Centrifugal model studies on laterally loaded pile groups in sand

Etudes de modèles de centrifugation sur des groupes des pieux chargés latéralement en sable

K. R. KULKARNI, Professor, Indian Institute of Technology, Bombay, India
V. S. CHANDRASEKARAN, Professor, Indian Institute of Technology, Bombay, India
G. J. W. KING, Senior Lecturer, University of Liverpool, UK

SYNOPSIS The results of centrifugal model experiments conducted on single, two- and three-pile groups in medium dense, dry sand are presented and discussed. Two loading directions are considered for each group together with two and three diameter spacings. The results of laterally loaded single piles are compared with those estimated on the basis of subgrade reaction and elastic continuum theories in which the soil stiffness is assumed proportional to depth. Analysis of two-pile groups based on elastic continuum model and using interaction factors showed that even at small loads the observed values of deflections were larger than the computed ones. In the two-pile and three-pile groups the effective soil resistance to the rear piles was found to be diminished by interaction effects.

1. INTRODUCTION

In foundation engineering practice, piles are frequently used to resist large, horizontal loads from the superstructure. They are quite often installed in groups of several piles at fairly close spacings. Extensive literature is available on the laboratory and field performance of laterally loaded single piles and some methods based on certain simplifying assumptions have been proposed for their analysis and design (Reese and Matlock, 1956; Banerjee and Davies, 1978; Poulos, 1971).

O'Neil and Gazzally (1977) proposed a method based on p-y relationships, but introducing group interaction factors computed by means of the Mindlin's solution. Poulos (1971) made use of the integral equation method modelling the soil as an elastic continuum. Randolph (1981) presented simplified algebraic expressions for purposes of design based on extensive finite element studies and Poulos's results of continuum model. It is recognised that these methods of analysis do not adequately reflect the actual mechanism by which the load transfer takes place within the soil medium and among the individual piles of the group. Thus in order to evolve a satisfactory method of analysis, it is necessary to obtain for comparison results of laboratory model tests or full-scale field tests on laterally loaded pile groups.

In recent years, centrifugal modelling has been increasingly finding favour with research workers in connection with a variety of civil engineering problems. In this paper, the results of a few simple pile group tests under lateral loads in a medium sized centrifuge are presented and discussed with a view to identify some main trends of pile group behaviour.

2. SCOPE OF EXPERIMENTAL WORK

The experiments were conducted on the centrifuge at the Soil Mechanics laboratory of the University of Liverpool, U.K. The machine essentially consists of two buckets, 40 cm x 46 cm x 23 cm deep, hinged at the ends of a revolving arm at an effective radial distance of 1.15 m. The machine can develop a maximum acceleration of 200 g at 400 rpm. More details of the centrifuge are available elsewhere (King,et al 1984).

The soil used in the experiments was dry sand, fine grained and uniform. It had an effective size of 150 microns and a uniformity coefficient of 1.5. About 80 percent by weight had particle sizes between 150 and 250 microns. The sand was compacted in layers of 25 to 40 mm thickness using a hand vibrator with base dimensions of 100 mm x 150 mm. A projection in the base, 15 mm wide and 50 mm long, provided easy access during compaction to the narrow space within the pile groups. The unit weight of sand as compacted was 16 kN/m^3.

Considering the size of the centrifuge bucket and the instrumentation requirements, the model piles selected were of 24.5872 mm OD, 0.3048 mm wall thickness and 330 mm length (of which the embedded length was 180 mm). The material of the piles was 304-SS grade, stainless steel with the Young's modulus value of 1.9284×10^8 kN/m^2 (28×10^6 psi).

Two and three pile groups at two and three diameter spacings (2D and 3D) between centres and rigidly connected to an aluminium cap, 12.5 mm thick, were used in the experiments. The general arrangement of the set-up is shown in Fig. 1 and the load configurations in Fig.2. Repeat tests were carried out in all cases to ensure fair reproducibility in the data obtained.

