Review of Methods For Predicting Ultimate Pullout Capacity of Pile

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Abstract- *Pile foundations are generally used to transmit the superstructure loads to deeper strata when the subsurface soil is of inadequate strength.*

High rise structures supported by piles need analysis for lateral loading due to earthquake and wind. Piles are frequently subjected to lateral forces and moments, for example, in quay and harbor structures, where horizontal forces are caused by the impact of ships during berthing and wave action; in offshore structures subjected to wind and wave action, in transmission-tower foundations, where high wind forces may act which tend to pullout the pile. The structures situated at the offshore there foundation is subjected to uplifting pressure due to capillary water. Extensive theoretical and experimental investigations have been carried out over the last few decades to study the behavior of piles subjected to axial pullout loads.

To improve the application of pile of it is necessary to predict the behavior of various kind of pile. In this current study represents comparative review of different kind of methods to predict pullout capacity of pile such as theoretical formulas, empirical formulas, model pile testing and filed testing.

From the analysis of piles embedded in homogeneous soil it is seen that pullout capacity of pile depends on soil parameters, shaft friction and aspect ratio of pile.

Keywords- Pullout capacity, Pile, Uplift, Vertical displacement, Shaft Friction

I. INTRODUCTION

Structures such as transmission towers, mooring system for ocean surface or submerged platforms, tall chimneys, jetty structures are subjected to uplift loads. The types of foundations to be adopted for these structures vary per the suitability of the site conditions. When poor soil at shallow depth or problem of caving or water table arises, the geotechnical engineers are compelled to adopt deep foundation in the form of piles. Similarly, lateral forces act on, the foundations of quay and harbor structures due to the impact of ship during berthing and wave action, offshore structures subjected to wind and wave action, earth retaining structures and lock structures. Large loads act on the foundations of retaining wall, anchors for bulk heads, bridge apartments, piers, anchorage for guyed structures and offshore structures which are generally supported on piles.

The current paper summarizes through comparative analysis of the models and methods in computing ultimate capacity of uplift pile proposed by scholars for engineering applications.

Failure of Uplift Pile:

Failure modes of uniform cross section of piles [37] under uplifting force are divided in to three categories:

(i) Pile length truncated inverted cone shear failure
(ii) Shear failure along the pile- soil wall interference (shaft friction), depends on surface area of pile
(iii) Compound shear failure

As studies on the pullout capacity of pile shows that pullout capacity of piles depends on side friction between pile and soil, as the rough pile shows more pullout capacity. These factors are governing by angle of friction and unite weight of soil. Intact inverted cone damage only occurs in stubby, caisson-type piles embedded in soft rock; and the oblique side of the inverted cone can also be presented as a curved surface. Meanwhile, compound shear failure can be identified when bored piles are used in hard clay.

Pile Pullout Mechanism:

When uplift loads act on the top of the pile, the relative displacement between the pile and the surrounding soil develops. Uplift loads transfer to the soil through lateral friction, while lateral friction increases rapidly under loads. When lateral friction limit is reached, shear failure occurs in surrounding soil characterized by pile and soil pulling out. Therefore, we take limit lateral friction as ultimate capacity of the uplift pile. The lateral friction is related to many factors, such as soil properties, pile stiffness, stress state of the soil, contact surface between the pile and soil.

Several computational models, theoretical formulas and filed tests have, therefore, been put forward and compared on the basis of results.

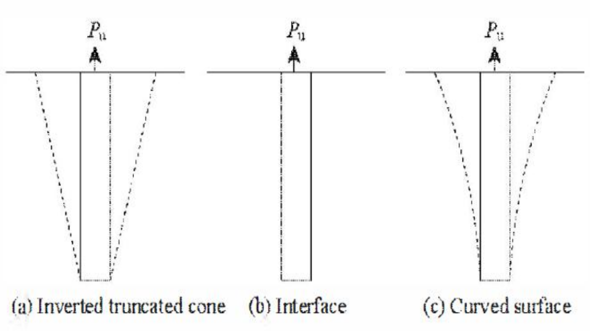


Fig. 1: Failure of Pile Under Uplift Force

II. DIFFERENT METHODS TO CALCULATE ULTIMATE PULLOUT CAPACITY OF PILE

1. Theoretical Analysis:

The failure surface is assumed curved and passing through the surrounding soil mass. The lateral horizontal extent of the failure surface is dependent on the angle of shearing resistance ø of the surrounding soil, soil-pile friction angle, δ, and aspect ratio L/d.

