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Analysis of vertically loaded pile raft foundation on cohesionless soil using ABAQUS

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Abstract. Pile foundations are widely used in weaker soil site to support superstructures. Study on bearing capacity of pile foundations is still gaining much attention to the geotechnical researchers. Besides laboratory and field tests, numerical method such as finite element method is used increasingly to deal with analysis of pile foundation problem. In this paper, a general purpose finite element based software "ABAQUS" has been used to explore the load bearing capacity of piled rafts. Soil profile has been used in this study is cohesionless soil with varying relative density. While we draw the load-settlement curve form "ABAQUS" viewport the result shows non-linear variation. To determine load capacity in pile raft system, interaction factor has been considered as available in literature. In accordance with the proposed pile raft model, the load sharing ratio, decreases as settlement increases which depend on the load capacity ratio. The value of load sharing ratio is increase with load capacity ratios. The proposed load sharing model has been verified using established formulas.
Keywords*:* Pile foundation; Non-linear; Raft; FEM; ABAQUS.

1 Introduction

The foundation system is one of the most significant aspects of any Geotechnical Engineering project. Due to increase of population and land scarcity problem, complexity of geotechnical problem also increase, to overcome the new challenges, geotechnical engineers try to established these two separate foundation systems namely shallow and deep foundation. The foundation engineer will be able to supply the appropriate values for the design in order to provide the requisite safety while also providing a more cost-effective solution by integrating these two systems. As a result, a hybrid system known as "piled raft foundation" has been developed. A number of researchers already documented study on behaviour of pile raft foundation on different types of soils. By employing a model test and numerical analysis, in soft clay Wu **et al. (2002)** were able to estimate the load-settlement response of a combine piled raft system. They discovered that sum of individual resistance capacity of pile and raft system is more than combine pile-raft system. **Mrouehand Shahrour (2002**) investigated the impact of urban tunnel development on surrounding piling foundations. It was performed by utilising 3Delastoplastic FE modelling. Based on a numerical investigation employing a 3D finite element approach**, Lee et al. (2010)** established three-dimensional behaviour of a piled raft on soft clay. Using an elasto-plastic soil model**, Peng et al. (2010)** developed a non-linear 3D analysis. To model the pile-interaction, they used an elastic pile material and interface element. **Hyuang et al. (2011)** proposed a simplified non-linear analysis for combine piled raft system in stratified soil medium under vertical loading. They found that the suggested technique can forecast the load distribution of single piles, pile groups, and pile rafts in stratified soils reasonably well. **Zhan et al.(2012)** developed a numerical modelling of vertical loading pile such as self-weight stress field, bearing resistance by ABAQUS which one is finite element based software. They predicted that bearing capacity of foundation increases and differential settlement is decreased with combine effect of pile-raft. **Nguyen et al. (2012)** suggested a design method of piled-raft foundation under larger external load considering interaction effects for pile-raft foundation for obtaining the ultimate load carrying capacity of pile-raft and settlement of the foundation. Vertically loaded floated large pile group explored using a multiphase approach by **Bourgeois et al. (2012),** with special attention on soil-pile interactions, which carry an essential influence in foundation performance. To explore the behaviour of rafts on settlement decreasing piles**, Garhy et al. (2013)** conducted an experimental programme on small scale model stacked rafts on sandy soil. **Lee et al. (2014)**investigated on the load sharing behaviour of piled-rafts. They proposed a load sharing model on the basis of settlement which behaves non-linear response and depend on piled-raft interaction effect. **Cho et al. (2014)** proposed a non-linear 3-D analytical method, numerical method and case studies to examine the load deformation characteristics pile-raft foundations subjected to vertical and lateral load. They discovered that this method provides a significantly bigger piled raft settlement than the linear elastic analysis results. **Lee et al. (2015)** analysed the load sharing behaviour of piled-raft embedded in granular backfill material using Finite Element Method with help of PLAXIS-3D software. **Wulandari et al. (2015)** estimated the settlements only raft foundation then piled foundation and finally piled-raft foundation under the same loading using PLAXIS-2D considering pile number as a variable. From the outcomes result they found that the settlement decreases in case of piled-raft foundation. Based on the review of literature objective of present work has been taken to carry out an interaction factor based load sharing study and non- linear load settlement characteristics of pile raft foundation with help of finite element method.

