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Evaluation of Nonlinear Load Sharing Ratio of Pile and Raft in Piled Raft Foundation in Cohesionless Soil

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Abstract. Load sharing ratio between pile and raft is an important parameter in designing the piled raft foundation. Load sharing ratio between pile and raft in piled raft foundation depends on many factors such as raft, pile and soil properties, spacing between piles, raft pile area ratio, stiffness ratio of the pile, raft, and soil. In the present study limited number of experimental study and extensive numerical analysis has been carried out to understand the behavior of piled raft foundation. Based on the experimental studies, the load sharing mechanism of pile and raft in a piled raft has been presented. Load sharing between pile and raft has been evaluated through experimental investigations on the model piled raft and three-dimensional finite element based numerical analysis. The nonlinear variation of load sharing between pile and raft with foundation settlement has been discussed by determining the pile-pile and pile-raft interactions. The influence of soil stiffness, soil-raft stiffness, pile group area and length to pile diameter ratio on load sharing of pile and raft in piled raft foundation has been presented. The parameters of numerical analysis have been considered similar to the experimental studies for the purpose of comparison of results. The study will be useful in developing the load sharing model for estimating the nonlinear load sharing between pile and raft in a piled raft foundation. The paper describes the modeling procedure, material properties, parameters adopted in the analysis and the results.

Keywords: Model, Pile, Raft, Load sharing, Settlement, Spacing, Numerical analysis

1 Introduction

Piled raft foundations are widely preferred as a suitable foundation system for tall buildings and several important structures such as silo, commercial buildings, nuclear power plants, hospitals etc. (Poulos and Davis 2005). Piled raft foundations consist of a raft, piles, and subsoil. Piled raft effectively improves the bearing capacity and reduces the settlement of the structure to permissible limits (Poulos and Davis 1980). The piles in a small piled raft (R_w / L_p< 1, R_w – width of raft and L_p – length of pile) improve the load carrying capacity of the foundation, whereas reduce the excessive total and differential settlement in a large piled raft foundation (R_w /L_p> 1). The load on the superstructure is distributed between the raft and pile in a piled raft. The complex soil-structure interaction based on factors such as the geometry of foundation elements and soil conditions governs the load sharing mechanism of piled raft foundations. The optimized piled raft design can be achieved by considering various important governing parameters such as L_p/D_p ratio (L_p- pile length, D_p - pile diameter), pile spacing, soil-raft stiffness ratio (K_{rs}), soil stiffness, which affects the performance of the foundation system (Horikoshi and Randolph 1997, Akbari et al. 2021). Several laboratory model experiments and centrifuge test has been conducted to understand the behavior of foundations (Horikoshi and Randolph 1996). However, these studies are limited due to high expenses and difficulty in execution. The theoretical investigations such as simplified analysis methods and analytical methods have been widely used to understand the behavior of the piled raft foundations (Poulos and Davis 1980, Kitiyodom and Matsumoto 2003). The rigorous finite element based numerical analysis of piled raft foundation has been widely used and found to be accurate among all methods of piled raft analysis (Bhartiya et al. 2020). Several researchers have proposed different models to predict the load sharing in a vertically loaded piled raft foundations. Randolph (1983) proposed an empirical relation to estimate the load sharing between the pile and raft based on the results obtained from rigorous numerical analysis of circular raft supported with small pile groups considering the pile-pile and raft-pile interaction. Clancy and Randolph (1996) developed an approximate method for estimating the load sharing distribution in piled raft foundation system for large pile groups. Lee et al. (2014) developed a model using the normalized non-linear load–settlement relationship considering the effect of piled–raft interaction to predict the load sharing between pile and raft. Kumar and Choudhury (2018) proposed simplified expression for the evaluation of load sharing ratio of piled raft foundation considering the serviceability requirement of the structure.