1.1. Tran-Vo-Nhiem (1971)

Tran-Vo-Nhiem developed an equation for uplift capacity of piles on the assumption that the passive pressures act on the side of the pile. He considered that the passive pressures on the side of the pile are proportional to the square of the depth. By integrating the vertical component of these passive pressures on the shaft of the pile he developed the following expression

$Q_u = A_s (\gamma\ L\ M_{øR} + C\ M_{CR})$
A_s = Embedded surface area of the pile
$M_{øR}$, M_{CR} = Dimensionless coefficients depending on ø and d/l ratio

1.2. Chattopadhyay and Pise (1987) [8]:

Assumptions made:

1. For a particular slenderness (aspect) ratio the lateral horizontal extent of the failure surface from the axis of the pile is maximum for δ=ø.
2. For δ = 0, the failure surface coincides with the interfacial plane between the pile and soil.
3. For piles with soil-pile friction angle $\delta \geq 0$, under ultimate uplift force, P_u the resulting failure surface initiates tangentially to the pile surface at the tip of the pile and moves through the surrounding soil.
4. For $\delta > 0$, the inclination of the failure surface with the horizontal at the ground surface approaches (45°- ø/2).

On account of his theory friction increases in a linear way with increasing depth based on his test.

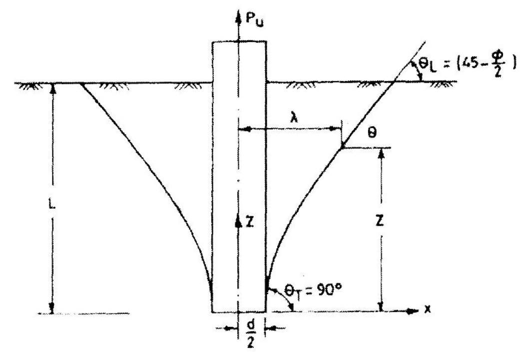


Fig. 2: Pile and Failure Surface (Chattopadhyay and Pise 1987)

$(L/d)_{er} = 0.156\ D_r = 3.58,\ D_r \leq 0.7$,................3
$(L/d)_{er} = 14.5,\ D_r \geq 0.7$, ...4
Ultimate capacity of uplift pile in sand is determined by the following:

$$P_u = \frac{1}{2}\pi d\gamma L^2 K_u \tan\delta, \quad \frac{L}{d} \leqslant \left(\frac{L}{d}\right)_{cr}, \quad (5)$$

$$P_u = \frac{1}{2}\pi d\gamma L_{cr}^2 K_u \tan\delta + \pi d\gamma L_{cr}(L - L_{cr}) K_u \tan\delta, \quad \frac{L}{d} \geqslant \left(\frac{L}{d}\right)_{cr}. \quad (6)$$

1.3. Deshmukh et al.(2010) [14]:

Proposed semi-analytical method is simple and provides a closed-form solution for the net uplift capacity of a pile anchor for the depths up to critical embedment ratio.

In the proposed method, Kotters equation is employed to evaluate vertical soil reaction R_v in which failure surface is an inverted truncated cone, on the failure surface. This equation that is valid for plane strain condition was successfully used for the analysis of a retaining wall. Author considered the sum of vertical soil pressure at failure surface and the weight of the pile and soil in failure zone equal to uplift capacity of the pile.

