# Investigation of load sharing mechanism of Piled Raft Foundations in sandy soils

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**Abstract**

Over the past few decades, there has been a significant increase in the use of Combined Piled Raft Foundations (CPRF), which are made up of three components: piles, a raft, and soil. Unlike traditional piled foundation designs, where the piles bear the majority of the load, piled raft foundations allow for the load to be distributed between the raft and piles. Therefore, it is necessary to investigate the factors that affect this mechanism. To do so, a 3D finite element model was created using Plaxis 3D Foundation software and validated through a centrifuge experimental test. The model was then used to conduct a sensitivity analysis on key parameters that affect load sharing, such as pile length, internal friction angle of the soil, and raft thickness. The investigation revealed that pile length and internal friction angle of the soil (when under 30 degrees) significantly impact the load sharing of piled raft foundations, while raft thickness has little effect. These findings can be useful for optimizing the design of piled raft foundations.

**Keywords: Combined Piled Raft Foundations (CPRF), Finite Element Method, Piled Raft Load Sharing, Sandy Soil**

## 1. INTRODUCTION

In recent years, the Combined Piled Raft Foundation (CPRF) has gained popularity as a preferred choice for a variety of structures constructed on different soil types. This innovative foundation type is highly regarded for its ability to simultaneously distribute load-carrying capacities between the raft and piles, making it an optimized solution for many construction projects [1, 2]. The combination of a raft with piles plays a crucial role in reducing settlement, leading to cost-effective foundation design without compromising safety. The concept of using piles as settlement reducers was first introduced by Burland et al. in 1977 [3]. Studies have indicated that a CPRF's raft can transfer 30% to 50% of the applied load to the soil [4]. Furthermore, a CPRF design typically requires fewer piles compared to a pile group design to meet the same capacity and settlement requirements. Additionally, the raft in a CPRF enables the redistribution of load from a defective pile to other piles, enhancing the foundation's resilience [5]. These characteristics make CPRF a promising and efficient foundation system for various construction applications.

Piled raft foundations exhibit complex soil-structure interactions. In the analysis, interactions between pile-soil, pile-pile, raft-soil, and raft-pile must be considered. This often necessitates the use of numerical methods, such as the Finite Element Method (FEM). Numerous parametric studies have been conducted to ascertain the impact of various parameters on the performance of piled-raft foundations in terms of load distribution and settlement. However, most of these studies focus on the effects of the geometrical and mechanical parameters of the piles and the raft on the performance of piled raft foundations under working load conditions. Limited research has explored the influence of these parameters on the load-settlement relationship and load distribution in piled raft foundations on sandy soil at significant settlements. Omeman (2012) developed a design theory for predicting the settlement and the distribution of load between the raft and the piles [6]. Mandolini et al. (2005) noted that understanding the load distribution between piles and the raft is essential for advanced design techniques and new codes pertaining to piled raft foundations [7]. This research analyzes the load-sharing mechanism in piled raft foundations in sandy soil through parametric analysis using the finite element method. To this end, three different types of foundations, as depicted in Figure 1, are examined. Following the validation of the numerical model, the effects of pile length, soil internal friction angle, and raft thickness parameters are investigated.

