MODEL STUDY OF VERTICAL PILES SUBJECTED TO CENTRAL INCLINED LOADS

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ABSTRACT: The ultimate bearing capacity of the single vertical model piles of Mild steel, Aluminium and PVC with different L/d ratios, has been determined under central inclined load with different inclinations ranging from vertical to horizontal. The ultimate bearing capacity of pile groups with L/d @ 25 arranged in inline (1 × 4) and side-by-side (4 × 1) pattern spaced @ 3 times pile diameter c/c, has been determined under central inclined load with different inclinations ranging from vertical to horizontal. On the basis of model test results, the influence of inclination on the ultimate bearing capacity can be represented by simple interaction between the ultimate load and the ultimate vertical load, indicated by reduction factor.

1. INTRODUCTION

Pile foundations of offshore structures, transmission towers, wind energy converters, are often subjected to inclined loads and moments from usual structural dead load and horizontal loads generated by wind, waves, earth pressure etc. For proper functioning of such structures, two criterias must be satisfied: (1) a pile should be safe against ultimate failure (2) normal deflection at working loads should be within the permissible limit. For design of such piles, quantitative estimates of piles subjected to inclined compressive loading are needed.

2. BRIEF REVIEW

If a vertical pile is subjected to an inclined and eccentric load, the ultimate bearing capacity in the direction of the applied load is intermediate between that of a lateral load and a vertical load. When load acts vertical, it is resisted by pile through skin friction and base resistance but when load acts with inclination, the deficiency in the base resistance and to some extent in the shaft friction leads to decrease in carrying capacity of single pile. Current design practice involves separate analysis of the axial and lateral responses of piles and does not consider the effect of interaction between the different load directions. Model tests to determine pile load capacity have been reported by Tschebotarioff (1953), Yoshimi (1964), Awad & Petrasovits (1968), Meyerhof & Ranjan (1972), Meyerhof, Sastry & Mathur (1983). Meyerhof (1986) suggested that the vertical component ($Q_v$) of the ultimate eccentric and inclined load can be expressed in terms of a reduction factor $r_f$ on the ultimate concentric vertical load ($Q_o$). Poulos (1980) suggested that the ultimate inclined capacity of pile can be given by the least of $P_u\sec \alpha$ and $H_u\cosec \alpha$, where $P_u$ and $H_u$ denotes ultimate axial load capacity of pile and ultimate lateral capacity of the pile respectively and $\alpha$ denotes the angle of inclination of load with the vertical pile axis. However, in most of studies, model tests were carried out with a constant vertical load and increasing horizontal load. An attempt has been made here to study the effect of inclination by carrying out a model test on vertical pipe pile and pile groups in sand under actual central inclined load with inclination ranging from vertical to horizontal.

3. MATERIALS OF INVESTIGATION

3.1 Soil Data

The sand used in the present investigation is brought from Bhadarpur near Sankheda, situated in Gujarat, India, with natural moisture content of 3.7%, $Cu = 2.62$, $C_c = 0.90$, angle of internal friction = 38°, experimental density = 16.54 KN/M³, relative density = 68%, vertical modulus of subgrade reaction $K_v = 110$ MN/m³, coefficient of soil modulus variation $\eta_k = 44$ MN/m³ using API curves for sand.
3.2 Pile data
The piles of Aluminium pipes \((D = 23.90 \text{ mm}, d = 21.90 \text{ mm}, \Omega = 18^\circ, E = 60 \text{ GPa})\), Pvc pipes \((D = 25 \text{ mm}, d = 23 \text{ mm}, \Omega = 14^\circ, E = 5.7 \text{ GPa})\), Mild steel pipes \((D = 21.82 \text{ mm}, d = 17.82 \text{ mm}, \Omega = 22^\circ, E = 210 \text{ GPa})\), were used. Mild steel pile cap and wooden plugs fitted at pile tip were used for all the tests as shown in Figure 1.

Fig. 1: wooden plugs and mild steel caps

4. EXPERIMENTAL SETUP & PROCEDURE
To carry out the model study of vertical piles subjected to vertical, horizontal and inclined loading, a square tank of size \(1.2 \text{ m} \times 1.2 \text{ m} \times 1.2 \text{ m}\) is fabricated with mild steel. The model tank was placed centrally in a reaction frame fabricated from angle section and channel section. Different proving rings of different capacity were used depending on loading requirement. Mechanical Screw jack of 5T capacity was used for vertical and inclined loading. Load was applied gently by lowering the jack (Fig. 2).

Fig. 2: Concept of Setup for Inclination

For lateral load stud of 32 mm diameter was used as jack. Lateral load was applied gently by moving stud towards pile with help of handle (Fig. 3).

Fig. 3: Setup for Lateral Load

Dial gauges of capacities 30 mm and 50 mm with sensitivity of 0.01 mm were used to measure settlement of pile head. To study the group action of piles, piles were arranged along and across the horizontal load line i.e. inline and side by side as shown in Figure 4.

Fig. 4: Setup for Lateral Load for Inline and Side by Side Arrangement of Pile Group

The collar portion of cap is made such as to facilitate the suitable insertion of respective pile. The collar portion is welded with mild steel plate of size \(30 \text{ cm} \times 4 \text{ cm} \times 0.5 \text{ cm}\) thick. The piles are spaced at centre to centre spacing of 3D \((D = \text{pile diameter})\). Separate collar and pile cap is fabricated for each pipe pile according to its outer diameter.

Rigid steel triangle piece is welded at top of pile cap such that the line of action of inclined load when applied through this piece will pass through centre of pile group at bottom of pile cap.

