TECHNICAL PAPER

An experimental study to analyse the behaviour of piled-raft foundation model under the application of vertical load

Vikas Kumar[1] · Arvind Kumar[1]

Abstract

Piled-raft foundation nowadays has become the most popular foundation to be used in high-rise buildings. It has been found that traditional foundations are insufficient to take such heavy loads coming from the super structures in the form of self-weight, wind load and seismic load as well as combination of these. Apart from this even pile and raft foundations alone are not economical for these high-rise buildings. The parameters which affect behaviour of pile–raft foundation depend upon the properties of raft, pile and subsoil. In order to study the behaviour of piled-raft foundation, an experimental setup was designed and experiments were conducted on built model for raft foundation and piled-raft foundation in sandy soil at different relative densities. The experimental setup was aimed to investigate the behaviour of raft on settlement-reducing piles. Experimental tests are conducted on two different length and diameter of pile. The length-to-width (L/B) ratio for experimental study was chosen to be 0.67 and 2.0, where B is width of raft footing in prototype used and L is the length of pile. The diameters of pile used were of 10 and 20 mm size. The dimensions of the model raft used in the experimental study were 30 cm × 30 cm × 2.5 cm. The results of the experiments conducted on the designed model showed the effectiveness of using piles as settlement reduction measure with the rafts. Thus, it was concluded that as the number of settlement-reducing piles increases, the load improvement ratio increases and the differential settlement ratio decreases.

Keywords Piled-raft foundation · Bearing capacity ratio · Settlement

Introduction

With growing population the demand for ample infrastructure is increasing day by day. To fulfil this there is a continuous need of high-rise buildings, express highways and bridges, etc. Some of the high-rise buildings like Burj Khalifa, Mile towers, etc. are changing the face of the buildings and the utility. Making these skyscrapers require stable and economical foundations to be built because very high self-weight, wind loads and seismic load come through the superstructure and subsequently increasing load on the foundation. Use of traditional foundations like shallow foundation, raft foundation and pile alone is not stable and economical for such high-rise structures which have tremendous load to be borne by the substructure. In order to facilitate this, new type of foundation such as pile–raft foundation

is required in those skyscrapers. Pile–raft foundation is a composite structure which constitutes three elements—pile, raft and subsoil [1]. Though the raft foundation alone can satisfy the bearing capacity criteria, it may not fulfil the settlement criteria for given load in poor soil [2]. Various research works has been done to increase the bearing capacity of the soil in shallow foundation by the use of different reinforcement techniques. Sridhar and Prathapkumar [3] determined the bearing capacity of coir geotextile-reinforced sand. Nimeri et al. [4] present a new model which was developed to assess load–settlement response up to ultimate soil failure. The model utilizes Mohr–Coulomb criteria coupled with a stress–strain relationship that captures the behaviour of granular soil up to large strains, but for high loaded building this may not be the appropriate design foundation. Pile foundation is generally used where the load is transferred to hard rock strata mass which have high bearing capacity. Wang et al. [5] explored the innovative hybrid monopile foundation for oiled water tank which is an optimization of the original monopile foundation with broader applications, but cost of such a type of foundation is very high

✉ Vikas Kumar
  vikaskumarnitk@gmail.com

[1] Dr BR Ambedkar National Institute of Technology, Jalandhar, Punjab, India

compared to traditional foundation system. In order to make stable and economical foundation, piles can be coupled with a raft foundation to provide adequate bearing capacity to it or to reduce settlements to an acceptable level. Abdel-Fattah and Hemada [6] present the proposed methodology for the combined piled–raft design based on the conventional philosophy is applied to evaluate existing conventionally designed piled foundations of two identical residential towers located in Cairo, Egypt. Sahraeian et al. [7] explored a series of centrifuge model tests was performed to investigate the mechanical behaviour of oil tank supported by piled-raft foundation on liquefiable saturated sand and non-liquefiable dry sand. The common design of piled raft was based on the assumption that the total load of the superstructure was supported by piles, ignoring the bearing contribution of the raft. This results in a conservative estimate of the foundation performance, and therefore an overdesign of the foundation is required. A different approach, involving the use of piles as settlement reducers, had been reported by Randolph [8], Burland [9], Sanctis et al. [10], and Fioravante et al. [11]. The basic concept of this approach was that the foundation would comprise only a number of piles that are necessary to reduce settlements to a tolerable amount and the loads from the structure are transmitted, via a raft, in part to the piles and in part to the foundation soil (load shared between the raft and piles). Mali and Singh [12] has done the numerical analysis on the piled-raft foundation using the finite element method. This approach allows the piled-raft design to be optimized and the number of piles to be significantly reduced. After various studies, piled-raft foundation system was verified to be an economical foundation type comparing the conventional piled foundations, where, only the piles were used for reducing both total and differential settlements and the contribution of the raft was generally disregarded. Kumar and Choudhury [13] explored the complex soil structure interaction factors to estimate load-bearing capacity of a combined pile–raft foundation (CPRF). Bouassida [14] present a review of the book titled "Design of column-reinforced foundations" The design of foundations on reinforced soil by columns is tackled within a general framework, where several aspects are taken into consideration: modelling of reinforced soil, bearing capacity, settlement, acceleration of consolidation, and improvement of soil characteristics with selected case histories.

Many researchers had conducted numerical analysis of piled rafts [15–23] but only limited information is available in the open literature on the experimental data of piled rafts as given by Horikoshi et al. [16], Lee and Chung [24], Bajad and Sahu [25], Fioravante et al. [11] and Phung [26]. The experimental data was helpful in verifying the results of numerical analysis of piled rafts. Horikoshi et al. [16] investigated the load–settlement behaviour and the load sharing between the piles and the raft in the piled-raft

system through a series of static loading tests (vertically and horizontally) on piled-raft models in sand. Lee and Chung [24] pointed out that for a proper pile group design, factors such as the interaction among piles, the interaction between cap and piles, and the influence of pile installation method all need to be considered. Lee and Chung [24] studied the effect of these factors on the performance of pile groups in sand soil through model tests on single pile, single-loaded centre piles in groups, unpiled footing, freestanding pile groups, and piled footings. Chen et al. [27] investigate the reduction of vibration due to the pile–raft foundation through field measurement and finite element (FE) prediction for a high-tech electronics workshop in Suzhou, China. Huang et al. [28] presented the simplified nonlinear approach to study the behaviour of flexible piled-raft foundations. Bajad and Sahu [25] investigated the effect of pile length and number of piles on load sharing and settlement reduction behaviour of piled rafts resting on soft clay through 1 g model tests on piled rafts (i.e. 10 cm × 10 cm raft with different thickness on four (2 × 2), nine (3 × 3), and sixteen (4 × 4) piles). Fioravante et al. [11] investigated the behaviour of rafts on settlement-reducing piles through a centrifuge model test on rigid circular piled rafts resting on a bed of loose and very fine silica sand. The testing programme included an unpiled raft, rafts on 1, 3, 7 or 13 piles. Phung [26] presented the data of three extensive series of large-scale field model tests performed on piled footings in non-cohesive soil in order to clarify the overall cap–soil–pile interaction and the load–settlement behaviour of piled footing. All the pile groups were square in geometry and consisted of five piles (i.e. one centre and four corner piles).

In this paper, the behaviour of piled raft (i.e. raft with a limited number of piles beneath the central raft area called settlement-reducing piles) was investigated through model tests on piled raft at different relative densities of sand. The settlement and bearing capacity characteristics of the pile-supported-raft foundation under different conditions such as different pile length, pile diameter, number of pile, pattern of pile, pile spacing, and soil properties need to be investigated in sufficient detail to understand the effect of various influencing factors on the behaviour of this type of foundation. Study of tests conducted on model has to be done to understand the behaviour of piled-raft foundation. This will help to understand the effect of different parameters on the overall performance of the piled-raft foundation.

Mechanism of piled-raft foundation

In the design of piled rafts, design engineers have to understand the mechanism of load transfer from the raft to the piles and to the soil media to predict (1) the behaviour of
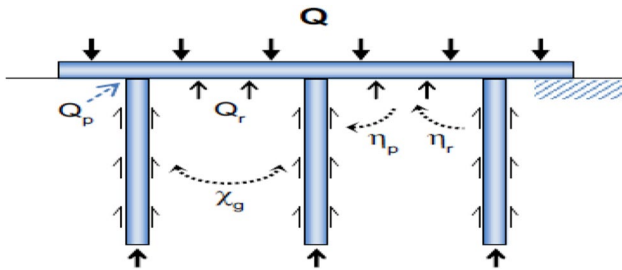
Fig. 1 Schematic view of various interactions for piled raft [29]

the raft which includes the settlements, bending moments and the proportion of load-bearing capacity carried by the raft, and (2) the behaviour of the piles which includes the displacements and load distributions among the piles. Interactions between piles, raft and soil are of major concern in the analysis.