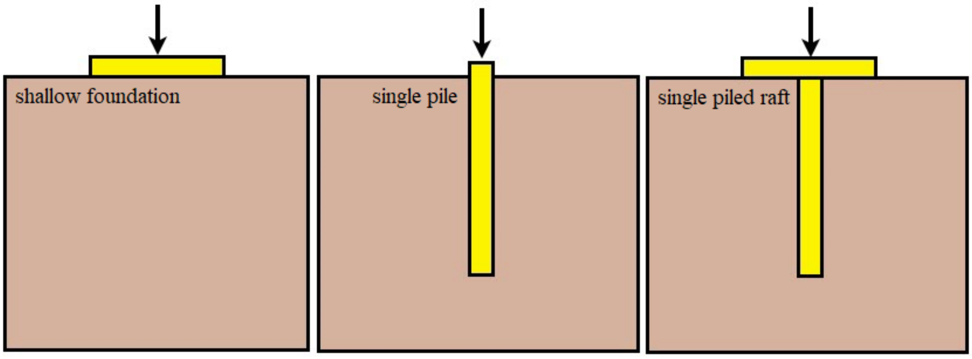


**Figure 1. Different types of foundation that are investigated in this study**

## 2. DEFINING THE FINITE ELEMENT MODEL

The PLAXIS 3D FOUNDATION software was utilized to explore an appropriate analysis approach based on the finite element method. To establish the numerical model and conduct a simulation, it was necessary to specify an appropriate mesh size, boundaries, initial conditions, and constitutive behavior. Medium refinement was employed to achieve a more accurate model. The boundary conditions of the finite element model used in this study to analyze CPRF are depicted in Figure 2, which is intended to be symmetric perpendicular to the page. To simulate these conditions, roller boundaries were set along symmetry planes. Additionally, the outer and bottom planes of the numerical models were constrained using roller boundaries to ensure stability [8].

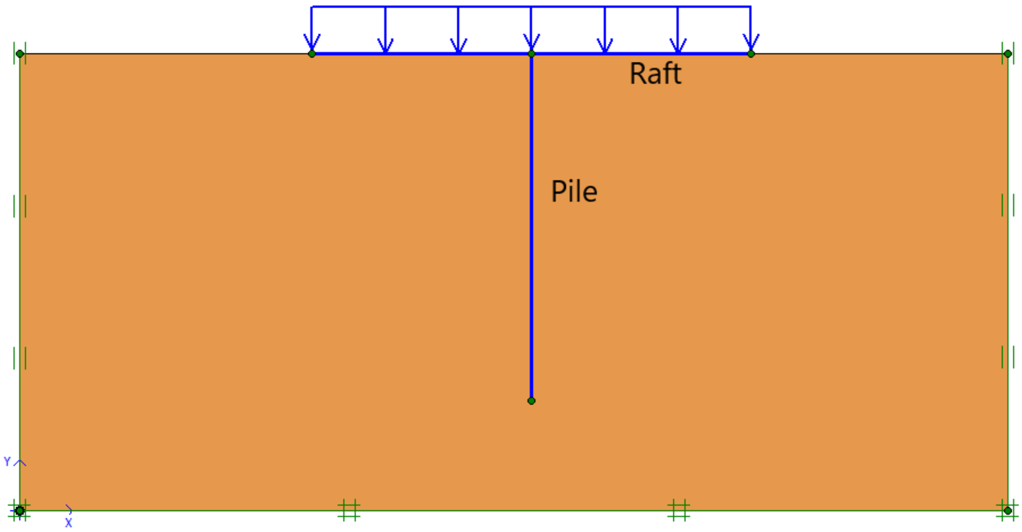


**Figure 2. Boundaries conditions of finite element model**

Three components were considered in the numerical model (raft, piles and soil). Soil, raft and piles were modeled as clusters and each cluster is divided into 15-node triangular finite elements. The soil-pile interface region was modeled by using interface elements along the piles shafts to simulate the frictional interaction in this region. The interface element is compatible with the 15-node triangular element used for the soil and piles. The interface element used in this model is a line element with five pairs of nodes and five stress points. The piles were assumed as non-displacement concrete piles. The raft was considered as a reinforced concrete slab. The behavior of the raft and the piles was assumed linear [6].

Therefore, the linear-elastic model was utilized to simulate the materials behavior of the piles and the raft. For the linear-elastic model two main parameters are used, which are the modulus of elasticity, E, and

Poisson's ratio, μ. This model is based on the Hooke's law of isotropic linear elasticity [9]. The soil was assumed to be homogenous sand soil. To predict the behavior of piled raft foundations at large settlements a non-linear analysis is required. Therefore, the behavior of the soil was considered as non-linear.

The elastic perfectly-plastic Mohr-Coulomb model was used to simulate the non-linear stress-strain behavior of the sand soil [6]. For this model, the modulus of elasticity of soil, Es, and Poisson's ratio, μs, are used for the soil elasticity while the friction angle, ϕ, and the cohesion, c, are used for the soil plasticity and the dilatancy angle is needed to model the increase of volume [9].

## 3. VERIFICATION OF THE MODEL

Fioravante and Giretti (2010) conducted a series of tests using a centrifuge model to explore the mechanisms of load transfer between a square rigid raft and a group of instrumented piles that were jacked into dry, dense sand [10]. These piles were either in direct contact with the raft or separated from it by a layer of granular material. The model, which was geometrically scaled down N times and made from the prototype material, was accelerated at N times the Earth's gravity. This centrifuge acceleration replicated the same stress and strain in the model as would be experienced in the prototype. These centrifuge loading tests were carried out using the ISMGEO Geotechnical Centrifuge, a device that was comprehensively detailed by Baldi et al. (1988) [11].

