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Exploration of Pile Foundation Design for an Ultra-High-Rise Complex Abroad

Yanqing GAO[1], and Nasr Saba[2*]

1 Chief Engineer, CSCEC Middle East
2 Department of Construction and Building Engineering, Faculty of Engineering, October 6 University, 6th of October City, 12585, Giza, Egypt.

* Corresponding author's email: Dr_nasr.saba@yahoo.com

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Abstract – Pile foundations are pivotal in ultra-high-rise building projects, serving not only as structural supports that provide requisite load-bearing capacity and seismic resilience but also as solutions to challenges posed by complex geological conditions and economic considerations. This study investigates the pile foundation design of a super high-rise complex in the Alamein region of Egypt, focusing on its distinctive geological context and design specifications. The project features a 300-meter landmark tower and four apartment-style hotels, each 221.74 meters tall. The site is characterized by complex geological conditions dominated by limestone with karstic features. Through the integration of geological survey data and structural load analysis, pile foundations with varying load capacities were employed. The design was optimized using test piling and post-grouting techniques to enhance load-bearing capacity and control settlement. Guided by the principles of balancing economic efficiency with structural safety, a staggered diamond-shaped arrangement of piles was adopted in the core tube area, while peripheral areas were arranged according to project requirements. The optimization led to ample load-bearing capacity and significant reductions in construction costs.

Keywords: Super high-rise buildings; Pile foundation design; post-grouting technology; Pile-raft foundation; Karst geology; Optimization of layout configuration

I. PROJECT OVERVIEW

The project is located in the Alamein region of Egypt and represents a key initiative under the Egypt Vision 2030 master plan, envisioned as a future landmark for European tourism and leisure. Situated 5 kilometers from the Mediterranean coastline, the development comprises five ultra-high-rise towers with podiums. Among these, the T01 landmark tower stands at 300 meters with 68 stories and a total floor area of 462,873 m^2. Additionally, four identical apartment-style hotels, referred to as D buildings, rise to 221.74 meters with 54 stories each, featuring a total floor area of 159,034 m^2 per building. All high-rise towers adopt a cast-in-place reinforced concrete shear wall structural system, and the foundations are designed as pile-raft systems. The peak ground acceleration (PGA) for seismic design was determined as 0.125g based on Egyptian standards, corresponding to a seismic intensity of 7－8 on the Chinese scale [3]. Wind loads were calculated using a 50-year return period with a basic wind speed of 42 m/s, and ground roughness was classified as Category A [1].

II. GEOLOGICAL CONDITIONS

The paper should be written in A4 (210mm by 297mm) size. Your manuscript should be on two sides of a sheet, with margins of 2.5 cm on left and 1.5 cm on right side and 2.44 cm on top and 3 cm bottom side, respectively, of each page. Distance from edge must be 0.55 cm from header and 2 cm from footer. The suggested length of a regular paper would be 4~6 pages not numbered and in this style. The subsequent headings are called subsection. All fonts are Times New Roman. The Alamein coastal region exhibits distinct coastal depositional geomorphology formed by post-marine regression sedimentation, including features such as notches, caves, and platforms. A sediment distribution map of the project area is shown in Figure 1. The geological strata are primarily composed of limestone (carbonate rock) with politic and fossil inclusions, as depicted in Figure 2. Due to the water-soluble nature of carbonate rocks, numerous voids exist within the limestone, forming karstic features, as shown in Figure 3.

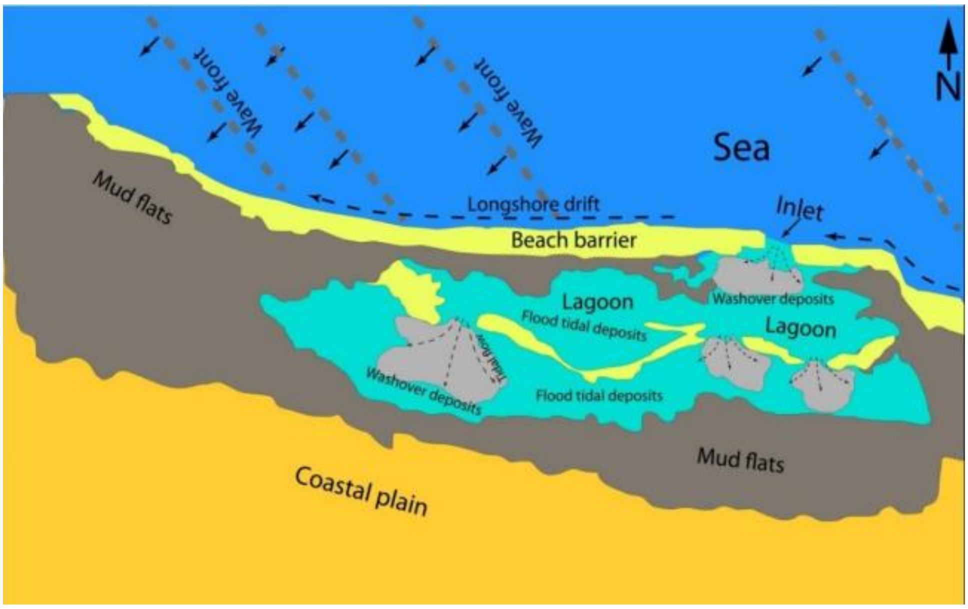


Figure 1: Sediment Distribution Map of Project Area

Figure 2: Field Photograph of Regional Rock Strata

Figure 3: Karstic Voids Formed in Limestone under Karst Processes

Table 1: Design Parameters of Physical and Mechanical Properties for Each Soil Layer

