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Numerical Analysis of Piled Raft Foundation on Port Said Soil

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ABSTRACT

The main purpose of any foundation system is to distribute and transmit the load from the structure to the soil. This study investigates the performance of piled raft foundations in multi-layered soils, specifically under the unique geotechnical conditions of Port Said, Egypt, using advanced finite element modeling with PLAXIS 3D. The research focuses on settlement reduction, shear stress, and bending moment behavior under vertical loading. The methodology includes investigating the most effective pile diameter and length, determining that a 1-meter diameter and 48-meter length pile provides the best performance. The case study varies the pile group-to-raft width ratio (Bg/Br) at 0.7, 0.8, and 0.9 values, adjusting pile spacing accordingly. Additionally, the raft thickness varies at 2.0, 1.5, 1.2, 1.0, and 0.8 meters, while the number of piles is distributed gradually in configurations of 10x10, 9x9, 8x8, 7x7, 6x6, and 5x5.

The study results show that a pile group-to-raft width ratio (Bg/Br) of 0.9 with 81 piles and a 2.0-meter raft thickness offers the best performance in terms of settlement reduction, providing a 22% improvement compared to configurations with fewer piles. For more cost-sensitive projects, a Bg/Br ratio of 0.8 with 49 piles was found to be a practical and economical alternative, achieving a similar level of settlement reduction while significantly reducing the number of piles. Thinner rafts, such as those with a thickness of 0.8 meters, led to 18% greater bending moments and 4% higher shear stresses than the 2.0-meter raft.

Keywords: Piled raft, Port Said East Egypt, Stiff Clay, Multi-Layer, Settlement, straining actions, Bending Moment, Shear Stresses.

1. INTRODUCTION

The main purpose of any foundation system is to distribute and transmit the load from the structure to the soil. A shallow foundation is used when the load-bearing soil is below the foundation and can carry the stresses acting on it. A deep foundation is used when the shallow foundation cannot provide the safety requirements for the structure.

A combined system of shallow and deep foundations is used as a design approach. A piled raft foundation is a combination of a deep pile group and a shallow raft foundation. To understand the mechanism of load transfer between the raft, pile, and soil, the researchers need to study (i) the behavior of the raft which includes settlement, straining action, and the load carried by the raft, and (ii) the behavior of the piles which include vertical displacement, lateral displacement and vertical loads carried by piles.

The objective of the study is to conduct a comparative analysis of the complex piled raft foundation system interaction between pile to pile, pile to raft, pile to soil, and raft to soil. Piled raft foundations are increasingly used for structures on soft ground, but their application on weak clay soils remains limited due to concerns about excessive settlement and insufficient bearing capacity [1].

Nonetheless, some successful applications on weak soil have been reported [2]. Recently, advanced numerical methods, including analytical models and three-dimensional (3D) finite element (FE) methods, have been developed for analyzing piled rafts on weak soils [3], [4]. However, current design and analysis methods under vertical loading are still considered inadequate. The behavior of piled rafts is influenced by the 3D interaction between soil, piles, and rafts. Settlement magnitudes vary significantly across different soil conditions under similar applied loads, making the soil-structure interaction more complex. A reliable analytical model is essential to accurately evaluate these interactions. Numerical methods have gained traction over the last two decades as a cost-effective approach for analyzing diverse foundation geometries compared to field or model tests. According to Poulos [1], numerical methods can be classified into three types: simplified calculation methods, approximate computer-based methods, and more rigorous computer-based methods. Among these, the 3D linear/nonlinear FE method is considered the most effective. While nonlinear 3D FE analyses have been conducted recently, challenges related to modeling the soil-structure interface persist.

This study aims to investigate the behavior of piled rafts on multi-layered soils using 3D FE analysis. The effects of raft thickness variations, pile-soil interaction, and pile distribution on the behavior of piled rafts under vertical loading were analyzed. Displacement and settlement behavior were examined over a Long-term period, focusing on the most effective configurations for bearing behavior. Additionally, the study evaluated the relationship between settlement, shear forces, and bending moments across rafts with varying thicknesses [5-8].

2. Model Configuration

2.1 Rigid Elements

The effect of model boundary conditions on the resulting settlement and straining actions induced in piled rafts are investigated in this section. The raft is simulated as a plate element of linear elastic concrete material properties: Young's modulus E = 34 x 10^6 Mpa, Poisson's ratio ν = 0.20 with interface strength 0.7, concrete unit weight = 25 $\mathrm{kN/m^3}$ with thickness = 2.0 m. The pile is simulated as a pile element and varies pile diameter (dp) and pile length. with the material properties: young's modulus E = 23.5 x 10^6 Mpa, Poisson's ratio ν = 0.20, and concrete unit weight = 25 $\mathrm{kN/m^3}$.

The effect of the model resulting in settlement and straining actions induced in the piled raft is investigated in this section. The raft is simulated as a plate element of linear elastic concrete material properties: Poisson's ratio υ = 0.20 and concrete unit weight = 25 $\mathrm{kN/m^2}$.

Fig. 1. provides an overview of the proposed raft configuration, illustrating both its geometry and the column loads. The raft is a 40 m by 40 m square slab with a thickness of 2 m, and columns are placed at 4.5 m intervals. Under the applied loads, the raft experiences an average stress of 200 kPa. Specifically, the corner column carries a load of 2030 kN, the edge column 3080 kN, and the inner column 4620 kN.

