Chapter 5

Formulation of Predictive Models for Interaction Factors

5.1 Introduction

The strategic optimization of geometrical parameters in piled raft foundations ensures better settlement control and enhanced load-bearing capacity (Burland et al., 1977; de Sanctis et al., 2002). Piled rafts have garnered attention for their ability to provide sufficient safety, serviceability, and performance, resulting in significant reductions in expenses (Poulos, 2001b). In recent years, academics have shown a growing interest in piled rafts due to their distinctive load-sharing properties, with the objective of fully comprehending their behaviour and enabling greater utilization in the field.

The load distribution among the foundation components of a piled raft, namely the raft and piles, is determined by their interactions with each other and the underlying soil. These interactions give rise to a complex relationship within the piled raft foundation (Kumar and Choudhury, 2018). Since the piled raft distributes the upcoming load to underlying soil via the raft and the piles, its load-bearing capacity should be computed as the cumulative capacities of the standalone raft and the pile group. However, the interaction phenomenon introduces a notable variation in the response between these two scenarios. This emphasizes the importance of considering the interaction as a critical factor in analyzing the piled raft behaviour. Consequently, appropriate interaction factors are applied to multiply the summation of individual capacities (Park and Lee, 2015).

Several design approaches have evolved over the years for analysing piled raft foundations. As previously discussed, these approaches can be broadly classified into simplified (Butterfield and Banerjee, 1971; Davis and Poulos, 1972; Randolph, 1983; Burland, 1995), approximate (Poulos, 1991, 1994; Clancy and Randolph, 1993; Horikoshi and Randolph, 1998; Kim et al., 2001; Nguyen et al., 2013), and numerical (Hooper, 1973; Ottaviani, 1975; Sommer et al., 1985; Lee and Small, 1991; Poulos, 1993, 1994; Ta and Small, 1995, 1996; Russo, 1998; Katzenbach et al., 1998; Prakoso and Kulhawy, 2001; Chow, 2007; Oh et al., 2008; Basile, 2015; Luo et al., 2018; Chanda et al., 2020) methods. Experimental investigations are also conducted to gain insights into the load-settlement and load-sharing behaviour of piled rafts.

Increasing recognition has motivated researchers to examine the response of piled rafts under static as well as dynamic loading scenarios (Kumar et al., 2016; Sinha and Hanna, 2016; Samanta and Bhowmik, 2017). Evaluating the performance of piled raft foundations necessitates a thorough examination of soil-structure interaction, including numerous factors such as pile and raft stiffness, interface behaviour, soil nonlinearity, interactions among soil and foundation elements, etc.

Originally, the design entirely disregarded the contribution of the raft in bearing the imposed load (Burland et al., 1977). Subsequently, researchers also focused on design approaches considering the interaction effects (Reul and Randolph, 2004). The interaction between piles and the raft in a piled raft foundation occurs because the loads imposed on the foundation are shared and transferred between these foundation components. When a load is applied to the structure, stress and displacement fields overlap at the interface between the piles and the raft. This overlapping of stress and displacement fields results in a complex load-bearing mechanism (Park and Lee, 2015). This interaction is crucial for the foundation's overall performance, affecting its load-carrying capacity, settlement behaviour, and overall stability. Understanding this complex interaction is essential for designing and optimizing piled raft foundations to ensure their safe and efficient operation under various loading conditions.

Researchers have shown great interest in understanding the interactions between piled raft foundations throughout the past few decades (Poulos, 2001b; Lee and Chung, 2005). Katzenbach et al. (2000) analyzed the interaction effects in piled raft foundations through interaction factors and categorized them as the raft-pile interaction factor (α_{rp}), pile-raft interaction factor (α_{pr}), and pile-pile interaction factor (α_{pp}). Figure 5.1 illustrates a schematic representation of the interaction factors considered in the present study. Long (1993) proposed that the load-bearing capacity of piles within a piled raft is greater compared to that of pile groups, primarily because of the interaction effect between the raft and piles. Conversely, the downward soil movement induced by loading on the rafts can lead to a reduction in pile skin friction. This is attributed to the diminishing relative displacement between the piles and the surrounding soils (Han and Ye, 2006). Several studies have focused on evaluating interaction factors, primarily emphasizing the influence of geometrical properties and soil characteristics (Table 5.1). However, less attention has been given to performance-based design, which involves estimating interaction factors based on settlement. This approach can significantly aid in understanding the load-sharing behaviour in piled raft foundations.