El-Mossallamy and Franke [29] present that in a piled-raft foundation, the total load of the super structure is partly carried out by piles through skin friction and the remaining load is taken by a raft through contact with the soil as shown in Fig. 1. In piled-raft systems, the design procedure differs from traditional foundation design, in which the loads are assumed to be carried either by the raft or by the piles, considering the safety factor. In the design of piled rafts the load sharing between the piles and the raft is taken into account. Loads imposed on piled raft are supported and shared by piles and raft at a certain load sharing ratio. The load sharing ratio indicates the ratio of load carried by piles to total load imposed on piled raft defined as follows:

$$\alpha_p = \frac{Q_P}{Q_{Pr}} = 1 - \frac{Q_r}{Q_{Pr}}, \tag{1}$$

where α_p is loading sharing ratio, Q_{Pr} is load imposed on piled raft, Q_P and Q_r are load carried by piled and raft, respectively.

Experimental programmes

A series of laboratory tests were performed on model unpiled raft and the piled raft with different number of piles below the raft (i.e. raft on settlement-reducing piles). The experimental programme consisted of number of tests as shown in Table 1. Two tests were carried out on model raft at relative density of 40 and 70% of sand and remaining tests were conducted on model piled-raft foundation. In this study effect of parameters, such as number of piles, length of pile, diameter of piles, pattern of piles

Table 1 Properties of sand used in the study

Property	Value
Specific gravity, G	2.65
D_{10} (mm)	0.15
D_{30} (mm)	0.22
D_{60} (mm)	0.332
Coefficient of uniformity, C_u	2.21
Coefficient of curvature, C_c	0.97
Classification (USCS)	SP
Maximum dry unit weight, γ_{dmax} (kN/m³)	16.79
Minimum dry unit weight, γ_{dmin} (kN/m³)	13.59
Friction angle (φ) from direct shear test	
ID 40%	28°
ID 70%	31.4°
Friction angle (φ) from triaxial compression test	
ID 40%	
ID 70%	32°

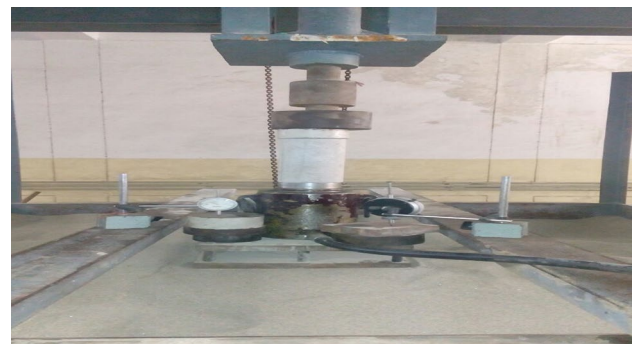**Photo 1** Model raft used in experimental analysis

Photo 2 Experimental test setup

and relative density of soil on the behaviour of piled-raft foundation has been proposed to be investigated and the comparative study of the behaviour of raft and piled-raft foundation to be considered (Photos 1, 2).

Test material

Sand

In this study, the sand used was locally available river sand obtained from Nasrala, situated in Punjab, India. The sand was cleaned to make it free from vegetation like grass roots and other organic materials and then placed in oven before tests. Particle size distribution [30] of sand is shown in Fig. 2. The uniformity coefficient (C_u) and coefficient of curvature (C_c) were found to be 2.21 and 0.97, respectively. According to the Unified Soil Classification System (USCS) [31], the soil can be classified as poorly graded sand (SP). Specific gravity [32], maximum dry density [33], minimum dry density [34] and other properties are presented in Table 1. Direct shear tests as per ASTM D 6528-07 were performed on samples prepared at relative densities (ID) of 40 and 70%.

The value of shear modulus of sand G, in kPa at any depth Z below the ground surface can be determined by the model given by the El-Garhy et al. [35]:

$$G = 300 + 400z. \tag{2}$$

The Poisson's ratio of tested sand was assumed as 0.30 as recommended by Bowles [36]. The modulus of elasticity of the tested soil E_s can be calculated from the soil shear modulus and Poisson's ratio:

$$E_s = 2G(1 + v_s). \tag{3}$$

The relative flexibility of a raft is expressed by the raft–soil stiffness ratio, K_{rs}, proposed by Hain and Lee [37]:

$$K_{rs} = \frac{4}{3\pi} \frac{E_r \left(1 - v_s^2\right)}{E_s} \frac{B}{L} \left(\frac{t_r}{L}\right)^3, \tag{4}$$

where B and L are the width and length of the raft, respectively, and t_r is the raft thickness. The values of K_{rs} ranging from 0.01 to 10 cover very flexible to very stiff rafts [37].

The best match between measured and predicted values was obtained at the value of G equal to 500 kPa. The raft–soil stiffness ratios for the tested raft models were calculated by Eq. (4). For 25-mm-thick raft value of K_{rs} was found out to be 3.57 which was stiff in nature.

Model of rafts and piles

Two square steel plates of $300 \times 300 \times 25$ mm size bolted with nine columns of 16 mm diameter served as a model of raft developed. The base of the model raft was made with holes threaded internally so that the piles could be screwed in vertical position at the required spacing. The model piles used in the experiment were of mild steel rod of length 200 and 600 mm and diameter of pile varied between 10 and 20 mm. These lengths represent the L/D ratio of 10, 20, 30 and 60, respectively. The modulus of elasticity and Poisson's ratio of the steel pile were kept as 2.1×10^8 kPa and 0.20, respectively, as determined from the data sheet of the technical department of the manufactured company.

Fig. 2 Experimental setup
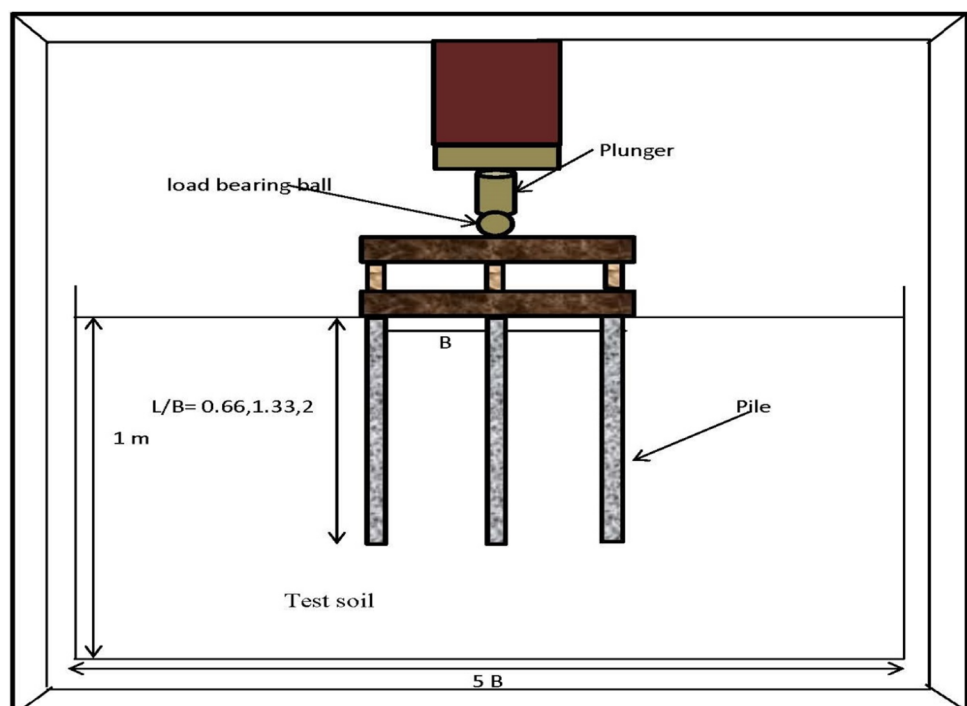
Steel tank and main frame

The size of tank was designed keeping in view the size of footing to be tested and zones of influence. The dimensions of the tank were fixed as 1.50 m (length), 1.50 m (width) and 1.0 m (depth). The sides and bottom of the tank were made up of 9-mm-thick steel sheet, welded to the base framework of steel angles and plates. Vertical load was applied to model footing with the help of hydraulic jack of 250 kN capacity.

Measuring devices

Three dial gauges of 0.01 mm accuracy were used to measure the vertical settlements. One dial gauge was located near the centre and two were located at the middle sides of the raft. The dial gauges were fixed to the raft by means of steel rods. The steel rod consisted of a vertical rod connected to the horizontal beam of the main frame and a horizontal rod which carried the dial gauge. A hydraulic jack uses a fluid, which is incompressible, that is forced into a cylinder by a pump plunger. Oil is used since it is self-lubricating and stable. When the plunger pulls back, it draws oil out of the reservoir through a suction check valve into the pump chamber. When the plunger moves forward, it pushes the oil through a discharge check valve into the cylinder. The suction valve ball is within the chamber and opens with each draw of the plunger. The discharge valve ball is outside the chamber and opens when the oil is pushed into the cylinder. At this point, the suction ball within the chamber is forced shut and oil pressure builds in the cylinder.

Experimental test setup

In the present study, a series of laboratory model plate load tests were performed on piled-raft foundation and raft foundation supported on sand. Test series A were performed on raft foundation. Four different series of tests B, C, D and E were perform on the piled-raft foundation. In test series B only one pile was provided at the centre of footing. In test series D and E the arrangement of pile below the footing is shown in Figs. 3 and 4, respectively. Details of the test series are presented in Table 2.