All the models were tested under an acceleration field of 65g. A scaling factor of N = 65 was chosen to model groups of piles with adequate spacing loaded by a sufficiently small raft to minimize the boundary effects due to the proximity of the lateral container walls and the container bottom. Figure 3 shows the linear displacement transducer (LDT).

The Experiments were performed using dry silica Venice Lagoon sand (VLS), with 15% finer grains than 0.075 mm. The geometry model raft was a square with 115mm width and 25mm height. Model piles were close ended and free headed with the diameter of 8mm and the length of 292mm [10]. The rest of properties is described in Table 1.

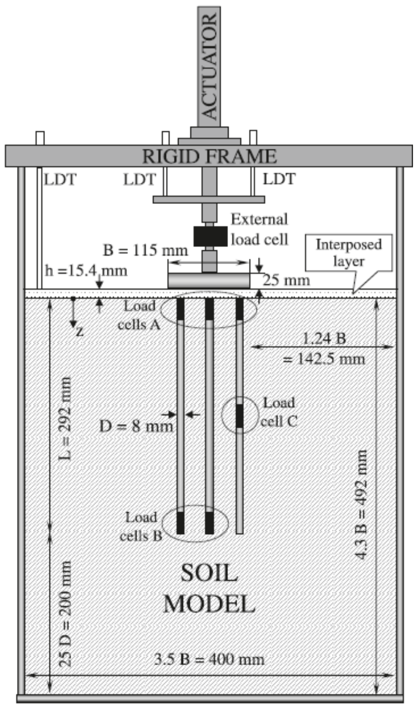


**Figure 3. Boundary conditions and test model set-up for loading tests on the piled raft with the interposed layer. LDT, linear displacement transducer [10]**

The testing program included the tests on unpiled raft and piled rafts with 1 and 4 displacement piles (Figure 4). The test results have shown that contact piles act as settlement reducers by diffusing the load applied to their heads to greater and deeper volumes of soil [10]. Figure 5 shows the comparison between the results of centrifuge model tests and predicted settlement using PLAXIS 3D FOUNDATION model. As shown in the Figure, the predictions of PLAXIS's models were in reasonable agreement with measured results.

**Table 1- Characteristics of soil, raft and piles for loading tests**

| Parameter | Symbol | Unit | Value |
|---|---|---|---|
| Maximum dry density of soil | $\Upsilon_{d,max}$ | KN/m$^3$ | 16.5 |
| Minimum dry density of soil | $\Upsilon_{d,min}$ | KN/m$^3$ | 13.08 |
| Median grain size | $D_{50}$ | mm | 0.18 |
| Cohesion of soil | $C_u$ | KN/m$^2$ | 3.33 |
| Critical state friction angle | $\phi'_{cv}$ | Degree | 35 |
| Soil Young's modulus | $E_s$ | MPa | 115 |
| Elastic modulus of piles and raft | $E_r$ and $E_p$ | MPa | 2.1E5 |
| Soil Poisson's ratio | $\nu_s$ | - | 0.2 |
| Pile and raft Poisson's ratio | $\nu_r$ | - | 0.3 |

