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Bored Pile Groups Under Vertical Load in Sand

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Introduction

Several analyses have been developed recently for predicting the ultimate bearing capacity and settlement of pile groups for a given load from the knowledge of load-displacement behavior of single piles (6,10,12,13,18,20,21). These analyses are based on tests carried out either on model or prototype uniform diameter piles. Moreover, no information seems to exist for handling bored underreamed pile groups. To provide a rational approach for the design of such pile groups, systematic field experimental studies were performed: (1) To study the mechanism of load-displacement characteristics of pile groups; (2) to provide guidelines for estimating the load-displacement characteristics of groups of underreamed piles from the known behavior of single pile; (3) to estimate the influence of number and spacing of piles on the efficiency of a pile group; (4) to estimate the contribution of pile caps to the load carrying capacity of a pile group; and (5) to evaluate existing procedures for obtaining the load-displacement behavior of pile groups.

Review of Literature

Bearing Capacity of Pile Groups.—Several formulas are available for evaluating the bearing capacity of pile groups (5;17). These formulas give values of group efficiency factor, η

$$\eta = \frac{Q_{gu}}{n\,Q_{su}} \quad \text{(1)}$$

in which Q_{gu} = the ultimate bearing capacity of a pile group; n = the number

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TABLE 1.—Values of Group Efficiency Factor

Reference (1)	Soil type (2)	Method of installation (3)	Pile spacing (diameters) (4)	Efficiency factor (5)	Remarks (6)
Press (16)	Medium sand	Driven bored	1.3, 2.3	1.8, 1.5, 1.3	Efficiency reduced with increase in spacing
Kezdi (6)	Loose fine sand	bored Driven	3 2	0.6 2	
	Dense fine sand	Driven	3	1.3	
Meyerhof (10)	Sand	Driven	2–4	1	
Kishida and Meyerhof (7)	Loose sand	Jacked	1–6	1	Full cap contributes towards bearing capacity for individual action whereas only outer rim contact area in case of equivalent pier failure
	Dense sand	Jacked	1–6	1	
Vesic (21)	Medium sand	Jacked	2–8	1.7 Pile cap resting condition	Only outer rim contributes
	Dense sand	Jacked		1.3 Free standing condition	
Nagaraj (13)	Dense sand	Driven	5	1.1	
Meyerhof (12)	Sand	Driven	2–4	Maximum 1.3–2.6 1	
		Bored	2–4	0.67	

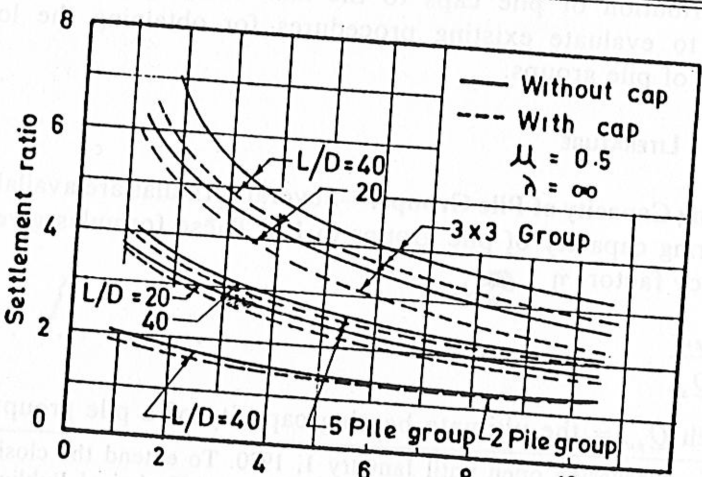

FIG. 1.—Comparison of Settlement Ratio of Cap Bearing Pile Groups with Free Standing Pile Groups

of piles in the group; and Q_{su} = the ultimate bearing capacity of a single
The efficiency formulas generally yield η values of less than unity. Prob
these formulas may be considered to be better suited for predicting the gr
efficiency of piles in soft clays and bored piles. This is corroborated by
findings published in literature (Table 1) which shows η values less than u
in case of bored piles. The validity of an efficiency formula is, however, diffi
to be strictly established as there are many factors which influenced the
foundations and none of the existing efficiency formulas take into account
the variables.

Settlement of Pile Groups.—The majority of the theoretical solutions
prediction of load-settlement behavior of pile groups are based on Mindli

