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Influence of Taper Section in Uplift Loading Behaviour of Piles in Sand

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Abstract - *Pile foundations are used to account for huge vertical, uplift and lateral loads due to different loads and impacts on them. Straigh piles are commonly used in the practice. Increasing loads on these structures has resulted in piles of large diameter and depth at a significantly higher cost. Studies presented in this paper is intended to provide important information regarding the uplift behaviour of the tapered piles. As a result, significant saving in foundation cost, resulting from an economical design, may be achieved. Experiments were performed on conventional straight monopile and tapered piles embedded in sandy soil under uplift loading condition. The investigations were done by changing the taper angles (0.46°, 0.92° and 1.38°) of taper pile and relative density of sand (30% for loose condition and 50% for medium condition). In each test, pile was installed by same method at the same embedment. Pile head upward movement was obtained using dial gauges. The datas were suitably presented on load – deflection curves. The results showed that the ultimate uplift capacity of tapered piles is slightly higher than that of conventional straight monopiles with similar average diameter and length. The uplift capacity of tapered piles was found to be comparable to that of straight-sided wall piles at higher relative density, suggesting that the performance of actual tapered piles (with greater length) would be comparable to that of straight-sided wall piles. The test results showed that the ultimate uplift capacity of the tapered pile was greater than that of the conventional monopile with 29%.*

***Key Words*: Conventional Monopile, Tapered Pile, Uplift performance, Pullout Test, Ultimate Uplift Capacity**

1. INTRODUCTION

Pile foundations are generally used to support compressive load from super structures, and transfer onto stiffer or more compact and less compressible soils or onto rock. In practice, however a working pile is not always subjected to a compression load. Sometimes, they are required to resist uplift loads acting due to hydrostatic pressure, seismic activity or overturning moments. These forces are expected when supporting transmission towers, jetties, tall structures, chimneys, jetties etc. Moreover, uplift forces may be experienced when piles are installed in expansive soils. Therefore, the uplift performance of the piles may become the governing factor in their design.

There has been considerable debate over the relative magnitude of pile shaft capacity in tensile (uplift) loading, compared with compressive loading. However, there is widespread experimental and numerical evidence that in sand the straight-sided shaft capacity is significantly lower for tensile loading than for compressive loading. In the case of tapered piles, this difference is expected to be even more significant.

Tapered piles have a substantial advantage over straight sided wall piles with regard to their load-carrying capacity in the downward frictional mode. The axial force in the pile decreases towards the bottom. A tapered pile with its cross section increasing towards the top makes for a more efficient utilization of the pile material. If a friction pile subjected to a downward vertical load, has its sides parallel, the transfer of load to the surrounding soil is entirely by the shear at the interface. However, in tapered pile, a part of the downward load is transferred by direct bearing on the sides over the area. This bearing results in an increased normal pressure when compared to the pile without taper, which consequently increases the frictional component of the bearing resistance. Tapered piles are therefore very effective in frictional soils such as sand. A wedge which is difficult to drive in the face of increasing resistance, but easy to pull out, is another analogy for explaining the behavior of a tapered pile.

Different types of tapered piles are used in practice including steel (Taper tube type), wooden piles, or pre-cast concrete piles. Tapered piles vary in length between 6 m and 12 m, with diameters varying between 200 mm to 350 mm and taper angles varying between 0.2° and 1.5°.

To obtain a complete comparative picture of pile action, it was considered essential to study not only tapered piles but conventional monopile piles. Therefore, in this study a program is adopted consisted of installing test piles of different taper angles into a loose and a medium-dense sand, placing them in a test tank, and subjecting them to pullout loading conditions. The ultimate uplift load capacity of the piles were established and the datas were represented using load-deflection curves.

2. SCOPES AND OBJECTIVES

The primary objective of this study was to experimentally study the behaviour of tapered pile under uplift loading conditions when installed in cohesionless soil. If a pile is provided with a taper, a part of the downward load is transferred by direct bearing on the sides over the area. This bearing results in an increased normal pressure when compared to the pile without taper, which consequently increases the frictional component of the bearing resistance. Tapered piles are therefore very effective in frictional soils

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such as sand. Also, significant saving in foundation cost could result from strengthening or enlarging the upper segment of the pile only.

