

“Analysis of Model Piled Raft foundation in sand with emphasis on Pile-Soil, Raft-Soil Interaction”

Synopsis of the

Ph.D. thesis

Proposed to be submitted for the degree of

DOCTOR OF PHILOSOPHY (CIVIL)

By

Mrs. Arpita V Patel

GUIDE

Dr. N.H.Joshi

Associate Professor

Applied Mechanics and Structural Engineering Department



Applied Mechanics and Structural Engineering Department

Faculty of Technology and Engineering

The Maharaja Sayajirao University of Baroda

Vadodara-390001

Synopsis of the Thesis on

Analysis of Model Piled Raft foundation in sand with emphasis on Pile-Soil, Raft-Soil Interaction

The piled raft foundation system is mainly used for high-rise structures in which the analysis of forces carried by raft, piles and soil are very complex in nature. This complex soil-structure interaction mechanism involves the interaction among foundation elements and their surrounding soil and can be classified into five categories: (1) pile - pile interaction, (2) pile - raft interaction, (3) raft – soil interaction, (4) pile - soil interaction, (5) pile base - pile shaft interaction. Piled raft foundations (PRF) are found suitable for strong soil like dense sand and stiff clay and unfavorable for soft soils near the ground. The major advantage of using combined system is reduction in maximum and differential settlements with considerable improvement in serviceability criteria, increase in overall stability of foundation, reduction in number of piles compared to conventional pile foundation and reduction in bending stresses for the raft. The key design component for piled raft is the proportion of load carried by the raft and piles, as both contribute to the load carrying behavior of piled rafts. The estimation of the load carrying capacity of piled raft is complex due to uncertain aspects associated with the load sharing behavior and interaction effects that vary with settlements.

Akinmusuru (1980) conducted experiments on unpiled raft, pile groups and piled raft and showed that the bearing capacity of the piled raft foundations exceeds the sum of the bearing capacity of the raft and pile group. **Liu et al. (1985)**, conducted field studies on piled raft foundations in sand and reported that block failure does not occur for groups of bored piles in sand. **Cooke (1986)** observed that the load distribution between piles in piled raft foundations is affected by pile number and spacing. **Phung (1993)** and **Lee and Chung (2005)** carried out field test in loose to dense sand and found that raft-pile interaction is the governing factor for pile raft behaviour, which causes an increase in skin friction of piles due to contact pressure of raft on soil. **Fioravante et al. (2008)** found that the raft's contribution begins as the piles approach their maximum capacity. They also noticed that piled-raft stiffness increased with the increase in the number of piles supporting the raft and displacement piles are more successful than non-displacement piles in reducing raft settlement. **Balakumar Venkatraman (2009)** found that at lower settlements piles share more load whereas raft shares higher load with increase in settlement. **Dr. Mosa J. Al-Mosawi et al (2011)** did experimental study to investigate the behavior of piled raft system in sandy soil and found that the percentage of the load carried by piles was increased with the increase of number of piles. **El-Garhy et al. (2013)** conducted a series of small scale tests to investigate the behavior of piled raft foundations in sand and found that raft thickness and pile length have insignificant influence on piled raft load sharing while increasing the number of piles increases pile share when pile spacing and raft size are constant. **A. Juneja and others (2013)** conducted 1g model tests to understand the effects of raft

thickness, number and length of piles on the load shared by the piles and found that for a larger number of piles, the load shared by the piles increased with the length of the pile and was roughly the same for different raft thicknesses. A large contribution of raft was obtained when fewer piles were used. **Jaymin D Patil et.al (2014)** has performed experiments to study the behaviour of piled raft foundation system subjected to vertical load on dry sand and concluded that the raft thickness has insignificant effect on the settlement and the load sharing between piles and raft. The efficiency of piled raft foundation system in reducing settlement is minimal beyond a certain number of piles.

Rouzbeh Vakili (2015) studied the load sharing mechanism of a piled raft foundation in sandy soil through small scale tests and three dimensional numerical analyses and concluded that the load sharing of a non-displacement piled raft foundation in homogeneous sand is a function of two variables, S/d_p (spacing to pile diameter ratio) and w/d_r (settlement to raft width ratio) ratios, but independent of soil relative density, number of piles, and pile slenderness ratio. **Dongyu Park and Junhwan Lee (2015)** investigated the load responses and interaction effects of piled rafts embedded in sands by performing experiments and found that the interaction factors between pile groups, piles and rafts, and rafts and piles displayed state-dependent and nonlinear variations with settlement. **A.Z. Elwakil et al (2016)** have done experimental and numerical study (PLAXIS 2D) of piled raft system proposed to construct the piled raft at $S/B = 0.7\%$ for the optimal performance. **Nemanja Bralovi' c et. Al (2022)** conducted experimental analysis on small-scale 1g physical models of piled raft foundation structures with a group of 2×2 piles in loose sand and found that the current conventional approach to design of piled raft foundations, at a high safety load factor in piles that assume to take the whole external applied load, is very conservative. Instead, it is more economical to apply a low bearing capacity factor for piles as settlement reducers and maximize use of raft bearing capacity to carry part of the external load. **Irfan Jamil et. Al (2023)** carried out experimental and numerical studies on different small-scale models of piled raft foundations under vertical and lateral load and found that as the number of piles increased from 1 to 13, the load shared by piles of piled raft foundation increased from 13% to 85%.

Randolph (1983) presented a simplified approach from numerical analysis for evaluating a piled raft foundation's load sharing. This approach was designed for a single piled raft unit with a floating pile coupled to a stiff circular cap and supported by an elastic semi-infinite mass. **Clancy and Randolph (1993)** derived the equations for estimating piled raft stiffness, load shared by piles and raft in piled raft based on the stiffness of pile group and unpiled raft foundation. **Burland (1995)** developed a simplified design approach for piles designed to act as settlement reducers and to achieve their full geotechnical capacity at the design load in piled raft foundation. **Poulos, H. G. (2001)** discussed the design process for a piled raft, considering a three-stage process. (a) A preliminary stage to determine whether utilizing a piled raft is feasible; and the necessary number of piles to meet design requirements. (b) A second stage to determine