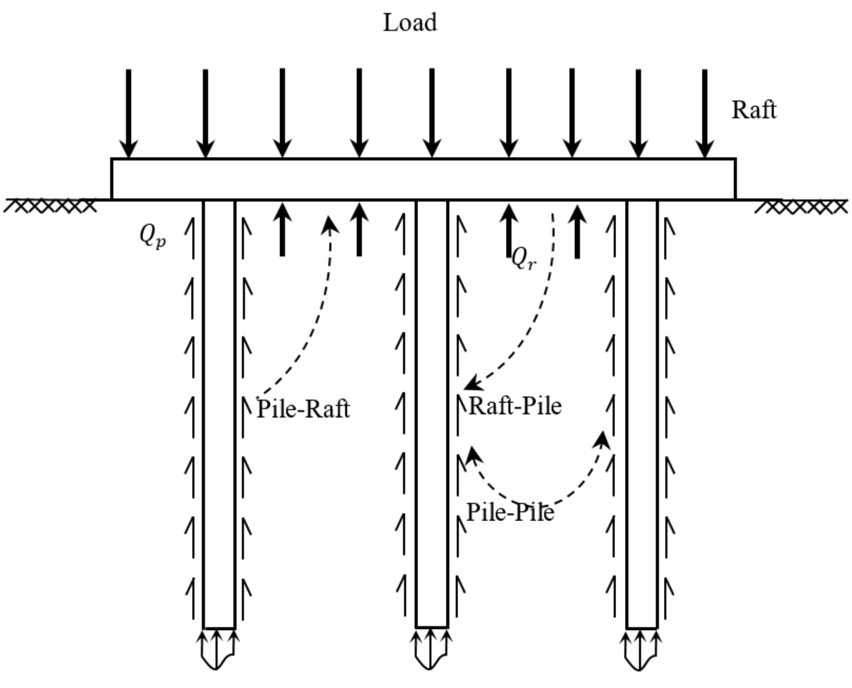


Figure 5.1: Schematic representation of the interactions within a piled-raft foundation

Table 5.1: Expressions for Interaction Factors

References	**Interaction**	**Expressions**
Randolph (1994)	Pile-Raft	$\alpha_{pr} = 1 - \frac{ln(r_r/r_p)}{ln(r_m/r_p)}$
Clancy and Randolph (1996)	Pile-Raft	$\alpha_{pr} = \frac{k_p}{P_p}\left(w_{pr} - \frac{P_r}{k_r}\right)$
de Sanctis and Mandolini (2006)	Pile-Raft	$\alpha_{pr} = 1 - 3\frac{(A_g/A)}{(S_p/B_p)}$
Nguyen et al. (2013)	Pile-Pile	$\alpha_{kj} = \frac{\Delta w_k}{w_{1j}Q_j}$
	Pile-Raft	$\beta = \frac{\Delta W}{n}$
Kumar and Choudhary (2018)	Pile-Raft	$\alpha_{pr} = 1 - e^{[-10.55(w/B_r)^{0.26}]}$
	Raft-Pile	$\alpha_{rp} = (\eta - \alpha_{pr})\frac{Q_{PG}}{Q_{UR}}$
Deb and Pal (2019)	Pile-Raft	$\beta_{pr} = 1.6(w/B_r)^{0.25}$
	Raft-Pile	$\beta_{rp} = \frac{1}{1-\alpha_{PR}} - \frac{\beta_{pr}}{(Q_{UR}/Q_{GP})}$

Recently, significant attention has been directed towards the design and analysis of piled raft foundations, primarily due to their effectiveness in distributing structural loads and addressing settlement issues. Since these foundations are crucial in supporting large and sophisticated structures, developing precise predictive models to optimize their performance becomes imperative. The main objective of this study is to create a predictive model for interaction factors, raft-pile interaction factor (α_{rp}), pile-raft interaction factor (α_{pr}), and pile-pile interaction factor (α_{pp}), enabling the determination of load sharing within piled raft foundations. The model is derived from 1g laboratory tests conducted on the raft, pile group, and piled raft, simultaneously supported on sand and clay. The proposed model offers practical applications and assists designers in comprehending the load-sharing mechanism, which is vital for ensuring the structural integrity and stability of piled raft foundations.

5.2 Interactions in Piled Raft Foundation

As previously mentioned, the load-bearing capacity of a piled raft is not merely the sum of the capacities of the isolated raft and pile group. Instead, it is determined by multiplying appropriate interaction factors with their respective individual capacities. Park and Lee (2015) expressed the load-bearing capacity (Q_{PR}) of the piled raft foundation, incorporating the interaction factors, as follows:

$$Q_{PR} = Q_R + Q_P = \alpha_{pr} Q_{UR} + \alpha_{rp} Q_{PG} = \alpha_{pr} Q_{UR} + \alpha_{rp}\alpha_{pp} \sum Q_{SP} \tag{5.1}$$

The load sustained by both the piles and the raft within a piled raft system is symbolized as Q_P and Q_R, correspondingly. Q signifies the load-carrying capacity, with the subscripts PR, UR, PG and SP denoting the piled raft, unpiled raft, pile group, and isolated single pile, respectively. α_{pp}, α_{rp} and α_{pr} signify the interaction factors between piles, between the raft and piles, and between piles and the raft, respectively.

