Study on Vertical Piles Batter Piles and Pile Groups Under Uplift Load Conditions in Non-Cohesive Sub-soil

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Abstract. Model study was carried out in the laboratory to know the effect of uplift loads on vertical piles, batter piles and pile groups. Mild steel piles having 22 mm outer diameter and 1 mm thickness were considered for the study. Different slenderness ratios of 18, 28, and 38 and various angles such as 0°, 15°, 25°, 35°, and 45° were considered for the study. Sand was poured at a fixed relative density in the mild steel tank. The experimental study shows that the pile and pile group attain a maximum value of uplift load capacity when the batter angle reaches to 35°. Further, increase in batter angle causes a reduction in the uplift capacity of the pile. It is also noticed from the experiment that the uplift capacity increases with the slenderness ratio of the pile but its variation is not linear. Pile group of four piles with two vertical piles having L/D ratio 38 and two batter piles of L/D ratio 28 offers same resistance as of the same pile group with all the piles having L/D ratio 38. Numerical modeling was performed using Plaxis-3D to analyse the behavior of vertical piles, batter piles and pile groups under uplift loads. A good correlation between Plaxis-3D results and experimental results was observed.

Keywords: Uplift load; Load-carrying capacity; Vertical piles; Batter piles; Plaxis-3D

1. Introduction

Pile foundation undergoes different loading conditions viz. lateral, uplift, oblique and combination of these loads. Uplift loads act on the pile foundation due to the action of wind and waves. Due to the application of lateral loads in the structures, uplift forces are also generated in the pile foundation; hence it is necessary to observe the performance of piles under uplift loading conditions. Batter piles are known for resisting high lateral loads but in current study the focus is on finding the uplift load capacity of the vertical as well as the batter pile having different angles. Various researchers ([11], [3], [10-20], [22], [26], [28]) have already performed study on vertical and batter piles under lateral loads, but only a few have conducted study on uplift capacity of the vertical and batter piles [4], [9], [21], [27]. In the current study experiments were conducted on small scale model piles and it also includes the change of the slenderness ratios and variation of batter angles.

A few researchers have worked on the numerical modelling of the vertical and batter piles. Researchers viz. Rajasheer and Sitharam 2001 [23], Ravishankar and Satyam 2013 [24], Ghosh et al. 2017 [8], Dandagawhal 2019 [7], Al-salih 2019 [2] have performed numerical modeling on vertical pile whereas, only a few researchers viz. Isenhover et al. 2014 [10], Rezazade and Kalantari 2017 [25], Xie et al. 2017 [31], have performed numerical modeling on the batter piles. So, to verify the model tests results, numerical modeling on both vertical and batter pile was also performed using Plaxis 3D software.
2. Experimental Investigation

Different materials used in the testing are as follows;

2.1. Soil

Sand was used as a foundation material for all the tests and was collected from the local region of Raipur, Chhattisgarh, India. By adopting the rainfall technique, soil from a height of 55 cm was poured in the tank, and 60% relative density ($R_d$) was kept for all the tests. The interface angle was calculated from direct shear test. Gradation curve for sand is shown in Figure 1. The values of all the soil parameters are tabulated in Table 1.

![Gradation Curve for Sand](image)

**Figure 1. Sand Gradation Curve**

| Parameters                        | Value     |
|-----------------------------------|-----------|
| Sand fraction (%)                 | 98        |
| Silt fraction (%)                 | 2         |
| Specific gravity ($G_s$)          | 2.63      |
| Minimum dry unit weight (kN/m$^3$)| 15.6      |
| Maximum dry unit weight (kN/m$^3$)| 17.4      |
| Average dry unit weight (kN/m$^3$) at 60% $R_d$ | 16.5 |
| Coefficient of uniformity ($C_u$) | 3.46      |
| Coefficient of curvature ($C_c$)  | 0.79      |
| Classification                    | SP        |
| Angle of internal friction ($\Phi$) at 60% $R_d$ | 34° |
| Interface angle ($\delta$) at 60% $R_d$ | 25° |

2.2. Pile

Fabrication of the piles was done using mild steel. To replicate the pile behavior in the field, scaling laws were used for the physical modeling of the piles [29], [30] and based on that, the size of testing tank was decided. The piles had three different lengths, as shown in Figure 2. The outer and inner diameter was kept same for all the piles i.e., 22 mm and 20 mm, respectively. To keep the G.I. wire horizontal, a 50 mm free-standing length was provided above the soil bed. In the field, an interesting example of the usage of
batter piles is in New Orleans (US) can be seen, where 628 steel batter piles (288 ft. long) were used in the construction of the Great Wall of Louisiana. These mild steel piles were provided with a batter angle of 33˚. So, the same material i.e., mild steel as used in the foundation of the Great Wall of Louisiana was adopted.