the locations where piles are needed and their overall characteristics. (c) A final comprehensive design step to determine the ideal number, placement, and configuration of the piles and to compute the loads and moments of the piles as well as the exact distributions of settlement, bending moment, and shear in the raft. **Polous (2001)** proposed equations for calculating the proportion of the total applied load carried by the raft, stiffness of piled raft and based on that he suggested a method to predict the tri-linear behavior of load settlement of piled raft foundation and also suggested one equation to calculate the load corresponding to intersection of first two linear part of the load settlement curve (at which pile group capacity may be fully mobilized). **Prakaso and Kulhawy (2001)** used simplified linear elastic and nonlinear (elastic plastic) 2-D plane strain finite element models to predict the performance of piled raft foundations and proposed a displacement based design procedure for piled raft based on the analysis. **Oh et al. (2008)** used finite element analysis to study the performance of piled raft foundations in sand. According to the findings of this study, raft thickness influences differential settlement and bending moments but has little effect on load sharing and maximum settlement. **Zkaria Mohamed Omeman et al (2012)** created a simple model for predicting raft-pile settlement and load sharing for piled-raft foundations based on stiffness of pile groups and unpiled raft. **Omeman (2012)** used a series of 2D finite element analyses to investigate the effect of different parameters on the load sharing of a piled raft foundation in sandy soil and found that increasing the pile diameter and the number of piles decreases the raft share; however, pile length has no effect on piled raft load sharing. **Lee et al. (2014)** investigated the load response and load carrying capacity of piled rafts focusing on the non-linear load sharing behavior of piled rafts and proposed a normalised load-sharing model, taking into account settlement-dependent load-sharing behaviour and load capacity ratio. **N. M. Alsanabani (2017)** proposed simplified method for computing the load carried by piles, and settlement of piled raft based on the characteristics of an un-piled raft, pile group, and soil. In this study, the stiffness values of the piled raft (k_{pr}), unpiled raft (k_{ur}), and pile group (k_{pg}) for a certain settlement were used. **Ashutosh Kumara and Deepankar Choudhury (2018)** proposed a new prediction method to estimate both the ultimate limit state (ULS) and serviceability limit state (SLS) bearing capacity of CPRF by evaluating the pile-raft and raft-pile interaction factors. **Priyanka Bhartiya et al (2020)** performed systematic linear-elastic finite-element analyses on a series of unpiled rafts (rafts without piles), pile groups, and piled rafts with different geometries and pile configurations to determine the stiffness of these rafts, pile groups, and piled rafts. **Santosh Niraula, Dr. Indra Prasad Acharya (2021)** dealt with successive analysis of parameters of piled-raft foundation system using PLAXIS 2D as a FEM tool and concluded that among the various analytical approaches for studying piled raft behaviour, 3D finite element and finite difference analyses offer the highest level of accuracy and complexity.

From the numerous case studies presented **Rolf Katzenbach, et.al (2005)** had given an overview of the theoretical and practical development of CPRF foundations and concluded that by using CPRFs as a foundation for high-rise buildings in the settlement-sensitive Frankfurt clay, a

considerable settlement reduction of more than 50% compared to raft foundations could be achieved. Due to its enhanced design philosophy, a CPRF reduces the costs for piles by more than 60% compared to a conventional pile foundation. **Ryuuichi Sonoda et.al (2009)** constructed a building and its foundation in sandy ground using a reverse construction method and examined settlements of the foundation for the validity of the design methods. The measured settlements were smaller than those predicted in the design stage, satisfying the design requirements for the building. The main difference between a reverse construction method and a conventional construction method was that the piles were cast in place and are partially loaded by the superstructure early during the construction process. **Yamashita et al. (2011)** proposed a piled raft foundation with in situ measurements for nineteen story residential tower on loose to medium sand and eleven story base-isolated offices building on thick layer of sand and gravel to prevent overall and differential settlement.

Many researches had been done on piled-raft foundation but due to complex soil-structure interaction the behavior of piled raft foundation yet not fully understood. To understand this complex behavior of piled raft foundation, the experimental work has been carried out on model unpiled raft, single pile, pile groups and piled raft foundation with different parameters of model foundation and foundation soil. The parameters considered in this study for model foundations are shape of raft with equal contact area with soil, length to diameter ratio of piles (L/d), spacing between piles (S), configurations of piles (CF), soil-pile friction angle (δ) and c/s shape of piles with equal c/s area while for foundation soil the variables were types of sand and relative density of sand bed. There were four shapes of raft namely square, circular, rectangular and trapezoidal with 48400 mm^2 contact area used in the study of shape of raft. The square raft of size $220 \text{ mm} \times 220 \text{ mm} \times 25 \text{ mm}$ was used in the study of L/d ratio of pile, spacing of piles, configuration of piles and soil pile friction angle. The internal and external diameter of pile used in this study were 7.8 mm and 9.7 mm respectively in all experiments except in the study of shape of piles. The embedded lengths of pile used in this study to represent L/d ratio = 10, 20, and 30 were 97 mm , 194 mm and 291 mm respectively. The study of L/d ratio of pile was made in a 5×5 group of piles with $5d$ spacing. The study of spacing between piles was made in pile group (3×3) with $3d$, $5d$ and $7d$ spacing (d = external diameter of pile) and piles with $L/d = 30$. The study of soil-pile friction angle was made in a 3×3 pile group with $5d$ spacing and L/d ratio of pile as 30. The size of the raft used in the study of shape of pile was $240 \text{ mm} \times 240 \text{ mm} \times 25 \text{ mm}$ and shape of pile was H, hollow circular (HC) and hollow square pile (HSQ) with 88 mm^2 c/s area and 300 mm embedded length of piles. The Orsang river sand was used as a foundation soil in the study of all experiments except shape of piles where Narmada river sand was used. The relative density (I_d) of sand bed was kept 40%, 60% and 80% in all experiments except in the study of configuration of piles. The configuration of piles was tested on sand bed with 60% relative density. All the experiments were performed in a steel tank of size $1200 \text{ mm} \times 1200 \text{ mm}$ in plan and 1070 mm in depth. The load was applied on the model foundation using mechanical screw jack which was measured using proving ring and settlements were recorded using

LVDTs/Deformation dial gauges. The contact pressures of raft with soil were measured using miniature earth pressure cells (EPC) kept flushed with the bottom surface of the raft. The experimental results compared with numerical results and the effect of pile configurations on the behaviour of prototype piled raft foundations was analyzed using PLAXIS 3D. The study was conducted using three-dimensional finite element analyses with PLAXIS 3D at 60% relative density of sand. Nine different configurations, including square (S1 to S9) and circular patterns (C1 to C9), with pile length-to-diameter ratios (L/d) of 10, 20, and 30 were subjected to varying point loads.

