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14786 BORED PILE GROUPS UNDER LOAD IN SAND

KEY WORDS: Efficiency; Interactions; Pile caps; **Pile foundations; Pile groups; Pile loading tests; Reaming; Sands**

ABSTRACT: The results of field tests of bored underreamed pile groups under sustained vertical loads are presented, along with an empirical approach for estimating group efficiencies and load-displacement characteristics of pile groups from the known behaviour of single piles. The effectiveness of available methods for estimating group settlements are compared, resulting in a conservative estimate.

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Design of pile groups under vertical load in sand

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K. G. Garg

The paper presents an extensive review of the literature available on the behaviour of groups of piles in a foundation of sand. Methods of determining the ultimate load-carrying capacity and the settlement of pile groups are discussed. Also, the influence of the pile cap on the carrying capacity of the pile group is indicated. The merits and demerits of each method are discussed, clarifying the situations in which a particular method may be more suitable than others.

Significant advances have taken place in recent years in the construction technology of deep foundations, particularly of pile foundations. However, investigations aimed at understanding the behaviour of pile foundations have been directed, mainly, towards obtaining solutions for special problems. The traditional problem concerning the behaviour of pile groups subjected to sustained vertical loads is yet to be properly understood. Particularly, much remains to be achieved with respect to the load transfer of pile group capacities and the behaviour of the group of piles under vertical loads in sand.

Many static and dynamic formulae are available for predicting the pile capacities. Also available are the procedures for evaluating the ultimate capacity from the load test data. All these approaches, instead of providing a specific answer, give different values of ultimate capacity. Still greater inconsistencies prevail in the case of pile groups. Though several efficiency formulae suggest a set of values and trends, experimental evidence shows a complete reversal in behaviour. In this review, an attempt has been made to survey the approaches available in the literature for the design of pile groups in sand. The piles in a group are installed at a few pile diameters apart and are connected with rigid concrete pile caps or cross beams, which may or may not be in contact with the ground. The spacing of piles in a group is governed by technical requirements and economic considerations. A foundation engineer is interested in knowing for a particular pile group what are its working and ultimate loads and what is its settlement under the corresponding loads.

Pile group capacity

The methods available for determining the capacity of a group of piles can be classified into two categories, namely, empirical approaches and experimental evidence.

Empirical approaches: Several efficiency formulae are available for evaluating the carrying capacity of pile groups. The formulae given by Feld[3] define a certain group efficiency factor, η as the ratio of the ultimate load carrying capacity of the pile group, Q_{gu} to the ultimate load carrying capacity of a single pile, Q_{su} multiplied by the number of piles in the group. Knowing η, the pile group capacity can be worked out for the given value of the capacity of a single pile.

Based on the experience of the failure of pile groups in the field, Terzaghi and Peck[18] observed that the load-carrying capacity of a pile group cannot be greater than that of a block foundation defined by the exterior perimeter of the group, provided the piles and the confined soil mass sink as a unit like a pier. The ultimate load of the pile group Q_{gu} is given by

$$Q_{gu}=q_d\,B\,L + D_f\,(2B+2L)\,S \qquad ..(1)$$

where, q_d = the ultimate bearing capacity per unit of area of a rectangular loaded area of dimensions $B \times L$ and at depth D_f, which may be estimated by means of approximate equations

B = width of pile group

L = length of pile group

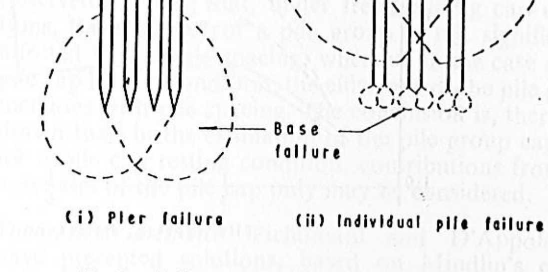
S = average shear resistance of soil per unit of area for a depth D_f.

A pile group can be considered safe against such a failure if the total design load does not exceed $\frac{Q_{gu}}{3}$.

