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Bearing Capacity of Pile Groups under Eccentric Loads in Sand

Capacité portante d'un groupe de pieux soumis à des charges excentrées dans le sable

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SUMMARY

Model tests on free-standing pile groups and piled foundations with varying numbers and spacings of piles under central and eccentric loads in loose and dense sands are analysed by an extended theory of bearing capacity of foundations.

SOMMAIRE

Des essais sur modèle de groupes de pieux isolés et de fondations sur pieux en modèles avec variation du nombre et de l'espacement des pieux sous charges centrées et excentrées dans les sables meubles et denses sont analysés par une extension de la theorie de la capacité portante des fondations.

PREVIOUS RESEARCH on the bearing capacity of pile groups in sands is limited to free-standing groups (pile caps above ground surface) under central loads (Cambefort, 1953; Kezdi, 1957, 1960; Stuart, *et al.*, 1960; Hanna, 1963). A series of model tests has therefore been made on such groups and on piled foundations (pile caps resting on soil) under central and eccentric loads in sands, and the results are compared with an extended theory of the ultimate bearing capacity of pile groups (Meyerhof, 1959, 1960).

THEORY

When a pile is driven into loose sand, its relative density is increased, and the horizontal extent of the compacted zone along the shaft has a width of about 6 to 8 times the pile diameter (Meyerhof, 1959). However, in dense sand, pile driving decreases the relative density because of the dilatancy of the sand, and the loosened zone along the shaft has a width of about 5 times the pile diameter (Kérisel, 1961). From these observations the authors made the assumption that the angle of internal friction ϕ of sand changes linearly with the distance from the pile (where $\phi = \phi_2$), to a radius of about 3.5 times the pile diameter (where $\phi = \phi_1$), as shown in Fig. 1.

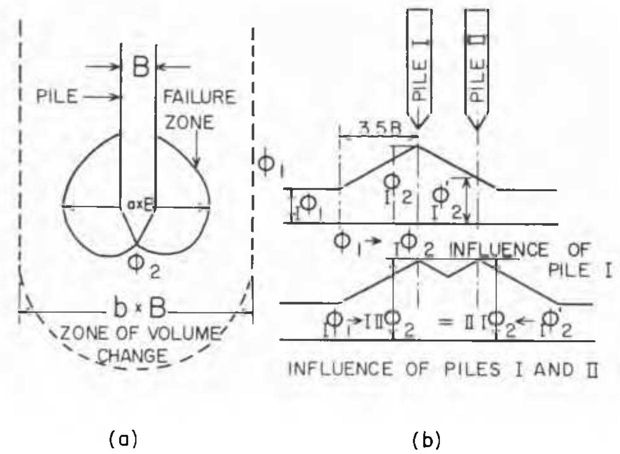

FIG. 1. Characteristic zones near piles in sand: (*a*) zones of failure and volume change near single pile; (*b*) influence zones of change in angle of internal friction near piles in group.

Based on the above-mentioned field data the relationship between ϕ_1 and ϕ_2 in sands may be written

$$\phi_2 = \tfrac{1}{2}(\phi_1 + 40^\circ). \tag{1}$$

An angle of $\phi_1 = \phi_2 = 40^\circ$ from Eq 1 means no change of relative density due to pile driving; this critical value was confirmed by shear-box tests in which the applied vertical load was 20 per cent of the unit point resistance of single piles. The distribution of ϕ_2 due to pile groups can be obtained approximately by superposition of Eq 1 in the sequence of pile driving (Fig. 1b).

The bearing capacity of a single pile can be estimated by the bearing capacity theory (Meyerhof, 1959) in which an average value of ϕ within the failure zone of an over-all width of about 4 times the pile diameter is used (Fig. 1a). The total bearing capacity of free-standing pile groups is governed either by individual pile failure or by pier failure, whichever gives the lower value (Meyerhof, 1960). For individual pile failure the total bearing capacity can be estimated as the sum of that of the individual piles, which differs from the sum of that of single piles. The ratio between these two values was checked by tests and was theoretically related to the prestressing and change of principal stresses in the sand caused by the adjacent piles. For pier failure the total bearing capacity can be estimated by taking the equivalent pier area limited by the centre of the perimeter piles as outside surface and using an average ϕ within a failure zone of an over-all width of 4 times the equivalent pier width.

The total bearing capacity of piled foundations is estimated from the bearing capacity of free-standing pile groups by allowing for the influence of the pile cap. This influence consists of the bearing capacity of the pile cap and its surcharge effect on the point resistance of the piles of the group, using the whole pile cap for individual pile failure (Fig. 2b) and using the portion of the pile cap outside the equivalent pier area for pier failure (Fig. 2a).