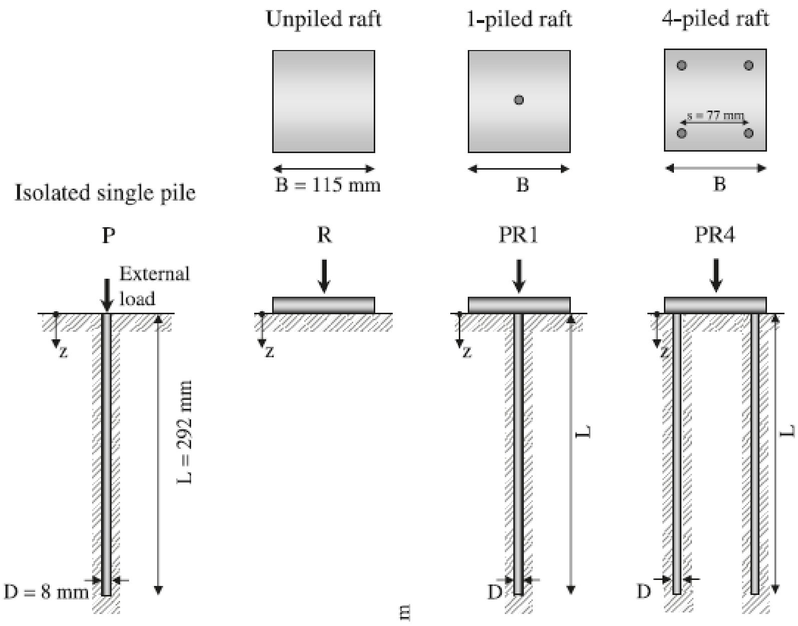


**Figure 4. Model schemes. P, isolated pile test; R, unpiled raft test; PR1, 1-contact piled raft test; PR4, 4-contact piled raft test [10]**

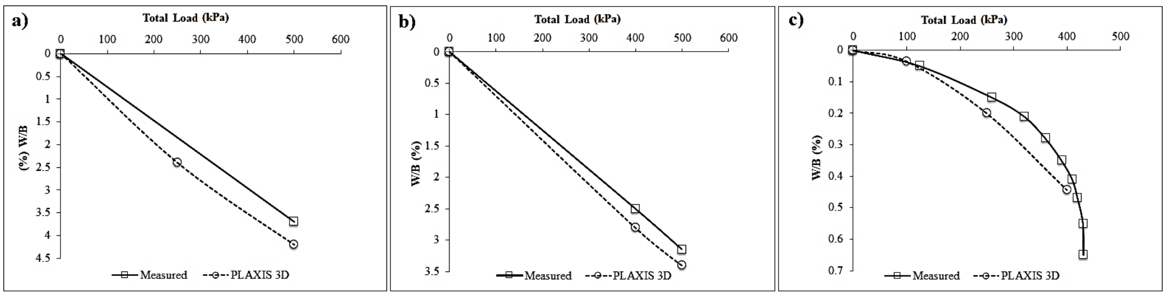


**Figure 5. Comparison between measured settlement of square piled-raft with the results predicted by PLAXIS 3D for a) unpiled raft, b) piled raft supported by one pile, c) piled raft supported by four piles**

## 4. Investigation of effective parameters on load sharing between raft and piles

The load sharing between raft and piles in CPRF, is affected by various factors such as length of piles, angle of internal friction of the soil, raft thickness, diameter of piles, space between piles and Soil and raft Young's modulus. In this study, the first three parameters are investigated. The distributed load 100 to 800 KPa is applied on the raft. The supposed raft has dimensions 3*3 $m^2$ and thickness 0.5 m and the level of the underground water is -40 m and the dimensions of the model are 20*20 $m^2$. The Mohr-Coulomb (MC) failure criterion is selected for soil and drained condition and boundary conditions equals to $u_x$=0, $u_z$=0, is supposed. The range of variations of parameters is shown in Table 2.

The distribution of normal force for one of the piles is demonstrated in Figure 6. The other piles have the same appearance.

A new parameter, named ρ is introduced here which is the ratio of the load carried by the piles to total load. In the equation (1), $N_i$ is axial load of pile, q is the superstructure load, $W_{raft}$ is the net weight of raft, Lr is the width of raft, np is the numbers of piles, $\Upsilon_p$ is the specific weight of pile, $A_p$ is the cross section of pile and $L_p$ is the length of pile.

$$\rho = \frac{\text{load carried by the piles}}{\text{total load}} = \frac{\sum_{i=1}^{n} N_i}{(q + W_{raft}){L_r}^2 + n_p \gamma_p A_p L_p}$$

**Table 2- The range of variations of the studied parameters**

| Parameter | Symbol | Unit | Variation range of parameters |
|---|---|---|---|
| Length of piles | L | m | 12,18, and 24 |
| Angle of internal friction of the soil | $\phi$ | Degree | 25, 30, 35, and 45 |
| raft thickness | t | m | 0.7, 1, 1.5, and 3 |

