PARAMETERS INFLUENCING LOAD DISTRIBUTION DYNAMICS IN PILED RAFT FOUNDATIONS

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Abstract

In regions with complex soil conditions, the piled raft foundation is vital for tall structures. This design mitigates settlement issues and strengthens the foundation. The challenge lies in understanding the load interaction between the raft, piles, and soil. Our study uses a numerical method to study these piled raft systems, focusing on parameters like pile count, diameter, spacing, and slenderness in sandy clay soil. Our findings, showcased via 2D contours, enhance understanding of load-sharing mechanics.

Keywords

Piled raft foundations, numerical modelling, load distribution

1 INTRODUCTION

In regions characterized by challenging geotechnical terrains and soils with diminished bearing capacities, the significance of raft foundations becomes paramount. These foundations are designed not only to support and distribute the structural loads but also to ensure the structural equilibrium is unaffected by the underlying soil complexities. As soils often present varied and intricate mechanical attributes, sometimes showing inconsistent load-bearing characteristics across depths, it becomes imperative to strategize the foundation design. A widely accepted and proven strategy in such scenarios involves the integration of raft foundations with pile groups. This hybrid approach ensures that loads are judiciously distributed across both shallow strata, where the raft is more effective, and deeper soil layers, which are accessed by the pile groups. This dual-level distribution can be visualized in Fig. 1.

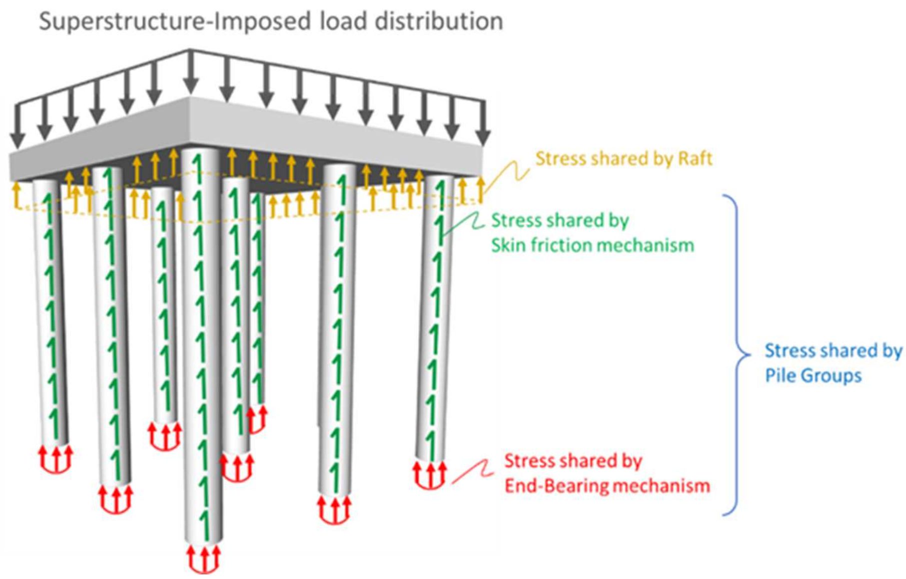

Fig. 1 The scheme of the load distribution mechanism in the piled raft system.The study of such piled raft systems is an expansive domain, with a myriad of methodologies introduced over the years. A consolidated review of these methods has been notably presented by Poulos et al. [1], [2]. A brief categorization of these methodologies includes simplified and numerical methods.

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Simplified Calculations: These are basic methods that often involve elementary modelling of soil profiles and loading conditions on the raft. Davis, Poulos [3], Randolph [4], and Burland [5] are some of the pioneers of these techniques, providing foundational frameworks for this category.

Approximate Numerical Techniques:

a) The "Strip on spring" model, as proposed by Poulos [6], interprets the raft as segmented strip footings, and piles as springs.

b) Alternatively, the "Plate on spring" methodology (e.g., Viggiani [7]) envisions the raft as a plate, with piles acting as supportive springs.