![Aluminium piles having different lengths](image)

**Figure 2.** Aluminium piles having different lengths

2.3. **Pile caps**

Mild steel pile caps with dimensions are shown in Figure 3. Holes for different angles viz. 0˚, 15˚, 25˚, 35˚ and 45˚ and approximately same size of the pile were provided in the pile caps, so that the pile having same diameter can be inserted. After filling the tank up to a 200 mm height, pile was then positioned in the tank and sand was again filled using the rainfall technique. To apply the uplift load, hooks were welded on the top of the pile caps, as shown in Figure 3.

![Pile caps for single pile and 4 piles](image)

**Figure 3.** (a) Pile caps for single pile (b) Pile caps for 4 piles

2.4. **Model Tank**

The test setup for uplift load test is shown in Figure 4. Mild steel model tank has dimensions of 1m×1m×1.1m (Height). It was designed according to Bajaj et al. 2019b [4], a gap between the pile surface and the tank surface was maintained such that the boundary effects can be avoided.
3. Methodology
Uplift loads were applied on piles having different slenderness ratios i.e., 18, 28, and 38 at various angles viz. 0˚, 15˚, 25˚, 35˚, and 45˚. The pile cap was subjected to uplift load without any lateral load, so pile having -15˚, -25˚, -35˚, -45˚ and 15˚, 25˚, 35˚, 45˚ supposed to behave in the same way. IS: 2911 (Part-4) 1985 [5] and IS 2911 (Part 1/Sec 1) 2010 [6] were followed for the conduct and application of the uplift loads. The test setup and loading arrangement is shown in Figure 4. A hook was connected to the G.I. wire, which makes the way across the pulley to the loading pan; static load was applied on the pile cap by placing slotted weights on the loading pan in various increments. The load was applied until the pile failure (permanent deformation of the pile section) or up to a displacement value of 12 mm.

3.1. Single Pile Behavior under Uplift Loads
The behavior of single vertical and batter piles under uplift load tests was observed. The load-displacement curves for single pile having different slenderness ratios and angles are shown in Figure 5. The UULC for the vertical pile having slenderness ratios 18, 28, and 38 from Figure 5 was obtained as 108 N, 175 N, and 288 N respectively. The ultimate uplift load capacity (UULC) of vertical and batter piles is tabulated in Table 2.
It is observed that the UULC of the pile increases till a batter angle of 35˚ and it achieves a maximum value, and thereafter, it starts decreasing. It is clear from Figure 5 that the least value of UULC i.e., 108 N is observed for the vertical pile having L/D ratio 18. With the increase of batter angle, the UULC also increased by 6.5%, 22%, and 34.5% for 15˚, 25˚, and 35˚, respectively. However, further increase in angle from 35˚ to 45˚ lead to a slight reduction in the UULC but was still found to be 29.5% more than the vertical pile. Table 1 shows the percentage increase in UULC of the batter pile with the increase in angle. When the L/D ratio changes from 18 to 38, the UULC of the pile also increases. This increase is because the larger surface area of the pile creates contact with soil which ultimately provides higher skin friction to the pile.

The batter pile shows higher UULC than the vertical pile because as the batter angle increases, the overburden pressure on the pile also increases. The behavior is attributed to the dilation that occurs when dense sand is subjected to shear stress causing an increase in the earth pressure. Ultimately the coefficient of earth pressure in batter piles plays an important role.

For calculating the uplift capacity of batter pile, the uplift coefficient depends on the $K_p$ value.

$$K_u = K_p \tan \delta$$

The maximum value of $K_p$ is obtained at 35˚; hence, the value of $K_u$ will also be maximum according to Eq. 1. When the angle is further increased, $K_u$ starts decreasing so is the value of $K_u$.