In this paper, load sharing in a square small piled raft embedded in cohesionless medium and subjected to vertical loading has been presented. The variation of complex pile-pile and pile-raft interaction with foundation settlement has been discussed from experimental investigations. The mechanism of load sharing in a piled raft foundation has been presented using the experimental results of single pile, unpiled raft, pile group and piled raft foundation. The effect of soil stiffness, soil-raft stiffness, pile group area and length to pile diameter ratio on load sharing of pile and raft has been investigated using three dimensional finite element analyses. The parameter of numerical analysis has been considered similar to the experimental studies for comparison purposes of load sharing of pile and raft.

2 Experimental Setup

The steel tank of 1600 mm × 1250 mm × 1250 mm has been used in the present study. The possibility of volume changes during tank filling and subsequent loading has been eliminated by stiffening it with steel channels at different levels. The test tank has rigid boundaries on all sides except the top surface. The lateral boundaries of the tank are greater than 5 times the raft width and the vertical boundaries are greater than 10 times the pile diameter from the pile tip. These boundaries are sufficient to minimize the boundary effect (Chanda et al. 2021). The model piles are close-ended hollow circular pipes with an outer diameter of 20 mm and wall thickness of 1 mm. Two different pile length (L_p) of 500 mm and 1000 mm has been used in the present study. The A_g/A_r of the tested piled raft is 0.032, where A_g is the area of piles and A_r is the area of raft. The piles are made of the same grade of aluminium alloy as the model raft. They are connected to the raft with nut bolt connection at 6D centre to centre spacing. The piles are instrumented with strain gauges of 120 Ω gauge resistance and gauge factor of 2.13. The strain gauges are pasted at $0.05L_p$, $0.25\ L_p$, $0.50\ L_p$, $0.75\ L_p$ and $0.97L_p$ to measure the strain distribution along the pile length. The model raft is 200 mm × 200 mm in plan and 10 mm in thickness. The rigidity of the raft has been evaluated by the following relationship (Horikoshi and Randolph 1997)-

$$K_{rs} = 5.57\frac{E_r}{E_s}\frac{1-\nu_s^2}{1-\nu_r^2}\left(\frac{B}{L}\right)^{0.5}\left(\frac{t_r}{L}\right)^3$$

Where, E_r and E_s are Young's moduli of the raft and the soil, respectively, ν_r and ν_s is the Poisson's ratio of the raft and soil, respectively, B is the breadth and L is the length of the foundation and t_r is the thickness of the raft. Hain and Lee (1978) defined the rigidity of the raft based on the K_{rs} ratios ranging from fairly flexible (K_{rs}= 0.01) to effectively rigid (K_{rs}= 10). The K_{rs} of the raft in present study is estimated to be 2.87 which show the raft to be rigid. Fig. 1 shows the complete experimental model test set up and its different components.

