Experimental Study of Eccentric Loading on Single Piles

Etude Expérimentale d'un Chargement Excentrique sur Pieux Individuels

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SYNOPSIS

This paper presents the results of an experimental study on the effect of eccentric loading on single piles particularly in relation to soil response and bearing capacity and to the structural behaviour of the pile. The study was made on end-bearing and on friction piles in the field as well as on model piles in the laboratory. In order to monitor pile behaviour under eccentric loads of up to ultimate failure and at eccentricities of from zero to two pile diameters, a model pile was instrumented such that the distribution along the shaft of axial load, bending moment, horizontal shear force and lateral movement could be measured. The results showed that eccentric loading had little effect on the load-settlement behaviour at the pile head and that with restraint of the pile top, the embedding soil produced a small increase in bearing capacity. However, with a "buried pile", the effect was to decrease slightly the ultimate load. The substantial influence which eccentric load has on the distribution of bending moment and horizontal shear along the length of the pile shaft, was confined to the upper half of the pile.

INTRODUCTION

A single pile is seldom placed with such accuracy that the axis of the pile will coincide with the axis of application of the resultant force. This is more so in the case of a building complex in which each column is supported by a single pile. Most codes of practice and specifications stipulate a maximum eccentricity irrespective of the size of pile, the magnitude of the eccentric load or the condition of the soil in which the pile is embedded. For example CP 2004:1972 - The Code of Practice for Foundations - stipulates that piles should not deviate more than 3 inches from their designed positions at the working level of the piling rig and that any pile deviating beyond this limit and to such an extent that the resulting eccentricity cannot be taken care of by redesign of the pile cap or pile ties should be replaced or supplemented by one or more additional piles.

This paper presents the results of an experimental study of the effect of various eccentricities in loading on (a) the ultimate capacity of the supporting soil, (b) the load-settlement relationship at the pile head and (c) the behaviour of a single pile as a structural member particularly the distribution along the length of the pile of bending moment, shear and lateral displacement.

MODEL PILES

Load-settlement observations were made at the pile head of single steel piles of 1 in. diameter which had been driven at a constant rate of penetration into remoulded lateritic soil to depths of from 9 to 12 inches.

Table I gives a typical set of results. The model pile in this test series was driven to a depth of 9 in. into lateritic soil remoulded at a moisture content of 15% and a bulk density of 110 lbf/cu.ft. Vertical static loads were applied in the first load test, at the centre O of the cross-section. The eccentricity was then increased along a diameter through O to 2.5, 5.0, 7.5 and to 10.0 mm in the fifth load test. In the sixth and seventh load tests, the loadings were applied on the opposite side of O at eccentricities of 3.0 and 6.0 mm respectively.

At each value of eccentricity the static loads were increased in successive steps of about 25, 40, 60, 80 and 90% of the ultimate value of the driving load.

The ultimate load is determined by evaluating the inverse slope 1/m of the plot of Δ/P against an abscissa of Δ, where Δ is the settlement of the pile head corresponding to a load P (CHIN - 1972). As is seen from Table I, eccentric loading does not affect the supporting capacity of the soil as the values of 1/m for the seven different eccentricities do not differ significantly. Further, there is a good linear relationship between Δ/P and Δ, for all values of eccentricity e; that is, the relationship between P and Δ remains hyperbolic for all the eccentricities.

END BEARING PILES

Eccentric loading tests were carried out on three Franki piles of nominal diameter 17 in. The piles were embedded 20.5, 18.3 and 25.5 ft. in soil of which the upper layer of about 15 ft. was essentially loose fill with a SPT value of one. Weathered sandstone was encountered at a

