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Validation and Parametric Optimization of CPRF Systems

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***Abstract*— Increased urbanization and reduced availability of land have increased the demand for safe, cost-effective, and efficient foundation systems, especially in soft cohesive soils where differential settlement may be significant. The Connected Piled Raft Foundation (CPRF) system has emerged as an effective solution due to its ability to combine the both foundations, but there is a lack of real-case–calibrated PLAXIS 3D models incorporating the Hardening Soil model to accurately capture their behavior in soft cohesive soils. A finite element model was developed in Plaxis 3D to realistically simulate soil-structure interaction and validated against Messe-Torhaus piled raft foundation. A comprehensive parametric study was then conducted where different parameters like pile configuration, raft thickness, pile length, and diameter are varied and an improved configuration with better economy higher efficiency in load sharing was found. The optimized configuration of CPRF showed performance comparable to the original design with a 10% reduction in construction cost.**

***Index Terms*— Plaxis 3D, Piled-raft foundation, Load sharing ratio.**

I. INTRODUCTION

The last few decades have seen a sharp increase in the demand for very high-rise structures because of rapid urbanization. Since many of these urban centers are running out of space, many structures are constructed in soft, weak, or compressible areas, especially in congested urban regions where rock layers are not readily accessible. In these circumstances, excessive settlement becomes a significant problem. Piled raft foundations have become a widely used effective solution in these circumstances.

In this foundation system, raft, the piles, and the soil form a combined system which all share the applied load. This system takes advantage of the synergy in the increase of the bearing capacity, the reductions in total settlement and differential settlement, as well as bending stress in the raft. Because of these benefits, piled rafts are more economical than fully piled foundations and outperform ordinary shallow foundations.[1]

Nonetheless, the complexity of soil-structure interaction makes the behaviour of piled rafts foundation systems complicated. The fracturing of loads between a raft and piles, as well as the subsequent bearing capacity predictions, becomes critical to the design of such foundations. Global standard codes outside of Eurocode 7 are yet to publish a universal guideline, thus safety-based design methods and numerical models have been proposed by researchers. Notably, Germany has made significant contributions to this area. Piled rafts were first used successfully in Germany at Frankfurt.

The piled-raft foundation system is a composite structure of piles and raft, where a load-bearing raft replaces the pile cap.

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This way, both raft and pile collectively share the superstructure load and distribute it to the soil more effectively. This approach leads to a reduction in several required piles, resulting in significant cost savings. This hybrid enhances the overall foundation performance, ensuring stability and keeping settlement within permissible limits. Piled rafts combine the benefits of both their components and can be effectively used to support heavy structures, infrastructure, and in weak or variable soils, optimizing load distribution and controlling settlements. Piled raft foundations employ piles to manage settlement, with the piles offering the majority of stiffness under serviceability loads, while the raft component contributes extra capacity when ultimate loads are reached. Typically, the number of piles needed can be decreased when the raft supplies this additional capacity. [2] Among its many advantages, the PRF system is cost-effective, as it requires fewer piles than traditional piled foundations, reducing material and construction costs. It also improves the bearing capacity of the soil-structure system, offering greater stability for tall buildings. Furthermore, the PRF design allows for flexibility in terms of pile length, spacing, and raft thickness, which can be adjusted based on specific soil conditions and loading requirements. This versatility ensures optimized performance for different structural needs. PRFs have been successfully implemented in iconic structures such as the Burj Khalifa in Dubai, the Petronas Towers in Malaysia, and the Messeturm building in Frankfurt, demonstrating their reliability and efficiency in real-world applications.[3] Despite these advantages, real-case modelling integrated with parametric optimization still has some gaps especially in the context of soft cohesive soils typical of Indian metropolitan areas. Currently, the majority of studies are investigating parameters one-by-one, making use of simplified analytical assumptions, and not being fully calibrated against the behaviour observed in the field. Additionally, there has been little work done on combining the Hardening Soil model with fully connected raft–pile interaction into a single 3D framework for the exploration of the optimum configurations of pile number, spacing, diameter, length, and raft thickness. Consequently, there is a demand for a comprehensive study which not only accurately represents CPRF behaviour through modeling but also provides inexpensive solutions for design under realistic soil conditions. The absence of a design method for CPRF that has been both validated and optimized might lead to foundations experiencing excessive settlement, inefficient load-sharing, or material requirements that are not economically viable. As a result, this investigation's primary goal is tantamount to the development and confirmation of the three-dimensional PLAXIS based numerical model of a Connected Piled Raft Foundation aided with extensive parametric analysis to identify the optimized configuration suitable for soft cohesive soils. The research, through this methodology, aims to offer better design guidance, settlement control, and economically efficient CPRF solutions that are in line with local Indian engineering practice.

