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A study on failure surface in case of pullout of pile groups in sand

Une étude sur la surface de rupture en cas de dégageement des groupes de pieux dans le sable

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ABSTRACT : Uplift capacity of anchors depends on the shape and extent of failure surface. Once the failure surface is established uplift capacity may be obtained by limit equilibrium method. Failure surface profiles for single piles and pile groups (2x2, triangular, 3x3) were determined from laboratory tests and finite element formulation. Nature of failure surface profiles were found to be different for deep and shallow anchors. Higher embedment ratio yielded failure surface of greater extent.

1 INTRODUCTION

Piles and pile groups constructed under transmission towers, offshore platforms etc. are often subjected to uplift due to horizontal load and wave action. The uplift capacity is influenced by the embedded depth, spacing and diameter of piles and strength of foundation medium. These parameters determine the shape and extent of failure surface. Once the failure surface is established the uplift capacity may be computed considering limiting equilibrium of the system. Meyerhof and Adams (1968), Meyerhof ((1973), Vesic (1975), Tagaya et. al. (1988), Rahman et. al. (1990) stated that failure surface profiles of shallow foundation had a distinctly convex curvature towards the anchor and they reached the ground surface at $(45^\circ - \phi/2)$, [ϕ = angle of shearing resistance] to the horizontal. The profiles started tangentially to the vertical surface. Meyerhof and Adams (1968) reported that in case of deep anchors in dense sand failure surface progressed from base and ultimately became vertical. No attempt was made to establish the failure surface by either experimental or theoretical means. Only some assumptions regarding the failure surface were made. In the present investigation an attempt has been made to observe the failure surface for different pile groups. The experimental results are supplemented with the help of a finite element model of different cases.

2 EXPERIMENTAL INVESTIGATION

2.1 Test programme

Tests were carried out with 25mm diameter aluminium model piles of varying embedment length, spacing and arrangement of piles in a group. The test programme is shown in Table 1.

2.2 Test procedure

Fig. 1 shows the test setup. A loading frame was fabricated and put in position. A screw jack was fixed centrally in an inverted position with horizontal reaction beam of the frame. A segmented aluminium tank was put below the screw jack in central position.

Model piles were placed along with the pile cap. One aluminium pile cap along with the piles were connected to a proving ring attached to the jack. Sand pouring with Ennore sand (uniformity coefficient = 1.1) was then started by rainfall technique to achieve a placement density of 1.62 gm/cc. Heated vermicellis were placed around the pile / pile group in a horizontal plane in different radial directions for observing the

Table 1. Test Programme

No. of Piles	Spacing S(cm)	Embedment Length L(cm)	Arrangement of piles of group single pile Equilibrium triangle
1	-	60,75,90	--
3	7.5, 10, 12.5 (3d) (4d) (5d)	-do-	Equilateral triangle
4	-do-	-do-	Square
9	-do-	-do-	-do-

d=pile diameter

surface of failure after the test at any level. This was repeated at each 10cm interval along the length of piles as the filling progressed. To measure the upward axial movement of pile/pile group two dial gauges were fixed with the help of holding arrangement. The uplift load was applied gradually. At every stage proving ring dial and strain dial readings were noted. The test was continued till failure. Even after failure upward movement was applied to the pile/pile group with the expectation of development of failure surface and thereby breaking of vermicellis. The aluminium boxes of the segmented tank were then taken out one by one. After taking out one box the sand was removed very slowly and carefully. At first the end of the vermicellis was observed by removing sand. Then very carefully the sand was removed by fingers when the vermicellis were allowed to rest on the bottom sand. Thus it became possible to locate the points at which the vermicellis broke due to pullout of the piles / pile group. The distances of these points from the outer periphery of the pile / pile group were measured directly by scale. This was continued till all the boxes were taken out except the last one. At a particular level the average of the distances of the broken ends of vermicellis from outer periphery of the pile / pile group was considered to be a point on the failure surface at that particular level. The trace of failure surface for each test was obtained by joining these points located at different levels.

