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Effect of Vertical Contact Pressure on the Lateral response of Combined Piled Raft Foundation: A Numerical Study

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Abstract

In combined pile-raft foundations (CPRF), geotechnical engineers often assume that the lateral load is mainly supported by the piles, ignoring the contribution of the raft. This assumption can lead to a more expensive and less efficient foundation system. Various studies have examined the effects of factors such as the number of piles, pile length, pile configuration, and spacing-to-diameter ratio on the raft's contribution to lateral load. However, there is limited research on how vertical contact pressure beneath the raft affects the lateral load distribution between the raft and piles in CPRF. This study investigates the influence of vertical contact pressure on the lateral load distribution of raft and piles, focusing the impact on the front and back piles, and the effect of pile-raft configuration on lateral load distribution, while maintaining constant average vertical and lateral load per pile. In first case, a parametric study was conducted through finite element software PLAXIS-3D on small-scale piled raft model with configurations of 4 piles. A total of 14 models were created where vertical load was uniformly increased under a constant lateral load to observe the lateral response. In the second scenario, a piled raft with 4, 6 and 9 pile configurations were analysed such that average vertical and lateral load per pile across each model was maintained uniform. The results indicated that increasing vertical load enhanced the lateral response and reduced differential settlement in CPRF. The raft's lateral load contribution was found to be directly proportional to the vertical contact pressure. Additionally, at lower vertical loads, the front piles bear more lateral load than the back piles. As vertical load increased, the lateral load-bearing capacity of the back piles improved due to increased soil stiffness in front of the back piles.

Keywords: Combined pile raft foundation (CPRF), settlement, pile configuration, vertical contact pressure and PLAXIS-3D

1. Introduction

Combined Pile Raft Foundation (CPRF) and pile group foundation are both deep foundation systems that integrate piles with a raft into a single unit. They reduce the total as well as differential settlement as compared to raft alone (Bandyopadhyay et al., 2020). The key distinction between them is that in CPRF, the raft is in direct contact with the soil, necessitating interaction factors during analysis. In contrast, in a pile group foundation, there is a gap between the raft and the soil, and therefore, the pile cap is not resisting any load. For CPRF under lateral load, the rear piles bear more load than the front piles, which contrasts with pile groups where the front piles carry a greater load than the rear piles (Jamil et al., 2024). A CPRF offers lateral resistance that is approximately 2.5 to 6 times greater than that of similarly configured pile group foundations (Siddiqi et al., 2024a). Well-designed deep foundations can accommodate expansive soil conditions by modifying the pile length and diameter. Piles that extend beyond the active zone's thickness are more effective at countering volumetric changes. In highly expansive soils, granular anchor piles are far more effective than concrete piles, performing over 50% better at mitigating the adverse effects of soil expansion (Alnmr et al., 2024). Deb and Pal (2021), found that the lateral load capacity of a PRF improves with the application of a vertical load. This vertical load also boosts the raft's lateral load capacity. When the spacing between piles and the diameter ratios ranged from 3 to 5, both the pile and raft's lateral load capacity increased by roughly 14–25%.

A lot of research had been conducted on CPRF regarding the factors affecting the vertical and lateral response of piles and raft (Siddiqi et al., 2024b; Jamil et al., 2023; Kumar and Kumar, 2018; Nguyen et al., 2013; Small and Zhang, 2002). An experimental and numerical study was carried out by Jamil et al. (2023) to investigate the factors influencing the lateral load contribution of the raft in a piled raft foundation system. The findings showed that the raft's lateral load contribution is positively correlated with vertical pressure, while factors such as pile length, number of piles, and the spacing-to-diameter ratio are negatively correlated. By increasing pile spacing to diameter ratio, the Differential settlement in CPRF can be increases (Deb and Pal, 2022). By increasing the relative stiffness of raft and the soil, differential settlement of CPRF will be decreased (El-Garhy et al., 2013). As the number of piles increases, the raft's percentage contribution to resisting the lateral load decreases (Jamil et al., 2023). A numerical study about the load sharing mechanism of CPRF was conducted (Nguyen et al., 2022), and concluded that, the load sharing ratio of CPRF increases significantly with an increase in pile spacing, foundation settlement, and the depth of the raft base, while it decreases with a reduction in the number of piles. Influence of pile configuration, pile spacing, pile length and raft thickness etc., on the performance of pile raft embedded in sand under vertical loading condition was evaluated by Halder and Manna (2022) and found that, the piles experience a dragging force from the raft and behaves like anchors in large deformation. The decrease in shear and moment demand also leads to a reduction in the lateral deflection of the piles by approximately 50% (Jamil et al., 2021). Load-deflection characteristics in pile group was studied by Sazzad et al. (2018) and found that the ultimate bearing capacity of piles was dependent on the configuration of the piles used. An experimental study was conducted by Katzenbach and Turek (2001) on CPRF and pile-group under combined loading, predicted that lateral resistance of CPRF is much higher than the pile-group. Pile-raft connections have a significant impact on the bending moments and tunneling induced deflections in pile groups foundations, with these connections playing a major role in influencing the tunneling induced deflections and bending moments in the pile group (Gu et al., 2024).

In the literature, CPRF has been studied under vertical load, but the effect of vertical contact pressure on the lateral load shearing behaviour is still unclear. Therefore, a numerical study was conducted through PLAXIS-3D software to examine the effect of vertical contact pressure on the lateral response of CPRF.

2. Methodology

Finite Element Modelling of CPRF in PLAXIS 3D begins by defining the setup and parameters required for analysing the Combined Pile Raft Foundation (CPRF). In Case #1, a total of 14 CPRF models were analysed in PLAXIS 3D. In each model, same lateral load of 100 (psf) was applied but each model was subjected to an incremental vertical load of 100 (psf). This step aims to observe the lateral responses under varying vertical loads.

In Case #2, the piled raft configuration with 4, 6 and 9 piles were studied such that the average vertical and lateral load per pile remains constant throughout the analysis. Finally, the results are derived, focusing on the pile load distribution pattern, settlement behaviour, and the overall performance of the CPRF under the given scenarios. Figure 1 indicates a conceptual view of our entire methodology.