II. PLAXIS 3D MODELLING

This study employed PLAXIS 3D, a finite element-based geotechnical engineering software, to simulate and assess the load-sharing behavior and performance of a raft foundation supported by piles embedded in soft cohesive soil. To carry out a finite element analysis, a 3D model consisting of lines, 2D surfaces, volumes, etc, were developed and assigned material properties of soil and concrete. This is followed up by creating a 3D finite element mesh and defining the different construction phases to perform calculations. Plaxis3D allows soil to be modelled in a variety of material models like Mohr-Coulomb, Linear Elastic, Hardening Soil, user-defined, etc. Out of these, the Mohr-Coulomb and Hardening Soil models were used. [4]

The Mohr–Coulomb (MC) model is a simple, linear elastic–perfectly plastic constitutive model that uses a single failure surface, assuming that soil behaves elastically until it suddenly yields. It uses 5 main parameters: Cohesion (C), angle of Frictional Resistance (phi), Modulus of Elasticity (E), and Poisson's ratio (nu) to represent and simulate soil behavior. Because of this simplification, MC does not capture stiffness variation with stress level, nor does it realistically represent soil stiffness during unloading–reloading cycles, which makes it suitable mainly for preliminary designs or homogeneous soil conditions where high accuracy is not essential. This model is suitable for cohesionless soils and hence it was used for quaternary terrace gravel layer. The soil properties of that soil layer are listed in Table I. [5]

TABLE I: SOIL PARAMETERS USED FOR GRAVEL LAYER

Parameter	Symbol	Unit	Value
Modulus of Elasticity	E	KN / m^2	75,000
Cohesion	C	KN / m^2	0
Angle of Frictional Resistance	f	°	32.5
Unit Weight	g	KN / m^3	18
Poisson's Ratio	n	-	0.25
Interface Reduction Factor	R_{inter}	-	0.95

The Hardening Soil (HS) model, on the other hand, is an advanced, stress-dependent, nonlinear elastoplastic model that uses three different stiffness moduli to represent soil behavior under loading, unloading, and confined compression. The HS model also includes hardening behavior, meaning the soil stiffness increases with plastic straining, providing a much more realistic representation of settlement, lateral deformation, and foundation response. This model uses 3 different types of Elastic Modulus:

- E_{50} (Secant Stiffness in Drained Triaxial Loading): It represents the soil stiffness during primary loading up to 50% of the failure stress in a triaxial test.
- E_{oed} (Oedometer Stiffness): It represents the soil compressibility in a 1D compression (oedometer) test under vertical loading with no lateral strain.
- E_{ur} (Unloading Stiffness): It represents the much higher stiffness of soil when it is unloaded or reloaded, capturing the reversible part of soil deformation.

Therefore, HS is preferred for detailed geotechnical analysis, piled raft foundations, and cases where nonlinear stress–strain behavior is important. It is useful for cohesive soils and was used for modelling Frankfurt Clay. The properties of Frankfurt Clay are listed in Table II. [6]

TABLE II: SOIL PARAMETERS USED FOR FRANKFURT CLAY LAYER

Parameter	Symbol	Unit	Value
Cohesion	C	KN / m^2	20
Angle of Frictional Resistance	f	°	20
Unit Weight	g	KN / m^3	18.5
Modulus of Elasticity	E_{50} / E_{oed} / E_{ur}	KN / m^2	50,000 / 50,000 / 150,000
Power	m	-	1.0
Interface Reduction Factor	R_{inter}	-	0.85

The raft is modelled as a combination of soil volume and plate. The soil element is a Linear Elastic, non-porous model to mimic the behaviour of concrete. The soil rests on a thin plate element of really low stiffness compared to the soil. The plate serves as a connection point between the raft and piles (embedded beams) and transfers part of the load acting on the raft to the embedded beams.

Interfaces are created on all the faces of the raft except the top to create proper contact between the foundation and the rest of the soil. However, for Axisymmetric models, the faces lying on the model boundaries don't require interfaces. Figure 1 depicts the foundation layout.