The load-settlement characteristics of unpiled raft foundation, single pile, pile group and piled raft was analyzed. The ultimate load of unpiled raft Q_{ur} of circular shape was found minimum at all relative densities of sand compared to other shapes. The above results are consistent with the theory. The ultimate bearing capacity (q_{ult}) of circular raft at 40%, 60% and 80% relative density was found 191.69 kN/m², 213.60 kN/m², and 356 kN/m² respectively which is obvious as increase in relative density increase in ϕ values hence the ultimate bearing capacity. The range of percentage increment in Q_{ur} of square, rectangular, and trapezoidal rafts with respect to Q_{ur} of circular rafts was 36% to 96%. The Q_{ur} of circular raft at 60% and 80% relative density was increased by 11% and 86% respectively as compared to $I_d = 40\%$. The increment in Q_{ur} of square raft at 60% and 80% relative density was found to be 53% and 117% respectively with respect to 40% relative density. As compared to $I_d = 40\%$, the Q_{ur} of trapezoidal and rectangular raft was found to be increased around 46% to 52% and 115% at $I_d = 60\%$ and $I_d = 80\%$ respectively. The Q_{ur} of square raft (240 mm \times 240 mm \times 25 mm) at 60% and 80% relative density was found to be 11% and 119% respectively with respect to 40% relative density. The range of initial tangent stiffness of circular unpiled raft (UPR) (k_{ri}) was 1283.11 kN/m to 2718.29 kN/m. The range of increment in initial tangent stiffness of unpiled raft (UPR) (k_{ri}) at 60% and 80% relative density as compared to 40% relative density was found to be 36% to 54% and 96% to 130% respectively i.e. greater ϕ and density of the foundation sand bed revealed greater stiffness. The increment in k_{ri} of raft (240 mm \times 240 mm \times 25 mm) at 60% and 80% relative density as compared to 40% relative density was found to be 25% and 42% respectively. The secant stiffness of unpiled raft foundation was varying linearly with width of raft, exponentially with relative density of sand and in terms of power with load. The loads calculated from EPC readings were nearer to the actual applied load. Modulus of subgrade reaction was obtained by performing a model plate load test and modulus of elasticity using a simple triaxial test. Correlations between modulus of elasticity and modulus of subgrade reaction developed by various investigators were found in the literature review, and it was observed that the pattern of change of modulus of subgrade reaction with respect to change in the relative density of sand obtained in the present study was closer to the correlation developed by Vesic and Selvadurai.

Due to block action, the load carrying capacity of pile group with 3d spacing has maximum load carrying capacity amongst 3d, 5d and 7d spacing. At 40% relative density, the load carrying

capacity was decreased as the spacing of pile increased. At 60% and 80% relative density, the load carrying capacity of pile group was decreased as the spacing of pile increased from 3d to 5d and after that it was increased at 7d spacing. This is attributed to block action at 3d spacing, individual pile pressure bulb overlapping at 5d spacing and full individual action of piles at 7d spacing. The initial tangent stiffness of pile group (k_{pg}) increased with increase in relative density of sand and L/d ratio of piles in pile group. The initial tangent stiffness of pile group (k_{pg}) obtained from experimental results and same value calculated using Fleming's relation are coming nearer to same except in spacing criteria at $I_d = 80\%$.

The load settlement characteristics of piled raft foundation in all most all the cases were tri-linear in nature where in the first yielding was denoted as initial yield load (IYL) and second yielding was denoted as final yield load (FYL), however after that also some residual capacity was observed in many cases. The IYL and FYL of piled raft foundation (PRF) with different shape of raft was increased with increase in relative density of sand and the minimum and maximum values of IYL and FYL were found in PRF with circular raft and square raft respectively. The above results indicate that the carrying capacity of piled raft is consistent with effect of shape of raft provided same pile group and its influence remain the same. At all relative densities considered in this study, the range of IYL of PRF with circular, rectangular, trapezoidal and square raft was 4.77 kN to 11.93 kN, 5.31 kN to 15.93 kN, 7.97 kN to 15.93 kN and 11.63 kN to 22.32 kN respectively. The range of FYL in PRF with circular, rectangular, trapezoidal and square raft was 9.54 kN to 21.21 kN, 13.28 kN to 34.52 kN, 15.93 kN to 29.21 kN and 21.59 kN to 38.27 kN respectively.

The contact pressure of raft measured by EPC located in one quadrant of 3×3 pile group was higher than other locations in UPR and PRF with all shapes of raft at all the relative densities of sand which shows that in UPR the contact pressure is maximum at center and in PRF due to confinement of sand between adjacent piles the contact pressure was found to be maximum. In all most all cases the % load shared by the pile group (% LSPG) was higher compared to % load shared by raft (% LSR) up to the initial range of relative settlement (s/B_r) and gradually it decreased and at certain relative settlement (s/B_r) the (% LSPG) and (% LSR) became equal. The reason behind this may be that the pile reaches at ultimate capacity at lower settlement compared to raft. % LSPG and % LSR were found equal (i.e. 50%) in circular PRF at $s/B_r = 0.032, 0.01,$ and 0.02 for 40%, 60% and 80% relative density respectively. In rectangular PRF, the % LSPG and % LSR were found equal (i.e. 50%) at $s/B_r = 0.001, 0.02,$ and 0.001 for $I_d = 40\%, 60%$ and 80% respectively. In PRF with trapezoidal raft the % LSPG = % LSR were found at $s/B_r = 0.01, 0.07$ and 0.04 for $I_d = 40\%, 60%$ and 80% respectively. In PRF with square raft the % LSPG = % LSR were found at $s/B_r = 0.04$ for $I_d = 60\%$ while at $I_d = 40\%$, the % LSPG was greater than % LSR at all relative settlements this may be attributed due to less bearing was available to raft in loose state of sand however friction capacity in pile was still considerable. At $I_d = 80\%$, the % LSR was greater than % LSPG at all relative settlements this may be attributed due to

high bearing was available to raft in dense state of sand. The load shared by raft (LSR) and load shared by pile group (LSPG) at IYL of circular and trapezoidal PRF increase as the relative density of the sand bed increases. At IYL, the value of LSPG was higher than the LSR in all shapes of PRF at all relative densities, except in rectangular and square piled rafts at 80% relative density of sand. The IYL of PRF with a circular raft was the lowest out of all the shapes considered in this study.

Piled raft coefficient (α_p) was decreased rapidly with increase in s/B_r upto $s/B_r = 0.01$ to 0.07 and after that it remained more or less constant. The range of ratio of load shared by raft (LSR) to the load of unpiled raft at the same settlement corresponding to the IYL ($(P_r)_{s_i}$) was found to be 0.38 to 0.82, 0.59 to 0.90, 0.67 to 1.14, and 0.48 to 0.78 in circular, square, rectangular, and trapezoidal piled raft foundation respectively. The range of ratio of load shared by pile group (LSPG) to the load of only pile group at the same settlement corresponding to the IYL ($(P_{pg})_{s_i}$) was found to be 1.7 to 5.05, 2.45 to 12.1, 1.7 to 4.7, and 2.6 to 5.15 in circular, square, rectangular, and trapezoidal piled raft foundation respectively. i.e. it represents increasing pile skin friction caused by increase in confining stresses within the soil by raft pressure due to contact of raft (pile cap) with sand (Long 1993; Frankeet al. 2000; Katzenbach et al. 2000). The effect of increasing confining stress may differ depending on stress level and location of piles within the raft.