Comprehensive Numerical Methods:

a) The Boundary element technique applies elasticity theory, considering both the pile and the raft in unique ways, exemplified by the Kuwabara method [8].

b) Finite element strategies often involve plane strain or axisymmetric considerations. They are complemented by analytical tools like the FLAC-2D program (e.g., Desai [9], Hooper [10], Gue & Hewitt [11]).

c) Advanced 3D finite element and finite difference analyses have been championed by researchers like Zhuang et al. [12] and through tools like the FLAC-3D program.

d) Some pioneering works have combined both boundary and finite element methods to craft unique models, such as those proposed by Russo and Viggiani [13].

Historical and recent research has offered a spectrum of estimates on the load capacity of rafts, suggesting they can bear between 20% to 60% of the overarching structural loads [14], [15], [16]. This research paper delves deep into the influence of pivotal parameters, like the number of piles, their arrangement, diameters, and lengths, on the load distribution within a consistent sandy clay soil environment. Utilizing the capabilities of PLAXIS 3D software, we ran simulations, ensuring their accuracy by juxtaposing our findings with the acclaimed Poulos-Davis-Randolph (PDR) design methodology, as documented by Raut et al. [17]. The culmination of this research is represented in a detailed contour graph, emphasizing the relationship between load distribution in piled raft foundations, the ratio of pile area to raft surface area, and the pile's aspect ratio, or slenderness.

Material

In the geotechnical realm, understanding the intricacies of soil characteristics, coupled with the mechanical properties of construction materials, plays a pivotal role in ensuring structural integrity. In our analysis, we rigorously adhered to the geotechnical parameters and material properties delineated in the seminal study by Raut et al. [17]. The geological stratigraphy under consideration showcases a uniform layer of sandy clay soil. Crucially, the groundwater table is positioned at the ground surface level, thereby ensuring that the entire soil stratum is saturated. This condition is vital as it can significantly influence the behaviour of the foundation system.

Turning our attention to the material modelling, the Mohr-Coulomb (MC) criterion was the chosen approach. This model was adopted for its capability to aptly represent the mechanical responses of soils under various stress conditions, and the specifics of this model, as applied to our study, are detailed in Tab. 1. Concurrently, for the construction of the raft and piles, we operated under the assumption of utilizing C30 grade concrete.

Tab. 1 The properties of sandy clay soil.

Characteristic	Unit (SI)	Value
Moist unit weight	kN / m^3	18.5
Saturated unit weight	kN / m^3	19.5
Cohesion	kPa	50
Angle of Internal Friction	(°)	20
Elastic Modulus	MPa	7
Poisson's Ratio	-	0.3

Tab. 2 The properties of concrete (C30 grade).

Characteristic	Unit (SI)	Value
Unit weight	kN / m^3	25
f_{ck}	MPa	30
f_{ctm}	MPa	2.9
Elastic Modulus	GPa	32.8
Poisson's Ratio	-	0.2

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This grade of concrete is renowned for its balanced strength and durability attributes, making it a preferred choice for foundation systems. The specific properties and characteristics of this concrete grade, as relevant to our study, are elaborated upon in Tab. 2.

2 METHODOLOGY

Analytical PDR Method

In the complex domain of geotechnical engineering, understanding the intricacies of piled raft systems is of paramount importance. Among the well-regarded methods in this area stands the PDR method, which methodically estimates the load-bearing contribution of both the piles and the raft utilizing stiffness elements as its foundation. Through this analytical framework, an expression for the collective stiffness of the piled raft system is derived, as presented in equation (1):

$$K_{pr} = \frac{K_p + K_r \times (1 - \alpha_{cp})}{1 - {\alpha_{cp}}^2 \times \frac{K_r}{K_p}} \tag{1}$$

where K_{pr} embodies the integrated stiffness of the pile-raft synergy, K_p and K_r depict the stiffnesses of the pile group and the individual raft respectively, and α_{cp} is a key coefficient capturing the interaction between the pile and the raft. Delving deeper into the mechanics, the stiffness of a singular pile can be ascertained through classical elasticity theories. Notable contributions in this area include methodologies championed by luminaries such as Wardle and Fraser [18] and Poulos and Mayne [19].

