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Study on Piled Raft Foundation Subjected to Inclined Compressive Loading Condition

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Abstract

Foundation of many structure like transmission, radio and television towers are subjected to inclined compressive and uplift loads. Additionally, foundation of tall buildings and bridges are also subjected to high lateral loads along with other verticals loads coming for the superstructure. In such cases, to increase the load bearing capacity of such foundation system and to decrease the corresponding vertical and lateral deflection piles may be employed along with raft footing. This paper presents an experimental study of the effectiveness of using short piles either rigidly connected or hinged to the raft (instead of long piles) on the behavior of a loaded raft. The load configuration was designed to simulate rafts under inclined loads. Several arrangements of piles with different lengths and numbers along with the effect of the relative density of the soil and the load inclination with vertical were studied. Test results indicate that the inclusion of short piles adjacent to the raft edges not only significantly improves the raft bearing pressures but also leads to a reduction in raft settlements and tilts leading to an economical design of the raft. However, the efficiency of the short piles-raft system is dependent on the load inclination ratio and pile arrangement. Also, connecting short piles rigidly to the raft gives greater improvement in the raft behavior than hinged piles for case of obliquely loaded pile raft system.

Keywords: Piled raft; Short Piles; Settlement; Sand; Inclined load.

INTRODUCTION

Raft foundations are widely used in supporting structures when relatively strong layers are present at shallow depth. Sometimes, although the shallow layers of soil have an adequate bearing capacity, a raft foundation can induce excessive settlements. In such cases, piled rafts (raft foundations enhanced with piles) are used. While the loads are assumed to be carried by the raft, piles are included for reducing raft settlement. The piles can be arranged to reduce differential settlement in the raft. The concept of using piles to reduce raft settlement was first proposed by [1] Burland et al. (1977) who placed one pile under each column of a building. Several reports were published on the use of piles as settlement reducers by [2] Poulos and Davis (1980), [3] Clancy and Randolph (1993), [4] Randolph (1994),[5] Horikoshi and Randolph (1996), [6] Kim et al. (2001), [7] Prakoso and Kulhawy (2001); [8] Poulos (2001), [9] Cunha et al. (2001); [10] Small and Zhang (2002); [11] Reul and Randolph (2004).

[2] Poulos and Davis (1980) studied the number of piles required to achieve the allowable settlements under a raft. [3] Clancy and Randolph (1993) studied the load capacity of settlement reducing piles for an efficient design of piled rafts. [4] Randolph (1994) studied the effect of pile locations on the differential settlements of a raft. [5] Horikoshi and Randolph (1996) verified the concept of a piled raft supported on clay with a centrifuge model test. [6] Kim et al. (2001) studied the optimal pile arrangement scheme for minimizing the differential settlements of piled raft foundations. [7] Prakoso and Kulhawy(2001) reported the effects of raft and pile group geometries on the average and differential displacements and raft bending moments. [10] Small and Zhang (2002) presented a finite-layer method for analysis of vertical and horizontal loads on piled rafts. [11] Reul and Randolph (2004) carried out a parametric study on the effect of the pile positions, number, length, and the raft-soil stiffness ratio on the piled raft behavior.

In traditional pile-raft systems, piles are usually long and connected to the raft. While these long piles are effective in reducing raft settlement, they may lead to significant straining actions (shear forces and bending moments) which affect the structural design of the raft. Due to the increase in their geotechnical bearing capacities, the piles should be enlarged to avoid the structural collapse in their sections. Also, these piles attract high shear force and mobilize high bending moment in the raft leading to an uneconomic design. In order to overcome these problems of high stresses in the piles and raft, [12] Wong et al. (2000) and [13] Cao et al. (2004) suggested that the piles be detached or hinged with the raft and to treat these piles as mere reinforcement to the subsoil rather than as structural members. However, no trial was made to compare the behavior of a raft with connected piles and rafts supported on sand reinforced with unconnected piles. In areas subjected to high wind or seismic loading, due to the effect of these lateral loads, raft foundations are subjected to a resultant inclined loading that may cause the structure to tilt particularly in the case of a narrow building. Using a piled raft in such cases may increase the stability of the building and may reduce the tilt of the raft. However, such a case of a raft subjected to oblique compressive load has not been studied.

In this paper, the new concept of using hinged piles is checked experimentally which is provided for overcoming the structural problems of the piled raft. Also, the loading condition is unique. The applied load is being inclined to some certain angle with the vertical axis of the raft. The idea of using short piles below the raft fixed or hinged instead of using only connected long piles was investigated. As these piles were short, their geotechnical capacity is much less than their collapse loads leading to avoiding the problems of high axial stress in piles and high shear forces in the raft due to the pile reactions. However, the effect of using short piles either fixed or hinged on the load settlement performance of the piled raft is not clearly understood. It should also be mentioned that most of the aforementioned papers are parametric numerical studies that have investigated the performance of piled rafts considering either evenly distributed loads or concentrated column loads rather than the case of oblique loads accompanied with overturning moment which is more commonly found in practice. To the best of author's knowledge, [14] Meyerhof et al. (1972) had proposed approximate inclined load bearing capacities of single pile and pile groups based on 1g models. However, the results of the empirical expressions proposed by Meyerhof et al. (1972) scatter a lot from the detailed experimental work undertaken by the [15] author (2013). Following that, till date, no exhaustive experimental programs were undertaken to formulate more exact relationship for load bearing capacity of vertical piles subjected to compressive oblique load. Authors have conducted series of experimental studies on inclined eccentric load carrying capacity of unpiled raft and piled rafts in sand [15,16] (2012, 2013). It has been found that capacity of both raft and piles varied a lot when compared to values predicted from available theories as these theories analyses both the raft and the piles separately if a lateral load is present along with a vertical load.

Therefore, the aim of this study was to gain more understanding about the behavior and the failure mechanism for either fixed or hinged short piles subjected to a combined lateral and vertical loading condition. Loading condition on piled raft foundation resting on sand is kept such that there is both lateral load and vertical load, gradually increasing and acting at a certain angle from the vertical axis of raft. The main objective was to determine and establish experimentally the relationship between the raft behavior and the load inclination condition, the relative density of the sand that the piles are in, and other variable parameters of short piles. The load inclination angles are varied from 0^0 to 15^0 and 30^0 with the vertical axis of raft. To achieve those objectives, more than 40 tests were carried out. The effects of a wide range of pile lengths, pile numbers, and pile arrangements were studied and the obtained results are presented and analyzed.

