Settlement of Model Pile Foundations In Sand

by

B.V. Ranganatham*

Shenbaga R. Kaniraj**

Introduction

Out of the two design criteria, namely, bearing capacity and settlement, the settlement considerations rather than the bearing capacity considerations generally govern the design of pile foundations in sand. The numerous, not too well understood and interdependent complex factors that play a role in the behaviour of pile groups in sand render an analytical approach to the problem of settlement very difficult. In the absence of rational analytical approaches, the problem, in practice, is surmounted by conducting a load test on a representative individual pile, the load-settlement data collected from such a test being extrapolated to comprehend the behaviour of pile groups. The two parameters commonly used to relate the behaviour of a single pile with that of a group are : (*i*) group efficiency η and (*ii*) settlement ratio (R_s). The usual definitions adopted for these two parameters are :

Group efficiency is the ratio of the ultimate load of the pile group to the ultimate load of a single pile multiplied by the number of piles in that group. Symbolically,

$$\eta = \frac{P_g}{N\,P_s} \qquad ...(1)$$

where P_g = ultimate load of the pile group

P_s = ultimate load of single pile

and N = number of piles in the group.

Settlement ratio is defined as the ratio of the settlement of the pile group to the settlement of the single pile at the same average load per pile. *Symbolically,*

$$R_s = \frac{\rho_g}{\rho_s} \qquad ...(2)$$

where ρ_g = settlement of group for a load of $(N \times p)$

and ρ_s = settlement of single pile for a load of p.

The group efficiency has been found to depend on the nature of the deposit and is slightly less than 1 in dense sand deposits and more than 1 in loose sand deposits. The determination or use of this parameter is only of

*Professor, Department of Civil Engineering, Indian Institute of Science, Bangalore-560012, India.

**Lecturer, Department of Civil Engineering, Indian Institute of Technology, New Delhi-110029, India.

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limited interest as it has been found in practice that it is invariably the settlement criterion which has a preponderance over the bearing capacity criterion. Thus settlement ratio assumes the role of important parameter and this ratio is in general greater than 1 for pile groups. This in other words means that the settlement of a pile group is more than the settlement of a representative single pile, for the same average load per pile. Skempton (1953) advanced a possible explanation for this behaviour of pile groups in sand. According to this theory, the large magnitude of the pressure bulb underneath a pile group and the high compressibility of the sand mass inside it in relation to that of a single pile contribute to the higher settlement of a group than that of a single pile for the same average load per pile.

In the past various investigators have tried to study the behaviour of pile groups in sand through experiments. Significant among them are the investigations of Press (1933), Cambefort (1953), Kezdi (1957), Stuart et al (1960), Berezantzev et al (1961), Hanna (1963), Schiff (1964), Kishida and Meyerhof (1965), Beredugo (1966), Vesic (1967) and Tjchman (1973). However, in many of the investigations the emphasis had been on the ultimate bearing capacity of groups rather than on the settlement of groups. It is also observed that a great many of the investigators have used very small size model piles in their studies. The extension of the results of those small scale laboratory tests to the prediction of the behaviour of pile foundations might give miseading information due to the unclarified scale effects between the model and prototype behaviour. In view of this, the only authentic test data available, particularly with respect to settlement under controlled conditions, seem to be due to Vesic (1967). He recommends to use piles of at least 3.75 cm diameter to get reliable data and has used 10 cm diameter piles in his investigations. But when viewed in the background of Skempton's theory of settlement of pile foundations in sand, the test results of Vesic can be seen to be beset with limitations. In the tests carried out by Vesic, the piles of a group were installed by pushing them into the sand as a whole and not one after the other. This procedure of installing the group as a whole not only differs from the standard field practice but also fails to simulate the mechanism of settlement suggested by Skempton. If the piles are installed individually the prestressed zone covers only the pressure bulb of each individual pile which is only a part of the pressure bulb of the entire group. But when the piles are installed as a group the entire soil mass inside the pressure bulb of the group gets prestressed. As a result, when loaded, the settlement of the groups thus installed would be smaller than the settlement of similar groups constructed by individual installation of piles. Thus the settlement ratio values observed by Vesic tend to be less than the actual values. As such, there is considerable scope for study of settlement behaviour of pile groups in sand.

Experimental studies on pile groups in sand

The experimental study has been undertaken chiefly with the view to investigate the interaction between the piles in a group and the consequent influence on the settlement of the group. Tests on 56 mm outer diameter GI model piles, in groups of two, three (equilateral triangle) and four (2^2) have been carried out for different spacings in each group with and without the pile cap resting on sand. The merit of the present investigation lies in the fact that the tests have been carried out in such a manner as to understand the behaviour of a pile in a group at various stages like, immediately after installation, prior to group loading and after group loading, so that a comprehensive picture of the settlement mechanism of pile foundations is obtained.

Test facility, equipment and materials : Galvanised iron pipes 56 mm outer diameter and 4.5 mm wall thickness were used as piles. The overall length of each pile was 105 cm and the embedded length inside the sand was 90 cm (L/D = 15). The bottom end of the pile was closed with a 6 mm thick flat mild steel plate. Pile caps were made of 12.5 mm thick mild steel plate. Figures 1 and 2 illustrate some of the accessories used in the investi-

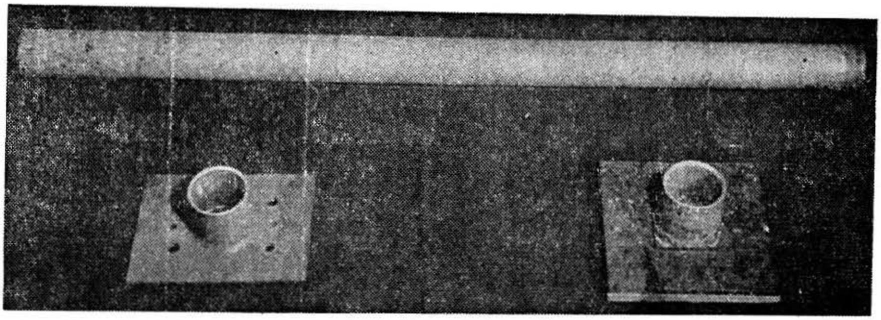


FIGURE 1 : Pile (top) Guide sleeve (left) Cap (right)

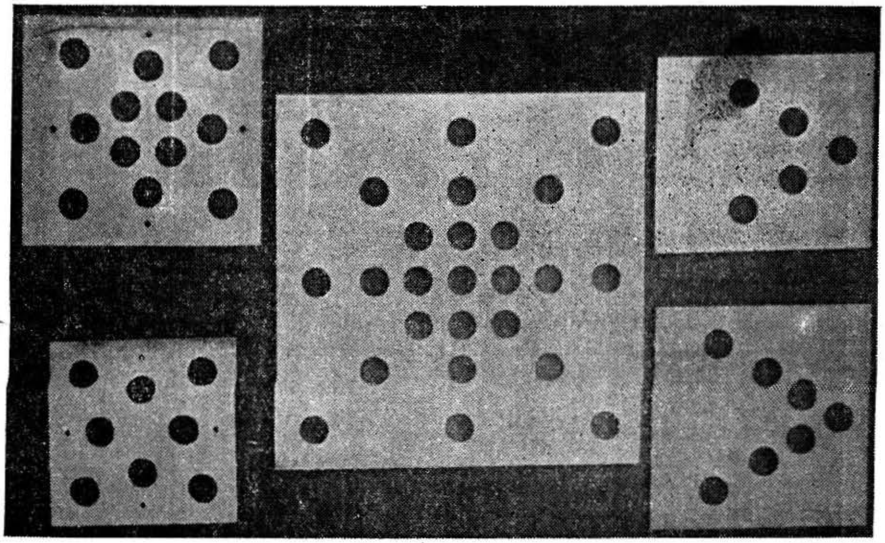


FIGURE 2 : Wooden templates

gation. Air dry river sand was used as the foundation medium, the gradation characteristics of which is as shown in Figure 3. The mechanical properties of the sand used are given in Table 1. Tests on piles and pile groups were carried out in a structure-soil interaction study test tank. The test tank 3.9 m × 3.9 m in plan and 2.1 m deep, has a self straining loading frame of 100 tons capacity. For the test on a 2^2 group in loose sand, a wooden

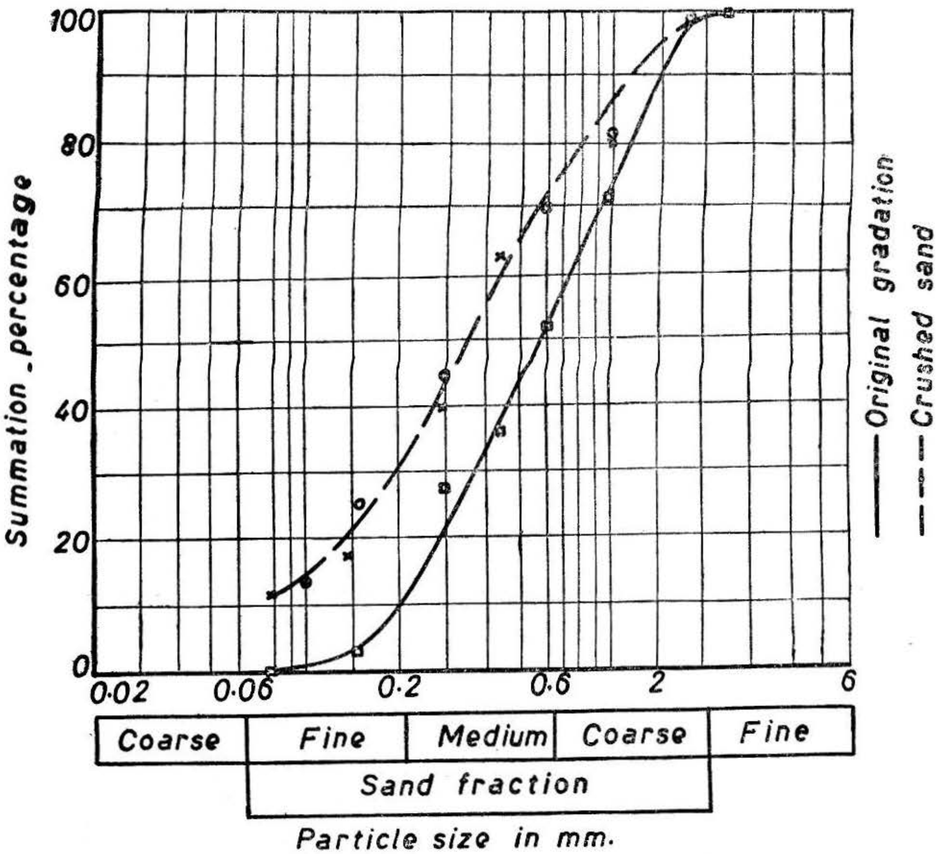


FIGURE 3 : Particle size distribution for sand (original and after crushing)