The range of primary stiffness of piled raft ($(k_{pr})_p$) (slope of initial linear portion of load settlement curve of PRF) with circular, square, rectangular and trapezoidal raft was found to be 1560.10 kN/m to 3129.65 kN/m, 5262.22 kN/m to 9873.06 kN/m, 3976.92 kN/m to 6215.72 kN/m, 3411.18 kN/m to 6235.71 kN/m respectively, where as the range of secondary stiffness of piled raft ($(k_{pr})_s$) (slope of line joining IYL and FYL of PRF) was found to be 534.06 kN/m to 1226.04 kN/m, 593.20 kN/m to 1601.48 kN/m, 660.39 kN/m to 1243.46 kN/m, 647.98 kN/m to 1470.10 kN/m respectively. The majority values of primary stiffness ($(k_{pr})_p$) predicted from **Zkariaomeman** method was varied by less than 20% of experimental ($(k_{pr})_p$) in case of PRF with 3×3 pile group while it was more than 100% with 5×5 pile group. The equations (1) to (4) proposed for predicting IYL, FYL, $(k_{pr})_p$ and $(k_{pr})_s$ respectively and in most of the cases the predicted values were vary by less than 25% of the experimental values. The symbols used in the proposed equations are defined in Chapter 5.

$$IYL = C_1 * (P_r)_{s_i} + C_2 * (P_{pg})_{s_i} \quad (1)$$

$$FYL = C_3 * Q_{ur} + C_4 * Q_{u, pg} \quad (2)$$

$$(k_{pr})_p = 2012.05 + 9237.72B_r - 119.54TLP - 110.49I_d + 2.19k_{ri} + 0.98(k_{pg})_i \quad (3)$$

$$(k_{pr})_s = 15.13I_d + 0.018k_{ri} \quad (4)$$

The settlement reduction ratio (SRR) for PRF with a circular raft, rectangular raft, trapezoidal raft, and square raft varied between 7% and 52%, 1% and 74%, 2% and 69%, and 30% to 86%, respectively, at a load of up to 15 kN. The load improvement ratio (LIR) in PRF was around 1 at initial settlement and increased to 1.5 - 2 at higher settlement, considering all raft shapes.

The IYL and FYL of PRF were increased with increase in L/d ratios of piles and relative density of sand. The range of IYL of PRF with L/d ratio = 10, 20, and 30 were found to be 7.85 kN to 12.81 kN, 10.63 kN to 19.65 kN, and 12.38 kN to 22.15 kN respectively at 40%, 60% and 80% relative density of sand. i.e., The percentage increase in IYL of PRF with L/d ratio = 10, 20, and 30, at 60% and 80% relative density as compared to 40% relative density, were 34% and 63%; 51% and 85%; and 39% and 79% respectively. The range of FYL of PRF with L/d ratio = 10, 20, and 30 were found to be 14.68 kN to 30.39 kN, 22.43 kN to 40.04 kN, and 23.87 kN to 48.35 kN respectively at 40% to 80% relative density of sand. i.e., The percentage increase in FYL of PRF with L/d ratio = 10, 20, and 30, at 60% and 80% relative density as compared to 40% relative density, were found to be 48% and 107%; 21% and 78%; and 43% and 103% respectively. At 40% relative density of the sand bed, the percentage increase in IYL of PRF with L/d ratios of 20 and 30 was 35% and 58%, respectively, compared to PRF with L/d ratios of 10, and in FYL, the same values were 53% and 63%. When comparing PRF with an L/d ratio of 10 to PRF with L/d = 20 and 30, the percentage increase in IYL was 53% and 64%, respectively, at 60% relative density of the sand bed, while in FYL it was 25% and 58%. At 80% relative density of the sand bed, the percentage increase in IYL of PRF with L/d ratios of 20 and 30 was 53% and 73%, respectively, compared to PRF with L/d ratios of 10, and in FYL, these values were 32% and 59%. At $I_d = 40\%$, the s/B_r value was 0.036, 0.008, and 0.022, at which the % LSPG and % LSR in the piled raft became equal (i.e., 50%) for PRF with L/d = 10, 20, and 30, respectively. At $I_d = 60\%$, the s/B_r value was 0.012, 0.036, and 0.016, at which the % LSPG and % LSR in the piled raft became equal (i.e., 50%) for PRF with L/d = 10, 20, and 30, respectively. For PRF with L/d = 10, 20, and 30, respectively, the % LSPG and % LSR in the piled raft became equal (i.e., 50%) at $I_d = 80\%$, where the s/B_r value was 0.008, 0.008, and 0.0. When the relative density of sand increased, the LSPG at IYL of PRF with L/d = 10 increased as well. However, in the case of PRF with L/d ratios of pile = 20, and 30, the LSPG at IYL increased at 60% relative density as compared to 40% relative density and decreased at 80% relative density as compared to 60% relative density. When the relative density of sand increased, the LSPG at FYL of PRF with L/d = 10 and 30 increased as well. The LSPG of PRF at FYL decreased at 60% relative density as compared to 40% relative density and increased at 80% relative density as compared to 60%

relative density for $L/d = 20$. The LSR of PRF with all L/d ratio of pile at IYL and FYL was increased with increase in relative density of sand. There was no significant effect of the relative density of sand on the relation between the piled raft coefficient and the relative settlement of PRF with an L/d ratio of 10. The range of primary stiffness of piled raft $(k_{pr})_p$ and secondary stiffness of piled raft of PRF $(k_{pr})_s$ with different L/d ratios of the pile was 1765.02 kN/m to 6645.11 kN/m, and 734.98 kN/m to 1122.42 kN/m respectively. It increased with increase in relative density of sand and L/d ratio of piles.

The IYL and FYL increased as the relative density of the sand bed and the spacing between piles increased. The range of IYL and FYL of PRF with 3d spacing at different relative densities was 8.07 kN to 13.95 kN and 13.88 kN to 29.49 kN, respectively. With 5d spacing and varying relative densities, the PRF's IYL and FYL ranged from 9.3 kN to 15.94 kN and 15.94 kN to 31.89 kN, respectively. IYL and FYL of PRF with 7d spacing ranged from 11.63 kN to 22.32 kN and from 21.59 kN to 38.27 kN, respectively, at different relative densities. In comparison to 40% relative density, the differences in IYL of square rafts with varying pile spacing ranged from 29 % to 65 % at 60 % relative density. The variations in IYL of square rafts with different spacing between piles were 71 % to 92 % at 80% relative density as compared to 40% relative density. As compared to 3d spacing, the IYL of square PRF with 5d and 7d spacing increased in the range of 10 % to 76%. In comparison to 40% relative density, the differences in FYL of square rafts with varying pile spacing ranged from 33 % to 50 % at 60 % relative density. The variations in FYL of square rafts with different spacing between piles were 77 % to 113 % at 80 % relative density as compared to 40% relative density. As compared to 3d spacing, the FYL of square PRF with 5d and 7d spacing increased in the range of 2 % to 56%.