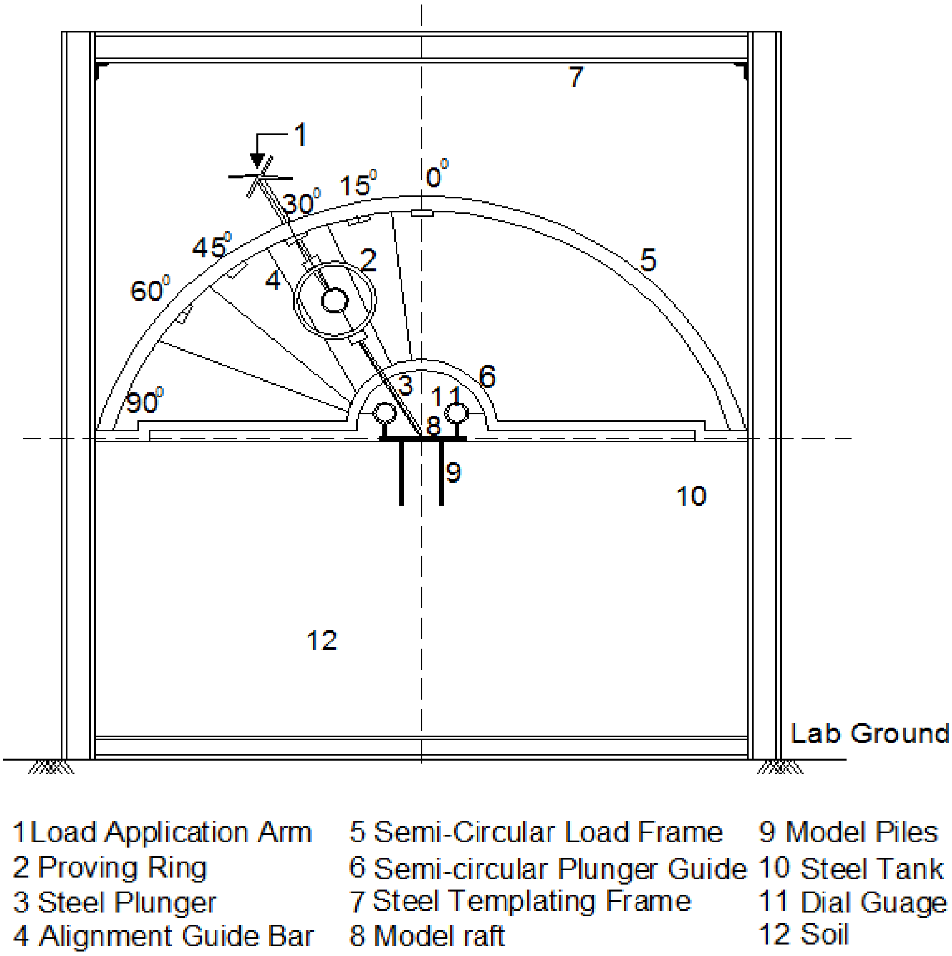


Fig.1 Schematic view of the experimental apparatus

EXPERIMENTAL SETUP

The laboratory model tests were conducted in a test box, having inside dimensions of 120 cm by 120 cm in plan and 100cm in depth. The tank is made from steel with the front wall made of20-mm-thick glass and is supported directly on two steel columns as shown in Fig. 1. These columns are firmly fixed to two horizontal steel beams, which are firmly clamped to the laboratory floor by bolting. The loading system is mounted by a semi-circular I-beam of steel supported by the two columns. It consists of a hand-operated wheel axle loading system and precalibrated load ring. The load was applied by the rotating the axle arrangement fixed with the semi-circular loading frame which is attached to a rigid platform as shown in Fig. 1. The semicircular loading frame was so placed that the load can be applied at the center of the model raft as well as on any position on the raft for applying eccentric load with easy placing of deflection measuring dial gauges. Therefore, the load system consists of two assemblies: the wheel axle applies a gradually increasing concentrated load inclined at fixed inclination as desired and lower semi-circular plunger guide maintains the load alignment. The semi-circular load frame was designed to be detachable at end so that it can be removed during deposition of the sand and returned back, when sand deposition is completed, to the original loading position above the tank. Detailed description of the apparatus developed by the authors is given in detail in Roy et al. (2012)& Roy et al. (2013).

A model strip raft made of mild steel with plunger groove on its top surface has been used. This model was chosen to simulate the raft of several cases of a narrow building subjected to both vertical and lateral loads. The model raft was 200 mm in diameter and 10 mm in thickness. A raft thickness of 10 mm was chosen to simulate rigid rafts which are commonly used in practice. The model raft was positioned on the sand bed such that it lies exactly at the center of the semi-circular load frame. A rough base condition was achieved by fixing a thin layer of sand onto the base of the model raft with poxy glue. The model raft was made with holes threaded internally so that the piles could be put in vertical position at the required spacing of the piles. Model piles with 20 mm and 15 mm outer and inner diameters, respectively, made of hollow steel tubes (E=0.207X10^6MPa) were used in the study. The piles were 200, 300, and 400 mm in length and the corresponding length-to-diameter ratios of the piles were 10, 15, and 20.

The load was applied by fixed amount at a constant rate with the wheel axle arrangement. The load is transferred through the ball bearing accommodated at the top of the proving ring in a hole on its top surface. The desired load through the plunger is measured through the proving ring as shown in Fig. 2. A small seating pressure was applied first for ensuring proper transfer from the loading arrangement tothe model raft through two ball bearings and two rods accommodated in sockets of loading frame and grooves on the top surface of the raft. The sockets on the semi-circular loading frame can be adjusted to a desired angle. Thus, the applied load may be inclined at any desired angle from complete vertical to a purely lateral condition. The inclined alignment of the applied load is maintained by alignment guide mild steel bars attached with the load frame. The plunger is also guided through another semi-circular guide bar fitted at the lower end of the larger semi-circular load frame. Such an arrangement allowed an easy application of static inclined compressive loads on the raft or on the piled raft foundation as it approached failure and eliminated any potential moment transfer from the loading fixture. The settlements of the raft were measured using five 50 mm travel dial gauges accurate to 0.001 mm placed on the raft across section *S*-*S* as shown in Fig. 2.