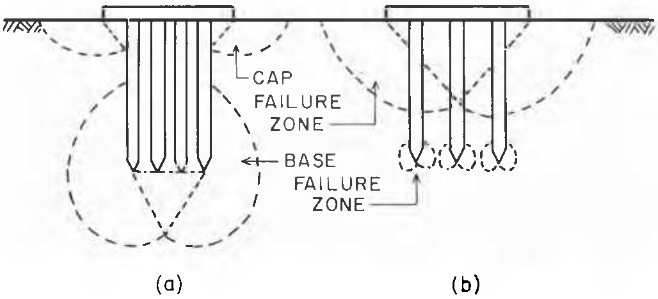

FIG. 2. Failure zones at piled foundation: (*a*) pier failure, (*b*) individual pile failure.

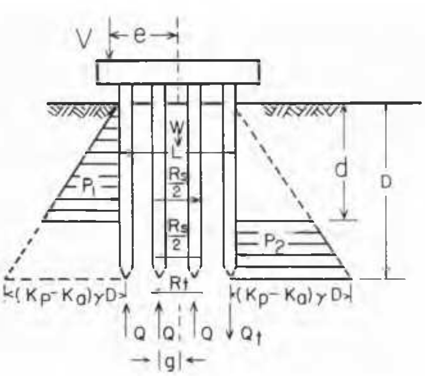

FIG. 3. Free-standing pile group under eccentric load at failure.

The bearing capacity of pile groups under eccentric loads can be estimated by including the lateral forces on the sides of the groups and, for individual pile failure, also the uplift resistance of piles (Meyerhof, 1960). For free-standing pile groups carrying a vertical load V with an eccentricity e (Fig. 3), the equilibrium equations of moments for the rotation, vertical, and horizontal forces are, respectively,

$$Ve = P_1 \frac{[D - 2d]}{3} - P_2 \left[\frac{(D - d)(D + 2d)}{3(D + d)}\right] + R_s \frac{D}{3} + \Sigma Qg + Q_t \frac{L}{2} \tag{2}$$

$$V = \Sigma Q - Q_t - W \tag{3}$$

$$P_1 = P_2 + R_t \tag{4}$$

where D = embedded length of piles, d = depth of rotation of group, L = width of group, P_1 and P_2 = total net horizontal earth pressure on end piles, Q and Q_t = bearing capacity and uplift resistance of individual pile, R_s and R_t = horizontal resistance on side and toe of group, and W = weight of group. The depth of the centre of rotation was estimated at about 0.7D from Eq 4 assuming $P_1 = P_2$.

The moment caused by eccentric load, $V \times e$, is balanced by the moment due to lateral forces on the sides of the pile group until it reaches the maximum value corresponding to the coefficient of passive earth pressure. Within this limit, the eccentricity of load has no effect on the point resistance, while the skin friction on the end piles increases