The pile was assigned, while the squared raft was modeled with rigid pile-to-raft connections. Leveraging the symmetry of the setup, the entire domain was discretized using finite elements.

The soil–pile interface incorporated both base and skin resistance to account for bearing and frictional capacity, while a smooth contact was assumed for the raft–soil interface. A relatively fine mesh was adopted in the vicinity of the piled raft and interfaces, transitioning to a coarser mesh away from these critical regions. The model was placed atop a rigid layer, permitting vertical movement of the soil layers to capture raft displacement. For the far-field boundaries.

The main model used a 100 m offset from the raft edges and a 120 depth in the soil, although this distance was adjusted in certain analyses to achieve the most accurate numerical results [9].

In this study, three primary sections(X-X), (Y-Y), and (Z-Z) are analyzed to provide a comprehensive understanding of the raft's structural performance under the specified loading conditions. Specifically, the (X-X) section corresponds to the column strip, while the (Y-Y) and (Z-Z) sections serve as field strips. By examining these cross-sections, the analysis captures the variations in internal forces and deformations across different regions of the raft, ensuring a more detailed assessment of its overall behavior.

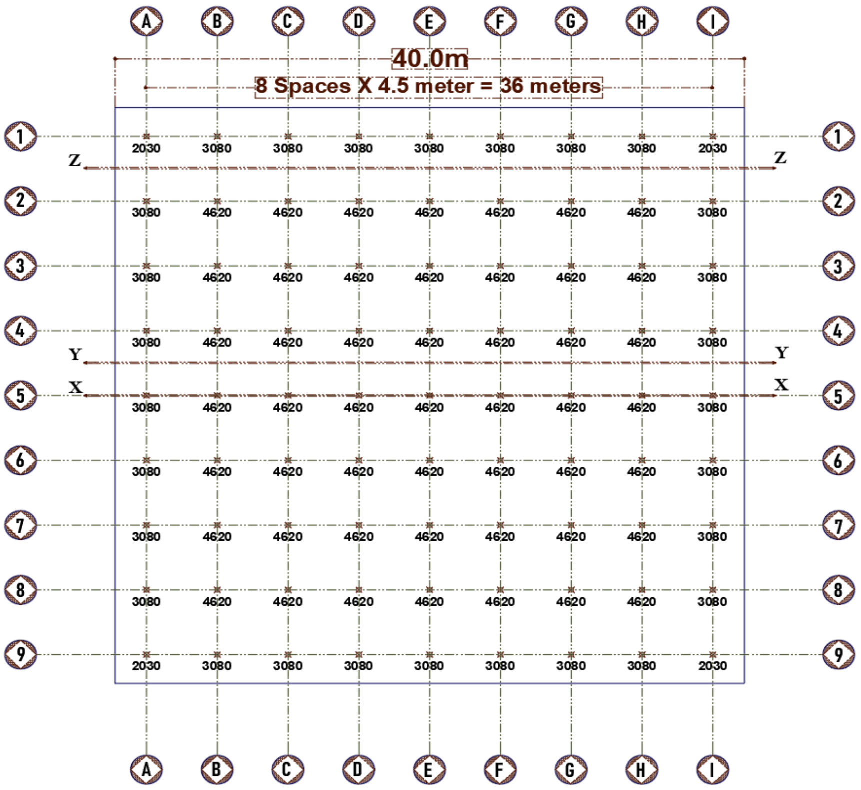

Fig. 1: Column loads on raft

2.2 Case study

A comprehensive geotechnical investigation evaluated the multi-layered soil profile East of Port Said. This investigation combined field and laboratory tests to accurately determine the geological conditions and derive essential geotechnical parameters for the pump station location. The gathered data offers valuable insights into the subsurface layers, facilitating reliable soil characterization and informing subsequent engineering design decisions.

A borehole of a multi-layer soil of the comprehensive site investigation program followed ASTM standards, encompassing borehole drilling, sampling, laboratory testing, and CPTU tests. Laboratory analyses included physical properties tests such as Atterberg limits, natural water content, and grain size distribution for soil classification and preliminary assessment of engineering behavior. Mechanical properties were evaluated via consolidation tests on undisturbed cohesive samples at various load increments to derive parameters like the compression and recompression indices. Additionally, CPTU readings were used to classify soil types based on cone resistance and friction ratio, providing insights into soil strength, stiffness, and behavior as the next data shown in Tables 1, 2, and 3.

Table 1: Soil Properties and Geotechnical Parameters

soil		top	bottom	Bulk density	saturated density	E50	Eoad	Eur
units		m	m	KN/m^3	KN/m^3	KN/m^2	KN/m^2	KN/m^2
1	fill	0	2	18	19.5	30000	30000	90000
2	silty sand	2	4.7	18	19.5	36000	36000	108000
3	clayey silt	4.7	14	17.5	19	15000	15000	45000
4	very soft clay	14	19.5	16	17.5	2500	2500	7500
5	soft to medium clay	19.5	35	18.6	20	3500	3500	10500
6	medium clay	35	49	19	21	13000	13000	39000
7	V.D silty sand	49	57	19.5	21	50000	50000	150000
8	Very stiff clay	57	58.5	20	21.5	22500	22500	67500
9	V.D silty sand	58.5	70	20	21.5	50000	50000	150000