Soil Layer No. and Name	Undrained Shear Strength Cu （kg/cm2)	Unconfined Compressive Strength Qu (kg/cm^2)	Internal Friction Angle ϕ（°）	SPT Blow Count	RQD (%)
① Fill	Neglected				
② Sandstone	3.1	31	30	100	8
③Limestone	3.6	36	30	100	4.7
④ Clay/Silty Clay	2	-	-	-	-

According to the geotechnical investigation report, the subsurface soil profile consists of four primary layers. The top layer is a loose fill material, extending 0.5－1 meter below the surface. Beneath it lies a layer of weathered calcareous sandstone, light Gray to brown yellow in colour, fractured, and calcified, with depths ranging from 2 to 15 meters. The third layer comprises weathered limestone, white to light Gray, fractured, and interspersed with silty clay, extending to a depth of 79 meters. The deepest layer is clay or silty clay, olive green to dark Gray, stiff, and highly plastic, containing iron oxides with an average liquid limit of 60% and a plasticity index of 33%. Groundwater levels are located between 9 and 9.5 meters above the absolute elevation datum, and the physical and mechanical parameters of these soil layers are summarized in Table 1.

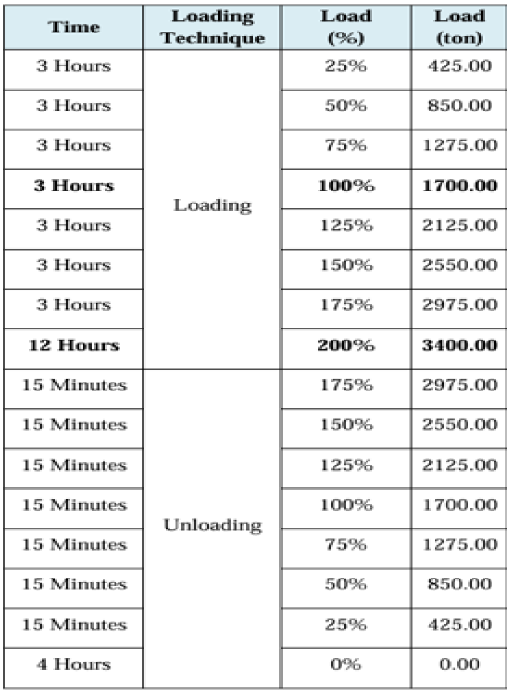
Cross-hole testing on-site determined an average shear wave velocity of 600 m/s for the upper 30-meter soil layers. Standard penetration test (SPT) blow counts exceed 50, and undrained shear strength exceeds 250 kPa. According to Egyptian standards, the site soil is classified as Category B. Based on the seismic parameter zoning map of Egypt, the PGA for the Alamein region is 0.125g.

III. PILE AND PILE-RAFT FOUNDATION DESIGN

A. Test Piles and Results

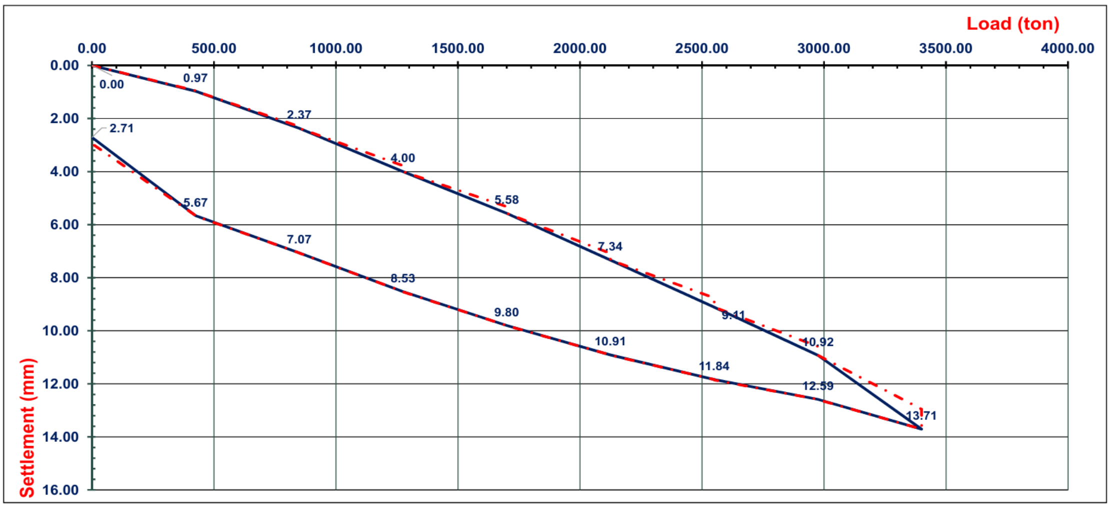
To accommodate varying load demands across different regions of the tower foundation, the design incorporates piles with load-bearing capacities of 1400 tons and 1700 tons. The primary distinction between these two types lies in their respective pile lengths and concrete strength. A field photograph of the test pile load setup for the 1700-ton capacity pile is presented below

B.