TABLE 1

Mechanical properties of sand

	Density gm/cc	*Void ratio*	ϕ*
Maximum values	1.74	0.85	48°
Minimum values	1.44	0.53	34°

* ϕ values calculated from direct shear tests without correcting for volume changes.

box made of 19 mm thick plywood sheets and of plan dimensions 1.125 m × 1.125 m was prepared. The total height of the box was 1.95 m which was fabricated in two sections of 97.5 cm each. An assembly of a drum fitted with a funnel at the bottom and a flexible rubber hose emanating from the stem of the funnel was used to pour the sand in a loose condition inside the box. The entire set up of the wooden box and the drum assembly is shown in Figure 4. The investigations consisted of the sequence of preparing the sand bed to the required density, constructing the pile groups on this sand bed by pushing the individual piles into sand using a hydraulic jack and carrying out the planned programme of testing.

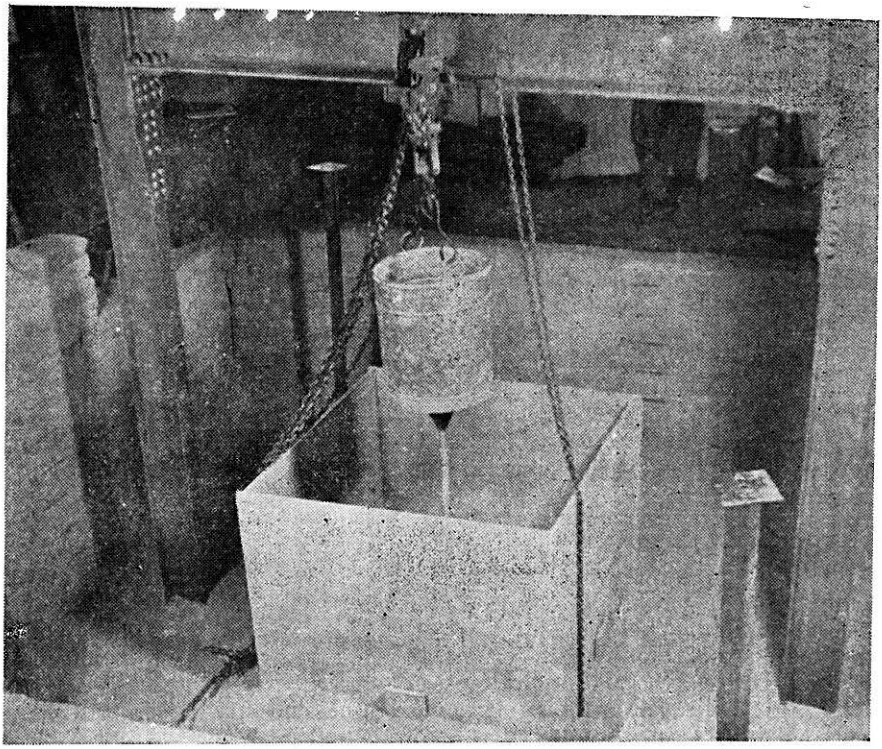


FIGURE 4 : Set up for test in loose sand

Sand bed preparation: The dense sand bed was prepared in layers of 17.5 cm thickness up to a total depth of 1.925 m. A weighed quantity of sand was poured in from top for each layer which was then levelled and compacted with the aid of an earthmaster. The earthmaster is a manually operated device in which a free falling weight of 7.9 kg imparts a blow on a base plate of dimensions 25 cm × 20 cm. The height of drop of the weight is 57.5 cm. After the levelling operation of the sand surface, 25 earthmaster blows were delivered at any one place to compact the sand. The thickness of the compacted layer was then measured at several points. A fairly uniform thickness of 17.5 cm obtained for each layer indicated a uniform compaction of the foundation medium. The density of the sand bed was calculated from the known quantities of weight and thickness of sand for each layer and the floor area of the tank. The average density of the sand bed thus prepared was 1.6 gm/cc which corresponds to a relative density of 60 per cent. In all five such sand bed preparations were required for the investigations apart from the single sand bed prepared for the test in loose sand in the manner explained below.

The sand bed preparation in loose condition was confined to a central area of 1.125 m × 1.125 m of the tank. After the test tank was completely emptied of sand a hollow wooden box of plan dimensions 1.125 m × 1.125 m and height 97.5 cm was placed centrally in the tank. Weighed quantities of sand were poured in a drum assembly (Figure 4). The sand inside the drum flows into a funnel at the bottom of the drum and through a flexible rubber hose attached to the stem of the funnel. The flowing sand was poured inside the wooden box keeping the mouth of the hose always a little above the sand surface at any place. The drum assembly can be moved either up or down or moved laterally using a chain and pulley block system shown in Figure 4. When a layer of loose sand was built up to a thickness of about 30 cm the thickness of the layer was measured at 32 grid points and the average value considered for density calculations. Before the filling up operation of the next layer was started a sand layer 30 cm thick (without any consideration to its density) was built up outside the box on the entire area of tank taking care not to disturb the sand in loose condition inside the box. The sand was just poured from the top and levelled but no compaction was done. In this manner the sand bed inside and outside the box was built up progressively and the tendency of the box to yield under either the inside or outside lateral pressure was prevented. When the sand layer thickness reached near the top of the first box, the second section of the wooden box was placed exactly over the first box and the operations were continued. The loose sand thus prepared had an average density of 1.51 gm/cc which corresponds to a relative density of 26 per cent.

Test procedure and programme

The test programme consisted of carrying out a series of tests on pile groups varying certain of the factors that influence the pile group behaviour like (*a*) number of piles in a group, (*b*) spacing of piles, (*c*) nature of pile cap either free standing or resting on sand and (*d*) density of sand, all these variations being adopted for a constant pile length of 90 cm (L/D = 15). The entire test programme is tabulated in Table 2. In order to facilitate presentation the test series has been classified into two as (*i*) tests on free standing groups and (*ii*) tests on groups with pile cap resting on sand. In general, any pile group covered in the test programme was constructed by installing each pile individually, one after another, using a hydraulic jack to push the pile into sand. Figures 5 and 6 show the details of individual pile installation process. Figure 7 illustrates how the correct configuration for a 2^2 group was possible using a template. Further, immediately after a pile was pushed in to the required length it was subjected to an axial load test only after which the installation of the next pile was taken up.

Free standing groups: After the construction of the entire pile group a pile cap made of two 6 mm thick steel plates was laid over the pile heads projecting above the sand surface. Metal plate stiffeners were added in order to impart rigidity to the pile cap and a load test on the pile group was then carried out. The load test thus conducted is nearer to the actual field behaviour of a free standing pile foundation. After the first load test on the group the load on the pile group was released and the load test on the pile group was repeated. This second load test on the group may be considered akin to those carried out by Vesic (1967).

Whereas the above procedure was adopted for groups of two piles and three piles (FS1, FS2, FS3, FS4, FS5, FS6, FS7, FS8), a slight difference in the testing procedure was adopted for tests on 2^2 groups. Two series of tests were carried out on 2^2 groups in medium dense sand and one test was carried out on a 2^2 group in loose sand. In the case of medium dense sand, in order to investigate the influence of installation operations of adjacent piles on the load-settlement behaviour of the earlier installed piles, in the

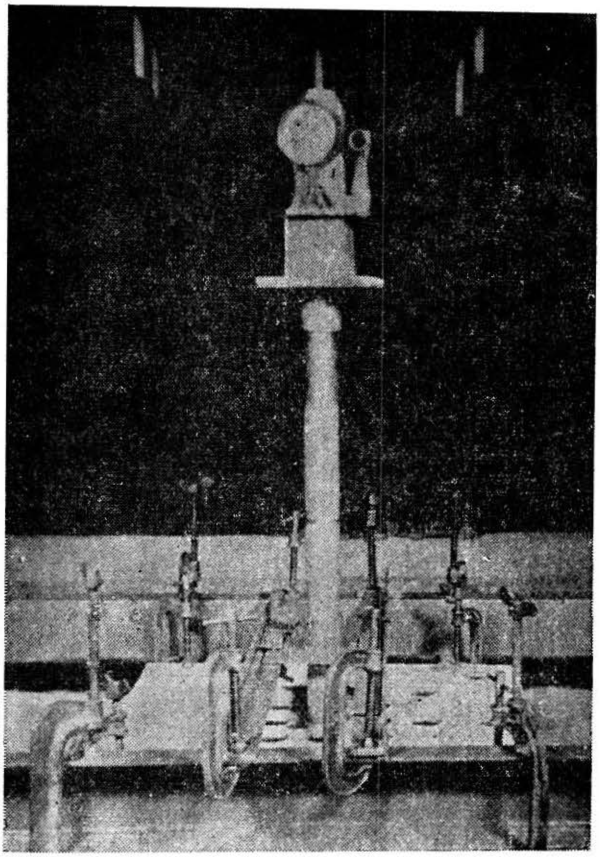


FIGURE 5: Procedure of single pile installation

first of the two series (FS9, FS10, FS11), after the construction of each group and before the load test on that group a second load test on each individual pile of the group was carried out in the order of installation of the piles. After this second load test on each pile, the group load tests were carried out. This series will be referred to as A-series. In the second series of tests on 2^2 groups in medium dense sand (FS12, FS13, FS14), the construction of the groups and the load tests were carried out in the same manner as for the two pile and three pile groups i.e., without subjecting the individual piles to a second load test prior to group loading. But in this series in order to investigate the load-settlement behaviour of individual piles in a group after group loading, each pile in the group was subjected to a reload test in the order of their installation after the load tests on the group. The second series will be referred to as B-series.