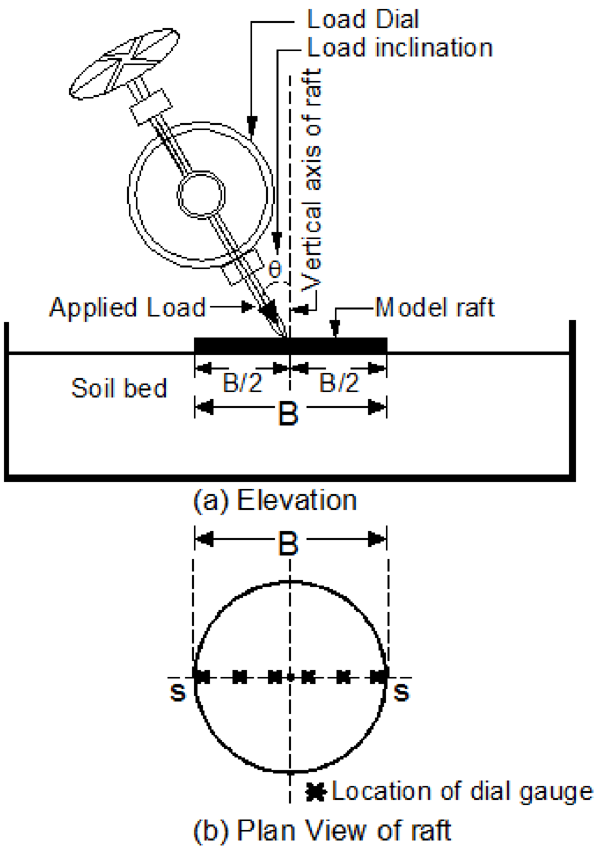


Fig.2. Schematic diagram of model raft and load arrangement

Test Material

The sand used in this research is dry brown uniformly graded Mogra sand obtained from sand mines of Hoogly district, West Bengal was used. The sand washed, dried, and sorted by particle size. It is composed of rounded to sub rounded particles. The specific gravity of the soil particles was determined through specific gravity bottle. Three tests were carried out producing an average value of 2.65. The maximum and the minimum dry densities of the sand were found to be 18.5 kN/m^3 and 15.1 kN/m3 and the corresponding values of the minimum and the maximum void ratios are 0.305 and 1.43., respectively. The particle size distribution was determined using the dry sieving method and the results are shown in Fig. 3. The effective size D10, uniformity coefficient (Cu) and coefficient of curvature for the sand were 0.45 mm, 1.25 and 0.96 respectively. In order to achieve reasonably homogeneous sand beds of reproducible packing, controlled pouring and tamping techniques were used to deposit sand in 50-mm-thick layers into the model box. Model soil layers 450 mm in height were constructed in layers with the bed level observed through the front glass wall. In this method, the quantity of sand for each layer, this was required to produce a specific relative density, was first weighed and placed in the tank and tamped until achieving the required layer height. The inner faces of the tank were marked at 50 mm intervals to facilitate accurate preparation of the sand bed in layers. The experimental tests were conducted on samples prepared with average unit weights of 16.1, 17.15, and 18.10 kN/m^3 representing loose, medium-dense, and dense conditions, respectively. The relative densities of the samples were 35, 55, and 80%, respectively. The estimated internal friction angle of the sand determined from direct shear tests using specimens prepared by dry tamping at the same relative densities were 25°, 35.5°, and 40°, respectively. Secant Young's modulus representing loose, medium-dense, and dense sands derived from a series of drained triaxial compression tests were more or less 12,000, 20,000, and 35,000 kN/m^2.

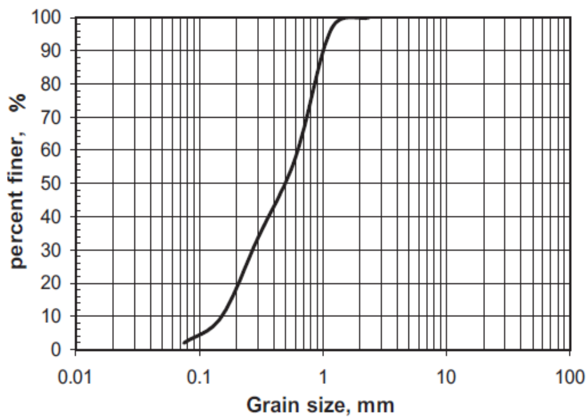


Fig. 3. Grain size distribution of foundation soil

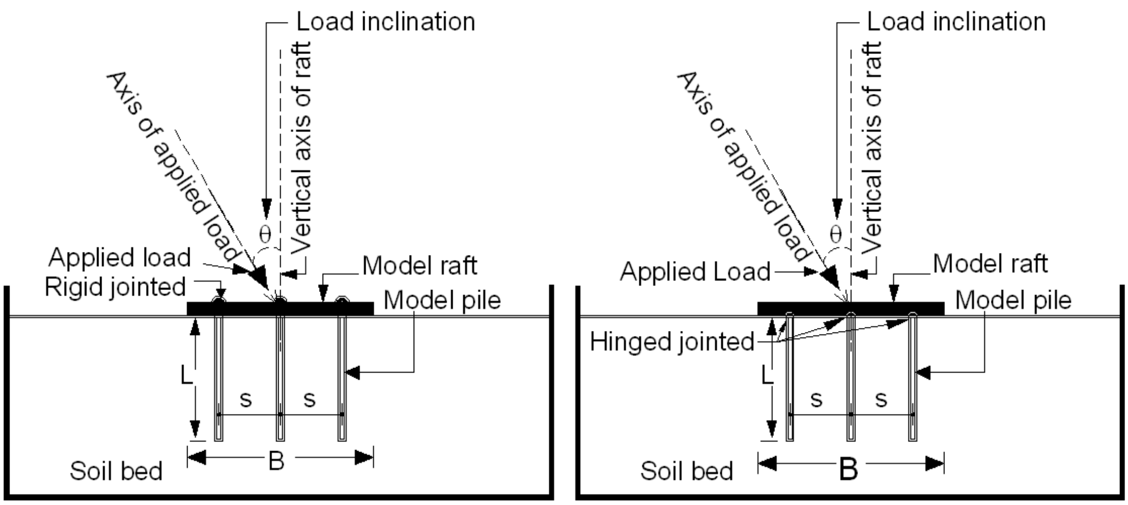


Fig. 4. Geometric parameters for the laboratory model test.

Experimental Program and Test Setup

An extensive test program was carried out to study the behavior of obliquely loaded model piled rafts resting on sand. The effect of using short piles as structural members either rigidly connected to the raft or hinged with the raft on the ultimate inclined load carrying of piled raft foundation system was examined. Once the setup of the sand bed was completed, great care was given to level the sand surface using special rulers and a water balance so that the top surface of the sand was exactly horizontal. Then, several rows of free standing model piles were installed singly one-by-one using a special guide system which held the piles vertical during the installation. The guide system was initially clamped to the tank from the top. The piles were template through thin weight less synthetic strings into their pre-determined positions.