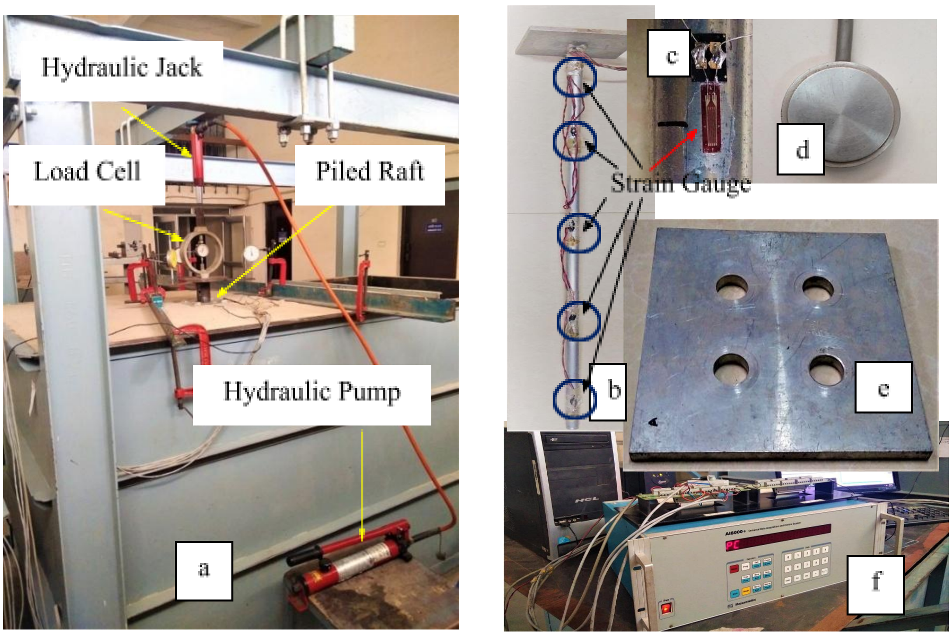


Fig. 1 Experimental test setup: a) piled raft in test tank, b) instrumented pile, c) strain gauge pasted on pile, d) earth pressure cell, e) raft and f) data acquisition system.

Solani river sand, mined locally in Roorkee, has been used in the tests. Fig. 2 shows the gradation of the sand used in the present study. The soil has been classified as poorly-graded sand. Sand particles are classified as sub-rounded based on morphological characterization. Table 1 shows the properties of sand. Sand mediums are prepared to a relative density of 80 %. The angle of internal friction is 38º as obtained from direct shear tests. The amount of soil required has been weighed to achieve the desired density for every 50 mm layer. The soil is poured and compacted manually up to the desired depth. The in situ density has been measured at four corners of the test tank during filling and after test completion.

Table 1: Properties of sand.

G_s	2.67
C_u	1.92
C_c	1.15
ρ_{max}(g/cc)	1.66
ρ_{min}(g/cc)	1.39
IS Classification	SP
φ (°)	38

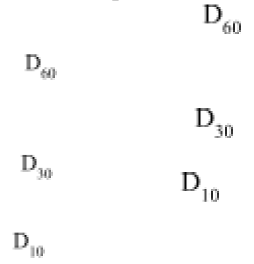


Fig. 2 Grain size distribution curve.

The dial gauges having least count of 0.01 mm have been mounted over foundation system to measure the settlement. The earth pressure cells have been placed beneath the raft to measure the load carried by raft. The tests have been conducted in a load-controlled manner. The vertical load on the piled raft has been applied through a hydraulic jack and measured through a calibrated load cell. The load has been applied in steps, and each load increment of 60 N is applied only when the settlement corresponding to the preceding load becomes very negligible.

3 Numerical Modeling Procedure

The behavior of the piled raft foundation has been studied by developing a three-dimensional numerical model in PLAXIS 3D. It consists of the soil continuum, the pile and raft geometry and the boundary conditions. The trial calculations have been performed by varying the boundaries of numerical domain until the deformations and stresses of the piled raft are insignificantly influenced by the further increase in the soil domain Fig. 3 shows the discretized three-dimensional model of piled raft foundation.

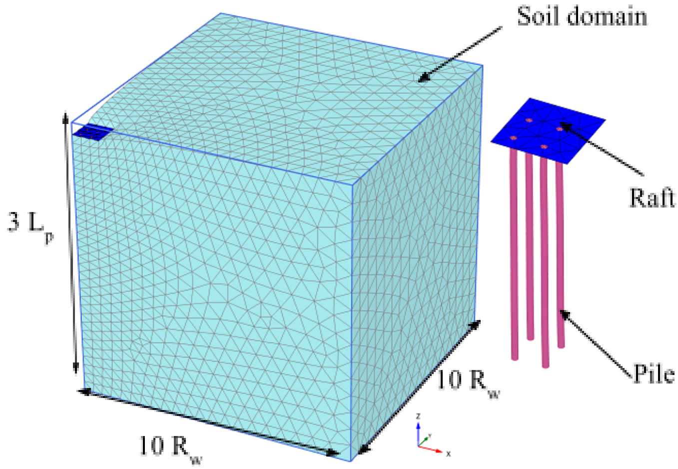


Fig. 3 Discretised three-dimensional model of piled raft foundation.