TABLE I

P - lbf (x 11.59)	Δ (0.0001")	Δ/P	r	1/m
First load test:		Eccentricity e = 0.0 mm		
50	7.5	0.150		
72	17.2	0.239		
84	24.9	0.296		
95	33.2	0.350		
107	194.9	1.820	0.9998	112 (1291 lbf)
Second load test:		Eccentricity e = 2.5 mm		
50	4.1	0.082		
61	7.5	0.123		
72	12.9	0.179		
84	19.1	0.228		
95	26.5	0.279		
106.5	266.7	2.502	0.9999	109 (1261 lbf)
Third load test:		Eccentricity e = 5.0 mm		
51.5	2.4	0.047		
62	5.8	0.094		
74	9.4	0.127		
85	15.2	0.180		
97	22.4	0.231		
109	266.9	2.450	0.9999	111 (1282 lbf)
Fourth load test:		Eccentricity e = 7.5 mm		
49.5	4.4	0.089		
61	7.9	0.129		
72.5	11.4	0.157		
84	18.4	0.219		
96	28.4	0.296		
106.5	84.1	0.791	0.9998	114 (1325 lbf)
Fifth load test:		Eccentricity e = 10.0 mm		
50.5	6.4	0.127		
61	8.9	0.146		
72	14.4	0.200		
83.5	20.8	0.249		
94.5	27.7	0.293		
106.5	76.5	0.718	0.9996	119 (1388 lbf)
Sixth load test:		Eccentricity e = -3.0 mm		
50	3.5	0.070		
62	6.1	0.098		
72.5	9.6	0.132		
84	15.8	0.188		
95.5	22.0	0.230		
106.5	237.0	2.220	0.9999	109 (1260 lbf)
Seventh load test:		Eccentricity e = -6.0 mm		
51.5	2.2	0.043		
62	4.1	0.066		
74	8.1	0.109		
85.5	14.3	0.167		
97	21.9	0.226	0.9991	108 (1252 lbf)

depth of about 20 ft. at which the SPT rapidly rose to 50. These three test piles were therefore, essentially end-bearing piles.

The eccentric loading was carried out soon after a number of repeated axial load tests. The eccentricity was increased by ¼ inch after each test up to a maximum eccentricity of 1¼ in.

It is observed that up to an eccentricity of 1¼ in., eccentric loading has very little effect on the load-settlement behaviour at the top of the piles. Figure 1 gives the load-settlement curves for Test Pile No. 3

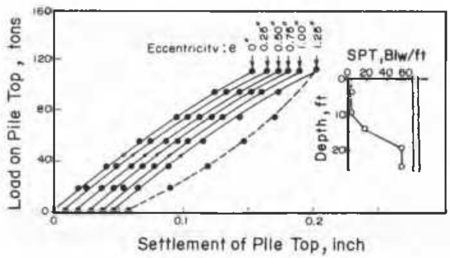

Fig. 1 - Load-settlement curves - eccentric loading on Franki pile No. 3

FRICTION PILES - TUBULAR SECTION

Two tubular steel piles - X, which is a hollow rectangular section 6"x3", and Y, a steel pipe 5" diameter - were driven and embedded 15 ft. into the ground. Except for the top three feet which had been consolidated by surface activity, the soil was a fairly uniform sandy clay for a depth of 35 ft. In-situ vane tests gave an average sensitivity of 1.5. The SPT values were 6 for the top three feet of soil and thereafter they averaged 5 for a depth of 30 ft.

A channel section was welded on to the top of each of the piles to provide a proper seating for the jack and to enable the load to be applied at the required eccentricity. Jack reaction was provided by means of a reaction beam which was anchored by four reaction piles.

Initial load tests showed that for any given eccentricity, repeated CRP tests yielded fairly consistent ultimate loads and load-settlement behaviour after the first cycle. In the case of the 6"x3" pile, compression tests were carried out at eccentricities of 0, 1, 2, 3 and 4 inches (measured from the centre of the cross-section), first allowing the pile head to deflect freely under the eccentric load and then the test series was repeated with the pile head restrained against lateral displacement. The load-settlement results are given in Figure 2.