2. Numerical Modelling

In general, a theoretical solution found by finite element method must satisfy equilibrium, compatibility, constitutive material and boundary conditions. To find a solution for a foundation problem with finite element method, certain idealization and some assumptions have to be made. In particular, the soil behaviour must be defined as a material constitutive relationship, the geometry and boundary requirement for pile-raft analysis. The assumptions are considered in the present study are as a homogeneous, isotopic, linear elastic behaviour, absence of pore fluid, to develop an FE model in ABAQUS environment for Pile-Raft embedded in homogenous cohesion less soil. Friction contact is used in interaction module. An eight nodded linear brick element is considered for this study.

3. Geometric Modelling

Numerical modelling and analysis has been carried out for Pile-Raft embedded in cohesion less soil with different pile diameters and raft size.Fig.1.shows the representational diagram of soil pile raft system. For the purpose of analysis, it is required to choose a finite domain. The combined piled raft foundation (CPRF) system geometry has been modelled as a 3D model in this study. Due to symmetry of the soil pile and raft, only quarter for FE simulation of the domain has been choose, this will also speed up the analysis approach. In this present numerical modelling and analysis, the diameter of pile has been taken as 'B_p' and length of pile has taken as 'l'. In FE simulation the border must be shifted such that the boundary effect is minimal. In this study boundary of the domain for the soil block has been shifted to a distance of 3$l$in vertical direction and *l in horizontal* direction from centre of pile-raft**.**

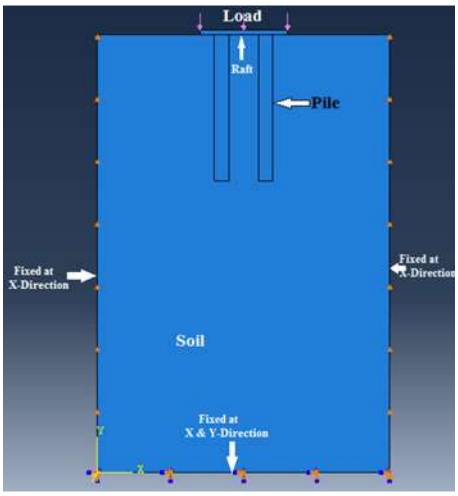

Fig.1. Representational diagram of soil pile raft foundation system

4. **Material Properties**

4.1Material Properties of Sand

The soils employed in the FE analyses were sands with three distinct relative densities, D_R = 30%, 50% and 70%. The value of relative density has been chosen based on the earlier researcher (Lee et al.2015). The Mohr-Coulomb elastic perfectly plastic constitutive model used to understand the failure behaviour of these soils. In accordance with Bowles (2005) the Poisson's ratio of sand kept as 0.32 for entire analysis. The values of Young modulus, angle of internal friction, and density of the sand for respective relative density are presented in the Table1.

Table-1Properties of Sand

Density Index (%)	Void ratio (%)	Density(kg/m^3)	Young modulus (kPa)	Angle of internal friction(degree)
30	69	1550	32508	32
50	63	1610	37108	35
70	57	1670	42261	38

4.2Properties of Pile and Raft

In the present investigation, the values of pile raft materials viz., unit weight (kN/m^3), E (kPa), and Poisson's ratio has been considered as 25, 30×10^6, and 0.15 respectively. The value of properties of the pile raft has been chosen based on the earlier researcher (Lee et al.2015).

5. Mesh generation: The geometry has been partitioned into a huge into a number of small elements in order to do finite element computation. The basic soils elements of a three dimensional finite element mesh are represented by eight nodded brick elements represent the basic soil element in a three dimensional finite element mesh. 115 numbers of elements have been generated on pile-raft and 8803 elements have been generated on soil. C3D8R is the standard for this element; hour glass control is employed with 8-node linear brick with reduced integration. An element size of 600 mm × 600 mm has been created in the case of pile-raft; an element size of 600 mm × 600 mm is adopted in loading area of soil and minimum size of 600 mm and maximum size of 900 mm has been used in the case of rest of the soil. The deformed shape of model is shown in Fig 2.