For the collective stiffness of the pile group, a theoretical elasticity framework proves instrumental, with references to pioneering works by Davis and Poulos [4], Fleming et al. [20], and Poulos [10]. It is noteworthy that contemporary approaches often resort to the theory of elasticity to deduce the stiffness of individual piles, which is subsequently adjusted via coefficients that encapsulate the influence of the pile group. The intricate relationship between the load shouldered by the raft (P_r) and the entire imposed load (P_t) can be articulated through equation (2):

$$\frac{P_r}{P_t} = \frac{K_r \times (1 - \alpha_{cp})}{K_p + K_r \times (1 - \alpha_{cp})} = X \tag{2}$$

where, X encapsulates the fraction of the load born by the raft in relation to the overall applied force. This proportional distribution hinges on the interaction coefficient α_{cp}, which can be further distilled using equation (3):

$$\alpha_{cp} = 1 - \frac{\ln(\frac{r_c}{r_0})}{\zeta} \tag{3}$$

where r_c denotes the mean radius that encapsulates the influence of a pile, which aligns with the per-pile raft area. r_0 stands as the pile's radius, while ζ can be extracted from equation (4):

$$\zeta = \ln(\frac{r_m}{r_0}) \tag{4}$$

where r_m can be extracted from equation (5):

$$r_m = \{0.25 + \xi \times [2.5 \times \rho \times (1 - \upsilon) - 0.25\} \times L \tag{5}$$

In this equation, L symbolizes the pile's length (m), and ρ captures the soil's Poisson's ratio and ξ is a coefficient that can be derived from equation (6) and (7):

$$\rho = \frac{E_{sav}}{E_{sl}} \tag{6}$$

$$\xi = \frac{E_{sl}}{E_{sb}} \tag{7}$$

These relationships pivot around the elastic moduli: E_{sl} (soil's modulus along the pile axis), E_{sb} (soil modulus beneath the pile tip), and E_{sav} (average modulus along the pile) [2].

Raut et al. [17], utilized this analytical approach to explore how the dimensions of the components in a piled raft system influence the load-sharing ratio.

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FEM Method

In the realm of geotechnical research, high-precision numerical analysis is a critical component for obtaining reliable results.

The model for the process of validation

In the system under study, the piled raft foundation (PRF) system being examined features a rectangular raft foundation. The dimensions of this foundation are precisely 18 meters in length, 8 meters in width, and it boasts a substantial thickness of 0.5 meters. Complementing this raft foundation is a symmetrically organized set of 16 piles. Each pile within this ensemble reaches a depth of 12 meters and is characterized by a diameter of 0.6 meters.

For the purpose of executing a rigorous and in-depth numerical analysis, the study employed the cutting-edge PLAXIS 3D software. Within this framework, mesh discretization was implemented using 15-node elements to ensure precise representation of the structural and geotechnical elements. In an effort to accurately emulate the stratification of the geological layers, a singular borehole was strategically defined. Moreover, the groundwater level was meticulously positioned at the ground surface level to reflect realistic environmental conditions.

The modelling process gave special attention to the complexities of soil-structure interaction. This included detailed analysis of the interaction between the pile sleeve and the surrounding soil matrix, the interface of the pile tip with the underlying soil, and the nuanced subsurface interaction of the raft with its adjacent soil layers. To facilitate this level of detail, both the piles and the raft elements were classified as distinct volume clusters within the simulation.

A pivotal aspect of this study is the emphasis on the interaction between the soil matrix and the concrete structural components. These interactions were meticulously defined by incorporating interface surface elements. A strength reduction factor of 0.67 was applied in accordance with the established reference guidelines delineated by PLAXIS [21]. This approach ensured a coherent and precise simulation, thereby contributing to the reliability and applicability of the study's findings.

The models for parametric study

In our pursuit to unravel the intricate interplay of pile characteristics on load distribution, the foundation of the raft underwent a calculated modification, settling into a perfect square with an expanse of 18 meters on each side. This study probed into a diverse array of pile configurations, encompassing groups consisting of 4, 9, 25, and an expansive 36 piles. It is imperative to note that for every configuration, meticulous adjustments were made to ensure consistent spacing, manifesting a symmetrical and uniform pile arrangement. Pile diameters, in this study, oscillated between a modest 0.5 meters and an extensive 1.2 meters. However, the pile length was held constant across the board at 12 meters. In Tab. 3, the outlined options are presented in conjunction with their corresponding model numbers.