During this procedure last sand layer placement was paused. After templating and properly checking the vertical alignment of the model piles, last sand layer was placed. No visible movement in the sand surface was observed during this process. Piles were also not allowed to undergo any disturbance during last layer of sand bed preparation. Then the sand surface was leveled again and finally the model raft was placed carefully over the piles. Rigid connections between piles and raft were done by bolting the pile heads with the raft plate. Great care was given to keep the plate horizontal during the bolting operation. After that a small seating pressure was applied through wheel axel arrangement on the center of the plate to confirm the contact between the raft and sand surface. The difference in the relative density of the sand, which occurs during pile installation due to the difference in pile lengths, was considered to be small and neglected. Finally, the proving ring is threaded with ram of the wheel axle. The other end of the ring is kept over a ball bearing which is placed over the plunger. The plunger head is placed over the raft plate. The dial gauges for measuring the settlement were placed over the raft as shown in Fig. 2. The load was applied incrementally. Each load increment was maintained at a constant value until the model raft settlement had stabilized. The foundation model assembly was loaded till failure. The geometry of the soil, model raft, and model piles are shown in Fig. 4.

The experimental program consisted of three groups of tests in 12 series carried out on the model raft and piles as shown in Table 1. In the first group, the behavior of obliquely loaded model rafts without piles supported on loose, medium-dense, and dense sand conditions were determined. In the second group, the effect of inclusion of short piles as hinged with raft with different lengths, numbers, and pile arrangements on the behavior of the model raft was studied. Then the same variations of parameters of short piles rigidly connected to the raft were examined. The effects of the relative density along with the load angle of inclination of load were also studied. In each series of the tests, one parameter was varied while the other variables were kept constant. The studied variables included the pile length (L), the pile number (N), the load inclination (θ), the sand relative density (R_d), and the pile arrangement. Fig. 5

shows the three different pile arrangements adopted in the study to investigate their effects on the behavior of the rafts. The same arrangements of the piles are used but the pile lengths are varied. The first arrangement consisted of four numbers of piles in radial pattern with a spacing of 3 times pile diameter. The second arrangement consisted of 8 piles in radial pattern with same spacing as above. Several tests were repeated at least twice to verify the repeatability and the consistency of the test data. The same patterns of load-settlement relationship with the difference in the measured bearing pressures or maximum settlements values of less than 2.0% were obtained. The difference was considered to be small and neglected.

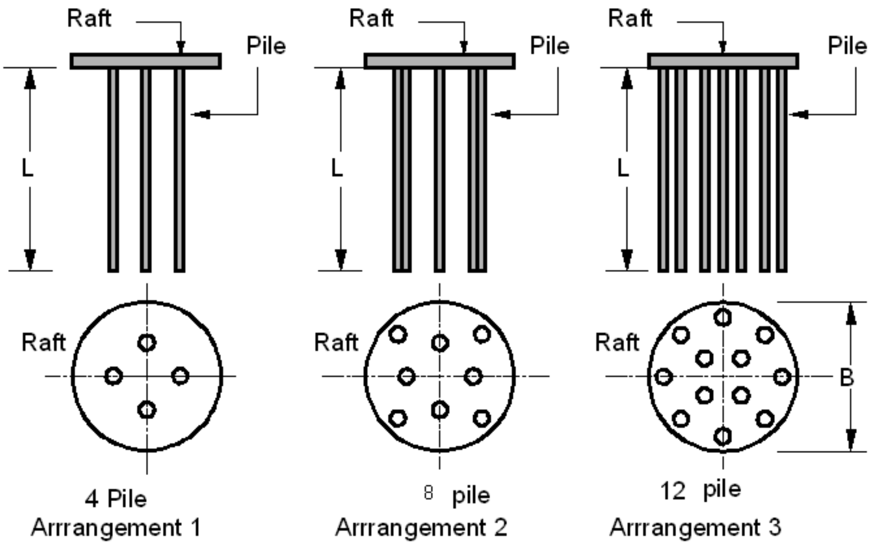


Fig. 5. Pile arrangement in the laboratory model test.

Table 1. Model Test Program

Series	Constant Parameters	Pile to raft / cap Connection	No. of piles	Variable Parameters
1	Unpiled Raft R_d = 55%			$\theta = 5^0, 15^0, 30^0$
2	Unpiled Raft $\theta = 15^0$			R_d = 30%, 50%, 75%
3	Pile Group, $\theta = 15^0$; L/d = 10	Fixed	4	R_d = 30%, 50%, 75%
4	Pile Group, $\theta = 15^0$; L/d = 15	Fixed	4	R_d = 30%, 50%, 75%
5	Pile Group, $\theta = 15^0$; L/d = 20	Fixed	4	R_d = 30%, 50%, 75%
6	Pile Group, Rd = 55%, L/d = 10	Fixed	4	$\theta = 5^0, 15^0, 30^0$

7	Pile Group, Rd = 55%, L/d = 15	Fixed	4	$\theta = 5^0, 15^0, 30^0$
8	Pile Group, Rd = 55%, L/d = 20	Fixed	4	$\theta = 5^0, 15^0, 30^0$
9	Piled Raft, Rd = 55%, $\theta = 15^0$	Hinged	4	L/d = 10, 15, 20
10	Piled Raft, Rd = 50%, $\theta = 15^0$	Fixed	8	L/d = 10, 15, 20
11	Piled Raft, Rd = 55%, $\theta = 15^0$	Hinged	8	L/d = 10, 15, 20
12	Piled Raft, Rd = 50%, $\theta = 15^0$	Fixed	4	L/d = 10, 15, 20
13	Piled Raft, Rd = 55%; L/d = 20	Fixed	8	$\theta = 0^0, 15^0, 30^0, 45^0, 60^0, 90^0$
14	Piled Raft, Rd = 55%; L/d = 15	Fixed	8	$\theta = 0^0, 15^0, 30^0, 45^0, 60^0, 90^0$
15	Piled Raft, Rd = 55%; L/d = 15	Hinged	8	$\theta = 0^0, 15^0, 30^0, 45^0, 60^0, 90^0$
16	Piled Raft; $\theta = 15^0$; L/d = 10	Hinged	4	R_d = 30%, 50%, 75%
17	Piled Raft, $\theta = 15^0$; L/d = 10	Fixed	4	R_d = 30%, 50%, 75%
18	Pile Group, Rd = 55%, L/d = 15, $\theta = 15^0$	Fixed		No. of piles = 4, 8, 12
19	Pile Group, Rd = 55%, L/d = 15, $\theta = 15^0$	Hinged		No. of piles = 4, 8, 12