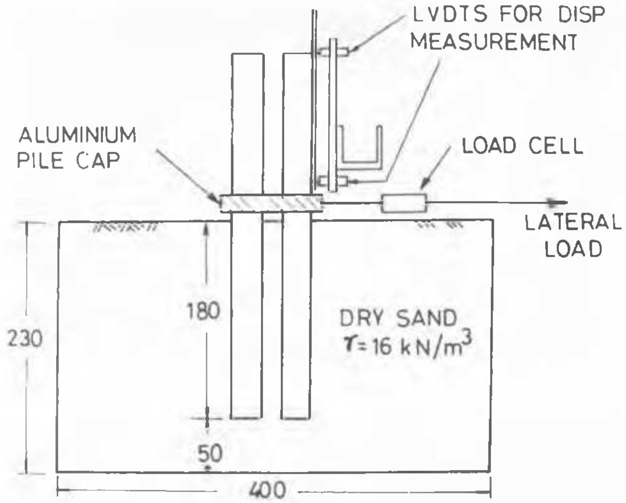

Fig. 1. Experimental Set-up

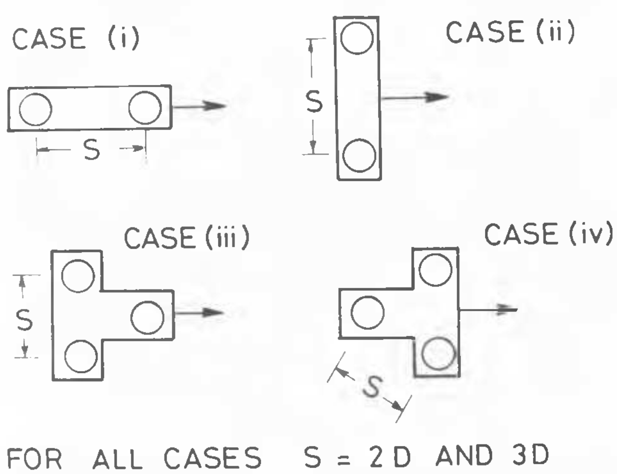

Fig. 2. Group and Load Configurations

Two piles were instrumented, one with 12 pairs and the other, with six pairs of strain gauges, fixed internally in the tubular section.Lateral load was applied to the pile cap through a cable pulled by a gear box-motor unit which was operated externally through slip rings. The applied load was measured by means of a load cell and the pile cap deflection and rotation measured through two displacement transducers. Lateral load was applied in suitable increments until the pile head deflections reached values of about 10 per cent pile diameter, i.e. about 2.5 mm. The model pile used in this investigation represents a prototype steel pile of 1.23 m diameter and 15.2 mm thickness embedded in sand to a depth of 9 m below the ground level. All experimental results are presented for the prototype.

3. RESULTS AND DISCUSSION

3.1 Single pile tests

The deflection at ground level and rotation at head are shown in Fig. 3. The load-deflection curve exhibits an initial linear variation upto a deflection of 5 to 10 mm (that is, upto about 0.4 to 0.8 per cent pile diameter), then a curvilinear portion upto about 50 mm deflection (corresponding to nearly 4 per cent pile diameter) and a third segment which continues to be linear even upto 120 mm deflection (about 10 per cent pile diameter). The pile itself showed no signs of permanent deformation.

By back-analysis the rate of increase of horizontal subgradereaction n_h was determined by matching the deflections at levels corresponding to one-half and one per cent pile diameter with the aid of coefficients developed by Reese and Matlock (1956). The corresponding n_h values worked out to 25676 kN/m^3 and 19929 kN/m^3. The pile length to characteristic length ratios L/T at these deflections were 3.73 and 3.55 respectively. It may be noted that these values are only slightly smaller than the lower limit for long, flexible piles. The results were also back-analysed using the elastic half-space model in which the elastic modulus is proportional to depth. The proportionality constant m^* for shear modulus, as defined by Randolph (1981), was found to have values of 4474 kN/m^3 and 3525 kN/m^3 for one-half and one per cent deflections at ground level respectively.