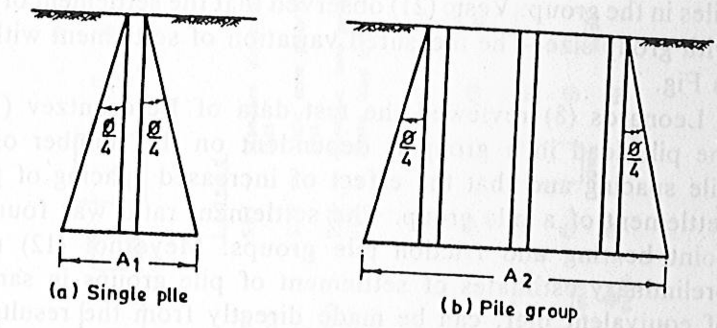

FIG. 2.—Imaginary Areas of Single Pile and Pile Groups

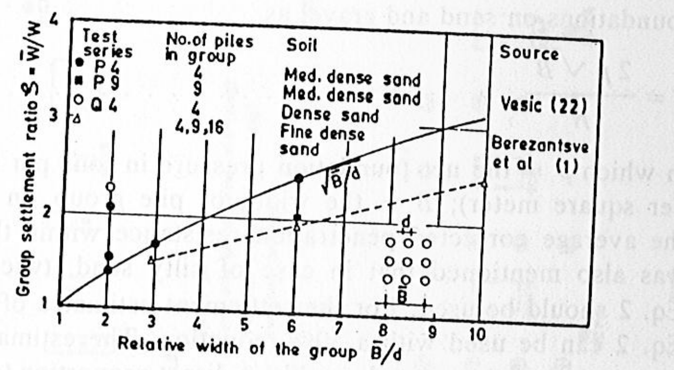

FIG. 3.—Variation of Group Settlement Ratio

elastic half space concept. Pichumani and D'Appolonia (14) have presented solutions for evaluating the distribution of load and the displacements in the case of square pile groups both floating and end bearing, embedded in soil which exhibits perfect elastic-plastic behavior. Poulos and Mates (15) developed design charts for evaluating load-displacement behavior of pile groups. Solutions are provided for symmetrically placed two-pile groups, assuming the piles to be identical in behavior. Two pile group analysis is extended to four and bigger pile groups. For estimating settlements of pile groups, certain group reduction factors are recommended. Values of these reduction factors have been provided for floating and point bearing pile groups for different widths of pile groups and number of piles in a group. In a similar elastic analysis Butterfield and Banerjee (2) have considered pile group-pile cap interaction effects and provided design curves (Fig. 1) for estimating pile group settlement for different spacing to diameter and length to diameter ratios of piles. These curves are for pile groups having different numbers of piles.

Various investigators (6,10,18,19) have concluded based on their model and field tests in loose to medium sand that settlement increases with the increase in the width of a pile group. In dense sand it is found that the settlement increases with spacing up to a spacing of 2.5 times to 3 times the pile diameter. Further increase in spacing reduces settlement. Berezantzev, et. al (1) found the settlement of a pile group to increase linearly with certain imaginary pile group areas as shown in Fig. 2. The settlement of a pile group would be $\sqrt{A_2/A_1}$ times the settlement of single pile at the worked out load per pile. In this case the settlement of a pile group would be unaffected by the number of piles in the group. Vesic (21) observed that the settlement of a pile group increases with group size. The measured variation of settlement with group size is shown in Fig. 3.

Leonards (8) reviewed the test data of Berezantzev (1). He observed that the pile load in a group is dependent on the number of piles in addition to pile spacing and that the effect of increased spacing of piles is to reduce the settlement of a pile group. The settlement ratio was found to be different for point bearing and friction pile groups. Meyerhof (12) recommends that the preliminary estimates of settlement of pile groups in sand, using the concept of equivalent pier, can be made directly from the results of penetration tests as for spread foundations (9). For this Meyerhof (11) himself proposed a conservative expression for obtaining the total settlement, S, of the shallow foundations on sand and gravel as

$$S = \frac{2p\sqrt{B}}{N} \quad (2)$$

in which p = the net foundation pressure in tons per square foot (kilonewtons per square meter); B = the width of pile group, in feet (meters); and N = the average corrected penetration resistance within the seat of settlement. It was also mentioned that in case of silty sand, twice the right-hand side of Eq. 2 should be used. For the settlement estimates of deep spread foundations Eq. 2 can be used with a 50% reduction. The estimated settlements, in other cases, can be interpolated roughly in direct proportion to the ratio of the effective depth to width (D'/B) of pile group. Accordingly Eq. 2 was modified by Meyerhof (12) and the settlement of a pile group, S_g in inches (millimeters) is given as:

$$S_g = \frac{2p\sqrt{B}\,I}{N} \quad (3)$$

in which I = the influence factor of effective group embedment and is approximately given by

$$I = 1 - \frac{D'}{8B} \geq 0.5 \quad (4)$$

Maximum settlements of a pile group can also be estimated using the results of static cone penetration tests in the relationship (11)

