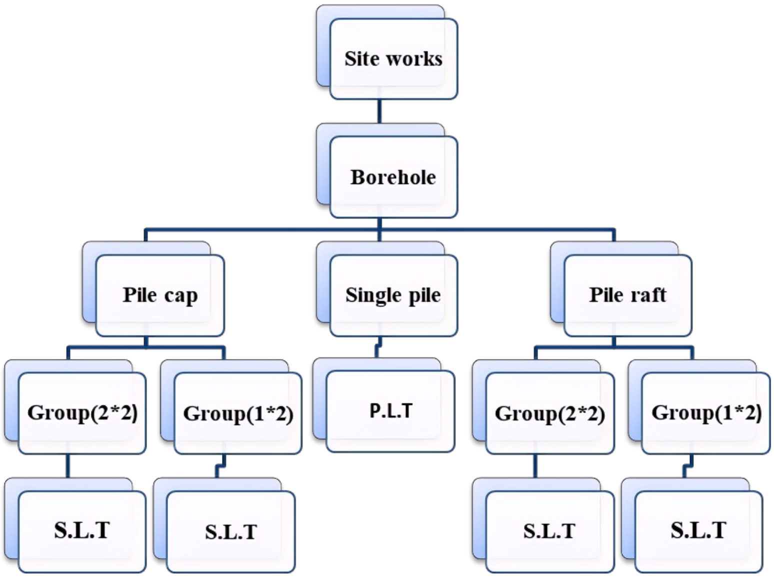

Figure 2. Schematic flowchart of the experimental program showing site investigation and foundation testing configurations, including pile cap systems (group 2 × 2 and 1 × 2), single pile load test (PLT), and piled raft systems (group 2 × 2 and 1 × 2), along with corresponding static load tests (SLT).

The use of full-scale testing as the main experimental procedure was an important consideration during experimentation. Full-scale tests involve testing structures of the same size as those under analysis. Unlike small-scale laboratory models and computer simulations, full-scale testing provides realistic interaction behavior between the structure and foundation soils. In addition, the use of different configurations with differing pile counts provided an opportunity to examine the correlation between the number of piles used, the efficiency of load distribution, and the amount of materials utilized. This consideration is especially important when evaluating material efficiency because it helps to identify combinations of piles that provide the best performance while minimizing the use of reinforced concrete.

On the whole, the proposed methodological approach in this research combines standard testing protocols, realistic material properties, and controlled comparative testing to ensure an in-depth analysis of the efficiency of reinforced concrete foundations. The application of internationally known ASTM test standards assures validity and repeatability of the research results, whereas the execution of a full-scale test allows one to understand the behavior of the foundation structures. With the combination of the above methods of geotechnical, materials and structural analysis, it is possible to evaluate the relation between building materials and foundation structures. Many scientists have studied the behavior and performance of piled raft foundation systems in terms of analytical, experimental, numerical and hybrid models. Previous research has shown the advantages of the piled rafts in reducing settlement, load-sharing, and bearing capacity. Nevertheless, numerous studies were confined to lab-scale testing, and numerical simulations or full-scale field tests were lacking. In order to define the research gap and place the current study within the existing body of literature, the comparative table of selected studies is provided in **Table 3**.

Based on the results highlighted in **Table 3**, previous studies have shown that there are many benefits associated with piled raft foundations regarding their load-sharing ability, minimizing settlement effects, and increasing bearing capacity through the use of analysis, numerics, and scale model test methods. However, most of the literature is constrained in one way or another through simple assumptions in analysis, unrealistic numerical models, scaled laboratory tests, or lack of full-scale field verification. In addition, comparative studies of piled raft foundations compared with the traditional pile cap foundations have not been done much, especially in terms of efficient concrete reinforcement use and sustainable foundation design. The above-mentioned shortcomings define the research gap filled in this study through full-scale field tests.

Table 3. Summary of representative studies on piled raft foundation systems, including methodologies, soil conditions, key findings, and identified limitations, highlighting the research gap addressed by the present full-scale experimental investigation.

Study	Method	Soil Type	Main Findings	Limitation
Randolph [15]	Analytical	Various soils	Piles reduce raft settlement	Limited field validation
Fattah et al. [16]	Experimental	Sandy soil	Pile spacing influences capacity	Laboratory scale
Singh et al. [18]	Numerical (FEM)	Cohesive soil	Improved load sharing mechanism	Numerical assumptions
Mukherjee and Borthakur [19]	Experimental/Prediction	Various soils	Enhanced bearing capacity prediction	Limited full-scale data
Ahmed et al. [21]	FEM–ML Hybrid	Soft clay	Improved capacity estimation	Lack of field verification
Present Study	Full-scale field testing	Clay soil	Direct comparison of piled raft and pile cap systems with material efficiency assessment	Site-specific conditions

2.1. Concrete Specifications

All foundation elements were constructed using normal-strength reinforced concrete designed to satisfy the structural requirements of the experimental program. The concrete was specified to be of C30 grade concrete made of ordinary Portland cement, river sand as fine aggregate, and crushed stone as coarse aggregate. The design compressive strength of concrete was 30 MPa for a 28-day period, whereas the average value of compressive strength was 43 MPa from the compression tests.