Table 2: Soil profile and parameters

Soil layers		Power (m)	(eo)	(Cc)	(Cs)	(Cv)	(OCR)
1	units	-	-	-	-	Cm^2/min.	-
	fill	0.65	0.6	-	-	-	1
2	silty sand	0.65	0.5	-	-	-	1
3	clayey silt	0.75	0.97	0.22	0.02	0.78	3
4	very soft clay	1	0.97	0.68	0.06	0.06	1.65
5	soft to medium clay	1	0.92	0.61	0.07	0.06	1
6	medium clay	0.75	0.99	0.52	0.04	0.04	1
7	V.D silty sand	0.5	0.5	-	-	-	1
8	Very stiff clay	0.5	0.4	0.15	0.01	0.02	1
9	V.D silty sand	0.5	0.5	-	-	-	1

Table 3: Idealized soil profile and parameters

soil		C'	ø'	Ψ	Cu	øu	Ψ	K	R inter
1	units	KN/m^2	°	°	KN/m^2	°	°	m/sec	-
	fill	0	32	2	0	32	2	$1X10^{-4}$	0.67
2	silty sand	10	34	4	0	34	4	$1X10^{-4}$	0.7
3	clayey silt	10	30	0	10	20	0	$1X10^{-7}$	0.7
4	very soft clay	20	20	0	10	0	0	$1X10^{-9}$	0.8
5	soft - med. clay	30	22	0	12.5:50	0	0	$1X10^{-9}$	0.8
6	medium clay	50	25	0	50:100	0	0	$1X10^{-9}$	0.7
7	V.D silty sand	0	38	0	0	38	8	$1.5X10^{-2}$	0.7
8	Very stiff clay	150	31	1	150	0	0	$1X10^{-9}$	0.7
9	V.D silty sand	0	38	8	0	38	8	$1.5X10^{-2}$	0.7

2.3 Constitutive Model Configuration

Those Models examine the impact of model boundary conditions on the settlement and straining actions in the piled raft system. The piles are modeled as elements with a diameter (dp) of 1.0 m, a length (Lp) of 48 m, and a spacing (Sp) of 4.5 dp. The pile material properties include a Young's modulus (E) of 23,500 MPa, a Poisson’s ratio (v) of 0.20, and a concrete unit weight of 25 kN/m³. A total of 81 piles are distributed beneath the raft, subjected to vertical loads, with a raft-to-pile spacing Pile Group to raft Width ratio (Bg/Br) of 0.9 as shown in Fig. 2.

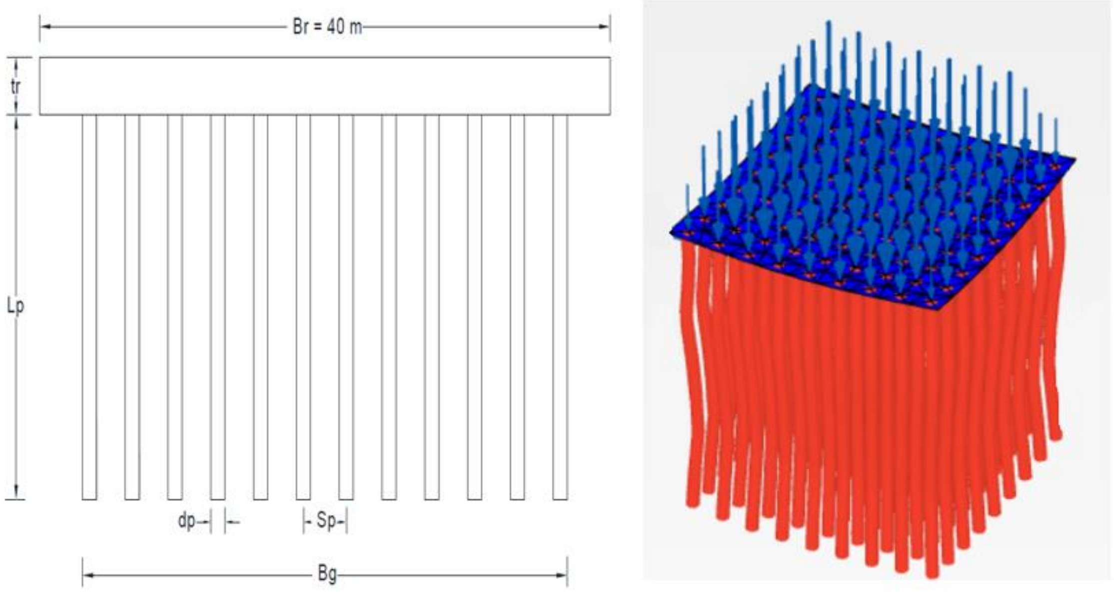

Fig. 2: Piled Raft Foundation

The proposed piled-raft geometrical configurations. The piles are defined by a length of 40 m, and a diameter of 1.0 m as the Reference model then the most effective pile length and pile diameter, and a spacing of 4.5 times the diameter. The configuration varies with the piled group to raft width ratio (Bg/Br), set at 0.90 for the reference model and adjusted to 0.90, 0.80, and 0.70 in the parametric study. The number of piles (Np) is 81 in the reference model and varies based on changes in Bg/Br and other parameters in the study.
The time study, spanning 20 years, shows that settlement progressively increases, reaching 100% of the maximum settlement by the end of the period. Time simulations reveal that the settlement for both the unpiled and piled raft systems is maximized after 2837 days, representing the most efficient settlement behavior throughout the study. This analysis includes the construction period of 300 days, with each load stage contributing 10% of the total load applied incrementally over 30-day intervals. These results provide a detailed and accurate prediction of settlement over time, accounting for the entire construction and long-term performance phases.