The interaction factors have a significant role in determining the load-sharing mechanism of a piled raft system, thereby making it a complex phenomenon. Consequently, it is crucial to thoroughly evaluate these interaction factors and understand their impact on the load sharing between the piles and raft. Figure 5.2 illustrates the schematic diagram of the foundations selected for testing in the current investigation. It also displays the interactions among the components utilized in the study. Figures 5.2a and 5.2b illustrate an unpiled raft and a single pile subjected to vertical loading, where there is no possibility of interaction between the components as they are considered individual units. Conversely, figures 5.2d and 5.2c showcase a piled raft foundation and a pile group, respectively, along with the interactions among the foundation components. In a pile group, factor α_{pp} represents the interaction between the piles (pile-pile), commonly referred to as the pile group effect. For the piled raft, factors α_{pr} and α_{rp} signify the pile-raft and raft-pile interactions, respectively.

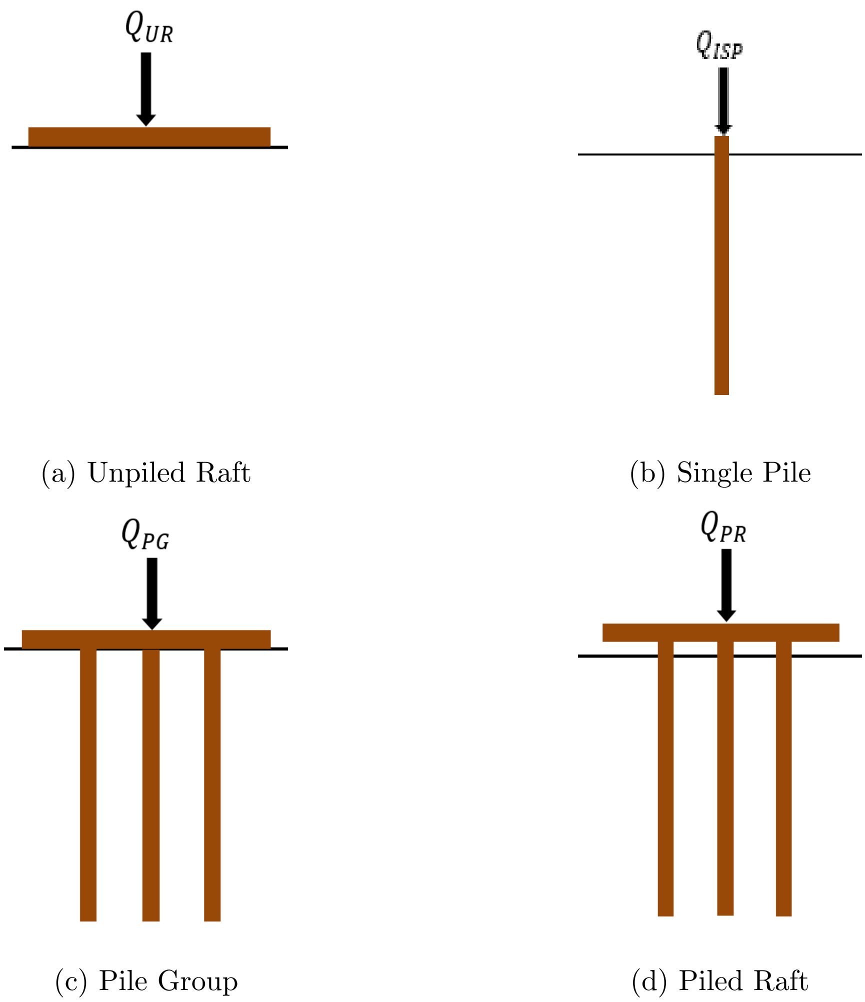


Figure 5.2: Schematic diagrams of foundations used in the experimental study

5.3 Overview of the Experimental Analysis

All experimental investigations were conducted in the preceding chapter, including parametric studies involving pile length and the number of piles. To achieve this, a spacious wooden container was constructed to house the soil, with dimensions carefully chosen to eliminate any boundary effects arising from the settlement of model piled rafts. Model piles were attached to model rafts to achieve various configurations. Subsequently, soil was uniformly placed inside the container to maintain consistent relative density. The model piled raft was then inserted into the soil using a hydraulic jack mechanism to apply the load. Displacement readings were recorded, and load-settlement curves were plotted.

The central emphasis of the present chapter lies in evaluating interaction factors inherent to the piled raft system. Three specific interaction factors—pile-pile interaction factor (α_{pp}), raft-pile interaction factor (α_{rp}), and pile-raft interaction factor (α_{pr}) are subjected to analysis. The subsequent section delves into examining these interaction factors within the contexts of sand and clay. These interaction factors are graphically depicted, and predictive models are subsequently derived based on these graphical representations. The regression analysis of the graphs pertaining to the piled raft reveals a strong correlation among the variables being examined, accompanied by a favourable coefficient of determination (R^2).