The assumed mix proportion of concrete that was used in the experimental foundations was cement to fine aggregate to coarse aggregate of 1:1.8:3.0 with the water-to-cement ratio of 0.45. All concrete processes, such as mixing and casting of concrete, were done according to relevant construction practices in order to ensure uniformity in the test cases.

The steel reinforcement used in the experimental foundations had a nominal yield strength of 420 MPa. Steel reinforcing bar placement was done to satisfy structural needs and avoid premature cracking due to loading. The reinforcement bar placement included longitudinal and transverse bars in the foundation elements.

2.2. Instrumentation and Settlement Measurement

Vertical settlements were determined by dial gauges and displacement transducers arranged symmetrically about the circumference of the tested foundation element. The layout of instruments was meant to allow not only recording of the average settlement but also possible differential settlements under loading. The instruments were installed on a separate reference frame that is independent of the loading system in order to avoid errors due to the deformations of the reaction frame.

The data on vertical settlement were taken at all stages of loading and unloading. The average settlement was taken as a basis for determination of the load-settlement curve.

2.3. Equipment Calibration and Quality Control

Before testing, all the hydraulic loading machines, load cells, dial gauges, and displacement sensors were checked and calibrated in line with the manufacturer's recommendations and appropriate testing procedures. The calibration certificates were checked prior to conducting the experimental work to ensure accurate and consistent measurements. Furthermore, alignment of the loading system and the instrumentation was checked prior to each test to reduce any eccentricity of loading and measurement uncertainties.

2.4. Geotechnical Properties of the Clay Soil

Along with the CPT evaluation, the engineering properties of the clay formation were assessed to offer a complete description of the test site. In particular, the soil profile examined was found to be comprised mainly of clay of medium to high plasticity through the entire depth affected by the foundation structure.

The following geotechnical properties were taken into account in the study: groundwater conditions, undrained shear strength, unit weight, plasticity, and compressibility. All these parameters assisted in interpreting the results of full-scale loading tests.

3. Results

The results obtained with the help of the full-scale experimental study allow for a detailed analysis of the structural behavior and material performance of reinforced concrete pile-raft and pile cap foundations in clay soils. This conforms to the research objective of assessing material-structure interaction in field conditions. It may be concluded on the basis of the Cone Penetration Test carried out in accordance with the provisions of ASTM D5778 that the variability of the cone resistance (varying from approximately 1.0 MPa in the deeper soil layers to approximately 4.0 MPa in the shallow soil layers) implies that the soil profile consists of cohesive soils demonstrating the tendency to increased compressibility at greater depths. The soil stratification was the major factor influencing the load-settlement characteristics of the considered foundation systems. Reinforced concrete, with a grade of C30 and an experimentally established compressive strength of 43 MPa according to ASTM C39, was used in constructing all structural members, providing satisfactory rigidity for distributing the applied loads effectively in raft-type foundations. Steel reinforcement with a yield strength of 420 MPa guaranteed structural durability when applying high loads without experiencing structural collapse. The results of load-settlement relationships of different foundation types are presented in **Table 4**.

The load–settlement relationships that were established during the static loading test carried out according to the ASTM D1143 specification gave an insight into the comparative analysis of different pile configurations. As far as the single pile—piled raft combination is concerned, the load-settlement relationship showed the linearity of the response up to 70–80 kN, corresponding to settlements up to 5 mm. That means that the behavior was elastic, caused by the high stiffness of the reinforced concrete raft. However, beyond the mentioned values, a nonlinearity of the response occurred between 80 and 140 kN, where the settlement continued to increase gradually from 5 mm to 15 mm due to the contribution of pile shaft resistance and participation of the surrounding clayey material. The ultimate load-carrying capacity of the investigated configuration, calculated with the help of the tangent intersection method, was equal to 109 kN. It can be considered substantially larger than in the case of the isolated piles. That improvement in the ultimate load carrying capacity is possible because of the composite effect of the raft-pile combination, since the raft contributes to the load transfer directly by soil contact. **Table 5** summarizes the ultimate load capacities and corresponding settlements for all tested foundation configurations, including the single-pile, two-pile, and four-pile piled raft systems, together with the two-pile and four-pile pile cap systems. Among these configurations, the four-pile piled raft foundation achieved the highest ultimate load capacity (approximately 300–310 kN) and was therefore selected as the representative case for graphical presentation in **Figures 3** and **4**. The remaining configurations are discussed quantitatively using the values presented in **Table 5**.

Table 4. Summary of load–settlement response for different reinforced concrete foundation configurations.

Foundation System	No. of Piles	Load Range (kN)	Settlement Range (mm)	Behavior Stage
Piled Raft	1	0–80	0–5	Elastic
Piled Raft	1	80–140	5–15	Nonlinear
Piled Raft	2	0–100	0–3	Elastic
Piled Raft	2	100–200	3–10	Transition
Piled Raft	4	0–230	0–5	High stiffness
Piled Raft	4	230–330	5–20	Nonlinear
Pile Cap	2	0–100	0–5	Elastic
Pile Cap	2	100–200	5–12	Nonlinear
Pile Cap	4	0–150	0–5	Elastic
Pile Cap	4	150–250	5–30	Progressive yielding

Table 5. Comparison of ultimate load capacity and corresponding settlement for different foundation systems.