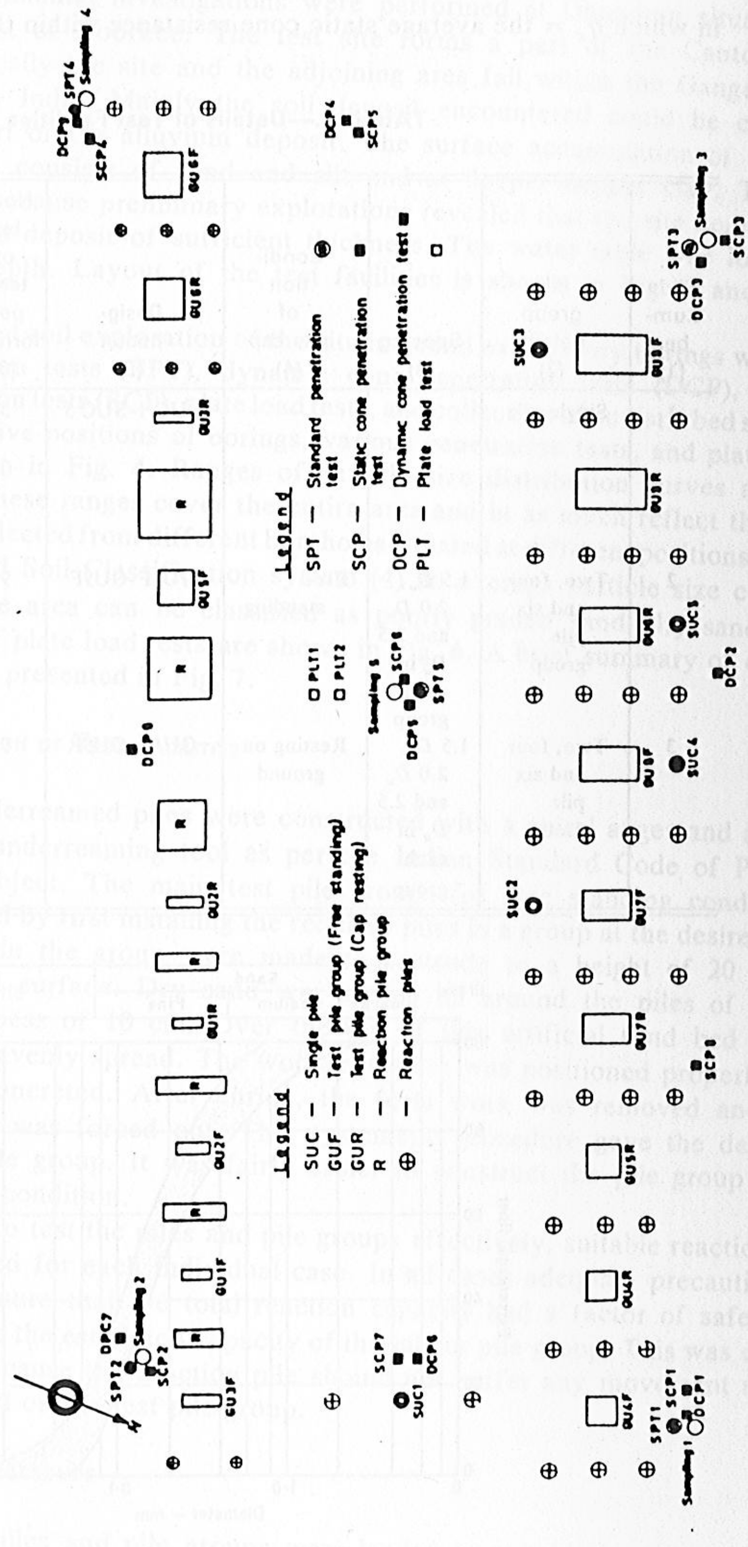

FIG. 4.—Layout of Test Facilities at Test Site

$$S_g = \frac{p\,BI}{2\,q_c} \quad \ldots\ldots (5)$$

in which q_c = the average static cone resistance within the seat of settlement.

TABLE 2.—Details of Test Facilities

Slide number (1)	Pile group details (2)	Spacing (3)	Condition of pile cap (4)	Designation (5)	Number of tests performed (6)	Remarks (7)
1	Single pile	—	—	SUC 1–SUC 5	5	All piles are bored single underream of 15-cm shaft diameter, d, 37.5-cm underream diameter, D_u and 3.0-m deep
2	Two, four and six pile group	1.5 D_u, 2.0 D_u and 2.5 D_u in each group	Free standing	GU1F–GU9F	9	In the piles and pile cap reinforcements were provided based on suitable design procedures and as per Indian Standard (3).
3	Two, four and six pile group	1.5 D_u, 2.0 D_u and 2.5 D_u in each group	Resting on ground	GU1R–GU9R	9	All piles and pile groups were tested in compression.

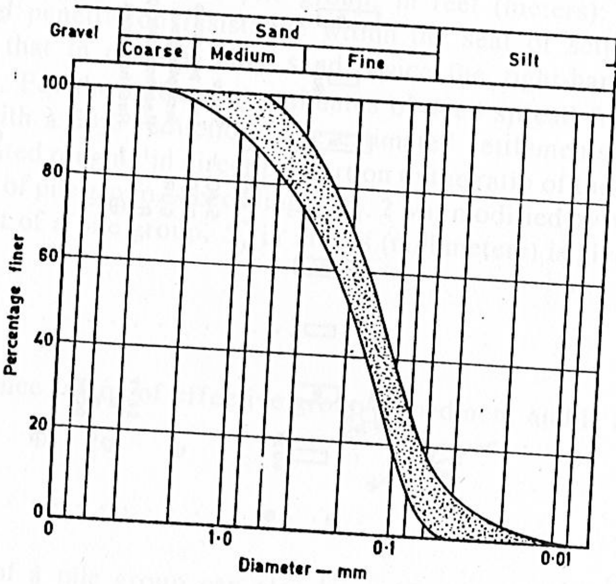

FIG. 5.—Grain Size Distribution of Soil at Test Site

Test Site Conditions

Experimental investigations were performed at Dhandera situated at 5 k southeast of Roorkee. The test site forms a part of the Cantonment are Geologically the site and the adjoining area fall within the Gangetic plains c northern India. Mainly the soil deposit encountered could be considered t be a part of the alluvium deposit. The surface accumulation of the Gangeti alluvium consists of sand and silt and at deeper depths clay. The site wa chosen because preliminary explorations revealed that the site contains uniforn silty-sand deposit of sufficient thickness. The water table was located belov 8.0 m depth. Layout of the test facilities is shown in Fig. 4 and detailed in Table 2.

Detailed soil exploration of the site included exploratory borings with standard penetration tests (SPT), dynamic cone penetration tests (DCP), static cone penetration tests (SCP), plate load tests, and collection of undisturbed soil samples. The relative positions of borings, various penetration tests, and plate load tests are shown in Fig. 4. Ranges of particle size distribution curves are given in Fig. 5. These ranges cover the entire area and in as much reflect the gradation of soil collected from different boreholes situated at different positions. According to Unified Soil Classification system (4) an average particle size curve of the soil in the area can be classified as poorly graded sand-silty sand (SP-SM). Results of plate load tests are shown in Fig. 6. A brief summary of exploratory borings is presented in Fig. 7.