Experimental evidence: Press[16] reported experimental findings based on the field tests on small driven piles and large-diameter bored piles in natural, medium-grained, moist, and dense sand. Driven piles were tested in groups of two to eight, whereas bored piles were tested in a group of two piles only. In the case of large bored piles, the reported value of efficiency was only about 0.6 at a pile spacing of three diameters. On the other hand, the efficiencies of driven piles were larger than unity. A decrease in the efficiency was observed with an increase in spacing.

Kezdi[6] reported an efficiency value greater than 2 for a group of four concrete driven piles in fine sand at a spacing of two to six pile diameters in a row, or in a square. The group action was found to discontinue for piles driven at a spacing of six diameters in the case of dense sand, and the group efficiency reduced to 1.3 at a spacing of three pile diameters. Kishida[7] also obtained group efficiency values greater than unity in the case of driven piles in medium dense sand at spacings of two to four pile diameters.

Kishida and Meyerhof[8] observed from model tests on piles that, in loose sand, the load-carrying capacity is greater than the sum of the bearing capacities of single piles whilst the reverse holds true for dense sand. They suggested that the load-carrying capacity of a pile group,



(i) Pier failure (ii) Individual pile failure

Fig 1 Failure zones of pile foundations

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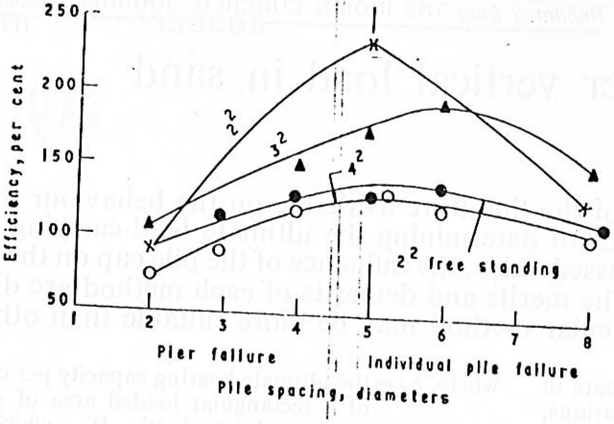


Fig 2 Variation of efficiency with spacing of piles for a 1-mm settlement

with the pile cap in contact with the ground, results from a general shear failure under the outer rim of the surface of contact of the cap if the group fails as an equivalent pier as shown in *Fig* 1. According to the same suggestion, the cap would contribute to load-carrying capacity over its entire contact surface if the pile spacing is large enough for the piles to fail individually.

Nagarajan[12] observed maximum values of efficiency between 1.3 and 2.6 at a spacing of five to six pile diameters in the case of jacked piles in dense sand in model tests as shown in *Fig* 2. Vesic[10] reports on one of the most comprehensive large-scale model tests on pile groups embedded in medium and dense sand. The piles were jacked into position. Groups of four and nine piles were tested at a spacing of two to eight pile diameters. Tests were done with the pile cap both resting, and not resting on soil. It was noticed that the overall group efficiency of the pile group with the pile cap resting in medium dense sand was about 1.7 at a spacing of three to four pile diameters. For the free-standing case, the group efficiency was reduced to 1.3, *Fig* 3. However, in dense sand the group efficiency reduced to 1.1. Also, it was observed that a certain amount of contribution was available if the pile caps were allowed to rest on the ground as shown in *Fig* 3.

Settlement of pile groups: Prediction of the load-settlement behaviour of pile groups is extremely complex, considering the interaction effects of soil, pile and pile cap and the interaction effects of individual piles in a group. Though, logically, a solution of this problem is essential from a designer's point of view, very meagre reliable information is available on the subject. All available methods can be grouped into two categories, namely semi-empirical approaches and theoretical approaches.