It may be seen that even within the small deflection range of one per cent, there is a large variation in the model parameters n_h and m^*. This indicates that linear theories have only limited applicability in the prediction of pile deflections.

The bending moment distributions along the pile length computed by both the approaches are shown in Fig. 4 along with the experimental values. Both the distributions agree reasonably well with the observed values in the upper half of the pile, while there is some difference in the lower half. The estimates of maximum bending moment and the corresponding depths are also in close agreement with the experiment.

The abovea analysis shows that the choice of model parameters is of crucial importance for prediction of pile behaviour. In this respect,

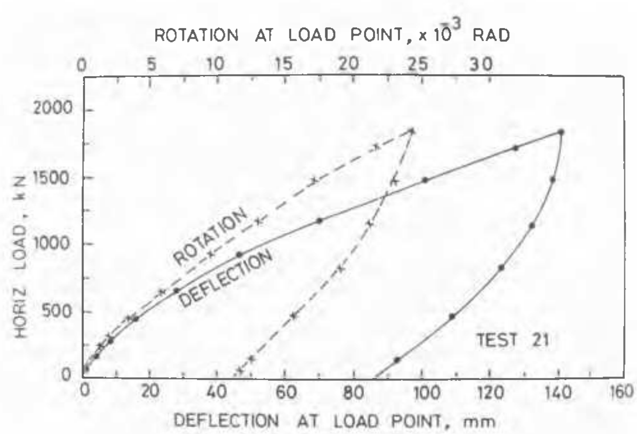

Fig. 3. Pile Head Displacements : Single Pile

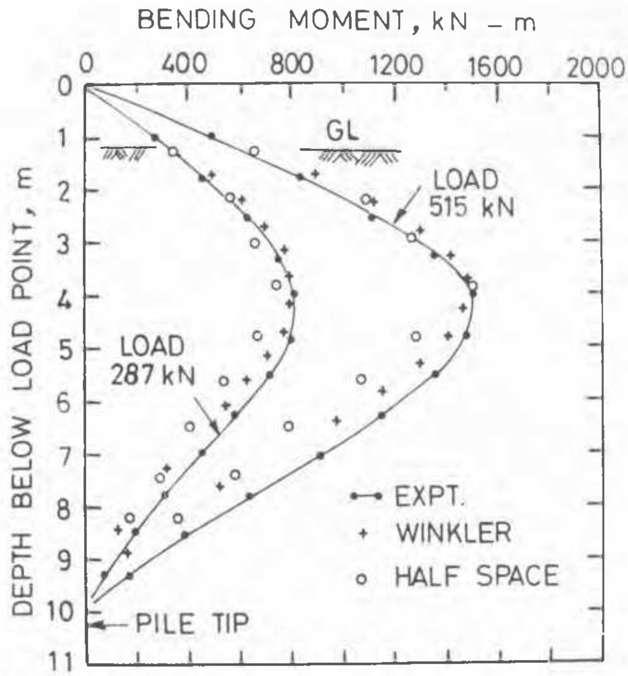

Fig. 4. Comparison of Bending Moments for a Single Pile

the subgrade reaction theory is less helpful for design purposes, since the n_h parameter is not unambiguously related to any basic soil characteristics.

3.2 Two-pile groups

The results of two-pile groups are shown in Fig. 5. When the pile groups are subjected to horizontal loads in a direction normal to the line joining the pile centres (case ii), a closer spacing of 2D is seen to make little difference compared to 3D spacing. Nevertheless the group load is less than that carried by two single piles. The difference, however, is small indicating a low level of interaction between adjoining piles. Computations based on the elastic continuum model, using the m* parameter determined for the single pile at one per cent deflection and using Randolph's (1981) interaction factors for this configuration, give loads of 669 kN for 2D spacing and 699 kN for 3D spacing. The corresponding observed value for both spacings was about 600 kN. Thus even at one per cent deflection, the computations tend to overestimate the lateral load.

When lateral loads are applied along the line joining the pile centres in a two-pile group (case i), the group behaviour is influenced by a combination of three effects, viz. the interaction between piles through the soil medium; the axial push-pull effect which would increase the group rigidity depending upon the pile spacing in the configuration; and the type of restraint that develope between the cap and the individual piles.