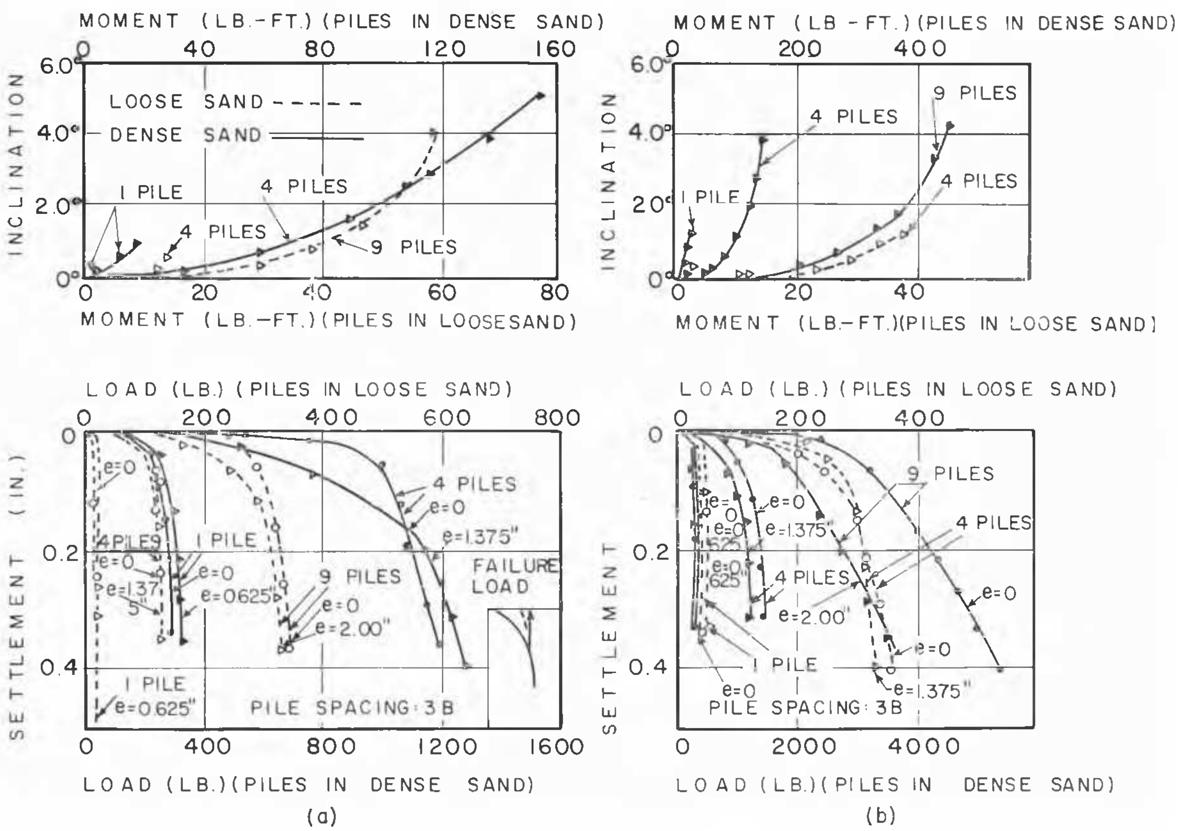

FIG. 4. Typical results of loading tests on model pile groups in sand: (*a*) free-standing pile groups, (*b*) piled foundations.

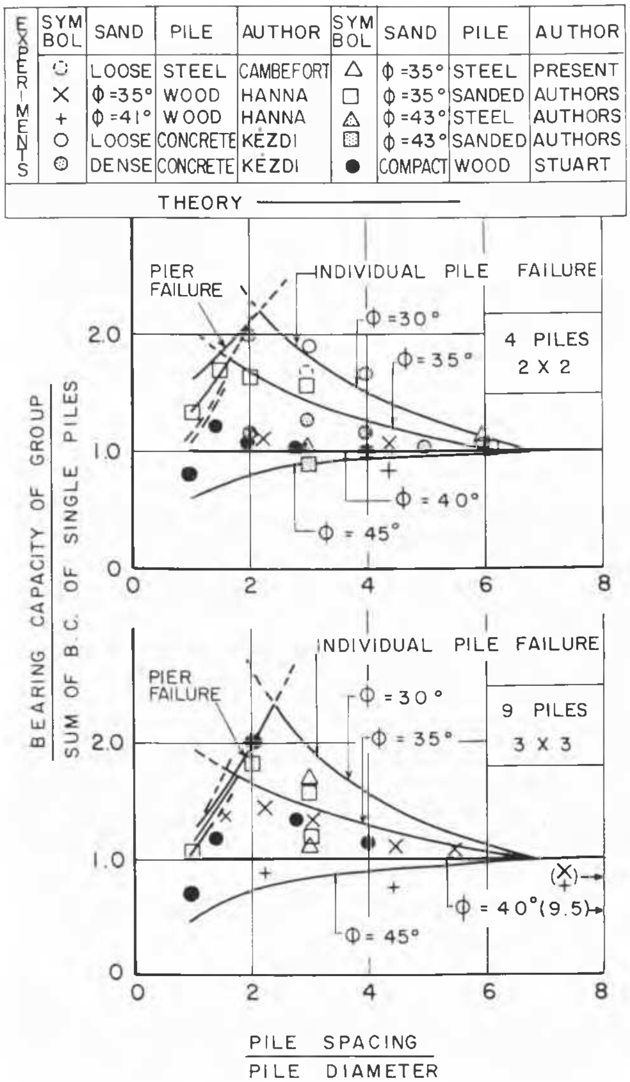

FIG. 5. Bearing capacity of free-standing pile groups under central load in sand.

with the mobilization of the earth pressure, and the total bearing capacity is thus expected to increase slightly. When the moment $V \times e$ is greater than the ultimate moments as a result of side resistance, the difference between these two moments must be balanced by an eccentric point resistance and, for individual pile failure, by any uplift resistance of piles (Fig. 3). This resistance acts on the effective contact width of the foundation as for shallow foundations (Meyerhof, 1953) and the total bearing capacity decreases with an increase of eccentricity.

