UPLIFT AND BEARING BEHAVIOUR OF OBJECTS BURIED AND PARTIALLY BURIED IN SOFT CLAY

by

N. SANTOSH RAO

Department of Civil Engineering

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Earthquake foundation

Dedicated

to

My Parents

for Making Me

What I Am

Today

CERTIFICATE

This is to certify that the thesis entitled "**Uplift and Bearing Behaviour of Objects Buried and Partially Buried in Soft Clay**" being submitted by **N. Santosh Rao** to the Indian Institute of Technology, Delhi, is a record of bonafide research work carried out by him under my supervision and guidance. The thesis work in our opinion has reached the standard, fulfilling the requirements for **Doctor of Philosophy** degree. The research report and the results presented in this thesis have not been, submitted in part or full, to any other University or Institute for the award of any degree or diploma.

Manoj Datta
Professor
Department of Civil Engineering
Indian Institute of Technology, Delhi
Hauz Khas, New Delhi - 110016
INDIA

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N. Santosh Rao
N. Santosh Rao

ABSTRACT

In geotechnical engineering practice, especially in offshore geotechnical engineering, the knowledge of uplift behaviour of objects embedded in soft clay is necessary to design various types of anchor and foundation systems consisting of drag anchors, flukes, piles, suction caissons etc for various types of offshore structures. In offshore geotechnical engineering, the soils in which these anchor and foundation systems are embedded are usually just beneath the seabed level where soft to very soft clays are often encountered.

The review of literature has shown that while there have been a number of research studies reported by various investigators over the last few decades on the uplift behaviour of objects embedded in soft clay, most of the research studies primarily considered only the uplift resistance offered by the soil above the object. Some recent studies have clearly identified and delineated the presence of a suction force beneath the object during uplift and have shown that this suction force can be of significant magnitude.

However, the variations observed in the reported values of the suction force shows that the factors influencing the development of the suction force have not been clearly established. In addition, the uplift behaviour of the objects under conditions of full development of the suction force has also been observed to have not been studied in detail.

The review of literature has thus shown the need for a comprehensive study which takes into account all the aspects of uplift behaviour including most importantly, the suction force developed beneath the object during uplift.

The objectives of the present study thus follow from the review of literature as given below :

a. To study the uplift behaviour of objects buried and partially buried in soft clay under undrained conditions.

b. To delineate the influence of suction on the uplift behaviour.

c. To compare the uplift behaviour of objects with the bearing behaviour of the objects.

d. To validate existing theories on uplift behaviour of objects and propose modifications/extensions where necessary.

e. To provide design recommendations.

To achieve a greater reliability in the prediction of the uplift behaviour of objects embedded in soft clay, a comparison of the same with the bearing behaviour of the object has been attempted in the present study. As the bearing behaviour of objects embedded in soft clay has been well established, the same affords a benchmark with respect to which the uplift behaviour of the object can possibly be predicted.

Laboratory experimental investigations have been conducted to study the uplift as well as bearing behaviour of model objects embedded in soft saturated clay under different burial conditions (i.e. buried and partially buried). To determine the suction forces, tests have been conducted with and without venting so as to eliminate or not to eliminate the suction forces respectively.

The effect of variables identified from the literature review, on the uplift behaviour has also been studied. The variables that have been considered in the experimental investigations are namely type of burial (i.e. buried or partially buried), embedment depth (o.5, 1, 2, 4 and 6 times the diameter of the object), displacement rate (0.2,1,5,25,125 mm/min), shape in elevation (plate, sphere and dual cone), aspect ratio (cylinders of height / diameter ratio of 1, 2 and 4) and type of soil (kaolinite clay, bentonite clay).

The forces and the corresponding force factors (derived as the (forces at failure) / ((undrained shear strength of the soil) x (projected area in plan of the object))) that have been determined in the experiments have been termed as the (i) total force in uplift determined from uplift tests with suction force below base not eliminated, (ii) breakout force determined from uplift tests with suction force below base eliminated, (iii) suction force in uplift determined as the difference of (i) and (ii), (iv) total force in bearing determined from bearing tests with suction force above top not eliminated, (v) bearing force determined from bearing tests with suction force above top eliminated and (vi) suction force in bearing determined as the difference of (iv) and (v).

The results obtained from the experimental investigations have been presented in the form of the force-displacement curves along with the variations observed due to the effect of the identified variables. The observed force-displacement curves show that in general, for buried as well as partially buried objects embedded in kaolinite clay, the forces in uplift as well as the forces in bearing increase continuously but at a decreasing rate with respect to the displacement of the object. However, some of the forces tend to become constant at large displacements of the object. A higher initial slope is observed in the force-displacement curves for the forces in bearing.