The results indicate that, in general, for this configuration the load carried by the group at a given deflection is less than twice the corresponding single pile loads. However, at 3D spacing, the load per pile at a given deflection is larger than at 2D spacing.

Estimates of lateral load for one per cent deflection were made on the basis of the continuum model using the interaction factors and the m* parameter determined for the single pile. At 2D spacing, the load required was found to be 915 kN, compared to the observed value of 750 kN. For 3D spacing, the computed and measured lateral loads were 1238 kN and 850 kN respectively. The consistently lower experimental values of loads compared to the calculated ones indicate that even at very small deflections, the elasticity theory is inadequate, in as much as it does not account for the plastic flow of the soil behind and around the front pile and the consequently diminished reaction on the rear pile.

It may be noted from Fig. 6 that the front pile experiences a much larger bending moment than

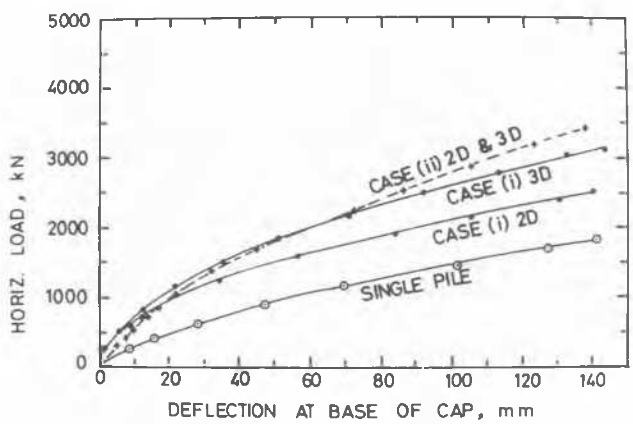

Fig. 5. Comparison of Two-pile Groups

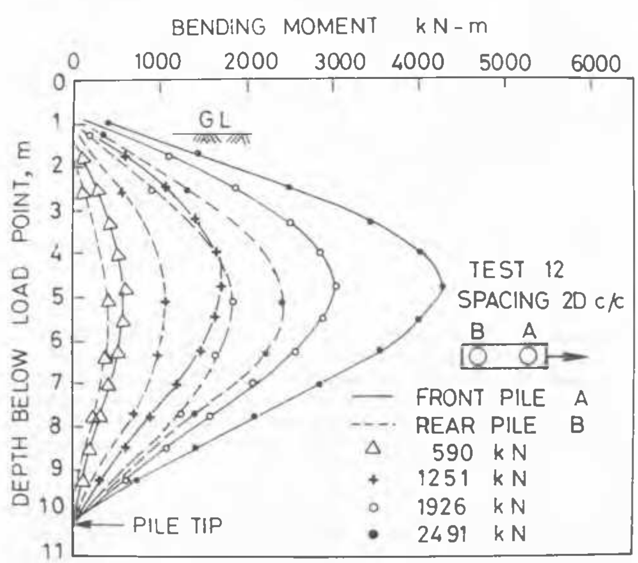

Fig. 6. Bending Moments in Two-pile Groups

the rear pile to the extent of about 100 to 120 per cent. The elastic continuum model, however, envisages equal sharing of the horizontal load among the individual piles and consequently leads to an underestimate of the flexural stress.

The observed slopes of the bending moment curves at the level of the base of the cap indicate that the front pile shares a larger proportion of the applied load. This should be expected in view of the greater soil resistance likely to be encountered by the front pile. The restraining moments at the cap level are also observed to be larger for the front pile.