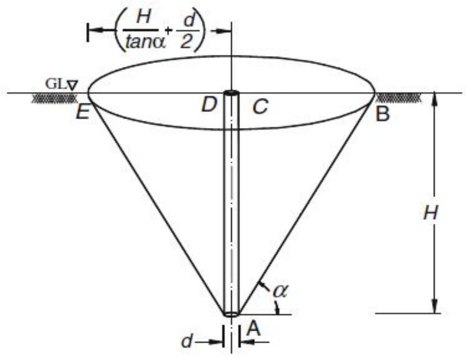


Fig. 3: Geometry of pile anchor in axis-symmetric solid body failure surface (Deshmukh et al.2010)

1.4 HUANG and WANG (2010) [17l:

He did theoretical and experimental study about ultimate bearing capacity of reamed pile with difference in lengths before and after excavation by using simplified method, both uniform section uplift piles with side grouted and enlarge-base uplift pile were examined.

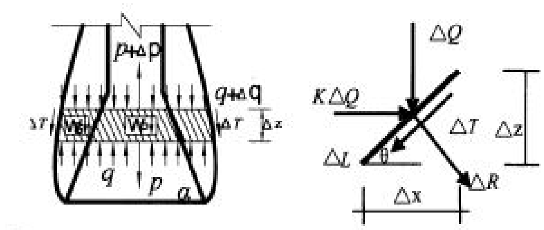
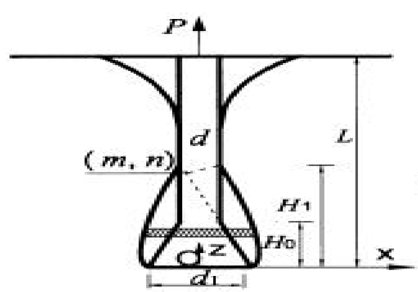


Fig. 4: (a) Force on the wedge (b) Force on failure surface



(c) A unified failure mechanism (HUANG and WANG 2010)

Under an ultimate state, the failure surface was formed by a ¼ elliptical local failure surface at the enlarge base, while along the straight shaft, an exponential function of failure surface was assumed

On account of him ultimate capacity of uplift pile includes three parts:

1. expanded head,
2. Uniform cross section affected by expanded head,
3. Uniform cross section not affected by expanded head.

2. Model Test:

2.1. Das and Pise (2003) [9]:

The stage of compressive loading is a significant parameter influencing the net uplift capacity of a pile. The net uplift capacity decreases with increase in the stage of compressive loading. To attain the peak uplift resistance displacement in the range of 0.08d to 0.25d was required. The decrease in net uplift capacity may be due to the reduction in soil-pile friction angle, ɗ, caused by the presence of compressive loading, which has been exhibited by the proposed logical approach. The net uplift capacity at any stage of loading increases with increase in L/d ratio. An assumption of a decrease in soil-pile friction angle, and using Chattopadhyay and Pise's method (1986) predicts uplift capacity of a pile, which is reasonably in agreement with the experimental value.

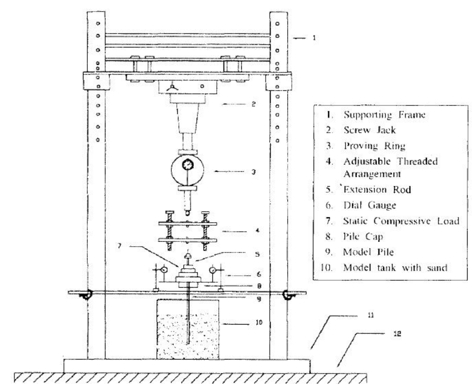


Fig. 5: Diagram of experimental setup (Das & Pise 2003)

2.2. Krishna et al. (2004) [21]:

He did laboratory model tests on single steel model pile of cross-sectional 20mm X 20mm with length 400mm & 600mm. It is observed that the axial displacement depends on the normal components of thee pull and also the normal displacement depends on the axial components of the pull. Oblique capacity of piles decreases with increase in % of compressive load. On account of paper pullout capacity depend on embedment length, compressive load applied on pile, oblique pullout load.