The unpiled raft model in PLAXIS 3D showed a settlement of 310.18 mm after loading and 487.78 mm after 2837 days. This represents 96.51% of the 20-year maximum settlement of 505.4 mm, confirming the study period's adequacy for long-term settlement analysis [10], [11], [12].

The reference model investigated the effect of varying pile diameters and lengths across 16 models to identify the most efficient configurations for settlement reduction between unpiled and piled raft systems. The results revealed that the optimal pile diameter is 1 meter, which provided the highest settlement reduction [8].

For pile lengths, the settlement reduction increased progressively, with reductions of 73.73% at 36 m, 76.71% at 40 m, 79.99% at 44 m, and the maximum reduction of 83.23% at 48 m. Based on these findings, the study will proceed with a pile length of 48 meters and a pile diameter of 1 meter to achieve the most effective settlement performance.

After determining the diameter and pile length, the parametric study will focus on varying the pile group to raft widths of 0.7, 0.8, and 0.9. This will result in changes to the pile spacing and number, with configurations such as 10x10, 9x9, 8x8, 7x7, 6x6, and 5x5 at Bg/Br = 0.9. Additionally, variations in raft thickness will be considered at Bg/Br = 0.9, with values of 2, 1.5, 1.2, 1, and 0.8 meters, as shown in Fig.3.

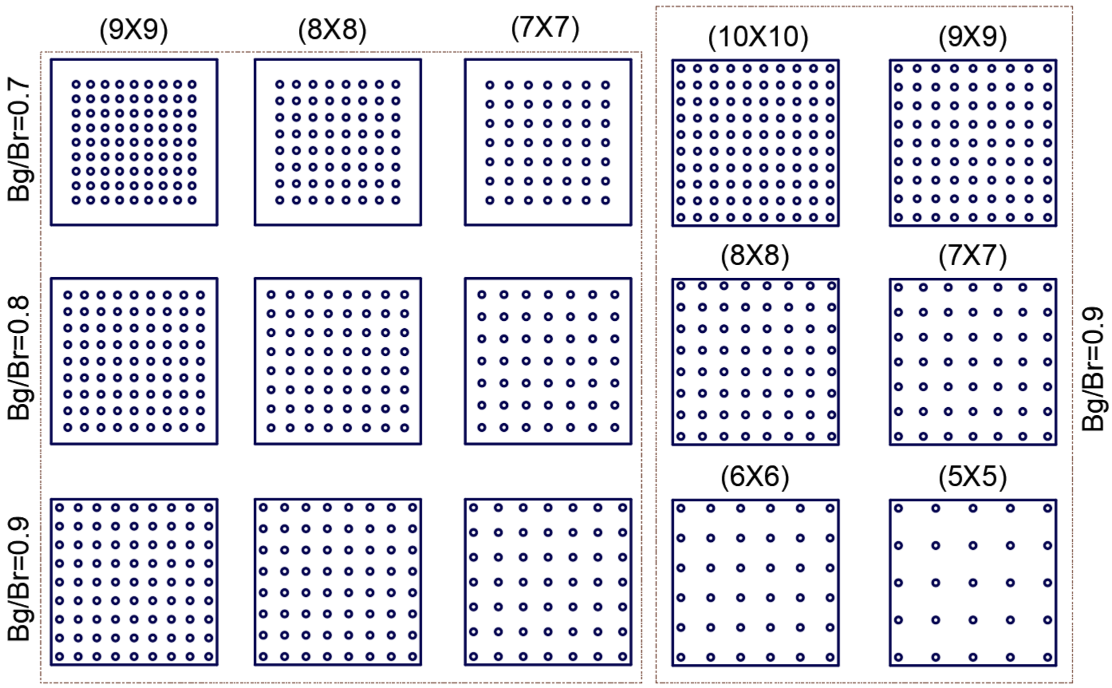

Fig. 3: Piled Raft Parametric Study changing

3. POST ANALYSIS

The vertical settlements from the 3D FE analyses were used directly, and the average settlement Savg was represented by the Differential settlement control approach: piles arranged uniformly below the raft to reduce settlement and differential settlement, but the main purpose of the pile is this approach to minimize differential settlement rather than average settlement.

The effect of pile position acting on settlement values se in this study used one pile distributing below the vertical load directly and compared vertical loads as distributed and concentrated loads to show which vertical load was more effective and which pile distributing more resisted with load and settlement [13].

Following the selection of a reference model that demonstrated optimal settlement performance and load-sharing ratio, the subsequent phase involves a detailed parametric study to evaluate the influence of key design parameters. These parameters include variations in the pile group-to-raft width ratio, which impacts pile spacing and the number of piles, as well as changes in raft thickness. The objective is to systematically analyze how these factors affect the settlement behavior, the straining actions of the raft, and the load-sharing ratio between the piles and the raft with soil. This investigation aims to provide a comprehensive understanding of the interdependence between these variables and their role in optimizing the structural performance and economic efficiency of piled raft systems.