For an initial relative settlement of around 0.05 to 0.07, the contact pressure distribution in a piled raft foundation with 5d and 7d spacing was found to be greater within the pile group compared to outside the group which shows the effect of confinement of sand between adjacent piles. In PRF with 3d and 5d spacing, the LSPG at IYL was more than the LSR at IYL at all relative densities of sand, and it increased with an increase in the relative density of the sand bed. In PRF with 7d spacing, the LSPG at IYL was more than the LSR at IYL for 40% and 60% relative density of sand bed while at 80% relative density it was less than LSR.

In PRF with 3d spacing, the % LSPG and % LSR became equal at relative settlement $(s/B_r) = 0.13$ and 0.016 for $I_d = 60\%$ and 80% , respectively, while at $I_d = 40\%$, the % LSPG was more than % LSR at all relative settlements. In PRF with 5d spacing, the % LSPG and % LSR became equal at relative settlement $(s/B_r) = 0.05$ for $I_d = 40\%$, while at $I_d = 60\%$ and 80% , the % LSPG was more than % LSR at all relative settlements. In the case of PRF with 7d spacing and $I_d = 40\%$, the % LSPG was more than % LSR at all relative settlements. The % LSPG and % LSR were equal at relative settlement $(s/B_r) = 0.04$ for PRF with 7d spacing at 60% relative density. In the case of PRF with 7d spacing and $I_d = 80\%$, the % LSPG was less than % LSR at all

relative settlements. The range of primary stiffness of piled raft $(k_{pr})_p$ and secondary stiffness of piled raft $(k_{pr})_s$ of PRF with different spacing were 1743.67 kN/m to 9873.06 kN/m, and 315.97 kN/m to 1601.48 kN/m, respectively.

The maximum values for IYL and FYL were observed in configuration CF-9, while the minimum values were seen in CF-7. This indicates that the length of the piles in PRF has an effect on the IYL and FYL, as CF-9 had long piles and CF-7 had short piles. It was found a group of configurations with almost identical values of IYL, namely (CF-2, CF-7), (CF-3, CF-6), and (CF-4, CF-5, CF-8). CF-2 and CF-7 are characterized by a larger number of small piles located at the periphery of the pile group. On the other hand, CF-3 and CF-6 both have the same number of long piles. The IYL of the piled raft foundation was observed to follow a decreasing order based on the configuration, with CF-9, CF-1, CF-8, CF-4, CF-5, CF-6, CF-3, CF-2, and CF-7 having the highest to lowest IYL respectively. Among CF-9, CF-1, and CF-4, the periphery piles were mainly long piles; for CF-8, CF-5, and CF-6, the periphery piles were mainly medium piles; and for CF-3, CF-2, and CF-7, the periphery piles were mainly short piles. This indicates that the IYL of PRF (Piled Raft Foundation) is dependent on the arrangement of piles. The PRF showed higher, moderate, and lower IYL with long piles, medium piles, and shorter piles respectively nearer to the periphery of the raft. The percentage increase in IYL for CF-1 to CF-9 compared to CF-7 were 50%, 6%, 14%, 40%, 39%, 21%, 0%, 53%, and 64%, respectively.

In all configurations except CF-1 and CF-7, piles at IYL shared a greater load than rafts. The reason behind the lower contribution of piles in CF-7 at IYL may be due to the short length of the piles, whereas in CF-1, it may be because the sand below the raft is confined due to the arrangement of long piles at the periphery of the pile group. In all configurations at FYL, the load shared by the raft was found to be greater than that shared by the piles. Based on our findings, the percentage of Load Shared by Pile Group (% LSPG) decreased as the relative settlement (s/B_r) increased, while the percentage of load shared by raft (% LSR) increased with the same increase in s/B_r for all configurations. In the case of CF-1, the % LSPG was less than 50% at all relative settlements. The %LSPG and %LSR were equal at $s/B_r = 0.03, 0.065, 0.09, 0.03, 0.02, 0.01$ and 0.03 in piled raft with CF-2, CF-3, CF-4, CF-5, CF-6, CF-7 and CF-8 respectively. In the case of PRF with CF-9, the % LSPG was more than 50% at all s/B_r values.

The initial yield load (IYL) and final yield load (FYL) of piled-raft foundation (PRF) increased with an increase in soil-pile friction angles (δ_0 to δ_3) for all relative densities of sand, but the amount of increment was much less. At 40% relative density, the IYL and FYL of PRF ranged from 9.30 kN to 10.92 kN and 15.94 kN to 16.75 kN, respectively, for different soil-pile friction angles. The LSPG at IYL and FYL increased as the soil-pile friction angle was increased. The value of LSR at IYL was decreased by 0.66 kN, 0.98 kN and 0.92 kN at $\delta_1 = 24.36^\circ$, $\delta_2 = 25.8^\circ$, and $\delta_3 = 27.1^\circ$, respectively, as compared to at $\delta_0 = 22.4^\circ$. That means it was decreased by 16%, 24%, and 22%, respectively, in percentage. The value of LSPG at IYL was increased by 0.76 kN,

1.88 kN, and 2.54 kN at $\delta_1 = 24.36^\circ$, $\delta_2 = 25.8^\circ$, and $\delta_3 = 27.1^\circ$, respectively, as compared to at $\delta_0 = 22.4^\circ$. It means it was increased by 15%, 36%, and 49%, respectively, in percentage. The % LSPG and % LSR became equal when $s/B_r = 0.05$, and further increase in s/B_r , the % LSPG decreased up to $s/B_r = 0.09$ and then increased in a very small amount for PRF with $\delta_0 = 22.5^\circ$ at $I_d = 40\%$. The % LSPG was found to be more than the % LSR in PRF with $\delta_1 = 24.36^\circ$, $\delta_2 = 25.8^\circ$, and $\delta_3 = 27.1^\circ$ at $I_d = 40\%$. The α_p decreased as the PRF settled, and the maximum and minimum α_p were found at $\delta_3 = 27.1^\circ$ and $\delta_0 = 22.5^\circ$, respectively. At the angles of $\delta_0 = 22.5^\circ$, $\delta_1 = 24.36^\circ$, $\delta_2 = 25.8^\circ$, and $\delta_3 = 27.1^\circ$, the SRR (settlement reduction ratio) ranges were found to be 41% to 60%, 31% to 81%, 22% to 71%, and 57% to 75%, respectively. Additionally, the LIR (Load improvement ratio) ranges were found to be 1.19 to 1.51, 1.18 to 1.31, 1.32 to 1.58, and 1.33 to 1.68 at the same respective angles.