In the case of tests carried out in loose sand (LF 18), the group was constructed in the regular manner except that measurements were also made for the vertical movement of earlier installed piles during the installation of latter piles. After the group construction and prior to the group loading, each individual pile of the group was subjected to a second load test in the order of installation. Following this the group load tests were

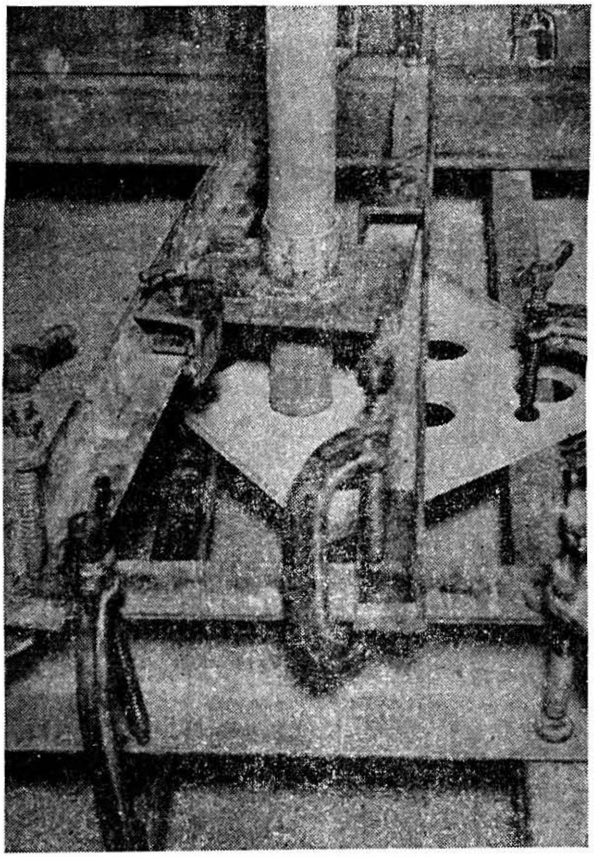


FIGURE 6: Details of single pile installation using guide sleeve and wooden template

carried out and after the group load tests a load test on each pile was again carried out in the order of their installation.

For the tests on two-pile and three-pile groups the different spacing of piles adopted were 2D, 3D, 4D and 5D and for the series of tests on 2^2 group in medium dense sand the spacings adopted were 2D, 3D and 4D. For the test on the 2^2 group in loose sand a spacing of 3D was adopted. The order of installation of the piles had been kept the same for all the 2^2 groups and is as shown in Figure 8.

Groups with pile cap resting on sand : In this series, with a fixed spacing of 3D for all the pile groups, one test was carried out on each of a two-pile group (CR 15), a three-pile group (CR 16) and a 2^2 group (CR 17). Since the same piles which had been used for the tests on free standing groups were used in this series also in order to have the same L/D ratio of 15, pre-cast concrete blocks with vertical holes at the appropriate locations were used to serve as integrated spacers for pile caps (Figure 9). Observations were also made for the vertical movement of the earlier installed piles in a group during the installation of the latter piles of that group. After the construction of the group the concrete block was inserted and rested on sand. Then the entire top surface of the concrete blocks was

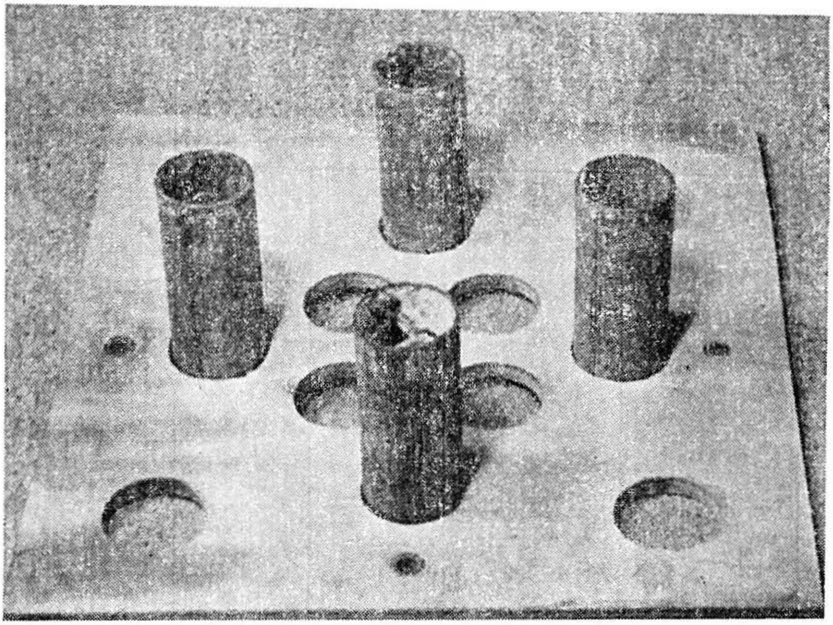


FIGURE 7 : Configuration of 2^2 pile group using wooden template

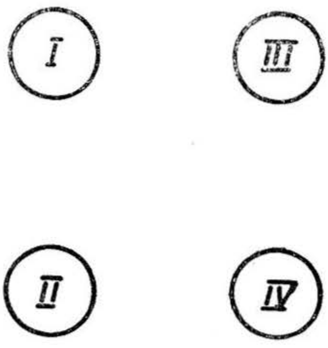


FIGURE 8 : Order of installation of piles for 2^2 groups

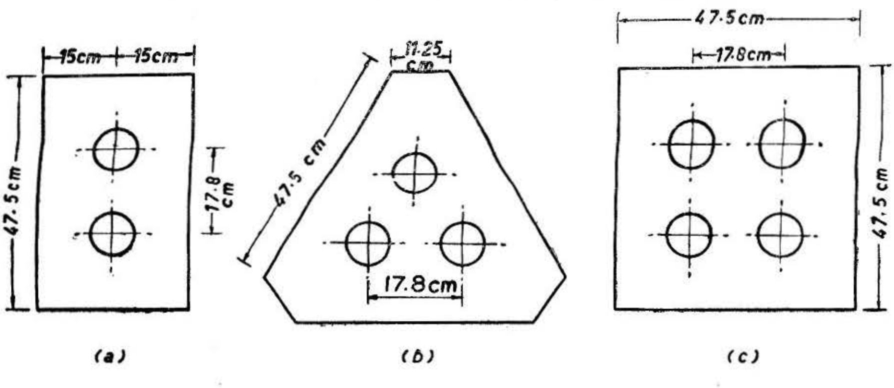


FIGURE 9 : Concrete block details

TABLE 2

Test Programme

Sl. No.	Test No.	No. of piles in group	Spacing of piles	Pile cap details	Density state of sand
1	FS1	2	2D	Free	Medium Dense
2	FS2	2	3D	Free	Medium Dense
3	FS3	2	4D	Free	Medium Dense
4	FS4	2	5D	Free	Medium Dense
5	FS5	3	2D	Free	Medium Dense
6	FS6	3	3D	Free	Medium Dense
7	FS7	3	4D	Free	Medium Dense
8	FS8	3	5D	Free	Medium Dense
9	A-series FS9	4 (2^2)	2D	Free	Medium Dense
10	A-series FS10	4 (2^2)	3D	Free	Medium Dense
11	A-series FS11	4 (2^2)	4D	Free	Medium Dense
12	B-series FS12	4 (2^2)	2D	Free	Medium Dense
13	B-series FS13	4 (2^2)	3D	Free	Medium Dense
14	B-series FS14	4 (2^2)	4D	Free	Medium Dense
15	CR15	2	3D	Piled	Medium Dense
16	CR16	3	3D	Piled	Medium Dense
17	CR17	4 (2^2)	3D	Piled	Medium Dense
18	LF18	4 (2^2)	3D	Free	Loose

Note: The plan configuration of the three pile group is equilateral traingle.

covered with steel plates and group load tests were carried out as explained for the free standing groups. After the group load tests the concrete block was removed and a load test on each pile of a group, in the order of installation was carried out in order to investigate the post-group loading load-settlement behaviour of the individual piles of the group. The order of installation of the 2^2 group is shown in Figure 8.

At two different times when the sand was being removed after tests for the next tank filling, two samples of crushed sand were recovered at the level of the pile tips. These samples were collected in medium dense sand beds. The details of the test results and their analysis are presented in the following section.