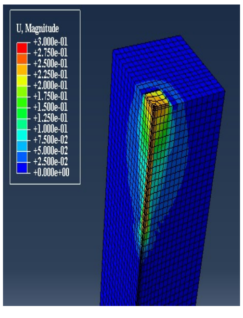

Fig.2 Deformed shape of pile raft model

6. Result and Discussion

6.1 Load variation of Raft, Pile and Piled-Raft foundation

Figs 3, 4 and 5 show the variation of load versus displacement curve for Raft, Pile and Piled-Raft system for different relative density (D_R) of 30%, 50%, and 70% respectively with pile diameter 0.5m and raft size 2m×2m. Figs. 6, 7 and 8shows the variation of load versus displacement of Raft, Pile and Combined Piled-Raft foundation (CPRF) for different relative density (D_R) of 30%, 50%, and 70% with pile diameter 0.75m and raft size 3 × 3m respectively. Figs. 9, 10 and 11 show the variation of load versus displacement of Raft, Pile and Combined Piled-Raft Foundation (CPRF) for different relative density (D_R) of 30%, 50%, and 70% respectively for pile diameter 1.0m and raft size 4 × 4m. From the Figs.3-5 it is found that with increase in relative density loose sand (D_R=30%) to medium dense sand (D_R=70%), the load carrying capacity of pile group, Raft, pile raft increases irrespective of settlement under study. Similar trend also observed in case of other figures (Figs.6 to 11). It may be due to that with increase in relative density as results of shear strength increases.