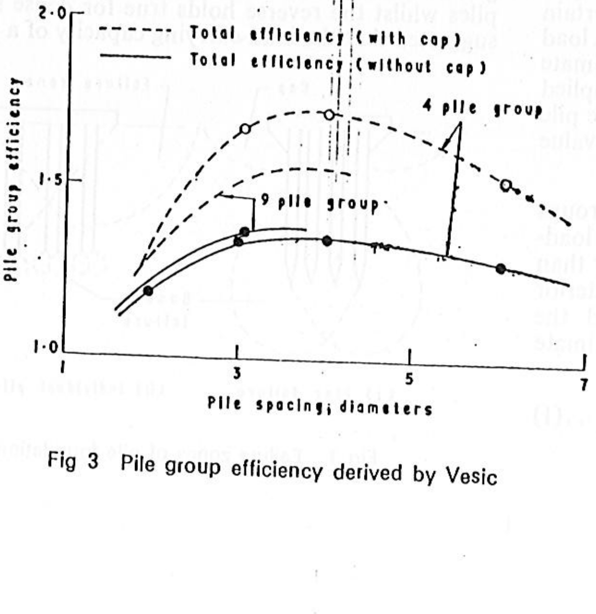


Fig 3 Pile group efficiency derived by Vesic

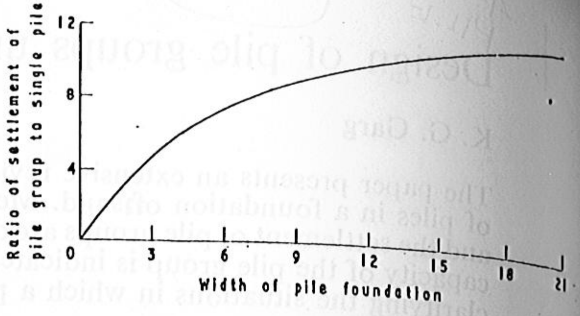


Fig 4 Variation of the relative settlement with width of the pile group as derived by Skempton

In the semi-empirical approaches, Skempton et al[14] attempted to investigate the influence of spacing on the settlement of pile groups. The variation of the settlement ratio with the width of the pile group is shown in *Fig* 4. This is, by far, the most widely used design curves. The empirical relation for this curve is given by

$$S_g = \frac{(4B+9)^2}{(B+12)^2} S_l \qquad \ldots(2)$$

where, S_g = the settlement of pile group
B = the width of the pile group
S_1 = the settlement of single pile.

According to Meyerhof[10] the settlement of a pile group can be 20 times the settlement of a single pile if the spacing of piles is large. Based on model tests on pile groups in sand, the settlement of pile group can be predicted by

$$S_g = \frac{S\left(5 - \frac{D}{3}\right)}{\left(1 + \frac{1}{r}\right)^2} \qquad \ldots(3)$$

where, S = the ratio of the spacing of piles to the diameter of the pile base
r = the number of rows of piles.

Kezdi[6] has investigated the effect of spacing on the load-settlement behaviour of pile groups. While observing the settlement of pile groups in a row, he found the settlement to decrease with an increase in the pile spacing.

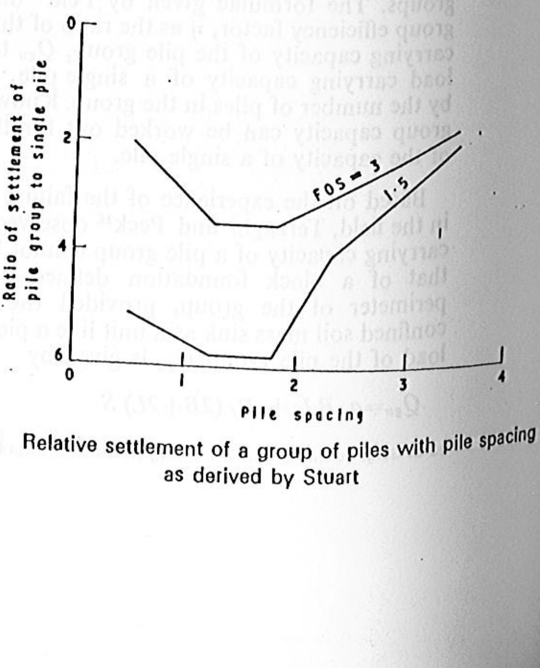


Fig 5 Relative settlement of a group of piles with pile spacing as derived by Stuart

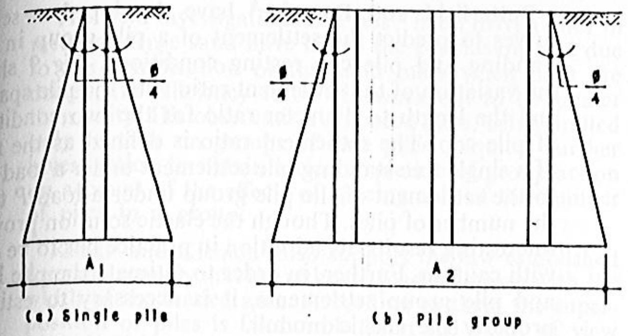


Fig 6 Imaginary areas of a single pile and a pile group

His earlier studies[2] on a group of four piles had indicated that, under an applied load, the settlement increases with pile spacing.