Test procedures

1. Each experiment started with placing the sand soil in the steel tank in layers. The maximum layer thickness was 10 cm. The total height of the tank was divided into equal intervals from the inner side by making signs every 10 cm height to help to put a specified weight in a specified volume to get the required sand density by compaction. A calculated weighted quantity of sand was compacted by means of a specified compaction tool in the steel tank. The compaction continued until the soil was compacted to fill the first 10 cm layer. A steel arm with circular plate of 15 cm in diameter and 0.8 cm in thickness was used for compaction. The process was repeated until reaching the height of the steel tank (i.e. 95 cm). The final soil layer was 5 cm thick to avoid soil overflowing during the compaction process.

Fig. 3 Arrangement of pile in test series D
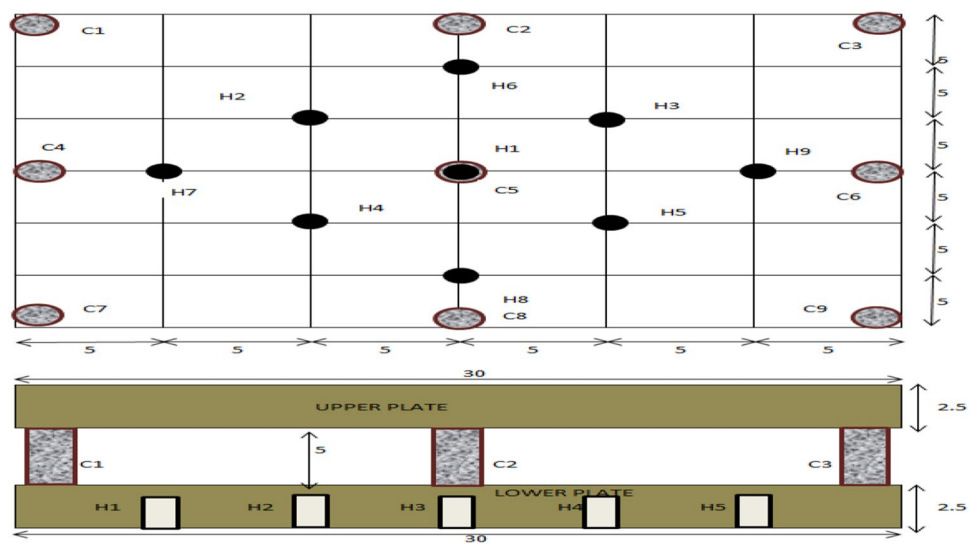
Note:
1 C = columns designated by numbers C1 to C9
2 H = Holes for piles formation, designated by H1 to H9
3 Diameter of columns P1 to P9 = 1.6 cm
4 Diameter of Holes H1 to H9 = 1 cm
5 Arrangement of columns = 8 columns on circumfrence and 1 at center
6 All dimension in cm.
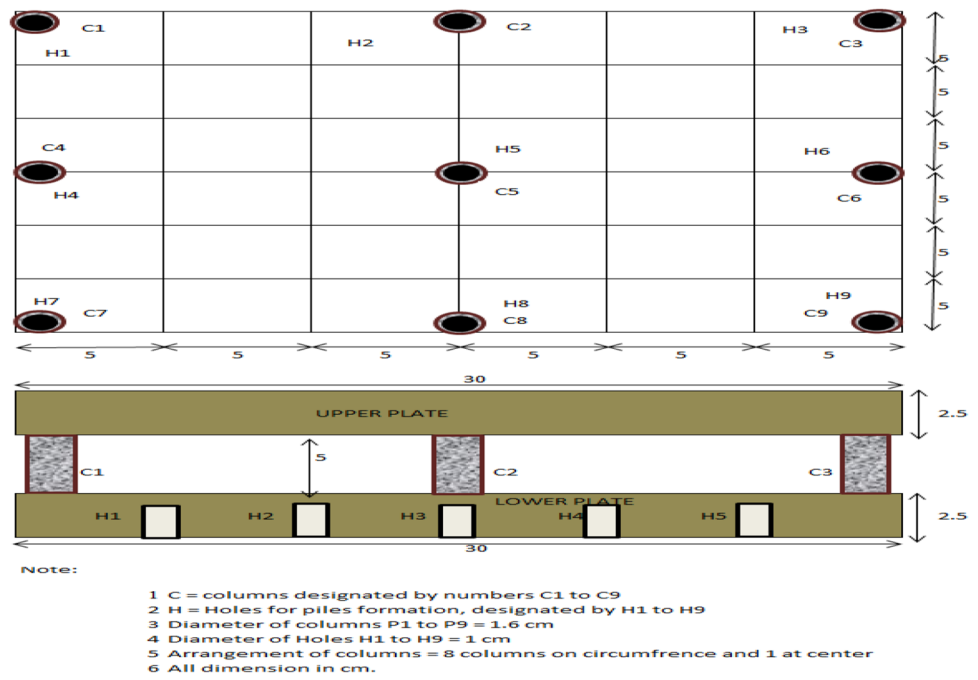
Fig. 4 Arrangement of pile in test series E

Table 2 Details of tests on raft and piled-raft foundation system

Test series	Foundation	Pattern of piles	Relative density (%)	Length of pile (mm)	Diameter of pile (ϕ) (mm)	No. of piles
A	Raft	–	40, 70	–	–	–
B	Piled-raft	P1	40, 70	200 and 600	10, 20	1
C	Piled-raft	P2	40, 70	200 and 600	10, 20	5
D	Piled-raft	P3	40, 70	200 and 600	10, 20	9
E	Piled-raft	P4	40, 70	200 and 600	10, 20	9

2. In case of piled-raft foundation, piles were connected to the model raft through the threaded holes provided at the bottom face of footing. On connected piles, the piled raft (the plate with attached piles) was pushed vertically initially by hand and then by the hydraulic jack in small increments. Great care was taken to keep the plate horizontal during pushing by applying the jack load on the centre of the plate until the plate was fully supported on the 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 ball bearings, bearing rods, and the load platform were placed and the load was applied by the hydraulic jack. The load was applied incrementally until reaching failure. Each load increment was maintained at a constant value until the model raft settlement had stabilized. Sand was exactly horizontal. Then, the raft model was placed on the sand surface and the horizontality of the raft model was adjusted by a level.

3. A vertical loading bar and a calibrated proving ring, of 100 kN maximum capacity, were connected to the hydraulic jack. The jack arm was lowered slowly toward the loading cap, until the dial gauge of the proving ring started to respond. The raft model was then loaded incrementally by using the hydraulic jack. The vertical settlements were recorded at the end of each load increment by the use of three dial gauge. The rate of loading was 0.1 kN/min. The loading was continued till the failure was not observed or till the length of jack.

Results and discussion

The experimental results obtained from the laboratory tests are analysed and discussed in this section. The shapes of the measured load–settlement curves indicate that the load at failure was not achieved. Therefore, the allowable and the ultimate raft capacities were determined from the load-average settlements curve at 30, 60, 90 and 120 mm, respectively. To express the data, non-dimensional parameters like
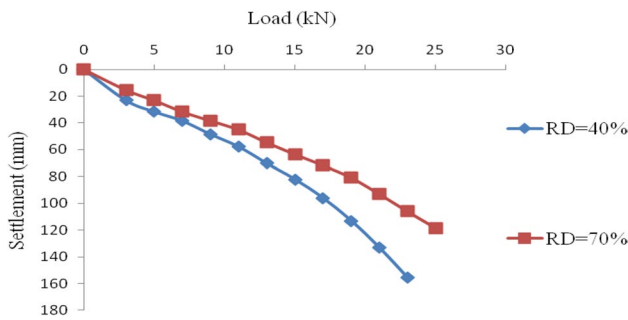
Fig. 5 Load–settlement behaviour of model raft foundation at different relative densities

improvement factor (IF) in percentage and settlement ratio (S/B) are used, where IF can be defined as factor which is the ratio of load-carrying capacity of piled raft at given settlement to the load-carrying capacity of raft at the same settlement. Settlement ratio is defined as the ratio of settlement of footing to width of footing.

Unpiled raft

Model tests were conducted on raft foundation at 40 and 70% relative density. As the density of soil increases the subgrade modulus of soil increases as result the stiffness of the soil increases. The load–settlement behaviour of unpiled-raft foundation at relative density of 40 and 70% is shown in Fig. 5. It is clear that the bearing capacity of the soil increases as the density of the soil increases. The percentage improvement in the bearing capacity of the soil is 63% when the density of soil changes from 40 to 70%.

