A Review of Uplift Load Carrying Capacity and Failure Mechanism of Cylindrical and Belled Pile

Devashish Babulal Kumavat[1], A. K. Verma[2], B. R. Dalwadi[3]

[1]*M.Tech Student, Department of Structural Engineering, Birla Vishvakarma Mahavidyalaya Engineering College, Vallabh Vidyanagar, Anand, Gujarat, India*
[2]*Professor, Department of Structural Engineering, Birla Vishvakarma Mahavidyalaya Engineering College, Vallabh Vidyanagar, Anand, Gujarat, India*
[3]*Associate Professor, Department of Structural Engineering, Birla Vishvakarma Mahavidyalaya Engineering College, Vallabh Vidyanagar, Anand, Gujarat, India.*

Abstract - *Foundations of some structures like tall chimneys, transmission towers, mooring systems for ocean surface or submerged platforms, jetty structures etc. are subjected to overturning moments and uplift loads due to wind effects, seismic events, wave actions or ship impacts. Hence, it is very important to know the uplift load carrying capacity of the pile along with failure pattern of soil in different soil conditions. Ample amount of research is being conducted around the world for finding the uplift load carrying capacity of cylindrical and belled piles by using different materials. An attempt is made in this paper to review the same.*

Key Words: *Uplift load carrying capacity, Failure mechanism, Belled pile*

1. INTRODUCTION

Uplift piles are commonly used as foundation systems for structures requiring uplift resistance such as high-rise structures and transmission lines. However, evaluation of ultimate uplift capacity and determination of the position of failure surface is still an area of concern in geotechnical engineering. The pile-soil interaction mechanism is not well understood, and very few literatures are available on the analysis of the ultimate uplift capacity and failure mechanism. The ultimate load carrying capacity aims at determining the load that the pile can handle before failure; while, the calculation of the settlement caused by the superstructure should not exceed the limits of the allowed deformation for stability, function and aspects of construction. Research on the ultimate load carrying capacity problems can be carried out using either analytical solutions or experimental investigations. The former could be studied through finite element analysis while the latter is achieved through conducting prototype, model and full-scale tests. A satisfactory solution is found only when theoretical results agree with those obtained experimentally.

A literature survey on the subject shows that there are different types of soil on which uplift load carrying capacity of pile is studied. Many of the existing design methods for uplift capacity of enlarged base pile are based on results obtained from small laboratory model test on anchor foundation. Soil properties were assumed to remain constant for the uplift load analysis, and therefore analytical solutions, like Meyerhof and Adam's method of estimating uplift capacity theory, matched with the experimental results. However, in cases where the soil properties vary with depth, most of these theories cannot be implemented and the analytical solutions that take into consideration the non-homogeneity of the soils are approximations, and hence the results are inaccurate.

2. REVIEW OF PREVIOUS WORK ON UPLIFT LOAD CARRYING CAPACITY OF PILE.

Liu Wenbai, Zhou Jian, MongkeTei-Mohr (2004) [1]

Field prototype tests have been carried out for under-reamed piles bearing uplift loading in the loess of droughty area. In these tests, uplift displacement and horizontal displacement of under-reamed piles bearing uplift loading and horizontal loading, displacement of surface layer soil, and relationship of loading and displacement were measured. The ultimate uplift bearing capacity and failure mechanisms of piles were studied. It is very effective on improving ultimate uplift bearing capacity of pile to raise height of belled-out section of under-reamed piles. Strength failure mechanism of pile and soil is solved by gradual failure to be due to damage softening and reduction pressure softening of the soil. A theoretical model has been proposed to calculate the ultimate uplift bearing capacity in the loess, and comparing the calculation results with the test data, both are basically similar, which shows to have chosen correct calculation
pattern.

Dr.A.K.Verma, Joshi Ronak K. (2010) [2]

Authors have conducted uplift load carrying capacity of single piles, group of piles and enlarged based piles (anchored piles)using model piles of circular solid concrete pile, hollow PVC and Galvanized Iron pipe pipes. Pile groups of 2x1 and 2x2 are used in the experimental investigation.

Square mild steel plate of thickness 4 mm is used as base enlargement of size 2d and 3d. L/d ratio has been kept 24 in all the cases. Spacing between two piles is kept as 3d constant in case of pile groups Behavior of uplift capacity for different materials, effect of base enlargement, effect of grouping of piles were studied in this study. Earth pressure coefficient Ks for single piles and pile groups has been modified with respect to the experimental results. With increase in base to diameter of pile ratio (B/d), ultimate uplift capacity can be increased exponentially. 3d base enlargement causes more than 300% increment in ultimate uplift capacity with respect to single pile for G.I. and concrete piles and it causes more than 800% increase for PVC piles. It suggests prime need of base anchorage for smooth surface piles.