2.1. Finite Element Modelling (Fem) In Plaxis 3d

PLAXIS3D is a numerical finite element software which is efficient in modelling CPRF. All the Properties of CPRF are taken as the same as that of experimental study conducted by Jamil et al. (2022a) on Piled Raft foundation. Advanced hardening soil model was used for modelling the sand under drained condition. In Modelling of CPRF, Piles were modelled as an “embedded beam element” with depth of 0.68m. In piles both skin resistance and base resistance are taken in account in modelling of Piles. Their axial skin resistance was taken as linear with an appropriate value of base resistance. Raft was modelled as a square plate element having length and width, 0.3m. Same thickness of 25mm of raft is taken. The whole assembly was surrounded by a soil box of 9.84m, 13.12m and 16.4m length, width and depth respectively, also modelled as a plate element. All the properties of Soil, Raft, Piles and Soil box are same as that of Experimental study conducted by Jamil et al. (2022b). These properties are listed in Table 1 and Table 2.

An interface element was also defined between soil and raft for appropriate modelling of complex interactions (Jamil et al., 2022a). The parameters of interfaces were same as that of sand except that of strength reduction factor R, where δ is interface friction angle and φ is angle of internal friction, $R = \tan(\delta)/\tan(\varphi)$. After all the parameters were defined, a 10 nodded tetrahedral element was used for generating the 3D Mesh as shown in Figure 2.

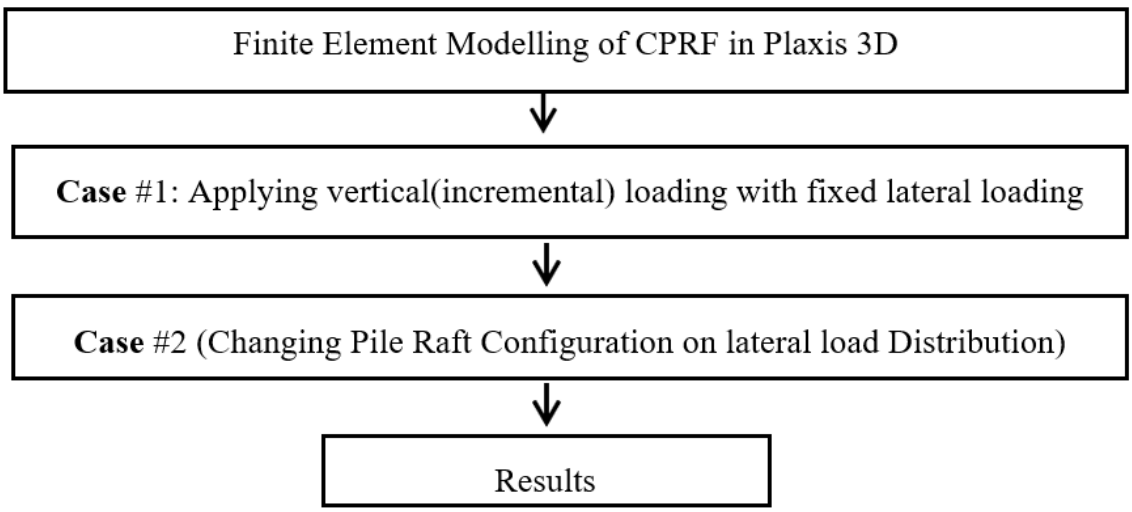


Fig. 1. Research Methodology

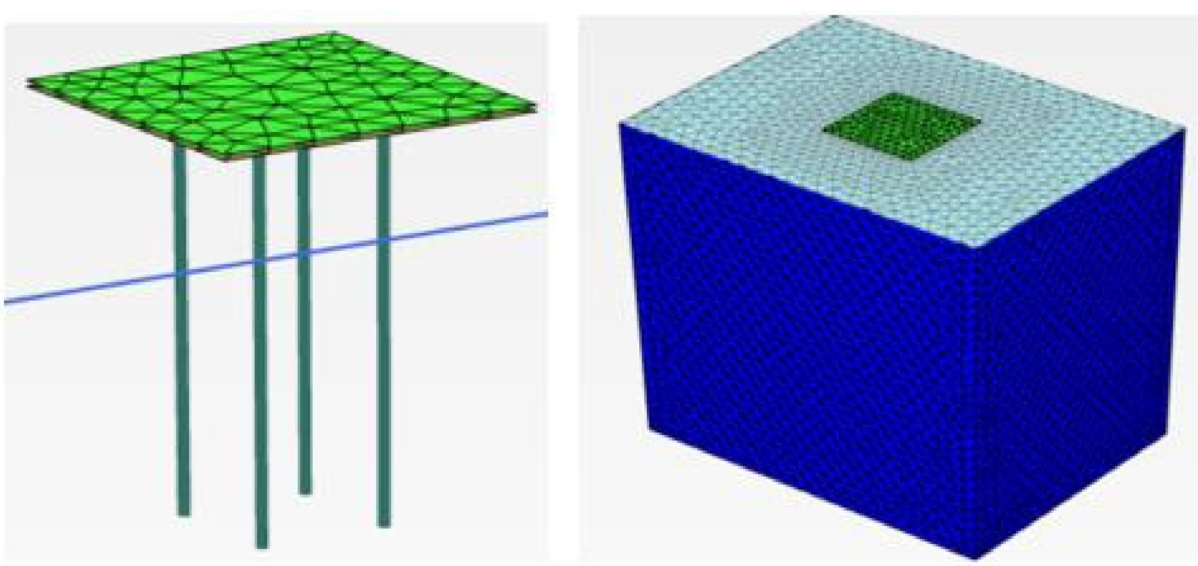


Fig. 2. Three-dimensional Mesh generated in PLAXIS 3D.

For accurate results local meshing (mesh refinement) was done at the critical location i.e., at the central volume of CPRF model. All the parameters of sand, interfaces, piles, raft and soil box are listed in Table 1 and 2 respectively.