Piled-raft foundation

The experimental tests were conducted on model piled-raft foundation by installing different number of piles of varying length and diameter at different configuration and the load–settlement curves of the model piled rafts were plotted as shown in Figs. 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30 and 31.
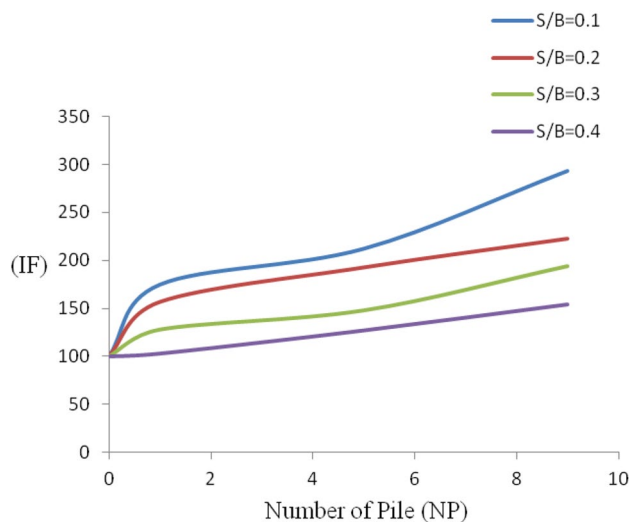
Fig. 6 Load–settlement behaviour of model piled-raft foundation at $L/B = 0.66$ and $\phi = 10$ mm

Fig. 7 Load–settlement behaviour of model piled-raft foundation at $L/B = 2$ and $\phi = 20$ mm
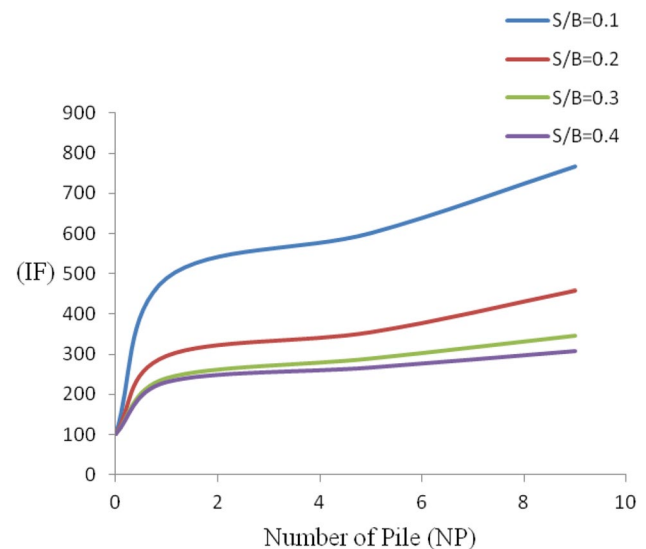
Fig. 8 Percentage improvement in bearing capacity of soil at RD = 40%, L/B = 0.66 and ϕ = 10 mm

Fig. 10 Percentage improvement in bearing capacity of soil at RD = 70%, L/B = 2 and ϕ = 20 mm
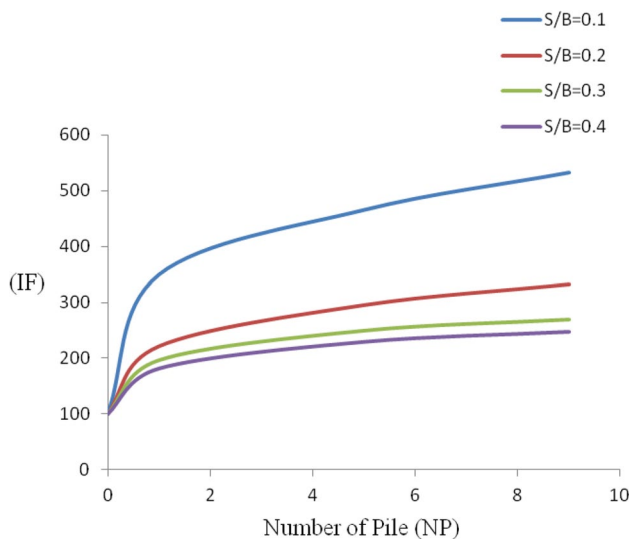
small number of piles increases the load-carrying capacity of the raft foundation, and this enhancement effect is greater for higher soil stiffness. Balasurbamaniam and Oh [41] observed that the maximum settlement of the piled rafts depends on the number of piles. The maximum improvement in the bearing capacity of soil at different number of piles is obtained at S/B = 0.1, as shown in Figs. 8, 9 and 10.

It is observed from Figs. 8, 9 and 10 that maximum improvement in the bearing capacity of soil takes place at S/B = 0.1; after that percentage improvement in the bearing capacity is reduced. From Figs. 11, 12 and 13, it is observed that as the number of piles, diameter of pile and length of piles increase, bearing capacity of soil increases. The maximum improvement in the load-carrying capacity of soil takes place at NP = 9, ϕ = 20 mm and L/B = 2 at relative density of 70%. At L/B = 2 and RD = 70%, the percentage improvement in the load-carrying capacity is 88% when the number of pile changes from 1 to 9. The increase occurred because the piles started interacting with the soil across a larger surface area and thus more load is carried by the piles.

Fig. 9 Percentage improvement in bearing capacity of soil at RD = 70%, L/B = 2 and ϕ = 10 mm

Effect of number of piles

Poulos [38] has observed that increasing the number of piles while generally is beneficial, does not always produce the best foundation performance and there is an upper limit to the number for piles beyond which very little additional benefit is obtained. Maharaj and Gandhi [39] has found that the addition of even a small number of piles increases the load-carrying capacity of a raft foundation. The axial load distribution shows that the piles reach their ultimate capacity earlier than the raft. Singh and Singh [40] have observed that the addition of even a

Effect of length of pile

Maharaj and Gandhi [39] has said that the effect of pile of length even equal to the diameter of the raft is found to reduce settlement of raft foundation significantly and also to increase load-carrying capacity. Such piles of smaller length can be used successfully as settlement-reducing piles in piled raft. For the same length of piles below raft, the improvement is more for smaller raft than that for the larger raft. Balasurbamaniam and Oh [41] had observed

Fig. 11 Percentage improvement in load-carrying capacity at RD = 40% and *L/B* = 0.66
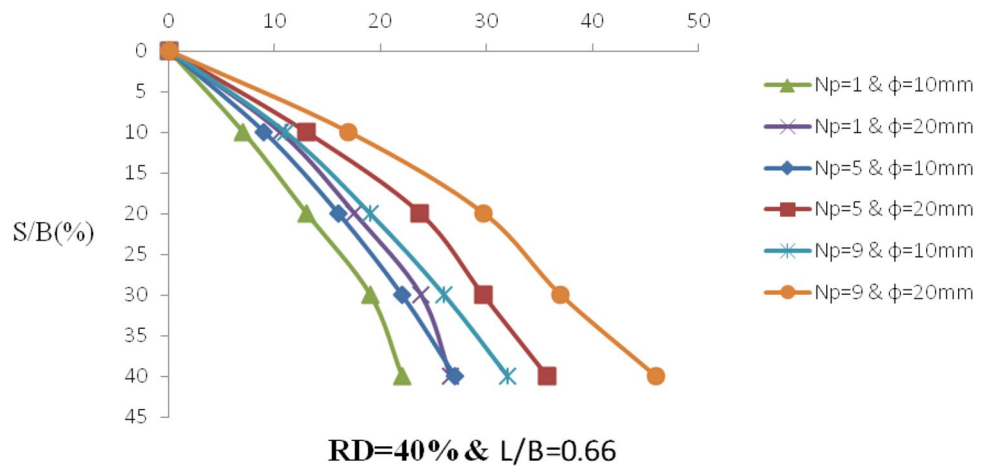

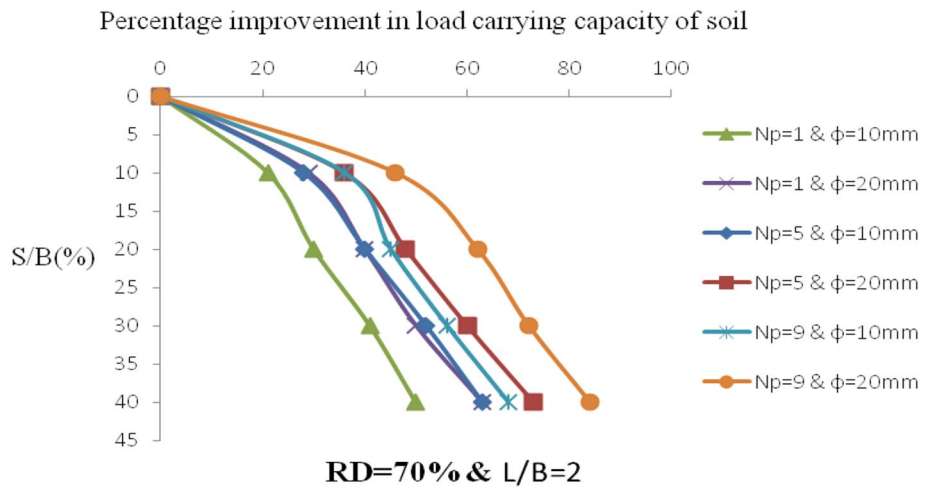**Fig. 12** Percentage improvement in load-carrying capacity at RD = 70% and *L/B* = 2