The homogeneous soil layer has been considered in the present analysis. The horizontal and vertical boundaries has been extended up to 10 times the raft width (R_w) and 2 times the pile length (L_p) from the pile tip to eliminate the undesirable boundary effect (Samanta and Bhowmik 2019). The bottom boundaries are fixed in all directions, while vertical boundaries of the numerical model have been fixed in perpendicular directions and allowed to move in the plane only and the top surface is free to move in all directions. Cohesionless soil is modeled using elastic-perfectly plastic Mohr–Coulomb constitutive model. Drained behavior of the soil medium is considered in the analysis. The strength reduction factor (R_{int}) of 0.7 has been considered between pile and soil. The soil continuum has been discretized using 10 noded tetrahedral elements, having three translational degrees of freedom in three perpendicular directions (Brinkgreve and Swolfs 2012). Several researchers have used this constitutive model to simulate the behavior of sand (Manoharan and Dasgupta 1995, Kumar and Choudhury 2016). Pile and raft are modeled using embedded beam and plate elements respectively. Table 2 shows the range of soil properties and geometries of the pile and the raft used in the present analysis. The load settlement response obtained through finite element methodology has been compared with Chanda et al. (2021). The piled raft is subjected to vertical loading consists of 3x3 pile group rigidly connected with square raft of 10 m width and 1 m thickness. The pile length of 20 m and 0.6 m diameter embedded in loose cohesionless soil medium has been considered in the analysis. Fig. 4 shows the load-settlement response of piled raft. The results are in close agreement confirming the validation of numerical model used in the present study.

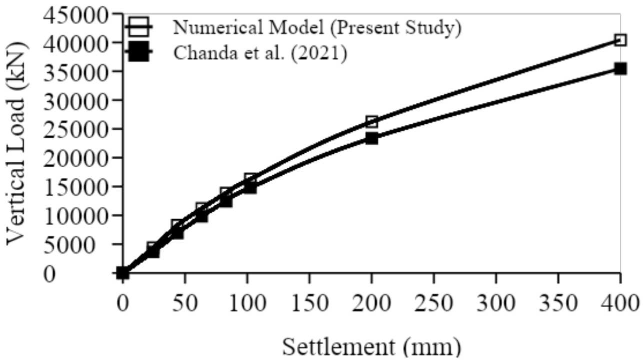


Fig. 4 Comparison of the load-settlement response obtained by Chanda et al. (2021) and present numerical model.

4 Results and Discussions

4.1 Experimental Investigations

4.1.1 Load settlement performance

The load settlement behavior of the single pile (SP), unpiled raft (UR), pile group (PG), and piled raft (PR) has been determined from the experimental investigations.

Table 2: Geotechnical properties of soil and mechanical properties pile and raft.

Parameters	Soil	Raft	Pile
E (kPa)	8.7 – 46.4 x 10^3	25 x 10^6	25 x 10^6
ρ (kN/m^3)	15.5 – 17	25	25
ν	0.28 – 0.30	0.2	
C (kPa)	0	-	-
φ (°)	28 – 33	-	-
Diameter (m)	-	-	0.5 – 1.0
Length (m)	-	7.5	20 – 40
Width (m)	-	7.5	-
Thickness (m)	-	0.75 – 2.5	-