Foundation System	No. of Piles	Ultimate Load (kN)	Settlement at Ultimate Load (mm)
Piled Raft	1	109	~20–25
Piled Raft	2	225	~15
Piled Raft	4	300–310	~20
Pile Cap	2	200	~25
Pile Cap	4	250	~30

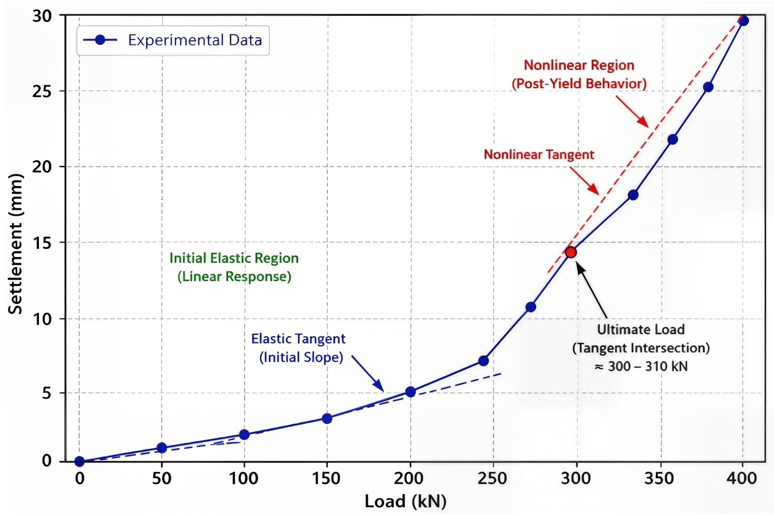

Figure 3. Representative load–settlement response of the four-pile reinforced concrete piled raft foundation obtained from full-scale static load testing, corresponding to the ultimate load capacity reported in **Table 5**.

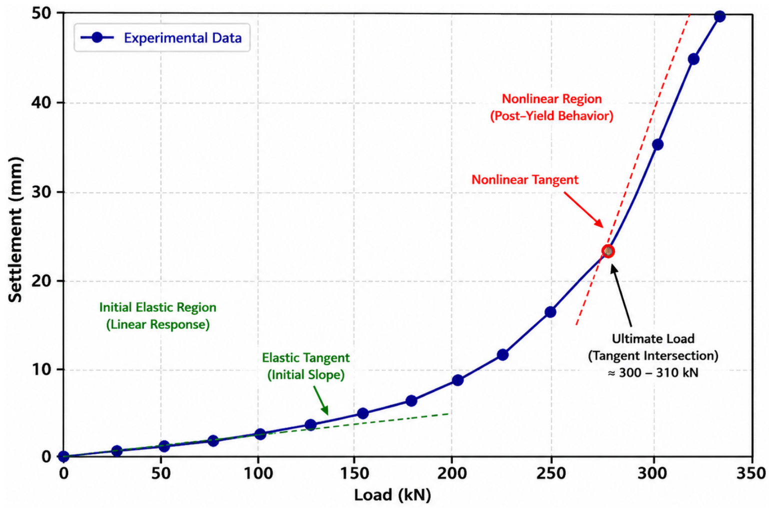

Figure 4. Representative load–settlement curve of the four-pile reinforced concrete piled raft foundation illustrating the tangent-intersection method used to determine the ultimate load capacity (300–310 kN) reported in **Table 5**.

In the case of the two-pile piled raft foundation, a marked improvement in stiffness and load capacity has been recorded. The first elastic range ranged up to around 100 kN, where the settlement was small, i.e., less than 3 mm, indicating the high degree of rigidity due to the presence of extra piles. The next nonlinear range spanned from 100 kN to 200 kN, where the settlement was noted to be about 8–10 mm, meaning that there was a progressive activation of shaft resistance along the shafts. For high loads of around 300 kN, the settlement was about 13–15 mm, with a relatively constant slope of the graph, indicating that there was adequate distribution of loads between the raft and piles. The allowable load capacity for the two-pile configuration was calculated to be around 225 kN, which was about twice the load-carrying capacity of the one-pile system. Notably, this increment in load-carrying capacity cannot be entirely attributed to the addition of more piles, thus reflecting the nonlinear effect of the pile-soil-raft system and the efficiency of the piled raft method in saving materials. **Figure 3** presents the representative load–settlement response obtained from the four-pile piled raft foundation, which exhibited the highest load-bearing capacity among all tested configurations. This representative curve was selected to illustrate the characteristic transition from the initial elastic response to nonlinear deformation, and the tangent-intersection method was adopted for determining the ultimate load capacity in accordance with ASTM D1143. The load–settlement responses of the remaining foundation configurations (single-pile piled raft, two-pile piled raft, two-pile pile cap, and four-pile pile cap) are summarized quantitatively in **Tables 4** and **5** and discussed throughout this section.