Construction of Test Facilities

The underreamed piles were constructed with a spiral auger and a manually operated underreaming tool as per the Indian Standard Code of Practice (3) on the subject. The main test pile groups for free standing condition were constructed by first installing the required piles in a group at the desired spacing. The piles in the group were made to protrude to a height of 20 cm above the ground surface. Dry sand was spread all around the piles of the group to a thickness of 10 cm. Over the top of this artificial sand bed polythene sheet was evenly spread. The wooden former was positioned properly and the cap was concreted. After curing, the form work was removed and sand at the bottom was forced out. This systematic procedure gave the desired free standing pile group. It was fairly easier to construct the pile group with pile cap resting condition.

In order to test the piles and pile groups effectively, suitable reaction facility was designed for each individual case. In all cases adequate precautions were taken to ensure that the total reaction capacity had a factor of safety of 2.0 compared to the estimated capacity of the pile or pile group. This was extremely desirable because the reaction pile should not suffer any movement under the ultimate load on the test pile group.

Load Test Procedure

The test piles and pile groups were loaded in suitable increments with the help of hydraulic jacks. The load was recorded with the help of proving rings.

In case of pile groups, the movements of the group were recorded using dial gages at different selected locations. Care was taken to obtain a rigid loading arrangement. The probable ultimate load of each pile and pile group was determined with the knowledge of soil properties at the test site. The number of load increments in the first and last one-third range of ultimate load was more than in the middle range. In each case care was taken to obtain sufficient points to describe the load displacement characteristics of the piles and pile groups. Each load increment was maintained for a duration of 2 hr or until

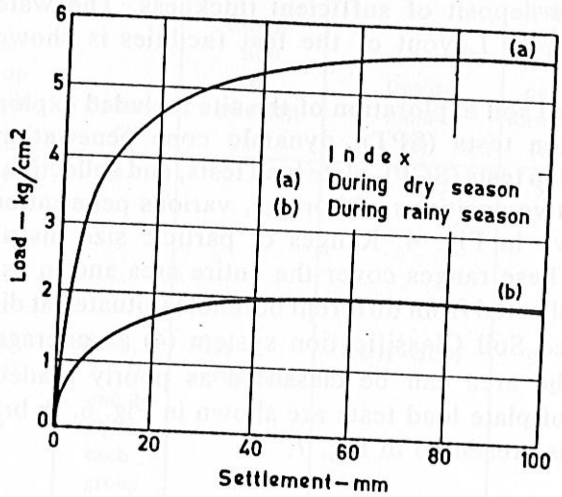

FIG. 6.—Load-Settlement Curves from Plate Load Test (1 kg/cm² = 98 kN/m², 1 in. = 25.4 mm)

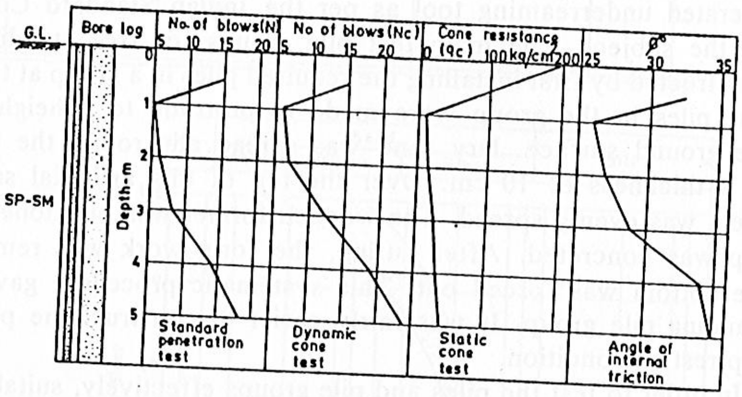

FIG. 7.—Soil Profile and Variation of Average Penetration Resistance

the deflection rate was less than 0.02 mm/hr, whichever was achieved earlier. The movement of the pile group was measured at an interval of 15 min until the desired rate was achieved.

Test Results and Analysis

Single Piles.—The single piles were placed at different arbitrarily chosen locations within the site. The range of load-displacement characteristics of these five piles are shown in Fig. 8. It is seen from this figure that there is no appreciable scatter. Thus, it can be construed that the soil deposit in the area is more or less uniform, ensuring that the different tests can be compared.

In all the individual load-displacement curves for single piles, no definite failure load was indicated. However, the initial and final rate of deformation

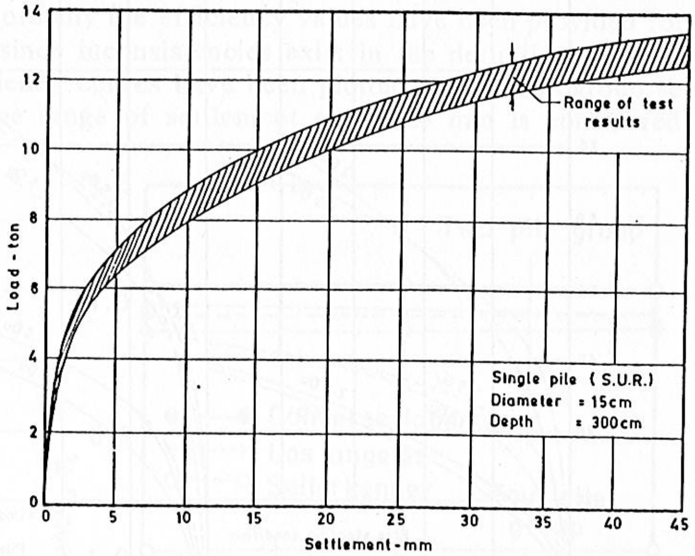

FIG. 8.—Range of Load-Settlement Results of Five Single Test Piles (1 in. = 25.4 mm)