Fig. 5 shows the results of a repeat test performed on a single pile to check the reliability and uniformity of the experimental investigation. Fig. 6 shows the load settlement responses of SP, UR, PG and PR. It can be seen that the pile load on SP increases linearly up to the settlement of 10 % of pile diameter and increases nonlinearly up to the settlement of 55 % pile diameter. At this settlement level, the pile reaches its ultimate capacity and the load becomes constant with further foundation settlement. In 2x2 PG, the load on pile increases up to 10 % of pile diameter and increases non linearly up to 25 % of the pile diameter. At this settlement level the pile reaches its ultimate capacity and the load becomes constant with further settlement. It can be noted that the load carrying capacity of the 2x2 PG is lower than the summation of 4 SP due to the pile-pile interaction which has been discussed in the subsequent section. The load on the UR increases non linearly with the foundation settlement. The load on PR increases linearly up to the settlement of 0.002 R_w, where R_w is raft width. The load on piled raft increases non linearly beyond this settlement level. It can be seen from the load settlement responses of the UR, PG and PR that once the pile achieves its ultimate capacity corresponding to settlement of 25 % of pile diameter (i.e. 5 mm), further load on the piled raft is carried by the raft. Fig. 7 compares strain distribution along piles in SP, PG and PR at vertical loading of 900N. The strain gradually decreases with the depth of pile in SP, PG sand PR respectively. The strains at pile head in PG and SP are 1.54 and 8.94 times the strains in PR respectively. SP experiences higher strains compared to piles in PG and PR depicting the lowest load carrying capacity of the piles. The piles in PR show lower strains at the pile head depicting the highest load carrying capacity.

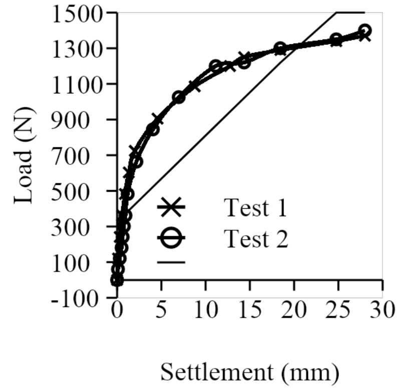


Fig. 5 Load settlement response of single pile.

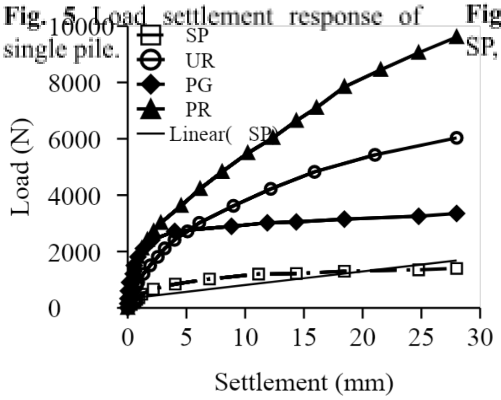


Fig. 6 Load settlement response of SP, UR, PG and PR.

4.1.2 Evaluation of Load sharing

The load carried by the four piles in a 2x2 PR has been evaluated by summing the load carried by four SP and multiplied with pile-pile interaction factor. The load carried by the raft has been evaluated by multiplying the load carried by raft and pile-raft interaction factor. The estimation of interaction factors has been discussed in subsequent section. Fig. 8 shows the nonlinear load sharing of pile and raft in a piled raft foundation with foundation settlement. The pile load sharing increases up to foundation settlement of $0.03R_w$ and decreases with further foundation settlement. The pile load sharing at $0.03R_w$ is 94 % and 70 % with slenderness ratios (L/D) 50 and 25 respectively. The raft load increases with foundation settlement greater than $0.03R_w$. The raft load share becomes stable approximately at foundation settlement of $0.1R_w$. The raft load sharing at $0.1R_w$ is 44 % and 40 % with pile slenderness ratios 25 and 50 respectively.

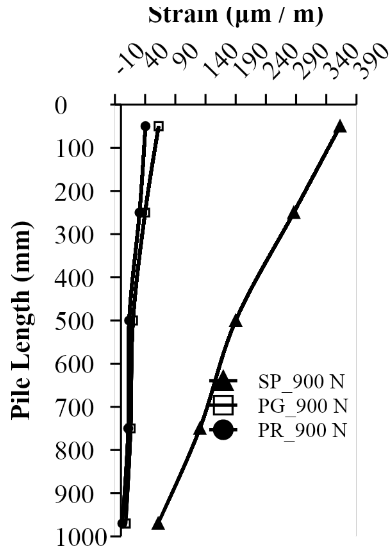


Fig. 7 Strain distribution along pile in a SP, PG and PR.