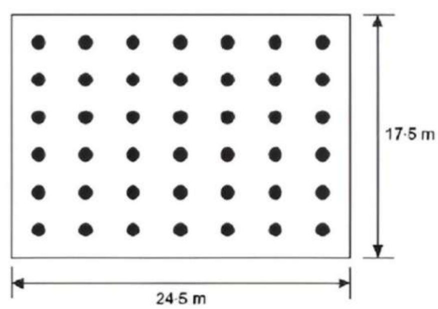

Figure 1. Raft Layout of Messe-Torhaus building

The raft has plan dimensions of 24.5 m × 17.5 m with a thickness of 2.5 m. Its unit weight is taken as the self-weight of concrete, equal to 25 kN/m³. The modulus of elasticity of the raft material is 34,000,000 kN/m², and the Poisson's ratio is assumed to be 0.2. The total load acting on each raft is 200MN, which comes out as 466.5 KN/m2 distributed uniformly throughout the raft. Table III contains a list of all these parameters. [5]

TABLE III: LIST OF RAFT PROPERTIES

Parameter	Symbol	Unit	Value
Raft Dimensions	L x B	m	24.5 x 17.5
Thickness of Raft	D	m	2.5
Uniform Loading	q	KN / m^2	466.5
Unit Weight	gamma	KN / m^3	25
Modulus of Elasticity	E	KN / m^2	34,000,000
Poisson's Ratio	nu	-	0.2

Piles were modelled as embedded beam elements, comprising beam elements coupled with specialized interface elements that simulate the interaction between the pile and the surrounding soil.These beams are manually drawn in the drawing space or their endpoint coordinates can be input into the command lines. The concrete properties of piles are similar to those of rafts and are listed in Table IV. In Axisymmetric models, if the embedded beams are located at the edge, their properties like surface area and tip resistance are halved, since they are located at the plan on symmetry and therefore, only half of the pile is modelled to ensure the best results.

TABLE IV: LIST OF PILE PROPERTIES

Parameter	Symbol	Unit	Value
No. of Piles	n	-	42 (6 x 7)
Pile Depth	L	m	20
Pile Diameter	d	m	0.9
Pile spacing (c/c)	s	-	3d to 3.5d
Unit Weight	g	KN / m3	25
Modulus of Elasticity	E	KN / m2	25,000,000

III. MODEL VALIDATION

Before conducting a parametric study in PLAXIS 3D, it is essential to first establish the accuracy and reliability of the adopted modelling approach.This is done by selecting a real structure with on-site testing data or any other reliable study and comparing it to our model, developed using similar parameters.

The case selected for the validation purpose is the piled raft foundation of the Messe-Torhaus building located in Frankfurt, Germany. This building was selected because it was one of the first implementations of connected piled raft foundations. On top of that, its settlement behavior was rigorously monitored using multiple strain gauges, load cells, extensometers etc, thus having available settlement behaviour to compare to. The Plaxis model is depicted in Figure 2. [7]

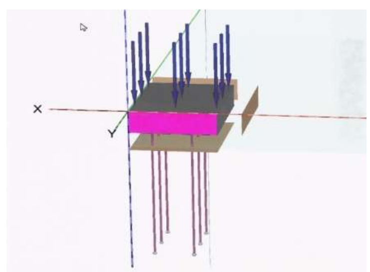

Figure 2. Plaxis3D model of the Messe-Torhaus building's foundation

The model developed in Plaxis3D was analyzed by loading incrementally in 20000 KN intervals till the service load and the output was compared to the settlement recorded on the site of the Messe-Torhaus building using strain gauges. As seen in Figure 3, the results obtained from Plaxis3D were mostly accurate to the real observations, except at the very end, where the real settlement increases substantially compared to the one simulated in Plaxis3D.

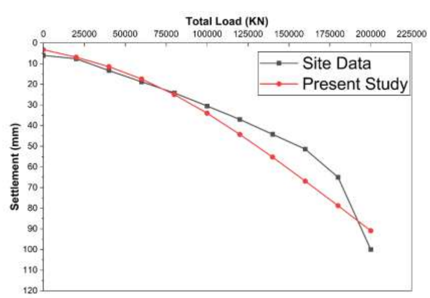

Figure 3. Comparison between the Load settlement curve of the Messe-Torhaus piled raft foundation

This discrepancy is primarily due to the modelling approach. The Plastic calculation approach doesn't take into account long term consolidation effects and the loading takes place instantaneously in each calculation phase.

Whereas the load application on the Messe-Torhaus building's foundation took place gradually over a period of months, allowing for consolidation settlement to take place.

