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An Experimental Investigation on Interference of Piled Rafts in Soft Soil

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Abstract

By using small scale model tests, the interference effect on the vertical load-deformation behavior of a number of equally spaced rafts and piled rafts, placed in the artificially consolidated soft clay was investigated. The effect of spacing (s) among foundations on the results was explored. A new experimental setup was proposed in which uniform load was applied by using steel beam of adequate flexural strength and ball bearings to transfer the vertical load equally on both the foundations. The bearing capacity decreases continuously with decrease in spacing among the foundations. The interference effect becomes further prominent with piled raft foundation. In contrast to decrease in the bearing capacity, with decrease in spacing of foundations, an increase in the foundations settlement associated with the ultimate state of shear failure was observed. The present experimental observations were compared to the results obtained by using PLAXIS. The results of this laboratory investigation will be helpful in finding the minimum spacing between the rafts and piled raft foundation for better performance.

Keywords: Piled raft; Model test; soft clay; Interference effect; spacing; PLAXIS

1. Introduction

When considering foundations for high-rise buildings in urban areas, a major task is to restrict the settlement and differential settlement of the new structures and adjacent buildings to ensure their safety and serviceability. Compared to traditional piled foundations, where building loads are assumed to be transferred to the soil only by piles, the piled raft foundation is a new approach.

The study of the interference between closely spaced foundations of a particular structure is of fundamental importance to both geotechnical and structural engineering. Information regarding settlement, tilt and bearing capacity is required for an adequate design of the foundation. The mutual interference of foundations in a group has a significant influence on these design factors.

Stuart (1962) examined the state of interference, between two parallel strip footings placed at varying distances from each other on cohesion less soil. Mandel (1965) investigated a more general problem with structures on either side of a footing using the method of characteristics for a $c - \varphi$ soil. Both Stuart and Mandel demonstrated that a decrease in spacing between strip footings produced an increase in bearing capacity. They introduced factors reflecting the efficiency of interference for bearing capacity between footings. Agarwal (1970) investigated the interference effect for both strip and rectangular footings. An increase in the bearing capacity and simultaneous increase in the settlement characteristics was observed when the centre to centre spacing between the footings was reduced. Verma & Saran (1987) studied the effect of interference between two adjacent strip footings by using non- linear constitutive laws of soils. All the three aspects i.e. bearing capacity, settlement and tilt has been studied in clays and sands. Saran & Agrawal (1974) carried out two and three dimensional model tests to investigate the interference effect of footings in dry sand on settlement and bearing capacity.

Singh et al. (1973) reported experimental investigations on the interference effect of two adjacent smooth, square footings subjected to vertical load in cohesion less soil. It was observed that the interference changes both the load at failure and the settlement characteristics to values different from those of isolated footings. The interference of footings on dense sand was observed to cause an increase in bearing capacity and decrease in settlement with reduction of spacing. J.Kumar & P.Ghosh (2007) presented the ultimate bearing capacity of two interfering strip footings by using the method of stress characteristics.

L.de Sanctis & G.Russo (2008) reported case histories of five storage tanks resting on piled rafts in Port of Napoli for settlement and load sharing. They also studied the interaction effects between the different foundations and compared the result with the program NAPRA. The tilting of foundations due to interaction between adjacent piled rafts and the corresponding change in load sharing has been reported.

From the above review of literature it has been observed that interference effect of rafts and piled rafts have great influence on the settlement and bearing behavior of the structures, but all the reported case studies as well as laboratory models were either on stiff clay or sand bed. The study on piled raft foundations embedded in soft clay has not, however, been well addressed in the literature. In recent years, a large number of tall buildings are being constructed in and around Kolkata over soft alluvial deposits. For these structures piled rafts are, in general, being adopted to support the superstructure. In some cases, a number of piled rafts of small sizes are used under one building instead of a single large raft covering the whole building area. In such cases it seems that small sized piled rafts may have interfering effects due to the superposition of their pressure bulbs and may result in variation of settlements. Presently, no studies have been reported on the increase in settlement of smaller piled raft due to interference effect. The present paper highlighted increase in settlement of small piled raft due to interference effect obtained through a series of model tests over piled rafts in artificially consolidated soft clay deposit.

2. Experimental Work

The interference effect of rafts and piled rafts were studied by conducting 17 tests of load-settlement and time-settlement for different spacing.

Mild steel plate of size 200 mm x 200 mm and thickness 10 mm were used as model rafts. Model hollow piles made of steel of uniform diameter 10 mm and length 200 mm were used in the present investigation. External surface of the piles were glued with fine sand to simulate roughness of field concrete piles. The model test program is given in Tables 1, 2 and 3.