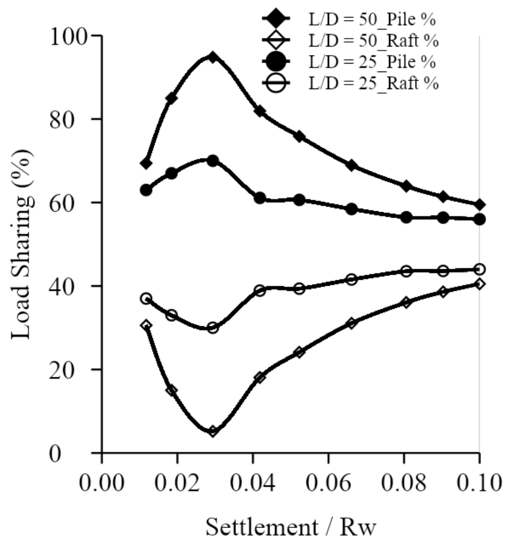


Fig. 8 Load sharing of pile and raft in a piled raft foundation.

The raft load sharing in a piled raft increases with the foundation settlement. Horikoshi and Randolph (1996) and Lee et al. (2014) observed similar results that the raft load sharing increases and pile load sharing decreases with the increasing foundation settlement. The load sharing of the foundation element gradually varies with foundation settlement and becomes constant at settlement of $0.1R_w$. Several studies considered the load corresponding to a settlement of $0.1R_w$ as the ultimate load carrying capacity of the piled raft foundation (Horikoshi and Randolph 1998, Poulos 2001).

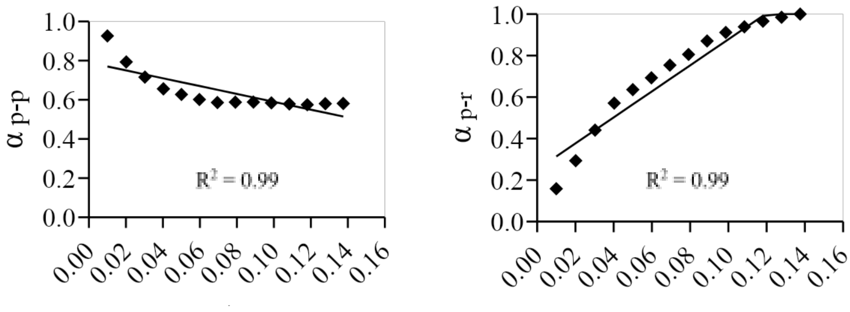
4.1.3 Evaluation of Interaction factor

The piled raft behavior is governed by the complex interaction between the soil-pile-raft interactions and varies with different settlement levels. The pile-pile ($\alpha_{p\text{-}p}$) and pile-raft ($\alpha_{p\text{-}r}$) interaction has been estimated using the following relationships-

$$\alpha_{p\text{-}p} = L_{PG} / \Sigma\, L_{SP}$$
$$\alpha_{p\text{-}r} = L_{R} / \Sigma\, L_{UR}$$

where L_{PG} – pile group load, L_{SP} – single pile load, L_R – load of raft in a piled raft, L_{UR} – unpiled raft load. It has been observed that the interaction between the foundation elements of piled raft varies with its settlement. Fig. 9 shows the variation of $\alpha_{p\text{-}p}$ and $\alpha_{p\text{-}r}$ with S/R_w, where S is the foundation settlement and R_w is raft width.

The pile-pile interaction decreases non linearly up to 0.59 corresponding to $0.06R_w$ foundation settlements. The pile-pile interaction is constant with further settlement. Lee et al. (2014) observed similar variation in pile-pile interaction with foundation settlement. The pile-raft interaction increases non linearly with the foundation settlement and becomes constant after 0.10 R_w foundation settlement. The pile load sharing decreases as the pile-pile interaction decreases, whereas the raft load sharing increases as the pile-raft interaction increases.



a)

b)

Fig. 9 Interaction factor: a) pile-pile ($\alpha_{p\text{-}p}$) and b) pile-raft ($\alpha_{p\text{-}r}$).