The project aims at achieving the following objectives:

- To evaluate the effect of relative density of soil condition in pullout behaviour of tension piles used
- To compare the uplift capacity of conventional monopile in loose and medium dense soil condition
- To compare the uplift capacity of tapered piles by varying the taper angles in loose and medium dense soil condition
- To determine the ultimate uplift capacity of each piles

3. MATERIALS

The materials required for the experiment includes Sand, Model Tank, Piles and Footing. The details regarding the materials are given below.

3.1 Sand

The soil used for the study was river sand and it was collected from Bharathapuzha River. Air dried soil samples were used for laboratory model study. All the laboratory tests for the sand was done by following IS Code specifications. The grain size distribution was found using IS: 2720-part 4. Table 1 definines the properties of sand used.

Table -1: Basic Properties of Sand

Properties	Values
Specific gravity	2.65
Uniformity coefficient, Cu	2.4
Coefficient of curvature, Cc	0.77
Gradation of sand	SP
Max. dry density (g/cc)	1.819
Min. dry density (g/cc)	1.777
Soil friction angle, ø	33°
Permeability (cm/s)	7.24×10^{-4}

3.2 Model piles

In this study, four instrumented mild steel model piles of equal length and average embedded diameter, approximately, but different taper angles were used. One is used as the conventional straight pile of length 310mm and diameter of 25mm as shown below in figure 2.

Fig -1: Straight pile

Other three model piles were fabricated as tapered model piles (T1, T2 and T3) with taper angles of 0.46°, 0.92° and 1.38° respectively. All the tapered model piles had the same top diameter of 25mm. The base diameter of T1 was 20mm, T2 was 15mm and whereas base diameter of T3 was 10mm. To facilitate loading, each pile had a small steel hook, which was welded on the square pile cap of dimension 50 mm x 50 mm and 3 mm thick, to attach the tension load via a steel wire. Model tapered piles are shown below in figure 2.

Fig -2: Straight pile

3.3 Model Test Tank

The test tank used for model tests was a rectangular tank, made-up of galvanized iron sheet having 1 mm thickness. The sand bed was prepared in a tank of inside dimensions 600 mm length, 600 mm width and 800 mm height. The tank was sufficiently large to take care of the effect of the edges of the tank on the test results as the zone of influence of the piles due to loading is reported to be in a range of 3-8 times pile diameter.

4. METHODOLOGY

Tests were carried out in 2 sections. In first section preliminary tests were conducted to study the basic properties of sand. The study includes determination of index properties of sand. Index properties are the properties which are used for the identification purposes. The various index properties of the sand include Specific gravity, Relative density, Sieve analysis, Direct shear test and permeability test. All the index properties of sand were estimated in accordance with the Indian Standard (IS) procedure. Second section comprised of conducting pullout test on the model piles by varying the relative density of soil from loose (Dr-30%) to medium (Dr-50%) dense. Model piles include conventional pile, and tapered piles with different taper angles.

Large scale model tests are designed to represent the actual three-dimensional field conditions. As per IS 2911 (Part 4) : 2013 for conducting pull out test, when the pile gets pulled up and the reaction is transferred to the ground through the supports which are at least 2.5 D away from the test pile periphery (where D is pile stem diameter of circular piles or diameter of the circumscribing circle in the case of square piles). The dimensions of the test tank for large scale model testing are fixed based on these criteria. In each test, piles were installed by same method at the same embedment. Pile head upward movement was obtained using dial gauges. The datas were presented on load – displacement curves.

4.1 Filling of Test Tank

The test tank was marked to equal layers. The quantity of sand was calculated for each layer corresponding to the required relative density. Then filled this predetermined quantity of sand in each layer with compaction using rammer. The sand was filled in layers up to the level where the tip of the piles was rest. Then pile was kept in correct embedment depth position and was centered. After placing the pile, the remaining successive sand layer was filled. Then the top surface of sand bed was levelled.

4.2 Setting of Deflection Measuring Device

After sand bed preparation, the static uplift loads were applied by means of dead weights placed on a loading hanger connected to center of pile cap via a flexible steel wire, which strung over a pulley which is exactly above the pile for uplift load test. A dial gauge, accurate to 0.01 mm was placed on the pile head to measure piles upward vertical displacement.