Emulating parameters from the previous Finite Element Method (FEM) model, we imposed a concentrated load of 22,000 kN, which was subsequently transformed into a surface load exhibiting an intensity of 69.7 kN/m^2. Maintaining a controlled experimental environment, the soil conditions remained unaltered, retaining the characteristics of sandy clay throughout the analytical procedures. During the analysis, configurations not aligning with the stringent spacing criterion - stipulating the inter-pile distance to be at least twice the pile's diameter – were diligently identified and excluded from the final analysis. The culmination of this rigorous methodology resulted in the generation of 59 distinct and carefully calibrated numerical models.

Tab. 3 The properties of concrete (C30 grade).

N. Models	***D***	***L/r* ratio**	***N***	***S***	A_p	A_p / A_r (%)	**Raft Load share**	**Pile Group Load share**	**Load share (Pile/Raft) [%]**
1	0.50	24.00	4	5.67	2.46	0.76%	96%	4%	0.04
2	0.55	21.82		5.63	2.98	0.92%	89%	11%	0.13

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⋮	⋮	⋮		⋮	⋮	⋮	⋮	⋮	⋮
14	1.15	10.43		5.23	13.04	4.02%	4.02%	48%	52%
15	1.20	10.00		5.20	14.20	4.38%	4.38%	47%	53%
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
55	0.50	24.00		2.58	0.62	6.85%	23%	77%	3.37
56	0.55	21.82		2.10	0.75	8.28%	13%	87%	6.51
57	0.60	20.00	36	2.06	0.89	9.86%	11%	89%	8.48
58	0.65	18.46		2.01	1.04	11.57%	8%	92%	11.18
59	0.70	17.14		1.97	1.21	13.42%	6%	94%	15.12

3 RESULTS

Results of the validation procedure

Fig. 2 illustrates the complex deformation behaviour of the piled raft foundation. Fig. 3 represents the numerical simulation conducted using PLAXIS 3D.

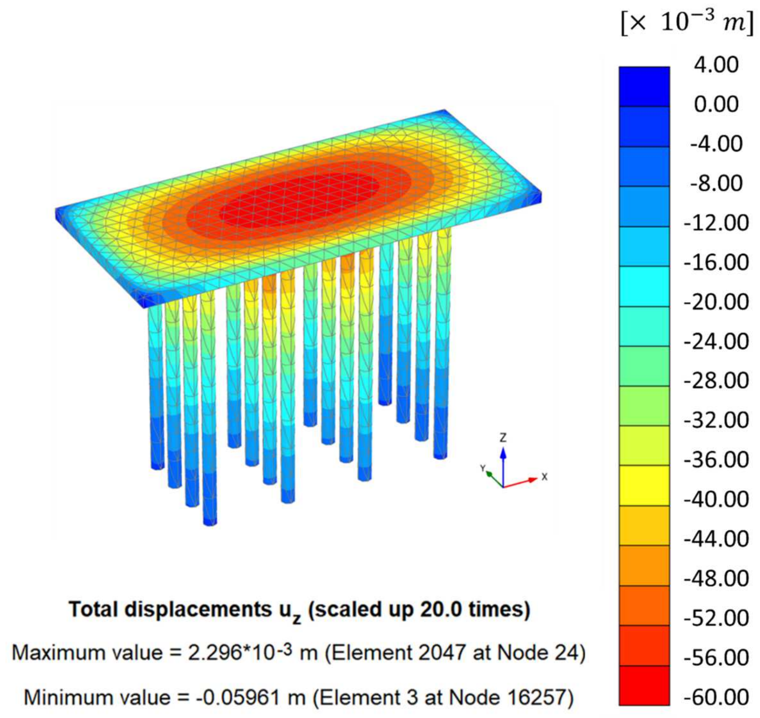

Fig. 2 The settlement contour within the piled raft system.