5.4 Assessment of Interaction Factors

5.4.1 Pile-Pile interaction factor (α_{pp})

The pile-pile interaction factor is crucial in analysing pile and piled raft foundations. It indicates interaction between individual piles within a pile group, measuring the influence of neighbouring piles on the behaviour of an individual pile in the group. In a pile group, the distribution of loads is not solely determined by the capacity of individual piles but is also influenced by the proximity and arrangement of neighbouring piles. When vertical loads are applied to the piled raft foundation, stress and displacement fields interact between adjacent piles, leading to load-sharing and group behaviour. This interaction may lead to variations in the load-carrying capacity of individual piles compared to their isolated capacities. This factor aids in expressing the load-bearing capacity of a pile group (Q_{PG}) in terms of the capacity of a single pile (Q_{SP}), as follows:

$$Q_{PG} = \alpha_{pp} \sum Q_{SP} \tag{5.2}$$

The value of the pile-pile interaction factor is influenced by several factors, including pile spacing, pile stiffness, pile group configuration, pile driving technique and soil properties (Long, 1993). Typically, in sands, the pile-pile interaction factor (α_{pp}) is greater than unity, signifying that the combined capacity of the pile group exceeds the sum of the individual capacities. This synergistic effect arises from the load-sharing and lateral support provided by neighbouring piles. However, it is worth noting that in the case of medium to dense sand, this factor is sometimes observed to be equal to unity (Poulos, 2000). In loose sands, it may be close to unity or even slightly greater than unity (Long, 1993).

In this particular experimental analysis, the interaction factor among piles is assessed by contrasting the load responses of a 3 × 3 pile group ($3 \times 3Q_{PG}$) with nine times that of a single pile ($9 \times Q_{SP}$) for both sand and clay conditions. Figure 5.3a demonstrates this comparison in the sand case, showing similar behaviour initially. However, as the load increases, the load-bearing capacity of the nine-times single pile surpasses that of the pile group. This higher load-bearing capability is even more evident in the clay case, as depicted in Figure 5.4a.

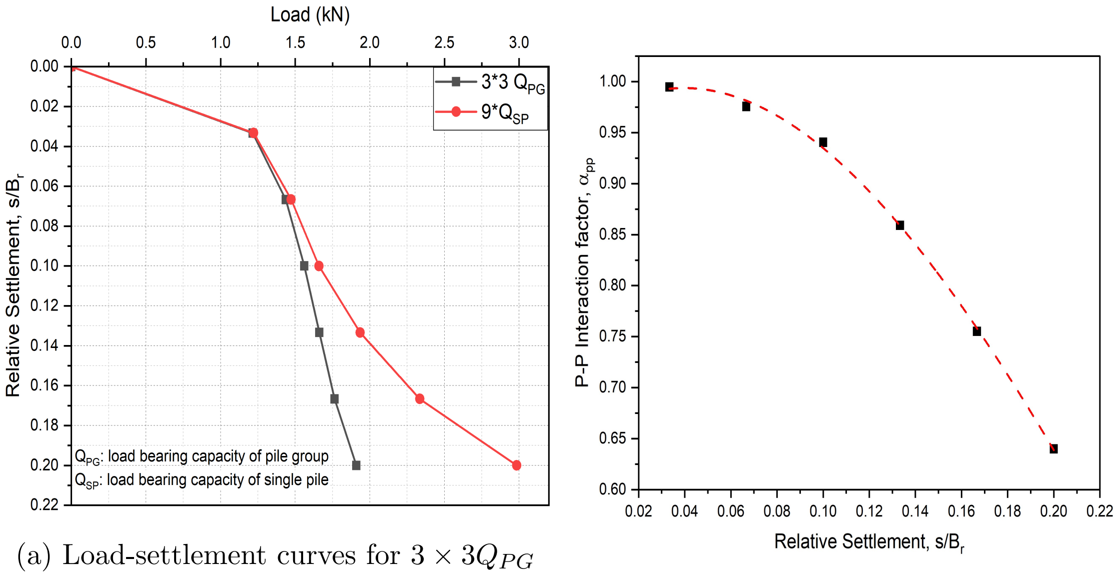
Equations 5.3 and 5.4 can be derived from analyzing the curve that best fits the data in the graphs. Long (1993) assumed $\alpha_{pp(sand)}$ to be 1 for sand, ensuring a conservative design. Figure 5.3b illustrates that the pile-pile interaction factor is consistently below 1.

$$\alpha_{pp(sand)} = 0.96458 + 1.5\left(\frac{w}{B_r}\right) - 20.39\left(\frac{w}{B_r}\right)^2 + 23.54\left(\frac{w}{B_r}\right)^3 \tag{5.3}$$

$$\alpha_{pp(clay)} = 0.738 - 1.789\left(\frac{w}{B_r}\right) + 10.615\left(\frac{w}{B_r}\right)^2 - 22.552\left(\frac{w}{B_r}\right)^3 \tag{5.4}$$

The trend depicted in Figure 5.3b and 5.4b illustrate that the (α_{pp}) value exhibits a declining pattern as the raft settlement increases. In the case of sand, the (α_{pp}) value starts near unity and gradually decreases to 0.65 at a settlement of 0.20. Conversely, for clay, the (α_{pp}) value experiences a relatively minor shift from 0.69 to 0.62 as the settlement changes. These variations in (α_{pp}) values linked to settlement alterations provide valuable insights into comprehending the impact of pile group behaviour under increasing load conditions.