Table 1: Parameters required in Hardening soil model in PLAXIS3D

Parameters	Definition	Sand	Interfaces	Units
E50	Secant stiffness in standard triaxial test	17	17	MPa
Eoed	Tangent stiffness for primary oedometer loading	17	17	MPa
Eur	Unloading / reloading stiffness (Eur = 3 E50)	51	51	MPa
c	Cohesion	0	0	KN/m²
Ψ	Dilatancy angle (φ-30̊: if φ is larger than 30̊)	4	4	Degree
φ	Angle of Internal friction	34	34	Degree
γ	Unit weight of soil	16	16	KN/m²
R	Interface factor	1	0.71	-

Table 2: Parameters of model piles and raft in finite element modelling in PLAXIS3D

Parameters	Piles	Raft	Soil Box	Units
Material Type	Elastic	Elastic	Elastic	-
Beam type	Circular tube	-	-	-
Diameter	0.01905	-	-	m
Thickness(D)	0.0023	0.025	0.025	m
Elastic modulus(E)	199	69	200	GPa
Poisson's ratio	0.3	0.33	-	
Unit weight (γ)	26.70	26.54	26.54	KN/m³

2.2.1 Case 1

A total of fourteen combined pile-raft foundation (CPRF) models, each consisting of four piles and a raft with the configuration as shown in Figures 3, were analyzed under combined vertical and lateral loading conditions. In these models, the vertical surface load was incrementally applied, with a consistent increase of 100 (psf) for each successive load step, while the lateral load remained constant across all tests. The details of the 14 models, including the uniform vertical load increments and the constant lateral load, are presented in Table 3.

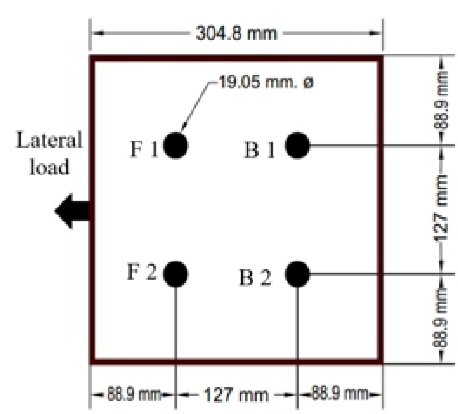


Fig. 3. Four Pile Raft Configuration

Table 3: Pile raft models under combined vertical and lateral loading

Model No	Vertical pressure (psf.)	Lateral Load (Ibs)
1	200	100
2	300	100
3	400	100
4	500	100
5	600	100
6	700	100
7	800	100
8	900	100
9	1000	100
10	1050	100
11	1100	100
12	1200	100
13	1300	100
14	1400	100

During the modeling process, the raft was assumed to be in direct contact with the underlying soil. A uniformly distributed vertical load was applied uniformly across the surface of the CPRF, while the lateral load was introduced as a point load. Figure 4 & 5 provides a clear representation of the finite element model used for the CPRF under combined vertical and lateral loading, allowing for an in-depth understanding of the foundation's behavior under the applied loads. The systematic variation of the vertical load and the consistent lateral load allows for a controlled investigation of the interaction between vertical and lateral forces on the foundation system.

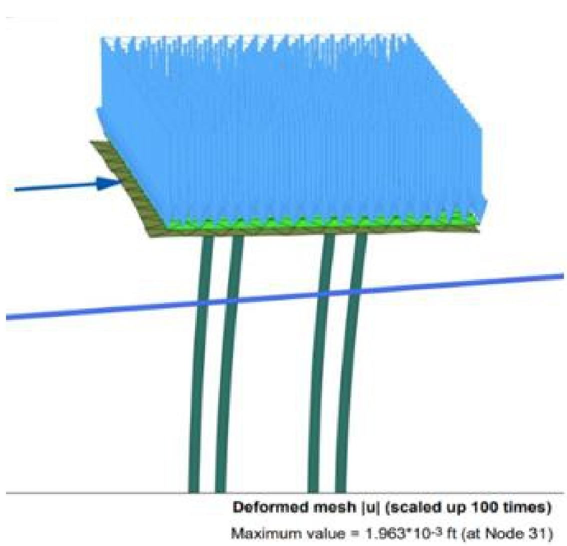


Fig. 4. CPRF under combined loading.

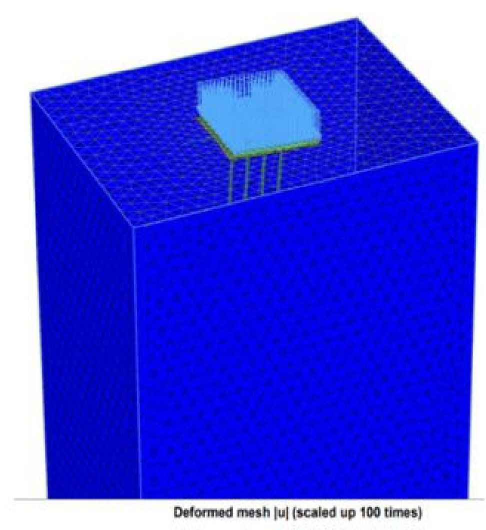
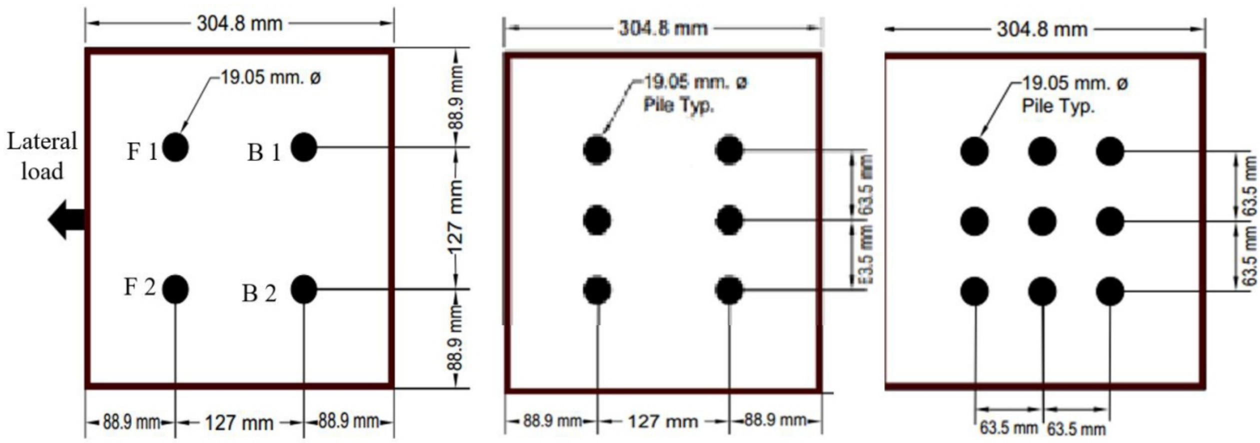