2.1 Interference of Rigid rafts

Six tests on interfering rigid rafts with different spacing are conducted to understand the effect of interference on load bearing capacity of rigid rafts. The details of tests are shown in Table 1.

Six tests on interfering rigid rafts with different spacing were conducted to understand the effect of interference on time dependent settlement of rigid rafts. The details of tests are shown in Table 2.

2.2 Interference of Rigid piled rafts

Time dependent settlement behaviour of typical rigid piled raft with 36 piles of 200 mm length was used to carry out the tests. Five tests with different spacing between the piled rafts were carried out. The details of tests are given in Table 3.

For the purpose of analyzing the test results the working loads were normalized by using a normalized load factor $N^* = P/c_u B^2$, where, P – working load, c_u – undrained shear strength (cohesion) and B – width of raft. The normalized load factors computed corresponding to the working load at factor of safety of 2.5 for the raft was 2.5. A detail of pile arrangement for model piled raft adopted in the present investigation is shown in Fig. 1.

A model tank of size 700 mm x 1400 mm x 600 mm made up of mild steel plates of 5 mm thickness was used for carrying out model tests on interfering rafts and piled rafts. The tank size was sufficiently larger than the zone of influence to avoid edge effect. A new experimental setup was used in which uniform load was applied by using steel beam of adequate flexural strength and ball bearings to transfer the vertical load equally on both the foundations. Schematic diagram of the model test set up is given in Fig.2.

All the model tests were carried out following the procedure described below. The consolidated soil bed was prepared in control condition for every test to get similar shear strength and other properties of soil.

2.2 Interference of Rigid piled rafts

Firstly large lumps of air-dried clay were broken; water was added and kept for 24 hours in order to prepare soil slurry of water content nearly 55 %. Then, the soil was placed in the mild steel bin (tank) in three layers, each being 150 mm to 200 mm in height and consolidated under the consolidation pressure of 30 kPa. A high stack of dead weights were required to be placed over the clay layer in order to reach the specified consolidation pressure. Consolidation period for the first two layers was 48 hours (2 days) for each layer and for the third layer it was 7 days. Undrained shear strength of the consolidated clay as measured by vane shear tests was found to be 8 ±0.5 kPa

Following the consolidation of the clay bed, model piles of specified lengths were driven vertically in the consolidated clay bed with the help of the template of 20 mm thickness. Next, the model raft was placed over the piles. The piles were connected to the raft by bolting, so that the piled raft acts as a monolithic structure. Further, for tests on piled raft and individual raft, full contact between the soil bed and the raft was ensured.

After the model set up is ready, the lever was placed over the piled raft for applying the load. To measure settlement, two linear variable displacement transducers (LVDT) having a 50 mm range with 0.01 mm sensitivity were used. For determining the immediate settlement, loads were applied in gradual increment and settlements were recorded till there was no appreciable change in settlement for a particular load increment. Then the next load increment was applied. The tests were continued until the settlement was more than 10 % of width of the raft.

2.4 Interference of rafts and piled rafts

Tests were performed on two model rafts of size 200 mm × 200 mm placed at different spacing on clay bed in a tank of inside dimensions 1400 mm long, 700 mm wide and 600 mm high. Vertical loads were applied to each model footing by a lever arrangement. At any stage, all the foundations were assumed to (i) carry exactly equal magnitude of load, and (ii) settle to the same extent. No tilt of the foundation was permitted. The tests were performed at a center-to-center spacing between the footings as 1 B, 1.25B, 1.5B, 1.75B and 2B, where B is the width of rafts and rafts were loaded simultaneously.

The working loads were calculated by applying a factor of safety (F.S.) 2.5 to the ultimate load carrying capacity of the corresponding unpiled raft. The ultimate load carrying capacity was determined from the load settlement curves at an immediate settlement of 10 % of B (width of raft) as suggested by Cooke (1986). These findings have been recently confirmed by centrifuge tests (Conte et al. 2003), as well as field tests (Borel 2001). These working loads were applied on the piled rafts and rafts to study their time dependent settlement behavior for a period of 48 hours, thereafter settlement ceases. During the experiment, soil deformation was monitored and the settlement readings were taken at regular time intervals until the relationship between settlement and the logarithm of time became nearly horizontal. In all the cases, the tests were repeated to check their reproducibility.