Tsuyoshi Honda, Yoshio Hirai, Eiji Sato (2011) [3]

This paper evaluates the uplift capacity of belled and multi-belled piles in dense sand. A two-dimensional distinct element (DE) analysis was applied in pullout tests on single piles to investigate the uplift resistance of the piles, the soil behavior around the piles, and the interaction between the soil and the pile surface. It was observed from the DE analysis that the soil mass adjacent to the projections of the belled and multi-belled piles moved vertically, and that the soil movements leaned slightly with the occurrence of relative displacement between the soil and the pile surface. A theoretical solution for predicting the uplift capacity of belled and multi-belled piles was derived from an upper bound limit analysis based on the soil movements in the DE analysis. The solution was able to reproduce the ultimate uplift resistance in the DE analysis using the friction angles in the aggregates and on the pile surface that were evaluated from a simulation of direct and simple shear tests. In addition, a continuity equation that satisfied the relationship between the displacement vector of the soil mass adjacent to the projections and the change in volume around the soil mass was proposed for predicting the uplift capacity of actual piles under axisymmetric conditions. The theoretical solution obtained with the continuity equation was in good agreement with the pullout resistance of the belled and multi-belled piles in centrifuge model tests and full-scale tests conducted in situ.

Bai Yang, Jianlin Ma, Wenlong Chen, and Yanxin Yang (2018) [4]

Field pull out test results of 500 kV double-circuit line of Luping-Fule are presented in this paper to investigate the uplift bearing behavior of rock-socketed belled short piles. A calculation model of rock-socketed belled short pile has been proposed. During the initial stage of loading test, uplift load is shared by even section and bell of the pile, and the bell continues to bear uplift load after the lateral resistance of even section pile reaches the limit. A different performance has been found on the case of long belled pile. At the ultimate state, the uplift resistance provided by bell accounts for about 54.9% and 34.7% of the total uplift capacity for the 6.0 m long and 7.0 m long piles, respectively. Increasing pile length has been found to noticeably increase the ultimate uplift bearing capacity, while it has less effect on the displacement of pile top. The uplift capacity of even section pile is associated with the shear strength of rock mass around the pile, and the test results demonstrate that the ultimate resistance can be equal to the shear strength. The calculation method proposed in this study is proven to be able to accurately predict the ultimate uplift bearing capacity of the rock-socketed belled short piles.

Jeet. N. Thacker, Dr.A.K.Verma (2019) [5]

Authors in this study have carried out 24 sets of vertical uplift loading experiments of single piles and pile groups of triangular patterns (2x1 piles), diamond pattern (2x2 piles) and square pattern (2x2 piles) pile groups using the model piles of cylindrical and belled shaped. The piles were made up of concrete (M20) , having diameter of 20mm and of varying L/d ratio have been kept as 18, 20 and 22 .The diameter at base of belled piles was kept 2 times diameter of pile and the length of belled portion was kept 40mm constant in all belled pile experiments. The single piles and pile groups are embedded in dry sand bed. The relative density is kept 0% for initial experiment and then was varied to 50% to understand the effect of the denseness of soil. The uplift load carrying capacity depends upon the parameter like L/d ratio, relative density and enlargement of the belled portion. The uplift load carrying capacity of belled piles was more than cylindrical piles for all l/d ratios. Belled piles with square pattern and l/d ratio = 22 with relative density 50% has the maximum uplift capacity among all the other pile configurations for all l/d ratios and therefore belled square pattern is most advantageous one.

3. REVIEW OF PREVIOUS WORK ON FAILURE MECHANISM OF SOIL

Hamed Niroumand, Khairul AnuarKassim, AminGhafooripour, Ramli Nazir (2012) [6]

This paper proposes the failure mechanism observed by different researchers. Dickin (1988) have summarized several existing design methods giving the uplift capacity of horizontal anchors in sand. He classified the assumed failure mechanism of most design methods into three categories which are vertical slip-surface model, inverted truncated cone model and curved slip-surface model. Majer (1955), one of the earliest researchers, assumed the failure mechanism is a vertical slip surface above the anchor. According to him, the uplift capacity is basically the total of weight of soil above the anchor and shear resistance along the perimeter of the vertical slip surface.