Fig. 5. CPRF surrounded by soil box under combined loading

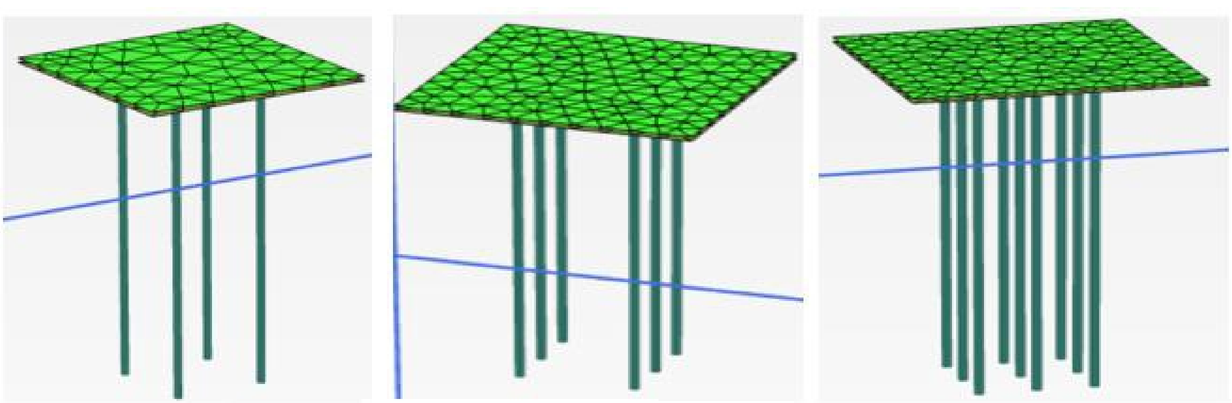
2.2.2 *Case 2*

Four, six, and nine piled raft configurations were modelled as shown in Figure 6. In this case combined loading was applied in such a way that the average vertical as well as lateral load per pile remained same. The parameters used in finite element modelling of CPRF were same as that of case 1. F and B indicated the front and back piles respectively in Figure 6a. PLAXIS-3D models of CPRF are shown in Figure 7.



a. 4 piles *b. 6 piles* *c. 9 piles*

Fig. 6. CPRF Configurations



a. 4 piles *b. 6 piles* *c. 9 piles*

Fig. 7. Finite element pile-raft configurations in PLAXIS 3D

3 Summary And Results

3.1 Case 1

3.1.1. Effect Of Vertical Contact Pressure On Pile Raft Contribution

As the vertical load was incrementally increased, the vertical contact pressure between raft and soil enhanced. This increase in vertical contact pressure strengthens the lateral load-bearing capacity of the raft and suppresses the load capacity of piles correspondingly, as shown in Figure 8, which presents the results of 14 pile raft models as described in Table 3. Each model in Table 3 was subjected to a 100 (psf) increment in vertical load. All the results are compiled and illustrated in Figure 8.

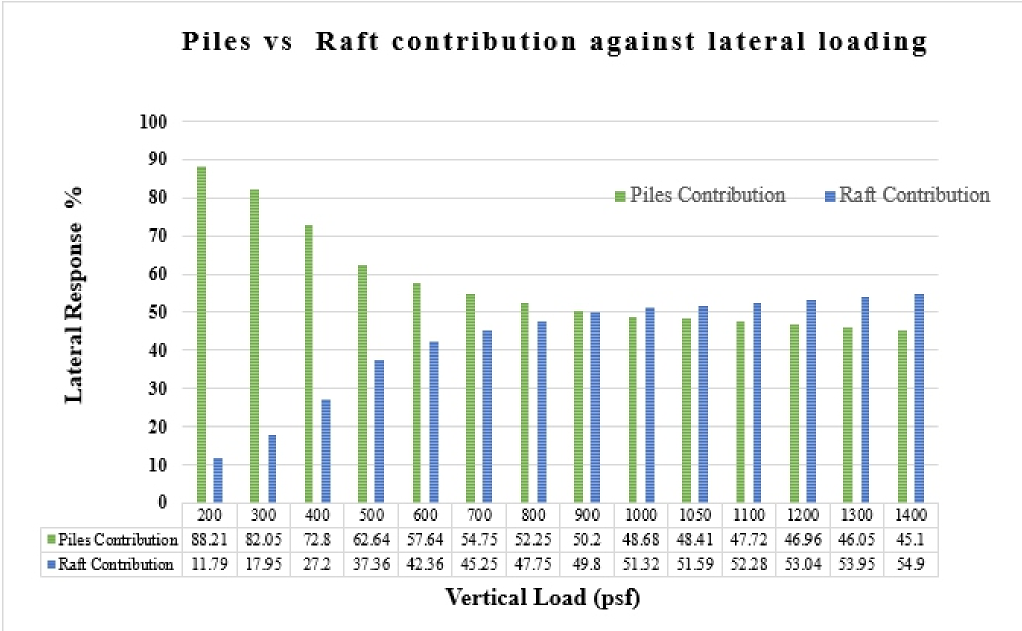


Fig. 8. Piles & Raft Contribution against varying vertical load in response of lateral load

This enhanced lateral response can be attributed to the increased stiffness of the soil beneath the raft, which, in turn, improved the raft's ability to resist lateral forces. The contact pressure between the raft and the soil intensified as the vertical load was progressively increased from 200 psf. to 1400 psf. This increase in vertical load resulted in a significant rise in the raft's lateral contribution, with the raft's lateral load resistance increasing from 11.79% to 54.9%. Similarly piles contribution get reduced from 88.21% to 45.1% as the vertical load increases from 200 (psf) to 1400 (psf) respectively. So, it is concluded that the raft lateral load distribution is directly proportional to vertical contact pressure or vertical load. Greater the vertical contact pressure greater will the raft lateral load contribution. Additionally, piles lateral load contribution is inversely proportional to vertical contact pressure. Greater the vertical load, lesser will be piles contribution.

This demonstrates the critical role of vertical load in enhancing the overall performance of the pile-raft system under combined loading conditions, particularly in terms of lateral load resistance

3.1.2. Effect Of Vertical Contact Pressure On Front And Back Piles

Figure 9 demonstrate that an increase in vertical load enhances the lateral response of Raft in combined pile-raft foundation (CPRF). This enhancement makes the soil more compacted in front back piles and ultimately leads to a more uniform distribution of lateral loads across the foundation system as shown in Figure 9.