The performance of the four-pile piled raft system was the best out of all systems, with an improved load-carrying capacity and well-controlled settlement. The load-settlement graph stayed almost straight up until about 200–230 kN, with the maximum settlement of less than 5 mm, implying that the initial stiffness is quite high due to the joint contribution of piles and the reinforced concrete raft. When the loading value exceeded 250–330 kN, a nonlinear load-settlement behavior occurred with a settlement value of about 15–20 mm. Finally, when the load exceeded 330 kN, there was an even steeper slope, meaning that plastic deformation of clay started, and shaft and end-bearing resistances were mobilized fully. Thus, the maximum load was about 300–310 kN, much more than those in the one-pile and two-pile systems. It is clear that the more piles there are, the better the capacity of the pile system becomes, but the function of the raft should not be overlooked. In terms of material efficiency, it can be concluded that the best load-carrying capacity is exhibited by the piled raft of four piles, although there was only a relatively small increase in the amount of concrete used. Material efficiency and concrete efficiency are measured using **Table 6**, whereas performance efficiency between piled raft and pile cap systems is analyzed using **Table 7**.

Table 6. Material efficiency assessment based on load capacity and pile usage.

Foundation System	No. of Piles	Relative Concrete Usage	Load Capacity (kN)	Efficiency (kN per Pile)
Piled Raft	1	Low	109	109
Piled Raft	2	Moderate	225	112.5
Piled Raft	4	High	300	75
Pile Cap	2	Moderate	200	100
Pile Cap	4	High	250	62.5

Table 7. Comparative evaluation of piled raft and pile cap systems in terms of structural and material performance.

Parameter	Piled Raft System	Pile Cap System
Load-bearing mechanism	Raft + piles + soil interaction	Piles only
Ultimate load capacity	Higher (up to ~310 kN)	Lower (up to ~250 kN)
Settlement control	Better	Moderate to high
Initial stiffness	High	Moderate
Material efficiency	High (fewer piles required)	Lower
Concrete utilization	Optimized	Higher consumption
Sustainability	Improved	Less efficient

On the other hand, the pile cap systems demonstrated completely different behavior because of the lack of contact between the raft and soil. In the case of the four-pile pile cap system, initially, the load-settlement curve depicted stiff behavior up to 100–150 kN load level, when the settlement did not exceed 5 mm due to elastic pile deformation along with soil deformation. However, with an increase of load above this load level, a strong nonlinearity became apparent and the settlement reached 25–30 mm at approximately 250 kN load level. Finally, the ultimate load for this particular system turned out to be approximately 250 kN, which is significantly less than the ultimate load of the four-pile piled raft system even though both systems have equal numbers of piles and almost identical material parameters. Therefore, the main function of the pile cap as a load transfer element does not exist in this case. Similarly, the two-pile pile cap system exhibited an ultimate load capacity of approximately 200 kN, with higher settlement values compared to the corresponding piled raft configuration, further emphasizing the advantages of raft–soil interaction in reducing settlement and enhancing capacity. For clarity, the tangent-intersection point corresponding to the ultimate load has been identified directly on the representative load–settlement curve shown in **Figure 4**.

The comparison among all of the designs shows how the piled raft design is more efficient regarding its capacity to bear loads and mitigate settlements. In particular, the results prove that the presence of a reinforced concrete raft directly interacting with the ground allows increasing load-sharing effectiveness and transferring part of the load from piles to the soil itself, thus reducing the load-bearing role played by piles. From a quantitative perspective, the four-pile raft design allowed increasing the bearing capacity by about 20% compared to the corresponding pile cap design and also proved smaller settlement values at equal loads. Such differences may be attributed to the characteristics of the reinforced concrete raft, especially in terms of flexural stiffness that makes the distribution plate effective. It can be noted that achieving higher performance with fewer piles can help in reducing concrete use and thus improving the environmental sustainability of the construction. As far as the relationship between load and settlement is concerned, it can be seen in **Figure 4** how the curve starts off being almost linear (elastic) until around 250 kN.

Material science-wise, the obtained data illustrate the importance of the reinforced concrete characteristics when considering the behavior of foundations. The high compressive strength (43 MPa) and stiffness of the C30 concrete helped achieve the initial elasticity of the system and prolonged the onset of the nonlinear zone, whereas reinforcement was necessary for ensuring the integrity of the structure and preventing cracks caused by the high level of stress. In addition, the interaction of the reinforced concrete raft and the clay soil affected the development of plastic strain zones due to the role of the raft as the distributing element, which prevents the formation of high-stress zones. Overall, the presented results prove that the characteristics of foundation depend not only on the geotechnical factors, but also on the choice of materials. According to **Figure 5**, the bearing capacity of the foundation substantially grows with the use of piles, with the maximum value observed for the four-pile raft.

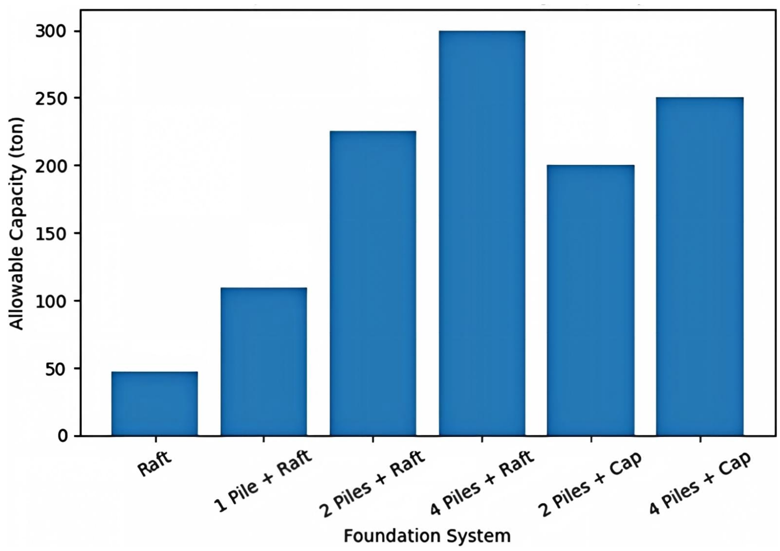

Figure 5. Comparison of allowable bearing capacity of different foundation systems, including raft, piled raft (1, 2, and 4 piles), and pile cap configurations, demonstrating enhanced load-carrying performance of piled raft systems.