With impressive R^2 values of 0.997 and 0.9984, the regression model effectively captures more than 99% of the variability present in the data points. This high R^2 value indicates a strong level of fit between the model and the actual data, suggesting that the derived regression equation is a reliable representation of the observed trends in the piled raft behaviour.



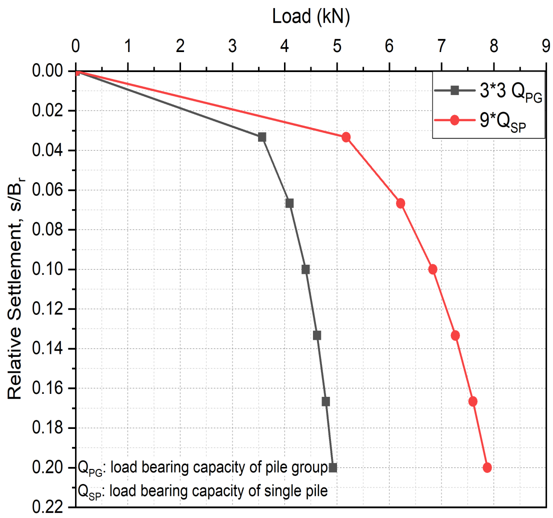
(a) Load-settlement curves for $3 \times 3Q_{PG}$ and $9Q_{SP}$

(b) Pile-Pile interaction factor in sand

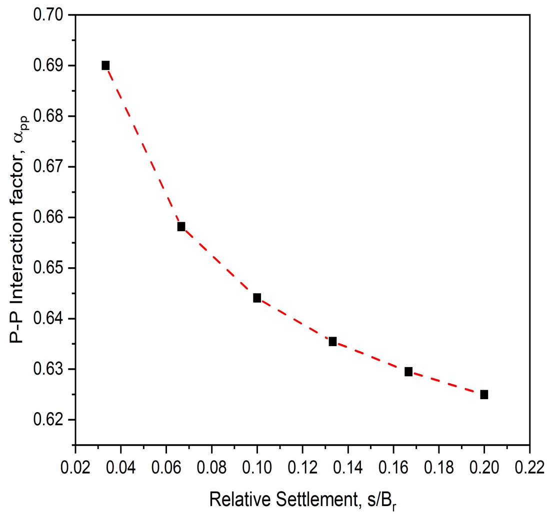
Figure 5.3: Development of pile-pile interaction factor in sand

5.4.2 Pile-Raft interaction factor (α_{pr})

The pile-raft interaction characterizes the variation in the load-bearing capacity of the raft resulting from the incorporation of piles under it. The piles slowly mobilise their skin friction as the subsidence occurs in the nearby soil. This results in a decrease in the confining pressure between the raft and the supporting soil, thereby reducing the load-bearing capacity of the raft. Hence, the load-bearing capacity of raft (Q_R) in terms of pile-raft interaction factor can be represented as follows:



(a) Load-settlement curves for $3 \times 3Q_{PG}$ and $9Q_{SP}$



(b) Pile-Pile interaction factor in clay

Figure 5.4: Development of pile-pile interaction factor in clay

$$Q_R = \alpha_{pr} Q_{UR} \tag{5.5}$$

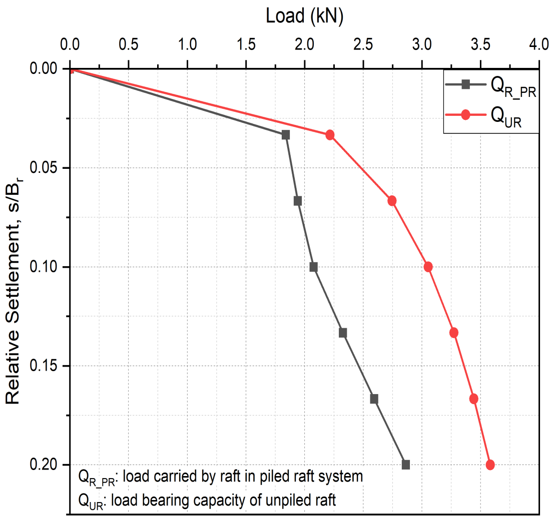
To assess the pile-raft interaction factor, the load-settlement behaviour of the unpiled raft (UR) configuration is contrasted with those of the 3×3 piled raft (Q_{R_PR}) configuration. The load-displacement graphs for UR and Q_{R_PR} are presented in figures 5.5a and 5.6a. Throughout the settlement range investigated during the model experiments, the load-carrying capacity of (Q_{R_PR}) is considered inferior to that of UR when dealing with sand. Conversely, the situation is reversed in the case of clay examined in the current study.