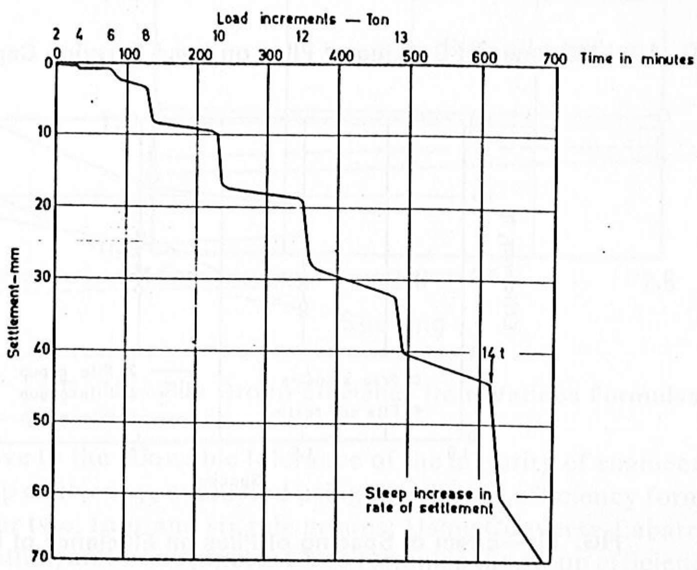

FIG. 9.—Time-Displacement Plot of Single Pile (SUC-4)

with load was different. The ultimate load for a single pile was obtained by the time-settlement plot (Fig. 9) corresponding to the point where an increase in settlement is disproportionate to the increase in load with time. For the analysis of pile groups the test result for pile SUC-4, which is near the average of 5 tests, has been used.

Pile Groups.—The load displacement characteristics of different pile groups are presented in Fig. 10. This figure also shows the effect of spacing on the load-displacement behavior of pile groups for the free standing and cap resting

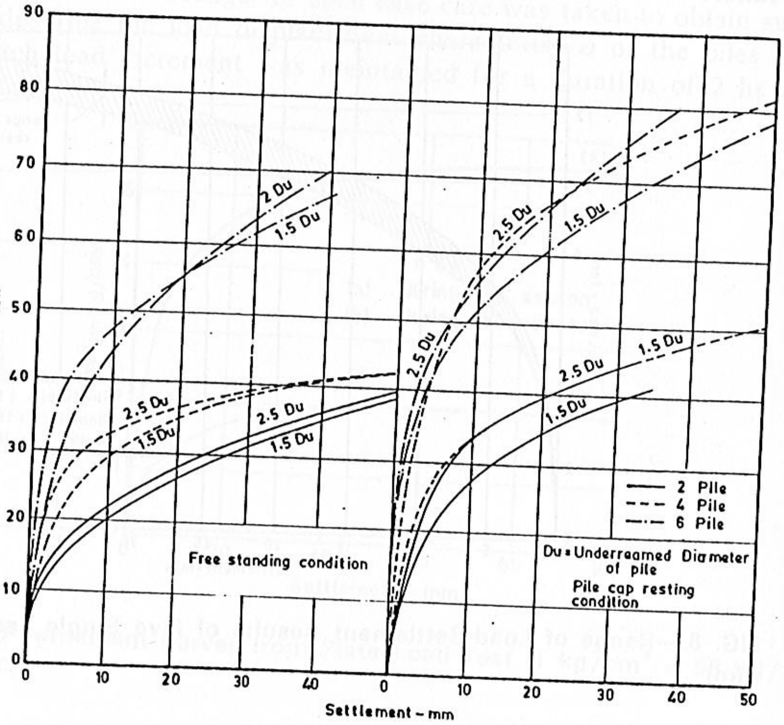

FIG. 10.—Influence of Spacing of Piles on Load Carrying Capacity of Pile Groups

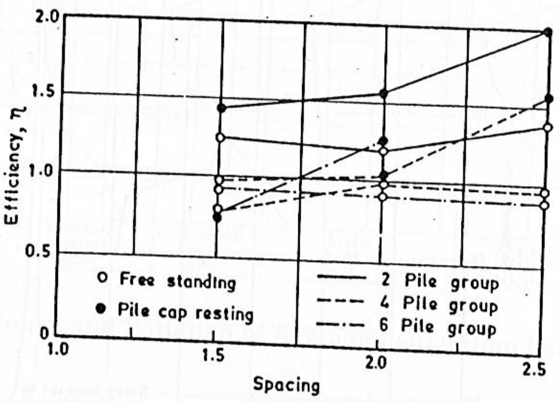

FIG. 11.—Effect of Spacing of Piles on Efficiency of Pile Groups

conditions. In all these curves, in general, it is seen that with the increase in pile spacing the capacity is also increased. Though freestanding conditions do not show appreciable difference in behavior for different spacings, the pile cap resting conditions display difference by virtue of the increase in size of the pile caps with increase in the pile spacing of groups.