3. THEORETICAL INVESTIGATION

Finite Element analysis was carried out for single pile and pile groups (2x2, triangular, 3x3) to explore the possibility of arriving at the uplift capacity and the most probable failure surfaces. The pile groups were approximated to axisymmetric cases which may

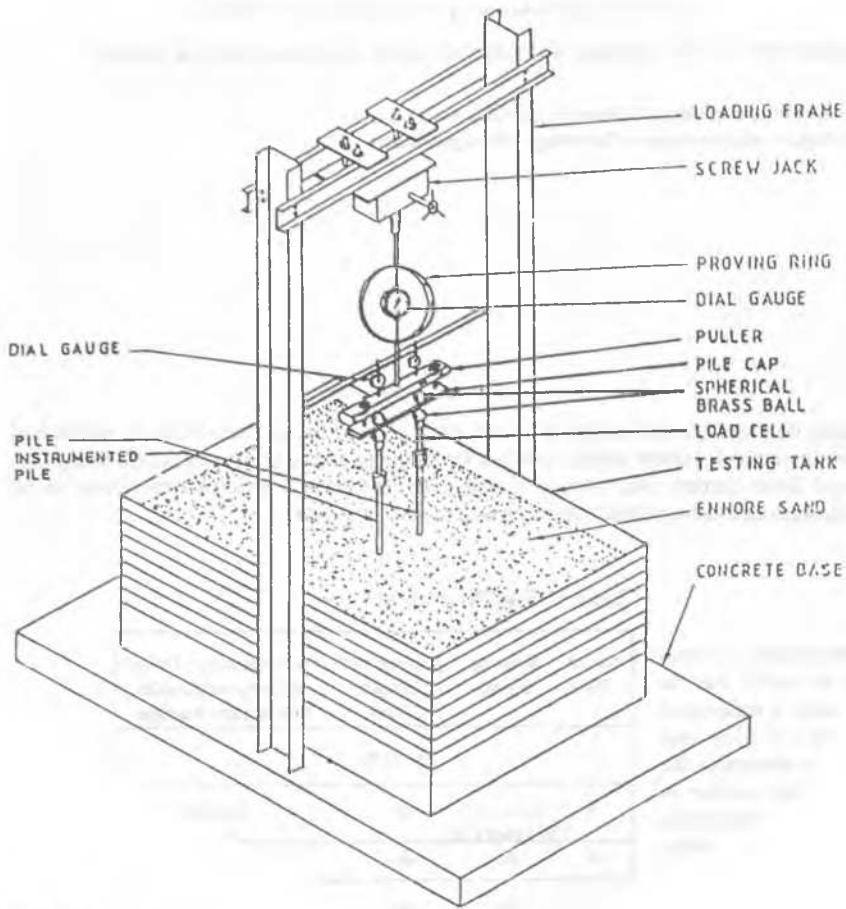


Fig. 1.. Test Set up

be considered to the within marginal error taking into account the convenience of the method. The cross section of each of these groups was transformed into equivalent hollow circular section retaining the areas of cross section and the surface of contact with soil same. The wall of the equivalent cross section was considered to be perforated and ratio of length of solid wall to total length along periphery at any level was taken as m . Under this condition Young's modulus (E_{eq}) of an equivalent material may be taken as $E_{eq} = m E_{al} + E_s$ where E_{al} and E_s are Young's modulus of aluminium and soil respectively. The equivalent material was considered to remain within the ring thickness and the central hollow space was assumed to be filled up with soil.

Soil pile system was discretized with 8-noded axi-symmetric rectangular iso-parametric elements. Material non-linearity of soil was considered and pile elements were taken to be elastic.

The equilibrium equation is given by $[K_s] \{\delta\} = \{F\}$ (1)