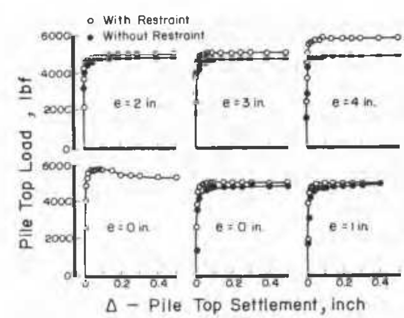

Fig. 2 - Load-settlement curves - eccentric loading on 6"x3" tubular steel pile.

It is clear that the ultimate capacities of the soil are slightly higher when the pile head is restrained. This is confirmed by the test results of the 5" diameter steel pile.(Table II). As is clear from Table II, for the same eccentricity, a slightly higher ultimate capacity is provided by the soil if the pile head is more effectively restrained against lateral displacement.

TABLE II

Eccentricity (inch)	Ultimate Load (lbf)	Lateral Displacement At Pile Head at Ultimate Load (inch)
1	7250 7170	0.021 0.037
2	7250 7170	0.014 0.100
3	7340 7170	0.029 0.184
4	7600 7170	0.020 0.222
5	8060 7520	0.025 0.283

INSTRUMENTED MODEL PILE

Static load tests were carried out on a 25 mm diameter instrumented pile, 2 metres long. This aluminium pile was installed in a large stiff container by building up beds of dry sand round it. The flexural rigidity EI of the pile was 4.90×10^8 $N\text{-}mm^2$ and the coefficient of horizontal subgrade reaction of the embedding sand at a depth of 0.5 metre was 90 MN/m^3.

In order to monitor pile behaviour, the pile was instrumented such that the distribution of axial load, bending moment, shear and lateral movement could be measured. All these tests were performed up to plunging failure at eccentricities of 0, ¼, ½, 1 and 2 pile diameters. The condition at the pile top was such that it was free to rotate and move vertically but not laterally.

The test results show that the effect of eccentricity on ultimate load P_{uc} is small; P_{uc} appears to decrease slightly with increasing e (Table III).

TABLE III

e	P_{uc}
0 D	725 N
¼ D	705 N
½ D	705 N
1 D	666 N
2 D	686 N

The effect of eccentricity on the load-settlement of the pile top is again small. (Figure 3)

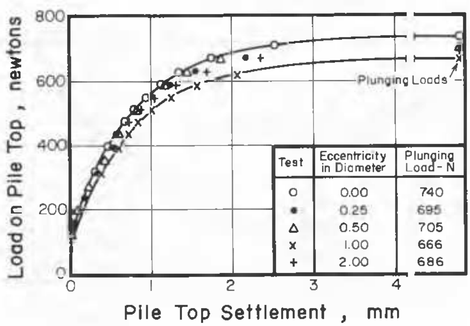

Fig. 3 - Load-settlement curves for eccentric loading - 25 mm diameter pile.

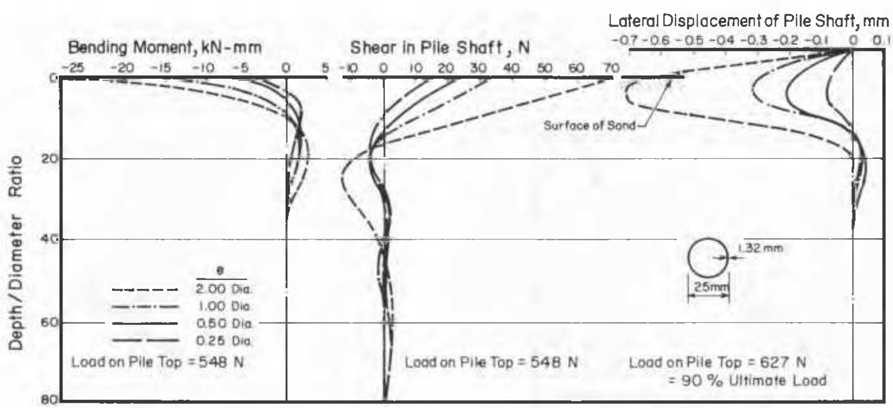

Fig. 4 - Distribution of bending moment, shear and lateral pile movement.