Test results

Free standing groups: Typical load test data on a single pile and on a 2-pile group in medium dense sand are presented in Figure 10. The curve

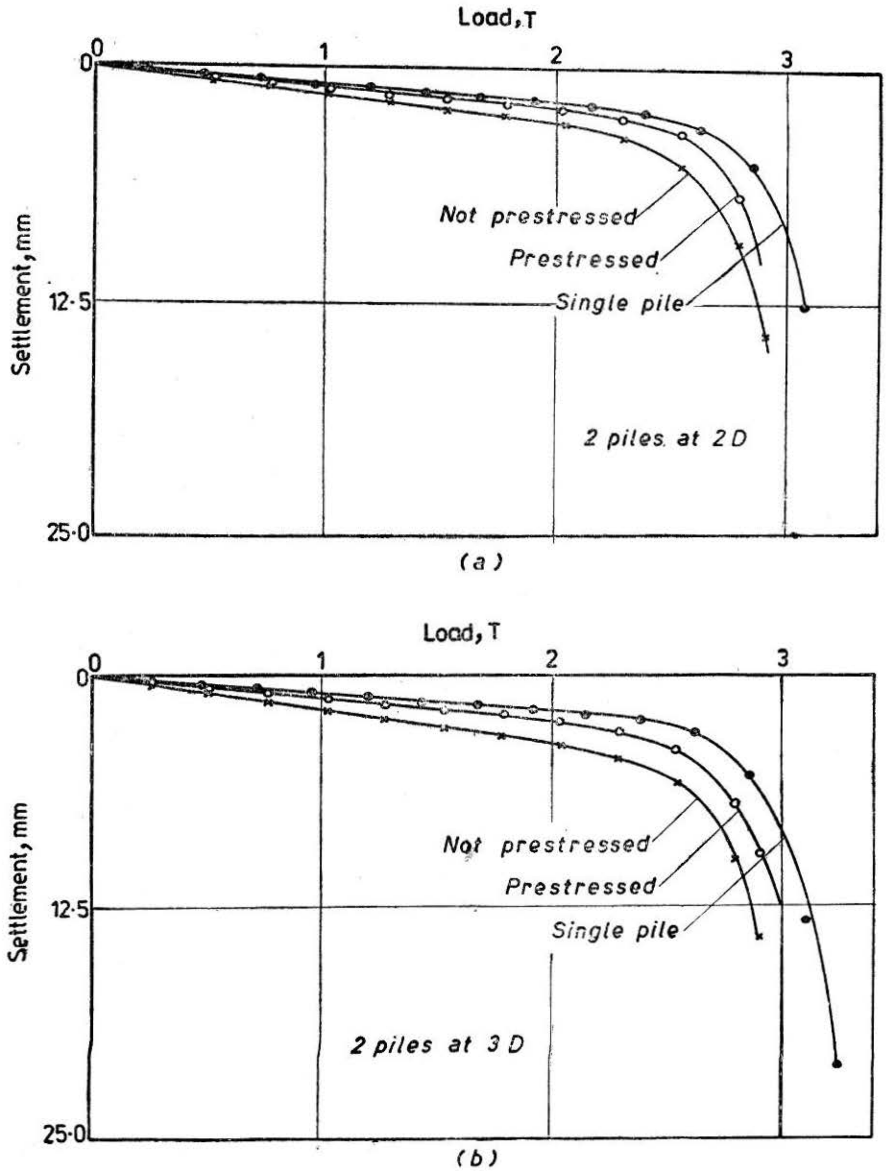


FIGURE 10 (a and b) : Load-settlement curves for 2-pile groups (FS1 and FS2)

marked *single pile* represents the load-settlement behaviour of the first pile (in the group) immediately after its installation. The behaviour of the first pile is considered to represent that of the test pile since the behaviour of the first pile immediately after installation is akin to that of an exploratory test pile in that there are no interference effects due to the installation of other piles. The curves marked *not prestressed* and *prestressed* represent the load-settlement behaviour of a hypothetical single pile of the group during the first and second group load tests respectively. The load on the hypothetical single pile is obtained by dividing the group load by the number of piles in the group and its settlement is that of the group. The curves are so designated because immediately after the construction of the driven pile group, according to Skempton (1953), the compressibility of the sand inside the pressure bulb of the pile group is more than that of the sand inside the pressure bulb of the single pile. This is because the sand inside the pressure bulb of the single pile has been already stressed during the installation of the single pile. This prestressing of sand, however, does not extend to the bulb of the group and is limited only to the zone of individual piles. The sand inside the bulb of the group is thus not in a prestressed state when the group is loaded first and hence the designation of *not prestressed* for this load-settlement curve. However, on the removal of the applied load much of the compressibility characteristics of the sand remains. Thus the sand inside the pressure bulb of the group is in a prestressed state during the subsequent reloading operations and hence the designation of *prestressed* for this load-settlement curve. A similar representation of the data on the free standing 2^2 group in loose sand is shown in Figure 11. The behaviour of the group in relation to that of a single pile with respect to both settlement and ultimate load and the effect of the group load test on the behaviour of the group during subsequent reloading is also evident in these representations.

Figures 12*a* to 12*d* show the load-settlement behaviour of a pile in a 2^2 group of the A-series immediately after its installation and its behaviour after the completion of the installation of all the piles in that group, each figure giving the details for one pile. These figures bring out the influence of installation of subsequent piles on the load-settlement behaviour of earlier installed piles. Figures 13*a* to 13*d* show the load-settlement behaviour of a pile in a 2^2 group in B-series immediately after installation and its behaviour after the completion of the group load tests on that group, each figure giving the data for one pile. In Figures 14*a* to 14*d* are presented the load-settlement behaviours of a pile in the 2^2 group tested in loose sand, immediately after installation, after the completion of installation of all the piles and after the completion of group load tests. The observations made for vertical movement of already installed piles in this test showed that practically no movement took place due to the installation of other piles.

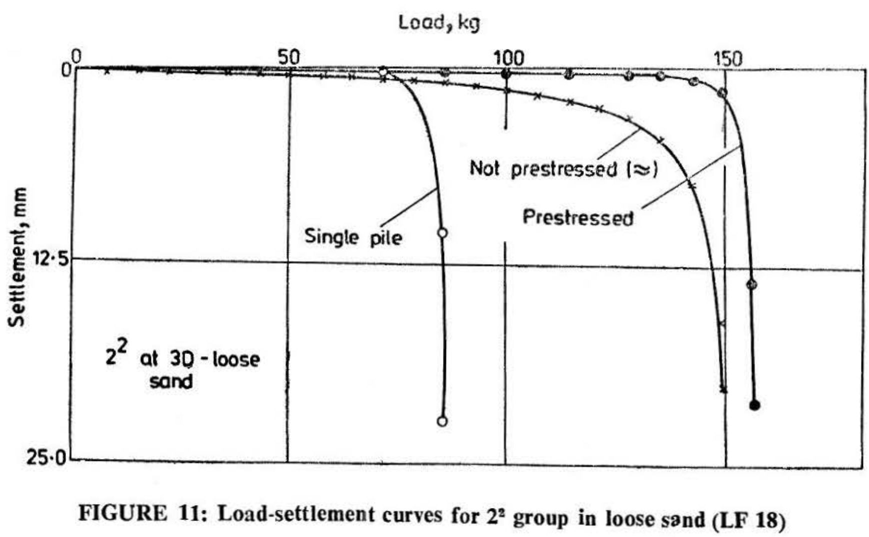
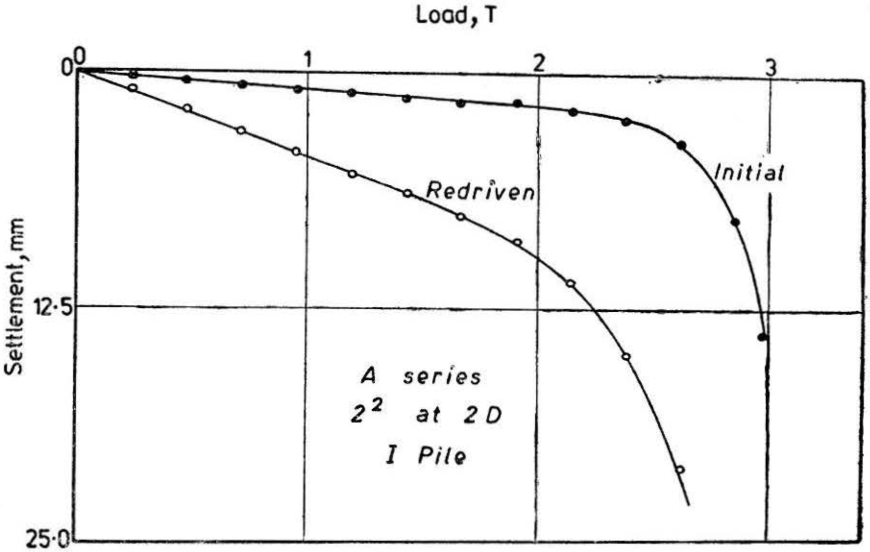
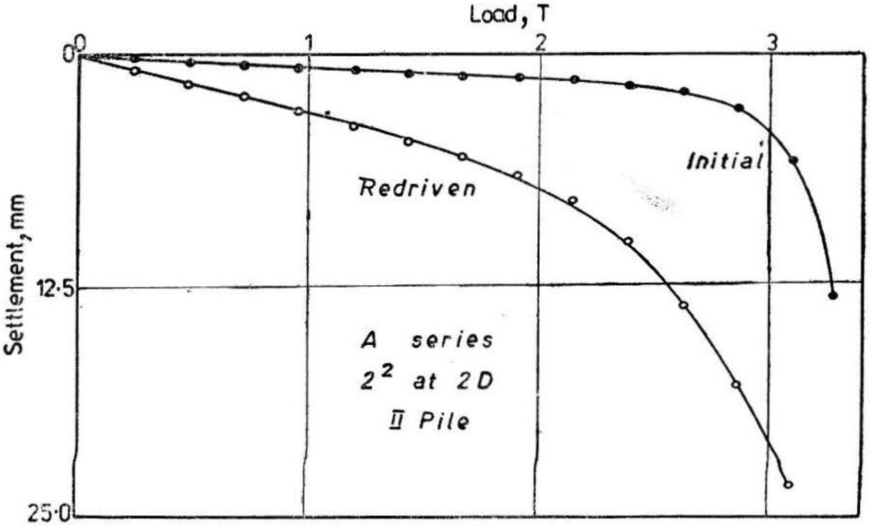


FIGURE 11: Load-settlement curves for 2^2 group in loose sand (LF 18)



(a)



(b)

FIGURE 12 (a & b): Load-settlement curves for piles after installation and after group cons truction (FS 9)

Groups with pile cap resting on sand: The comparison of the behaviour of the 3-pile group with that of the first installed single pile of the group is shown in Figure 15 in a manner similar to that explained for free standing groups. The observations for vertical movement of piles showed uplift of the earlier installed piles to take place during the installation of the latter piles and these data for the 3-pile group are reported in figure 16.