Where $[K_s]$ = global stiffness matrix
 $= \int_v [B]^T [D_e] [B] dv$

$\{\delta\}$ = global displacement vector

$\{F\}$ = nodal force vector

$[B]$ = strain displacement matrix

$[D_e]$ = elasticity matrix

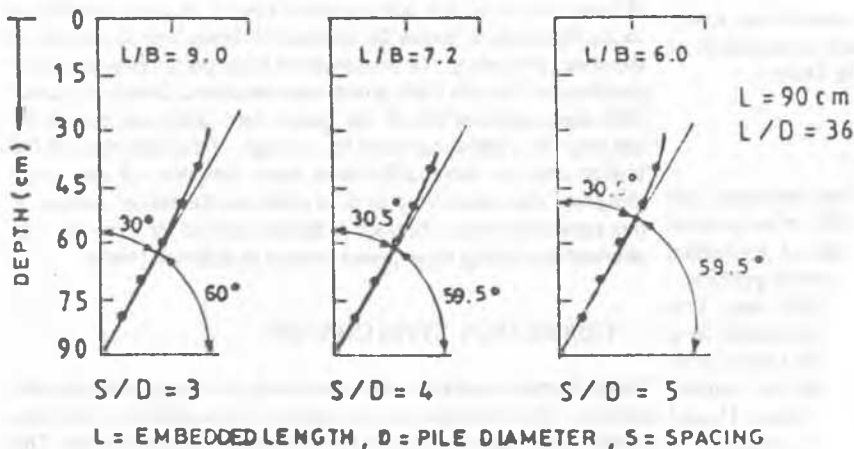


Fig. 2.1. Observed failure surfaces (group 2x2)

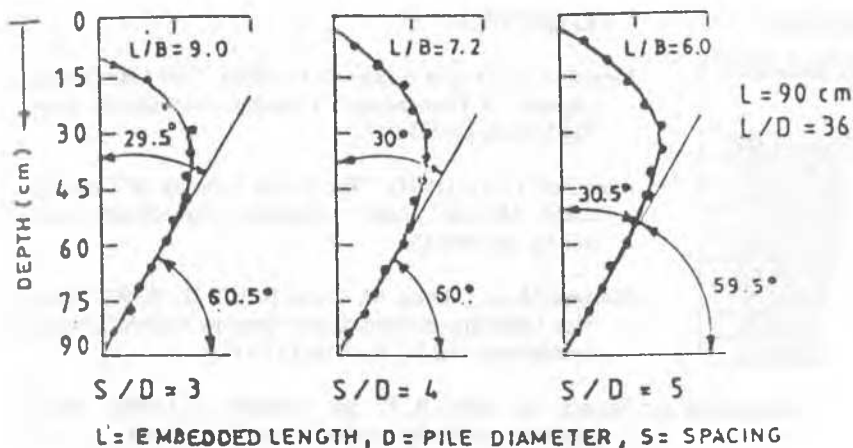


Fig. 2.2. Theoretical failure surfaces (group 2x2)

$$E \begin{bmatrix} 1-\nu & \nu & \nu & 0 \\ \nu & 1-\nu & \nu & 0 \\ \nu & \nu & 1-\nu & 0 \\ 0 & 0 & 0 & 1-2\nu \end{bmatrix} \quad (2)$$

[E = Young's Modulus
 ν = Poisson's ratio]

3.1 Material non-linearity of soil

Soil has been idealized as an elastic perfectly plastic material satisfying Mohr-Coulomb yield criterion.

Yielding can occur only if stress (σ) satisfies the general yield criterion

$$F(\sigma, K_h) = 0 \quad (3)$$

[K_h = hardening parameter and F is Yield Function]

A potential surface is defined by

$$Q = Q(\sigma, K_h) \quad (4)$$

It defines plastic strain increment in terms of Q and σ.

The particular case Q=F is known as associated plasticity, which was considered in the present study taking into account the point on load vs movement curve corresponding to ultimate load for different angles of dilatancy.

The elasto plastic matrix [Dep] is given by

$$[Dep] = [De] - [De] \left\{ \frac{\delta Q}{\delta \sigma} \right\} \left\{ \frac{\delta F}{\delta \sigma} \right\}^T [De] \quad (5)$$

[A + {δF/δσ}^T [De] δQ/δσ]⁻¹, where A is a factor which depends on hardening.

3.2 Solution procedure

The analysis was carried out by initial stress method. The load was applied in incremental steps and within an increment the equilibrium was obtained by modified Newton-Raphson technique.

3.3 Failure surface from theoretical formulation

The maximum shear stress at the middle of elements at any level was observed to fall rapidly starting from pile surface and gradually became constant as it approached boundary. The point of sudden change of slope of the curve was taken as the discontinuity of stress across the probable failure surface at a

level. The points, thus located at different levels were joined to obtain the profile of the failure surface.

4 RESULTS AND DISCUSSION

4.1 Failure Surface Profiles

The experimentally and theoretically obtained failure surface profiles for a typical 2x2 group are shown in fig 2.1 and fig 2.2 respectively. The following salient points were noted after studying observed and theoretical failure surfaces for all the cases of single piles and pile groups.