3.1 Pile group to Raft width (Bg/Br)

This analysis investigates the impact of the pile group-to-raft width ratio (Bg/Br) on piled-raft foundation performance. Simulations were conducted for Bg/Br ratios of 0.9, 0.8, and 0.7, with pile spacing varying from 3.5 m to 6.0 m across nine pile distribution patterns. Using reference parameters, including a pile length of 48 m, a diameter of 1 m, and multi-layered Port Said soil.

The study also assessed the effects of reducing raft thickness by 2 meters. Results revealed that settlement decreases with increased raft thickness up to a certain point, beyond which failure may occur due to insufficient support. Optimal stability was achieved at Bg/Br = 0.8, with pile distributions of 4.0 m spacing for 49 piles, 4.6 m spacing for 64 piles, and 5.4 m spacing for 81 piles. Settlement results indicated that for Bg/Br = 0.8 and 49 piles.

Maximum settlement matched Bg/Br = 0.9 with 81 piles (80 mm), highlighting that Bg/Br = 0.8 provides comparable performance with fewer piles. Increasing Bg/Br to 0.8 or 0.9 significantly improved settlement performance compared to Bg/Br = 0.7. Ultimately, Bg/Br = 0.8 was identified as an economical and efficient design, achieving settlement reductions like Bg/Br = 0.9 while requiring fewer piles as shown in Fig. 4.

The analysis reveals that the configuration Bg/Br=0.9 with 81 piles achieves the most efficient performance, with the lowest shear strength and bending moment values. Compared to this configuration, Bg/Br=0.7 with 49 piles shows a 142.85% higher shear strength (-8000 KN/m compared to -3300 KN/m) and a 122.22% higher bending moment (4000 KN·m/m compared to 1800 KN·m/m). Increasing the pile number to 64 piles for Bg/Br=0.7 reduces the differences, with shear strength being 96.96% higher (-6500 KN/m) and bending moment 94.44% higher (3500 KN·m/m). For Bg/Br=0.7 with 81 piles, the differences further reduce, with shear strength being 57.57% higher (-5200 KN/m) and bending moment 61.11% higher (2900 KN·m/m). Meanwhile, Bg/Br=0.8 with 49 piles offers a more balanced alternative, with shear strength 27.27% higher (-4200 KN/m) and bending moment higher (2200 KN·m/m) compared to Bg/Br=0.9 with 81 piles. This data emphasizes that while Bg/Br=0.9 with 81 piles provides the most effective reduction in straining actions, Bg/Br=0.8 with fewer piles can be an economical yet efficient alternative for structural performance optimization as illustrated in Fig. 5.

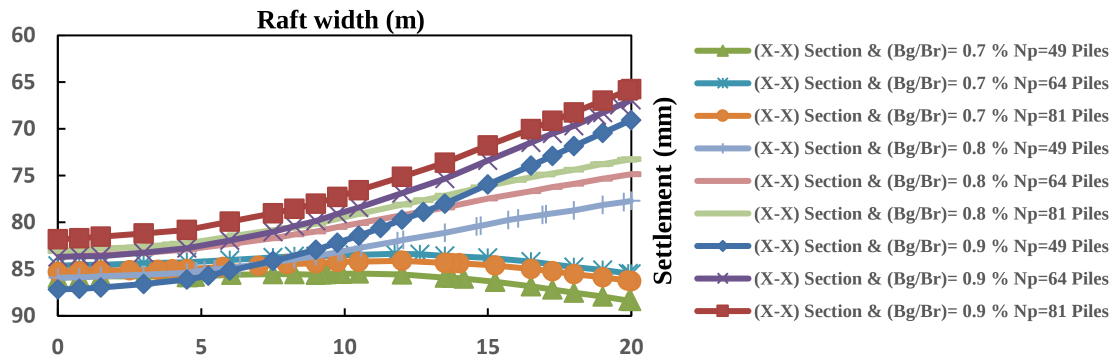

Fig. 4: Vertical Settlement Over Section X-X (tr = 2 m, dp=1.0 m, Lp=48 m)

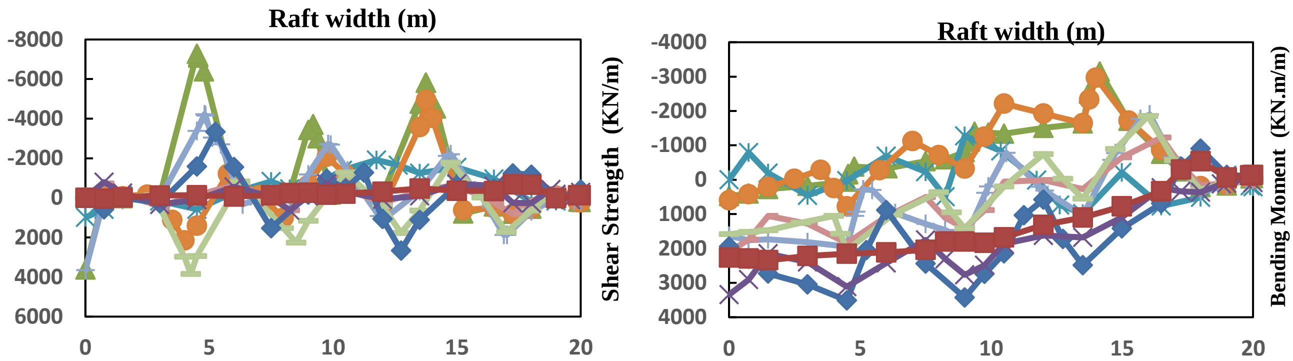

Fig. 5: Shear Strength & Bending Moment Over Section X-X (tr = 2 m, dp=1.0 m, Lp=48 m)