4.3. Test Procedure for Uplift Load Test

The load was applied vertically through pulley fixed above the center of the pile via a steel wire attached on the pile head, avoiding any eccentric load. The load was applied incrementally. To measure the uplift movement, a dial gauge of 25 mm capacity was used. Each load was kept constant until the difference between two successive displacement readings was less than 0.01 mm per minute. As per Indian standard procedures, the safe uplift load shall be taken as the least of the following: (a) Two – thirds of the load at which the total displacement is 12 mm or the load corresponding to a specified permissible uplift (b) Half of the load at which the load displacement curve shows a clear break. Here the obtained load deflection curves show nonlinear nature. So, the loading was continued until the complete length of the pile is pulled out from the sand bed. Figure 3 below shows the uplift load test setup used for this study.

Fig -3: Uplift Loading test setup

5. RESULTS

Initially the investigations on the behaviour of conventional straight piles, i.e., monopile in loose and medium dense sand bed under uplift load were performed to provide the essential data for comparative purposes. The relative density of the sand was varied as 30% and 50%. The ultimate uplift load was taken as the load at which the pile is completely pulled out from the soil. Chart 1 shows the load deflection response of monopile in loose and medium dense sand bed.

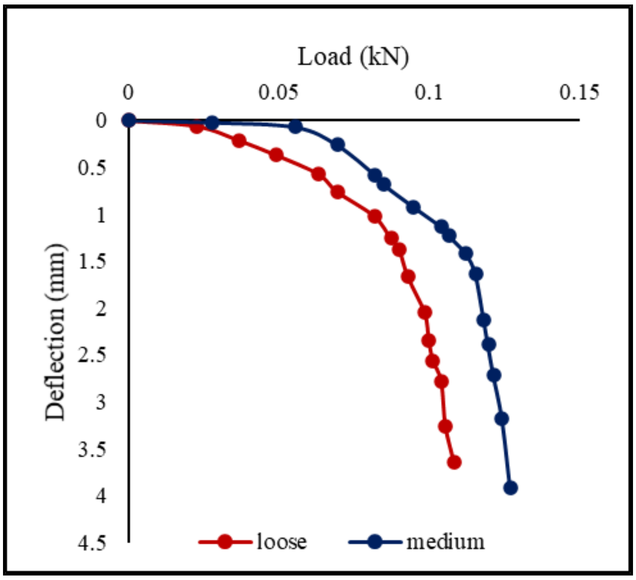

Chart -1: Load deflection curve for monopile in loose and medium sand bed conditions

The ultimate uplift load was taken as the load at which the pile is completely pulled out from the soil. From the above response, it can be noted that the ultimate uplift load increases with increase in relative density of sand. Because as relative density increases, angle of internal friction increases and there by shearing resistance increases. The increase in ultimate uplift is also due to increase in dry density and thereby increase in effective vertical stress along the pile shaft. The displacement increased sharply during the last load increment. In loose sand condition pile shows ultimate uplift load of 0.109 kN while medium dense sand condition shows the ultimate uplift load of 0.128 kN. By increasing the relative density of sand from 30% to 50% increased the ultimate uplift capacity from 0.109 to 0.128 kN. This is a 15% increase.

The following load – displacement curves shows the effect of pile taper along the pile shaft on the uplift behaviour of tapered piles. The uplift behaviour was studied by keeping the pile length and relative density as constant parameters. Chart 2 shows the load deflection curve of tapered piles with different taper angles in loose sand condition.