4.2 Numerical Analysis

The influence of different parameters on load sharing performances of the pile raft foundations under vertical loadings has been investigated by three-dimensional finite element analysis. The effect of soil stiffness, length to diameter ratio, area of pile and soil-raft stiffness has been discussed in this section.

4.2.1 Effect of pile-soil stiffness ratio

The effect of soil stiffness on load sharing of pile and raft has been investigated by varying the soil stiffness from loose to dense cohesionless soil medium. Fig.10 shows the variation of load sharing with foundation settlement in pile and raft with the variation in soil stiffness. The L/D ratio and A_g/A_r of 80 and 0.014 has been considered in the analysis respectively. The K_{rs} has been varied from 0.36 to 1.90. The load shared by the raft increases with an increase in soil stiffness, whereas the load shared by the piles increases with a decrease in soil stiffness. The pile load sharing increases with foundation settlement up to 0.05 R_w and further decreases gradually with increasing foundation settlement. The load shared by pile and raft at 0.05 R_w foundation settlement is 81.2%, 76.9%, 70.1% and 18.8%, 23.1%, 29.9% for E_p/E_s in the range of 2874 - 539 respectively. The pile load sharing increases to 11 and 6 % with increasing E_p/E_s from 539 to 1232 and 1232 to 2874 respectively. The increase in soil stiffness improves the normal pressure between the raft and underlying soil, which is effective in increasing the frictional bearing capacity of the raft (Akbari et al. 2021). The development of contact pressure with gradually increasing loading consequently increasing foundation settlements and results in increase of raft load sharing in the piled raft foundation. Similar foundation response has been obtained from the experimental investigations in the present study.

4.2.2 Effect of soil-raft stiffness (K_{rs})

The effect of soil-raft stiffness has been evaluated by varying the soil stiffness and the raft thickness. Soil-raft stiffness increases with increase in raft thickness and soil stiffness. The L/D ratio and A_g/A_r of 80 and 0.014 has been considered in the analysis respectively.

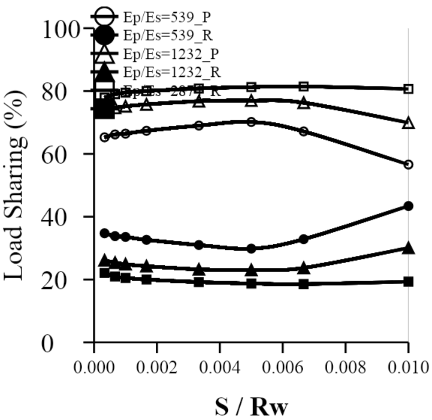


Fig. 10 Effect of E_p/E_s on load sharing in piled raft.

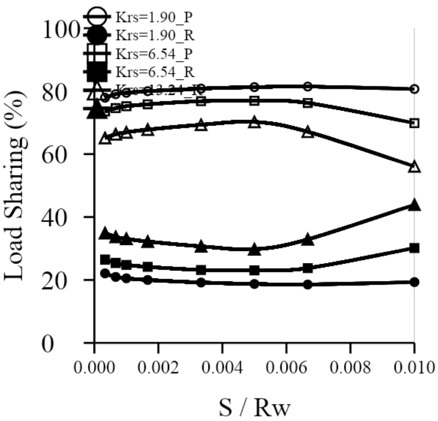


Fig. 11 Effect of K_{rs} on load sharing in piled raft.

Fig. 11 shows the effect of soil-raft stiffness on the load sharing of pile and raft in a piled raft. The raft load share increases and pile load share decreases with the foundation settlement. Similar results have been observed by El-Garhy et al. (2013) for piled raft foundations in sand subjected to vertical loading. The raft load share increases by 17 % and 24 % with varying K_{rs} from 1.90 to 6.54 and 6.54 to 13.24, respectively.