Fig. 13 Percentage improvement in load-carrying capacity at *L/B* = 0.66
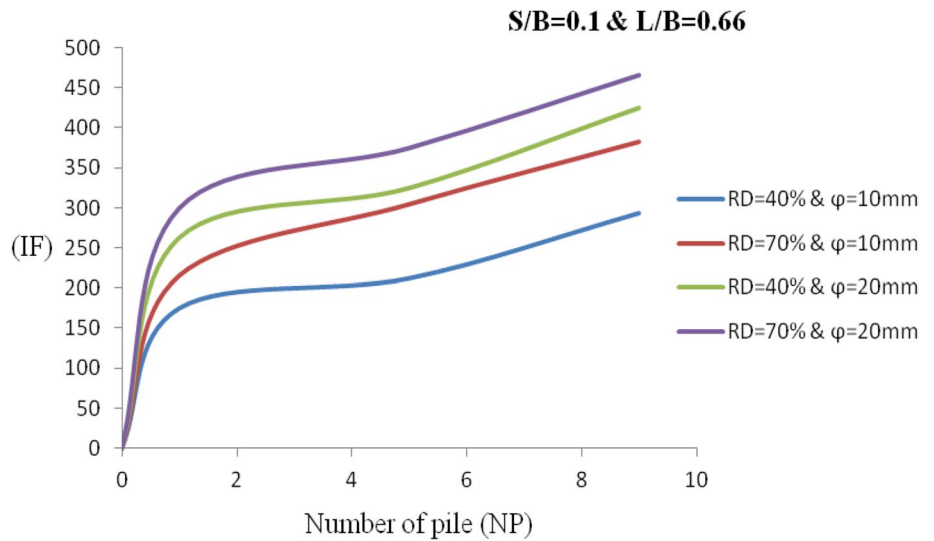
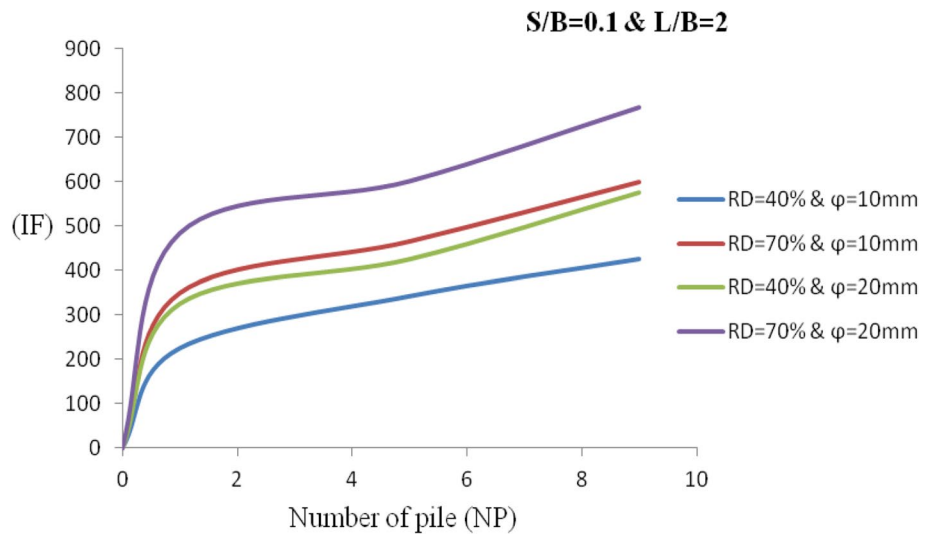**Fig. 14** Percentage improvement in load-carrying capacity at $L/B = 2$

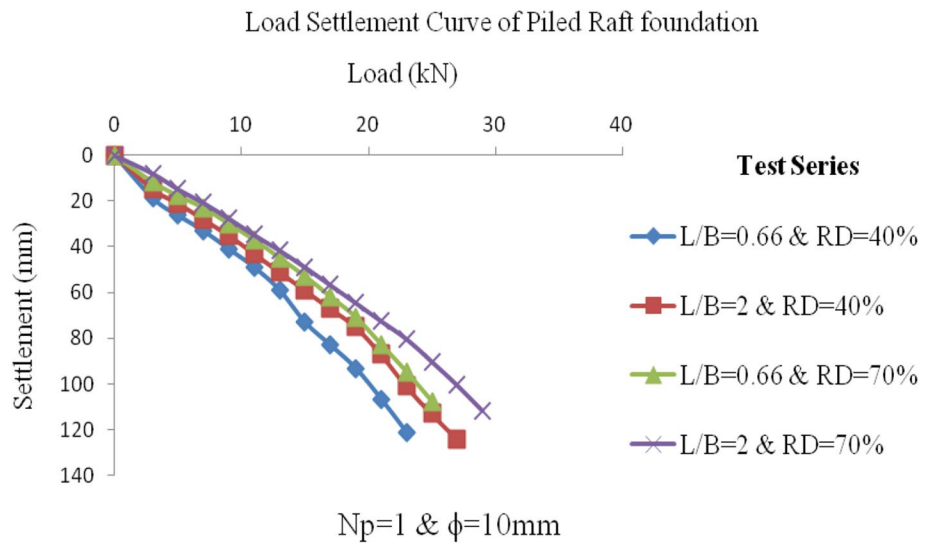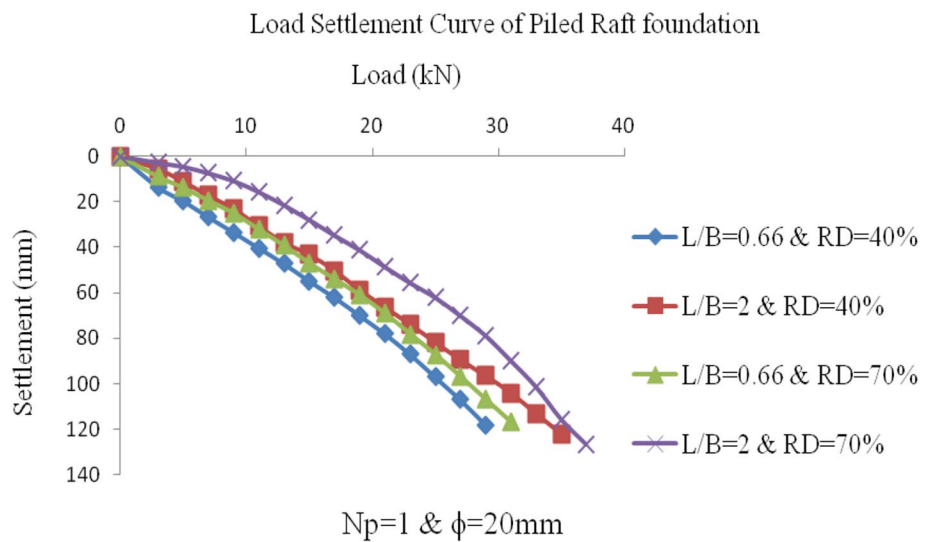**Fig. 15** Load–settlement behaviour of model raft foundation at NP = 1 and $\phi = 10$ mm

Fig. 16 Load–settlement behaviour of model raft foundation at NP = 1 and $\phi = 20$ mm

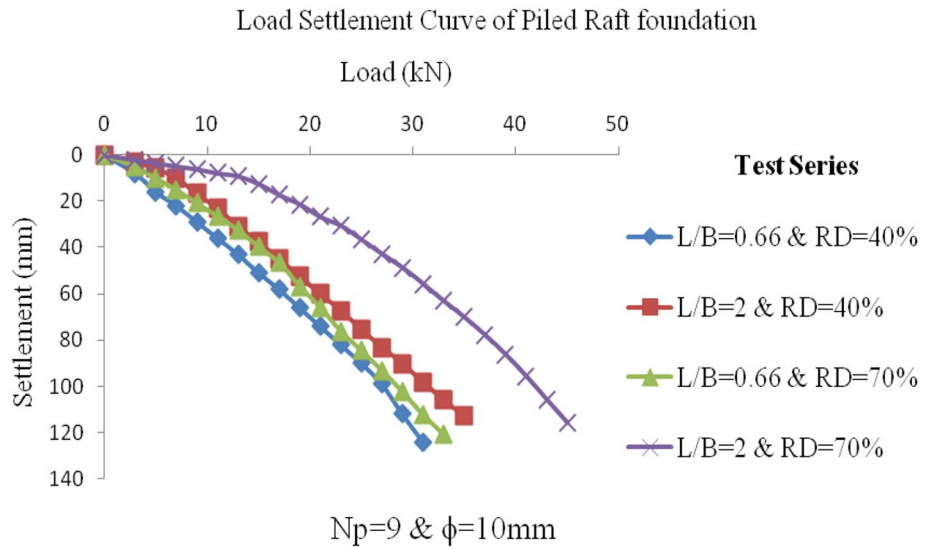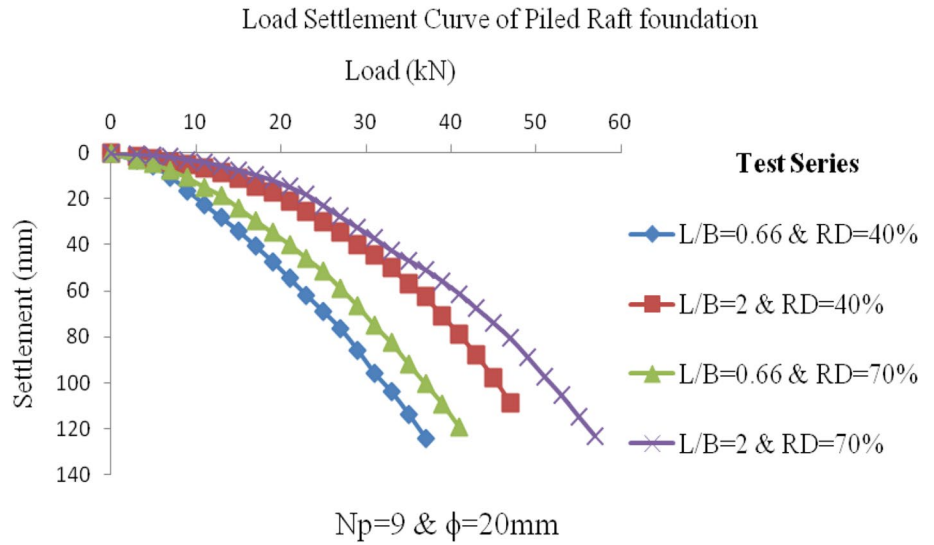**Fig. 17** Load–settlement behaviour of model raft foundation at NP = 9 and ϕ = 10 mm