In order to have a clear picture, the pile group efficiency, η, has been plotted against spacing in Fig. 11 for free standing and pile cap resting conditions for all the pile groups. Herein, for any settlements, η, is defined as the ratio of load taken by a group to that of the load taken by a single pile multiplied by the number of piles in group. These efficiency curves in each case represent the average of the efficiency values at five different settlements. In the available literature normally the efficiency values have been provided for ultimate loads. However, since inconsistencies exist in the definition of failure load, herein, these efficiency curves have been plotted for various group settlements up to 25 mm. The range of settlement above 25 mm is considered an impractical

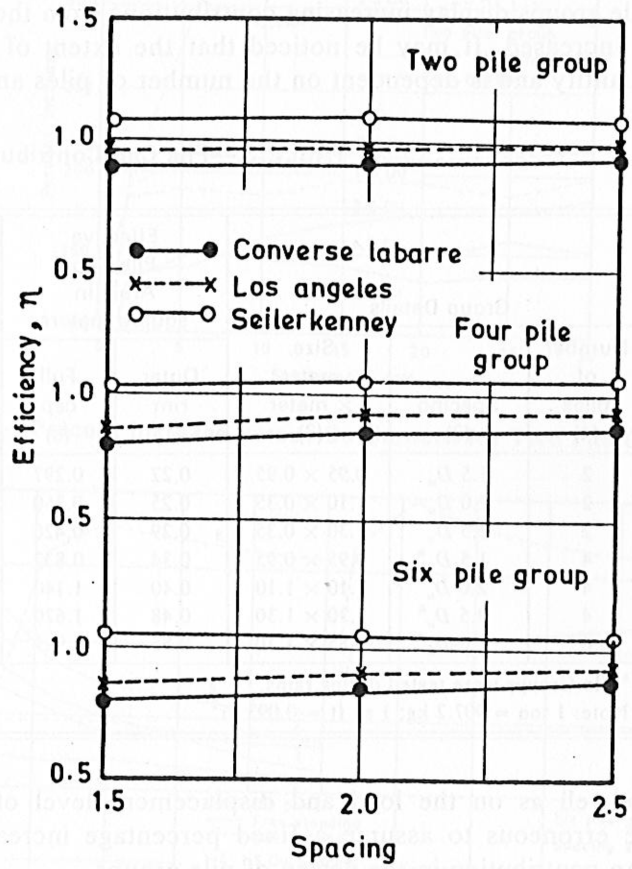

FIG. 12.—Pile Group Efficiency from Various Formulas

range relative to the allowable tolerance of the majority of engineering structures.

The group efficiency, evaluated using the various efficiency formulas, is shown in Fig. 12 for two, four and six pile groups. Using Converse-Labarre (unpublished communication) and Los Angeles Code formulas the group efficiency lies between 0.90 and 0.95, whereas for the Seiler-Keeney (17) formula the value is between 1.1 and 1.12. Felds rule (5) gives a constant value of 0.94 for two pile groups, and 0.82 for four pile groups. Comparing these computed efficiency values with those observed in the tests of free standing caps it is seen that none of efficiency formulas is able to predict the efficiencies to a fair degree of accuracy.

But for short-bored underreamed pile groups embedded in silty-sand or sandy soils in free-standing cap condition, the efficiency can be predicted by Converse-Labarre or Los Angeles Code formulas for approximate analysis as in general these give an efficiency value less than unity which holds true for bored piles. But for pile cap resting conditions these formulas underestimate the group capacity. However, it can be noted that these formulas do not differentiate between free standing and pile cap resting conditions.

Contribution by Pile Cap.—In Fig. 10 the performance of pile groups under free standing and resting pile cap conditions can be compared. It is seen that the load taken by the pile group under pile cap resting condition is more than under free standing condition for any settlement value. The two, four and six pile groups display increasing contributions from the pile cap as the pile spacing is increased. It may be noticed that the extent of contribution is not a fixed quantity and is dependent on the number of piles and their spacing in the group

TABLE 3.—Pile Cap Contribution

Group Details			Effective Pile Cap Area, in square meters		PILE CAP CONTRIBUTION, in tons		
					Computed		Observed
Number of piles (1)	Spacing (2)	Size, meter × meter (3)	Outer rim (4)	Full cap (5)	Outer rim (6)	Full cap (7)	Data (8)
2	1.5 D_u	0.95 × 0.95	0.22	0.297	11.88	13.87	8.00
2	2.0 D_u	1.10 × 0.35	0.25	0.350	13.50	16.35	8.50
2	2.5 D_u	1.30 × 0.35	0.29	0.420	15.65	19.62	15.50
4	1.5 D_u[a]	0.95 × 0.95	0.34	0.832	6.58[a]	10.66[a]	6.00[a]
4	2.0 D_u[a]	1.10 × 1.10	0.40	1.140	7.78[a]	14.20[a]	6.00[a]
4	2.5 D_u[a]	1.30 × 1.30	0.48	1.620	25.90	58.85	31.00
6	2.0 D_u[a]	1.85 × 1.10	0.55	1.929	10.66[a]	24.00[a]	10.00[a]

[a]Pile Groups were tested during rains.
Note: 1 ton = 907.2 kg; 1 sq ft = 0.093 m^2

as well as on the load and displacement level of group. Therefore, it may be erroneous to assume a fixed percentage increase in capacity for the pile cap contribution in the design of pile groups.

The observed and computed pile cap contributions corresponding to 25 mm settlement are compared in Table 3. These values are computed using the plate load test data (Fig. 6). The contribution is computed both for the concept of outer rim (7,21) and the total cap area, (7) obtained by deducting the cross-sectional area of all the piles from the total pile cap area. The field testing program spanned over a year involving both dry and rainy weather. Rain caused a significant change of soil properties to a shallow depth. During the dry season the top crust was very hard due to surface desiccation and resulted in high bearing capacity [Fig. 6(a)]. During rains the carrying capacity of the top soil was reduced to almost 50% as shown in Fig. 6(b). The later was utilized in calculating the contribution of pile caps of pile groups tested during rains. From Table 3 it is observed that there is not much difference in the values of cap contribution computed for the two concepts in case of two pile groups. This may be due to small differences in the total and effective pile cap areas. Whereas in other cases the computed values based on the entire cap area are substantially higher than the observed one, the values based on the outer rim concept are comparable. The reason for higher observed values in cases of two and four pile groups at 2.5 D_u spacing is due to desiccation of top surface. The marginal difference in other pile groups may be due to the reasons stated previously.