4.2. 3 Effect of A_g/A_r

The A_g/A_r ratio increases with increasing the pile diameter, consequently increasing the group pile area (A_g). The relatively stiff soil (E_s = 46400 kPa) and flexible raft (K_{rs} = 0.36) raft has been considered in the analysis. The slenderness ratio of pile varies in the range of 40 – 80. Fig. 12 shows the influence of A_g/A_r on the load sharing behavior of piled raft. The pile load sharing varies in between 65 to 78 % with the variation of A_g/A_r in the range of 0.01 to 0.05. The pile load sharing increases with an increase in pile diameter. This could be attributed to the improved pile capacity with a larger pile group area. The increase in pile diameter increases the cross sectional area of the pile tip and surface area of the pile shaft consequently improving the end bearing resistance and skin friction resistance of the pile respectively.

4.2.4 Effect of L/D ratio

The relatively stiff soil (E_s = 46400 kPa) and flexible raft (K_{rs} = 0.36) raft has been considered in the analysis. The A_g/A_r has been taken as 0.014. Fig. 13 shows the influence of pile length on load sharing of the piled raft. The load sharing of piles increases, and load sharing of raft decreases with increasing the slenderness ratio. The load sharing of pile varies in between 60 to 65 % with the variation of L/D in the range of 40 to 80. This increase in load proportion is observed 6 % and 3 %, when the L/D ratio changes from 40 to 60 and 60 to 80, respectively. The increase in pile length results in higher skin resistance due to larger surface area of the pile shaft attributing larger pile load sharing.

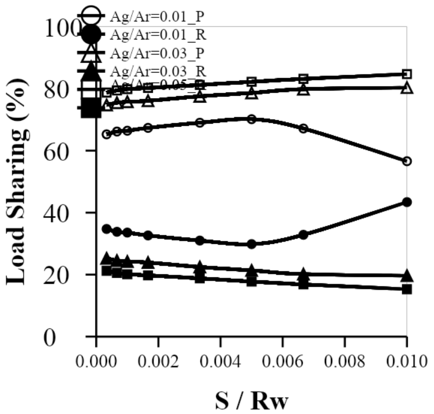


Fig. 12 Effect of A_g/A_r on load sharing in piled raft.

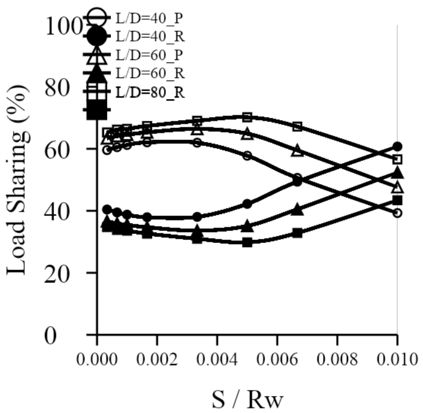


Fig. 13 Effect of L/D on load sharing in piled raft.

5 Conclusion

The experimental and numerical investigation on a vertically loaded small square piled raft in cohesionless soils shows the nonlinear load sharing of pile and raft. The complex pile-soil-raft interaction governs the load sharing between the foundation elements. The experimental and numerical investigations confirm that the load sharing between the pile and raft varies nonlinearly with the foundation settlement. The increase in foundation settlement results in a decrease in pile-pile interaction, leading to decrease in pile load sharing, whereas pile-raft interaction increases with foundation settlement which results in increase in raft load sharing in a piled raft. The parametric studies show that the load sharing of pile and raft in a piled raft foundation is greatly influenced by the stiffness ratio of the pile &soil, soil raft stiffness, ratio of pile group area and raft, and the length to diameter ratios of the pile. The pile shares 60 – 78 %, and the raft shares 22 – 40 % of the load applied on the piled raft for the parameters considered in the present study. The understanding of load sharing mechanism obtained from more experimental and numerical studies will be helpful to develop a model for predicting the load sharing in piled raft.

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