Crushing of sand: The gradation characteristics of the crushed sand

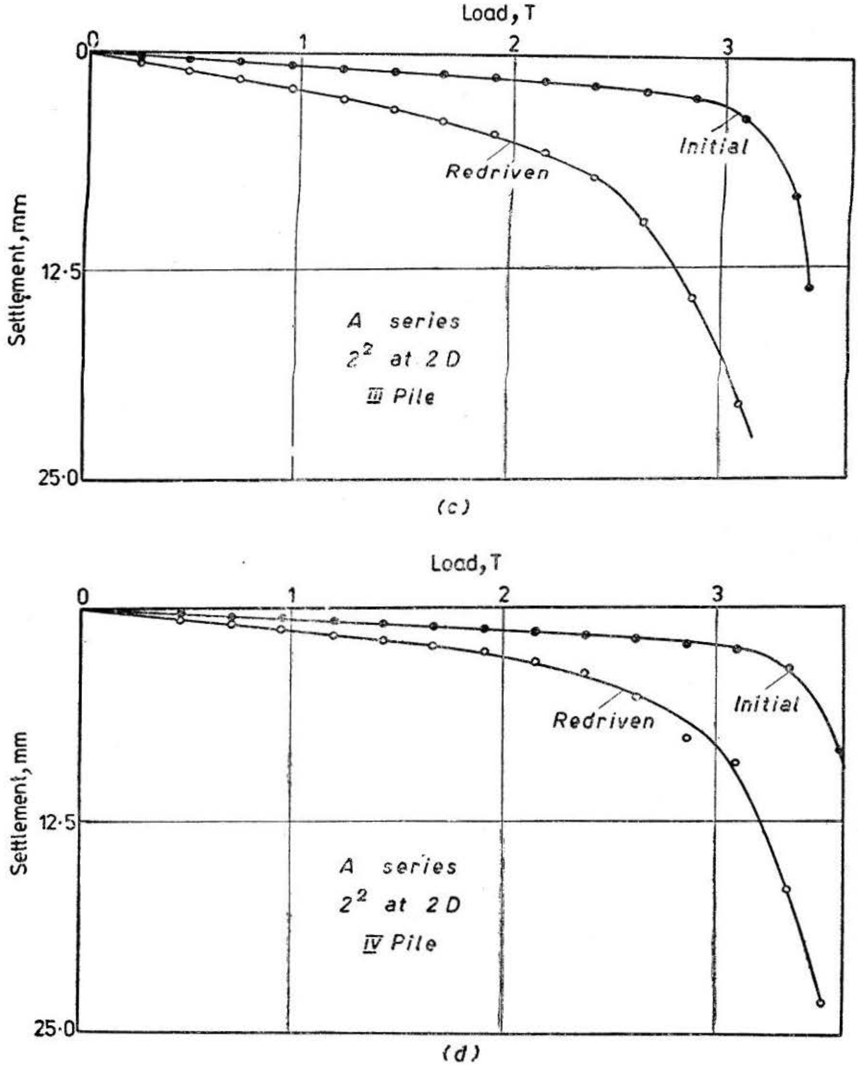


FIGURE 12 (c & d): Load-settlement curves for piles after installation and after group construction (FS 9)

specimen have been analysed and compared with the original gradation characteristics in Figure 3.

Analysis of test results

Free standing groups in medium dense sand: It is readily seen from Figure 10 that the pile groups settle more than the test pile (first pile) for the same average load per pile. Also the group efficiencies are found to be less than 1. These figures also bring out that the first loading of the group causes a distinct reduction in the settlement response of pile groups for the subsequent reloading. Calculations for settlement ratio for the first and second load tests on the pile groups and the reduction in settlement ratio owing to the first load test on the groups have been made and

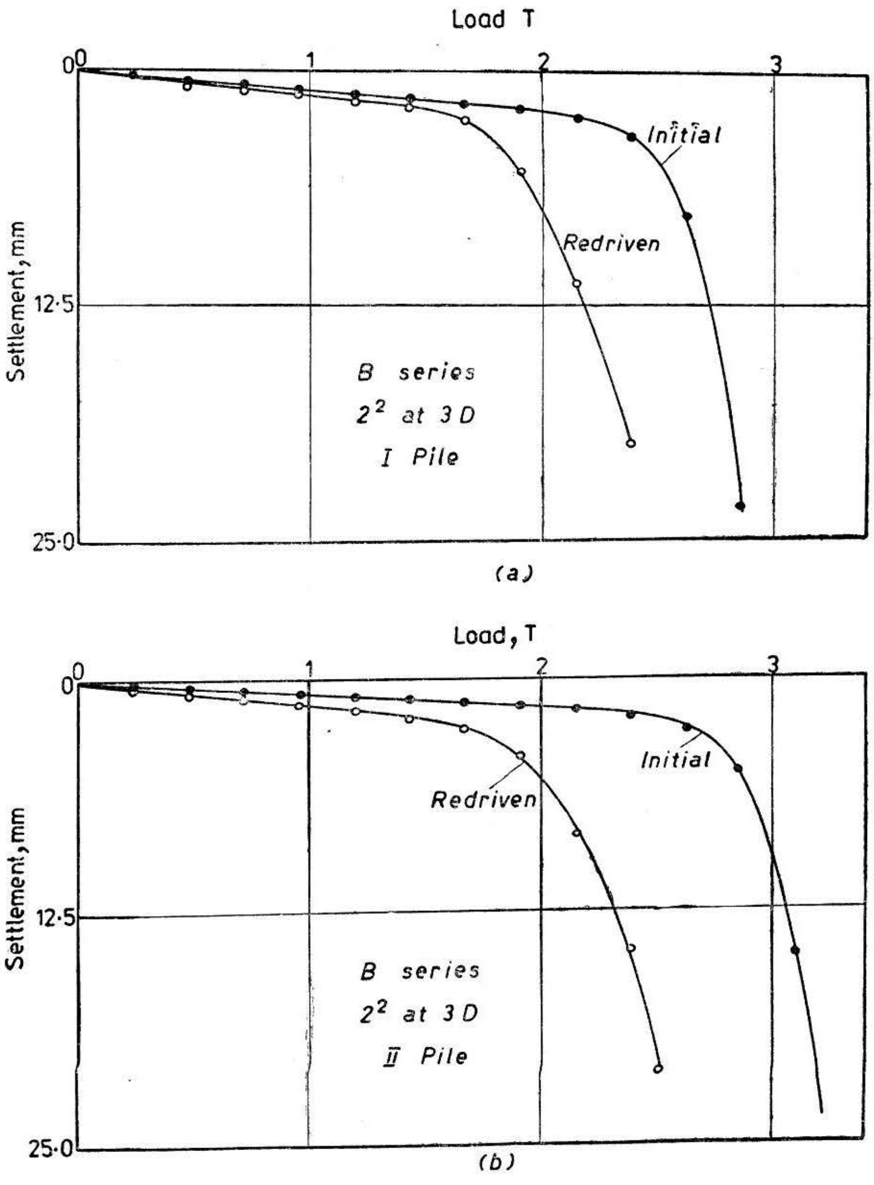
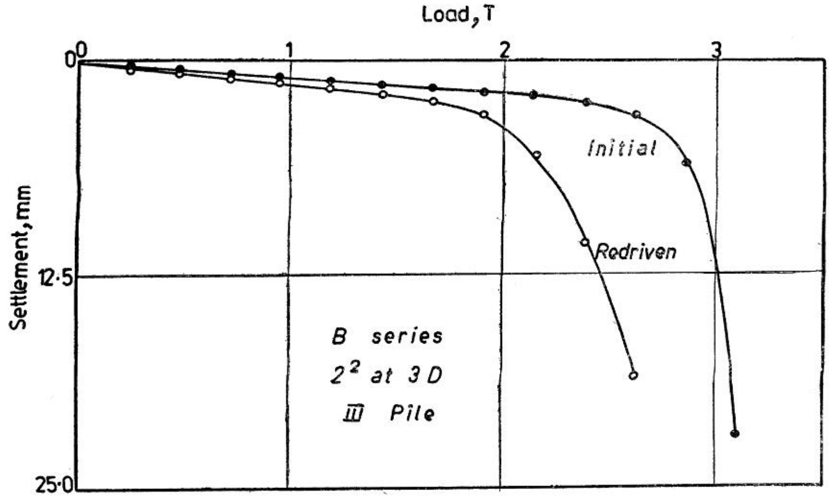
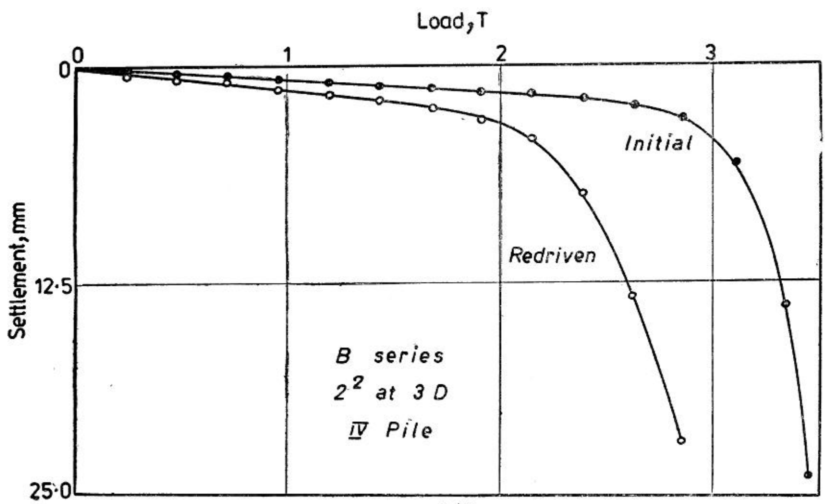


FIGURE 13 (a & b): Load-settlement curves for piles after installation and after group tests (FS 13)

are reported in Table 3. The settlement behaviour is analysed in terms of the slope of the initial (more or less linear) portion of the load-settlement curve (expressed in units of mm/tonne) since this is reasoned out to represent the settlement response of a pile foundation under working load condition. By this it follows that the settlement ratio is the ratio of the slope value of the hypothetical single pile to that of the test pile. With the limited test data, the inferences tend to be qualitative.