Stuart et al[17] also indicated an increase in settlement with pile spacing in loose and medium dense sand deposits. However, their studies point out certain deviations from those of other investigators in the case of dense sand, where settlement increased up to a spacing of 2.5 to 3.0 times the pile diameter. Thereafter, a further increase in the spacing resulted in reduced values of settlement under applied load. The variation of the settlement ratio with the pile spacing is illustrated in *Fig* 5. Berezantzev et al have indicated from their field tests on pile groups in dense sand that the settlement of a pile group increases linearly with certain imaginary pile group areas. The settlement of a pile group would be $\sqrt{\frac{A_2}{A_1}}$ times the settlement of a single pile at the load worked out per pile. A_1 and A_2 are the imaginary areas of a single pile and of a pile group as shown in *Fig* 6.

Vesic[19] observed that the settlement of a pile group increases with the size of the pile group, as illustrated in *Fig* 7. Vesic also emphasized the importance of the pile length and the initial relative density of the soil deposit while estimating the settlement of pile groups from the load-settlement behaviour of single pile and derived the equation

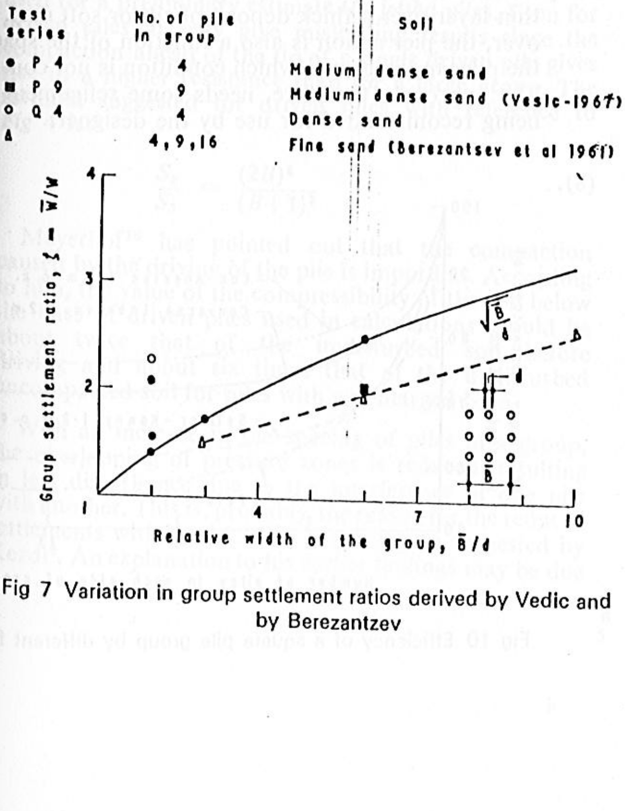


Fig 7 Variation in group settlement ratios derived by Vedic and by Berezantzev

$$\frac{\bar{W}}{W} = \sqrt{\frac{\bar{B}}{d}} \qquad \ldots(4)$$

where, W and $\bar{W}$ = settlement of a single pile and group of piles, respectively

$\bar{B}$ = width of the pile group

d = diameter of the pile.

Leonards[9] reviewed the test data of Berezantzev. He observed that the load per pile in a group is dependant on the number of piles in addition to the pile spacing and that the effect of the increased spacing of piles is to reduce the settlement of a pile group. Different settlement ratios were found for point bearing and friction pile groups.

