FINITE ELEMENT STUDY ON THE ROLE OF SAND RELATIVE DENSITY ON LATERAL LOAD DISTRIBUTION IN PILED RAFT SYSTEMS

[a] Hamad Khan*, [b]Qazi Khurshid Ahmad, [c]Abdullah Khan Jadoon

a: Department of Civil Engineering, UET Peshawar. 20pwciv5445@uetpeshawar.edu.pk
b: Department of Civil Engineering, GIK Institute of Engineering Sciences and Technology, Swabi. gcv2445@giki.edu.pk
c: Department of Civil Engineering, UET Peshawar. 20jzciv0405@uetpeshawar.edu.pk
* Corresponding author

Abstract- Combined Pile Raft Foundation (CPRF) has emerged as a widely adopted foundation system, particularly suitable for high-rise structures and sites with weak subsoil conditions. Previous research has extensively examined the influence of parameters such as pile spacing-to-diameter ratio, raft dimensions, and pile configurations on the load-sharing behavior of CPRF. However, the effect of relative density of sand on the lateral load contribution of piles and raft remains underexplored. This study presents a numerical investigation using small-scale CPRF models in *PLAXIS 3D*, a finite element software known for its capability in simulating soil–structure interaction. Relative density was modeled indirectly by varying the modulus of elasticity (E) and the internal friction angle (ϕ) of sand. The findings indicate that the raft's contribution to lateral load resistance increases with higher relative density, while the pile's share in lateral resistance decreases. Furthermore, both vertical settlement and horizontal displacement were observed to reduce as relative density increased. Specifically, settlement decreased by 71% (from 0.62 mm to 0.18 mm), and horizontal displacement reduced by 50% (0.40 mm to 0.2 mm). The shift in lateral load resistance from front piles to back piles was attributed to increased stiffness in the soil surrounding the rear piles. Understanding the role of relative density in CPRF systems can contribute significantly to their optimized and cost-effective design, reinforcing their potential as a sustainable foundation solution in geotechnical engineering.

Keywords- CPRF, Plaxis-3D, Finite Element Modelling (FEM), Relative Density

1 Introduction

During earthquakes, both vertical and lateral loads act simultaneously on pile raft foundations. CPRFs are advanced geotechnical systems that combine piles and a raft to collectively support structural loads. This system is particularly beneficial for high-rise buildings and sites with weak or compressible soils, where traditional foundations may fall short in terms of bearing capacity and serviceability [2], [5]. The interaction between the raft and piles allows for an effective redistribution of loads, leading to reduced settlement and enhanced lateral load resistance [1], [6], [8]. Extensive research, both experimental and numerical, has been conducted to assess the behavior of CPRF under different loading and soil conditions. For example, studies have shown that vertical loading can improve lateral load resistance; however, excessive vertical loads may destabilize the system [4]. Investigations using small-scale physical models [6], [8] and finite element simulations [2], [4], [7] have highlighted the role of pile spacing, pile configuration, raft geometry, and pile length in optimizing CPRF performance under lateral and vertical loading conditions. Seismic performance has also been explored, with findings indicating that pile group arrangement and load combinations significantly affect the system's response during dynamic events [4]. Moreover, soil parameters such as the modulus of elasticity (E), internal friction angle (ϕ), and Poisson's ratio (ν) have been shown to influence the interaction between the pile, raft, and surrounding soil, affecting overall foundation behaviour [7], [3]. Recent studies have compared the behavior of connected and disconnected pile raft systems and demonstrated that strategic pile placement can reduce total and differential settlement, while disconnection may help mitigate differential displacements [10]. Theoretical models developed by earlier researchers emphasized the importance of stiffness interaction and load-sharing mechanisms within CPRF systems, under both service and ultimate load conditions [9]. However, despite these advances, the effect of relative density (D_r) of sand—a key indicator of soil compactness on the lateral load distribution between the raft and piles in CPRF remains inadequately studied. D_r plays a critical role in defining the mechanical behaviour of sandy soils and thus significantly affects CPRF performance. As noted by Walter et al. [13]. A better understanding of how D_r affects the lateral load transfer in CPRF is essential for the safe and cost-effective design of foundations in sandy soils.