RESULTS AND DISCUSSION

Results of more than50number of model tests carried out on model rafts in coheionless soil are reported in this paper. The raft behavior under oblique load (inclination angle is written as θ with the vertical axis of raft) with the inclusion of short piles was studied and discussed. The relative improvement of the raft performance when supported on either a rigidly connected or piles hinged with raft is represented using a non dimensional factor, called the bearing pressure improvement (BPI). This factor is defined as the ratio of the bearing pressure of a piled raft (q_{piled}) piles either rigidly connected or hinged with the raft, to the bearing pressure of an unpiled raft (q_{unpiled}) at the same settlement level. The raft settlement (*S*) is expressed in nondimensional form in terms of the raft width (*B*) as the ratio (*S*/*B*, %). Pile to raft area ratio is denoted by A_{pr}. For comparisons of the piled raft response with the different studied parameters, two levels of settlement ratios (*S*/*B*), at 1% and 5%, were considered.

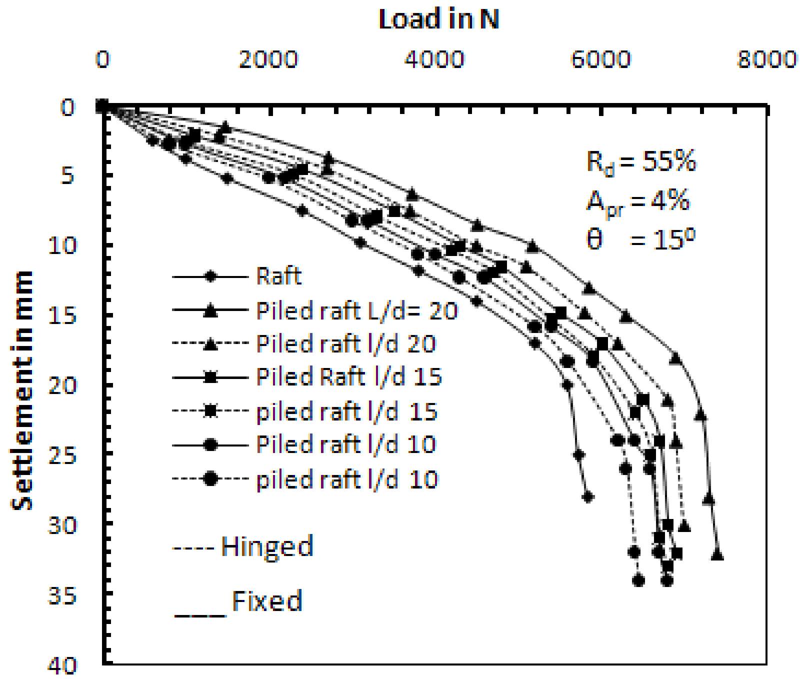


Fig. 6. Variation of load deformation behavior with maximum settlement for different pile lengths

Effect of Pile Length

Fig. 6 shows typical variations of the ultimate load versus maximum settlements of the raft centre under an inclined loaded on raft (θ= 15^0) for the different pile lengths. The behavior of an unpiled raft is also included in the figure for comparison. The figure clearly shows that the inclusion of piles either rigidly connected or hinged much improves the initial stiffness of the load-settlement curves (the ultimate load carrying much increase at lower rates of settlement). The figure also demonstrates that a pile rigidly connected to the raft has a more significant effect on the ultimate load carrying capacity of raft than that of hinged piles under inclined loaded condition. However, the improvements in the load carrying capacity at the same settlement level are greater with longer piles. The settlements decrease significantly for a pile connected to the raft for the same raft load. For example, comparing the curves of Fig. 6 at the ultimate load of the unpiled case, the value of the settlement decreased from 17.20 mm (unpiled case) to 15.6, 12.1, and 7.95 mm when using rigidly connected piles of *L*/*D*=10, 15, and 20, respectively.

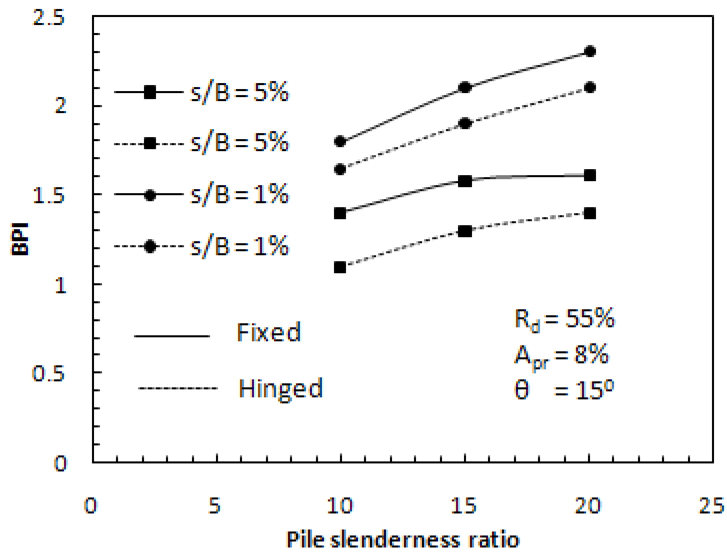


Fig. 7. Variation of BPI with L/d ratio at different s/B ratio

Fig. 7 shows the variations of BPI with the normalized pile length, *L*/*D*, for both rigidly connected piles and hinged piles at settlement ratios of 1 and 5%. The improvements in the raft ultimate load bearing capacity increase with longer piles. However, these improvements in the raft load bearing capacities when piles are rigidly fixed with the raft are greater than that when piles are hinged. Also, the improvements in the piled raft performance are greater at lower levels of settlement ratios. This is consistent with the reported observation by [11] Reul and Randolph (2004) that the overall stiffness of a piled raft increases with decreasing load level and hence the settlement ratio. Although it is apparent that increasing the pile length has much more influence on enhancing the stiffness of the piled raft system, using short piles might be more favorable to reduce the settlement of an obliquely loaded raft without the structural problems associated with long piles.

Effect of Pile Number

Two series of tests were conducted on a raft subjected to load with an angle $\theta = 15^0$ degree with vertical and resting on medium dense sand using same pile configuration (arrangement 3 in Fig. 5). While the piles were rigidly fixed with the raft in the first series, they were hinged with the raft in the second one (series 15 and 16 in Table 1). Fig. 8 shows the variations of BPI with pile number at different settlement ratios. The figure shows that the rate of BPI initially increases with the increase in pile number.