3. Numerical Analysis

By using the PLAXIS 3D FOUNDATION Version 2.2 software, numerical investigation has been carried out for the load settlement and time settlement behaviour of rafts and piled rafts of size 200 mm square. The piles in the piled raft foundation were modeled using embedded piles. The Hardening Soil model with Small-Strain stiffness (HSsmall) is used for simulating the soft soil behavior. The soil used in the present investigation is of soft consistency with cohesion 8 ± 0.5 kN/m2. For this type of soil, the modulus of elasticity under undrained conditions is in the range of 70 – 250 times cohesion coefficient (Bergado et al. 1990). Accordingly, Unloading/reloading stiffness has been considered to be 150Cu = 1200 kN/m2. As per PLAXIS reference manual E50ref = Eoedref = Eurref / 3. Further, initial or small strain shear modulus has been estimated by back calculating initial stiffness from the load settlement curve of the raft at very small settlement. All other parameters are selected using the guideline of reference manual of PLAXIS.

4. Test Results and Discussion

4.1 Load-Settlement Behavior

4.1.1 Interference of Rigid Rafts

The interference effect on the vertical load-deformation behavior of a number of equally spaced rafts, placed in the artificially consolidated soft clay was investigated and is shown in Figure 3. The effect of center-to-center spacing (s) among foundations on the ultimate bearing capacity of interfering rafts was presented in the figure .The test results of load settlement tests carried out for interference of rigid rafts of 200 mm square size placed at centre to centre spacing of 1.0B, 1.25B, 1.5B, 1.75B & 2.0B are plotted in the figure. The results obtained would serve for comparative analysis of the ultimate bearing capacity of interfering rafts with respect to spacing between them.

4.1.2 Time-Settlement Behavior

The working load corresponding to a factor of safety (F.S.) 2.5 was applied on the rafts and piled rafts with 36 numbers of piles, seems to be optimum, of 10 mm diameter and 200 mm length and centre-to-centre spacing of 1.0B, 1.25B, 1.5B and 2B to study the time dependent settlement.

The time settlement curves for interfering rigid rafts of 200 mm square size at working load with normalized load factor of 2.5 are plotted for different spacing between rafts and are shown in figure 4. Typical case of rigid piled rafts of 200 mm square raft size and 36 piles of 200 mm length are used for studying the interference effect of piled rafts (Rarea=7.6%). The time –settlement curves for interfering rigid piled raft with different spacing between them and at the normalized load factor, N* = 2.5 are shown in figure 5.

4.2 Interference Effect of Raft and Piled Raft

The load on a footing resting on soil stresses a particular prism of the soil. Usually, at failure, this zone extends to 2.5 times the width of the footing on either side of the footing in horizontal direction and twice the width of the footing in the vertical direction. An adjacent footing placed at spacing less than 2.5 B, B being the width of footing, the failure zones of two footings will interfere with each other. Due to this, the bearing capacity and settlement characteristics of such interfering footings will be different from that of isolated footings.This phenomenon of interference in foundations is of greater practical interest in closely built in areas where there may be overlapping of pressure bulbs in the foundation soils. Similar thing may occur when a large size raft/piled raft of a particular building is replaced by rafts/piled rafts of smaller sizes. An attempt has been made to study the settlement characteristics of such foundation and the results are discussed in the following section.

4.2.1 Load-Settlement Behavior

By using small-scale model tests, the interference effect on the vertical load-deformation behavior of a number of equally spaced rafts, placed on the artificially consolidated soft clay was investigated. The effect of center-to-center spacing (s) among foundations on the ultimate bearing capacity of interfering rafts were presented in terms of interference factor and shown in Figure 6. The interference factor (If) is defined as the ratio of ultimate bearing capacity of interfering rafts to the ultimate bearing capacity of isolated raft. From the figure, it is clear that the interference factor (If) increases continuously with increase in spacing between the foundations and is nearly 1.0 at s/B of 2.0 beyond which effect of interference seems to be negligible.

4.2.2 Time Dependent Settlement Behavior

The total settlement of interfering rafts and piled rafts of size 200 mm square and 200 mm pile length at

N* = 2.5 and pile to raft area ratio = 7.6 %, for different spacing (s/B) between the foundations and are presented in the Figure 7, as the ratio of total settlement of interfering raft/piled raft to total settlement of an isolated raft/piled raft. From the figure it may be seen that the ratio of total settlement of interfering raft/piled raft to that of an isolated raft/piled raft is maximum when the spacing between the interfering model foundations is in the range of 1.0 - 1.25 times width of raft. The maximum value of this ratio for only raft is found to be somewhat higher than that of piled raft. Beyond s/B 1.25 the ratio reduces with the increase in spacing and become close to that of isolated one at s/B=2.0. In figure 7, PLAXIS results are also presented. These numerical analysis results are in good agreement with experimental one.

5. Conclusion

By using small scale model tests, the interference effect on the load-deformation and time settlement behavior of rafts and piled rafts placed on the artificially consolidated soft clay were investigated.