The analysis identifies Bg/Br=0.9 with 81 piles as the most efficient system, achieving the lowest settlement (80 mm), shear strength (-3300 KN/m), and bending moment (1800 KN·m/m). This efficiency is attributed to the higher load directly carried by the piles, which reduces the shear strength and settlement significantly. However, Bg/Br=0.8 with 49 piles offers a cost-effective alternative, matching the settlement (80 mm) and maintaining moderately low shear strength (-4200 KN/m) and bending moment (2200 KN·m/m). In contrast, Bg/Br=0.7 shows higher settlement (up to 88 mm) and significantly larger straining actions, making it less efficient. Thus, Bg/Br=0.9 provides optimal performance by efficiently redistributing loads through the piles, while Bg/Br=0.8 is a more economical option.

The maximum settlement reduction occurs at the smallest pile spacing-to-diameter ratio (Sp/dp=3.5S) across all Bg/Br values. At this spacing, Bg/Br=0.9 achieves the lowest average settlement ratio, demonstrating the highest efficiency in vertical settlement reduction. Bg/Br=0.8 closely follows, providing comparable settlement reduction performance to Bg/Br=0.9, particularly at this smaller spacing. In contrast, Bg/Br=0.7 exhibits the highest settlement ratio, reflecting the least effective settlement reduction, even at smaller spacing values. Thus, Sp/dp=3.5 is the optimal spacing for maximizing vertical settlement reduction, with Bg/Br=0.9 performing the best overall as illustrated in Fig. 6.

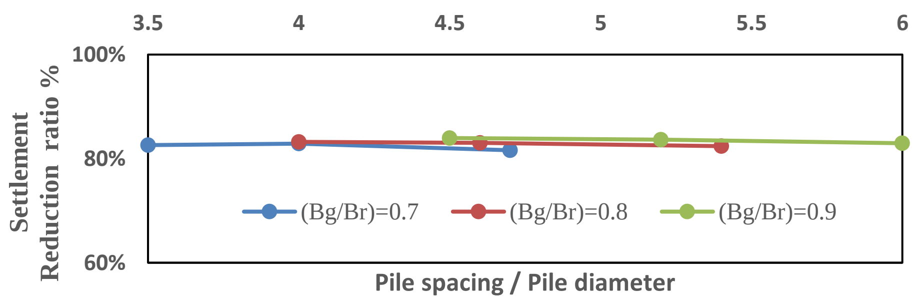

Fig. 6: Spacing Effect over settlement reduction (tr = 2 m, dp=1.0 m, Lp=48 m)

3.2 Number of Piles (Lp)

At Section X-X with tr = 2.0 m, the configuration Np=81 at Bg/Br=0.9 demonstrates the most efficient performance in terms of settlement, shear forces, and bending moments compared to other configurations. Np=81 achieves the lowest settlement of 65.75 mm, which is 22.65% more efficient than Np=25 (85.00 mm), 12.61% more efficient than Np=36 (74.04 mm), and 1.78% more efficient than Np=64 (66.92 mm). While Np=100 achieves a slightly lower settlement of 66.20 mm (only 0.68% better than Np=81), this improvement is negligible, highlighting diminishing returns with additional piles as illustrated in Fig. 7.

For shear forces, Np=81 achieves significant stabilization, with a value of -135.75 kN/m. This is 86.63% more efficient than Np=25 (-945.37 kN/m), 70.01% more efficient than Np=36 (-40.80 kN/m), and 105.5% more efficient than Np=64 (-279.25 kN/m). Although Np=100 achieves a slight improvement with a positive shear force of 91.86 kN/m, this improvement is minimal and does not justify the additional cost and complexity of the configuration as illustrated in Fig. 17. Regarding bending moments, Np=81 effectively controls straining actions, achieving a value of -135.71 kN·m/m. This is 52% more efficient than Np=25 (-91.95 kN·m/m), 23% better than Np=36 (29.90 kN·m/m), and 38.5% more efficient than Np=64 (84.89 kN·m/m). While Np=100 achieves a bending moment of 38.28 kN·m/m, this improvement is marginal and does not outweigh the increased cost of additional piles as illustrated in Fig. 8.