Time	Loading Technique	Load (%)	Load (ton)
3 Hours	Loading	25%	425.00
3 Hours		50%	850.00
3 Hours		75%	1275.00
3 Hours		**100%**	**1700.00**
3 Hours		125%	2125.00
3 Hours		150%	2550.00
3 Hours		175%	2975.00
12 Hours		**200%**	**3400.00**
15 Minutes	Unloading	175%	2975.00
15 Minutes		150%	2550.00
15 Minutes		125%	2125.00
15 Minutes		100%	1700.00
15 Minutes		75%	1275.00
15 Minutes		50%	850.00
15 Minutes		25%	425.00
4 Hours		0%	0.00

Figure 4: Field photograph of the test pile setup for 1700-ton capacity piles (left) and load test data (right)



Appendix (B)
Figure 03A: Load - Settlement Curve

Figure 5: Load-displacement curve for vertical pile load testing

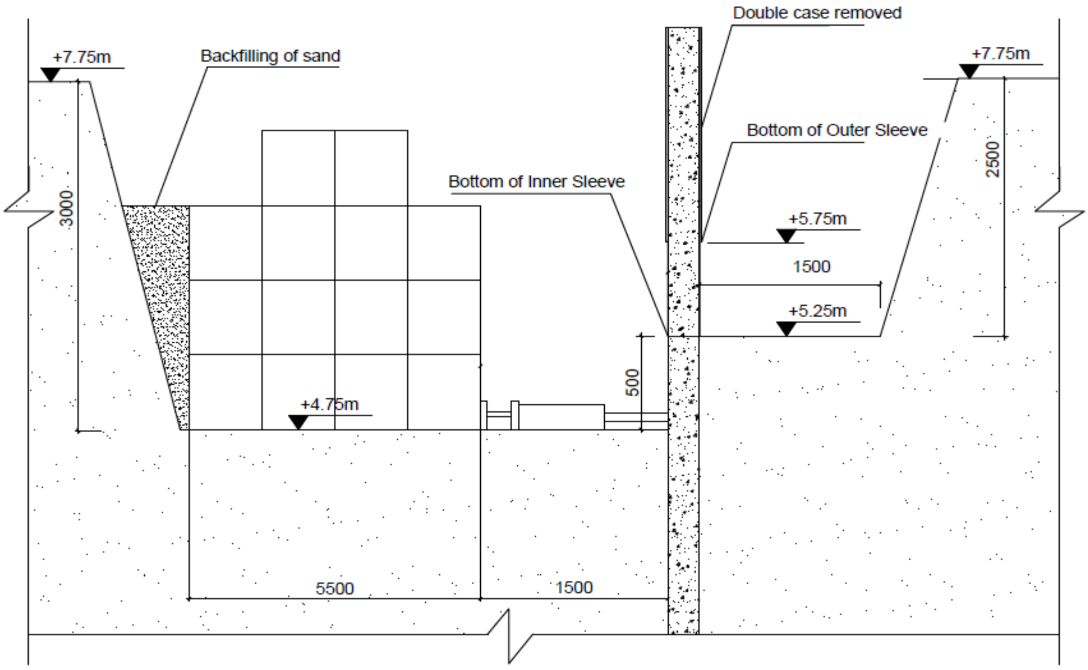


Figure 6: diagram of horizontal load testing equipment for the test piles

Figure 7: Field photograph of horizontal load testing equipment for the test piles