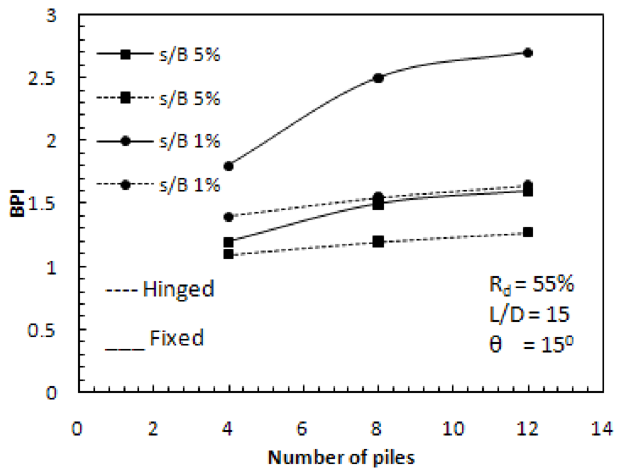


Fig. 8. Variation of BPI with number of piles at different s/B ratio

However, it seems that when the number reaches a certain value, the increasing rate of BPI becomes quite small and the effect on reducing the settlement of raft becomes small. The variations of the BPI with number of piles for the raft are similar for the two cases with greater values when the piles are rigidly fixed to the raft than the case in which the piles are hinged. This pattern of behavior is consistent with the conclusion by [2] Poulos and Davis (1980) 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.

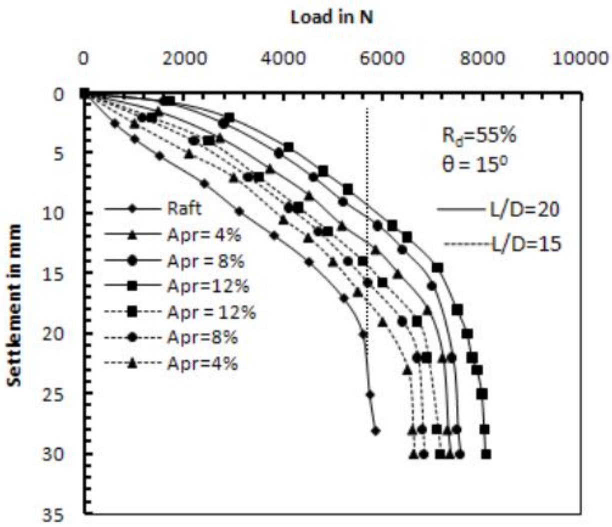


Fig. 9. Variation of Ultimate load with maximum settlement for different A_{pr}

Effect of Pile to Raft Area Ratio

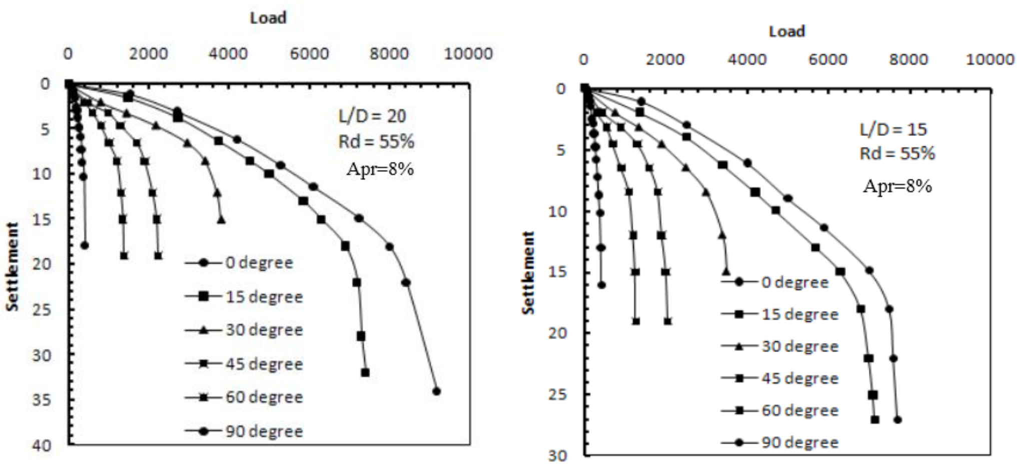
There are different recommendations regarding the optimal pile distribution that gives the best piled raft response and the least raft settlement depending on type of loading. [13] Cao et al. (2004) studied a typical loading condition consisting of a uniformly distributed load in the central core area and two symmetrical line loads and reported that concentrating the piles within the central area of the plate reduced the settlement at the center, but may increase the settlement at the edge. [11] Reul and Randolph (2004) reported similar observation for rafts under uniform loading. However, [6] Kim et al. (2001) reported different pile arrangements for three different load conditions based on minimizing differential settlement of a piled raft foundation. As the model raft geometry and load conditions studied in the paper are different from the previous cases, two series of tests using the two pile slenderness ratio were carried out to study the effect of pile arrangement on the behavior of a model raft footing supported on medium dense sand under oblique load with $\theta = 15^0$. Fig. 9 shows the load settlement response of the model raft for the different arrangements as shown in Fig. 5. For higher area ratio of pile to raft, it can be observed that greater stiffness and lesser settlements are achieved when using radial pattern in the peripheral region of the raft than that when using radial of pattern arrangement of piles in the central region of the raft only. For the considered case of a raft under inclined loading, using four piles placed adjacent to the edges of the raft provide the maximum resistance to the overturning moment and lead to a flatter settlement profile than using the other arrangements.

Effect of Load Inclination

Twelve tests were carried out on a model raft footing supported on medium dense sand to study the effect of the load inclination. While the first six tests were carried out on an piled raft model subjected to load having inclination varying from 0^0 to 90^0, the other six tests were carried out on the raft with model piles connected rigidlyfor same load inclination as previous as illustrated in Table 1. The same pile configurations (arrangement 2) with *L*/*D*=15 and L/D 20 were used. Fig. 10 shows typical variations of the measured load bearing capacities versus the measured maximum settlements of the raft for all the cases. The load bearing capacity of the raft alone decrease significantly with an increase in the load inclination angle, θ. Also at same load level, greater displacements can be observed with increased load inclination angle, θ. However, with the inclusion of piles with the raft, a significant increase in the ultimate load bearing capacity can be observed. It is also associated with much less displacement relative to the case of the unpiled raft which can be easily notified from Fig. 10 (a) and Fig. 10 (b). From the figures, it can be observed that piles having higher slenderness ratio has a greater effect than piles of lower L/D ratios.