At 60% relative density, the IYL and FYL of PRF ranged from 11.96 kN to 13.93 kN and 21.26 kN to 23.47 kN, respectively, for different soil-pile friction angles. At 60% relative density, the IYL of PRF increased by 5%, 16%, and 17% with an increase in soil-pile friction compared to the lowest soil-pile friction angle ($\delta_0 = 24.5^\circ$), while the FYL increased by 1%, 7%, and 10%, respectively. The % LSPG was more than 50% at all relative settlements for PRF with $\delta_0 = 24.5^\circ$ and $\delta_2 = 26.58^\circ$, at $I_d = 60\%$. The % LSPG was more than 50% from $s/B_r = 0$ to 0.03, and after that, it was less than 50% in PRF with $\delta_1 = 25.7^\circ$ at $I_d = 60\%$. The % LSPG and the % LSR in PRF with $\delta_3 = 26.58^\circ$ were equal at $s/B_r = 0.05$ and $s/B_r = 0.09$, and then it increased up to $s/B_r = 0.12$, and after that it became more or less constant. At the angles of $\delta_0 = 24.5^\circ$, $\delta_1 = 25.7^\circ$, $\delta_2 = 26.58^\circ$, and $\delta_3 = 28.62^\circ$, the SRR (settlement reduction ratio) ranges were found to be 48% to 59%, 38% to 57%, 14% to 45%, and 3% to 34%, respectively. Additionally, the LIR (Load improvement ratio) ranges were found to be 1.08 to 1.32, 1.09 to 1.3, 1.1 to 1.36, and 1.16 to 1.25 at the same respective angles.

At 80% relative density, the IYL and FYL of PRF ranged from 16.16 kN to 21.32 kN and 31.89 kN to 42.65 kN, respectively, for different soil-pile friction angles. At 80% relative density, the IYL and FYL increased by 10%, 21%, and 34% with an increase in soil-pile friction compared to the lowest soil-pile friction angle ($\delta_0 = 26.3^\circ$). At 40%, 60% and 80% relative density, the LSPG at FYL was found to be greater than the LSPG at IYL. The %LSPG and %LSR became equal at $s/B_r = 0.07$, and after that, %LSPG was decreasing for PRF with $\delta_0 = 26.3^\circ$ at $I_d = 80\%$. The % LSPG was more than the % LSR in PRF with $\delta_1 = 27.41^\circ$, $\delta_2 = 28.22^\circ$, $\delta_3 = 30.04^\circ$ at $I_d = 80\%$. At the angles of $\delta_0 = 26.3^\circ$, $\delta_1 = 27.41^\circ$, $\delta_2 = 28.22^\circ$, $\delta_3 = 30.04^\circ$, the SRR (settlement reduction ratio) ranges were found to be 55% to 68%, 3% to 48%, 6% to 46%, and 10% to 47%, respectively. Additionally, the LIR (Load improvement ratio) ranges were found to be 1.07 to 1.75, 1.16 to 1.97, 1.27 to 2.01, and 1.33 to 2.24 at the same respective angles. In most cases, the effect of soil-pile friction was found to be less on the load settlement characteristics of PRF but more on the load sharing characteristics of PRF. Moreover, an increase in soil-pile friction angle

resulted in a decrease in the primary stiffness of the piled raft, while the secondary stiffness of the piled raft increased.

The following results were observed during testing of PRF with different c/s shapes of piles (H, HC (hollow circular), and HSQ (hollow square)) on sand beds with different relative density: the HSQ pile showed the lowest values of IYL and FYL, while the H pile had the highest because of higher friction mobilized in H pile having greater outer surface area. Due to plug formation there is little variation in the base resistance for all piles. Compared to the sand bed's 40% relative density, the IYL of the H pile increased by 2.69 kN and 10.27 kN at 60% and 80% relative density, respectively, representing an increase of 26% and 100%. Similarly, the FYL of the H pile increased by 3.6 kN and 14.07 kN at 60% and 80% relative densities, respectively, or by 21% and 84% in comparison to the 40% relative density of the sand bed. The IYL of the HC pile increased by 1.41 kN and 7.96 kN at 60% and 80% relative density, respectively, when compared to the sand bed's 40% relative density, i.e., increased by 14% and 77%, respectively. The FYL of the HC pile was increased by 4.79 kN and 15.35 kN at 60% and 80% relative density, respectively, as compared to the 40% relative density of the sand bed, i.e., in percentages of 31% and 99%. The IYL of the HSQ pile increased by 4.23 kN and 9.21 kN at 60% and 80% relative density, respectively, compared to the sand bed's 40% relative density. This means that the IYL increases by 70% and 153% at $I_d = 60\%$ and $I_d = 80\%$ respectively. In the case of the HSQ pile, the FYL at 60% and 80% relative density increases by 5.62 kN and 13.42 kN respectively, when compared to the 40% relative density of the sand bed. This means that the FYL increases by 46% and 110%. At 40% relative density, the IYL of PRF with H and HC pile increased by 4.28 kN each, compared to the HSQ pile. This translates to a 71% increase for both H and HC piles. At 60% relative density, the IYL of PRF with H and HC pile increased by 2.75 kN and 1.46 kN respectively, compared to the HSQ pile. This translates to a 27% increase for H pile and a 14% increase for HC pile. At 80% relative density, the IYL of PRF with H and HC pile increased by 5.34 kN and 3.03 kN respectively, compared to the HSQ pile. This translates to a 35% increase for H pile and a 20% increase for HC pile.

At a relative density of 40%, the SRR range for PRF with H pile was found to be between 48% and 71%, with HC pile it was between 43% and 64%, and with HSQ piles, it was between 1% and 32%. At a relative density of 60%, the SRR range for PRF with H pile was between 4% and 39%, with HC pile between 1% and 37%, and with HSQ pile between 11% and 46%. At a relative density of 80%, the SRR range for PRF with H pile was between 4% and 39%, with HC pile between 4% and 53%, and with HSQ pile between 21% and 48%. At all relative density of sand, the LIR range for PRF with H piles, HC piles, and HSQ piles were around 1 to 1.65.

By analyzing the tri-linear pattern in the load settlement curve for various configurations in prototype piled raft foundation, the Initial Yield Load (IYL) and Final Yield Load (FYL) were determined. The obtained results for different configurations are as follows: The IYL and FYL for the configurations obtained were for S1: 94000 kN and 168000 kN, S2: 72000 kN and

120000 kN, S3: 72000 kN and 130000 kN, S4: 93000 kN and 156000 kN, S5: 72000 kN and 132000 kN, S6:72000 kN and 144000 kN, S7: 60000 kN and 108000 kN, S8: 660000 kN and 144000 kN, S9: 96000 kN and 180000 kN respectively. In case of the circular pattern also the IYL and FYL are as follows: C1: 84000 kN and 156000 kN, C2: 50000 kN and 102000 kN, C3: 66000 kN and 120000 kN, C4: 80000 kN and 146000 kN, C5: 66000 kN and 130000 kN, C6: 70000 kN and 140000 kN, C7: 48000 kN and 104000 kN, C8: 60000 kN and 144000 kN, C9: 90000 kN and 168000 kN respectively.