### 3.2. Pile Group Behavior under Uplift Loads

The behavior of the pile group having 4-piles was also observed under uplift loads. The UULC of the pile group was determined using load-displacement curves. A spacing of 3d (d = diameter of the pile) between the piles was kept for the pile group. Pile placement in 2x2 pile groups is adjusted in such a way that two holes were kept at 0˚ and the other two at 15˚, 25˚, 35˚ and 45˚ angles. Table 3 presents the UULC of the vertical pile and batter pile groups having different slenderness ratios. Figure 6 and Table 3 indicates that the change in the UULC of the pile group from L/D ratio 18 to 28 is higher in comparison to 28 to 38. It is because the mobilization of soil resistance occurs along the effective length of the pile; this mobilization is significant up to a particular length and has no effect afterwards.

| L/D ratio | UULC of vertical pile (N) | UULC of negative batter pile (N) | % Variation in the UULC of the batter piles with respect to vertical pile |
|-----------|-------------------------|---------------------------------|---------------------------------------------------------------------|
| 18        | 108                     | 115                             | 6.5                                                                  |
| 28        | 175                     | 185                             | 22                                                                  |
| 38        | 288                     | 300                             | 10                                                                  |

Table 2. UULC of piles having different slenderness ratios
The load-displacement curves for pile groups with vertical piles and batter piles having different batter angles are shown in Figure 6. The UULC of the vertical pile having slenderness ratios 18, 28, and 38 were obtained as 225 N, 570 N, and 720 N, respectively, as observed from Figure 6. The pile group with 4 piles shows a similar trend as of single pile; the change in the UULC of the pile group from L/D ratio 18 to 28 is higher in comparison to 28 to 38 and can also be seen from Table 3. The percentage variation in the UULC of the batter pile group when compared with the vertical pile group and is also shown in Table 3.

**Table 3.** UULC of vertical and batter pile group

| L/D ratio | UULC of vertical pile group (N) | UULC of negative batter pile group i.e., two vertical piles, two batter piles (N) | % Variation in the UULC of negative batter pile group i.e., two vertical piles, two batter piles w.r.to vertical pile group (N) |
|-----------|---------------------------------|---------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------|
| 18        | 225                             | (0°) 235 (15°) 255 (25°) 285 (35°) 275 (45°) 4.5 (15°) 13 (25°) 27 (35°) 22 (45°) |                                                                                                                                 |
| 28        | 570                             | 585 (0°) 610 (15°) 635 (25°) 625 (35°) 3 (45°) 7 (15°) 11.5 (25°) 10 (35°) 10 (45°) |                                                                                                                                 |
| 38        | 720                             | 750 (0°) 825 (15°) 870 (25°) 850 (35°) 4 (45°) 15 (15°) 21 (25°) 18 (35°) 18 (45°) |                                                                                                                                 |

The load-displacement curves for pile groups with vertical piles and batter piles for L/D ratios (a) 18 (b) 28 (c) 38

**Figure 5.** Load-displacement curves of vertical and batter pile for L/D ratios (a) 18 (b) 28 (c) 38
Figure 6 shows that the UULC of a pile with some batter angle is more than the vertical pile, and it increases with the increase in angle. A variation of around 4.5% to 27% in the UULC was observed for the pile group having batter angles -15° to -45° for L/D ratio 18. Similarly, for pile groups having L/D ratios 28 and 38, when the pile batter angle is varied from -15° to -45°, a variation of 3% to 11.5% and 4% to 21% respectively was observed in the UULC of the pile group.

![Figure 6](image-url)

**Figure 6.** Load-displacement curves for vertical pile group having 2 vertical piles and 2 batter piles under uplift loads at different L/D ratios (a) 18 (b) 28 (c) 38
4. Numerical Modeling

Numerical modeling was done on the vertical as well as batter piles using PLAXIS 3D software based on Finite Element Method (FEM). Using the PLAXIS 3D software, the deformation behavior of the piles can be observed under various loading conditions. In the present research, the geometry of the model tank and model pile is formed using the same dimensions as of model tests. Sand follows the Mohr-Coulomb (MC) criteria, and different properties such as Elastic Modulus ($E = 55$ MPa), Poisson's ratio ($\nu = 0.3$) for soil elasticity, angle of internal friction ($\phi = 34^\circ$), soil pile interface angle ($\delta = 23^\circ$), and dilatancy angle ($\Psi = 4^\circ$) has been included for modeling in PLAXIS 3D software. A medium size mesh was adopted for the analysis. Figure 7(a) shows a geometrical model of the batter pile having $35^\circ$ placed in sand whereas, Figure 7(b) illustrates the uplift load being applied from the downward direction of the pile cap. Discretization of the system is shown in Figure 7(c) where batter pile group is having two vertical piles and other two piles at $25^\circ$. Whereas, Figure 7(d) shows the displacement results of the pile at a particular load.