(c)



(d)

FIGURE 13 (c & d): Load-settlement curves for piles after installations and after group tests (FS 13)

As the number of piles in a group increases, there is a tendency for the settlement ratio to increase under similar conditions. As the spacing increases, the settlement ratio generally tends to decrease indicating the decreasing interaction between/among piles. Comparison of the test results for A- and B-series of tests on 2^2 group indicates clearly the reduction in the settlement ratio of A-series and this is due to redriving of piles prior to conducting group load test which operation should have counteracted part of the installation effects. The settlement ratios for the reload tests on pile groups being less than those of the first load tests on pile groups (on an average reduction of about 35 per cent) will also show that part of installation effects is counteracted by the first load test on group in addition to prestressing the soil in the pressure bulb underneath the pile group.

TABLE 3

Settlement Ratios for Free Standing Groups in Medium Dense Sand

Group No.	Slope of load-settlement curve for first pile (test pile) mm/tonne ×10⁻²	Slope of load-settlement curve for hypothetical pile mm/tonne×10⁻²		Settlement Ratios		Reduction in settlement ratio per cent $\frac{(5)-(6)}{(5)}\times 100$
		First test on group (Not prestressed)	Reload test on group (Prestressed)	First test on group (Not prestressed) (3)/(2)	Reload test on group (Prestressed) (4)/(2)	
(1)	(2)	(3)	(4)	(5)	(6)	(7)
FS1	91.07	142.28	102.14	1.56	1.12	28.76
FS2	95.77	186.16	118.90	1.94	1.24	36.08
FS3	107.60	180.41	116.27	1.68	1.08	35.71
FS4	115.52	134.15	—	1.16	—	—
FS5	86.64	219.04	127.27	2.53	1.47	42.06
FS6	91.07	187.16	115.40	2.06	1.27	38.54
FS7	101.14	182.04	105.02	1.80	1.04	42.22
FS8	106.77	188.79	116.15	1.77	1.09	41.98
FS9	91.07	132.90	116.32	1.46	1.28	12.33
FS10	115.40	144.90	116.27	1.26	1.01	19.84
FS11	90.57	148.53	119.52	1.64	1.32	19.57
FS12	97.02	187.54	127.52	1.93	1.31	32.12
FS13	101.02	182.54	138.28	1.81	1.37	24.31
FS14	94.52	225.04	139.03	2.38	1.47	38.24

Assuming that the redriving of the individual piles in A-series fully counteracts the installation effects, the reduction in settlement ratio in A-series due to first load test on a pile group (on an average about 17 per cent) could be construed as that due to prestressing the soil in the pressure bulb underneath the pile group. On this basis it can be inferred that the role of prestressing of sand mass as well as that of installation operation in effecting reduction of settlement ratio will be more or less of the same extent.

From Figures 12*a* to 12*d* it is seen that the installation of piles greatly affected the load-settlement behaviour of already installed piles. It brought about a considerable increase in their settlement response and a significant reduction in their ultimate load. In order to comprehend the magnitude of increase in settlement, the slope values of the initial linear portions of the load-settlement curves of the first load test immediately after installation and the second load test after the installation of all the piles in the group are compared. The ratio of this slope value of the second load test to that of the first load test of each pile is a measure of the influence of the installation of subsequent piles on its settlement. This ratio is referred to as *Influence Ratio (in settlement) due to Installation*, I_{RI}. From I_{RI} values it is observed that even a small penetration as 2.5 cm of the first three piles, which takes place during the second load tests on them, affects the settlement behaviour of the lastly installed (fourth) pile. It is seen that the settlement

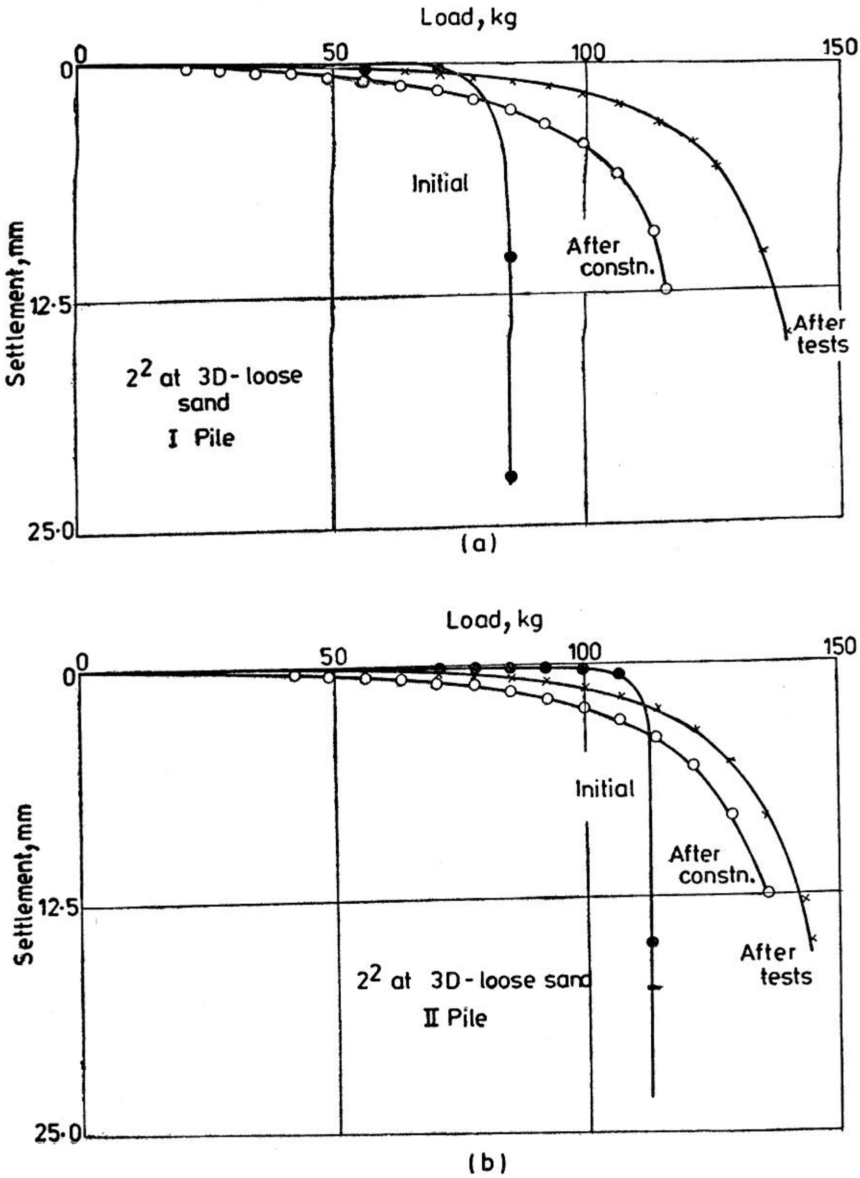
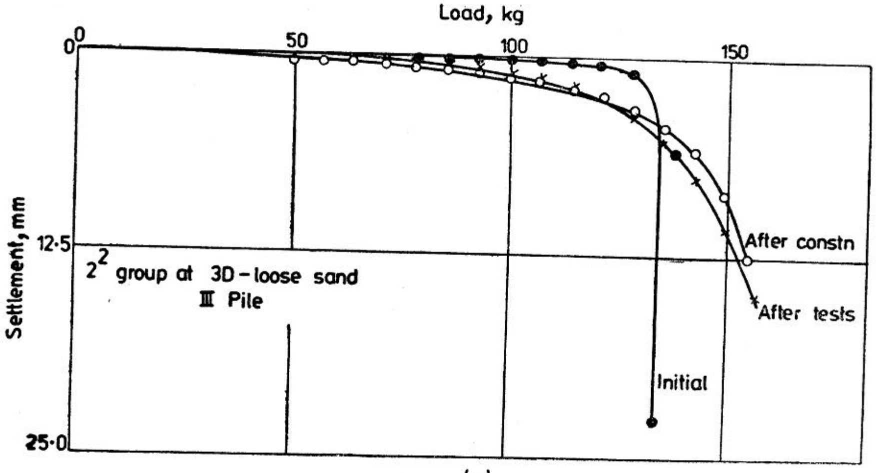
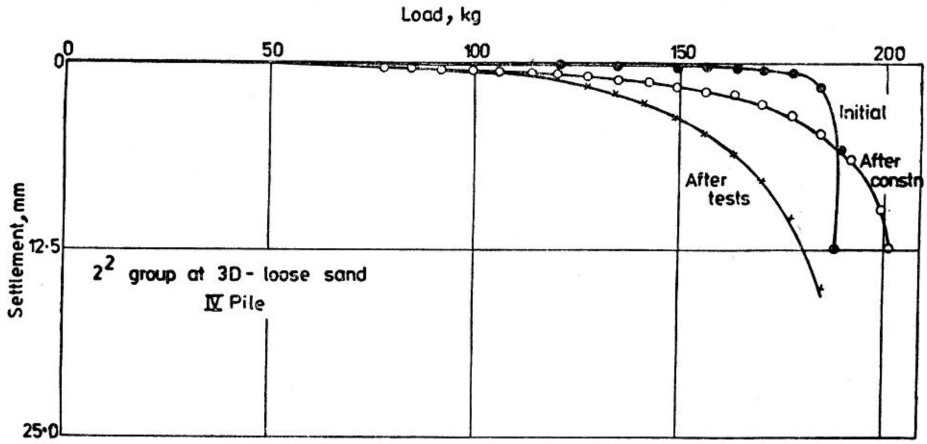