In prototype piled raft foundation S9 had the maximum IYL and FYL values while C7 had the minimum values. Furthermore, the range of load sharing was found to be quite similar in both experimental work and numerical analysis. Longer piles with an L/d ratio of 30 exhibited significant load-carrying capacity and contributed more to load sharing compared to other piles. At the initial yield load, the piles carried a greater portion of the load compared to the raft. However, at the final yield load, there was a reduction in the load-carrying capacity of the piles. The maximum load was shared by the piles in the S9 configuration, followed by C9, S1, and C1. The load shared by the piles ranged from 85% to 93% at the initial yield load and from 75% to 82% at the final yield load. In contrast, for the C7 configuration, the load shared by the piles was around 60% at the initial yield load and lower than 50% at the final yield load. Similar trends were observed in the S7 configuration, where the values were 63% and 47% respectively. PRF with shorter piles, the load taken by pile less and raft also has a significant role in load sharing, while longer piles carry a greater share of the load compared to the raft. The load shared by the piles ranged from 60% to 93% at the initial yield load and from 47% to 82% at the final yield load, depending on the configuration. Changes in load distribution were observed between the IYL and FYL for some configurations. At FYL pile located at the centre tend to take more load irrespective length of pile. The C9 configuration had the maximum reduction in settlement as compared to unpiled raft, followed by S1, C9, and C1. Additionally, at the IYL, the settlement reduction ratio of S4 was lower than S1 and C9, but at the FYL, it surpassed them. The configuration with the least settlement reduction was C7, followed by S7, C2, and S2.

Summary of findings:

1. In absence of plate load test data of sand the theoretical relationship developed by Vesic and Selvadurai can be used to determine modulus of subgrade reaction by knowing modulus of elasticity of sand from triaxial test.
2. The ultimate bearing capacity of unpiled raft is maximum with square shape and minimum with circular shape considering equal contact area of the foundation with soil.
3. The secant stiffness of unpiled raft for square and circular shape is given by following equation

$$k_{sr} = 7300B_r S_c e^{(0.028I_d)} P^{(-0.55)}$$

4. The efficiency of pile group is greater than 1 for circular pile with all L/d ratio of pile, all spacing between piles and relative density of sand bed considered in this investigation.
5. The initial tangent stiffness of pile group obtained from Fleming's equation is in good agreement with experimental results.
6. The load settlement characteristics of piled raft foundation in all most all the cases are tri-linear in nature.
7. The ultimate capacity of piled raft foundation (FYL) is more than the ultimate capacity of unpiled raft.
8. The IYL and FYL of piled raft increase with increase in relative density of sand bed.
9. The difference between FYL and IYL of piled raft foundation increases with increase in relative density of sand bed.
10. The contact pressure distribution in a piled raft foundation is greater in the space within the pile group as compared to outside the pile group.
11. At settlement corresponding to initial yield load of piled raft, the load shared by pile group is greater in PRF as compared to load taken by only pile group at that settlement whereas load shared by raft in PRF is less than that load carried by unpiled raft at same settlement.
12. The FYL of a piled raft is about 1.5 to 2.7 times the IYL of piled raft in the present study.
13. In most of the cases, the load shared by pile group in PRF at FYL is in the range of 1.4 to 5.7 times the ultimate load carrying capacity of only pile group and the load shared by raft in PRF at FYL is in the range of 0.4 to 0.9 times the ultimate capacity of unpiled raft foundation.
14. In a piled raft foundation the 50% load sharing by pile group and 50% load sharing by raft occurs in the range of relative settlement 0.001 to 0.07 in majority of cases. In some of the cases, the pile group and raft did not reach the 50% -50% load sharing.
15. In the early stages of load application, as the relative settlement (s/B_r) increases, piled raft coefficient (α_p) exhibits a rapid decrease from values close to 1 to ultimately falling within the range of 0.1 to 0.6. As the applied load continues to increase, α_p of most of the PRF stabilizes in the range of the relative settlement (s/B_r) = 0.02 to 0.04. Further increments in load result in either a constant value or a slight increase in α_p .
16. Within the loading range of unpiled raft the settlement reduction ratio of piled raft with 3 x 3 pile group is 7% to 52% for circular raft, 1% to 74% for rectangular raft, 2% to 69% for trapezoidal raft and 30% to 86% for square raft.
17. Within the loading range of unpiled raft the settlement reduction ratio of piled raft with 5 x 5 pile group are increases with increase in L/d ratio of piles.
18. Within the loading range of unpiled raft, the settlement reduction ratio of piled raft with 3 x 3 pile group is found maximum with 3d or 5d spacing at 80% relative density, 5d spacing at 60% relative density and 7d spacing at 40% relative density of sand bed.
19. Within the loading range of unpiled raft the settlement reduction ratio of piled raft with 3 x 3 pile group is found maximum with H pile at 40 % relative density, H and hollow circular pile at 60% relative density and at 80% relative density of sand bed.

20. The load improvement ratio of piled raft foundation increases with increase in relative density of sand in circular shape of raft while it decreases in square and trapezoidal shape of raft with few exceptions.
21. The load improvement ratio of piled raft increases with increase in spacing of piles, number of piles, and L/d ratio of piles.
22. Considering effect of configuration of pile, the load improvement ratio of piled raft foundation is found maximum in PRF with all long piles and minimum with all short piles.
23. The load improvement ratio increases with increase in soil-pile friction angle at all relative density of sand bed.
24. Considering effect of shape of pile, the load improvement ratio of piled raft foundation is found maximum in PRF with H pile at 40% and 60% relative density while at 80% relative density it is highest with hollow circular pile.
25. The primary stiffness of piled raft increases with increase in relative density of sand. It is highest with square shape of raft and in decreasing order with trapezoidal, rectangular and circular shape of raft.
26. Load sharing of pile group is higher at lower settlements where as load sharing of raft increases with increase in settlement in most of the cases considered in this study.
27. In prototype piled raft foundation, maximum value IYL and FYL was obtained in case of all long piles with configuration S9, C9 and at a configuration where longer piles were present in outer periphery S1, C1.
28. In prototype piled raft foundation, minimum value IYL and FYL was obtained in case of all short piles S9, C9 and at a configuration where shorter piles are present in outer periphery S2, C2.
29. Configuration C9 exhibited the highest settlement reduction ratio in prototype PRF, followed by S1 and C1, while C7 and S7 showed the least reduction.
30. The load shared by the pile group in prototype piled raft foundation ranged from 60% to 93% at the initial yield load and from 47 % to 82 % at the final yield load, depending on the configuration.
31. Configurations with shorter piles in prototype piled raft foundation showed less load carried by piles i.e., 60% in IYL and 47% in FYL and a significant role of the raft in load sharing.
32. Load distribution analysis revealed variations in load sharing among individual piles within each configuration.
33. Longer piles generally carried a greater portion of the load, while shorter piles contributed less in prototype piled raft foundation.
34. The primary stiffness of prototype piled raft foundation obtained by the numerical analysis when compared was 32% to 60% nearer to those obtained with PDR method in all configurations. PRF with shorter pile was found more nearer to PDR method.