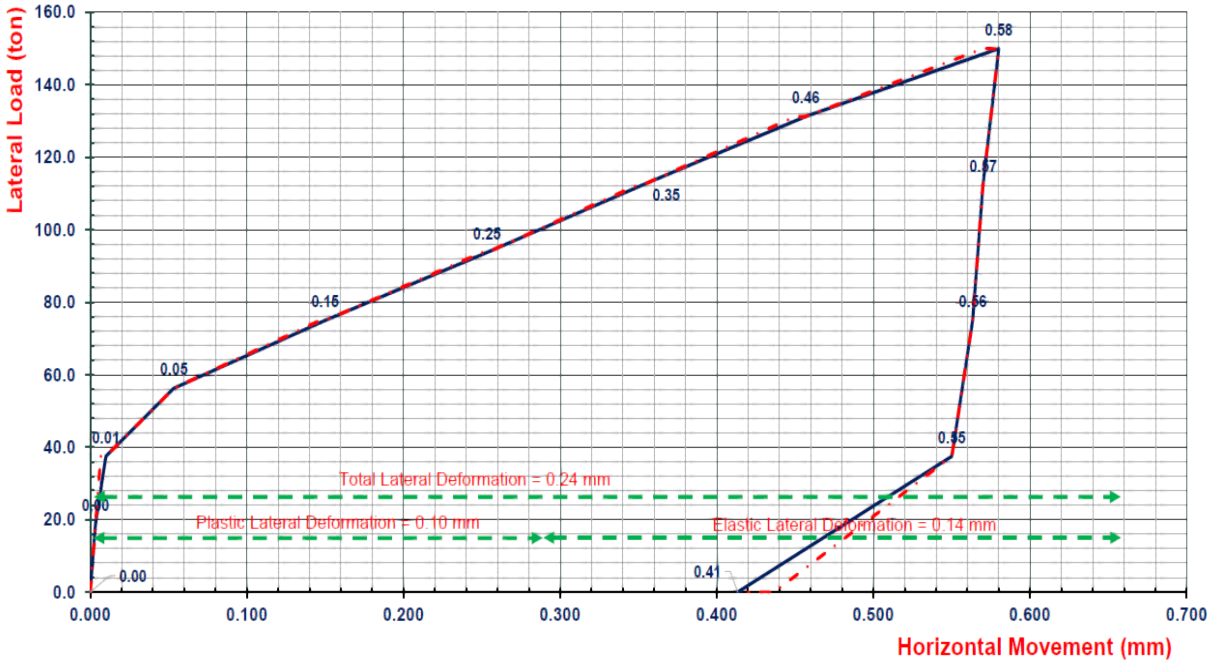


Figure 8: Load-displacement curve for horizontal pile load testing

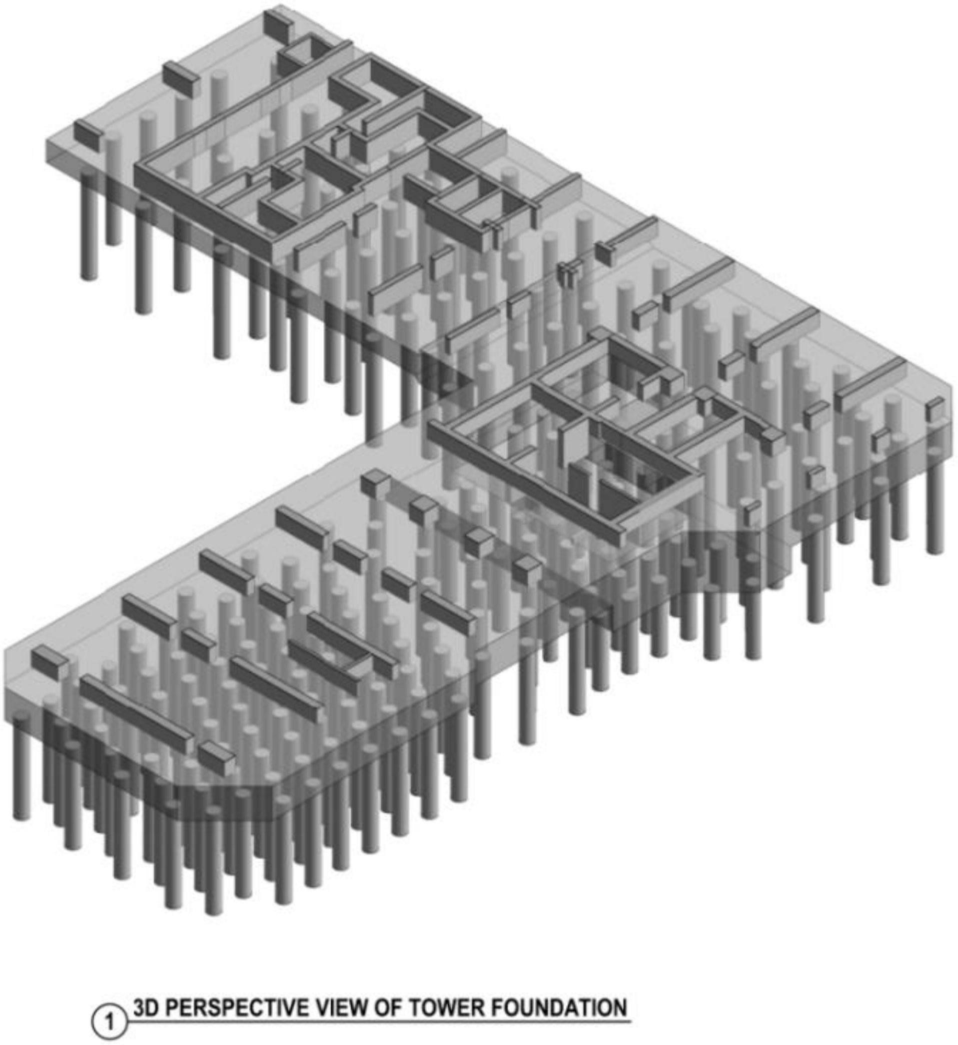


Figure 9: 3D view of pile-raft foundation layout

C. Horizontal Load Test and Results

In accordance with the design requirements stipulated by the structural consultant, the tower piles must possess sufficient horizontal load-bearing capacity. Specifically, each pile must sustain a horizontal load of no less than 50 tons. The test results confirm compliance with these design criteria, as illustrated in the following figures 6 and 7.

D. Layout of Pile and Pile-Raft Foundation

The layout of the pile and pile-raft foundation, along with a 3D view, is depicted below in figure 8.

The foundation layout was devised based on the structural loads derived from a combination of gravity, seismic forces, and wind loads, as per Egyptian design standards [2]. Different loading conditions across various zones of the tower foundation dictated distinct pile arrangements, as detailed below:Ground-Level Recessed Zone

Due to the L-shaped footprint of the tower, which gradually transitions to a rectangular layout as the structure ascends, the ground-level recessed zone spans five stories, tapering to approximately 21 stories. This zone experiences relatively low structural loads. Consequently, the piles in this area were arranged based on actual requirements, with consideration for settlement impacts. Most pile spacings exceeded 3D (where D is the pile diameter), as indicated by the shaded region. The majority of the piles in this zone were designed with a load-bearing capacity of 1400 tons.

1. Core Tube Zone

Pile arrangement in the core tube zone was optimized to accommodate the significant variations in load distribution. In regions subjected to higher loads, a staggered, diamond-shaped arrangement was employed to increase the number of piles [4], while maintaining a minimum pile spacing of 2.5D. In areas with lower load demands, pile arrangement adhered to actual requirements, with spacing designed to control settlement and maintain a minimum distance of 3D. This configuration is illustrated in Figure 9, Zone A.

2. High-Rise Zone

The high-rise zone of the tower experiences substantial structural loads, compounded by the effects of eccentricity and torsion, which introduce significant variations in pile load distribution. To address these challenges, this zone exclusively employed piles with a load-bearing capacity of 1700 tons. A staggered, diamond-shaped arrangement was used to maximize the number of piles while ensuring a minimum pile spacing of 2.5D. This approach ensured that the foundation raft remained compact without extending beyond the footprint of the tower, which would have otherwise interfered with the podium foundation. This configuration is detailed in Figure 9, Zone B.