Meyerhof[11] recommends the concept of an equivalent pier foundation for the preliminary estimates of the settlement of a pile group in a homogeneous sand deposit which does not rest on a more compressible soil at greater depths. The concept is derived directly from the results of penetration tests as for spread foundations[10]. According to him, the settlement of a pile group S_g in inches can be obtained by:

$$S_g = \frac{2p\sqrt{BI}}{N} \qquad \ldots(5)$$

where, p = the net foundation pressure in tons per square foot

B = width of pile group

N = average corrected penetration resistance with the seat of the settlement

I = influence factor of effective group embedment.

The value of I is given approximately by

$$I = 1 - \frac{D'}{8B} \geqslant 0.5 \qquad \ldots(6)$$

The maximum settlement of a pile group can also be estimated from the results of static cone penetration tests by

$$S_g = \frac{p\,BI}{2q_c} \qquad \ldots(7)$$

where, q_c = the average static cone resistance within the seat of settlement.

Based on the analysis of a large number of field tests on bored under-reamed pile groups in medium dense, silty sand deposits, Garg[4] has observed that the solutions of Butterfield and Banerjee[2] may be used to predict the load-settlement behaviour of pile groups. *Fig* 8 compares the observed load-settlement curves of a few pile groups with the predicted curves obtained by various approaches discussed in the paper. Moreover, this is the only method which makes a distinction between the pile cap resting and the free standing conditions. It has been observed by Garg that, under free-standing cap conditions, the efficiency of a pile group is not significantly affected by the pile spacing, whereas, in the case of the pile cap resting condition, the efficiency of the pile group increases with pile spacing. The conclusion is, therefore, drawn that, in the estimation of the pile group capacity for a pile cap resting condition, contributions from the outer rim of the pile cap only may be considered.

Theoretical methods: Pichumani and D'Appolonia[13] have presented solutions, based on Mindlin's elastic half-space concept, for evaluating the distribution of

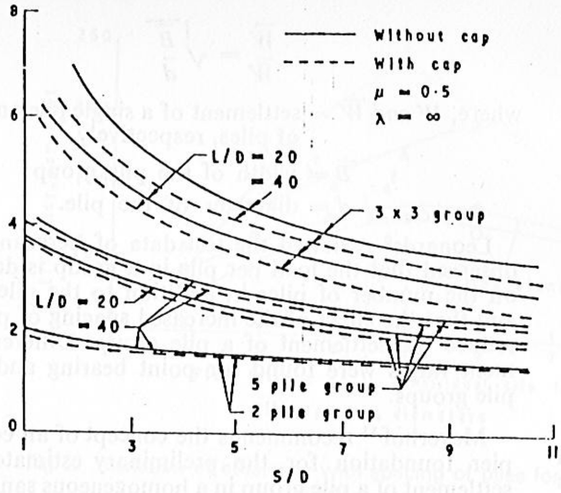
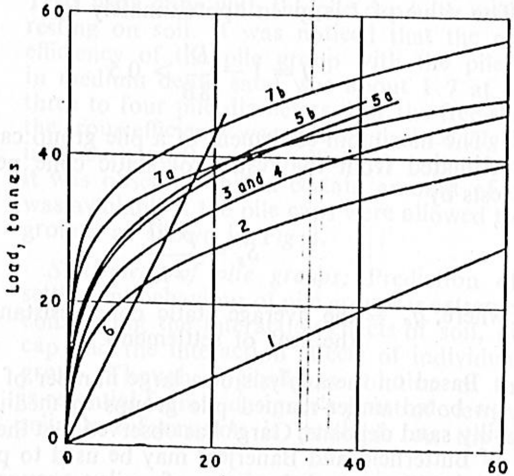


Fig 8 Comparison of settlement ratio of cap-bearing pile groups with free standing pile groups

load and the displacements in the case of square pile groups, both floating and end bearing, when embedded in soil of perfect elastic-plastic behaviour. Poulos and Mattes[14] developed design charts for evaluating the load-displacement behaviour of pile groups. Solutions are provided for groups of two symmetrically placed piles. Both piles are assumed to be identical in behaviour. The analysis for a two-pile group is extended to groups of four and more piles. Certain group reduction factors have been recommended for estimating the settlements of pile groups. The values of these reduction factors have been given both for floating and point-bearing pile groups for different widths of pile groups and for a number of piles in a group.