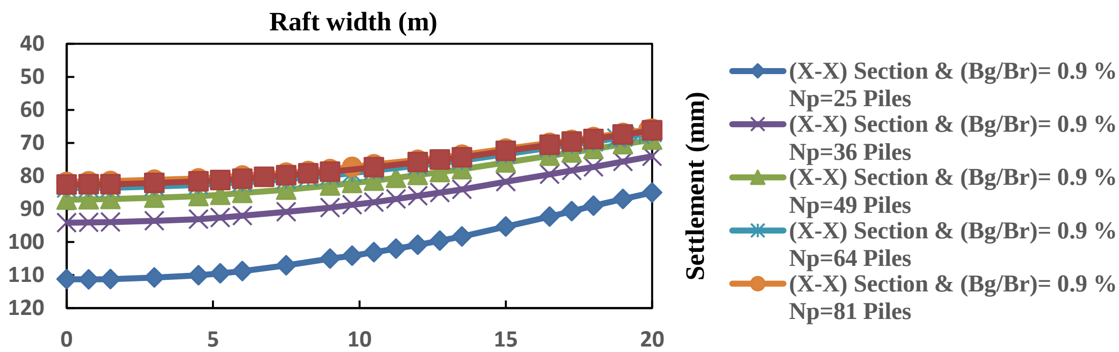

Fig. 7: Vertical Settlement Over Section X-X (Sp=4.5 m, Lp=48m, dp=1.0 m)

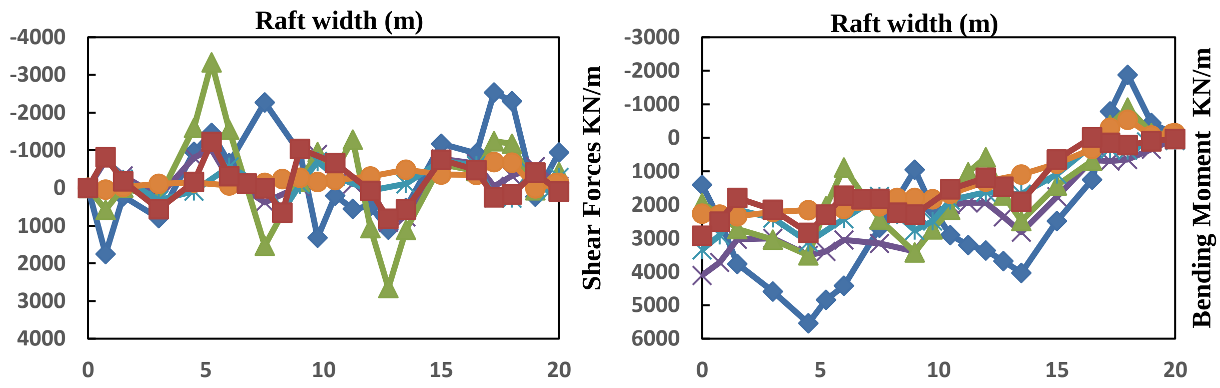

Fig. 8: Shear Stresses and Bending Moment Over Section X-X (Sp=4.5 m, Lp=48m, dp=1.0 m)

Overall, Np=81 proves to be the most balanced and efficient configuration, achieving the highest reductions in settlement, shear forces, and bending moments compared to configurations with fewer piles, while avoiding the diminishing returns seen in Np=100. With 22.65% better settlement, 86.63% better shear force stability, and 52% better bending moment control compared to Np=25, Np=81 provides the optimal balance of cost-effectiveness and performance, making it the most efficient choice for Bg/Br=0.9.

3.3 Raft thickness (tr)

The comparison between raft thicknesses of 0.8 m, 1.0 m, 1.2 m, 1.5 m, and 2.0 m reveals significant differences in settlement, shear strength (Q13), and bending moment (M11), highlighting the performance benefits of a thicker raft. At a thickness of tr = 2.0 m, the raft achieves the lowest maximum settlement of 65.75 mm, outperforming all other thicknesses. In contrast, a thickness of tr = 0.8 m exhibits the highest settlement of 57.32 mm, which is 14.73% higher than the 2.0 m case. Similarly, the settlements at tr = 1.0 m and tr = 1.2 m are 58.59 mm and 59.96 mm, respectively, indicating increases of 12.21% and 9.65% compared to 2.0 m. For tr = 1.5 m, the settlement rises slightly to 62.10 mm, marking a 5.54% increase relative to the thickest raft as illustrated in Fig. 19.

In terms of shear strength, tr = 2.0 m demonstrates the smallest peak value of -135.75 kN/m, ensuring the most uniform load distribution. However, as the raft thickness decreases, shear strength values fluctuate, reflecting reduced stability. At tr = 1.5 m, the maximum shear strength decreases significantly to -45.77 kN/m, a 66.28% reduction compared to 2.0 m. For tr = 1.2 m, shear strength is 20.60 kN/m, showing a considerable deviation from the optimal performance. At tr = 1.0 m, the value increases to 71.43 kN/m, a 52.58% rise, while for tr = 0.8 m, it peaks at 129.82 kN/m, surpassing the 2.0 m case by 4.44%. This trend underscores the higher stress concentrations and reduced stability associated with thinner rafts as illustrated in Fig. 9.

Regarding bending moments, tr = 2.0 m records the lowest value of -135.71 kN·m/m, demonstrating superior resistance to straining actions. Conversely, thinner rafts show progressively larger bending moments, reflecting their inability to effectively distribute loads. At tr = 1.5 m, the bending moment rises to -150.47 kN·m/m, a 10.85% increase, while at tr = 1.2 m, it further increases to -157.64 kN·m/m, representing a 16.14% rise. For tr = 1.0 m and tr = 0.8 m, bending moments reach -160.14 kN·m/m and -159.48 kN·m/m, reflecting increases of 18.00% and 17.49%, respectively, compared to the 2.0 m thickness as illustrated in Fig. 10.