Additionally, lateral loading on piles induces complex soil-structure interaction phenomena such as gapping behind piles and non-uniform stress distribution along the pile shaft [8]. Though the actual relationship is nonlinear, a simplified linear approach using the modulus of subgrade reaction is often adopted in design practice [12]. This research aims to fill the existing gap by numerically evaluating how variations in the relative density of sand influence the lateral load behavior of CPRF using PLAXIS 3D. By altering sand stiffness and strength parameters to simulate different relative densities, this study contributes to a deeper understanding of CPRF behavior and offers guidance for more optimized, reliable, and sustainable foundation designs in sandy soils.

2 Research Methodology

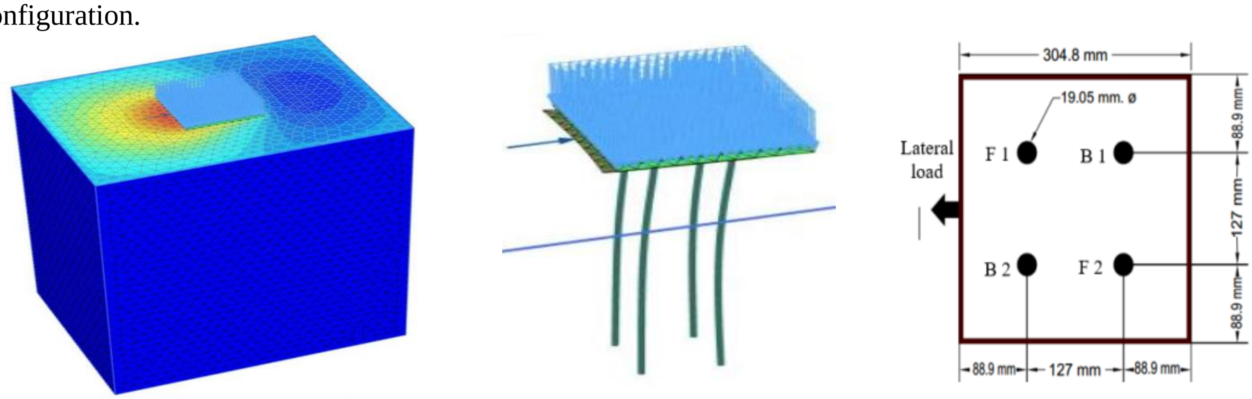
2.1 Finite Element Modelling (FEM) in Plaxis3D

CPRF with four number of piles are modelled in Plaxis3D under combined vertical and horizontal loading. Properties of soil, raft, piles, outer soil box and loading are same as that of experimental and numerical study conducted by [3] and [8] respectively. In Plaxis3D, relative density is varied by varying the value of soil stiffness (E) and phi (ϕ). Correlation between E and phi is taken from the study conducted by[3], shown in Table 1. Hardening Soil Model is used in Plaxis-3D.

Table 1 *Correlation of elastic modulus with friction angle* [3]

Model	Elastic Modulus E(Mpa)	Friction angle (phi(ϕ)
1	15	22
2	20	27
3	25	32
4	30	37
5	35	42

Figure 1a shows the complete finite element model of CPRF under vertical and lateral loading. Figure1b, depicts the 4-pile raft system showing piles raft under combined loading and figure 1c shows the 4-pile raft configuration.



a. *FEM of CPRF* ***b.*** *Piles and Raft under combined loading* ***c.*** *4-Pile Raft Configuration*

Figure 1 *Finite Element CPRF model in Plaxis3D*

3 Results

3.1 Effect of Relative density on lateral contribution in CPRF:

By increasing the relative density of sand in CPRF, three outcomes arrive, firstly, by increasing the relative density enhances raft contribution (from 14.89% to 40.03%) and reduces pile contribution (from 85.10% to 59.96%) due to increased vertical contact pressure beneath the raft, both settlements and horizontal displacement decreased by 71% (from 0.62 mm to 0.18 mm) and 50% (0.40 mm to 0.2 mm) respectively. As the sand becomes denser(stiffer), the lateral load response gradually shifts from the front piles (from 293.85 N to 203.85 N) to back piles(from 92.25 N to 71.82 N) slowly and gradually, due to the increased stiffness of the soil in front of the back piles.