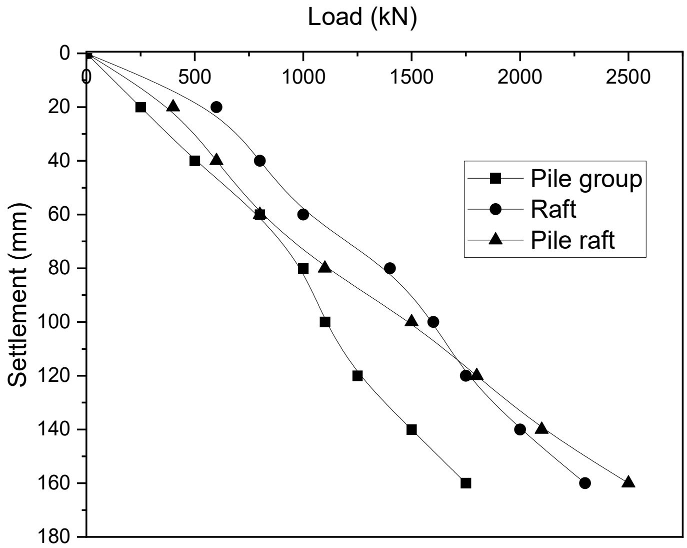

Fig.3 Load vs. Settlement curve for pile dia 0.5m and raft 2× 2m for DR=30%

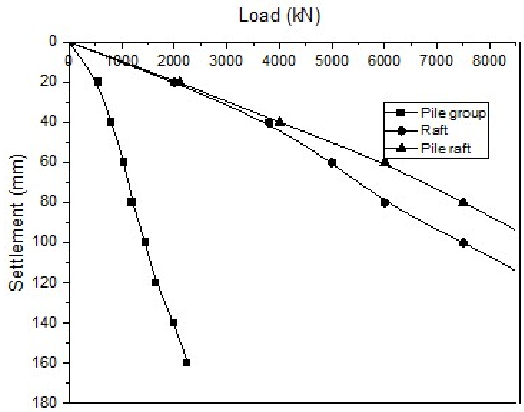

Fig.4 Load vs. Settlement curve for pile dia 0.5m and raft 2× 2m for DR=50%

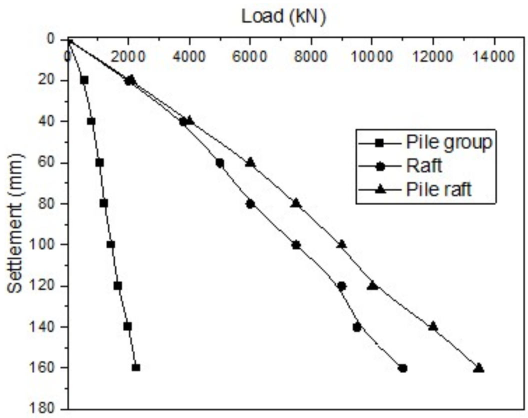

Fig.5 Load vs. Settlement curve for pile dia 0.5m and raft 2× 2m for DR=70%

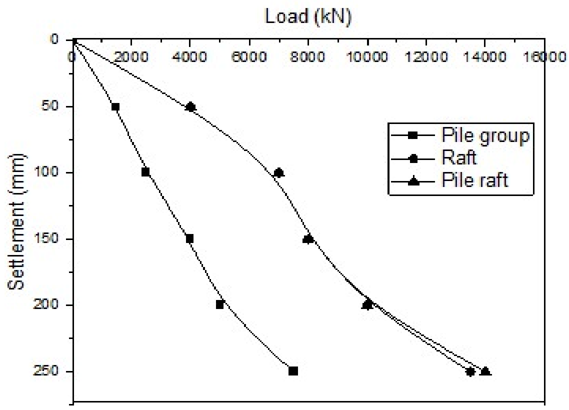

Fig.6 Load vs. Settlement curve for pile dia 0.75m and raft 3x3m for DR=30%

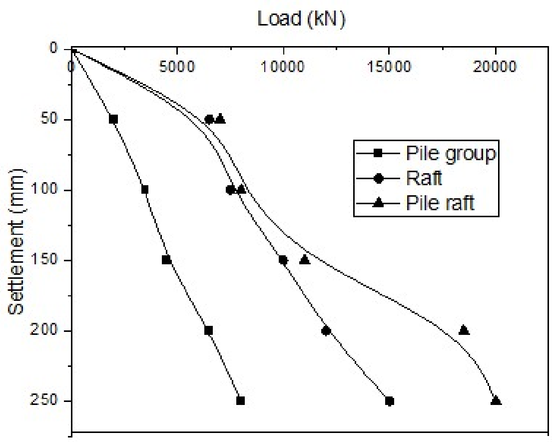

Fig.7 Load vs. Settlement curve for pile dia 0.75m and raft 3×3m for DR=50%

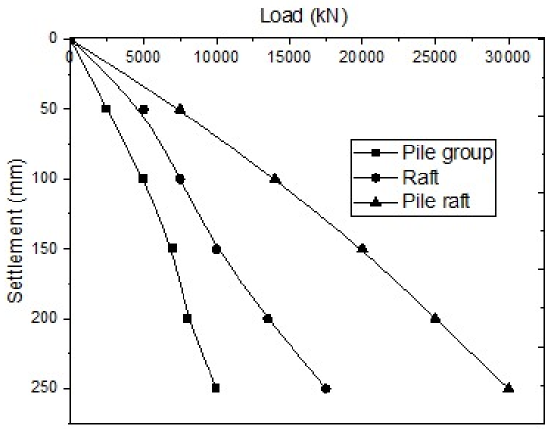

Fig.8 Load vs. Settlement curve for pile dia 0.75m and raft 3×3m for DR=70%

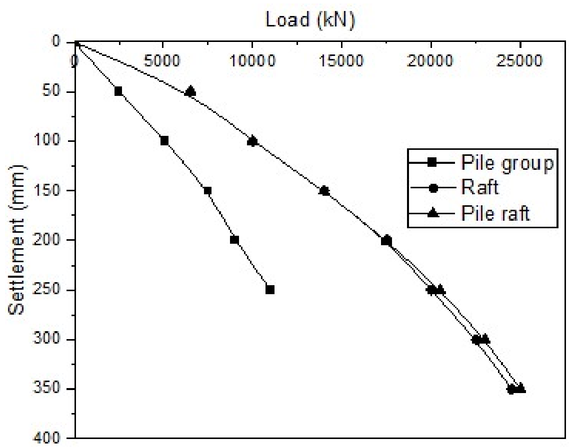

Fig.9 Load vs. Settlement curve for pile dia 1.0m and raft 4×4m for DR=30%

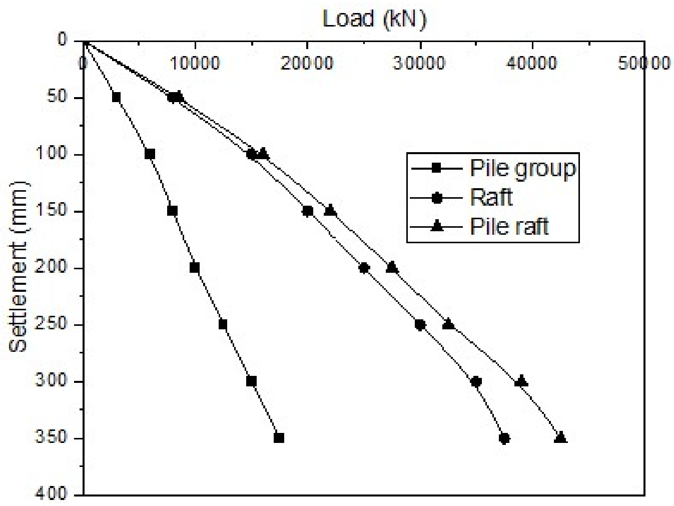

Fig.10 Load vs. Settlement curve for pile dia 1.0m and raft 4×4m for DR=50%

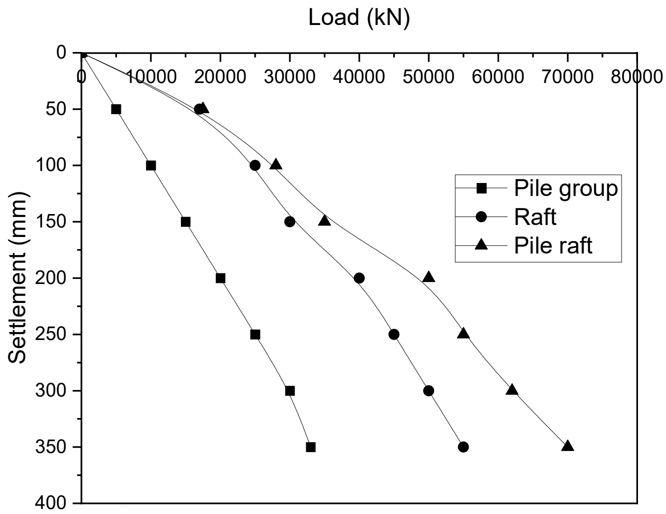

Fig.11 Load vs. Settlement curve for pile dia 1.0m and raft 4×4m for DR=70%

6.2 Combined pile raft load sharing

The load receiving capabilities of pile raft components are determined by the achieved settlement level and hence play a very crucial part in determining the structure serviceability requirement. It denote symbolically as a α_{CPRF}, defined as the proportion of pile load in pile raft system to the total applied load, as follows:

$$\alpha_{CPRF} = \frac{\alpha_{pr}}{\eta\left(1 + \frac{Q_{UR}}{Q_{PG}}\right)}$$

Table 3, Table 4 and Table 5 presents the load carrying capacity of Pile/Piles in Combined, single and Group Pile Raft for Relative Density 30%, 50%, and 70% respectively for measured value (Abaqus Value) as well as Calculated Value (Calculation has been done from equation presented by Kumar and Choudhury, 2018).Where ή, α_{pr} are pile raft efficiency and pile to raft interaction factor respectively. From the tables (Table 3-5) it is observed that with increase of pile diameter from 0.5m to 1.0m the value of α_{CPRF}increaseswith pile diameter and number of pile in group in group pile raft system increases. It may be due to that with increase in pile diameter and also number of pile in pile raft system, the surface area of the pile increases.