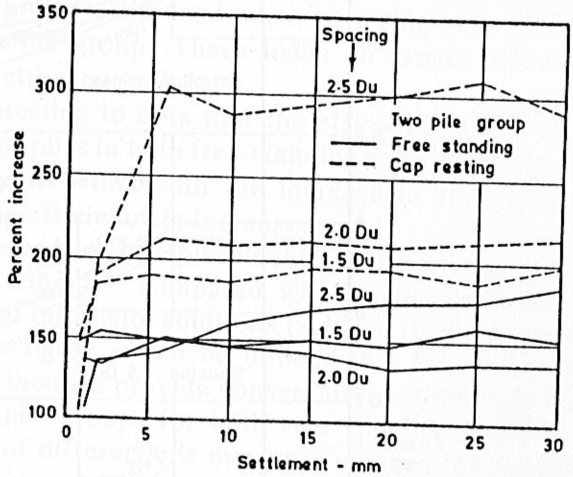

FIG. 13.—Percent Increase versus Settlement for Two Pile Groups

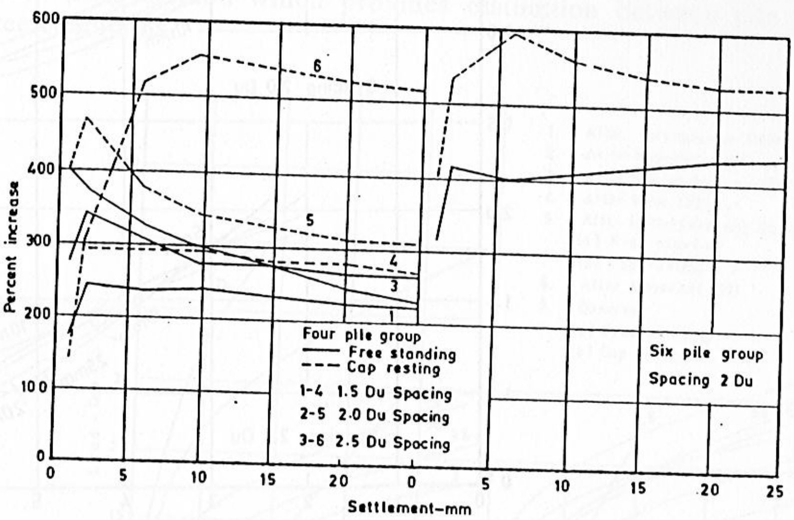

FIG. 14.—Percent Increase versus Settlement for Four and Six Pile Groups

Thus it is reasonable to conclude that when evaluating the capacities of pile groups for pile cap resting conditions, only the contributions from the outer rim of the pile caps may be considered. Considering the contribution by the total pile cap area will lead to unsafe designs.

Settlement of Pile Groups.—The majority of the experimental studies (6,10,18, 19) on pile groups embedded in sand seem to indicate that at any load level the settlement of the pile group increases with the size of the pile group. One of the important aspects to be noticed in these investigations is that the piles considered were piles driven in sand. Thus, the resulting compaction could have offset the true influence of the pile spacing and group size on the load-settlement characteristics of pile groups.

In this study it has been shown that under free standing cap conditions, the efficiency of the pile groups is not substantially affected by the pile spacing

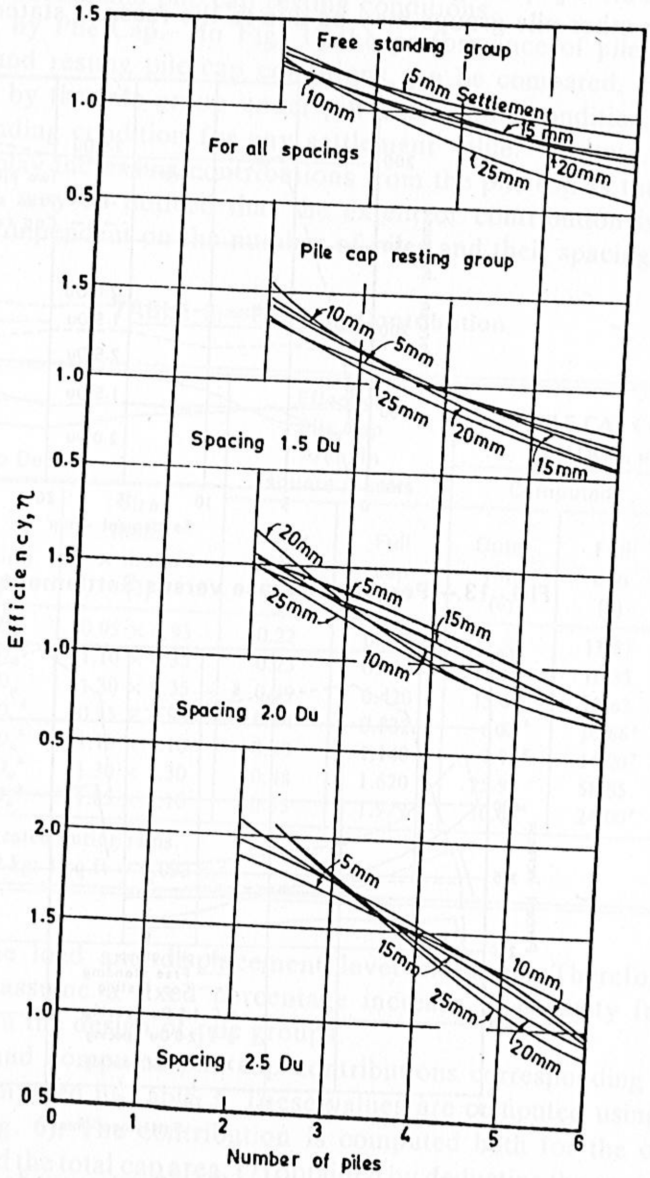

FIG. 15.—Pile Group Efficiency Versus Number of Piles in Group

and thus the pile group size. But in case of pile cap resting condition, the efficiency of the pile groups increases with the pile spacing.