At lower vertical load levels, ranging from 200 (psf.) to 900 (psf.) the front piles initially carry a greater proportion of the lateral load compared to the rear piles. This behavior is attributed to the tilting of the raft and the presence of un-compacted, loose soil in front of the rear piles, as illustrated in the Figure 9. However, as the vertical load increases beyond 900 (psf) a gradual shift in lateral load response occurs from the front piles to the rear piles. This shift becomes more pronounced as the vertical load approaches the threshold of 1100 (psf) at which the lateral load distribution stabilizes, with the rear piles beginning to resist more lateral load as shown in Figure 10. This shift is primarily due to the increased stiffness of the soil beneath the raft, resulting from the elevated vertical contact pressure in front of the rear piles, as shown in Figure 9.

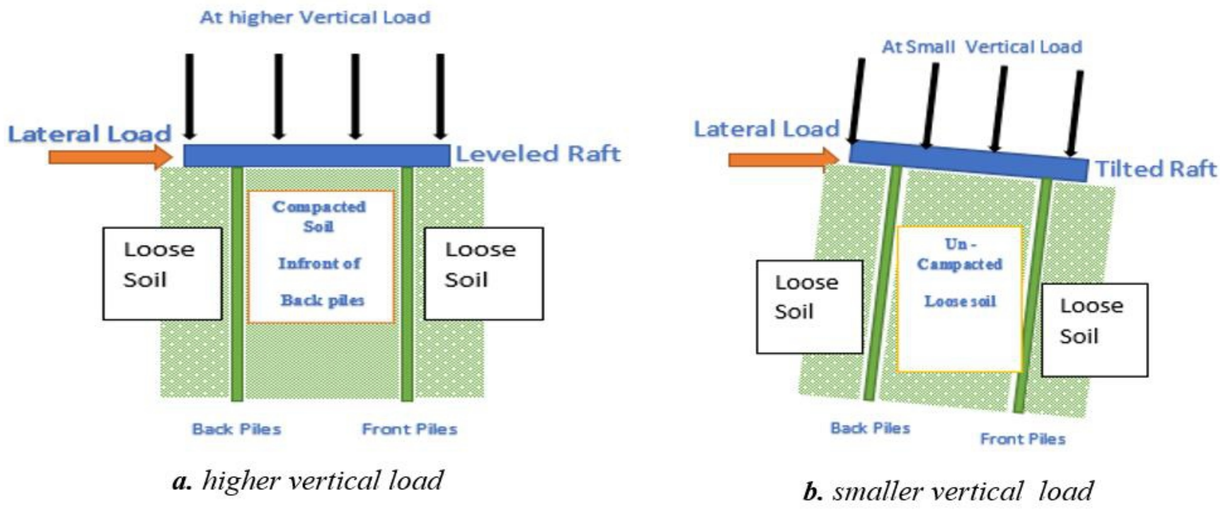
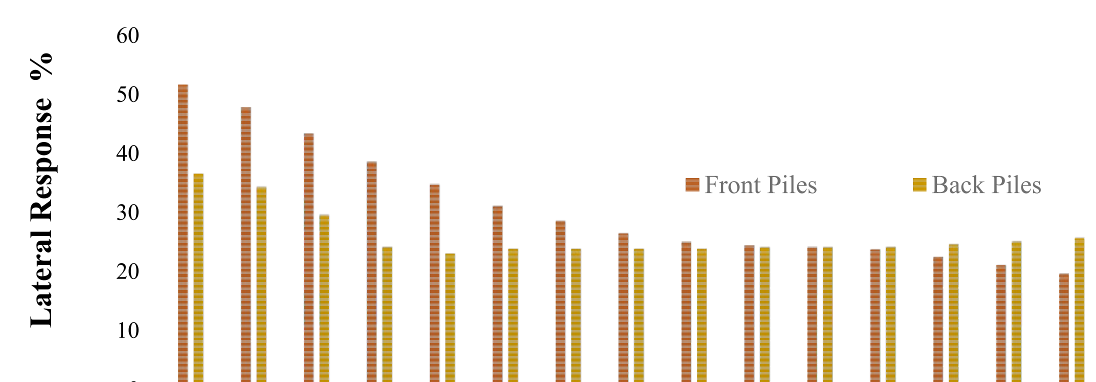


Fig. 9. Variation in soil stiffness and raft inclination due to variation in load (Jamil, 2021).



Vertical Load (psf)	200	300	400	500	600	700	800	900	1000	1050	1075	1100	1200	1300	1400
Front Piles	51.64	47.75	43.27	38.52	34.66	30.96	28.47	26.43	24.89	24.35	24.05	23.65	22.42	21.05	19.5
Back Piles	36.57	34.3	29.52	24.12	22.98	23.79	23.79	23.78	23.79	24.06	24.06	24.07	24.54	25	25.6

Fig. 10. Front and Back Piles Contribution in response of lateral load, against varying vertical load