IV. PARAMETRIC ANALYSIS

A set of parametric analyses were conducted in order to optimize the design of the structure, which was primarily designed based on empirical methods of the time.
While conducting these studies, the primary focus was on bringing acprf to nearly 0.50 and the overall settlement down, without compromising on the safety and improving economy of the structure. The parameters which were altered are listed below:

- Number of piles and their spacing
- Thickness of Raft
- Length of Piles
- Diameter of Piles

A. Pile Configuration

After examining several variations in pile spacing and pile count, it was observed that the original configuration contained an excessively large number of piles, resulting in nearly 80% of the load being transferred to the piles. It was also observed that the spacing was too close which led to reduced marginal gains in the capacity of the pile group due to pile-pile interaction. Thus, an alternate configuration adopted for the parametric study consists of a 4 x 6 configuration of piles with a uniform spacing of 4D, where D is the diameter of the pile.

B. Effect of Raft Thickness

With the chosen pile configuration, the raft thickness was varied to evaluate its influence on the load-sharing ratio, overall settlement, and differential settlement. The raft thickness was varied from 1.5m to 4m and the resulting graphs are depicted in Figures 4 and 5. The reduction in differential settlement is also depicted in Figure 6.

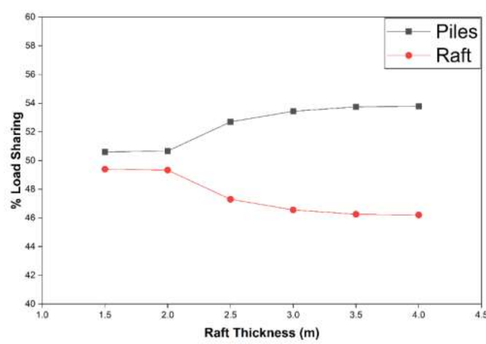

Figure 4. Graph showing variation of Load Sharing percentage (Y-axis) with Raft Thickness (X-Axis)

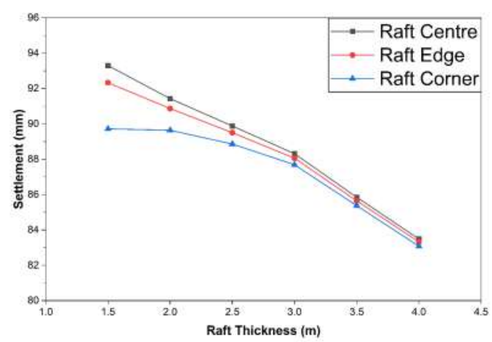

Figure 5. Graph showing variation of Raft settlement (Y-axis) with Raft Thickness (X-Axis)

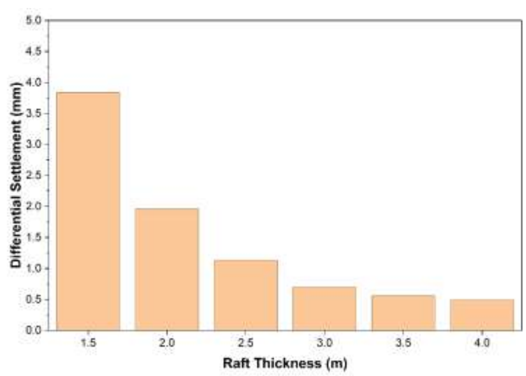

Figure 6. Graph showing variation of Differential Settlement (Y-axis) with Raft Thickness (X-Axis)

Based on the graphs, the following observations can be made:

- Increasing the raft thickness did not have a significant influence the load sharing ratio (acprf), which was the lowest at 2.5m raft depth.
- The load sharing ratio was closest to 50% at 1.5m thickness but it also had the maximum differential settlement.
- The settlement at the center of the raft reduced consistently with increase in raft thickness, from 93mm to 83mm. This reduction in settlement is good but not economical when considering the cost of increasing the thickness of the raft
- However, increasing Raft thickness showed a significant reduction in differential settlement, going from 3.58 mm at 1.5m thickness to 0.41 mm at 4m thickness. This reduction in differential settlement is clearly visible in Figure 6, where the curves for settlement in the raft's midpoint, corners and edges converge. This reduction is differential settlement is almost negligible after 3m raft thickness, as depicted by all 3 curves being almost parallel to each other, so increasing thickness beyond 3m won't bring much benefit for the cost it incurs.

C. Effect of Pile Length

Raft thickness of 3m was selected for conducting further analysis on pile length. The pile length was varied from 10m to 36m while keeping the remaining parameters constant and the variation in load sharing and settlement is presented in Figures 7 and 8. Figure 9.