On this basis the total bearing capacity of pile groups under eccentric load can be estimated from Eqs 2 and 3 on the assumption of a load V for given eccentricity e using a trial and error method. For the calculation of the side resistances, the equivalent width can be assumed as the pile spacing or 3 times the pile diameter whichever is less for individual pile failure, or 3 times the equivalent pier width for pier failure. The suggested theoretical calculations can readily be extended to pile groups, carrying a load V with double eccentricities e_x and e_y on the major axes as for shallow foundations.

ANALYSIS OF TESTS

In order to assess the validity of the theory the present experiments and those of previous investigations will be analysed below. The present model pile groups consisted of steel piles, ½ in. in diameter and 12 in. long, with 60° tips and steel caps, and they were either smooth or rough (sanded). Single piles and square groups of 4 to 9 piles with a spacing up to 6 times the pile diameter were pushed into dry well-graded sand, which was either loose (density of 94 lb/cu.ft. and friction angle of 35°) or dense (density of 117 lb/cu.ft. and friction angle of 43°) and contained in a large steel box. Free-standing pile groups with an embedded length of 11 in. and piled foundations with an embedded length of 12 in. were loaded to failure under different eccentricities of the load applied to the pile cap. The failure load was defined from a load-settlement curve, in which settlements were measured at the point of load application. Typical load-settlement and moment-inclination curves of the foundations are shown in Fig. 4.

For free-standing pile groups under central load the

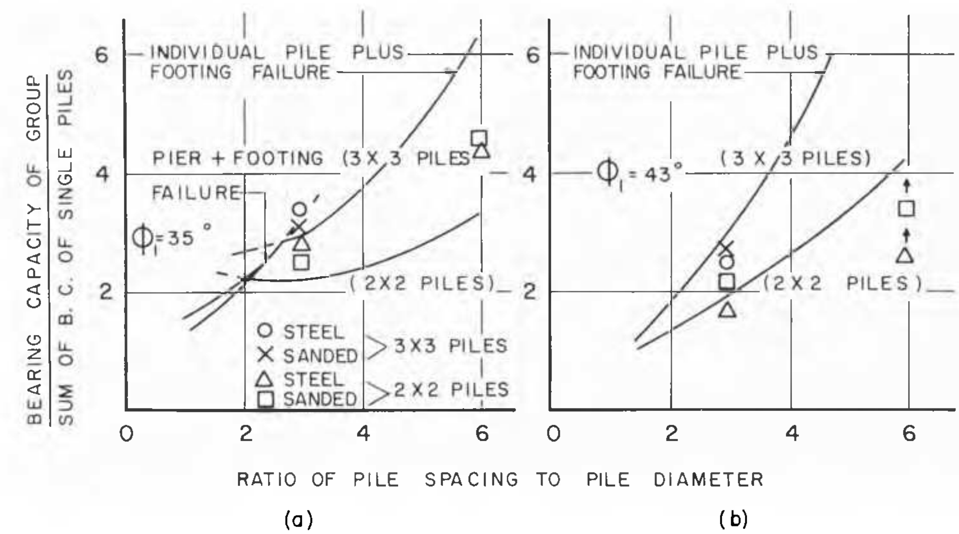

FIG. 6. Bearing capacity of piled foundations under central load in sand: (*a*) loose sand, (*b*) dense sand.