As per IS-2911 (part 4), Maintained Load Test Method (MLT) is adopted as pile material of different flexural rigidities are to be tested. The failure load was taken to be that load at which the load vs. pile head displacement (or displacement of pile cap C.G.) curve passes into steep and fairly straight tangent.
5. EFFECT OF INCLINATION

Figures 5 & 6 shows the effect of inclination on ultimate carrying capacity of single Aluminium pipe pile and inline arrangement of pile group (with four piles) with pile cap.

![Fig. 5: Effect of Inclination (Single Pile)](image)

6. REDUCTION FACTOR

6.1 Observed Reduction Factor

Figure 7 shows the observed reduction factor with respect to ultimate load ($Q_{u\alpha} = 0$) for long single piles of Mild steel, PVC & Aluminium. Figure 8 shows the observed reduction factor with respect to ultimate load ($Q_{u\alpha} = 0$) for pile group of different piles with inline arrangement in a group.

![Fig. 6: Effect of Inclination (Pile Group)](image)

6.2 Suggested Reduction Factor

$$Q_{u\alpha} = R_i Q_{u\alpha}$$

Where, $R_i = \left(1 - \frac{\alpha}{90}\right)$ for $\alpha \leq 30^\circ$

$$R_i = (1 - 0.01\alpha)$$ for $\alpha > 30^\circ$

($L_{eff}/L = 1.8 (K_{rs})^{0.12}$)  
(by Poulos, $K_{rs} = (E_{plp}/(\eta^2 L^5)$)

6.2.1 $L_{eff}/L > 1$,

Single pile

(Applicable to Vertical pile subjected to central inclined load)

$R_i \text{ min} = 0.4$
Model Study of Vertical Piles Subjected to Central Inclined Loads

Pile Groups
(Applicable to Vertical piles in a group of 4 piles spaced @ 3 pile diameter c/c subjected to central inclined load with inline and side by side arrangement with 4 nos. of piles in a group with pile cap, L /d > 10)

\( L_{\text{eff}} / L \) value for single pile of same material

\( R_i \) min = 0.25

6.2.2 \( L_{\text{eff}} / L \leq 1 \),

Single pile

\( R_i \) min = 0.2 & if \( \alpha > 30^\circ \) \( Q_{ua} \) = 0.8 * \( Q_{ua} \)

(\( Q_{ua} \) as in Eq.1)

Pile Groups
(\( L_{\text{eff}} / L \) value for single pile of same material)

\( R_i \) min = 0.15, & if \( \alpha > 30^\circ \) \( Q_{ua} \) = 0.6 * \( Q_{ua} \)

(\( Q_{ua} \) as in Eq. 1)

6.2.3 \( L/d \leq 10 \),

Single pile

\( 0^\circ \leq \alpha \leq 90^\circ \), \( Q_{ua} \) = 0.8 * \( Q_{ua} \)

(\( Q_{ua} \) as in Eq. 1)

6.2.4 Notations

Single pile

\( Q_{ua} \) = ultimate inclined load capacity of single vertical pile

\( Q_{ua}(\alpha=0) \) = ultimate axial (vertical) load capacity of single vertical pile

\( \alpha \) = inclination of load with vertical axis of pile in degree

\( R_i \) = reduction factor for inclination

\( L \) = embedded length of pile

\( K_{rs} \) = relative stiffness factor

\( L_{\text{eff}} \) = effective embedded length of pile

\( E_I/p \) = flexural rigidity of pile

\( \eta_h \) = coefficient of soil modulus variation

\( d \) = outer diameter of pile stem

Note: \( R_i \) min is not applicable, if \( L/d \leq 5 \)

Pile Groups

\( Q_{ua} \) = ultimate inclined load capacity of vertical pile group

\( Q_{ua}(\alpha=0) \) = ultimate axial load capacity of vertical pile group

\( \alpha \) = inclination of load with vertical centroidal axis of pile group in degree

\( R_i \) = reduction factor for inclination

Figures 9 & 10 shows comparison of the results as obtained by suggested equations (as above mentioned) and the results obtained by experiments.

7. CONCLUSION

7.1 Single Pile

(a) As \( L/d \) ratio of pile, relative density of sand, flexural rigidity of pile increases the ultimate load carrying capacity of pile increases.

(b) As the load inclination with vertical increases from \( 0^\circ \) to \( 12^\circ \), there is little decrease in the carrying capacity of pile, with further increase in inclination it decreases considerably up to \( 90^\circ \) load inclination. At smaller \( L/d \) ratios, the reduction in the load carrying capacity of the pile is more substantial.

(c) As the load inclination with vertical increases from \( 0^\circ \) to \( 90^\circ \), the piles with pile material having higher flexural rigidity shows lesser reduction in load carrying capacity.

(d) Results obtained using suggested equation for reduction factor reasonably agree with model test results, for \( L/d \) of pile @ 25.
7.2 Pile Groups

(a) As the flexural rigidity of pile material increases, the ultimate load carrying capacity of group of vertical piles with pile cap increases.

(b) As the load inclination with vertical increases from 0° to 90°, the load carrying capacity of group of vertical piles subjected to central inclined load decreases considerably irrespective of pile material and arrangement of piles in a group (inline or side by side).

(c) Inline arrangement of vertical piles in a group with respect to load shows greater group efficiency than side by side arrangement of vertical piles in a group with respect to load.

(d) Results obtained using suggested equation for reduction factor reasonably agree with model test results, for L/d of pile @ 25.

REFERENCES