Fig. 11 shows the variations of BPI with inclination of applied load, θ for piles either fixed rigidly or hinged with raft at two levels of settlement ratios. It is clear that the inclusions of piles are most effective on the raft behavior with the decrease in the load inclination angle, θ. For example, the gains in the bearing capacity of the model raft with piles connected rigidly to the raft at a settlement ratio of 1.0% are found to be 22% and 24% load inclination angle, θ equal to 15^0 and 30^0, respectively. For a load applied obliquely over the raft rigidly connection with the piles, ultimate bearing capacity values of the piled raft foundation has increased considerably for all the range of value of θ.

This improvement in raft behavior with piles can be attributed to the additional resistance offered by the piles on the compression side while the piles on the uplift side tend to work as anchor piles. This conclusion is very important to the several cases of a narrow building with site conditions being safe as far as bearing capacity is concerned but the raft settlements and tilts exceed the allowable values. Due to their aspect ratio and the effect of the lateral loads, the use of shallow foundations for such a narrow building is not safe leading to the use of deep piles and uneconomic design. In such a case, the use of short piles adjacent to the raft edges not only significantly improves the raft bearing pressures but also leads to great reduction in raft displacement and tilts required to achieve the allowable limits of the raft settlements and hence economic design of foundations.



(a) (b)

Fig. 10. Variation of load bearing capacities of piled raft models with different load inclinations

Effect of Relative Density

In order to study the effect of relative density, two series of tests were conducted on a model piled raft embedded in sandbed set up at three different unit weights representing dense, medium-dense, and loose relative densities. While the first series was carried out on piled rafts subjected to 15^0 degree inclined load, the second series were performed on a piled rafts subjected to 30^0 load inclination with model piles rigidly connected to the raft.

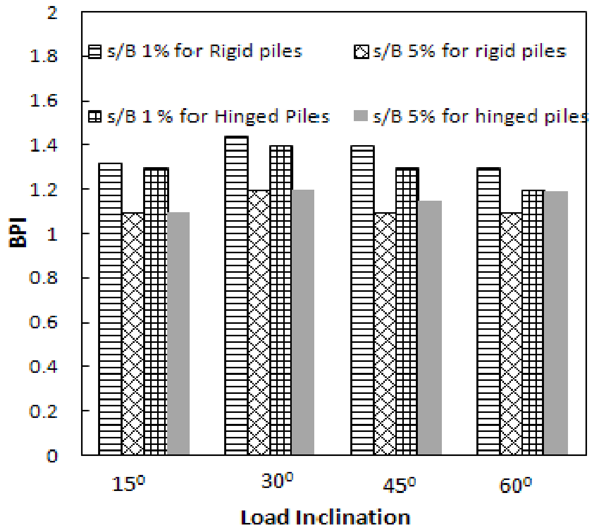


Fig. 11. Variation of load bearing capacity with inclination of applied load, θ

The same pile configuration (arrangement 2) with A_{pr} = 8% and *L*/*D*=15 were used. Typical variations of the bearing pressures versus maximum settlements under the raft are plotted in Fig. 12. As expected, the pile raft settlements decrease significantly with increasing soil density. With the inclusion of short piles, the overall stiffness of the raft significantly increases leading to greater values of bearing pressures at lower values of raft settlements. Fig. 13 shows the variations of BPI with relative density for the piled raft at two levels of settlement ratio.

The figure clearly shows the dependence of raft behavior on the relative density of sand. In loose sand conditions, a relatively lower gain in the bearing pressures relative to the improvements was obtained in medium dense to dense sand densities. This can be attributed to the additional resistance offered by the piles to raft settlement and tilt by the increase of pile bearing and pile skin friction due to the increase of relative density and hence the angle of friction. Furthermore, the part of load taken by the model plate increased with the increase of sand density. However, the decrease of the ratio BPI for dense sand than medium dense sand can be attributed mainly to the greater value of the bearing pressure of the unpiled raft.

It should be mentioned that not only the raft performance improved but also the failure mechanisms of the piled raft changed. Greater heaves of the sand surrounding the plate were observed in the tests carried out on dense sand, whereas only very little heave was seen around the medium-dense sand and no heave at all was observed on loose sands. Also in the tests carried out on dense sand with rigidly connected piles, it was observed that either the lower part of the originally vertical piles permanently deformed or the piles deformed at the connection point with the raft, while in tests carried out on dense sand with hinged piles, no visible changes in the pile section were observed.

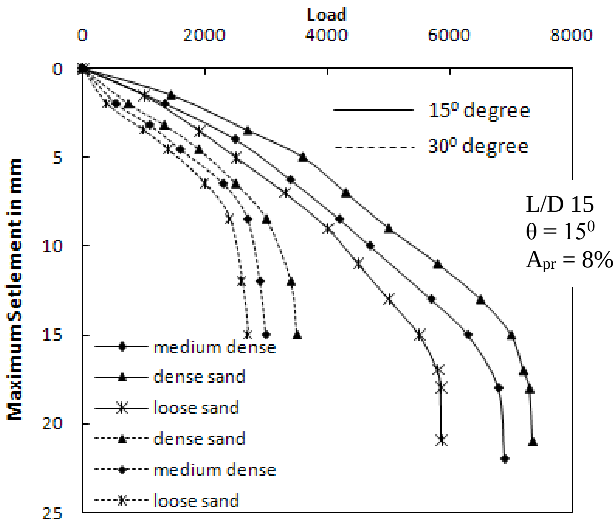


Fig. 12. Load deformation charecteristics of piled raft foundation with soil density