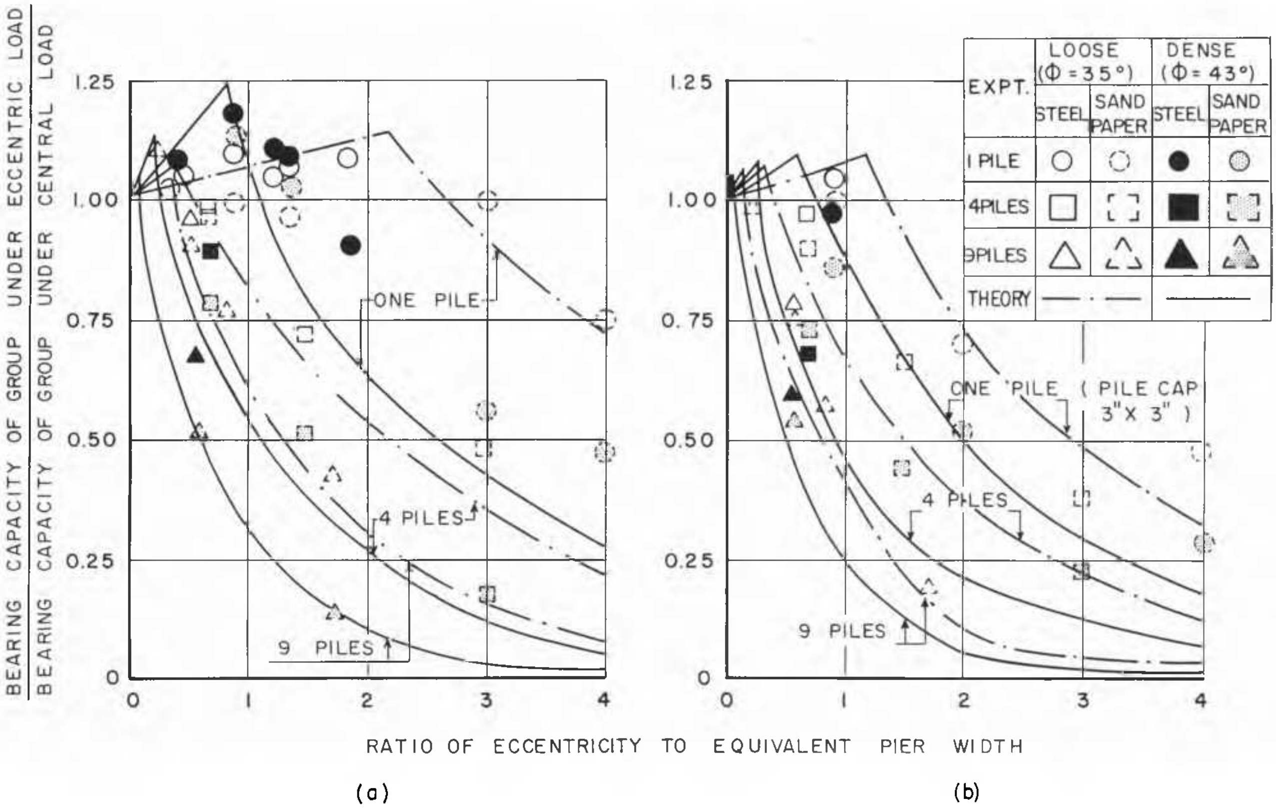

FIG. 7. Bearing capacity of pile groups under eccentric load in sand: (*a*) free-standing pile groups, (*b*) piled foundations.

theoretical and experimental results compare fairly well (Fig. 5). The total bearing capacity of a given number of piles in loose sand increases with smaller pile spacing from about 7 times the pile diameter to a maximum value at about twice the pile diameter. At about this pile spacing the failure criterion changes from individual pile failure to pier failure, when the bearing capacity decreases with smaller pile spacing. In dense sand the total bearing capacity decreases as the pile spacing decreases, and pier failure does not occur because of the effect of dilatancy. The critical value of the angle of internal friction, in which pile spacing has no significant effect on the total bearing capacity, was found to be about 40°. For a given pile spacing, the change of bearing capacity by group action increases with the number of piles, as would be expected.

For piled foundations under central load (Fig. 6) the total bearing capacity in loose sand increases with greater pile spacing and exhibits pier failure up to a pile spacing of about 3 times the pile diameter. For a greater pile spacing the total bearing capacity increases at a smaller rate and tends to support the estimated values. In dense sand pier failure does not occur, and the total bearing capacity is somewhat less than estimated.

For free-standing pile groups and piled foundations under eccentric load in both loose and dense sands the theoretical and experimental results are in fair agreement (Fig. 7). The total bearing capacity of a given number of piles increases somewhat with a small eccentricity of the load to a maximum value, after which the bearing capacity decreases rapidly with greater eccentricities. For a given ratio of eccentricity to equivalent pier width, the total bearing capacity decreases with a greater number of piles of a given length and approaches that of a shallow foundation, as would be expected.

CONCLUSIONS

The total bearing capacity of free-standing pile groups can be estimated from an extended bearing capacity theory of piles, which shows that in loose sand the bearing capacity is greater than that of the sum of single piles because of the compaction of the sand; the reverse holds true for dense sand because of dilatancy of the material. The total bearing capacity of piled foundations can be estimated from the bearing capacity of free-standing pile groups by allowing for the influence of the pile cap using simple methods of analysis.

Small eccentricities of the load have no significant influence on the bearing capacity of free-standing pile groups and piled foundations because the applied moment is mainly resisted by the earth pressure moment on the sides of the group. At larger eccentricities the total bearing capacity decreases rapidly because of smaller point resistance of the group by a reduction of the effective base area, as would be expected theoretically.

ACKNOWLEDGMENT

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