FIGURE 14 (a & b): Load-settlement curves for piles in loose sand (LF 18)

response of the first pile during second load test is four to five times that during the first load test and this increase is due to the installation of the three subsequent piles. The general decrease in I_{RI} values of a pile, as the spacing is increased, indicates that the influence of installation becomes less with increase in spacing. In order to comprehend the relative settlement behaviour of each pile in a group at the time of its installation, the ratios of the slope of the load-settlement curve during the load test after installation to that of the first installed pile have been computed. These values are a measure of the installation resistance of each pile compared to that of the



(c)



(d)

FIGURE 14 (c & d): Load-settlement curves for piles in loose sand (LF 18)

first pile and the results indicate that the installation resistance tends to increase for the subsequently installed piles. Similar ratios for the second load test on each pile after the construction of the group have also been computed. Though the trend of variation is similar to that after installation there is a large reduction in the values of ratios for subsequently installed piles which is primarily due to the large settlement response of first installed pile under second load test (as affected by the installation operation of the three subsequent piles). These values are considered to represent more or less the relative settlement behaviour of each pile in a group just prior to the first load test on that group. Though these values may not exactly represent such a behaviour (since even a small amout of penetration of adjacent piles due to load test has been found to affect the load-settlement behaviour of a pile) they still provide a qualitative picture of the phenomenon. For all the groups tested it is seen that this ratio decreases from the first installed pile to the last installed pile in the order of installation of the piles, thereby indicating that the resistance to settlement of the

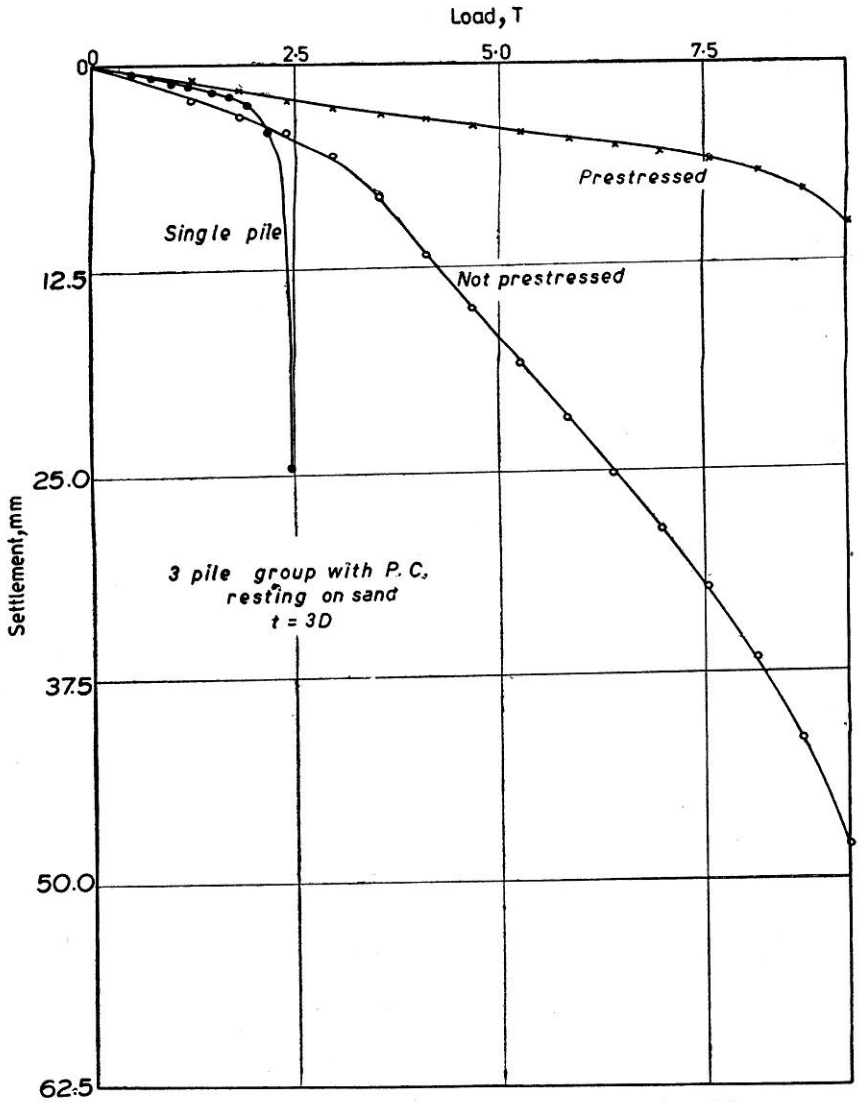


FIGURE 15: Load-settlement curve for piled group (CR 16)

piles in a group increases in the order of installation of the piles. From the observations above and of those made with respect to relative load bearing capacity of piles (Kaniraj, 1974) it is seen that in a pile group in medium dense sand the constitutive relationship (load-displacement) varies from pile to pile. Generally the resistance to settlement and the ultimate load are more for the latter installed piles. The pile cap being generally rigid will impose the condition of uniform settlement of all the piles in a group. Satisfaction of this compatibility condition of deformation of the piles is possibly achieved by such a sharing of load among the piles so as to increase in their order of installation.

For the second series of tests—B-series—carried out on 2^2 groups, where a second load test on each pile of a group was carried out after the load

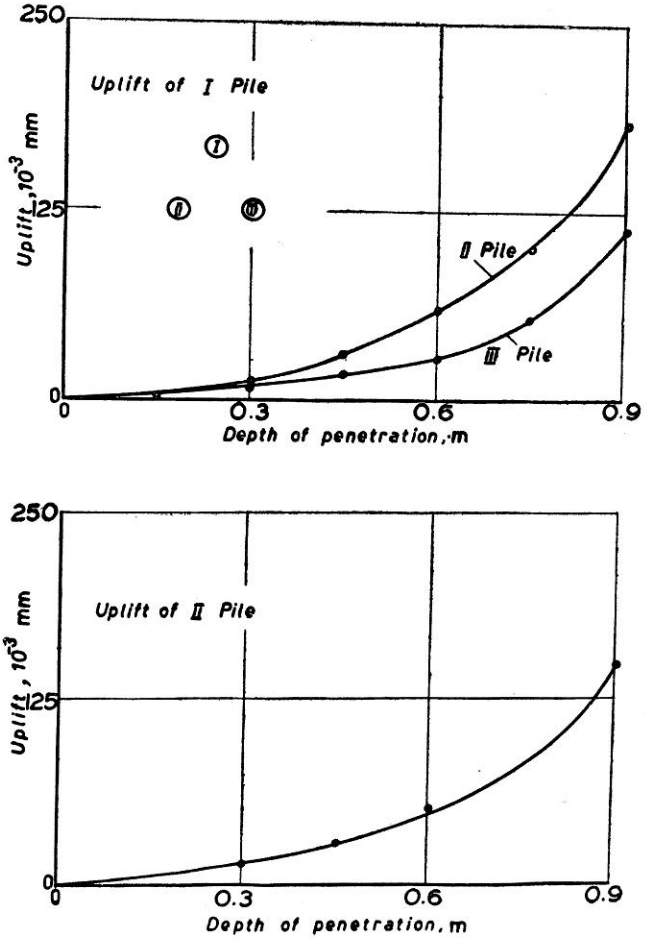


FIGURE 16: Uplift of piles during installation of latter piles (CR 16)

tests on the group, the relative settlement behaviour of each pile immediately after its installation has been studied in the same manner as explained for the A-series of tests. Similarly the relative settlement behaviour of each pile after group load tests has been studied by computing the ratio of the slope value of a pile during the second load test on it to that of the first pile. These ratios for all piles are found to exceed unity only slightly which indicated that the load and reload tests on a pile group have increased the resistance to settlement of earlier installed piles relative to their levels of resistance after the construction of the group. Load and reload tests on a pile group bring about a change in the state of the soil-pile interaction that governs the settlement behaviour of piles so as to make the conditions uniform for all the piles. *Influence Ratio* (*in settlement*) *due to Group Test*, I_{RT} for each pile has been calculated as the ratio of the slope of the load-settlement curve of the second load test to that of its first load test (i.e. immediately after installation). This I_{RT} value is considered as a measure of the net influence of effects due to installation and group load tests on the initial settlement behaviour of a pile. I_{RT} values deviate much less from unity than the I_{RI} values. However, there is still an increase in the settlement of each pile even after the group loadings and it is probable that this increase will become less with the number of cycles of group load test.