The analysis of results of the experimental investigations has been presented in terms of the force factors as also the effect of the identified variables on the above. The analysis of results has shown that :

a. All the force factors in uplift and in bearing, except the bearing factor increase with increase in displacement rate and reach almost constant limiting values at higher displacement rates. The bearing factor does not show any significant increase with increase in displacement rate.

b. The total factors in uplift and the total factors in bearing for the buried objects increase with increase in embedment ratio and reach almost constant maximum values of around 12.5 at higher embedment ratios greater than 2. While the total factors in uplift are lower than the total factors in bearing at shallow embedment of the object, at deeper embedment of the object they are similar.

c. The breakout factor increases with increase in embedment ratio and reaches almost constant maximum value of around 7 at higher embedment ratios greater than 4. The bearing factor for buried objects shows very little increase with increase in embedment ratio while the bearing factor for partially buried objects remains at an almost constant value at all embedment ratios . A maximum value of around 8.5 has been observed for the bearing factor for both buried and partially buried objects.

d. For partially buried objects, the suction factor in uplift is constant at all embedment depths of the object at around 0.8 times or in other words, around 80% of the bearing factor. For buried objects, the suction factor in uplift reduces from around 0.75 times the bearing factor at shallow embedment of the object to around 0.5 times the bearing factor at deep embedment of the object.

e. At shallow embedment depths, all the force factors except the suction factors are lower for the dual cone as compared to the plate and sphere while at deep embedment depths the above factors are similar for all the object shapes. No significant change is observed in the suction factors on account of variation in shape of the object.

f. The suction factor in uplift increases with increase in aspect ratio of the object and reaches almost constant values at aspect ratios greater than 4.

A comparative evaluation of the results of the experimental investigations with the results of other experimental studies and also with theories on uplift behaviour has been attempted so as to arrive at a satisfactory estimate of the uplift behaviour of objects. The comparative evaluation has shown that :

a. The lower and upper limits of the breakout force for different conditions of embedment as observed in the various reported experimental studies are similar to the limits derived on the basis of the reported theories.

b. For determining the bearing forces, the bearing capacity theory of *Skempton (1951)* alongwith the use of a reduced undrained shear strength of the clay to account for the compressibility of the soft clay as recommended by *Meyerhof (1951)* has been shown to give very satisfactory results.

Theoretical solutions have been developed using well established analytical techniques, for certain conditions for which existing theories prove to be inadequate. The theoretical study has brought out that :

a. Using upper bound limit analysis method and extending the work of *Chen (1975)*, the value of the total factors in uplift and in bearing is around12.68 for deep embedment of a buried object which is almost the same as the value of around 12.5 observed in the present experimental investigations.

b. The existing reversed bearing capacity theory for determining the suction factor in uplift proposed by *Finn & Byrne (1972)* has been modified to account for the difference in the undrained shear strength of the clay in triaxial extension (applicable in uplift of the partially buried object) and in triaxial compression (applicable in bearing of the partially buried object) as given by *Parry (1995)*. The suction factor in uplift has been shown to be approximately 0.8 times the bearing factor which is the same as the relationship observed in the present experimental investigations.

The major conclusions of the present study are :

a. The uplift capacity of buried objects which includes the suction force developed beneath the object, increases with increase in embedment depth of the object reaching a constant limiting value at deeper embedment depths. This is similar to the variation observed in the breakout capacity (based on breakout factors) of buried objects, when the suction force is eliminated, as observed in the present study and as also reported in earlier studies. The limiting value of the uplift capacity is reached at a shallower embedment depth as compared to that for the breakout capacity. Additionally, the limiting value of the uplift capacity is significantly higher than that for the breakout capacity.

b. The observed variation in the breakout capacity with embedment depth of the object has been shown to be in the range of limits determined based on a comparative evaluation of the results of other experimental studies and various reported theories.

c. The present study has shown that while the uplift capacity of a buried object is lower than the bearing capacity of the buried object at shallow embedment of the buried object, at deeper embedment of the buried object, the uplift capacity of the buried object is equal to the bearing capacity of the buried object.The similarity of uplift and bearing capacities at deep embedment of the buried object has been theoretically validated through a systematic approach using the limit analysis method.

d. The suction force developed beneath an object forms a significant part of the uplift capacity of both buried and partially buried objects. For a buried object, the suction force developed beneath the object decreases with increase in embedment depth of the object whereas for a partially buried object, the suction force developed beneath the object is a constant and does not decrease with increase in embedment depth of the object. The suction force is similar at shallow embedment of the object for both buried and partially buried object whereas at deeper embedment depths the suction factor for a buried object is lower than that for a partially buried object.

e. The suction force developed beneath the base of the partially buried object during uplift has been observed to be directly related but not equal to the bearing force developed beneath the base of the partially buried object under bearing, at all embedment depths of the object. The reversed bearing capacity theory as proposed by *Finn & Byrne (1972)* has been extended to substantiate the above observation.

f. The suction force developed beneath the object increases with increase in aspect ratio (height or thickness / width or diameter) of the object reaching a constant maximum value at larger aspect ratios greater than 4.

g. No significant change has been observed in the uplift behaviour of the object on account of change in shape of the object except at shallow embedment depth of the object.

Finally recommendations for design have been proposed for determining the uplift capacity, breakout capacity and bearing resistance of objects embedded in soft saturated clay under undrained conditions of loading.

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