From the results of this study, the following conclusions can be drawn

- The settlement of piled raft is initially higher at spacing below 1.25 times width of raft due to interference effect, thereafter, reduces with the increase in spacing, and becomes close to that of isolated one at spacing of twice the width of raft.
- The bearing capacity of rafts due to interference effect decreases continuously with decrease in spacing among the foundations.

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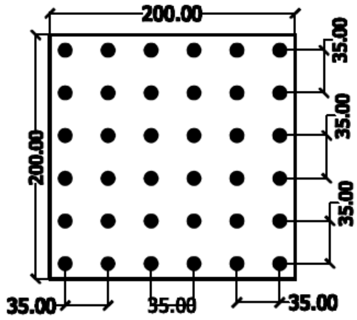
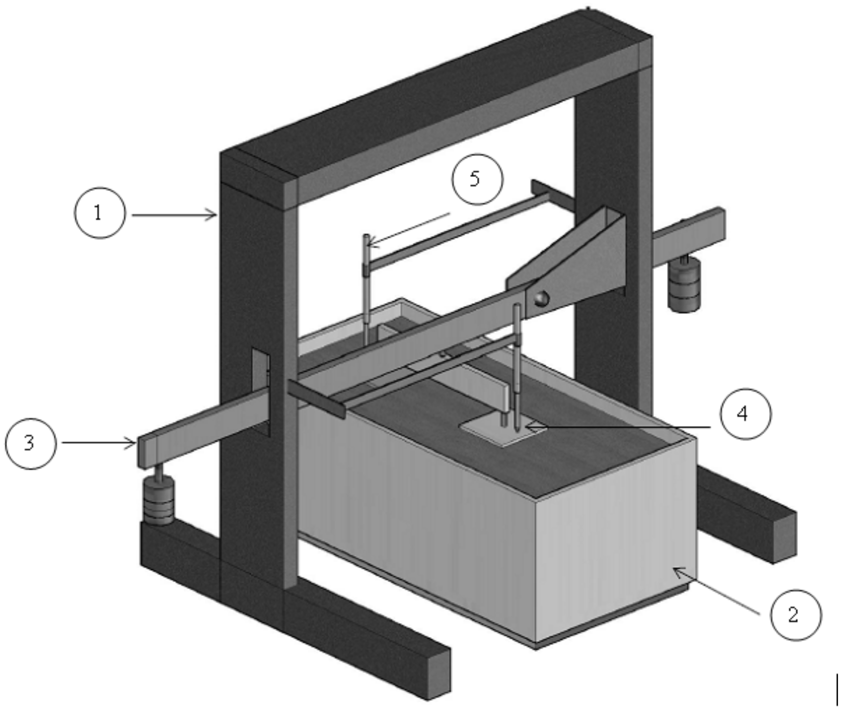


Figure 1. Pile arrangement for 200 mm square raft with 6^2 piles in groups in piled raft foundations.



1- Loading Frame

2- Model Tank

3- Loading Arrangement Model Raft / Piled raft (Two)

4- Linear variable displacement transducers (LVDT) (Two)

Figure.2. Schematic Diagram of Model Test set up.

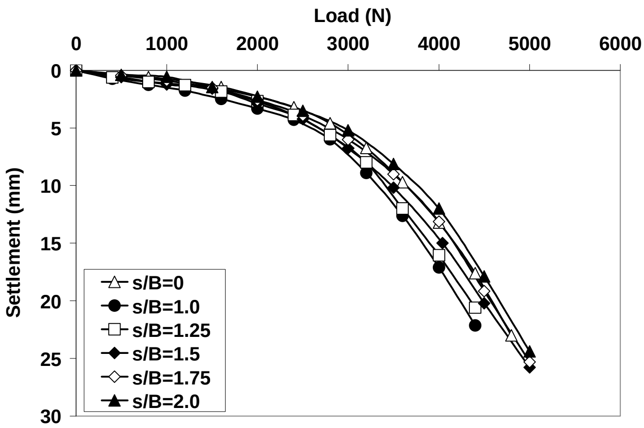


Figure.3. Load-settlement for interference effect of rafts with different s/B
(Rigid rafts: 2 - 200 mm X 200 mm).