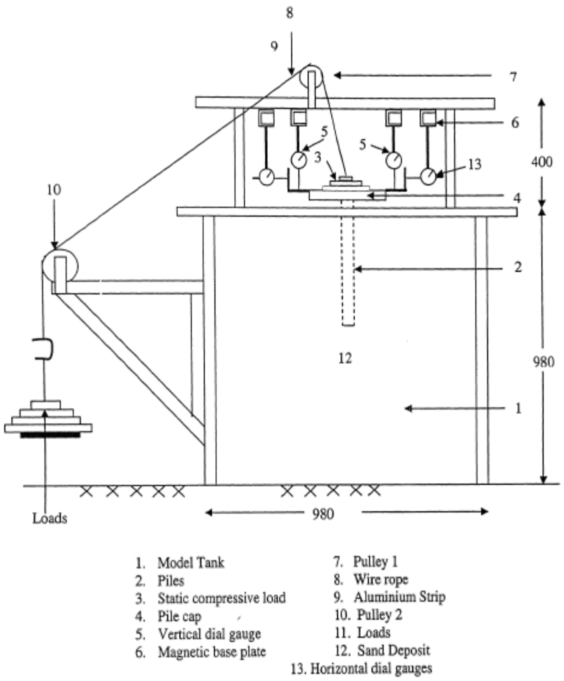


Fig. 6: Diagram of experimental setup (Krishna et al. 2004)

2.3. Srirama Rao et al. (2007) [3]:

This paper presents the results of field scale test of GPA (granular Pile anchors) of varying diameter and a length with aspect ratio varies from 2.5 to 10, piles where embedded in clay. The uplift load i.e. pullout capacity increased with the increasing diameter of the GPA. This is because the resistance to uplift increased with increasing surface area of the pile-soil interface consequent upon increase in the diameter. Pullout capacity also increases with increasing in length of pile.

When the length of the GPA was increased from 500 to 750 and 1000 mm, the percentage increase in the uplift load required for an upward movement of 25 mm was 33.3 and 55.5% respectively

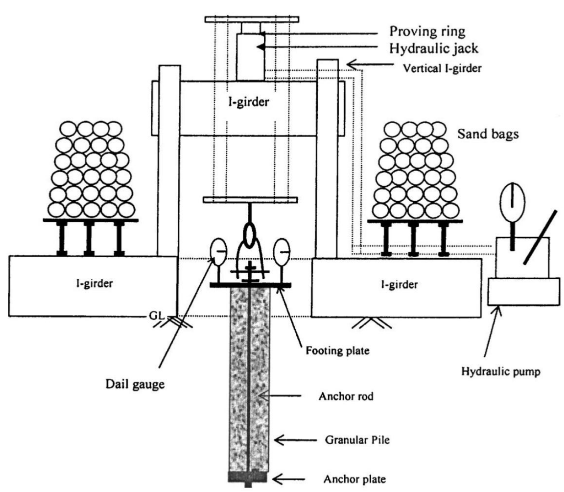


Fig. 7: Pullout load test setup (Srirama et al. 2007)

2.4. Sivakumar et al. (2012) [32]:

A new method of analysis for the determination of the ultimate pullout capacity has been presented and verified experimentally. This paper has presented the construction, testing, and performance of granular anchors in old filled deposits (QUB site) and an intact lodgement till deposit (TCD site).

Granular anchors with $L/D > 7$ principally failed by bulging whereas short granular anchors failed on shaft resistance.

In analogue to the ultimate pullout capacity of a rigid pile, the ultimate resistance of the granular anchor in shaft resistance, including its self-weight contribution, is given by

$$T_F = \pi D L \alpha C_u + \frac{\pi D^2 L \gamma}{4}$$

Where D and L are anchor diameter and length, respectively; α is an adhesion factor; Cu is the un-drained shear strength of the surrounding soil; and γ_g is the unit weight of the granular backfill.