Equations 5.6 and 5.7 present the formulations for α_{pr}, accompanied by R^2 values of 0.994 and 0.9994, respectively, for sand and clay scenarios. In the context of sand, the α_{pr} value declines to 0.68 when relative settlement reaches 0.10, then it rises. This initial decline can be attributed to the mobilization of pile capacity, which in turn reduces the pressure within the contact zone between the raft and the soil near the piles. As the pile load capacity becomes fully mobilised, the raft component begins to share the load, causing a subsequent increase in the α_{pr} value as settlement advances.

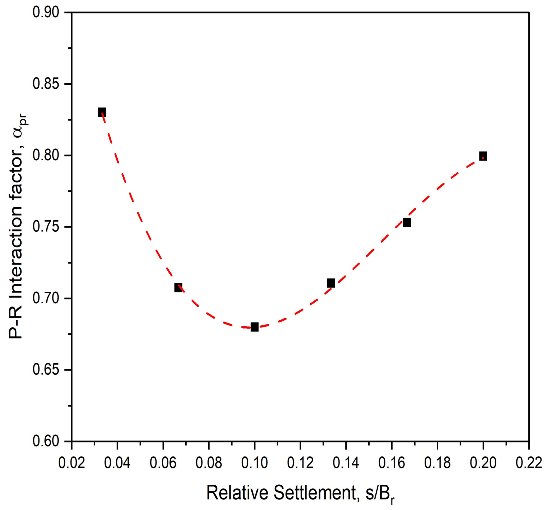
For clay, the initial trend involves reducing the pile-raft coefficient (α_{pr}) to 1.05 due to the mobilisation of piles. Following this, it rises to 1.30 because of the clay's confinement between the piles, leading to a more significant contribution from the raft. Finally, the clay adjacent to the raft demonstrates a cohesive behaviour until a specific threshold is achieved, prompting its subsequent decrease.

$$\alpha_{pr(sand)} = 1.07195 - 9.4524\left(\frac{w}{B_r}\right) + 70.19\left(\frac{w}{B_r}\right)^2 - 148.89\left(\frac{w}{B_r}\right)^3 \tag{5.6}$$

$$\alpha_{pr(clay)} = 2.09 - 43.23\left(\frac{w}{B_r}\right) + 592.91\left(\frac{w}{B_r}\right)^2 - 3030.6\left(\frac{w}{B_r}\right)^3 \tag{5.7}$$



(a) Load-settlement curves for Q_{R_PR} and Q_{UR}



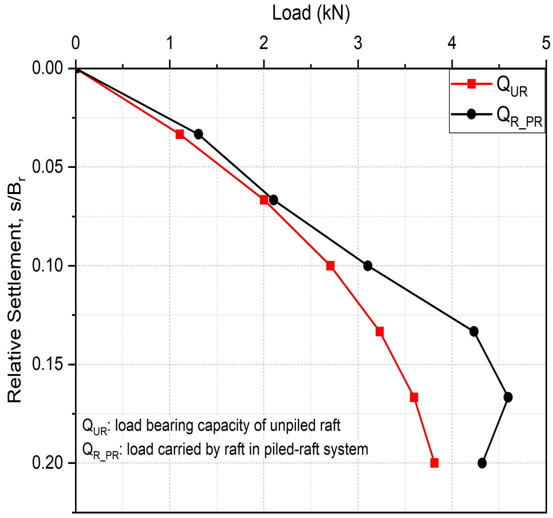
(b) Pile-Raft interaction factor in sand

Figure 5.5: Development of pile-raft interaction factor in sand

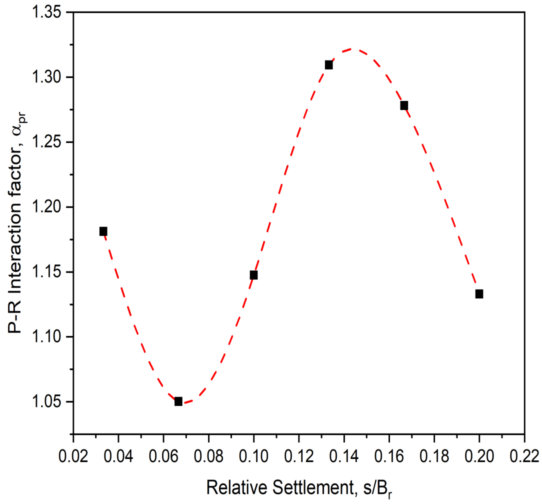
5.4.3 Raft-Pile interaction factor (α_{rp})