Free standing groups in loose sand : In the case of loose sand, the load-settlement curves are not found to be characterised by two, initial and final, linear portions with a non-linear section in between. But the non-linear behaviour is observed from the very beginning. Hence, the method of computing slope values is not possible here. In order to evaluate the settlement behaviour the settlement values at a pile load of 56.7 kg have been considered. This particular load chosen is within the range of the ultimate load of the piles and the pile group. The observed settlement values indicate that in loose sand the resistance to penetration or settlement is in general more for the latter installed piles whether immediately after installation, or after construction of group or after group load tests. Similarly computations for the influence of installation operations and also that of installation operations and group tests on the original settlement behaviour of piles have been made. These ratios can be considered to be similar to the *Influence Ratio* (*in settlement*) *due to Installation*, I_{RI} and *Influence Ratio* (*in settlement*) *due to Group Tests*, I_{RT}, respectively. The results show that there is a marked increase in the settlement response of a pile after the installation of adjacent piles. Though the group loading tends to narrow down the differences between the settlement that occurs in the test immediately after installation and that in the test after construction of group, there is still a considerable increase in the settlement of a pile over its initial value. Values of settlement ratio for the first and second group load tests have been calculated. The settlement ratio specially for the first group load test should be considered approximate, since the reload tests conducted on each pile after installation of the group but prior to group loading could have counteracted substantially the installation effects on the settlement of the group. However, it is evident from the observations that prestressing of sand mass brought about by first loading of the group considerably reduces the settlement of the pile group during its subsequent reloading.

The above observations in the case of pile groups in loose sand should be interpreted with great caution when pile installation in the field practice is done by driving or vibration. Such procedures are likely to effect greater compaction of the loose deposit which might modify the observations and results.

Groups with pile cap resting on medium dense sand : The pile cap has a large influence on the load-settlement behaviour of a group. The load-settlement curve (Fig. 15) for the first load test on a group consists of two, almost linear portions before reaching the ultimate load even which is not pronounced. The failure pattern corresponds to that of local shear failure. On the other hand a general shear failure type of load-settlement curve is obtained for the second load test on the group. For groups with pile cap resting on sand the prestressing of sand underneath the pile cap and in the pressure bulb beneath the pile tips seems to control settlement behaviour considerably. The effect in reducing settlement is so pronounced that the settlement ratio with respect to second group load test becomes less than 1. Whereas for free standing groups in medium dense sand, group loading tends to bring back the settlement behaviour of the individual piles to their initial behaviour (counteracting the installation effects) no such tendency could be observed in the case of groups with pile cap resting on sand. The high values of I_{RT} (ranging from 2.5 to 6) mean that even after load tests on groups with pile cap resting on sand, the settlement response of individual piles continues to be as high as or even higher than that after the installation of the group. In other words, the group load tests on this series have no doubt made the pile-soil interaction state for all the piles uniform without necessarily making them more resistant to penetration. Contrary to the order of settlement response behaviour of piles after group installation, the settlement response of the piles increases with the order of reload test on individual piles after group load tests.

Discussions

Beredugo (1966) from his studies on free standing groups concluded that installation order and pile positions are the most important factors governing the distribution of load among the individual piles in a group. He observed that for the first loading of the group initially the amount of load taken by each pile increases with the order of installation of the piles but as the load increases the pile position tends to govern the load carried by each pile. For the second, third and subsequent loadings of the group the manner in which the individual piles build up their loads is similar to the first loading except that the influence of installation order progressively diminishes. The findings of the present investigations are in conformity with the observations of Beredugo, though the load in each pile of a group has not been directly measured during group loadings. However, the behaviour could be inferred from the results of the two series of tests on 2^2 groups (A-and B-series). It is seen from the results of A-series that during the first loading of the group (immediately after construction of the group) the resistance to settlement and the ultimate load of individual piles increase from the first pile to the last pile in the order of installation. Since a rigid pile cap imposes the same settlement for each pile, initially for a load on the group the load shared by each pile tends to be in the order of installation of the piles. As the load on the group increases, the latter installed piles would build up rapidly their ultimate load after which readjustment has to take place within the group. The first group loading brings about changes in the soil-pile interaction state tending to make them uniform for all the piles in the group. This would decrease the influence of the installation effects on the load distribution among the piles even at small levels of load on the group during reload tests. The change brought about in the soil conditions by group loading is evident from the second load tests carried out on piles (after group tests) in the B—series of tests, where it is found that the group loading tends to make the settlement behaviour of all the piles in the group more or less the same corresponding almost to that of the test pile. A similar phenomenon of installation effects on the settlement behaviour of already installed piles is observed in the case of loose sand also. Thus pile installation operations have been found to cause an increase in the settlement response of the piles in both loose and medium dense sand deposits.

For the first loading of a group with pile cap resting on sand, the load-settlement curve has been found to have two approximately linear portions (the slope of the latter being such as to yield greater settlement) and it is also found to be indicative of the local shear type of failure. In the absence of detailed instrumentation to separate the load borne by the piles and the pile cap, an explanation of the phenomenon as a logical conjecture is attempted. During the first loading of the group, initially the load is carried primarily by the piles as the sand immediately below the pile cap is in a loosened state due to the earlier installation operations. As the load on the group increases the piles reach their normal ultimate load (i.e. as if the pile cap is not effective) and additional load is then resisted by the pile cap. These two parts of the mechanism are probably characterised by the two approximate linear portions of the load-settlement curve. The increase in the levels of normal stress in sand around the piles due to load transferred through the pile cap makes the piles proportionately more resistant to penetration. This is possible why the pile group with pile cap resting on sand does not register a distinct peak during the first load test on the group. But during the subsequent reloading of the group, the sand within the pressure bulb of the pile cap and within the pressure bulb below the pile tips is in a prestressed state. Since the resistance to settlement of piles compared to that of the pile cap would also be low at this stage (as is evident from the load tests on individual piles after group tests), the major share of the load even during the initial stages of the subsequent reloading of the group will be taken up by the pile cap. However, since these direct and indirect effects are governed by the plan dimensions of the pile cap and the relative depth of embedment of piles, the load-settlement behaviour of such a piled group is found to differ from test results in quantitative terms as affected by these factors.

In the light of the above discussions, it might be said that the Skempton's theory of settlement of pile foundations in sand, which considers that the greater settlement of a group compared to that of a single pile is primarily due to differences in the magnitude and compressibility characteristics of sand mass in their respective pressure bulbs, accounts for a part of the settlement mechanism of piled foundations with driven piles, since the influence of installation operations and the interaction of pile cap have not been explicitly given expression to. The caution with which the results of the earlier investigations on piles and pile groups, either installed as a whole unit or buried should be extrapolated for use in field practices becomes self evident now. Where the pile group has been installed as a whole, apart from the sand inside the pressure bulb of the group becoming prestressed, the influence of installation operations on the load-settlement behaviour of individual piles in the group is totally eliminated. These two factors consequently lead to a prediction, lower than the actual settlement value for the pile group. When the piles are buried, there is no zone of prestressing for single pile as well as for the group. As a result, the settlement of a buried single pile is more than that of a driven pile, other conditions remaining the same. Vesic (1967) reports that buried single piles require a settlement as much as 27 per cent of their diameter in order to reach their ultimate bearing capacity whereas for driven piles a settlement of less than 10 per cent of the pile diameter is all that is required. (It is observed to be about 8 per cent in the investigations reported here). But, for a buried pile group the settlement is likely to be less than that of a pile group constructed by individual driving of piles, since the influence of installation operations have been totally eliminated and the soil condition and the load-settlement behaviour for each pile are the same. Thus an increase in the settlement of a comparative single pile and a possible decrease in the group settlement give rise to smaller than actual settlement ratio values. Hence designs based on the results of such investigations (installed as a whole or buried) will have a tendency to err on the *unsafe* side in cases where piles are installed individually by driving.

Conclusions

The following conclusions are drawn based on the research studies reported in the paper.

1. Installation of an adjacent pile has significant effect on the behaviour of already installed piles. The effect is more marked for groups in loose sand than for groups in medium dense sand. In both these types of deposits, installation of a pile considerably increases the settlement of already installed piles. For free standing pile groups in medium dense sand, group loading tends to counteract the installation effects with respect to settlement whereas for piled groups in medium dense sand such a tendency is not clearly observed. In the case of free standing groups in loose sand, the group loading tends to minimise the installation effects, with respect to settlement, but not to the extent observed in the case of medium dense sand.

2. The first loading of a pile group conteracts installation effects and causes a prestressing of the sand mass inside the pressure bulb beneath the tip of the piles. Hence, the settlement during second loading in relation to the first loading of the pile group decreases thus effecting considerable decrease in the settlement ratio.

3. For the piled group in medium dense sand, during first group load test the load-settlement curve is characterised by two linear portions and by local shear type of failure. It is construed that the first linear portion of the load-settlement curve characterises the initial range when the load is mostly carried by the piles and the second portion when the additional load is taken up by the direct and indirect contributions of the pile cap. The local shear type of failure is attributed to the lack of prestressing of the ground and to the indirect contribution of the pile cap, namely, increasing normal stresses (from load transferred through the pile cap) giving rise to increased skin and point resistance of piles. The order of improvement in the behaviour of pile groups by such a phenomenon, under prototype condition, needs to be established. For the piled group in medium dense sand, during second group load test, general shear type of failure has been observed. Since the sand below the pile cap as well as beneath pile tips has been prestressed during first loading such an altered behaviour has been reasoned out to result. The pile cap has overwhelming influence on the settlement ratio of the pile groups tested. For the first group loading on a piled group there are two settlement ratio values corresponding to the two linear portions of the load-settlement curve, both of which are greater than 1. But, for the second group loading the prestressing effect is so great that the settlement ratio becomes even less than 1.

4. Investigations on pile groups, either installed as a whole or buried have been inferred to give lower than actual settlement ratio values. If designs were to be based on these results, the pile groups installed by driving of individual piles are likely to settle more than the predicted values.

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