![Figure 7](image_url)

**Figure 7.** (a) Geometrical model of batter pile ($35^\circ$) in sand (b) Application of load on batter pile (c) Soil-pile prototype having one vertical pile and one batter pile placed at $25^\circ$ batter angle (d) displacement results of pile
After performing the experiment on a vertical pile, a displacement of 12.02 mm was observed corresponding to an uplift load of 108 N for an L/d ratio of 18. However, in the numerical modeling, the same displacement is achieved at an uplift load of 127 N.

Similarly, for a single vertical pile having L/d ratio 28 and 38, the uplift capacity from numerical modeling was observed as 201 N and 325 N, respectively. For other piles and pile groups having slenderness ratios 18, 28 and 38, the ultimate uplift capacity values at 12 mm displacement are summarized in Table 4. The uplift loads were also applied on the vertical and batter pile groups having different angles and the results are summarized in Table 4. It is also observed that the numerical modeling results follow the same trend as shown by the model test results. A maximum variation of 18% was observed in the model tests results when compared with the numerical modeling results.

Table 4. Comparison of ultimate load of model tests for different batter piles with the numerical modeling values

| Type       | L/d Ratio | Experimental results of uplift capacity (N) | Numerical modeling results of uplift capacity (N) |
|------------|-----------|---------------------------------------------|--------------------------------------------------|
|            |           | 0°   | 15° | 25° | 35° | 45° | 0°   | 15° | 25° | 35° | 45° |
| Single     | 18        | 108  | 115 | 132 | 145 | 140 | 127  | 133 | 149 | 171 | 157 |
| Pile       | 28        | 175  | 185 | 200 | 230 | 220 | 201  | 212 | 231 | 265 | 252 |
| Group      | 38        | 288  | 300 | 317 | 355 | 335 | 325  | 340 | 362 | 396 | 383 |
| Pile       | 18        | 225  | 235 | 255 | 285 | 275 | 252  | 267 | 285 | 325 | 309 |
| Group      | 28        | 570  | 585 | 610 | 635 | 625 | 621  | 645 | 683 | 710 | 691 |
| Pile       | 38        | 720  | 750 | 825 | 870 | 850 | 777  | 810 | 871 | 926 | 905 |

Figure 8 shows the 2 x 2 pile group having two vertical piles with L/D ratio 18. It is observed from Table 5 that when a pile group having two vertical piles (L/D ratio 38) and two batter piles (L/D ratio 18) is subjected to uplift loads, the UULC of the pile group is less than the pile group with all the piles having L/d ratio 38. However, as the L/d ratio of the batter pile increases from 18 to 28, the UULC increases and is nearly the same as of pile group, with all piles having L/D ratio 38 (refer Table 5). This may be due to the resistance provided by the pile does not increase much with the increase in length of the pile and becomes constant after reaching a particular length. Further study on this may lead to use the same in the field and save the material as well. However, additional experimental investigation is needed to be done before its application in the field.

Figure 8. Pile group having 2 vertical piles and 2 batter piles of unequal length
Table 5. Ultimate uplift load of pile group having different lengths to diameter ratios

| Pile group configuration (2x2) | UULC of pile group (N) |
|-------------------------------|-------------------------|
|                               | 0°  | 15° | 25° | 35° | 45° |
| 2 vertical piles have L/D = 38, 2 batter piles have L/D = 18 | 515 | 535 | 585 | 630 | 610 |
| 2 vertical piles have L/D = 38, 2 batter piles have L/D = 28 | 700 | 735 | 810 | 850 | 835 |
| 2 vertical piles have L/D = 38, 2 batter piles have L/D = 38 | 720 | 750 | 825 | 870 | 850 |

5. Conclusions

1. The experimental study shows that the ultimate uplift load capacity of the pile and pile group attains a maximum value at 35°; thereafter an increase in angle causes a reduction in the uplift capacity of the pile and the pile group.
2. Experimental study also showed that the ultimate uplift load capacity of the pile and the pile group increases with the length of the pile, but its variation is nonlinear.
3. Pile group of four piles with two vertical piles having L/D ratio 38 and two batter piles of L/D ratio 28 offers same resistance as of the same pile group with all the piles having L/D ratio 38.
4. Numerical modelling results, when compared with the model tests results, show a good match with a maximum variation of 18%.

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