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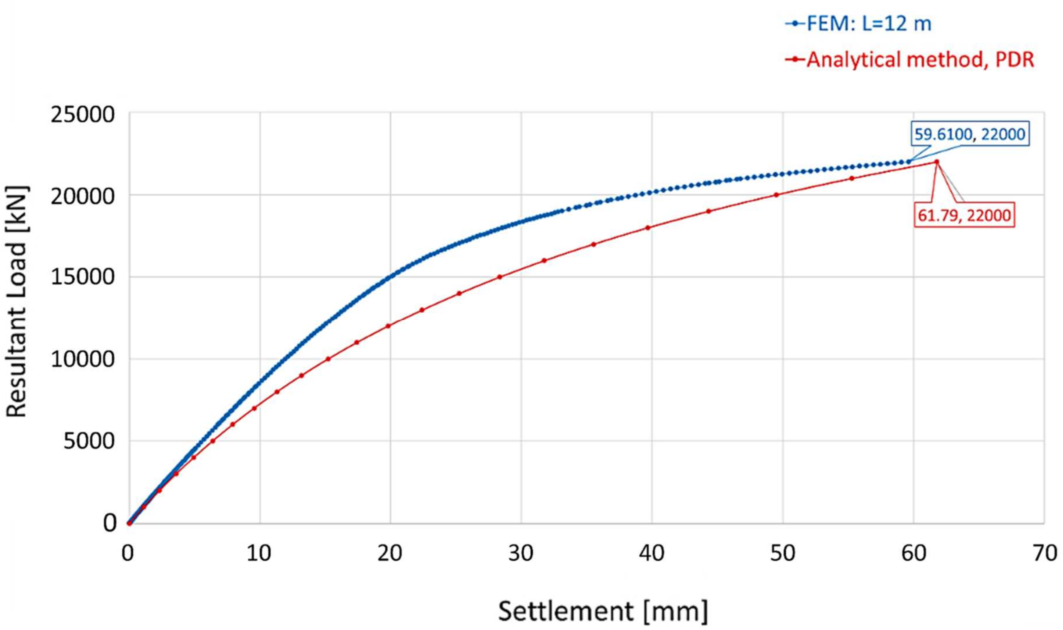

Fig. 3 The load-Settlement curve for the piled raft foundation derived from both analytical (PDR) and numerical methods.

Fig. 4 and Fig. 5 showcase the contact stress at the base of the raft and the top of the pile, respectively, for Model No. 24.