Balla (1961) come up with different assumption that the slip surface above small model anchors was a tangential curve. According to Balla, the failure surface for shallow footings embedded in dense sand was nearly circular in elevation and the tangent to the surface of ground contact was at an angle of approximately 450-φ/2 to the horizontal. He obtained a reasonable correlation between theory and the results of full-scale tests on shallow footings by assuming a circular failure path. Downs and Chieurzzi (1966), who had done field test observations on belled piers, hold on to the concept that the uplift capacity is derived from the weight of the soil in an inverted cone above the bell plus the self-weight of the pier. Then, Meyerhof and Adams (1968) suggested a pyramidal shaped slip surface above the anchor based on his observation in laboratory model tests. According to Clemence and Veesaert (1977), the angle θ in the inverted cone slip-surface model is equal to φ/2 to the vertical, where φ is the angle of friction.

Qian Su, Xiaoxi Zhang, Pingbao Yin, Wenhui Zhao (2014) [7]

Ultimate capacity and failure surface position of uplift piles are dependent on soil parameters. In this paper, the horizontal slice method is used to discuss the relation among the ultimate uplift capacity, the failure surface position, and soil parameters with Mohr- Coulomb failure criterion. According to the limit equilibrium analysis, the ultimate uplift capacity is calculated by dividing soil around the pile into slices with considering the potential failure surface as a group of several sectional planes. Then the multivariate function used to calculate ultimate capacity is established and optimized by the sequential quadratic programming. Through the numerical calculation and comparison with the previous research, the results show that the method is reasonable and effective and can be used to determine the failure surface and the magnitude of the ultimate capacity of uplift piles.

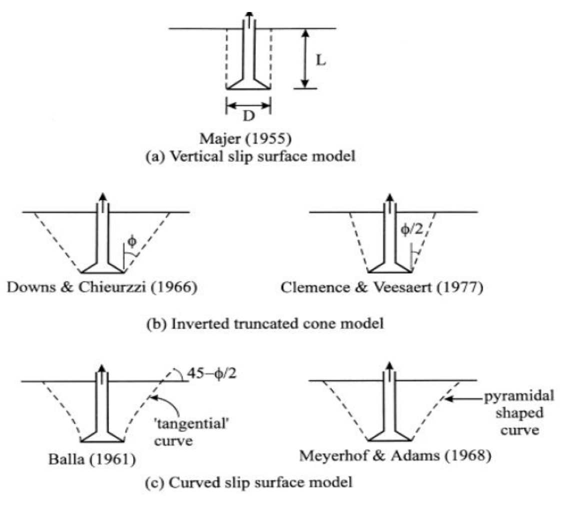

Fig -1: Assumed Failure Mechanisms for belled piers subject to uplift loads classified by Dickin (1988)

Ramli Nazir, Hossein Moayedi, A. Pratikso, Mansour Mosallanezhad (2014) [8]

The purpose of this research was to determine the capability of (and the factors which affect the performance of) an enlarged base pier in resisting uplift capacity. Experiments were conducted in the reinforced bin box of an enlarged base pier with a shaft diameter ranging from 30 to 50 mm, base diameters between 75 and 150 mm and base angles of α = 30°, α = 45° and α = 60°. Tests were conducted in both loose and dense sand packing. A failure mechanism was studied in a glass box for loose and dense sand packing. A dry sand u the bell angle and shaft diameter would result in a decrease of the net uplift capacity and failure displacement. This is due to the reduction in the amount of the sand column above the bell that resists the uplift of the pile. Failure displacements at a constant base diameter generally increased considerably with the increase of the embedment ratio but decreased with the increment of the sand density. It is thus apparent that the shaft diameter, bell diameter and bell angle are geometric factors which together with the embedment ratio and the sand density, should be considered in the design of enlarged base piers.

4. CONCLUSIONS

1. Uplift load carrying capacity of pile depends upon the length of the pile, diameter of the pile shaft, material of the pile, type of soil, pile arrangement pattern.
2. Uplift load carrying capacity increases gradually or linearly with increase in length of the pile to diameter of pile shaft ratio and exponentially with increase in base diameter to shaft diameter of pile.
3. In dry sand increasing the bell angle and shaft diameter would result in a decrease of the net uplift capacity and failure displacement due to less passive resistance of the soil.
4. Failure displacements at a constant base diameter generally increased considerably with the increase of the embedment ratio but decreased with the increment of the sand density.
5. Pullout capacity of pile in dense sand is more in comparison with loose sand but vertical displacements are catastrophic in dense sand and gradual in loose sand.

From the above review we can conclude that researchers have classified the assumed failure mechanism of most design methods into three categories viz. vertical slip-surface model, inverted truncated cone model and curved slip-surface model.

Failure mechanism of soil depends on the depth of embedment and bell angle of the pile.

Also, this paper clearly reflects that the amount of work done on uplift load carrying capacity of pile in cohesion-less soil is vast in comparison with that in cohesive soil.

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