Performance of piled raft foundation supported by either connected or unconnected piles

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Abstract. Piled raft is commonly used as foundation for high rise buildings. The design concept of piled raft foundation is to minimize the number of piles, and to utilize the entire bearing capacity. High axial stresses are therefore, concentrated at the region of connection between the piles and raft. Recently, an alternative technique is proposed to disconnect the piles from the raft in a so called unconnected piled raft foundation UCRF, in which a compacted soil layer (cushion) beneath the raft, is usually introduced. The piles of the new system are considered as reinforcement members for the subsoil. In the current study, the behavior of both connected and unconnected piled rafts systems has been studied experimentally. The effects of different factors, such as; the piles number and configuration, on the load settlement behaviour and pile load sharing are also investigated. The results indicate that when unconnected piles are used, the total settlement of the piled raft system is significantly reduced, and the pile load sharing considerably decrease, e.g., for piled raft with nine piles the total settlement has decreased by 35.6% and pile load sharing has decreased by 20.9%.

1. Introduction
The piled raft is a composite foundation that comprises three parts; raft, piles and soil. The design philosophy of piled raft differs from that in conventional foundation where it is assumed as either a raft or pile group that carry the superstructure loads and insuring a certain value of safety factor. Basically, piled raft concept is proposed in order to obtain an economic design compared to conventional pile foundation by using the required number of piles that are important to minimize settlement to an acceptable limit and the transmitted loads are shared between the raft and piles. However, very large bending moments may be developed when these small number of piles are structurally connected to the raft as well as cracks in the raft and relatively high axial stress concentration at the pile head may be occur. Thus, the probability of structural failure of the foundation is greater than that related to the bearing capacity failure of the supporting soil. The dimensions and number of piles may consequently be increased in order to prevent the possibility of structural failure. To overcome the problem of connection reaction an alternative approach has been proposed where unconnected piles are used and provided an interposed cushion layer between the raft and the piles. The piles in such condition will behave as soil stiffeners instead of as structural members [1-3].

Recently, many numerical studies have been presented to investigate the behavior of unconnected piled raft [1], [4-7]. In addition, many experimental studies [8-10] are dealing with the UCRF. Liang et al. reported that a granular cushion layer plays an important role in improving the bearing capacity of the subsoil and in changing the load transfer mechanism of piles. An elastoplastic numerical analysis was performed by Eslami and Malekshah, showed that the thickness and the stiffness of cushion affects the location of the maximum axial stress along piles. Cao et al. [8] reported that the settlement and the bending moments at the piles head are considerably reduced by using unconnected piled raft. Fioravante and Giretti [10] studied the stiffness of the foundation when the granular cushion layer was interposed between the raft and piles. They found that
the relative stiffness of pile and soil underneath raft affect the load distribution mechanism in the foundation. Also, it is found that the initial stiffness of foundation was essentially a function of the piles stiffness.

In the current study, the behavior of piled rafts with connected and unconnected piles is investigated experimentally. The influence of the cushion layer and number of piles used with connected and unconnected piled rafts is also investigated.

2. Testing equipment
The set up used to perform the experimental work of the current study comprises a loading frame and steel container measured 800 mm deep and (750mmx750mm) in plan as shown in Figure 1. A square steel plate, with side dimensions 210 mm and thickness 3mm is used as a model raft. The modulus of elasticity and Poisson’s ratio of the steel plates were 210 × 10^6 kPa and 0.30, respectively. According to raft-subsoil stiffness ratio, \( k_{rs} \), which is defined in Eq. (1) below, the model raft can be considered as flexible since its value is as low as \( k_{rs} = 0.2 \) [11]:

\[
k_{rs} = 5.57 \frac{E_r}{E_s} \left( \frac{1 - \nu_s^2}{1 - \nu_r^2} \right) \left( \frac{B_r}{L_r} \right)^{0.5} \left( \frac{t_r}{L_r} \right)^3
\]

An aluminum alloy model piles of hollow square section with outside dimension of 14 mm and inside circular hole of diameter 11 mm and a length, \( L_p \), of 420 mm were used. The piles were closed-ended with modulus of elasticity of about 50 x 10^6 kPa and Poisson’s ratio 0.3, the piles were treated as flexible in the test interpretation. Three model piles were instrumented by strain gauges to measure axial stresses at pile head and pile end. The side dimension of the container for all tests was greater than three times of the raft side and the end tip of piles located about 20D above the bottom of the container. The settlement of the foundation system was recorded by two LVDTs (Linear Variable Differential Transformer) of 0.01 mm accuracy positioned at the middle edges of the foundation system. The application of the Load was done by an electrical hydraulic jack tied to the top of the main loading frame. Load cell of 20 kN capacity was connected to the lower end of the jack to measure the applied load. All measurements devices were connected to the data acquisition to record and save all the readings automatically.

3. Materials
A dry sand was used as a foundation soil. The specific gravity of the solid particles is about 2.64. From the grain size distribution curve of the soil shown in Figure 2, the coefficient of curvature (\( Cc \)) is 0.91, the coefficient of uniformity (\( Cu \)) is 2.05, and the mean grain size (\( D_{50} \)) is 0.34 mm. According to the Unified Soil Classification System (USCS) the foundation soil can be classified as poorly graded sand (SP). The foundation soil is characterized by maximum dry unit weight 17.49 kN/m^3 and a minimum dry unit weight 15.04 kN/m^3. The soil was prepared for each model test to a relative density of about 50% which correspond to 16.81 kN/m^3 dry unit weight.