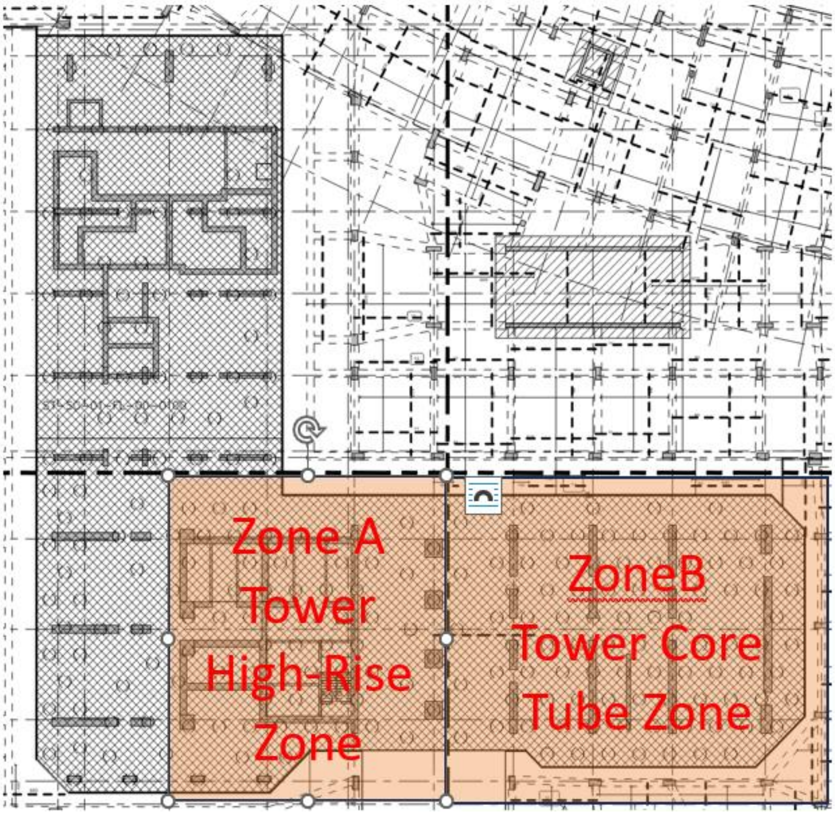


Figure 10: Pile and pile-raft foundation layout across different zones.

E. Test Pile Design, Experimentation, and Interpretation (1400-ton Test Pile as Example)

In the design of the test pile, C45 concrete was assumed, with the pile length designed at 35 meters, although the actual test length measured 35.59 meters. The pile diameter was 1200 mm. Given the designed working load of 1400 tons and adhering to the safety factor of 2.0 prescribed by Egyptian standards, the testing load was set at 2800 tons. Subsequently, a vertical load test was conducted on the single pile using a gradual step-loading and rapid step-unloading methodology. The maximum measured settlement reached 50.85 mm, which exceeded the allowable settlement value of 41.65 mm calculated based on Egyptian standards.

While increasing the pile length or diameter is a conventional method to reduce settlement, applying this solution across all 238 piles in the project would result in a significant cost increase. Therefore, alternative strategies were explored to enhance the load-bearing capacity of the piles, reduce settlement, and optimize costs. Considering that the subsoil primarily comprises fractured and porous limestone, post-grouting technology was employed. This technique utilizes pre-embedded grouting pipes at the bottom and sides of the reinforcement cage to inject high-pressure grout. The injected grout infiltrates, fractures, fills, and compacts the surrounding soil, binding it to the pile, solidifying the sediment at the pile base, and removing the mud skin around the pile shaft. These effects are particularly pronounced in limestone layers, significantly improving load capacity and settlement performance [5]. Based on these advantages, the project adopted post-grouting technology to enhance the load-bearing capacity of single piles to meet regulatory requirements, and additional tests on post-grouting bored piles were conducted.

F. Comparative Validation of Conventional Bored Piles and Post-Grouting Bored Piles

Before finalizing the pile design, test piles were strategically placed at sites representing the most unfavorable geological conditions. To determine the ultimate frictional resistance and end-bearing capacity of each soil layer, as well as to verify and calibrate the theoretical improvement coefficients for the frictional and end-bearing resistances of bored piles, both vertical and horizontal load tests were performed on single piles.