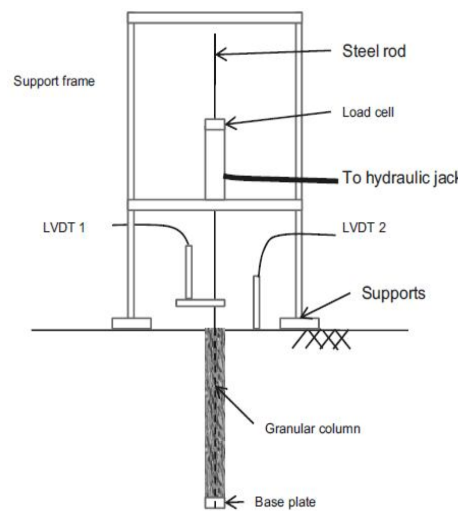


Fig. 9: Experimental setup (Sivakumar et al. 2012)

The study has also demonstrated that the pullout capacity can be increased significantly using a multiple-plate anchor system, provided the L/D ratio of individual column segments is greater than the critical value.

2.5. Kotal et al. (2015) [2]:

He did Experimental and theoretical investigations on model single pile anchor and pile group anchors of solid wooden pile having diameter of 40mm diameter and 600mm length. The truncated cone model is considered to predict the net uplift capacity of single pile anchor. In the truncated cone model the uplift force is resisted by,

- The weight of the soil in the truncated cone
- Shearing resistance of the soil along the failure surface
- Weight of the pile and pile anchor.

So from the analytical analysis for cohessionless soil (c=0). We get the final expression as:

$$Q_u = 2' \Upsilon\ k_b (L^2/2) \tan(\delta) + W$$

Fig. 8: Pullout load test setup (Kotal et al. 2015)

Pile anchors having more embedment depth offer more resistance capacity than pile anchors having less embedment depth. It is also observed that ultimate capacity increases with B/d ratio i.e. the ratio of anchor to shaft width increase is more for long pile anchors.

2.6. Naraynan et al. (2017) [29]:

Paper present measurement of uplift capacity of model reinforced cement concrete mono-piles embedded in sandy soil of various densities. Piles with l/d ratio equal to 4, 6 and 8 are taken for model testing. This paper shows change in pullout capacity due to change in surface area of pile which provides friction.

It predicts the uplift capacity of piles which has been validated by comparing the uplift capacity predictions with a number of laboratory and field test results of many investigators. According to his method the net uplift capacity of a mono pile is given by

Qu= Qf + Wp
Qu= net ultimate uplift capacity
Qf= total skin load
Wp= weight of pile

Generally the load–displacement responses of the mono pile subjected to pulling loads are nonlinear.

Long mono-pile offer more resistance than short mono-pile.

3. Comparison of experimental Pullout Capacity:

Comparison on the basis of experimental and field tests values find out by different test arrangements.

Table No. 1: Compression based on field test

Sr. No.	Author	L/D Ratio		
		4	6	8
1.	Srirama Rao et al. (2007)	8000	10000	13000
2.	Sivakumar et al. (2012)	11000	27000	14000
		Pullout capacity in (N)		

Table No. 2: Compression based on model test

Sr. No.	Author	L/D Ratio		
		4	6	8
1.	Das and Pise (2003)	50	80	115
2.	Kotal et al. (2015)	108	162	211
		Pullout capacity in (N)		

III. CONCLUSIONS

In this study the theoretical and experimental models for computation of pullout capacity of piles are summarized on the basis of studies conducted by research scholars. This paper mainly focused on different experimental methods which are used to find out pullout capacity of piles.

Following are some conclusions:

As from study it is found that pullout capacity of piles governs by the aspect ratio of pile, surface area, nature of surface and soil properties.

Unit skin friction along the depth of the pile varies approximately linearly up to critical embedment depth and beyond it the skin friction remains roughly constant.
The critical depth lies between 10-30 times the diameters of the pile [9]

Chattopadhyay and Pise [8] have also noted the presence of critical depth which depends on L/D ratio.

The embedded depth of pile also shows significant effect on pullout capacity because pullout capacity of short pile depends on site friction which increases by increase in surface area.

Enlarge base pile shows large pullout capacity and it is depends on diameter/shaft diameter ratio. [17]

The surface characteristics are related by the soil-pile friction angle, almost all the investigators found that soil-pile friction angle is very important. Rough surface of pile shows more pullout capacity [29]

Higher the relative density of the soil higher will be the pullout capacity.

All the models discussed in the current study adopted certain assumptions and consider only layered soil so deviations do exist.

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