In the unconnected piled raft tests, the cushion layer, prepared by using a well graded soil. The grain size distribution curve of the cushion soil is shown in figure 2. All unconnected piled raft tests were performed with cushion layer compacted to a maximum standard Procter dry unit weight and optimum moisture content. The maximum Procter dry unit weight and optimum moisture content were 18.65 kN/m^3, and 12.4, respectively. The thickness of cushion layer was taken 5 cm for all model tests.
4. Results and Discussions

Several model tests on connected and unconnected piled raft were performed in this study. The interposed cushion layer that was used with the unconnected piled raft models, was 5 cm in thickness and about 60 MPa modulus of elasticity. To evaluate the relative improvement of the raft performance with either connected or unconnected piles, a nondimensional factor, called the bearing pressure improvement BPI has been introduced. BPI can be defined as:

\[ BPI = \frac{q_{\text{piled Raft}}}{q_{\text{Raft}}} \]  \hspace{1cm} (2)

Where
\[ q_{\text{piled Raft}} \] = bearing stress of a connected or unconnected piled raft.
\[ q_{\text{Raft}} \] = bearing stress of raft only, at the same settlement level.

The settlement of the raft, \( S \), is expressed in terms of a nondimensional form as relative settlement ratio, \( (S/B) \) %, which it is the ratio of maximum settlement to raft width. The comparisons of the piled raft response considering the different studied parameters were taken at two levels of settlement ratios \( S/B \), at 1% and 5%. Figure 3 and figure 4 show the relationship between applied pressure and settlement ratio for different number of piles of connected and unconnected piled raft. The stress–settlement relationships of the CPR1, CPR4, CPR5, CPR9, UNPR1, UNPR4, UNPR5 and UNPR9 tests are almost linear up to a certain stress level. This trend of the initial part of the curve was also reported by Poulos [12], as shown in Fig. 11.

The variation of BPI with pile number of connected piled raft at two settlement ratios, 1%, and 5% is shown in Figure 5. It can be concluded from the figure that, initially the rate of BPI increases with increasing pile number. However, the increasing rate of BPI becomes quite small when the number of piles reaches a certain value and it seems that the effect on reducing the settlement of raft becomes insignificant. This pattern of behavior is consistent with the conclusion by Poulos and Davis [13] “that the number of piles required to reduce settlements under a raft to a tolerable limit is usually small and any further addition of piles may result in only marginal further reductions in settlements”. Figure 6
shows that the BPI for unconnected piled raft with different number of piles. From this figure it is clear that as the number of piles increases, the BPI increase approximately at the same rate. This may be attributed to the fact that the purpose of the unconnected piles is to reinforce the subsoil. In addition, the bearing pressure improvement ratio for connected and unconnected piled raft increase as the relative settlement ratio, S/B increase from 1% to 5%. Increasing BPI with increasing S/B ratio could be because of the influence of the densification of the sand produced due to load progressing and probable interactions between the piles. Figure 7 shows the comparison of BPI for connected and unconnected piled raft at relative settlement 1%.

V. Fioravante [10] stated that the performance of the settlement of an unconnected piled raft can be assessed by means of the settlement efficiency ratio, as it defined in following:

$$\eta = \frac{w_{unpiled} - w_{piled}}{w_{unpiled}} \quad (3)$$

Where \(w_{unpiled}\) and \(w_{piled}\) are the settlements amount of the unpiled raft and the UCPR, respectively. Since \(0 \leq \eta \leq 1\), the UCPR be more efficient as the value of \(\eta\) be larger, at a given load level. The settlement efficiency of the UCPRs with the applied vertical load is presented in Figure 8. It is shown that, at experienced range of displacement the settlement efficiency is approximately constant. This may be attributed to the reason that the piled raft did not reach the ultimate load. It can be concluded that the number of piles affect the settlement efficiency e.g.: \(\eta = 0.3, 0.4, \) and 0.68 for UNPR4, UNPR5, and UNPR9, respectively.

Figure 9 shows the Influence of number of piles on percentage of load shared by the piles. Generally, the percentage of load carried by piles increases with increasing the number of piles either for connected or unconnected piles. The comparison of pile load sharing between connected and unconnected piled raft for similar number of piles shown in Figure 10. From this figure it can be noticed that the load shared by unconnected piles is lower than that shared by connected piles except for piled raft with one pile, the unconnected pile carried load more than connected pile.
Figure 3. Relative settlement vs. bearing pressure for different number of connected and unconnected piled raft, A- one pile, B- four piles, C- five piles, D- nine piles.
Figure 4. Variations of pressures with relative settlements different number of piles, A- Connected piles, B- Unconnected piles.

Figure 5. Variation of bearing pressure improvement with different number of connected piled raft at two S/B ratios

Figure 6. Variation of bearing pressure improvement with different number of unconnected piled raft at two S/B ratios
Figure 7. Comparison of BPI for connected and unconnected piled raft

Figure 8. Settlement efficiency of unconnected piled raft.

Figure 9. Pile load sharing of piled raft, A- connected piles, B- unconnected piles
5. Conclusions

Within the scope of the experimental model tests performed in this investigation, the following conclusions can be stated:

1. The amount of settlement relevant to unconnected piled raft system is less than that of connected piled raft.
2. The bearing pressure improvement BPI with connected piled raft initially increases as the pile number increase then becomes quite small when the number of piles reaches a certain value. For unconnected piled raft, as the number of piles increase the BPI increase almost at the same rate.
3. In unconnected piled raft the settlement efficiency is approximately constant in the experienced range of displacement.
4. The percentage of load carried by piles increase with increasing the number of piles either for connected or unconnected piled raft.

6. References

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