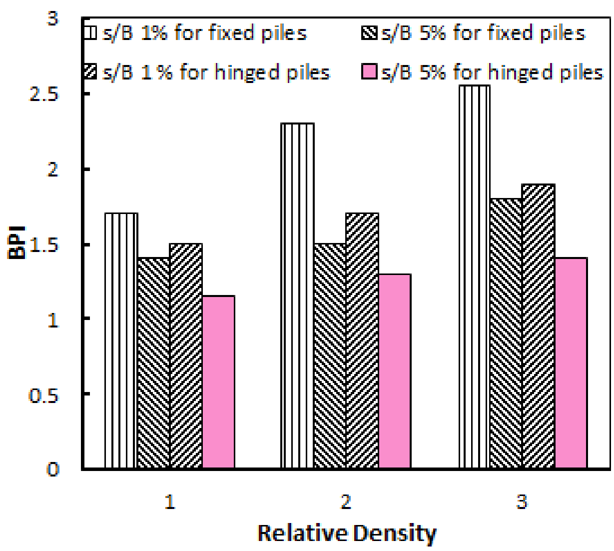


Fig. 13. Variation of BPI with soil density

Tilt of Model Raft

To compare the effects of inclusion of short piles either rigidly connected with the raft or hinged with the raft, the settlements along the centre line of the (line S-S defined in Fig. 2) model rafts supported on medium dense sands are plotted in Fig. 14. Test results of series (1, 14 and 15) carried out on model rafts with $\theta = 30^0$ and using model piles with L/D =15 were used. The results for the unpiled raft with the same θ and supported on the same sand are plotted for comparison. For all cases, the values of settlements were taken at the same load level (failure load of unpiled raft as shown in Fig. 9 across the vertical dotted line). The figure clearly shows that the failure of the unpiled raft is accompanied by tilting of the raft footing. The rotations of the model rafts (difference between maximum and minimum settlements divided by the distance between them) are greatly decreased by the pile inclusions. While the maximum settlement of the raft was significantly reduced from 15.20 mm to 3.8mm and 2.6 mm when using hinged piles and rigid piles, respectively, the minimum settlement at the other side of the raft slightly changed, leading to a significant decrease in both the rotation and the average settlement of the raft. Therefore, it can be concluded that with inclusion of short piles, not only the load-carrying capacity of the model raft has been increased but also the tilt and the average settlements of the raft have been reduced to acceptable limits leading to an economical design of the raft under oblique loading condition.

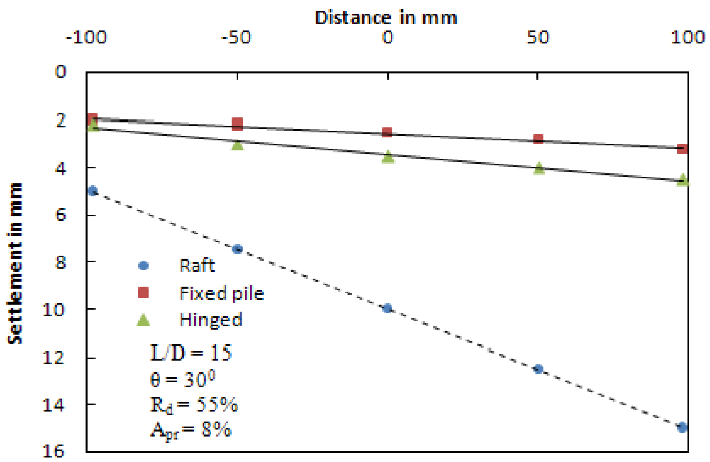


Fig. 14. Settlement along the centre line of unpiled raft and piled raft of different raft pile fixity condition

In order to compare the effects of different pile arrangements on the raft behavior, the settlements along sections *S-S* of the model rafts obliquely loaded with $\theta = 30^0$ and supported on medium-dense sand (series 1) are plotted in Fig. 15. Only the results of piles connected rigidly to the raft with *L/D*=15 along with the settlements for an unpiled raft are plotted. For the different pile arrangements, the values of settlement were taken at the same load level (failure load of unpiled raft shown in Fig. 9) across the vertical dotted line. The figure clearly shows that the maximum settlements and rotations of the raft are considerably reduced by the pile arrangement 3. The maximum settlements decreased from 15.20 mm to 5.70, 2.6, and 1.95 mm when using two, three, and four rows of piles, respectively. In terms of the average settlement and rotation of raft, the figure demonstrates that arrangement 3 where piles were placed in four rows adjacent to the raft edges is the optimal pile distribution to resist inclined load for relatively narrow rafts.

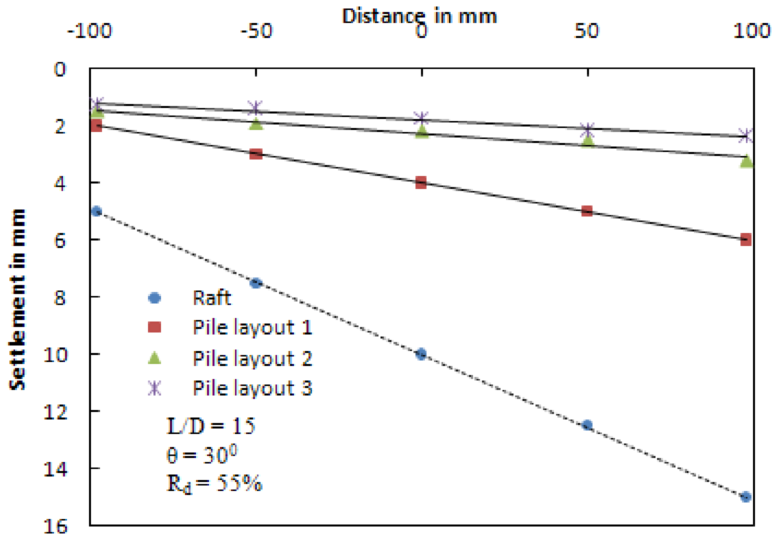


Fig. 15. Settlement along the centre line of raft and piled raft of different pile arrangement

CONCLUSION

The effectiveness of using vertical short piles under a structural member either rigidly connected to raft or hinged with the raft were studied. Several arrangements of piles in cohesionless soils of different relative densities were investigated. Based on the laboratory investigations, the following main conclusions are drawn:

In case of raft alone lateral displacement is excessive whenever it is acted upon by combined vertical and lateral loads. The inclusion of short piles has a significant effect on improving the load carrying capacity of a piled raft composite as well as it minimizes the lateral displacement of the foundation.

Pile arrangement has significant effect on the raft settlement particularly at higher lateral load levels. However, it seems that the optimum arrangement of piles is dependent on the magnitude of lateral load. Piles placed at the edges of rafts are found to more efficient in reducing the overall settlement in piled raft whenever lateral load is around 20% of vertical load.

With the inclusion of short piles, the piles which are rigidly connected to the raft has greater effect on enhancing the lateral load carrying capacity of the raft behavior than the piles hinged with the raft.

In the case of a shallow rafts acted upon by inclined compressive loading, by using short piles adjacent to the raft edges, not only increases the BPI ratio, but also both the average settlements and the tilt of the rafts reduces to acceptable limits leading to an economical design in respect of safety and serviceability.

Henceforth, for analyzing piled raft foundation which are designed for vertical and lateral load combinations, effect of load from both the directions should be considered unlike the available theories which simplifies the effect of vertical loads while designing piles for lateral loads.

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