Table 3 The Load Carrying capacity of Pile/Piles in Combined single and Group Pile Raft for Relative Density 30%

D_R=30%									
Model	Dia(m)	α_{pr}	ή	Q_{ult} (kN) (Measured Raft)	Q_{theo},u(kN) (Calculated Raft)	Q_{PG}(kN) (Measured)	Q_{PG}(kN) (Calculated)	α_{CPRF} (Measured)	α_{CPRF} (Calculated)
Single Pile Raft(2×2)	0.5	0.99	1.245	2040	1619.44	640	565.29	0.190	0.206
Single Pile Raft(3×3)	0.75	0.99	1.12	7360	5465.61	2640	2310.15	0.233	0.263
Single Pile Raft(4×4)	1	0.99	0.96	15440	12955.52	4640	4274.31	0.238	0.256
Group Pile Raft(2×2)	0.5	0.99	1.245	2040	1619.44	4400	4610.74	0.543	0.588
Group Pile Raft(3×3)	0.75	0.99	1.12	7360	5465.61	20600	20837.94	0.651	0.700
Group Pile Raft(4×4)	1	0.99	0.96	15440	12955.52	44000	48705.79	0.763	0.815

Table 4 The Load Carrying capacity of Pile/Piles in Combined single and Group Pile Raft for Relative Density 50%

D_R=50%									
Model	Dia(m)	α_{pr}	ή	Q_{ult}(kN) (Measured Raft)	Qtheo,u(kN) (Calculated Raft)	Q_{PG}(kN) (Measured)	Q_{PG}(kN) (Calculated)	α_{CPRF} (Measured)	α_{CPRF} (Calculated)
Single Pile Raft(2×2)	0.5	0.99	1.245	2680	2474.51	1240	1251.54	0.252	0.267
Single Pile Raft(3×3)	0.75	0.99	1.12	8760	8351.46	4360	3280.29	0.294	0.249
Single Pile Raft(4×4)	1	0.99	0.96	19780	19796.04	6640	5377.33	0.259	0.220
Group Pile Raft(2×2)	0.5	0.99	1.245	2680	2474.51	8800	10438.12	0.610	0.643
Group Pile Raft(3×3)	0.75	0.99	1.12	8760	8351.46	28000	29791.6	0.673	0.690
Group Pile Raft(4×4)	1	0.99	0.96	19780	19796.04	64000	68995.02	0.788	0.801

Table 5The Load Carrying capacity of Pile/Piles in Combined single and Group Pile Raft for Relative Density 70%

D_R=70%									
Model	Dia(m)	α_{pr}	ή	Q_{ult}(kN) (Measured Raft)	Qtheo,u(kN) (Calculated Raft)	Q_{PG}(kN) (Measured)	Q_{PG}(kN) (Calculated)	α_{CPRF} (Measured)	α_{CPRF} (Calculated)
Single Pile Raft(2×2)	0.5	0.99	1.245	3960	4534.92	1620	2520.07	0.231	0.284
Single Pile Raft(3×3)	0.75	0.99	1.12	13160	15305.35	5960	5018.18	0.276	0.218
Single Pile Raft(4×4)	1	0.99	0.96	33600	36279.35	11160	8340.79	0.257	0.193
Group Pile Raft(2×2)	0.5	0.99	1.245	3960	4534.92	14800	15260.9	0.672	0.613
Group Pile Raft(3×3)	0.75	0.99	1.12	13160	15305.35	44000	47521.4	0.680	0.669
Group Pile Raft(4×4)	1	0.99	0.96	33600	36279.35	96000	111557.4	0.764	0.778

7. Conclusions

From the above study, a finite element based analysis has been worked out to explore the load-sharing behaviour of combine piled raft system in homogeneous sand with different relative density. This study focuses on the impact of pile–raft interaction factor on the load-sharing behaviour.

The following conclusion can be derived from above studies, findings

1) The analysis shows that with increase of density index the ultimate load of pile, raft and piled raft also increases.
2) The ultimate load bearing capability is increased with increasing size of raft.
3) Larger load capacity ratios resulting higher load sharing ratio in piles in a combination piled-raft foundation.
4) The values of α_{CPRF} increases by increasing number of piles and increasing diameter of pile as well.

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