Prediction of Load-Displacement Characteristics.—To provide design curves for predicting the load-displacement characteristics of pile groups from the known load-displacement behavior of single piles, relationships between percentage increase in group capacity over single pile capacity for different settleme values have been plotted in Fig. 13 and Fig. 14. The percentage increase fo pile groups is defined as the ratio of pile group capacity minus single pile capacit to the single pile capacity. The pile group capacity and single pile capacit corresponds to the same settlement values.

For assessing the load displacement characteristics of groups having differer number of piles (between 2 and 6), a series of design curves has been provide in Fig. 15. The efficiency, η, has been defined as a ratio of load taken b a test pile group to the load taken by a single test pile multiplied by the numbe of piles in the group. These loads on groups and single piles correspond t the same settlement values.

It is interesting to note that the efficiency values decrease with the increase in number of piles in both free-standing and resting pile cap conditions. However, it may be noted that with the increase in spacing the stiffness of the group and thus the efficiency is increased.

The observed load displacement characteristics of two and four pile groups at 2 D_u spacing are compared with values predicted using scaling laws and curves based on elastic solutions (2,10,12,18,20,21) in Fig. 16.

From this figure it can be noticed that for settlements of less than 17 mm the existing theories provide conservative estimates of load-displacement characteristics of pile groups for both free standing and pile cap resting conditions. The degree of difference is more pronounced for pile cap resting conditions.

The theories of Butterfield and Banerjee (2) provide the best estimate of the load-displacement characteristics of the pile groups tested. Further, this is the only method which provides distinction between pile cap resting and free conditions.

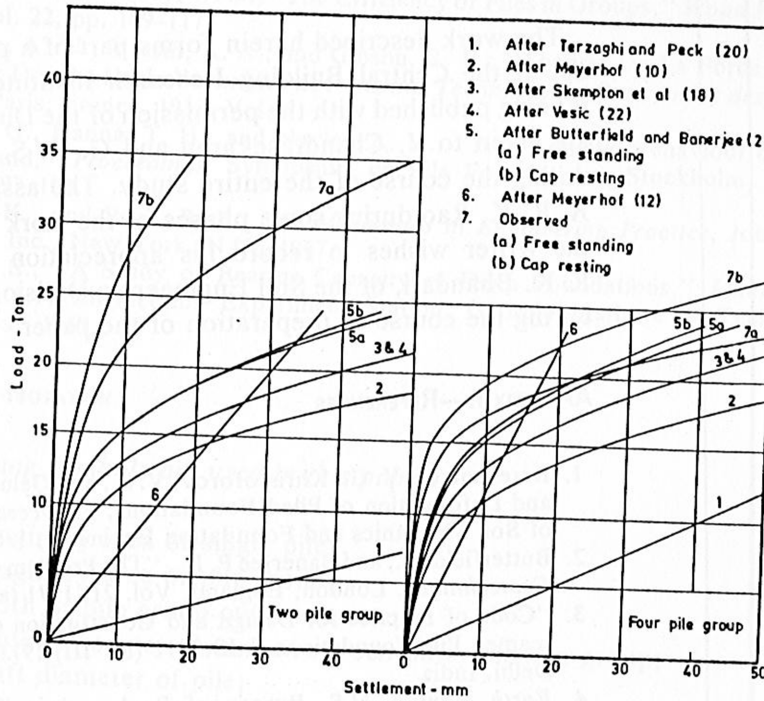

FIG. 16.—Predicted Load-Settlement Behavior of Pile Groups by Different Methods

The approach of Meyerhof (12) using empirical expressions (Eq. 3 and Eq. 5) may be used only for the initial estimates of settlements under the design loads. Therefore it is suggested that the procedure of Butterfield and Banerjee (2) can be used for predicting the load-displacement characteristics of pile groups comprising of bored-underreamed piles embedded in silty-sand and sandy soils.

Conclusions

The following conclusions may be drawn from this paper:

1. The efficiency formulas provided by Converse-Labarre and Los Angeles Code may be used for preliminary estimates of free standing pile group efficiency.
2. Empirical curves relating the load-displacement behavior of single piles and the load displacement characteristics of a pile group have been developed.
3. The stiffness of pile groups under free standing conditions is less than under pile cap resting conditions.
4. In the pile cap resting condition, the efficiency of a pile group increases with the increase in spacing. However, there is no marked effect of spacing in the case of free standing pile groups.
5. In the case of pile cap resting conditions, the contribution of the pile cap towards load carrying capacity of the pile group can not be defined as a certain percentage of the ultimate load. Based on this study, it seems reasonable to account for the cap contribution in terms of the outer rim of the pile cap.
6. The solutions of Butterfield and Banerjee (2) may be used for predicting the load-displacement characteristics of pile groups.

Acknowledgments

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Appendix II.—Notation

The following symbols are used in this paper:

A_1 = imaginary area of single pile;
A_2 = imaginary area of pile group;
B = width of pile group outer to outer;
$\bar{B}$ = center to center distance between outer piles in group;
d = shaft diameter of pile;
D' = effective embedded length of pile group;
D_u = diameter of underream bulb;