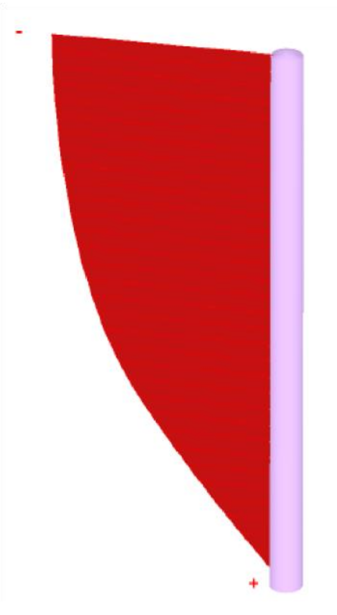


**Figure 6. Distribution of normal force in a pile**

### 4.1. The effect of pile length

The effect of the pile length on the load sharing relationship of piled-raft foundation supported by a single pile is shown in Figure 7. As seen in Figure, the change in length of piles has a significant effect on load sharing between raft and piles as well as it can be seen that increase of the total load leads to increase of the load shared to piles. The reason of that can be explained that the increase of pile length attributes to increase the stiffness of the pile group, which causes the contact pressure between the soil and the raft to reduce. In the length of 12 m, the gradient of increase is more than upper lengths. Other researchers reported a same observation regarding the effect of pile length on the load sharing. Rabiei (2009) studied the effective parameters in piled raft foundations and observed that the proportion of load carried by piles is increased by increasing the piles length [12].

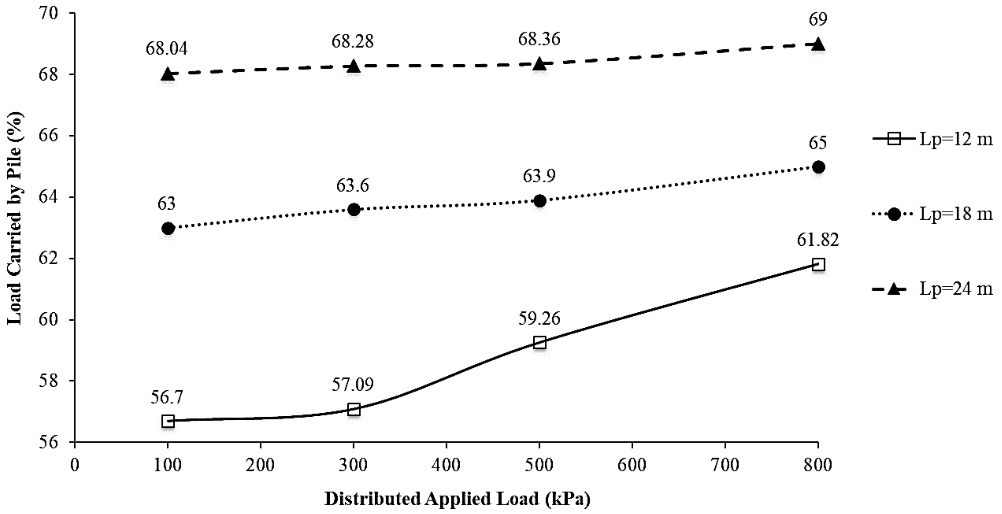


**Figure 7. Load carried by pile versus distributed applied load in various pile length for a CPRF supported by a single pile**

## 4.2. THE EFFECT OF SOIL'S ANGLE OF INTERNAL FRICTION

The effect of changing the angle of internal friction of the soil on the load sharing between the pile and raft studied and the results is shown in Figure 8. It can be seen that angle of internal friction of the soil has a negligible effect on load sharing between the pile and raft supported by single pile in the angles greater than 30° but in the angles smaller than 30° it has a significant effect. The reason of that can be explained that the shear strength of soil increases and the plastic zones emerge later. So it's concluded that the piled raft foundations will be efficient in the soils with the angle of internal friction smaller than 30° because it's load sharing feature. It seems that improving the soil strength under the raft using some soil improvement techniques such as compaction may enhance the contribution of the raft to the load carrying capacity in piled-raft foundations [6].

