TECHNICAL NOTE

STUDY ON UNDER-REAMED PILES IN COHESIONLESS SOIL UNDER TENSION

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ABSTRACT

Under-reamed piles are bored cast-in-situ concrete piles having under-reamed bulbs formed by developing the pile stem. The main advantage of under-reamed pile is the increased load carrying capacity due to the enlarged bearing area and locating the bulb in a stratum of larger bearing capacity. They are mainly used when the foundations are subjected to either compressive or tensile forces or both. The information available on ultimate uplift capacity (tension) of under-reamed pile in sandy soil is scarce. Therefore an experimental work was programmed and carried out to understand the effect of number of bulbs and their positions on the ultimate uplift capacity of under-reamed piles. The type of soil used in the present laboratory investigation was sand and mild steel under-reamed pile models. The effect of spacing of under-reamed bulbs on their ultimate uplift capacity (tension) to carry load has been experimentally determined. The ultimate uplift capacity of under-reamed piles increases with number of bulbs. From the laboratory study on pile models that there is no significant change in uplift capacity of under-reamed pile with spacing of the bulbs. The theoretical ultimate uplift load predicted by Bureau of Indian Standard Method is compared with the experimental values. The theoretical values are higher than the experimental values. Hence, a modified expression to compute the uplift capacity of under-reamed piles is developed and presented.

INTRODUCTION

The present day trend of modern civil engineering structures tends to rise high into the sky i.e., sky scrapers and tall structures have become the order of the day. Such tall structures subjected to high axial loads combined with large bending moments due to horizontal forces such as wind, have necessitated special types of foundation, such as deep foundation. These foundations are to be anchored to the soil by means of concrete root-like structures. The requirement of the concrete roots are that there should be sufficient bond between the soil and the pile, and is designated to carry vertical loads combined with bending moments. These foundations are called under-reamed pile foundations which can be used for transmission tower foundations, eccentrically loaded columns supported on soils of low bearing capacity and for multi-story buildings. The under-reamed pile foundations used for tall structure must have adequate capacity to resist upward pullout loads as well as downward bearing loads. Hence, resistance to pull out of the piles forms the main design criteria than the bearing capacity. Keeping this in view, a detailed study of under-reamed piles in cohesionless soils has been made which provides information on resistance to upward pullout loads. One of the most economical solutions for tall structures foundation is to provide under-reamed piles. These piles find extensive use in antenna and television towers due to extremely low settlements. The high anchorage capacity of under-reamed piles has resulted in their wide acceptance for use in transmission line towers, large underground tanks, reservoirs, dry docks and other dynamic structures for providing reaction against uplift due to buoyancy.

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SCOPE AND OBJECTIVE

The determination of load carrying capacity of the under-reamed pile is of much importance to the design engineer. Most of the expressions presently available are mostly empirical derived from out of field experiences. The Central Building Research Institute (CBRI) and the Bureau of Indian Standards (BIS) (1980) have recommended some methods to arrive at the load carrying capacities of piles. The factors influencing load carrying capacity in under-reamed piles are more than for plain or straight piles. Many investigators have reported (Kachroo and Kakroo, 1983; Silva Armand, 1956; Balasubramanium, et al., 1983; Meyerhof and Sastry, 1978; Gupta, 1983; Collins, 1953; Mohan and Jain, 1958; Mayerhof and Adams; Mohan and Chandra, 1961; Chandra and Khepar, 1964) on under reamed piles in expansive soils or cohesive soils, whereas a very few reported (Jain and Gupta, 1968; Sharma and Pise, 1994; Neely, 1990; Sayed and Baker, 1992; Nicola and Randolph, 1993; Michael and Raines, 1991; Kraft, 1991; Coyle and Ungaro, 1991; Vesic, 1963) on under-reamed piles in sandy soils. Therefore, an experimental program was planned and carried out to investigate the effect of number of under-reams and their spacing on the uplift load carrying capacity of under-reamed piles in noncohesive soils.

The object of this study is to understand the behaviour of under-reamed piles in general and effect of bulb spacing on uplift capacity in particular. There is not much experimental backup available for many empirical formulations. Only limited investigations have been carried out to study the uplift capacity of under-reamed piles in noncohesive soils. Experimental method has been adopted in the present investigation on model under-reamed piles subjected to tension. An attempt has been made to correlate the effect of spacing of bulbs in a double-bulb under-reamed piles with uplift resistance. This study also aims to compare the experimentally obtained uplift resistance values with the values determined from the method given by Bureau of Indian Standards (1980).