In general, the experimental results prove that piled raft foundations are a better choice than pile cap foundations in terms of efficiency and sustainability. The fact that high load capacity can be obtained using fewer piles contributes significantly to saving building materials, reducing construction expenses, and minimizing negative effects on the environment. In addition, the reliability of the experiments carried out under different conditions indicates the high reliability of the experimental methods used in this work. The combination of the study of material properties together with problems connected with the structure and geotechnics of the studied region makes it possible to give some valuable recommendations on the design of appropriate foundations in accordance with present tendencies in building materials science.

4. Discussion

It can be stated that good performance of the piled raft systems under consideration in the current paper is also confirmed by the results of the investigation conducted by Randolph [15], which shows that participation of the raft contributes to the reduction of settlement due to the redistribution of loads between the raft and the piles. Also, according to Fattah et al. [16], stiffness and load-sharing effectiveness of the foundation systems are improved when raft-soil interactions are taken into account in the design process. Thus, the current experimental data obtained during the field testing prove the above statement, as the piled raft systems had less settlement and higher bearing capacity compared to the respective pile cap systems. As far as the discussion about the current investigation is concerned, it should be noted that the experimental results will be interpreted in relation to the performance of the materials and load distribution, as well as application of the results in sustainable foundation design. It is clear from the experimental results that, apart from geologic factors, the performance of the foundation system is greatly influenced by the mechanical properties of the reinforced concrete components and their interaction. The reinforced concrete raft, with a relatively rigid cross-section and high compressive strength, was able to transfer loads actively without simply connecting piles. Therefore, stress was distributed within a greater area, while demands were shifted from the piles. This type of performance corresponds to the theory of piled rafts and the contribution of rafts to load distribution.

In terms of materials, the significance of reinforced concrete on the performance of the foundations is quite pronounced. The use of concrete with C30 grades, with a confirmed compression strength of 43 MPa, helped ensure the stability of the raft and pile structures even with high load values, thus helping achieve a smooth transition to a nonlinear stage of the loading curve, without causing any failures at the structural level. The stiffness of the concrete raft controlled the first stage of the curve, which was linear in nature—there was no movement of the structure even with an increase in the load values, thus showing that material stiffness is important for controlling the serviceability properties, especially in soils with a lot of clay where excessive deformations are a major problem. In addition, the inclusion of reinforcement with yield strengths of 420 MPa allowed the raft to have enough ductility. The influence of reinforced concrete stiffness observed in this investigation is also supported by previous studies. As observed by Singh et al. [18], increased stiffness of the rafts facilitates efficient load transfer and ensures proper control of settlement for cohesive soil. Similarly, Ahmed et al. [21] have found from their finite element analysis that optimal piled raft systems can attain high bearing capacity along with stability. The current study provides field-scale experimental evidence supporting these numerical and analytical findings.

In making this comparative analysis between the piled raft and pile cap foundations, it can be noted that there was better efficiency in terms of the amount of material used in the piles since the piled raft foundation carried heavier loads but with fewer piles compared to the other foundation type. This means that there was higher efficiency in the use of materials, which can significantly help in reducing costs of the construction projects. The main reason for this increased efficiency is the inclusion of the raft component in load-carrying, in which case there was less dependency on the piles for transferring loads. The isolation of the piles from the ground made this process difficult in the pile cap method, and the outcome was higher settlement and thus low efficiency [24–26]. This goes to show the significance of taking into consideration the interaction between the raft and the ground in design.

The non-linear behavior evident in the load-settlement graphs gives further understanding of the mechanisms involved in the foundations. Initially, the behavior exhibited was mainly elastic, whereby the raft carried most of the loads because it was directly in contact with the soil. As the loads continued to increase, the piles were increasingly contributing to the loading process by mobilizing shaft resistance and bearing capacity at their tips. This is evidence that the system transitions from one mode of operation to another when subjected to different loads. The lack of failure at a certain point in time, especially in clay soils, means that the system gradually fails, an aspect considered favorable during design since there are early warnings before the complete collapse of the system. This behavior supports the use of techniques such as the tangent intersection method in calculating ultimate loads.

The conclusions drawn from this experimental research are in general agreement with other studies related to piled raft foundations. Randolph [15] found out that using piles reduces settlement due to the presence of load transfer between piles and raft; therefore, the reduction in settlements is observed in this study as well. Singh et al.[18] have proven that load sharing in piles and raft helps to improve the foundation performance in cohesive soils and explains the increased carrying capacity of the studied piled rafts. In addition, Ahmed et al.[21] showed that optimization of piled raft systems helps to increase bearing capacity and at the same time save resources. This study contributes to this topic as it provides full-scale field results and compares the piled raft systems and pile caps in clay soil conditions. As a result, it is proven that the interaction of the raft and soil plays an important role in increasing load transfer efficiency and saving materials compared to the traditional pile cap foundations. Concerning sustainability, the present results are in line with the current scientific literature, which points out that reducing the number of piles via load sharing increases the resource efficiency of foundation systems.