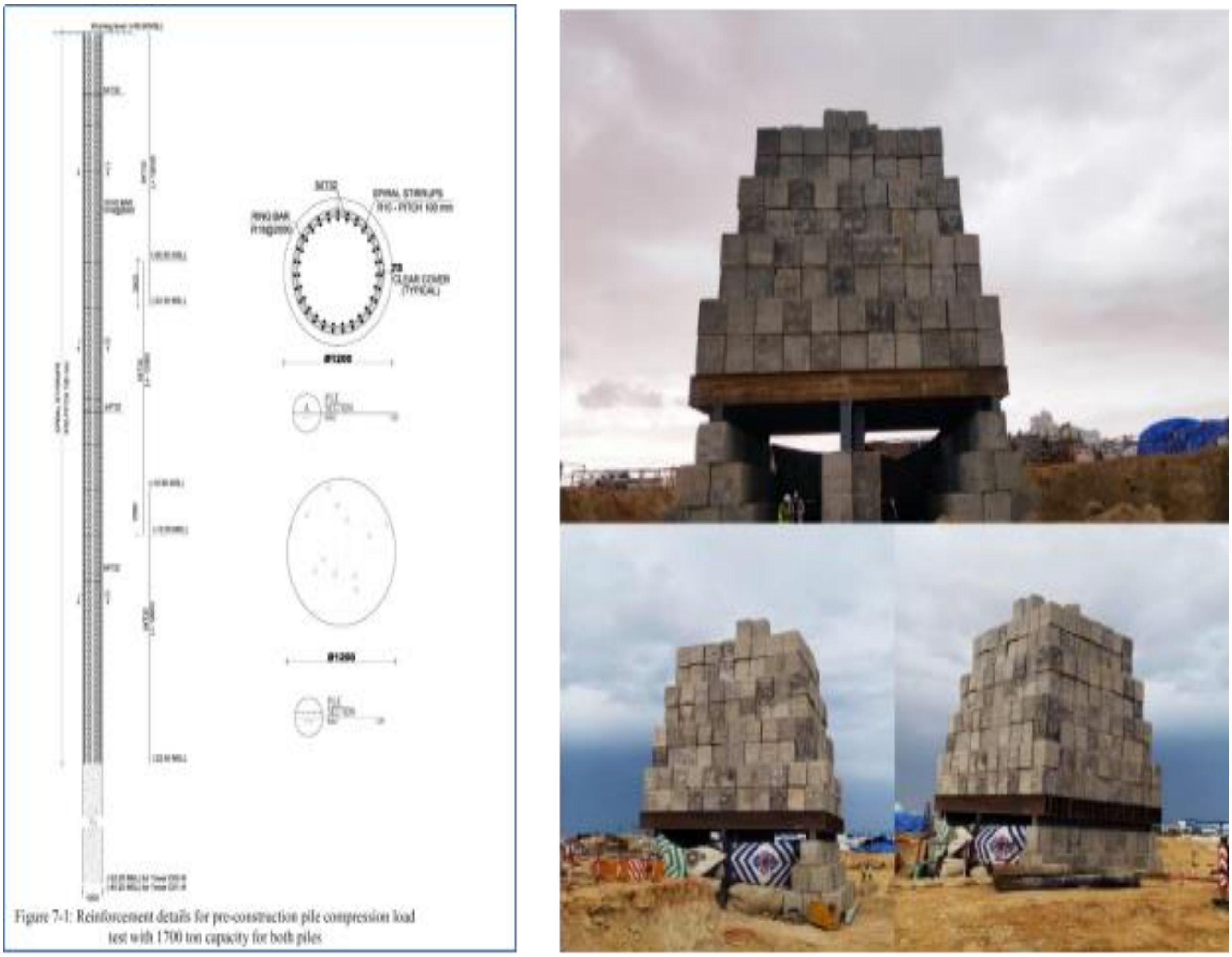


Figure 11: Single pile reinforcement and friction-end bearing resistance test results

1. Single Pile Vertical Load Test

In this test, C45 concrete was used, with a pile diameter of 1200 mm and a pile length of 35.8 meters (pile tip at -26.26 MSL). The designed working load for the pile's end-bearing capacity was 1400 tons, with a test load set at twice the working load, i.e., 2800 tons. Using a gradual step-loading and rapid step-unloading procedure, the test recorded a maximum settlement of 13.06 mm, which is well below the allowable settlement value of 41.65 mm as per Egyptian standards. The calculated maximum load-bearing capacity of the pile reached 6607.9 tons, yielding a safety factor of 4.72—substantially exceeding the standard requirement of 2.0.

2. Single Pile Horizontal Load Test

For the horizontal load test, the same pile specifications were used: C45 concrete, a pile diameter of 1200 mm, and a length of 35.8 meters (pile tip at -26.26 MSL). The designed working load for horizontal end-bearing capacity was 50 tons, and the test load was set at three times the working load, i.e., 150 tons. Using a constant-speed, step-loading and unloading procedure, the test measured a maximum horizontal displacement of 0.24 mm, meeting the requirements of Egyptian standards.

Figure 12: Single pile end-bearing resistance test results

During the vertical load tests, strain gauge readings revealed that, for post-grouting bored piles, most of the reactive force was provided by the side frictional resistance of the pile, with negligible contribution from the pile tip. Subsequent calculations and analyses resulted in the adoption of amplification factors for the post-grouting technique, as summarized below:

Table 2: Amplification Factors for Post-Grouting Technology

Soil Type	Side Friction Amplification Factor	End-Bearing Amplification Factor
Sandstone	1	1
Limestone	1.617	1

IV. OPTIMIZATION OF THE PILE FOUNDATION SCHEME

Based on the aforementioned findings and the application of post-grouting technology, the piles exhibited significant excess load-bearing capacity in their original lengths. Consequently, in the final design phase, the pile diameter was standardized at 1200 mm, while the lengths of 1400-ton capacity piles were optimized from 35.6 meters to 30 meters, and the 1700-ton capacity piles from 37.2 meters to 32 meters. The rationality of these adjustments was rigorously validated through both geotechnical and structural analyses.

During the design process, the project accounted for the influence of group piles and soil spring stiffness effects. Finite element analysis was employed to iteratively adjust the soil spring stiffness values by comparing actual settlement with calculated results, ultimately determining a stiffness value that most accurately reflected real-world conditions.

The maximum settlement, calculated to occur in the core tube region, was determined to be 45 mm, which aligns closely with the conclusions of the geotechnical analysis and satisfies the requirements of Egyptian standards.