Overall, tr = 2.0 m delivers the most efficient performance, achieving the lowest settlement, minimal shear strength, and least bending moment, ensuring structural stability and effective distribution of load. In contrast, thinner rafts (0.8 m to 1.5 m) exhibit progressively higher settlements (up to 14.73% more) and larger straining actions (up to 18.00% higher bending moments), making them less suitable for optimizing the piled raft system's performance.

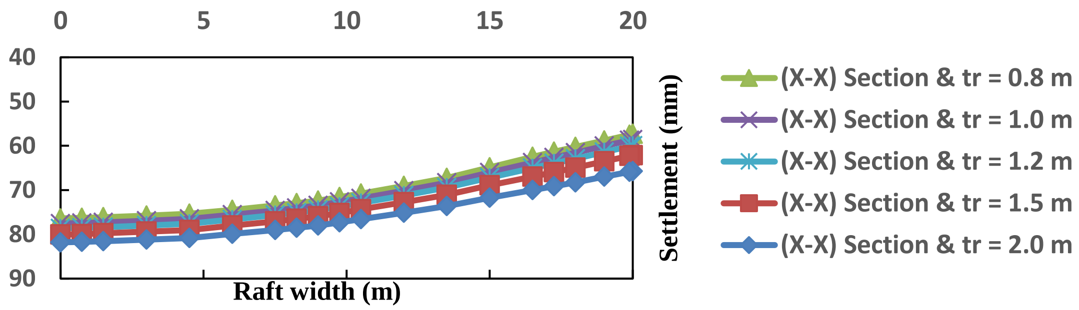

Fig. 9: Vertical Settlement((Bg/Br) =0.9, Sp=4.5 m, Np=81, Lp=48m, dp=1.0 m)

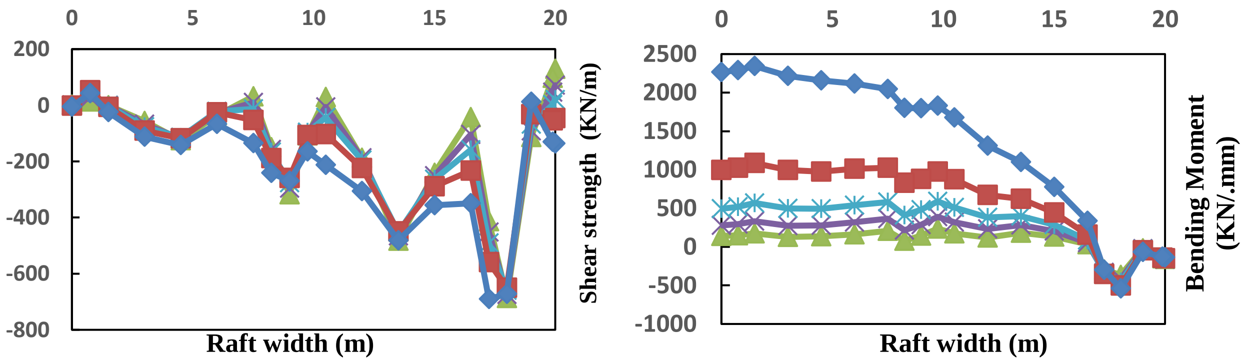

Fig. 10: Shear Strength and Bending Moment Over Section X-X ((Bg/Br) =0.9, Sp=4.5 m, Np=81, Lp=48m, dp=1.0 m)

4. DISCUSSION OF RESULTS

The analysis of piled-raft foundations in Port Said's multi-layered soil shows that a Bg/Br ratio of 0.9 with 81 piles and a 2.0 m raft reduced settlement by 22% compared to configurations with fewer piles. For cost-effective solutions, Bg/Br = 0.8 with 49 piles achieved a similar settlement reduction at a lower cost. Thinner rafts (0.8 m) increased shear stress by 4% and bending moments by up to 18%, highlighting the benefits of thicker rafts. Configurations with 81 piles offered optimal bending moment control while using 100 piles provided minimal improvements at higher costs. In summary, Bg/Br = 0.9 with 81 piles is ideal for performance, while Bg/Br = 0.8 with fewer piles offers a cost-efficient alternative.

5. CONCLUSION

This study evaluates piled-raft foundation systems in multi-layered soils, focusing on settlement reduction, shear stresses, and bending moments under Port Said's unique geotechnical conditions. Using finite element modeling, key design parameters like the pile group-to-raft width ratio (Bg/Br), pile numbers, and raft thickness were analyzed.

The optimal configuration for performance was 81 piles with Bg/Br = 0.9, offering the best settlement reduction, minimal shear stresses, and bending moments, ensuring stability and reliability. For cost-conscious projects, 49 piles with Bg/Br = 0.8 provided nearly the same settlement reduction with slightly higher straining actions, offering significant savings.

Raft thickness of 2.0 m paired with Bg/Br = 0.9 and 81 piles gave the best structural performance. For budget-focused designs, rafts between 1.2 m and 1.5 m offered good performance with cost savings. Ultimately, for maximum performance, the 81-pile configuration with Bg/Br = 0.9 and a 2.0 m raft is recommended. For cost efficiency, the 49-pile configuration with Bg/Br = 0.8 and a 1.5 m raft provides a viable solution. These findings guide the design of cost-effective, stable piled-raft foundations.

6. REFERENCES

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