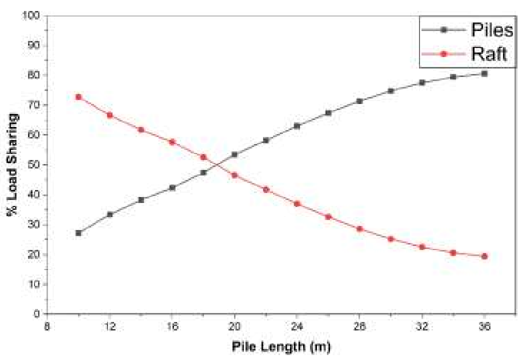

Figure 7. Graph showing variation of Load Sharing Ratio percentage (Y-axis) with Pile Length (X-Axis)

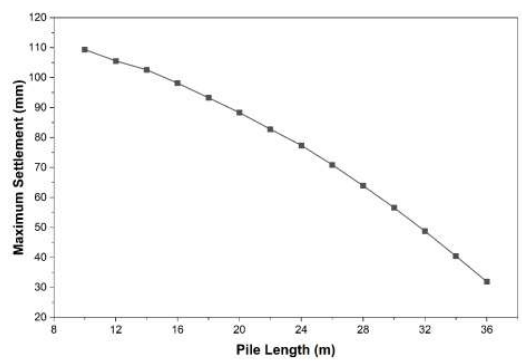

Figure 8. Graph showing variation of maximum settlement (Y-axis) with Pile Length (X-Axis)

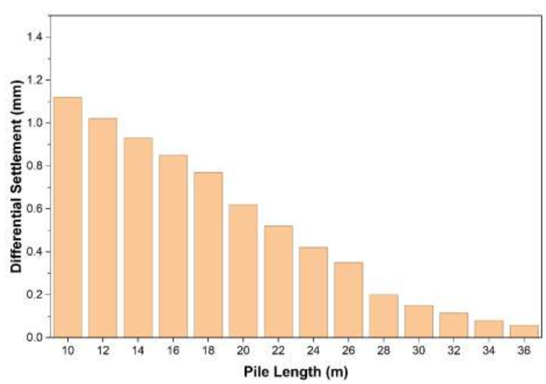

Figure 9. Graph showing variation of Differential Settlement (Y-axis) with Pile Length (X-Axis)

The following observations were made:

- Increasing the pile length showed a gradual and consistent increase in the load carried by the pile group, from 27% to 80%. However, the curves for both pile and raft begin to flatten after 34m, indicating a point of diminishing returns.
- Maximum raft settlement went down significantly by 70% (from 109mm to 32mm).

- Differential settlement went down from 1.12mm at 10m to 0.06mm at 36m, indicating that increasing pile length does affect differential settlement but not as significantly as pile spacing and raft thickness.
- a_{cprf} was closest to 0.50 at roughly 18m length.

Based on these observations, pile length of 18m was adopted for the next stage of analysis.

D. Effect of Pile Diameter

After selecting the pile length of 18m, the pile diameter was varied from 0.5m to 1.6m from the original diameter of 0.9m. The results are compiled in Figures 10 and 11. The variation of differential settlement is visualized in Figure 12.

The key observations made from these results are:

- Pile diameter increase was accompanied by an increase in pile load share as expected, but less so than increasing pile length. The load sharing curve also begins to plateau beyond 1.2m, indicating an increase in pile-pile interaction, which reduces the capacity of the pile group
- Settlement at center of the raft went down by roughly 18% (from 102mm to 83mm) which is a lot less compared to pile length.
- Differential settlement was restricted to 1mm or lower throughout this phase, with it dropping from 1.04mm to 0.44mm.

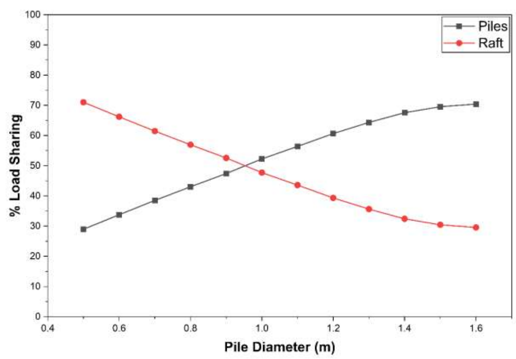

Figure 10. Graph showing variation of Load Sharing Ratio percentage (Y-axis) with Pile Diameter (X-Axis)