Load Settlement Curve of Piled Raft foundation

Load (kN)

Settlement (mm)

Test Series

L/B=0.66 & RD=40%

L/B=2 & RD=40%

L/B=0.66 & RD=70%

L/B=2 & RD=70%

Np=9 & φ=10mm

Fig. 18 Load–settlement behaviour of model raft foundation at NP = 9 and ϕ = 20 mm

Load Settlement Curve of Piled Raft foundation

Load (kN)

Settlement (mm)

Test Series

L/B=0.66 & RD=40%
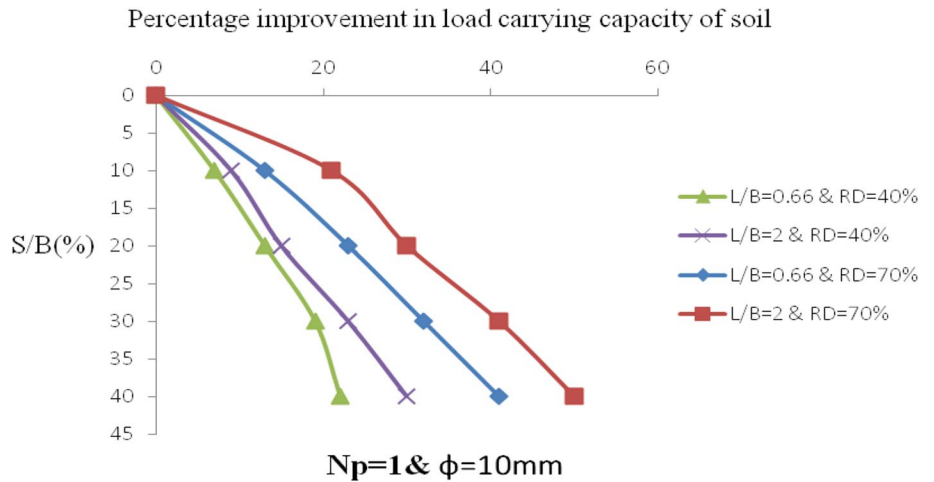
L/B=2 & RD=40%

L/B=0.66 & RD=70%

L/B=2 & RD=70%

Np=9 & φ=20mm

Fig. 19 Percentage improvement in load-carrying capacity at NP = 1 and ϕ = 10 mm

Percentage improvement in load carrying capacity of soil

S/B(%)

L/B=0.66 & RD=40%

L/B=2 & RD=40%

L/B=0.66 & RD=70%

L/B=2 & RD=70%

Np=1& φ=10mm

Fig. 20 Percentage improvement in load-carrying capacity at NP = 5 and ϕ = 10 mm

Percentage improvement in load carrying capacity of soil

Np=5 & φ=10mm

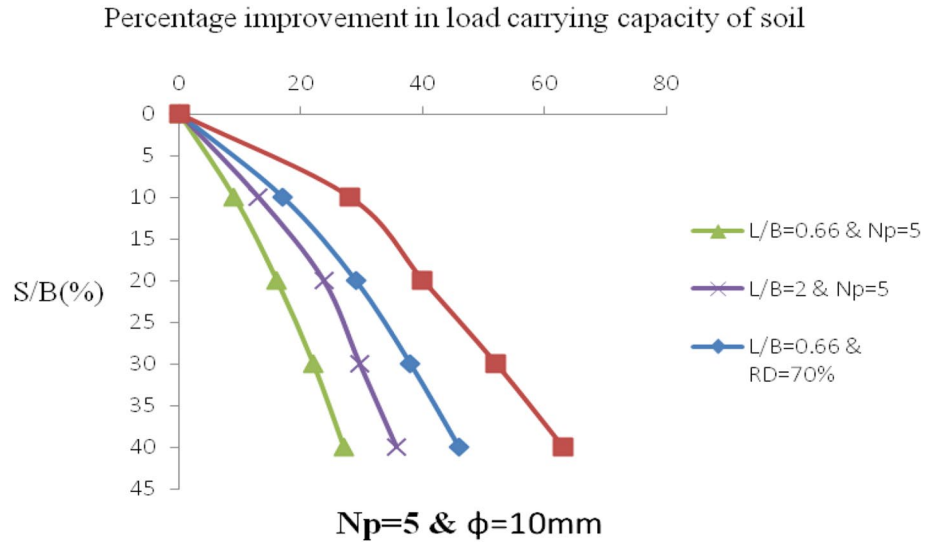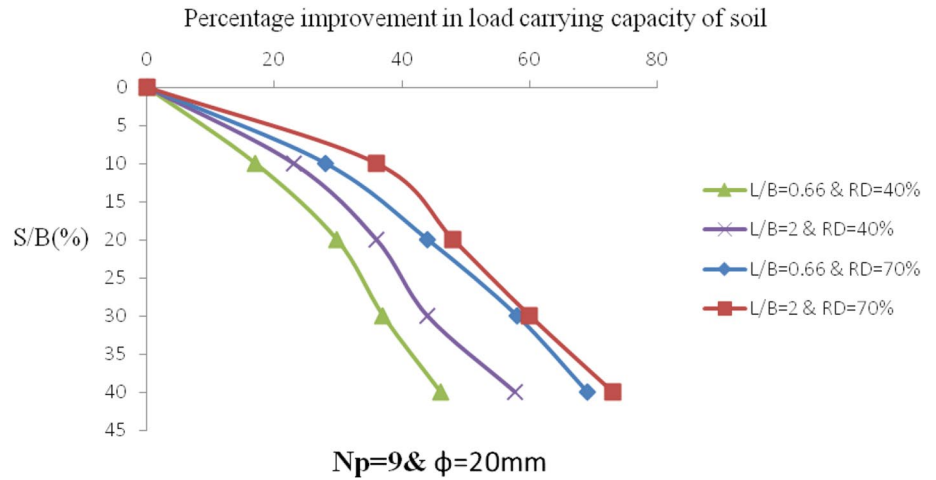**Fig. 21** Percentage improvement in load-carrying capacity at NP = 9 and ϕ = 20 mm

Percentage improvement in load carrying capacity of soil

Np=9& φ=20mm

Fig. 22 Load–settlement behaviour of model raft foundation at 10 mm diameter

Load Settlement Curve of Piled Raft Foundation
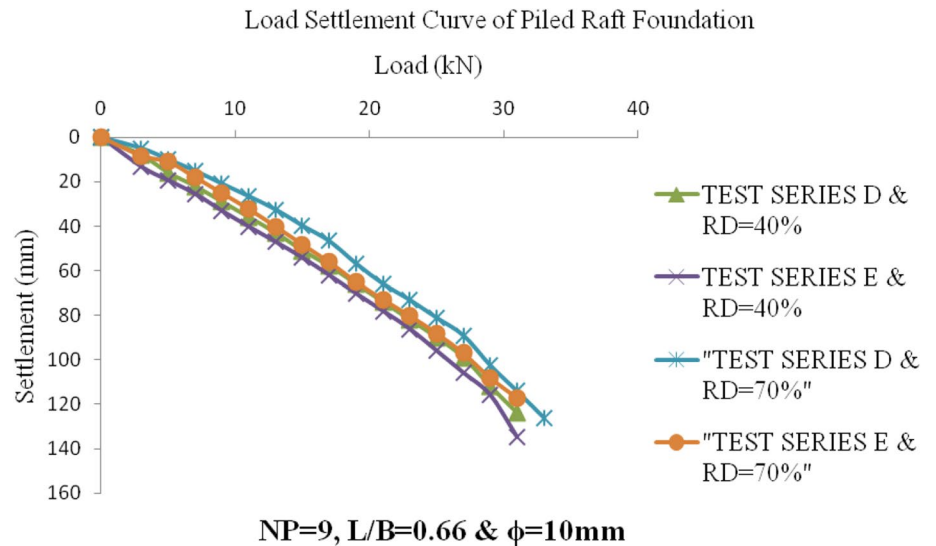
NP=9, L/B=0.66 & φ=10mm