- (a) There was a distinct difference in the nature of profiles for L/B > 6.0 (deep) and less than 6.0 (shallow). This was noted for both observed and theoretical profiles.
- (b) For shallow groups the failure surface was found to start from the pile tip almost tangentially to the vertical boundary of the group with convex curvature towards pile group and strike the top surface. This was revealed from both the observed and theoretical profiles.
- (c) The deep group yielded failure surfaces starting near pile tip at about (45-φ/2) with vertical. This indicates that the direction of major principal stress was vertical and along the axis of pile/pile group as it should be. The profiles had a concave curvature towards the pile unlike those for shallow groups. The theoretically obtained profiles were similar to the observed ones except that the theoretical ones came back

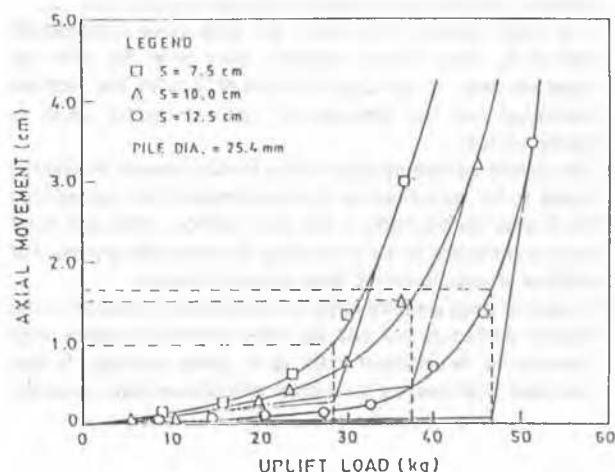


Fig. 3. Uplift load vs. axial movement curve (group 2x2)

Table 2. Ultimate Uplift Capacity P_u (Group: 2x2)

Spacing to diameter ratio	Embedded Length	P_u (Observed)	P_u (theoretical)
3	60	17.5	21.26 (21.48)*
3	75	19.9	24.03(20.75)
3	90	24.0	29.13(21.38)
4	60	23.1	28.67(24.1)
4	75	26.5	32.57(22.90)
4	90	32.0	39.74(24.19)
5	60	27.4	33.64(22.8)
5	75	34.7	39.59(24.9)
5	90	38.5	47.78(24.1)

* Values in parenthesis indicate variation in % with respect to experimental value.

to the boundary of the pile/pile group and approached the top surface along the vertical boundary of the pile/pile group whereas the observed ones did not reach the top surface.

- (d) Angle of inclination of tangent to the failure surface at the pile tip with vertical increased with increase of embedment ratio at a given spacing. The angle was also observed to increase with spacing for a given embedment ratio. This was found both for observed and theoretical ones.
- (e) The observed profiles fitted well with logarithmic spiral but the theoretical ones fitted well with second degree polynomial.

4.2 Ultimate Uplift Capacity

Uplift load vs axial movement curve was plotted for each test. A typical curve for 2x2 group is shown in fig 3. The ultimate uplift capacity was obtained by conventional double tangent method as the curves were nonlinear except for the last part for most of the cases. Table 2 presents the values of ultimate uplift capacity obtained by observation and Finite Element Method for group 2x2. It may be observed from the table that theoretical values overestimate the experimental ones approximately by 20-25 % only. The assumptions involved in the theoretical analysis may, therefore, be considered to be reasonable.

5. CONCLUSIONS

- (a) The shape of the observed failure surface is curvilinear and concave downwards for shallow groups (embedment ratio < 6.0) while convex downwards for deep ones (embedment ratio > 6.0). The failure surfaces start near the pile tip approximately at an angle of $(45-\phi/2)$ with the vertical indicating that the direction of major principal stress is nearly vertical.
- (b) The failure surface established by Finite Element Method is found to be very close to the experimental one except that the former comes back to the pile surface, while the latter stops somewhere in the foundation for deep pile groups. For shallow groups, however, both are nearly same.
- (c) In case of deep anchors angle of inclination of tangent to the failure surface at the pile tip with vertical increases with increase of embedment ratio at a given spacing. It also increases with spacing for a given embedment ratio anchors.

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