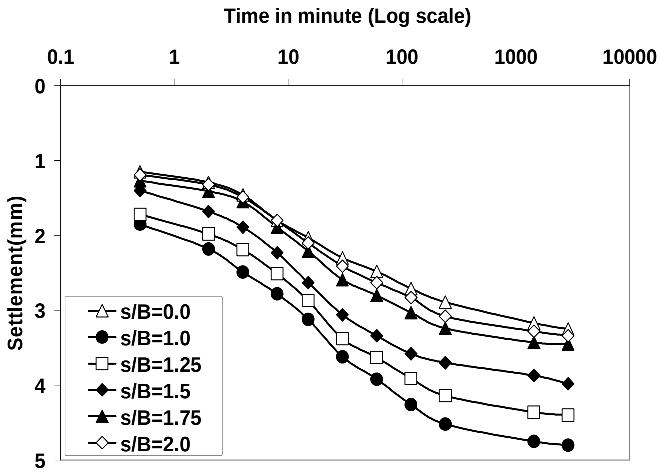


Figure 4. Time -settlement of Interference of Rigid Rafts with different spacing ratio (s/B) for Normalized load factor (N*) of 2.5.

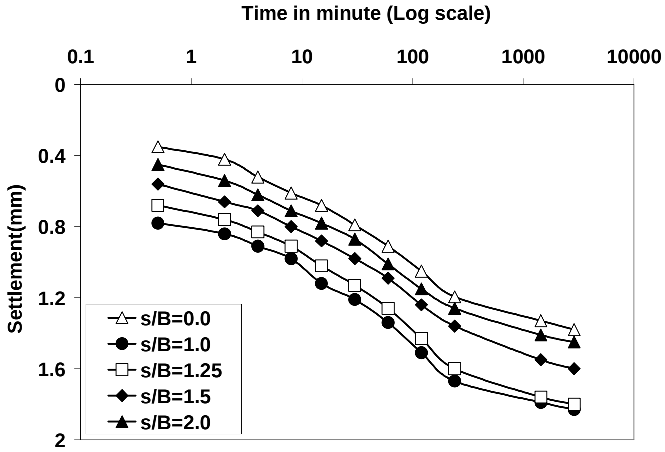


Figure 5. Time -settlement of Interference of Piled Rafts 36-200(R_{area} =7.6%) with different spacing ratio (s/B) for Normalized load factor (N*) of 2.5.

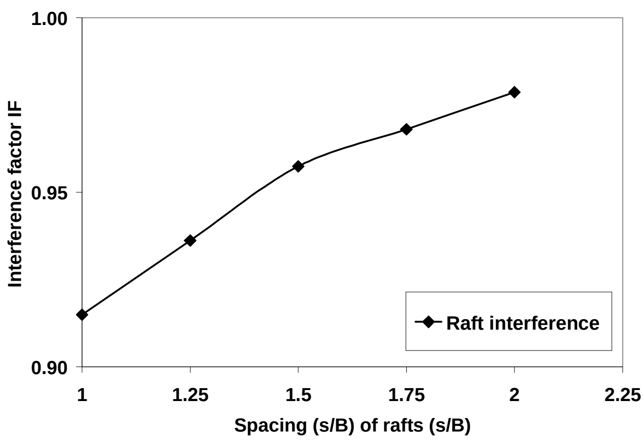


Figure 6. Variation of interference factor (IF) with spacing of rafts (s/B).

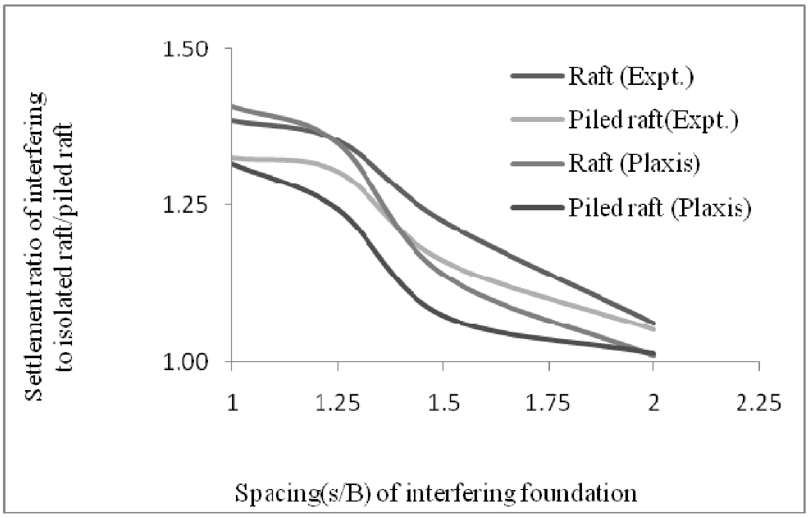


Figure 7. Total settlement ratio vs spacing (s/B) for Interference of two PRF 36-200 (R_{area}=7.6%) & Rigid rafts for the normalized load factor (N*) of 2.5.