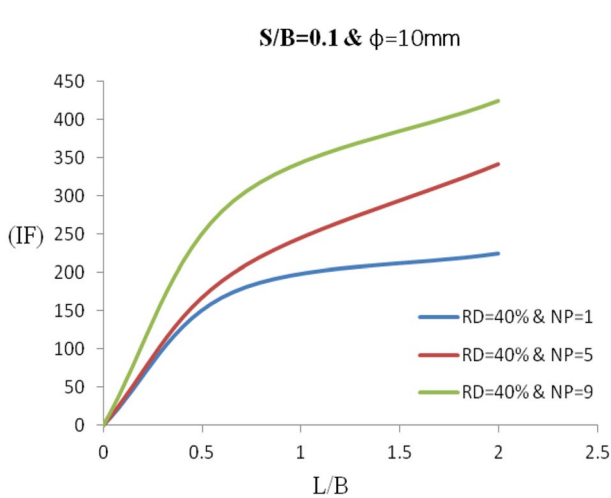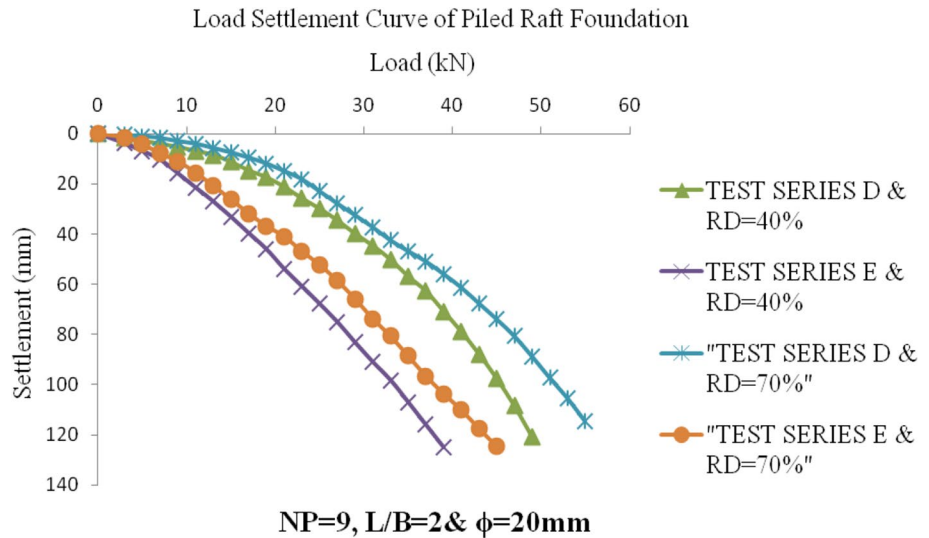**Fig. 23** Load–settlement behaviour of model raft foundation at 20 mm diameter

Fig. 24 Percentage improvement in load-carrying capacity at 10 mm diameter of pile
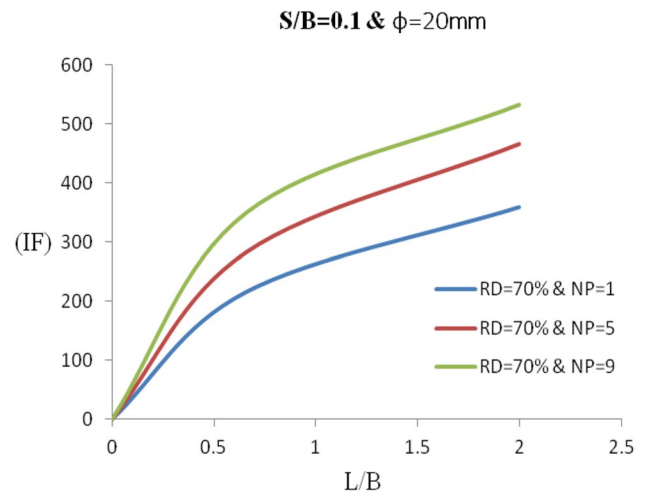

Fig. 25 Percentage improvement in load-carrying capacity at 20 mm diameter of pile

that, to reduce the maximum settlement of piled-raft foundation, optimum performance is likely to be achieved by increasing the length of the piles involved. Rabiei [42] had observed that maximum bending moment in raft increases with decrease in pile length.

It is observed from Figs. 15, 16, 17 and 18 that maximum improvement in the load-carrying capacity of soil takes place at $L/B = 2$. It is observed from Figs. 19, 20 and 21 the maximum reduction in the settlement take place at $S/B = 0.1$ after that percentage reduction in settlement of footing is reduced. At higher density and higher L/B ratio the maximum improvement in the bearing capacity of soil take place. The percentage improvement in load-carrying capacity of soil at 10 mm diameter of pile, NP = 9 and RD = 40% is 70% when L/B changes from 0.66 to 2.

Similarly for same diameter of pile, NP = 9 and RD = 70% the percentage improvement in bearing capacity of soil is 175% when L/B changes from 0.66 to 2.

Pile configuration

Poulos [17] has observed that for the control of differential settlement, optimum performance is likely to be achieved by strategic location of a relatively small number of piles, rather than using a larger number of piles evenly distributed over the raft area or increasing the raft thickness. Researchers have observed that performance of a piled-raft foundation can be optimized by selecting suitable locations for the piles below the raft. It is observed that the piles should be provided below the loaded area so that effective reduction in the settlement takes place. Also the spacing between the

Fig. 26 Percentage improvement in load-carrying capacity at RD=40% and *L/B*=0.66
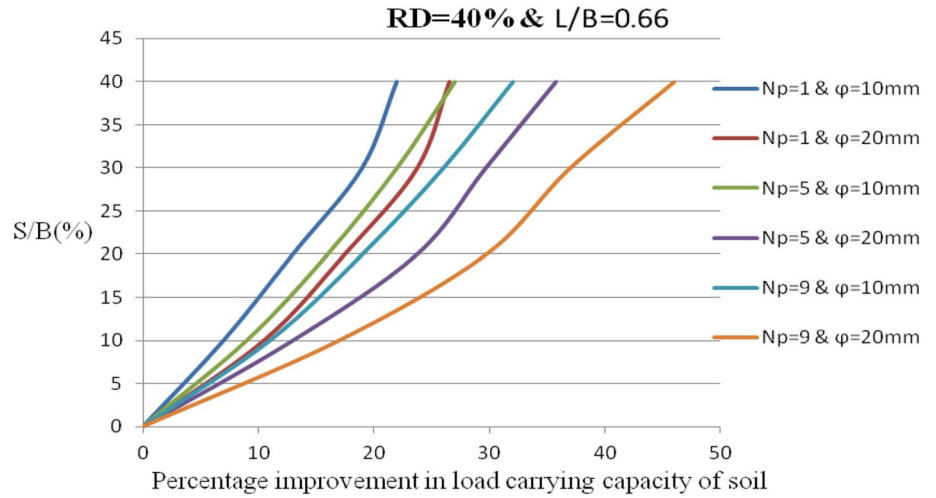

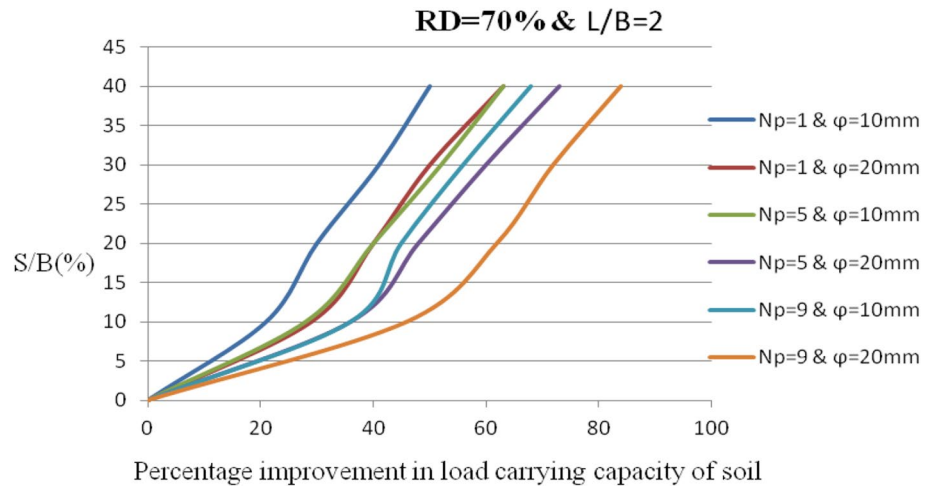**Fig. 27** Percentage improvement in load-carrying capacity at RD=70% and *L/B*=2