The raft-pile interaction factor is another parameter that represents any modification in the load-bearing capacity of pile groups due to the involvement of the raft. Hence, the bearing capacity of piles Q_P in terms of this factor can be written as:

$$Q_P = \alpha_{rp} Q_{PG} \tag{5.8}$$



(a) Load-settlement curves for Q_{R_PR} and Q_{UR}



(b) Pile-Raft interaction factor in clay

Figure 5.6: Development of pile-raft interaction factor in clay

An interesting aspect of this interaction is its ability to influence the load-bearing capacity of piles in both positive and negative manners (Katzenbach et al., 2000). The positive effect is associated with the increased pile skin friction resulting from the accumulation of confining stress beneath the raft (Long, 1993). The extent of this buildup depends on the position of the piles beneath the raft and the magnitude of the applied stress. In contrast, the raft-pile interaction factor also negatively impacts the reduced mobilization of pile skin friction resulting from the downward displacement of the underlying soils upon loading (Han and Ye, 2006).

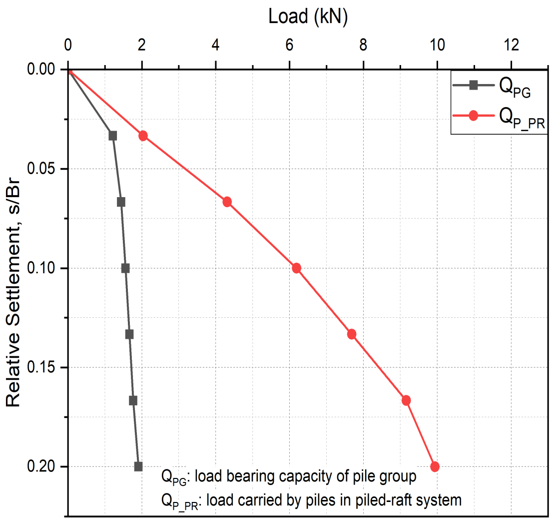
To assess the raft-pile interaction factor, the load-settlement curves of the 3×3 pile group (PG) and the individual piles within the 3×3 piled raft (Q_{P_PR}) are utilized. Figures 5.7a and 5.8a illustrate and compare the load behaviors of PG and (Q_{P_PR}). It is evident that (Q_{P_PR}) exhibits a greater load-bearing capacity than $3 \times 3PG$ for all levels of settlement in the case of sand. However, the opposite is observed when dealing with clay.

Figures 5.7 and 5.8 illustrate the pattern of the raft-pile interaction factor (α_{rp}) in sand and clay, respectively. In the context of sand, a noticeable beneficial influence is apparent, signifying an increased pile capacity primarily attributed to enhanced shaft resistance. The α_{rp} value consistently surpasses unity, experiencing a rise from 1.5 to above. Similarly, a favourable impact becomes evident for clay after the initial soil rearrangement. However, the α_{rp} value increases from 0.2 to 0.9 under the applied load while staying below unity.

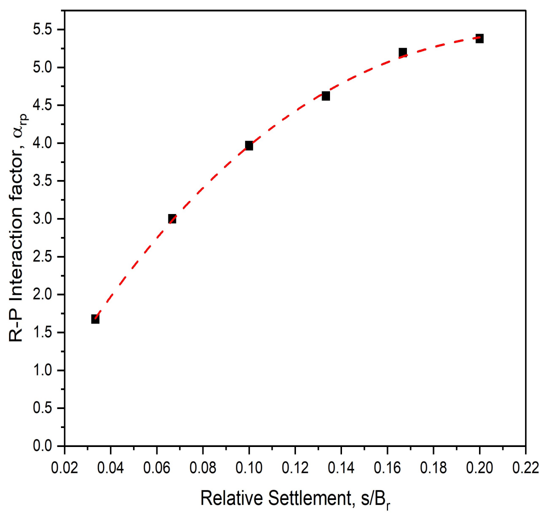
The expressions for α_{rp} are depicted through best-fitted curves in equations 5.9 and 5.10 for sand and clay. The equations for sand and clay exhibit a high R^2 value of 0.998 and 0.9986, respectively.

$$\alpha_{rp(sand)} = 1.07195 - 9.4524\left(\frac{w}{B_r}\right) + 70.19\left(\frac{w}{B_r}\right)^2 - 148.89\left(\frac{w}{B_r}\right)^3 \tag{5.9}$$

$$\alpha_{rp(clay)} = -0.04843 + 9.4021\left(\frac{w}{B_r}\right) - 86.234\left(\frac{w}{B_r}\right)^2 + 318.603\left(\frac{w}{B_r}\right)^3 \tag{5.10}$$