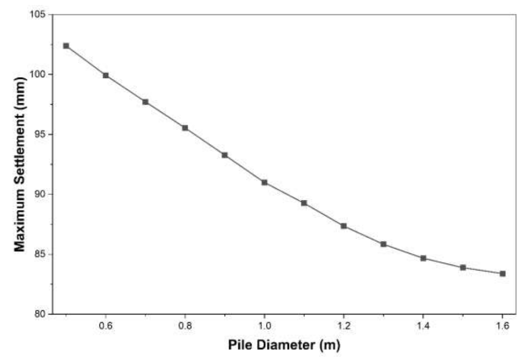

Figure 11. Graph showing variation of maximum settlement (Y-axis) with Pile Diameter (X-Axis)

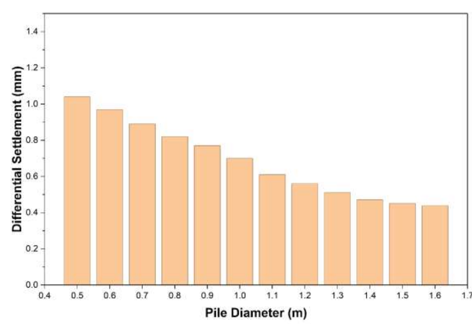

Figure 12. Graph showing variation of Differential Settlement (Y-axis) with Pile Diameter (X-Axis)

E. Difference between old and optimized version

Figure 13 compares the load settlement curves of the original Messe-Torhaus foundation design and the one derived at the end of the parametric study. The new version has slightly more settlement due to the reduction in piles. Overall, the new design has 18 fewer piles, the raft thickness has been increased by 0.5m and the pile diameters have gone up from 0.9m to 1.2m. Based on the detailed estimation carried out for both designs based on the 2024-25 CSR rates in India, the overall cost of construction went down from Rs. 2.24 crores to Rs. 2.02 crores, which is a cost reduction of about Rs. 22 lakhs (10%), indicating that the new iteration is not only equal to the old design in terms of performance but also more economical. But overall, that both curves are very similar in nature and have almost the same capacity with the alternative design is cheaper to build by at almost 10%.

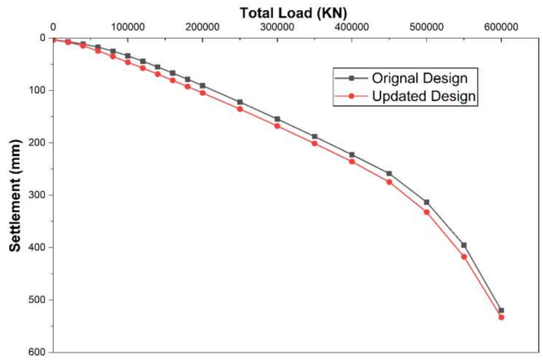

Figure 13. Comparison between Load-Settlement curves of the original and new designs of the foundation

IV. Conclusions

- The developed PLAXIS 3D successfully captured the interaction between soil, piles and raft, reliably predicting the load-settlement behavior of the Messe-Torhaus piled raft foundation.
- The Hardening Soil model was capable of replicating the nonlinear behaviour of Frankfurt Clay and provided realistic predictions of settlement, load transfer, and interaction effects. Similarly, the Mohr–Coulomb model was sufficient for the cohesionless terrace gravel layer.
- Static Pile Load Test simulations gave an individual pile capacity of about 4200 KN, which formed the basis for identifying the safe load of the piled raft, while the overall load-settlement response of the CPRF yielded an ultimate foundation capacity of 4,25,000 KN with a Factor of Safety of 2.125.
- The parametric analysis revealed that the original configuration with 42 piles was inefficient due to excessive pile–pile interaction and that an optimized 4 × 6 configuration resulted in a comparable performance with fewer piles and a more balanced load-sharing ratio.
- Increasing thickness of raft decreased the total and differential settlement substantially up to a certain limit (in this case, 3m), beyond which differential settlement wasn't significantly affected.
- Variations in pile length demonstrated a drastic increase in the load shared by piles and reduction in both total and differential settlements. However, the results start to diminish beyond a certain point (in this case 32m). Overall, 18 m piles yielded the most favourable balance of settlement reduction and a desired load-sharing ratio of 0.5.
- Increasing piled diameter resulted in higher load carrying by the pile group but beyond 1.2m diameter, the pile-pile interaction results in reduction in the capacity of the pile group.
- The final, optimized design prepared in this study had fewer piles with a slightly increased raft thickness and larger pile diameters. The ultimate capacity and settlement performance were also nearly identical to the original one, but with an estimated 100% reduction in construction cost, thus making the newer design more economically viable.

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