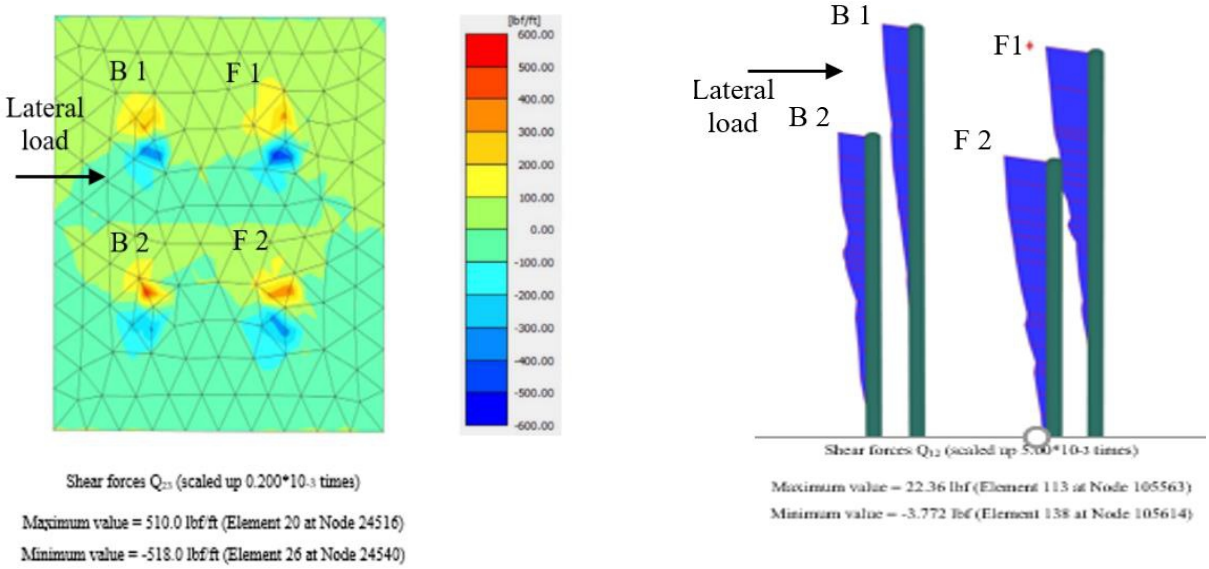


Fig. 11. show the corresponding shear forces (lateral responses) at a vertical load of 400 psf.

Further insights are provided in Figures 12, which display the shear (lateral responses) forces in the raft and piles, respectively, at a vertical load of 1400 psf.

The data from these (figures 11 & 12) reinforce the observed trend: at lower vertical loads, the front piles bear a greater share of the lateral load, while at higher vertical loads, the increased stiffness beneath the rear piles enables them to carry a larger portion of the lateral load. This behavior underscores the important role of vertical loading in influencing the lateral load distribution and overall performance of the CPRF.

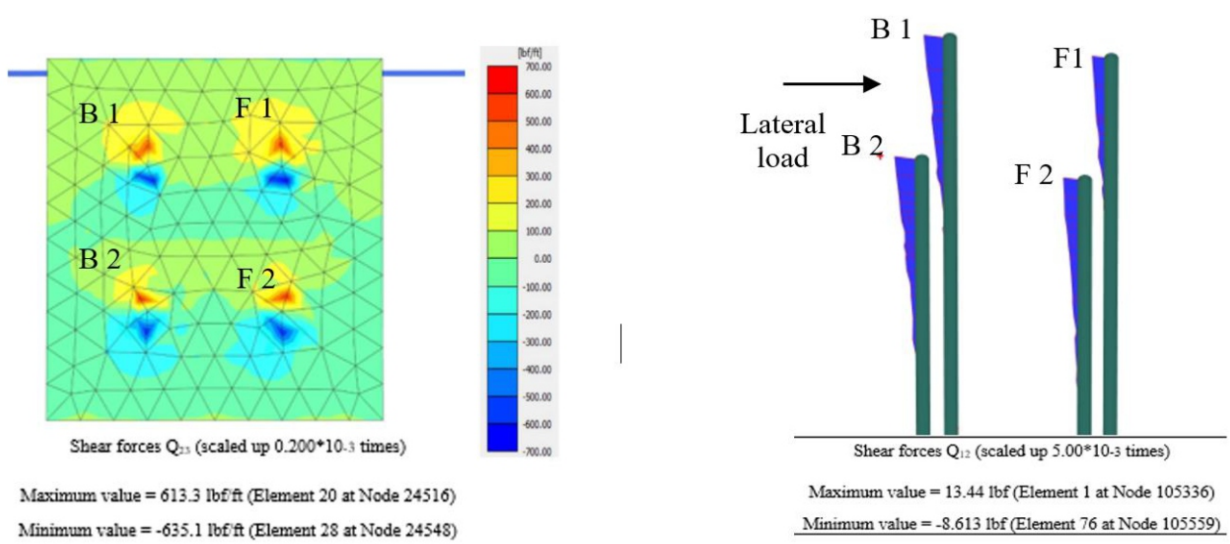


Fig. 12. Shear forces(Q23) in raft and Piles under V=1400 (psf.) in Plaxis3D

3.2. Effect of Vertical Contact Pressure on Lateral Displacement

Figure 13 indicated that as the vertical contact pressure increases with an increase in vertical load, lateral displacement of piles also decreases. With increase in vertical loading from 200 to 1400psf, lateral displacement of piles decreases from 0.00128 ft to 0.000592 ft. This is because of increase in raft soil contact pressure, which increases the soil stiffness between the piles and ultimately decreases the lateral displacement. Pictorial view of lateral displacements under 1400psf and 400psf are shown in figure 14 and 15 respectively.

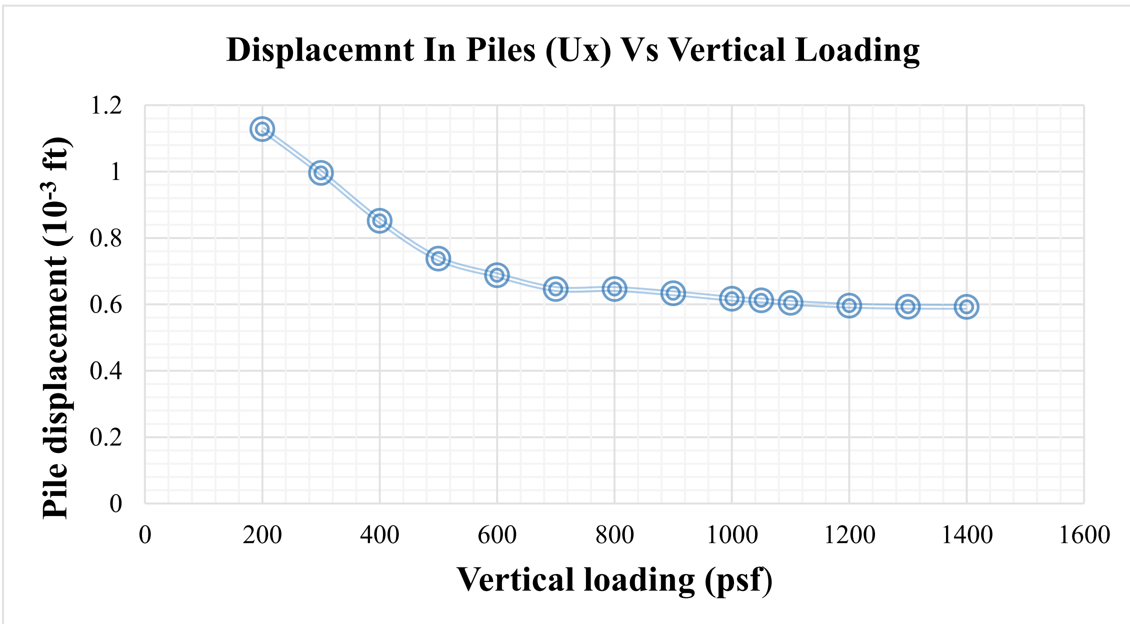


Fig. 13. Decrease in lateral displacement of piles with an increase in vertical load