35. The primary stiffness of prototype piled raft foundation with all long piles agrees well with Clancy method.

References:

- [1] Akinmusuru, J. O. (1980). Interaction of piles and cap in piled footings. *Journal of the Geotechnical Engineering Division*, 106(11), 1263-1268.
- [2] Liu, J. L., Yuan, Z. L., & Zhang, K. P. (1985). Cap-pile-soil interaction of bored pile groups. In *International conference on soil mechanics and foundation engineering. 11* (pp. 1433-1436).
- [3] Long, P. D. (1993). Footings with settlement-reducing piles in non-cohesive soil.
- [4] Lee, S. H., & Chung, C. K. (2005). An experimental study of the interaction of vertically loaded pile groups in sand. *Canadian Geotechnical Journal*, 42(5), 1485-1493.
- [5] Fioravante, V., Giretti, D., & Jamiolkowski, M. B. (2008). Physical modelling of piled rafts. *Deep foundations on bored and auger piles*, 241-248.
- [6] Balakumar, V., & Ilamparuthi, K. (2009). Effect of pile layout on the behaviour of circular piled raft on sand. *IGC, Guntur, India*, 673-677.
- [7] Al-Mosawi, M. J., Fattah, M. Y., & Al-Zayadi, A. A. (2011). Experimental observations on the behavior of a piled raft foundation. *Journal of Engineering*, 17(4), 1-11.
- [8] El-Garhy, B., Galil, A. A., Youssef, A. F., & Raia, M. A. (2013). Behavior of raft on settlement reducing piles: Experimental model study. *Journal of Rock Mechanics and Geotechnical Engineering*, 5(5), 389-399.
- [9] Juneja, A., Tyagi, A., & Bisht, R. (2013, December). Load Sharing in Piled Rafts. In *Indian Geotechnical Conference* (pp. 1-9).
- [10] Patil, J. D., Vasanwala, S. A., & Solanki, C. H. (2014). An experimental investigation on behavior of piled raft foundation. *International journal of geomatics and geosciences*, 5(2), 300-311.
- [11] Vakili, R. (2015). *Load sharing mechanism of piled-raft foundation in sand* (Doctoral dissertation, Concordia University).
- [12] Park, D., & Lee, J. (2015). Comparative analysis of various interaction effects for piled rafts in sands using centrifuge tests. *Journal of Geotechnical and Geoenvironmental Engineering*, 141(1), 04014082.
- [13] Elwakil, A. Z., & Azzam, W. R. (2016). Experimental and numerical study of piled raft system. *Alexandria Engineering Journal*, 55(1), 547-560.
- [14] Bralović, N., Despotović, I., & Kukaras, D. (2022). Experimental Analysis of the Behaviour of Piled Raft Foundations in Loose Sand. *Applied Sciences*, 13(1), 546.
- [15] Jamil, I., Ahmad, I., Khan, I., Ullah, W., Rehman, A. U., & Khan, S. A. (2023). Factors affecting the lateral contribution of a raft in a piled raft system. *Ain Shams Engineering Journal*, 14(5), 101968.
- [16] Randolph, M. F. (1983). Design of piled foundations. *Cambridge Univ. Eng. Dept., Res. Rep. Soils TR143*.

- [17] Clancy, P., & Randolph, M. F. (1993). An approximate analysis procedure for piled raft foundations. *International Journal for Numerical and Analytical Methods in Geomechanics*, 17(12), 849-869.
- [18] Poulos, H. G. (2001). Piled raft foundations: design and applications. *Geotechnique*, 51(2), 95-113.
- [19] Burland, J. B. (1995). " Piles as settlement reducers," Invited Lecture. *XIX Convegno Italiano di Geotecnica*, 2, 21-34.
- [20] Prakoso, W. A., & Kulhawy, F. H. (2001). Contribution to piled raft foundation design. *Journal of geotechnical and geoenvironmental engineering*, 127(1), 17-24.
- [21] Oh, E. Y. N., Huang, M., Surarak, C., Adamec, R., & Balasurbamaniam, A. S. (2008, November). Finite element modeling for piled raft foundation in sand. In *Eleventh East Asia-Pacific Conference on Structural Engineering & Construction (EASEC-11) "Building a Sustainable Environment" November 19* (Vol. 21).
- [22] Omeman, Z. M. (2012). *Load sharing of piled-raft foundations in sand subjected to vertical loads* (Doctoral dissertation, Concordia University).
- [23] Lee, J., Park, D., & Choi, K. (2014). Analysis of load sharing behavior for piled rafts using normalized load response model. *Computers and Geotechnics*, 57, 65-74.
- [24] Alsanabani, N. M., AL-Refeai, T. O., & Alshenawy, A. O. (2017). Simplified Method for Designing Piled Raft Foundation in Sandy Soils. *GEOTECHNICAL ENGINEERING*, 48(4), 122-128.
- [25] Kumar, A., & Choudhury, D. (2018). Development of new prediction model for capacity of combined pile-raft foundations. *Computers and Geotechnics*, 97, 62-68.
- [26] Bhartiya, P., Chakraborty, T., & Basu, D. (2021). Closure to "Settlement Estimation of Piled Rafts for Initial Design" by Priyanka Bhartiya, Tanusree Chakraborty, and Dipanjan Basu. *Journal of Geotechnical and Geoenvironmental Engineering*, 147(5), 07021005.
- [27] Niraula, S., & Acharya, I. P. (2021). Study on Parametric Analysis of Piled Raft Foundation System Using Finite Element Approach. *Journal of Advanced College of Engineering and Management*, 6, 143.
- [28] Katzenbach, R., Bachmann, G., Boled-Mekasha, G., & Ramm, H. (2005). Combined pile raft foundations (CPRF): An appropriate solution for the foundations of high-rise buildings. *Slovak Journal of Civil Engineering (SJCE)*, 19-29.
- [29] Sonoda, R., Matsumoto, T., Kitiyodom, P., Moritaka, H., & Ono, T. (2009). Case study of a piled raft foundation constructed using a reverse construction method and its post-analysis. *Canadian geotechnical journal*, 46(2), 142-159.
- [30] Yamashita, K., Yamada, T., & Hamada, J. (2011). Investigation of settlement and load sharing on piled rafts by monitoring full-scale structures. *Soils and Foundations*, 51(3), 513-532.
- [31] Sadrekarimi, J., & Akbarzad, M. (2009). Comparative study of methods of determination of coefficient of subgrade reaction. *Electronic Journal of Geotechnical Engineering*, 14(1), 45-61.