3.3 Three-pile groups

The experimental results for three pile groups are shown in Fig. 7. It may be seen that at 2D spacing both the load cases (iii) and (iv) have produced nearly identical load-deflection behaviour. The loading direction appears less relevant at this close spacing. At 3D spacing, the two front piles in case (iv) together mobilise a much higher soil resistance than the load case (iii). It was observed that the maximum bending moments in the front and rear piles are nearly equal and they also occur at about the same depths. This does not, however, imply equal sharing of horizontal load among the piles, since the slopes of the bending moment curves, that is, the shear, at the level of the base of the cap are significantly different for the front and rear piles. This observation emphasizes the fact that the rear piles experience a much lower level of soil resistance at nearly all stages of loading — a fact not considered in the elastic theories currently in use.

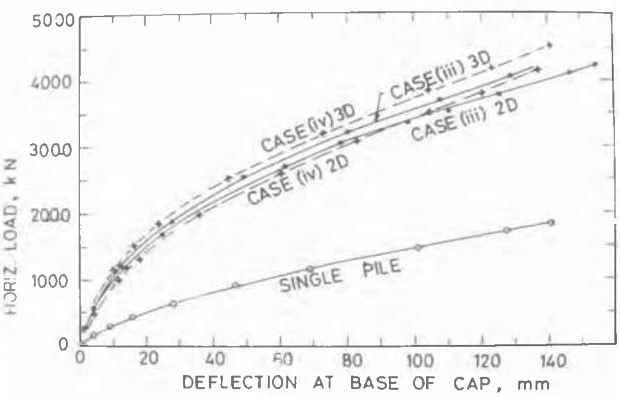

Fig. 7. Comparison of Three-Pile Groups.

4. CONCLUSIONS

The study has shown that with a judicious choice of appropriate parameters, the behaviour of single piles can be predicted fairly closely at deflections less than about one-half per cent pile diameter. At larger deflection levels, the non-linearity of the soil behaviour becomes increasingly important.

The consideration of non-linearity and possible plastic flow of soil around the piles is found to become even more important in the prediction of group behaviour. For two-pile groups subjected to lateral loads along the line joining the pile centres, the current elastic theories consistently overestimate the loads even at very small deflection levels. It is also noted that the front pile shares a greater proportion of the applied lateral load and also experiences a much larger magnitude of flexural stress than the rear pile. This possibility is not considered in the computational models based on elastic approach.

In three-pile groups, the maximum bending moments in the front and rear piles are found to be nearly equal at a given loading; but the shear at the cap level is considerably smaller for the rear pile than for the front one.

5. REFERENCES

Banerjee, P.K. and Davies, T.G. (1978). The behaviour of axially and laterally loaded single piles embedded in nonhomogeneous soils. Geotechnique (28), 3, 309-326.

Chandrasekaran, V.S. and King, G.J.W. (1982). Laterally loaded piles : Finite Element analysis and pilot centrifugal model studies. Report submitted to the University of Liverpool, U.K.

King, G.J.W., Dickin, E.A. and Lyndon, A.(1984). The development of a medium size centrifugal testing facility. Proc. Sym. on the Application of Centrifuge Modelling to Geotechnical Design. University of Manchester, U.K., 25-46.

Kulkarni, K.R. and King, G.J.W. (1984). Centrifuge tests on laterally loaded pile groups in sand. Report submitted to the University of Liverpool, U.K.

O'Neill, M.W. and Ghazzaly, O.I. (1977). Analysis of three dimensional pile groups with nonlinear soil response and pile-soil-pile interaction. 9th Annual OTC, Houston, Texas, 245-250.

Poulos, H.G. (1971).Behaviour of laterally loaded piles : I-single piles. J. Soil Mech. Fdn. Div., ASCE (97), SM5, 711-731.

Poulos, H.G. (1971). Behaviour of laterally loaded piles : II-pile groups. J. Soil Mech. Fdn. Div. ASCE (97), SM5, 733-751.

Randolph, M.F. (1981). The response of flexible piles to lateral loading. Geotechnique (31), 2, 247-259.

Reese, L.C. and Matlock, H. (1956). Non-dimensional solutions for laterally loaded piles with soil modulus proportional to depth, Proc. 8th Texas Conf. SMFE, 1-41.

Schofield, A.N. (1980). Cambridge Geotechnical Centrifuge Operations. Geotechnique (30), 3, 227-268.