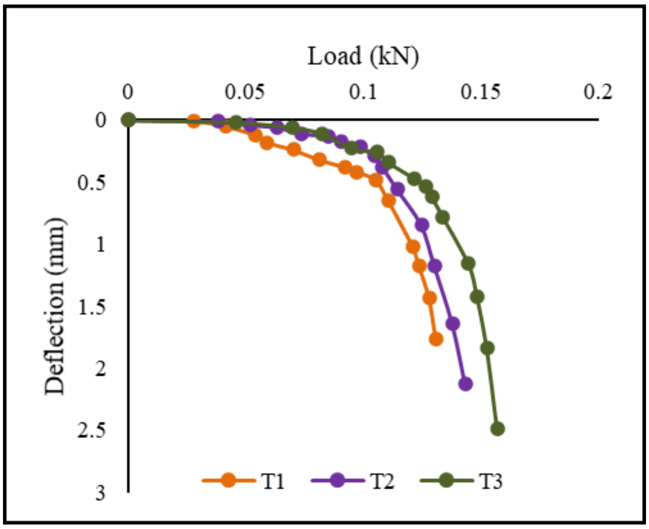

Chart -2: Load deflection curve for tapered piles in loose sand bed conditions

From the above results, tapered pile with taper angle of 1.38° obtained as better configuration for maximum uplift capacity. Because as the diameter of pile increases shaft resistance increases due to increase in vertical effective stress. In loose dense sand condition, the ultimate uplift load for the tapered pile T1 was 0.136 kN, 0.148 kN for T2 and 0.162 kN for T3 respectively. By enlarging the pile diameter from 0.1m to 0.2m for 1.38° of the taper angle increased the ultimate uplift capacity from 0.136 to 0.162 kN. This is a 16% increase. When the full length of the pile has a diameter of 0.25m, the ultimate capacity was also 0.109 kN, which indicate 32% increase.

Same test for tapered piles was conducted in medium sand condition to investigate the variation in ultimate uplift load with increase in relative density of sand. The variation in ultimate uplift load with increase in taper angle of pile in medium dense sand represented by the load deflection curve is shown in chart 3.

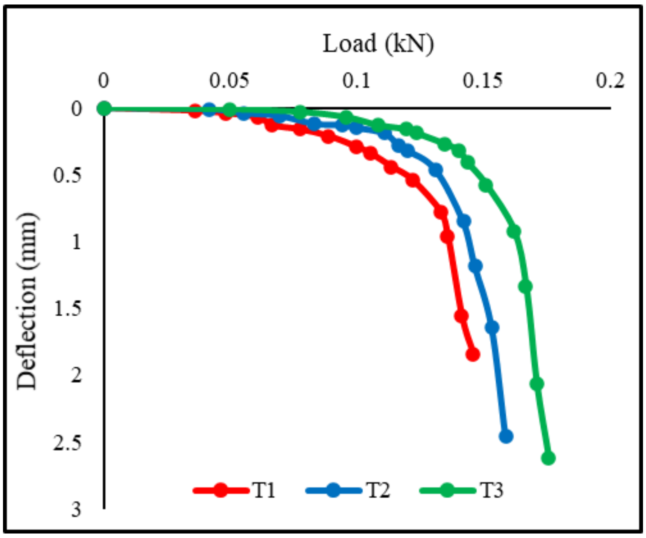

Chart -3: Load deflection curve for tapered piles in medium sand bed conditions

The above chart indicate that increasing the taper angle for the tapered piles has significantly increased the ultimate uplift capacity along with the increment in density of sand. In medium dense sand condition, the ultimate uplift load for the tapered pile T1 was 0.151 kN, 0.164 kN for T2 and 0.181 kN for T3 respectively.

By enlarging the pile diameter from 0.1m to 0.2m for 1.38° of the taper angle increased the ultimate uplift capacity from 0.151 to 0.181 kN. This is a 17% increase. When the full length of the pile has a diameter of 0.25m, the ultimate capacity was also 0.109 kN, which indicate 40% increase. Comparing all the test results obtained in this study, the maximum result has been obtained for the taper angle of 1.38° in medium dense sand condition (ultimate uplift resistance of 0.181 kN). This value is 29% higher than the ultimate uplift resistance obtained for monopile in medium dense sand.

6. CONCLUSIONS

An experimental investigation of the axial uplift response of conventional monopile and three mild steel piles with different taper angles installed in sand was presented and discussed in this study. A total of 8 uplift load tests were conducted to study the variation in ultimate uplift under different soil conditions. The uplift performance characteristics of the piles were investigated and the following conclusions were drawn:

- For both monopile and tapered piles, the ultimate uplift load significantly increased when relative density of soil changes from 30% to 50%.
- Ultimate uplift capacity of monopile in medium dense sand condition was 15% greater than in loose sand condition.
- The uplift capacity of tapered piles is slightly higher than that of conventional monopile with similar average diameter and length.
- Uplift capacity of tapered piles increases with an increase in the taper angle resulting slightly higher ultimate uplift capacity of 0.181 kN for taper angle of 1.38° in medium dense sand condition
- Comparing the maximum test result of ultimate uplift loads, taper pile with taper angle of 1.38° has 29% greater value than conventional pile in medium sand condition.

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