This notion is proven experimentally by the present research, as piled raft systems are capable of providing better performance in terms of structural design while using foundation materials in a more efficient manner compared to conventional pile cap systems. Differences in the performance of foundations are highly associated with the behavior of reinforced concrete materials in the investigated systems[27,28]. Using C30 concrete in conjunction with reinforcing steel having a yield strength of 420 MPa was found to have enough stiffness to ensure proper load distribution between raft, piles and the soil. The better performance achieved by the piled raft systems shows that efficient use of reinforced concrete materials could lead to improvement of load distribution without requiring any other foundation element. This research is important in the field of building materials science as it clearly shows that structural performance is the result of material and structure interaction. Better structural performance does not necessitate more use of materials. With the use of piled raft systems, efficient use of reinforced concrete materials can lead to better load-carrying capacity and settlement control. These advancements make possible sustainable construction techniques through reduction in the amount of material needed for comparable or better structural performance. Therefore, the results have implications in favour of the continuing trend in building materials research into high-performance and low-material usage structural systems[29–32].

A drawback of this current research is that there were no quantified results for the environmental and economic implications of the system studied, using methods such as material take-off analysis, costing, or life cycle analysis. In other words, the results on sustainability only relate to the potential improvement in use of foundations. Further research in sustainability should include quantification of embodied carbon content, material usage, and economic implications of piled raft foundation systems. In recent years, the notion that sustainable foundation engineering requires the combination of geotechnical efficiency and effective material usage to obtain increased structural reliability and decreased ecological footprint has received increasing attention from scientific communities. Recent studies indicate that the enhancement of the efficiency of interaction between the elements of the foundation and soil leads to load sharing, improved bearing capacity, and reduction of excess material usage. This fact supports the hypothesis that foundation engineering cannot be based merely on the increase of structural elements' quantity, but should rather be based on the improvement of efficiency of the system's operation[33–37]. The results obtained in the current study prove this idea by showing that piled raft reinforced concrete systems are capable of providing enhanced structural efficiency along with effective material usage.

5. Conclusions

This study was undertaken to address the limited availability of full-scale experimental investigations comparing piled raft and conventional pile cap foundation systems in clayey soils, particularly with respect to load-sharing behavior, structural performance, and material efficiency. Through the field tests conducted at controlled loads, this research was able to fill this gap in the knowledge base and to practically prove the performance of such foundations. In general, all research questions formulated at the initial stage of the research were properly covered in the course of the experimental study. It was possible to prove the effect of the raft-soil interaction in improving the behavior of such foundations and also the significance of taking into account the role of the raft as the load-bearing structure. In addition, information on the role of the reinforced concrete characteristics in the performance of foundations was obtained.

As for the proposed hypothesis that piled raft foundations would perform better in terms of load-bearing capacity, settlement behavior, and efficiency compared to pile cap foundations in clayey soils, the results confirmed its correctness. In general, the results proved that the combination of such factors as raft, piles, and soil provides more efficient load-bearing performance. The study evaluated the load–settlement behavior of different foundation configurations, investigated load-sharing mechanisms, assessed the contribution of reinforced concrete material properties, and examined the relative efficiency of piled raft and pile cap systems. This enabled the researchers to have a holistic appreciation of the foundation performance in the field.

The primary scientific contribution of this research is the production of full-scale experimental results on the interaction between piles, raft and clay soil. Different from many earlier investigations which focused mainly on analysis or numerically based experiments, the current study offers direct validation of the piled raft and pile cap foundations in field conditions. Besides, this research contributes to sustainable foundation engineering by demonstrating how the use of construction materials could be made efficient via foundation design optimization.

While the current study provided useful experimental results about the behavior of reinforced concrete piled raft and pile cap foundations on a full scale, there are some limitations of this study that need to be mentioned. First, the experiment was conducted under the condition of static load applied at one clay soil site, and the results cannot be generalized to different soil types or loading situations, such as seismic or impact loading. Second, the study involved only the conventional C30 reinforced concrete and certain pile-raft configurations, and did not consider more innovative cement materials, reinforcement systems, or optimized foundation designs. Moreover, the current investigation did not consider durability issues such as creep, shrinkage, reinforcement corrosion, variations in groundwater levels, or the effects of exposure of the structure over time. Sustainability has been considered only on a qualitative basis, that is, material efficiency, but no quantitative assessment has been done for embodied carbon footprint, life-cycle assessment, life-cycle costing and economic optimization of the structure. Future studies should overcome all these shortcomings in their investigations by carrying out full-scale tests under varied geotechnical conditions, considering various dynamic loading cases, examining the sustainable and high-performance concrete materials, and optimizing the pile raft foundation design through numerical and artificial intelligence techniques.

Author Contributions

A.L.H.: conceptualization, methodology, experimental investigation, data curation, formal analysis, and original draft preparation. A.A.H.A.-S.: supervision, validation, review and editing, and project administration. Both authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request. The experimental data, including load–settlement measurements and material test results, were obtained from full-scale field tests and are not publicly available due to project-specific and institutional constraints.

Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

The authors declare that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

References

[1] Eslami, A., Ebrahimipour, A., Imani, M., et al., 2026. Form and load transfer aspects of foundation systems: Case-based implementation and adaptation for buildings. Deep Underground Science and Engineering. 5(1), 176–192. DOI: https://doi.org/10.1002/dug2.12146

[2] Ranjbar, F., Asgari, A., Bagheri, M., et al., 2026. Insights into the mechanisms and seismic performance of reinforced concrete buildings on a pile foundation in liquefiable deposits. Structures. 87, 111557. DOI: https://doi.org/10.1016/j.istruc.2026.111557

[3] Chu, C., Yi, T., Qin, Y., et al., 2026. Model test study on the vertical bearing performance of post-grouted piles based on different grouting materials. Scientific Reports. 16, 14635. DOI: https://doi.org/10.1038/s41598-026-44882-x

[4] Khajeh, A., Salimi, M., MolaAbasi, H., et al., 2026. Zeolite-based soil stabilization: A review. Journal of Rock Mechanics and Geotechnical Engineering. 18(4), 3234–3265. DOI: https://doi.org/10.1016/j.jrmge.2025.06.039

[5] Rømhild, C.J., Rasmussen, N.S. Submerged structures supported on sand pumped underneath structure. In: Krokeborg, J. (Ed.). Strait Crossings 1994. CRC Press: London, UK. pp. 695–702. DOI: https://doi.org/10.1201/9781003761167-98

[6] Shah, Y.I., Zhou, H., Shah, D., 2026. Sustainable UHPC wet joints for precast slab: Material efficiency, structural performance, and lifecycle benefits. Journal of Building Engineering. 123, 115728. DOI: https://doi.org/10.1016/j.jobe.2026.115728

[7] Zhang, F., Yang, S., Panetta, R., et al., 2026. Eggshell powder-modified sustainable ultra-high-performance fibre-reinforced concrete for transportation preservation and rehabilitation. Case Studies in Construction Materials. 24, e05862. DOI: https://doi.org/10.1016/j.cscm.2026.e05862

[8] Sharma, M., 2026. Barriers to construction waste minimization and circular economy adoption in India: A BWM analysis. Environment Systems and Decisions. 46(2), 25. DOI: https://doi.org/10.1007/s10669-026-10088-9

[9] Zvarivadza, T., Grobler, H., Olubambi, P.A., et al., 2026. Advancing mine pillar design: Evaluating traditional methods and integrating AI for enhanced stability of pillars in the Great Dyke, Zimbabwe. Deep Underground Science and Engineering. DOI: https://doi.org/10.1002/dug2.70076

[10] Roberts, D., Gomathinayagam, G., 2026. Cost and Project Management of Modern Methods of Construction. Routledge: London, UK. DOI: https://doi.org/10.1201/9781003570431

[11] Leung, C.F., Tan, S.A., Phoon, K.K., 2026. Field Measurements in Geomechanics: Proceedings of the 5th International Symposium FMGM99, Singapore, 1–3 December 1999. CRC Press: London, UK. DOI: https://doi.org/10.1201/9781003761914

[12] Aaqib, M., Muhammad, S.A., Wani, K.M.N.S., 2026. Integrated experimental-numerical assessment of piled raft foundation on granular soils using varying configurations. Indian Geotechnical Journal. DOI: https://doi.org/10.1007/s40098-026-01518-1

[13] Rizal, A.F.B.M., Wahab, M.M.A., Yousafzai, A.K., 2026. Development of raft foundation structural design tool for residential buildings. Journal of Tropical Resources and Sustainable Science. 14(1), 35–44. DOI: https://doi.org/10.47253/jtrss.v14i1.2142

[14] Sengupta, I., Rajesh, S., Patra, N.R., 2026. Response of piled-raft foundation in soft soils under groundwater drawdown. Transportation Infrastructure Geotechnology. 13(4), 86. DOI: https://doi.org/10.1007/s40515-026-00856-0

[15] Randolph, M.F., 2026. Design of piled raft foundations. In: Balasubrmaniam, A.S. (Ed.). Recent Developments in Laboratory and Field Tests and Analysis of Geotechnical Problems: Proceedings of international symposium, Bangkok, 6–9 December 1983. CRC Press: London, UK. pp. 525–537. DOI: https://doi.org/10.1201/9781003763086-38

[16] Fattah, M.Y., Al-Obaydi, M.A., Al-Jalabi, F.A., et al., 2026. A study on piled raft system in collapsible clayey gypseous soil. Results in Engineering. 30, 110175. DOI: https://doi.org/10.1016/j.rineng.2026.110175

[17] Yin, C., Bu, J., Sui, C., 2026. Study on mechanism of soil displacement effect in large-diameter PHC pipe piles. Applied Sciences. 16(5), 2197. DOI: https://doi.org/10.3390/app16052197

[18] Singh, S., Solanki, C.H., Shukla, S.J., 2026. A finite element analysis on the performance and load-sharing mechanism of unconnected piled raft foundation on cohesive soil. Indian Geotechnical Journal. 56(2), 575–597. DOI: https://doi.org/10.1007/s40098-025-01182-x