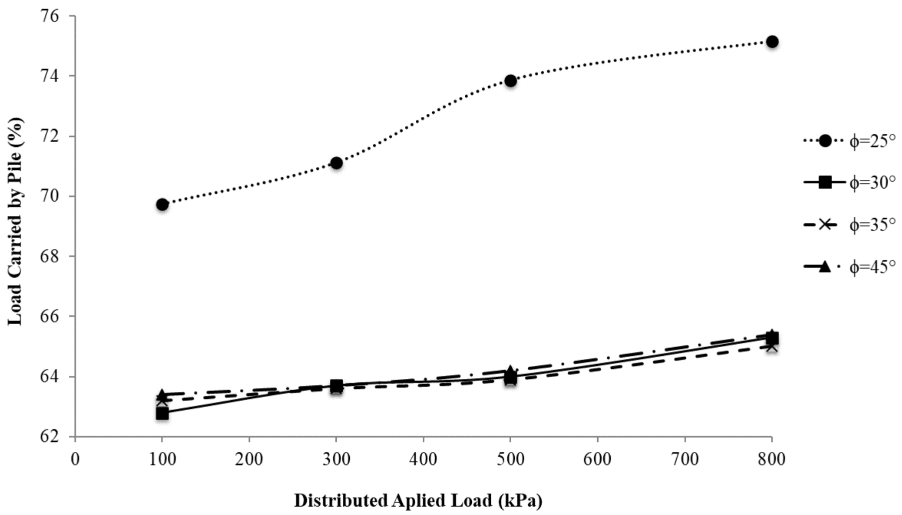


**Figure 8. Load carried by pile versus distributed applied load in the various angles of internal friction of the soil for a CPRF supported by a single pile**

## 4.3. THE EFFECT OF RAFT THICKNESS

Figure 9 shows the results from the parametric study of a piled raft foundation supported by one pile. The changing in raft thickness has a negligible effect on the load sharing between raft and pile. This result can be validated with other researcher's statement. Polous (2001) reported that raft thickness has a little effect on load sharing between raft and pile [13]. Oh et al. (2008) reported the raft thickness has negligible effect on load sharing between pile and raft [14]. It is worth mentioning that this conclusion is valid only for the range of thickness studied in this work. However, it should also be noted that increasing the raft thickness may be very beneficial in resisting the punching shear from both piles and column loadings [12].

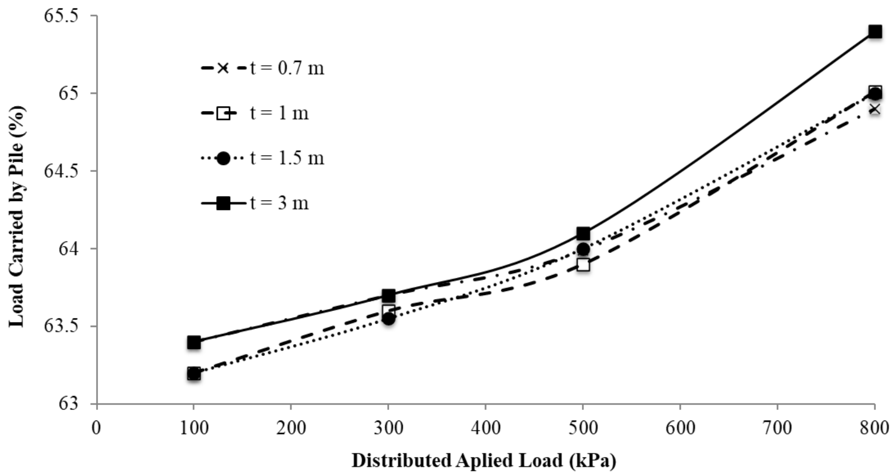


**Figure 9. Load carried by pile versus distributed applied load in the various raft thickness for a CPRF supported by a single pile**

## 5. CONCLUSION

In the past few decades, there has been a growing preference for using piled raft foundations, and their distinctive features have become well-recognized among engineers. This has led to extensive research efforts aimed at understanding the engineering behavior of these foundations through various methodologies. In the context of this research, a numerical model was created using the PLAXIS 3D FOUNDATION software, which is based on the finite element method. The model's accuracy was validated by comparing its predictions with the outcomes of a centrifuge experiment, revealing a reasonable correlation. The study scrutinized several critical factors that influence how the load is distributed between the raft and the piles in a system supported by a single pile. The findings indicated that certain factors, such as the length of the pile and the soil's internal friction angle when below 30 degrees, have a substantial impact on load distribution, whereas the thickness of the raft has a minimal effect. The study also concluded that piled-raft foundations tend to be more effective in sandy soils with internal friction angles under 30 degrees. The author suggests that future research should expand upon this work by examining the effects of concentrated loads or changes in the water table on the load-sharing dynamics between the raft and piles.

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