Fig. 28 Load–settlement behaviour of model raft foundation at different diameters of pile
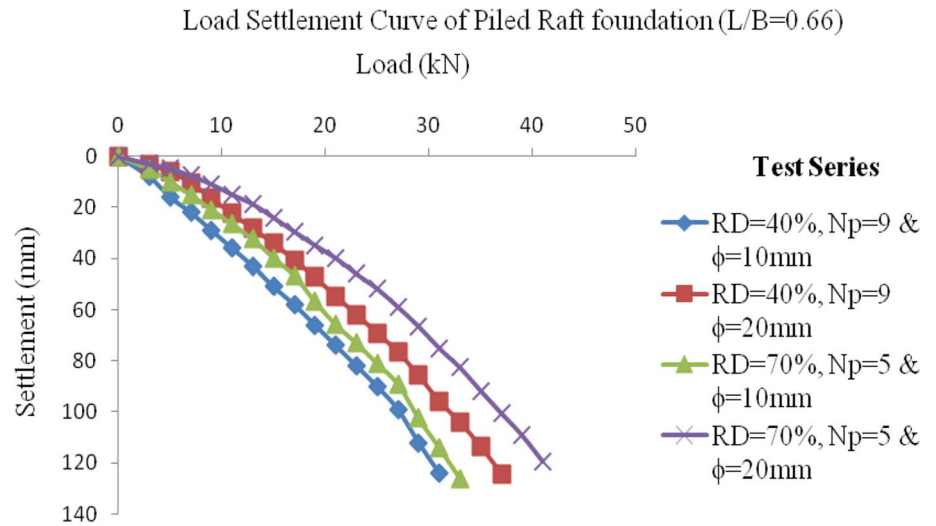
Fig. 29 Load–settlement behaviour of model raft foundation at different diameters of pile
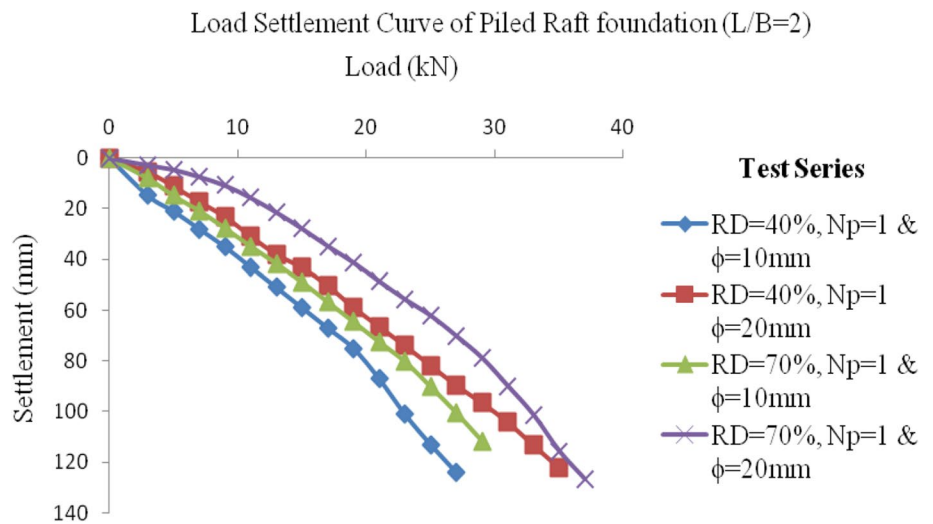

Fig. 30 Load–settlement behaviour of model raft foundation at different diameters of pile
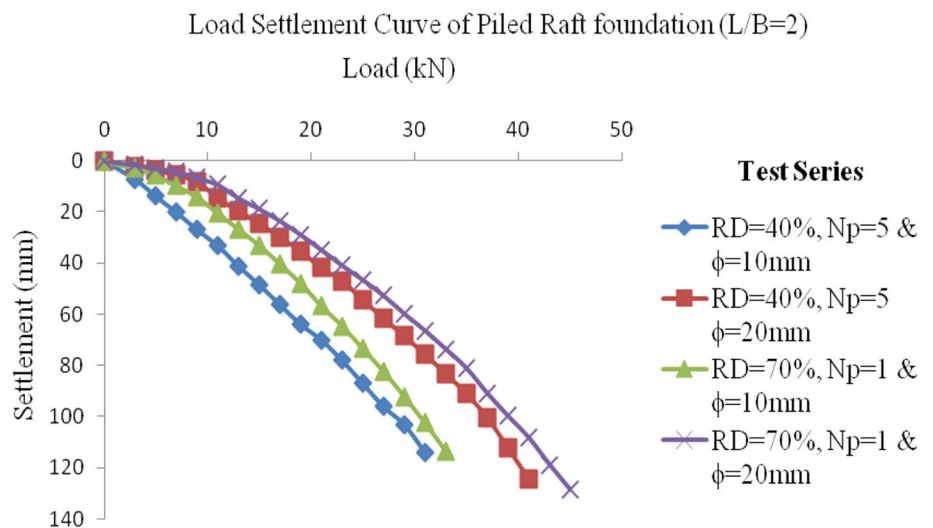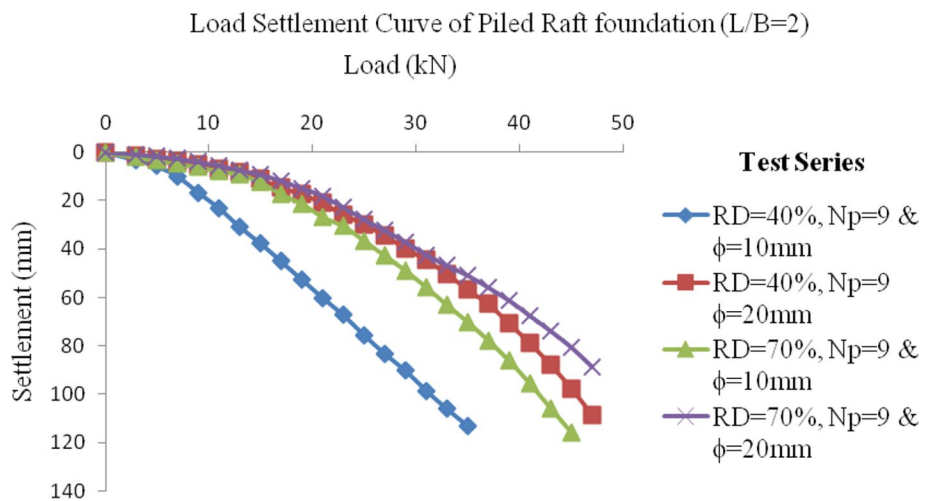

Fig. 31 Load–settlement behaviour of model raft foundation at different diameters of pile

piles should be optimum so that the number of piles can be reduced.

It is observed from Figs. 22 and 23 that as the spacing of pile is reduced, improvement in the load-carrying capacity of soil take place. In test series D the spacing provided between the piles is less as compared to test series E. In test series D the percentage improvement in load-carrying capacity is 70% while in test series E this value reduces to 57% as the spacing between the piles increases.

Effect of diameter of pile

The pile diameter has a significant effect on its load-carrying capacity and stiffness, which can affect the performance of the piled raft. As the pile diameter increases, the percentage of load taken by pile also increases. The increase occurred because the piles started to interact with the soil across a larger surface area and thus more load is carried by the piles. However, the effect of the pile diameter on the piles load share diminishes as the diameter reaches the higher end of the range considered.

The load–settlement curves from Figs. 28, 29, 30 and 31 show that as the diameter of pile increases the soil stiffness increases as a result bearing capacity of soil increases. The percentage improvement in the load-carrying capacity is 50% at NP = 1, RD = 40% and L/B = 0.66 when the diameter changes from 10 to 20 mm. Similarly when the RD = 70%, NP = 9 and L/B = 2, the percentage improvement in the load-carrying capacity is 76%. It is observed from Fig. 24 to 25 that the maximum improvement in the load-carrying capacity of soil takes place at S/B = 0.1.

Conclusions

The paper has presented experimental results of load tests on model rafts on settlement-reducing piles embedded in sand soil. Care has been taken during the modelling of the raft and piles so that the boundary effect has been reduced. The results of these model tests provide insight into settlement behaviour of rafts on settlement-reducing piles, and load sharing between piles and raft and may provide some general guidelines for the economical design of raft on settlement-reducing piles. It is observed that significant improvement is obtained at S/B = 0.1, beyond which the improvement is not so effective. Based on the results of model tests, the following conclusions have been drawn:

1. It has been studied from the tests result that in comparison to shallow (raft) foundations, piled rafts reduce the settlement effectively. The maximum reduction in the settlement take place at S/B = 0.1. It has been analysed from the test results that the maximum percentage improvement in the load carrying at NP = 9, L/B = 2, RD = 70% and diameter of pile (ϕ) = 20 mm is 105% when compared to unpiled raft at S/B = 0.1. This is due to the fact that in the load sharing behaviour of piled-raft foundation most of the load is to be taken by piles only.

2. As the numbers of piles are changed from 1 to 9 beneath the central area of the raft, the load-carrying capacity of the piled-raft foundation is increased. This increase occurred because the piles started to interact with the soil across a larger surface area and thus more load is carried by the piles. From the test results it was observed that the maximum improvement in the load-carrying capacity of soil is obtained when the number of pile is 9, density of soil is 70% and diameter of pile is 20 mm.

3. The load–settlement curves from Figs. 28, 29, 30 and 31 show that as the diameter of pile increases the soil stiffness increases as a result bearing capacity of soil increases. The percentage improvement in the load-carrying capacity is 50% at NP = 1, RD = 40% and L/B = 0.66 when the diameter changes from 10 to 20 mm. Similarly when the RD = 70%, NP = 9 and L/B = 2 the percentage improvement in the load-carrying capacity is 76%.

4. An investigation has been made to study the effect of pile arrangement on the behaviour of the piled-raft foundation. It has been found out that for optimum design, the pile group should cover the central 16–25% area of the raft. In test series D nine piles are arranged in the central area where in test series E the nine piles are arranged below the column. From the tests result shown in Figs. 22 and 23 it is observed that as the spacing between the piles reduces and the piles are more confined to central loaded area there will be an increase in the bearing capacity of the soil. The percentage improvement in the bearing capacity of soil is 57% in test series D as compared to test series E.

5. It was observed that, to reduce the maximum settlement of piled-raft foundation; optimum performance is likely to be achieved by increasing the length of the piles involved. From the test results shown in Figs. 13 and 14 the maximum increment in the improvement factor take places at S/B = 0.1, after that there will be reduction in the improvement factor take place. The percentage improvement in the load-carrying capacity at L/B = 2, RD = 70%, NP = 9 and diameter of pile is 20 mm is about to 75%.

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