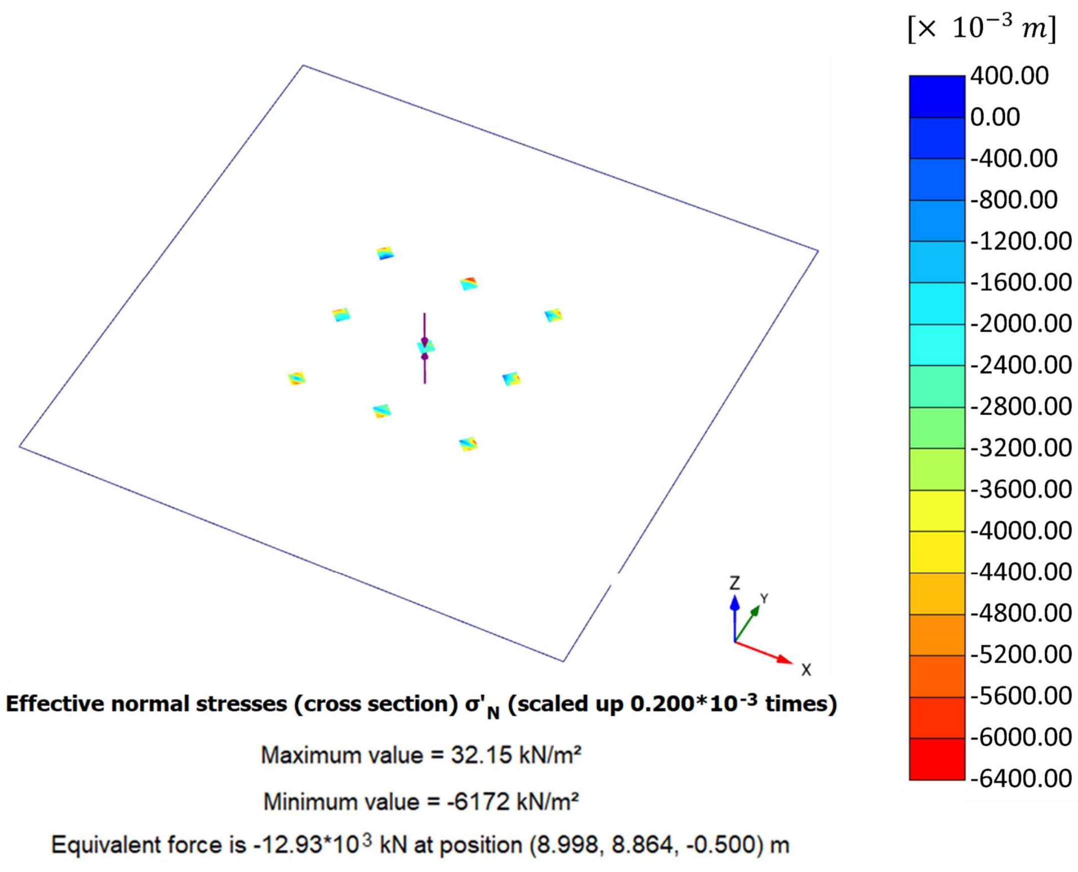

Fig. 4 The contour of load distribution in the raft.

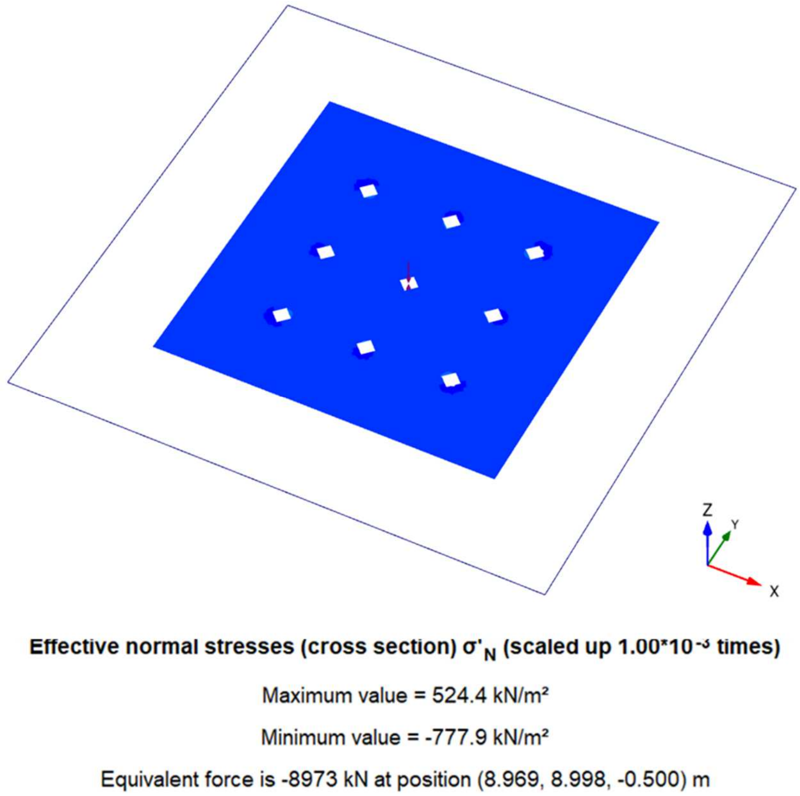

Fig. 5 The contour of load distribution in the pile group.