For loads over 50% of P_{uc}, the settlement is greater for increasing e for a given load. This is partly due to bending in the top half of the pile.

The effect of increasing e, for a given pile top load, is to increase the bending moment, shear and lateral movement. This is to be expected. Figure 4 shows that the effect of increasing e on bending moment, shear and lateral movement is substantial but is confined to the top half of the pile. The pile is thus behaving as a "long pile".

The effect of eccentricity on the distribution of axial load is hardly noticeable, considering the experimental scatter (Figure 5).

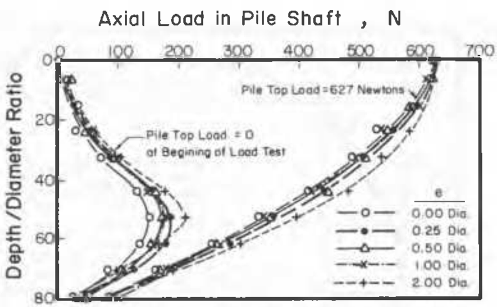

Fig. 5 - Distribution of axial load along shaft for pile top loads of (1) zero and (2) 627N (≑ 90% of ultimate load)

When considering the shaft friction in the top half of the pile, the effect of increasing e appears to decrease the shaft friction. This is probably due to bending (Figure 6). This accounts for the reduction of P_{uc} for increasing e. However, the reduction in shaft friction is very small (Figure 6).

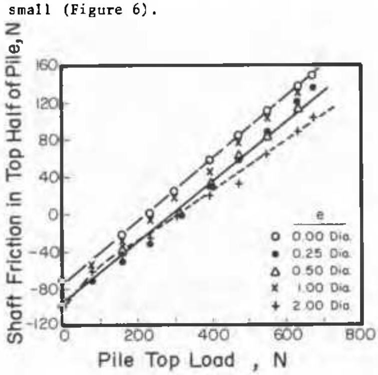

Fig. 6 - Response of shaft friction in top half of pile to pile top load.

The response in toe load due to pile top load is hardly affected by eccentricity (Figure 7).

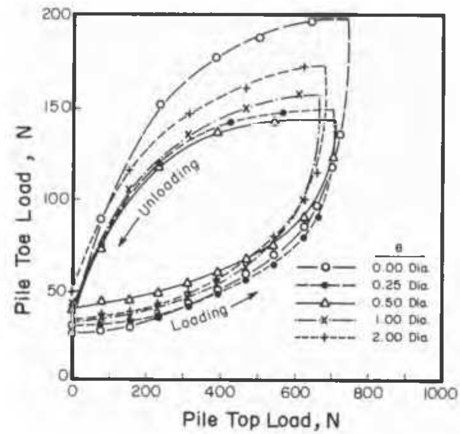

Fig. 7 - Response of toe to pile top load.

CONCLUSIONS

This experimental study would indicate that eccentric loading has greater effect on the capacity of a single pile as a structural member than on the capacity of the soil to support the load transferred to it by the pile.

There is a small increase in the supporting capacity of the embedding soil with increase in the effectiveness of the restraint of the pile head against lateral movement.

Eccentric loading has little effect on the load-settlement relationship at the pile top. This relationship remains approximately hyperbolic.

The effect of eccentric loading is to increase the bending moment, shear and lateral movement of the pile. For the instrumented pile and sand used, these effects are confined to the top half of the pile.

Due to pile bending, shaft friction in the top half of the pile decreases with increase in eccentricity.

Eccentric loading has little effect on the response of toe to pile top load.

ACKNOWLEDGEMENT

The experiments on the instrumented pile were carried out by the second author at the University of Sheffield. The authors would like to thank Professor T.H. Hanna, Head of the Department of Civil and Structural Engineering, University of Sheffield, for permission to publish the results.

REFERENCE

Chin, F.K. (1972), "The inverse slope as a prediction of ultimate bearing capacity of piles", Proc. Third Southeast Asian Conf. on Soil Engg. pp. 83-91.