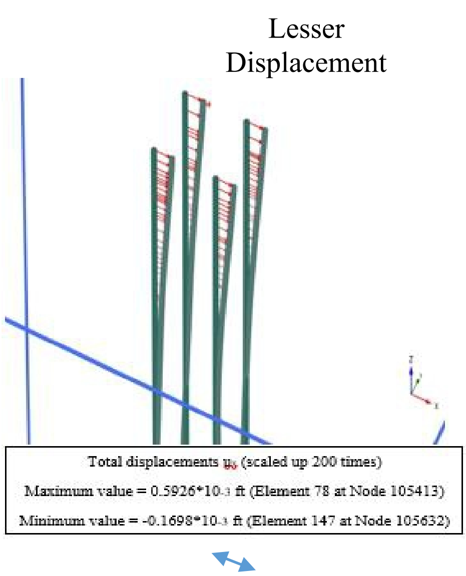


Fig. 14. Total Displacement (Ux.) in piles under V=1400 (psf.) in Plaxis3D

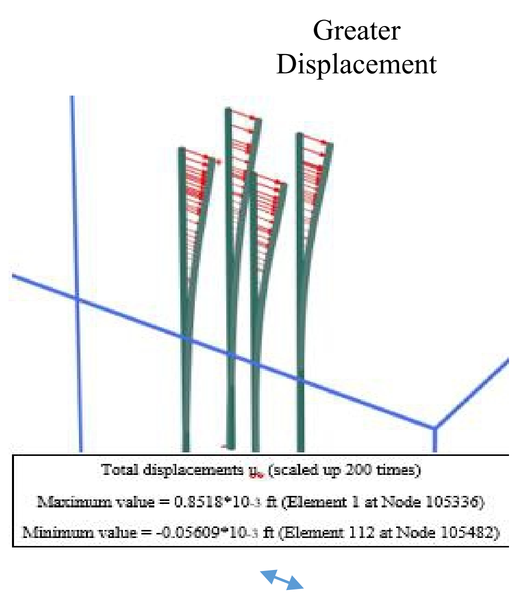


Fig. 15. Total Displacement (Ux.) in piles under V=400 (psf.) in Plaxis3D

The raft behaviour of lateral displacement as shown in figure 16 is almost same as that of piles. With increase in vertical loading from 200 to 1400psf, raft lateral displacement decreases from 0.00129 ft to 0.0005969 ft.

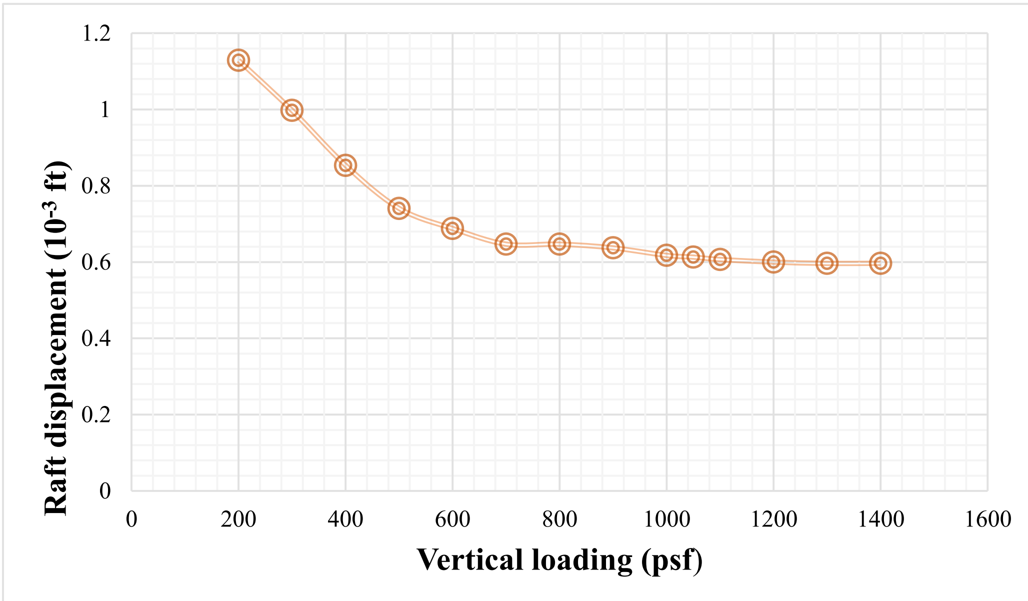


Fig. 16. Decrease in lateral displacement of raft with an increase in vertical load

3.3. Effect of Number of Piles

Results of case 2 with 4, 6 and 9 piles configuration were observed in Figure 17, which showed that in each pile raft configuration, there was approximately same lateral load contribution of raft. This was because of the same average vertical and lateral load per pile in each model configuration.