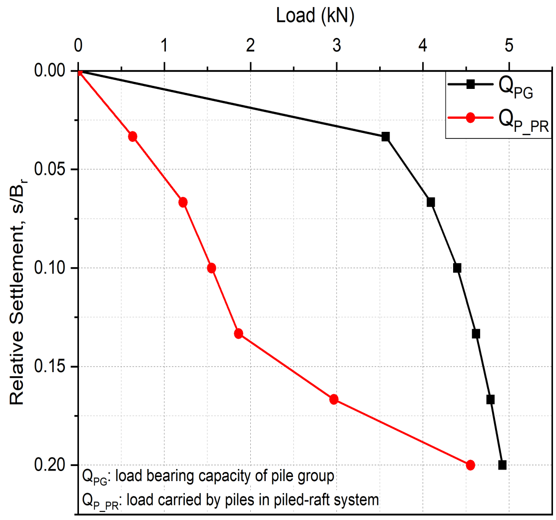


(a) Load-settlement curves for Q_{PG} and Q_{P_PR}

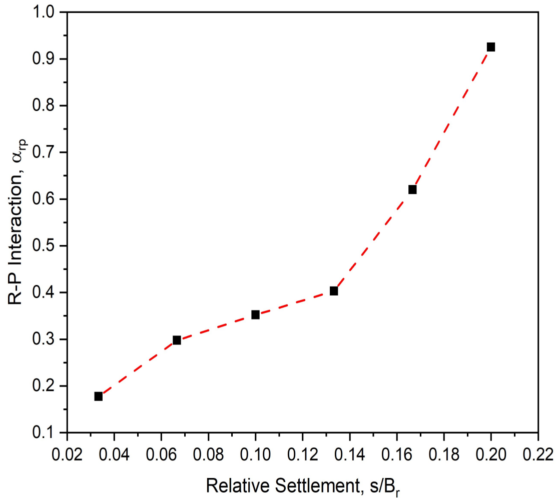


(b) Raft-Pile interaction factor in sand

Figure 5.7: Development of raft-pile interaction factor in sand



(a) Load-settlement curves for Q_{PG} and Q_{P_PR}



(b) Raft-Pile interaction factor in clay

Figure 5.8: Development of raft-pile interaction factor in clay

5.5 Summary

This chapter utilizes the outcomes of the experimental investigation discussed in the preceding chapter to evaluate various interaction factors. Predictive models based on settlement are formulated by the curve fitting method to represent pile-pile, pile-raft, and raft-pile interaction factors, leveraging the insights from the experimental findings. Drawing upon the findings of this study, the following conclusions can be deduced:

- The variation in load-settlement capacities between an unpiled raft and individual piles, compared to their performance within a combined piled raft system, is attributed to the presence of reciprocal interactions between the raft and piles that intensify as settlement increases.

- The (α_{pp}) value follows a descending trend with increasing raft settlement, as observed in Figure 5.3b and 5.4b. In sand, it starts close to unity and gradually decreases to 0.65 at a settlement of 0.20. In contrast, for clay, the (α_{pp}) value undergoes a relatively minor change from 0.69 to 0.62 with varying settlement. These variations in (α_{pp}) values, tied to settlement adjustments, offer crucial insights into understanding how to pile group behaviour responds under increasing load conditions.

- In sand, the α_{pr} value initially declines to 0.68 at a relative settlement of 0.10, attributed to pile capacity mobilization and reduced pressure in the raft-soil contact zone near piles. As pile load capacity fully engages, the raft assumes more load, causing the α_{pr} value to rise. For clay, the coefficient drops to 1.05 due to pile mobilization, then increases to 1.30 due to clay confinement between piles, leading to a greater raft contribution. Ultimately, the clay near the raft exhibits cohesive behaviour up to a threshold, resulting in a subsequent decrease in the α_{pr} value.

- In sand, a clear positive effect indicates heightened pile capacity due to improved shaft resistance. The α_{rp} value remains consistently above unity, rising from 1.5 and beyond. Similarly, a beneficial impact is observed in clay after initial soil reorganization, but the α_{rp} value increases from 0.2 to 0.9 under the applied load, remaining below unity.

- The development of predictive models for pile-pile, pile-raft, and raft-pile interaction factors might contribute significantly to our understanding of complex piled-raft foundation behaviours. These models offer a comprehensive framework to analyze the interplay between different foundation elements and their influence on overall structural performance.

- The proposed predictive models empower structural engineers with a valuable toolset for optimizing foundation system design. By accurately estimating interaction factors, designers can make informed decisions that enhance efficiency and cost-effectiveness, ensuring structural safety while minimizing overdesign.

- While the current study presents robust predictive models for foundation interaction factors, there remains scope for further research. Investigating the applicability of these models to dynamic loading conditions, considering longterm behaviour, and exploring their integration with advanced computational tools are potential areas for future exploration.

In conclusion, developing predictive models for pile-pile, pile-raft, and raft-pile interaction factors represents a significant advancement in understanding piled raft foundation behaviour. These models empower researchers and engineers with the means to optimize designs, reduce uncertainties, and explore innovative solutions while contributing to the overall sustainability and resilience of built structures.