1 Terzaghi and Peck
2 Meyerhof
3 Skempton and others
4 Vesic
5 Butterfield and Banerjee
(*i*) free standing
(*ii*) cap resting
6 Meyerhof
7 Garg
(*i*) free standing
(*ii*) cap resting

Fig 9 Comparison of load-settlement characteristics of a four-pile group by different methods

Butterfield and Banerjee[2] have developed a set of curves to predict the settlement of a pile group in free standing and pile cap resting conditions. *Fig* 9 shows the variation of the settlement ratio with the pile spacing and the length to diameter ratio for the two conditions of pile cap. The settlement ratio is defined as the ratio of a single free standing pile settlement under a load of P to the settlement of the pile group under a load P times the number of piles. Though the elastic solution provides interesting results, its adoption in practice has to be done with caution. Further, in order to estimate the pile loads and pile group settlements, it is necessary to estimate properly the elastic moduli.

Critical review

Pile group capacity: The various efficiency formulae, normally, result in an efficiency factor of less than unity. Some of these formulae are based on the shielding actions of adjacent piles based upon relative spacing and pile diameters, whereas others do not account for the spacing of piles. In general, they disregard pile lengths and the condition that horizontal sections at different elevations vary because stressed zones in pressure bulbs vary at different heights, for example, as in under-reamed piles and tapered piles. In addition to this effect of variation of soil properties with depth and stratification, the variation of ground water level and other conditions cannot be taken into account by using these formulae. Therefore, the formulae may be better suited for piles in cohesive soils and bored piles as the value of the efficiency factor, normally, works out to be less than unity in such cases. But no such mandatory restriction has been imposed on these formulae and, as such, they are widely used. *Fig* 10 shows the wide range of values that could be obtained for a group by using various efficiency formulae.

Terzaghi and Peck's observation[18] is based on groups consisting of driven piles. The driving of piles in loose to medium sand results in increased compaction of the latter and, therefore, the pile and the compacted earth core settles as one unit, as a result of which the point resistance part of the bearing capacity will definitely correspond to the bearing resistance of the areas of the base of the entire block. Therefore, such a failure can hardly occur unless the pile group consists of a large number of friction piles embedded in silt or clay or, alternatively, of point-bearing piles resting in a firm but thin layer over a thick deposit of silt or soft clay. Moreover, the pier action is also a function of the spacing of the piles in the group, which condition is not considered. The approach, therefore, needs some refinement before being recommended for use by the designer.

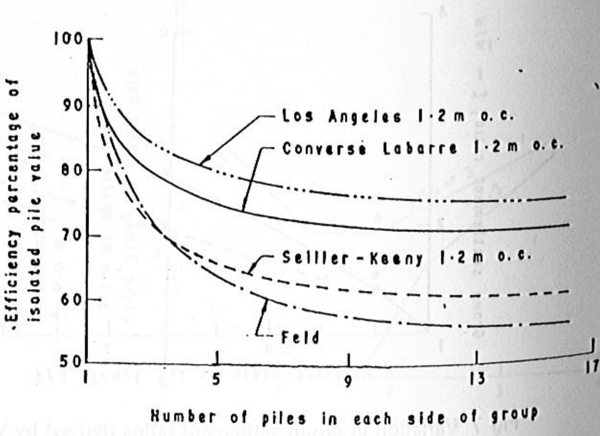


Fig 10 Efficiency of a square pile group by different formulae

The field investigations of Press[15] is on driven piles in medium dense sand have led to the conclusion that due to the densification of the sand mass when piles are driven, the efficiency value will work out to be greater than unity. His observation on bored piles, being limited only to tests on groups of two piles, requires further investigation to obtain a clearer picture of group action on account of the effects of spacing and of the number of piles in a group.

Kezdi[6] and Kishida[7] also support the law established for sand namely that the ultimate load increases with the width of the loaded area. According to them the superposition of piles is favourable from the point of view of their ultimate bearing capacity because, in the plane of the pile point, the loading of the adjacent pile increases the vertical stresses and a failure in the sideways direction is less likely to occur.