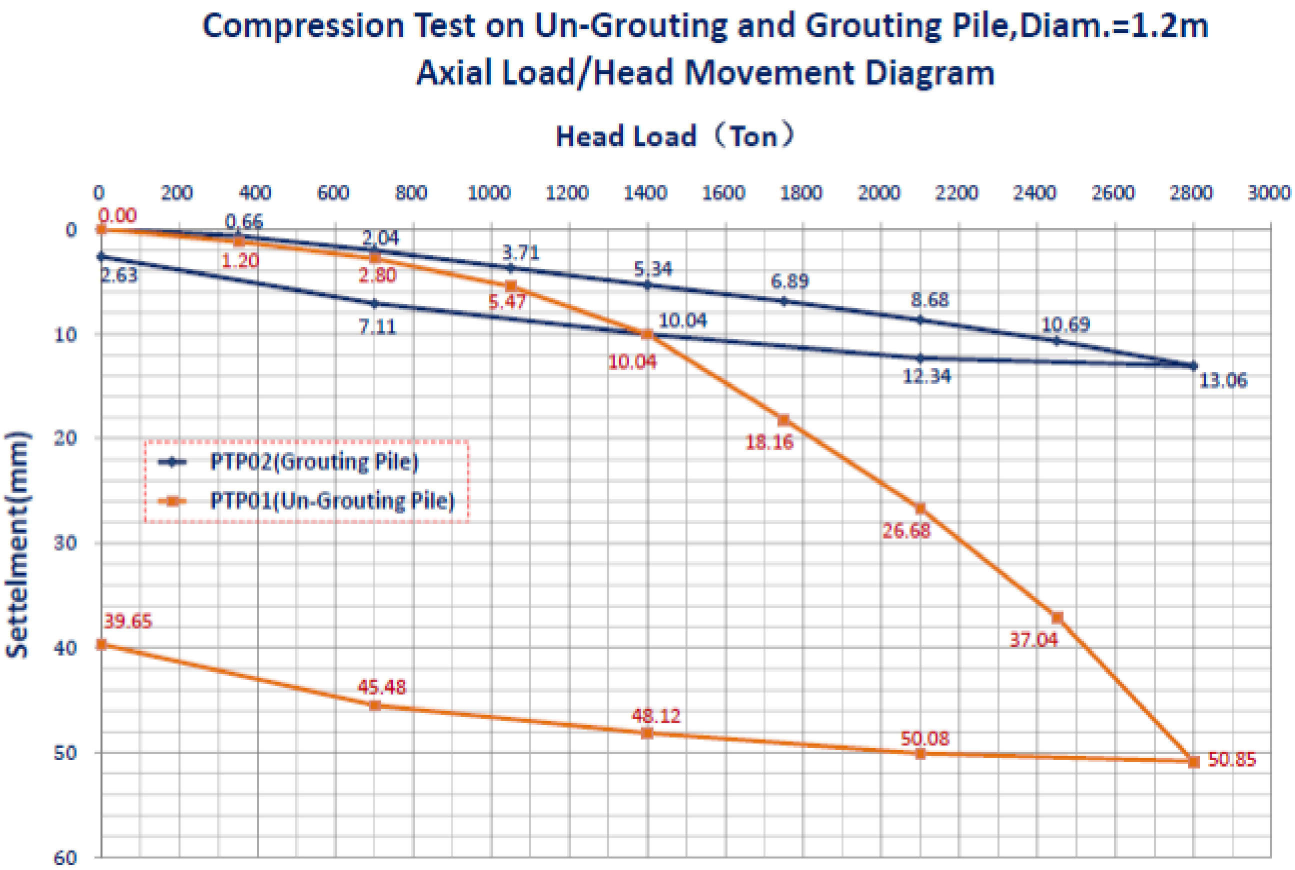


Figure 13: Comparison of maximum displacement values between conventional and post-grouting bored piles during testing

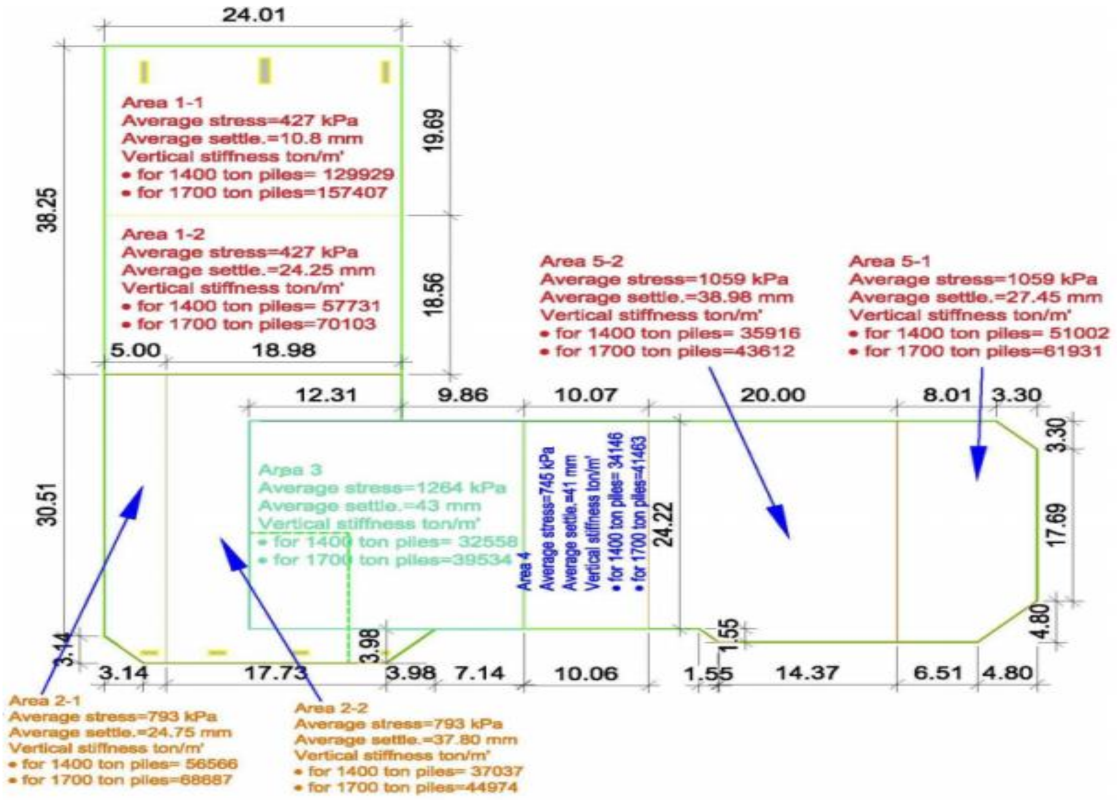


Figure 14: Average stress, settlement, and subgrade reaction modulus across various zones of D01