[19] Mukherjee, A., Borthakur, N., 2026. Prediction of bearing capacity for performance enhancement of micropiled raft foundations using ensemble boosting algorithms. Geotechnical and Geological Engineering. 44(1), 2. DOI: https://doi.org/10.1007/s10706-025-03515-2

[20] Guo, C., Ji, L., Sun, M., et al., 2026. Influence of existing pile group and strata induced by excavation of the adjacent twin tunnels with small clearance. Buildings. 16(8), 1618. DOI: https://doi.org/10.3390/buildings16081618

[21] Ahmed, D., Ajmal, M., Linda bt Taib, S.N., et al., 2026. A hybrid FEM-machine learning framework for prediction of piled raft bearing capacity in soft clay. Transportation Infrastructure Geotechnology. 13(5), 112. DOI: https://doi.org/10.1007/s40515-026-00886-8

[22] Soomro, M.A., Darban, S.A., Ma, Z.-G., et al., 2026. Numerical evaluation of twin tunneling effects on battered piled raft foundations in soft clay under lateral and combined loads. International Journal of Geomechanics. 26(4), 04026055. DOI: https://doi.org/10.1061/IJGNAI.GMENG-12991

[23] Arsyad, A., Alel, M.N.A., Widarta, P.K., et al., 2026. Predicting CPT-based shallow foundation design adequacy using machine learning. Geodata and AI. In press. DOI: https://doi.org/10.1016/j.geoai.2026.100060

[24] Li, Y., Zhou, Q., Zhao, W., et al., 2026. Novel method for adjusting pile–soil settlement in a composite foundation with end-bearing piles. International Journal of Geomechanics. 26(2), 04025330. DOI: https://doi.org/10.1061/IJGNAI.GMENG-11368

[25] Zhang, L.-J., Cui, Z.-D., Huang, M.-H., et al., 2026. Effect of pile foundation on seismic response of adjacent subway station buried in sand site by centrifuge shaking table tests. Engineering Structures. 359, 122728. DOI: https://doi.org/10.1016/j.engstruct.2026.122728

[26] Peng, Z., Geng, J., Gao, G., et al., 2026. Vibration isolation of concrete-filled trench for pile–net composite foundation under high-speed train loading. International Journal of Geomechanics. 26(6), 04026094. DOI: https://doi.org/10.1061/IJGNAI.GMENG-13125

[27] Reul, O., Randolph, M.F., 2004. Design strategies for piled rafts subjected to non-uniform vertical loading. Journal of Geotechnical and Geoenvironmental Engineering. 130(1), 1–13. DOI: https://doi.org/10.1061/(ASCE)1090-0241(2004)130:1(1)

[28] Han, Z., She, D., Liu, J., 2026. LSTM-based fast prediction of seismic response and fragility for bridge pile-group foundations: A data-driven design approach. Designs. 10(2), 37. DOI: https://doi.org/10.3390/designs10020037

[29] Robertson, P.K., 2016. Cone penetration test (CPT)-based soil behaviour type (SBT) classification system—An update. Canadian Geotechnical Journal. 53(12), 1910–1927. DOI: https://doi.org/10.1139/cgj-2016-0044

[30] Poulos, H.G., Davis, E.H., 1980. Pile Foundation Analysis and Design. John Wiley & Sons: New York, NY, USA.

[31] Tomlinson, M., Woodward, J., 2014. Pile Design and Construction Practice, 6th ed. CRC Press: Boca Raton, FL, USA. DOI: https://doi.org/10.1201/b17526

[32] Das, B.M., Sobhan, K., 2015. Principles of Geotechnical Engineering, 8th ed. Cengage Learning: Mason, OH, USA.

[33] Subramani, R., 2026. Analytic hierarchy process-based multi-criteria optimization of functionally graded thermoplastic architectures for enhanced viscoelastic energy dissipation. Journal of Composites Science. 10(5), 229. DOI: https://doi.org/10.3390/jcs10050229

[34] Raja, S., Sujitha, V.S., Yakkala, D., et al., 2026. Energy-harvesting cementitious materials for sustainable infrastructure: A critical review of piezoelectric, thermoelectric, and photovoltaic mechanisms. Innovative Infrastructure Solutions. 11(2), 73. DOI: https://doi.org/10.1007/s41062-025-02445-5

[35] Garg, A., Sawant, V.A., Kharsyiemiong, K., 2026. Numerical analysis of combined piled raft foundation as a sustainable foundation solution for high-rise structures. In: Cameselle, C., Gouveia, S., Urréjola, S., et al. (Eds.). Sustainable Energy and Infrastructure: Keynote Volume of 6th EGRWSE 2025. Springer: Cham, Switzerland. pp. 403–412. DOI: https://doi.org/10.1007/978-3-032-15286-2_36

[36] Suwondo, R., Vincensia, N., Juliastuti, J., et al., 2025. Sustainable design of raft foundations: Analyzing embodied carbon and cost impacts. Engineering, Technology & Applied Science Research. 15(1), 19677–19682. DOI: https://doi.org/10.48084/etasr.9370

[37] Uge, B.U., Guo, Y., Zhao, J., et al., 2025. A review of the load-carrying mechanism of connected and disconnected piled-raft foundations under static and dynamic loading. Sādhanā. 50(4), 291. DOI: https://doi.org/10.1007/s12046-025-02837-4