Findings of the model studies made by Kishida and Meyerhof[8], Nagarajan[12] and Vesic[19], on piles driven or jacked in an idealised soil medium are not applicable directly in practice. This is because of the simplified assumptions which are really quite different from field conditions. One important aspect studied by Kishida and Meyerhof was the effect of the pile cap contact condition on the load-carrying capacity of the pile. Different values of the critical spacing of piles in a group required for the pier action to take place have been reported by these authors. The concept of participation of the full pile cap contact area towards the bearing capacity of the pile group does not appear reasonable according to Vesic[14] and Garg[4]. Nagarajan[12] did model tests in dense sand whereas in practice there is very little chance of piling being used in such soils.

Experiments with large-scale models of jacked pile groups in medium dense and in dense sand show practically no group effect on the ultimate point loads. However, a substantial increase of the ultimate skin load is reported. The concept that the pile cap contributes to the overall bearing capacity, inasmuch as the piles are supported by sand along their outer rim, seems reasonable. A similar observation is reported by Garg[4].

Pile group settlements: Skempton's observation[16] is based mainly on limited field evidence and applies only to driven piles. No observed point lies on the curve. Settlements of bored pile groups estimated by Skempton's formula do not agree with the values observed in the field. Lee has pointed out that this approach may be used for a preliminary estimate for jetted piles. Even for driven piles, it may give misleading results since the compaction ahead of the tip of a single driven pile gives rise to a higher resistance than for a large group. The formula suggested for driven piles with reference to *Fig* 4 is:

$$\frac{S_g}{S_1} = \frac{(2B)^2}{(B+1)^2} \qquad ..(8)$$

Meyerhof[10] has pointed out that the compaction caused by the driving of the pile is important. According to him, the value of the compressibility of the soil below the base of driven piles used in calculations should be about twice that of the undisturbed soil before driving and about six times that of the undisturbed uncompacted soil for piles with an enlarged base.

With an increase in the spacing of piles in a group, the overlapping of pressure zones is reduced, resulting in less disturbance due to the interference of one pile with another. This is, probably, the reason for the reduced settlements with the increase in spacing as suggested by Kezdi[6]. An explanation to his earlier findings may be due to the increase in the ultimate load-carrying capacity of the pile group due to reduced spacing.

Stuart et al[17] support the findings of Press[15] for the relationship between spacing and settlement. According to the authors, the sequence of driving piles in a group has a marked influence on the settlement of pile groups.

According to Berezantzev et al[1], the settlement of a pile group is not affected by the number of piles in the group. On account of the narrow range of the relative width over which the investigations of Vesic[19] are spread and a wide scatter of the individual results, it is suggested that systematic studies should be made to establish a definite relationship between the relative width and the group settlement ratio. The proposed square root law for estimating the settlement of a pile group will also be affected by the relative length of the pile and, possibly, by the relative density.

Both analytical methods are based on the theory of elasticity. The method proposed by Poulos and Mattes[14] is quite detailed and provides a solution for both conditions of the pile cap, *i.e.*, resting and not resting on the ground. It provides a reasonable estimate of the settlement of a pile group within the elastic range, after which there can be wide departures from actual values.

Leonards[9] has recommended an extensive systematic field study to work out definite, more reliable settlement ratios for the satisfactory estimation of pile group settlements.

According to Meyerhof[11] the concept of an equivalent pier is advocated for the initial estimates of settlements of a pile group. Penetration test data (N-value) and also the static cone resistance can be used to obtain the group settlement. This, to some extent, seems to provide a simple approach.

Conclusions

The following conclusions can be drawn from a study of the various investigations:

(*i*) Terzaghi and Peck's bearing capacity formula for evaluating the capacity of a pile group seems to be highly conservative and, as such, it needs refinement.

(*ii*) Efficiency formulae may be used for preliminary estimates of the efficiency factor in the case of free standing pile groups.

(*iii*) The approach for predicting the group capacity which takes into account the total pile cap area in contact with the soil, seems to give results on the unsafe side. On the other hand, the concept of the contribution of the outer rim of the cap seems to give better results.

(*iv*) The square root law suggested by Vesic may be used to predict the settlement of pile groups in sand.

(*v*) The solutions of Butterfield and Banerjee may be used to predict the load-settlement behaviour of pile groups.

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