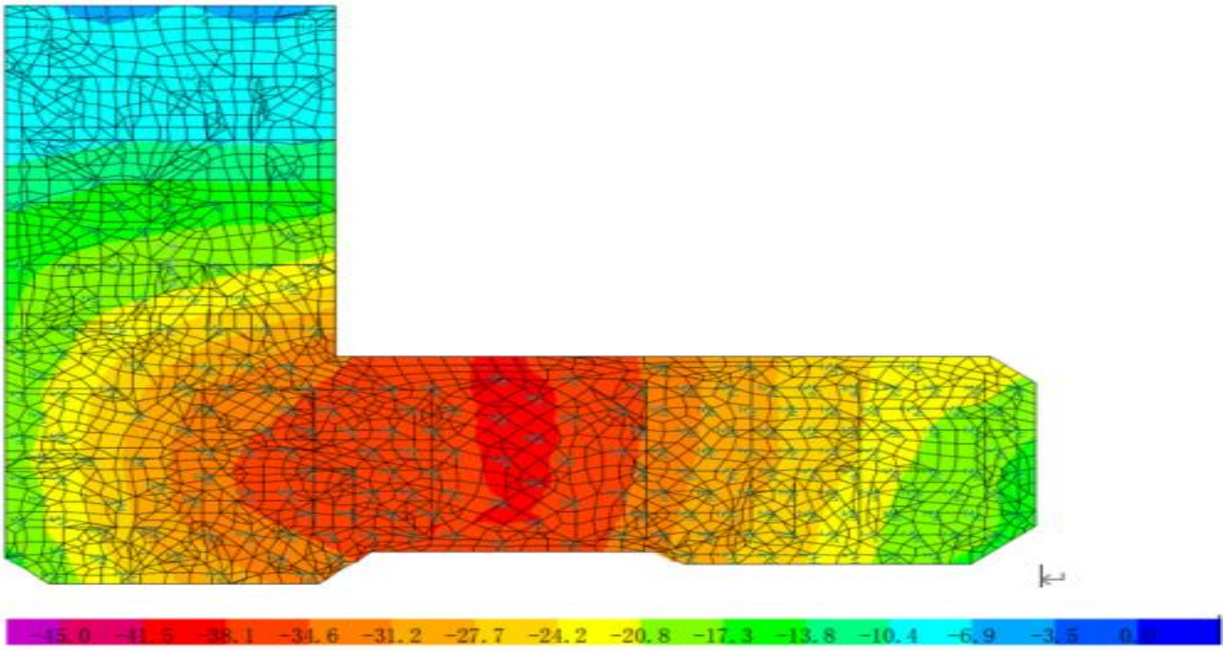


Figure 15: Settlement analysis results from ETABS software

CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

This study, conducted within the challenging karstic geological conditions of the Alamein region in Egypt, demonstrates the superior performance of post-grouting bored piles compared to conventional bored piles. Through comparative tests, post-grouting technology has been proven to significantly enhance single-pile load-bearing capacity and effectively reduce settlement. The adoption of this technique ensured compliance with regulatory requirements for pile capacity while simultaneously optimizing pile length, thereby reducing material usage and construction costs.

In terms of the pile foundation layout, the staggered diamond-shaped arrangement employed in the core tube and high-load zones improved load efficiency, while the on-demand arrangement in peripheral zones minimized settlement discrepancies. The maximum settlement was controlled within the regulatory limits and closely matched the structural analysis results. The optimized scheme not only met safety and design requirements but also achieved significant cost reductions in overall construction.

B. Practical Implications and Suggestions for Innovation

This project successfully integrated geotechnical conditions, design standards, and cost control considerations. By combining finite element analysis with on-site testing, the rationality and efficacy of the pile foundation design were validated, providing a reliable reference for future pile foundation designs in similar geological contexts.

C. Recommendations for Engineering Practice

In ultra-high rise building projects with similarly complex geological conditions, it is recommended to prioritize post-grouting technology to enhance pile performance. However, construction costs and technical complexity must be carefully considered, with design adjustments made to suit local conditions. The pile foundation layout should balance load distribution and settlement control, with denser or staggered arrangements in core regions and more flexible layouts in peripheral zones to reduce construction costs and avoid resource wastage. For suboptimal ground conditions, combining post-grouping with pile length optimization can effectively enhance load-bearing capacity while maintaining economic feasibility.

1. Future Research Directions

- Technological Advancements: Explore the applicability of post-grouting technology across diverse geological conditions, particularly in other karstic formations or high-plasticity clay soils.
- Long-Term Performance Studies: Conduct longitudinal studies on the long-term performance of post-grouting technology, assessing changes in pile load-bearing capacity and settlement trends over the lifecycle of the structure to inform future maintenance strategies.
- Intelligent Monitoring: Leverage big data and sensor technologies to establish dynamic monitoring systems for pile construction and usage, enhancing quality control during construction and efficiency in maintenance in post-construction.

- Sustainability Initiatives: Investigate the use of low-carbon, environmentally friendly materials and methods in pile construction to align with the green development goals of the construction industry.

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Additionally, sincere appreciation goes to the structural consulting firm for their technical support and professional guidance during the design phase, particularly for their insights into pile load-bearing analysis and layout optimization, which greatly enhanced the scientific rigor and reliability of the design scheme.

Finally, the author extends deep gratitude to all individuals and organizations involved in this project for their contributions and commitment. Thank you!

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