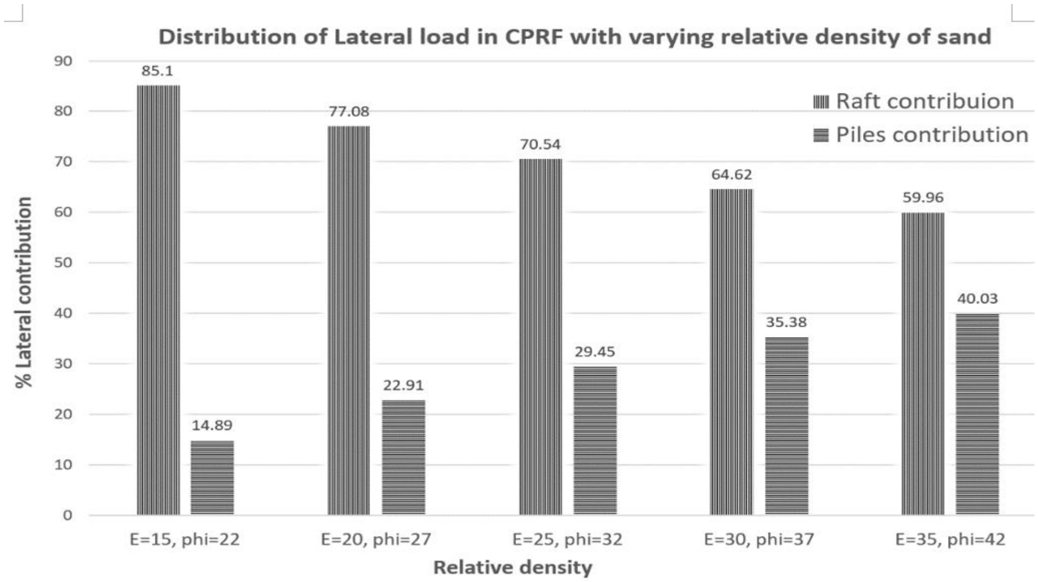


***Figure** 2 Effect of relative density on lateral load distribution in piles and Raft*

Figure 2 presents the effect of relative density of soil on Piles and raft contribution while Table 2 presents the effect on relative density on front and back piles.

***Table 2** Effect of relative density on lateral load distribution in front and back piles*

Parameters		Front Piles contribution (N)	Back Piles contribution (N)
E(Mpa)	Phi ϕ(degree)		
15	22	293.85	92.25
20	27	279.45	67.86
25	32	249.3	69.93
30	37	225.9	70.29
35	42	203.85	71.82

3.2 Use of Software

Plaxis-3d a finite element software is used in modelling of CPRF.

4 Practical Implementation

In real design, by considering the effect of relative density on lateral contribution of raft and piles, design of CPRF will be economical without the overestimation of shear forces, bending moments and displacements.

5 Conclusion

The following conclusions can be drawn from the conducted study:

1. Raft contribution in response of lateral load is directly proportional to relative density of sand. Greater the relative density of soil, greater will the lateral load response raft and vice versa.
2. By increasing the relative density i.e., stiffness of sand from 15 to 35Mpa, raft lateral contribution was increased from 14.89% to 40.03% and Piles contribution on the other hand, decreased from 85.10 %to 59.96% by increasing the relative density of sand.