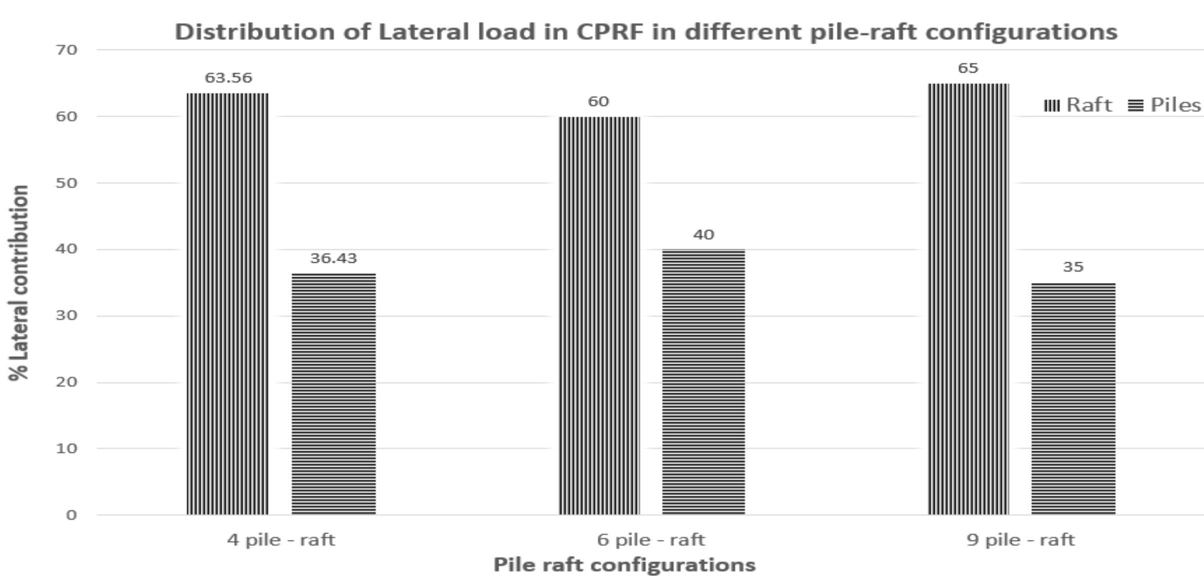


Fig. 17. Distribution of lateral load in CPRF with different configurations

4. Conclusion And Results

In this research work a numerical study was carried out on different small-scale models of pile-raft foundations under varying vertical and constant lateral load. The lateral load contribution and displacement of both piles and raft were investigated in each numerical model in a medium dense sandy soil substrate. The analysis was conducted in two different cases. In Case 1, a 4-pile raft model with sand enclosed in a soil box is examined, where a total of 14 models were prepared and subjected to vertical and horizontal load. The vertical pressure is incremented by 100 psf. in each model, while a fixed lateral load is applied. In Case 2, three CPRF models with 4, 6, and 9 piles are analysed, maintaining constant average vertical and lateral loads per pile across the configurations. The study provides valuable insights into the behaviour of CPRFs under combined vertical and lateral loading, emphasizing the shift in load distribution with increasing vertical pressure. Based on analysis performed, the following conclusions were found:

- The lateral response of the Combined Pile Raft Foundation (CPRF) significantly improves by increasing the vertical contact pressure. At smaller loads, due to tilting of the raft, the front piles carry more lateral load. However, after a certain vertical load at 1100 psf., the tilting of the raft is reduced, and the back piles begin to carry more lateral load due to the increase in stiffness of the soil beneath the raft.

- At high vertical loads, the lateral load is uniformly distributed throughout the raft, resulting in the elimination of differential settlements in the raft. At smaller loads, the front side of the raft and the front piles settle more, but at higher loads, the raft settles uniformly. This uniformity is due to the removal of tilting in the raft at high vertical contact pressure.

- The lateral response of the raft in contribution to lateral load is greatly influenced by the vertical contact pressure of the raft beneath the soil. With an increase in vertical load, vertical contact pressure increases, which in turn increases the soil stiffness beneath the soil, influencing the lateral contribution of the raft. It was concluded that the raft's contribution in response to lateral load is directly proportional to the vertical contact pressure of the raft. By increasing load from 200psf to 1400psf, the raft's lateral contribution was experienced as ranging from 11.79% to 54.9% in the test results.

- The study observed that for smaller vertical loads, the front piles bear the majority of lateral load, whereas for higher loads, the back piles become more prominent in resisting lateral forces. It is mainly due to the increase in subgrade stiffness of passive soil due to increase in vertical contact pressure. This shift in load-resisting behavior between front and back piles occurs after a vertical load threshold of 1075 psf. in the test results. Before reaching this threshold, the front piles are primarily responsible for resisting lateral response, whereas beyond 1075 psf., this pattern reverses, with the back piles taking on a more significant role in resisting lateral forces.

- Increasing the vertical load from 200 psf. to 400 psf. in CPRF results in lowering the lateral displacement in piles from 0.00128 ft to 0.000592 ft & 0.00129 ft to 0.0005969 ft in raft. This reduction is mainly due to the increase in the density of the soil underneath the raft, increasing in the piles and raft stiffness along with the soil, improvement in soil-pile interaction, force redistribution, and enhancement of the bearing capacity of the soil.

- Based on our results, in Combined pile raft foundation, with 4 number of piles at a vertical to lateral load ratio of 7.23, back piles carry more lateral load, below this ratio, front piles resist more lateral load.

- By increasing the number of piles and keeping the average vertical and lateral load per pile constant, there is no change in lateral contribution of the raft.

5. Practical Implementations:

This study emphasizes the important role of vertical load in improving the performance of pile-raft systems, particularly in resisting lateral loads.

Critical Vertical-to-Horizontal Load Ratio: In a specific 4-pile raft configuration, there is a critical vertical-to-horizontal load ratio at which the lateral load distribution between front and back piles becomes balanced.

Shift in Lateral Load Distribution: Beyond the critical ratio, lateral load gradually shifts from the front piles to the back piles.

Impact of Ignoring Raft's Horizontal Resistance: Neglecting the raft's horizontal resistance results in:

- Overestimation of shear forces
- Overestimation of bending moments
- Overestimation of horizontal displacements
- Underestimation of the total foundation resistance.

Optimization of Pile-Raft Foundations: For more economical and efficient pile-raft foundations, it is crucial to incorporate the raft's horizontal resistance in both the analysis and design. pile raft foundation, horizontal resistance of raft must be considered in analysis and design.

Author Contribution

This work was carried out through mutual coordination, with responsibilities distributed among the team members. Hamad Khan was responsible for numerical modeling and manuscript writing. Qazi Khurshid Ahmad assisted the first author in numerical modeling, played a crucial role in data collection and provision, and contributed significantly to addressing the reviewers' comments. Haq Nawaz Khan and Uzair jointly worked on the literature review and assisted in manuscript writing. Ilyas Siddique utilized his expertise in proofreading and eliminating errors in the paper. Irfan Jamil proposed the research concept and supervised the study from its inception to submission, providing valuable guidance and expertise throughout the process

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