4 DISCUSSION

Results presented in Fig. 2, with details of both the spread and magnitude of settlement, and in Fig. 3, further validate our analysis. This simulation highlights that the load-bearing capacity of the piled raft system is consistent with the renowned Poulos-Davis-Randolph (PDR) method, achieving an impressive ultimate load of 22,000 kN and a total deformation of 59.61 mm. Yet, when comparing the two methods, subtle differences in system stiffness emerge. The PDR method, rooted in elasticity principles, tends to yield a slightly lower stiffness value. In contrast, the numerical approach, based on the elastic-perfectly plastic concept of the Mohr-Coulomb theory, indicates a higher system stiffness. Illustrations in Fig. 4 and Fig. 5 provide insight into the load distribution, with the model comprising 9 piles. Each pile has a diameter of roughly 0.9 meters, though initially designed to be 1 meter, and they are uniformly spaced at intervals of 3.83 meters throughout the raft's expanse. Based on the data presented in the figures, the cumulative load of 22,000 kN is apportioned as follows: 12,930 kN is borne by the piles, while 8,973 kN is supported by the raft foundation. This translates to a load-sharing percentage of 59% for the piles and 41% for the raft, resulting in a load-sharing ratio of 1.43. For this scenario, the slenderness ratio stands at 3.33, and the proportion of the pile area to the raft area is 5.55%. Further analysis of the contour graph in Fig. 6 confirms a load-sharing ratio (pile to raft) of 1.43 for this particular case.

5 CONCLUSION

- A detailed comparison was conducted on the load-settlement behavior of the piled raft system using two methodologies: the analytical Poulos-Davis-Randolph (PDR) and the numerical finite element method. The alignment of settlement outcomes from both techniques, for a given load, emphasizes the accuracy of our numerical model. Notably, the numerical approach exhibited marginally increased stiffness, suggesting that the PDR method tends to be more conservative in its predictions.

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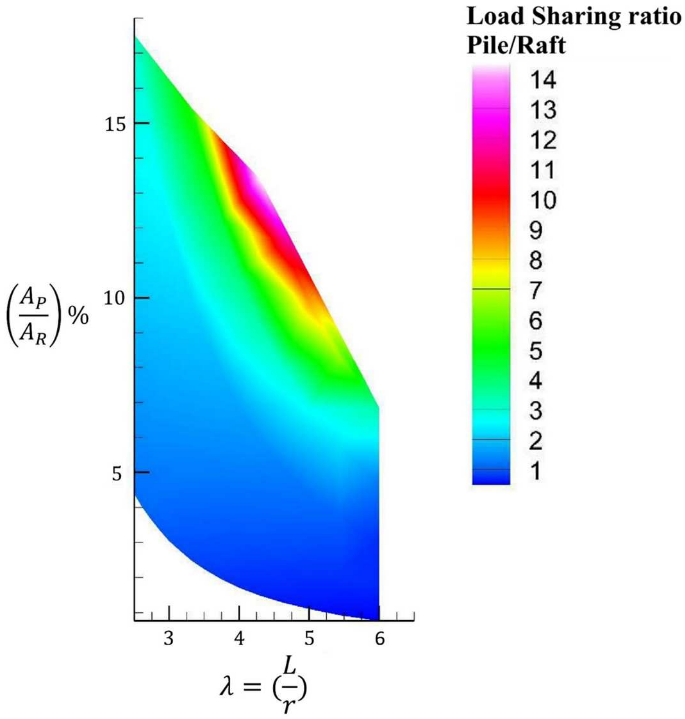

Fig. 6 A two-dimensional visualization of the load distribution (sharing) ratio in piled raft systems. *Ap* = the area of the pile groups, *Ar* = the area of the raft, *L* = the length of the pile groups, *r* = the radius of gyration for piles with a circular cross-section.

- The study further embarked on a comprehensive parametric analysis, adjusting various pile characteristics such as number, diameter, spacing, and length. This endeavor aimed to understand their combined and individual effects on the complex load distribution mechanism and to determine the balance of load distribution between the raft and the pile groups. The findings were effectively represented using 2D contour diagrams, plotted against the Ap / Ar ratio and slenderness ratio. These diagrams highlight a gradual transition in load-bearing towards the pile as its area increases and its slenderness decreases.
- Of the parameters evaluated, the pile's diameter was particularly influential. As the diameter increases, it not only expands the pile's effective area, allowing it to support a greater portion of the load, but also reduces its slenderness ratio, enhancing its load-bearing capacity.
- While this study has provided significant insights into the behavior of piled raft systems, there is potential for further exploration. Future research could encompass a variety of scenarios, from adjusting pile length, incorporating different soil types, to addressing the intricacies of multi-layered soil profiles.

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