At smaller relative density, front piles take more lateral load, as the soil get denser, lateral load contribution shifted from front to back piles gradually, (from 293.85 N to 203.85 N) in front piles and (from 92.25 N to 71.82 N) back piles due to increase in stiffness of soil. As the relative density increases, both settlement and horizontal displacement in piles and raft by 71% (from 0.62 mm to 0.18 mm) and 50% (0.40 mm to 0.2 mm) respectively.

References

[1] Al-Mosawi, Mosa J., Mohammed Y. Fattah, and Abbas A. O. Al-Zayadi. 2011. "EXPERIMENTAL OBSERVATIONS ON THE BEHAVIOR OF A PILED RAFT FOUNDATION." Journal of Engineering 17(04):807–28. doi: 10.31026/j.eng.2011.04.13.

[2] Bandyopadhyay, Srijit, Aniruddha Sengupta, and Yogita Parulekar. 2020. "Behavior of a Combined Piled Raft Foundation in a Multi-Layered Soil Subjected to Vertical Loading." Geomechanics and Engineering 21:379–90. doi: 10.12989/gae.2020.21.4.379.

[3] Khitrov, E. G., et al. "Interrelations of various soil types mechanical properties." Journal of Physics: Conference Series. Vol. 1177. No. 1. IOP Publishing, 2019.

[4] Deb, Plaban, and Sujit Kumar Pal. 2021. "Nonlinear Analysis of Lateral Load Sharing Response of Piled Raft Subjected to Combined V-L Loading." Marine Georesources & Geotechnology 39(8):994–1014. doi: 10.1080/1064119X.2020.1766607.

[5] Hussien, Mahmoud N., Ebraheem H. Ramadan, Mohamed H. Hussein, AbdelAziz A. A. Senoon, and Mourad Karray. 2017. "Load Sharing Ratio of Pile-Raft System in Loose Sand: An Experimental Investigation." International Journal of Geotechnical Engineering 11(5):524–29. doi: 10.1080/19386362.2016.1236224.

[6] Jamil, Irfan, Irshad Ahmad, Irshad Khan, Wali Ullah, Aqeel Ur Rehman, and Shahid Ali Khan. 2023. "Factors Affecting the Lateral Contribution of a Raft in a Piled Raft System." Ain Shams Engineering Journal 14(5):101968. doi: 10.1016/j.asej.2022.101968.

[7] Jamil, Irfan, Irshad Ahmad, Muhammad Shoaib Khan, Shahid Ali Khan, and Alam Khan. 2022. "A Parametric Study on the Interaction Factors of Pile-Raft System." Journal of Himalayan Earth Sciences Volume 55:14–24.

[8] Jamil, Irfan, Irshad Ahmad, Wali Ullah, Mahmood Ahmad, Mohanad Muayad Sabri Sabri, and Ali Majdi. 2022. "Experimental Study on Lateral and Vertical Capacity of Piled Raft and Pile Group System in Sandy Soil." Applied Sciences 12(17):8853. doi: 10.3390/app12178853.

[9] Katzenbach, R., and J. Turek. 2005. "Combined Pile-Raft Foundation Subjected to Lateral Loads." Pp. 2001–4 in Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering. IOS Press.

[10] Saady, Semaa Z. Al, and Mahdi Karkush. 2024. "Comparison Review between Behavior of Connected and Disconnected Pile Raft Foundation." in AIP Conference Proceedings. Vol. 2864. AIP Publishing.

[13] Walter, John E., William H. Highter, and Robert P. Vallee. 1982. "Determining Maximum Void Ratio of Uniform Cohesionless Soils." Transportation Research Record (897).

[11] Yenginar, Y., and M. Olgun. 2019. "Designing Piled Raft Foundations Using Simplified Analysis Methods." Eurasian Journal of Civil Engineering and Architecture 1(1):13–24.

[12] Khan, Hamad, et al. "Effect of Vertical Contact Pressure on the Lateral response of Combined Piled Raft Foundation: A Numerical Study." Journal of Himalayan Earth Sciences 58.1 (2025): 60-73.