EXPERIMENTAL INVESTIGATIONS

Engineers involved in the design, construction and efficient working of the various types of structures usually try to predict in advance how the structure would behave when it is actually constructed. For this purpose the investigators have to resort mostly to experimental investigation. Such experiments are also necessitated in the case of problems which cannot be solved thoroughly by simple theoretical analysis. Obviously the experiments cannot be carried out on the prototype size structures as the testing will be costly and cumbersome. It is, thus, essential to construct a small scale replica (model) of the structure and the tests are performed on it to obtain the desired information, this technique of model testing is adopted in this present work.

The pile model tests are quite economical and convenient, because the design, construction and operation of model may be altered several times if necessary (without incurring much expenditure) until all the defects of the model are eliminated and the most suitable design is obtained. However, the model test results have to be utilised with caution, while predicting the performance of the prototype. In this work an attempt has been made for the experimental determination of uplift load carrying capacity of model of double under reamed pile with different spacing of bulbs. Comparative study of simple pile and single under-reamed bulb models were also tested.

Preparation of Pile Models

Three sets of mild steel pile models of diameters 20, 25 and 30 mm were selected in the present study. Each of the three sets of piles contains 6 piles, i.e., plain pile, single under-reamed pile and four double under-reamed pile with bulb spacing of 1.0, 1.25, 1.5 and 1.75 times the diameter of the bulb. The diameter of under-reamed bulb adopted was 50, 62.5 and 75 mm for 20, 25 and 30 mm pile diameter, respectively.

Preparation of the Test Bed

This investigation was limited to cohesionless soils. Hence, sand was used in the test bed. The sand used for this investigation was brought from Gurpur River bank. The sand passing through IS 2.0 mm sieve and retained in IS 425 micron sieve was used in the investigation which was having coefficient of uniformity of 1.4 and coefficient of curvature of 1.03. The shear strength parameters of sand used were determined from direct shear test as per BIS specifications (BIS:2720 (part XIII) - 1972) and the angle of internal friction was found to be 38^0. Relative density test was also conducted on the sand as per BIS specification (BIS: 2720 (part XIV) - 1968) and density index value was found to be 68 percent.

The test bed was prepared in the rectangular box of size 1.5 X 1.0 X 1.0 m. The size of the box was chosen keeping in view that the influence of boundary restraint on the load is very marginal and may be in the order of about five percent or less. Sand was filled in layers of 100 mm. Each layer was compacted using a vibrator to get the required density of 1.5 g/cc. One side of the test box was transparent to facilitate observation during compaction of sand layer. At required depth, the pile was positioned on the bed. The piles were hung in position and were held vertically. It was ensured that piles were properly aligned using the axis of the pulley which was used for conveniently applying the pullout load. Three piles were held in position below the pulley axis. All the piles were embedded in sand with the five layers of sand i.e. 500 mm depth of sand. Care was taken to achieve the uniform density of sand throughout the test bed. The method of installation of piles in the field and laboratory is different, however, the effect may be marginal.

Loading Arrangement

The loading frame was fabricated in the Department of Civil Engineering and consists of two frictionless pulley aligned in pile axis over which a wire traverse through, connecting the hook of the pile at one end and the loading pan at the other end. This loading frame is a static incremental type of device in which incremental load can be applied without causing any impact on it. The incremental pulling load can be applied to the pile directly by adding known weights successively on the pan.

A known load was applied on the pan carefully without jerk and impact, which may result in a small incremental pullout load on the pile and the pile starts displacing. The corresponding uplift displacement of pile was recorded from the dial gauges. The next incremental pullout load was applied when the displacement completely stopped or if the rate of displacement is less than 0.1 mm/hour. The load was applied till the failure of pile. When the pile comes out of sand bed, it was considered as failure and the corresponding pullout load was taken as ultimate uplift load.

BUREAU OF INDIAN STANDARD METHOD OF ESTIMATING PILE UPLIFT CAPACITY

The procedure given by the BIS 2911 (part lll) for determination of the ultimate uplift capacity of an under-reamed pile in sandy soil was utilized. The shear parameters and in-situ density of the soil were required which were determined as per the BIS specifications. The shear parameters were determined by conducting direct shear test on sandy soil. The angle of internal friction was found to be 38^0. The bearing capacity factors as given by Vesic (1963) was used in determination of ultimate uplift capacity of piles. The ultimate uplift capacity of an under-reamed pile in sandy soil was determined and the values are tabulated in Table 2. The following is the expression as given in the BIS 2911 (Part III).

$$Q_u = A_a \left(1/2\, D_u\, n \gamma N_\gamma + \gamma N_q \Sigma_{r=1}^{r=n} dr\right) + 1/2\, \pi D \gamma K \tan\delta \left(d_1^{\,2} + d_f^{\,2} - d_n^{\,2}\right) \qquad (1)$$

where:

- A_a = $\pi / 4\,(D_u^2 - D^2)$ Where D_u is the under-reamed bulb diameter and D is stem diameter.
- n = number of under-reamed bulbs.
- γ = average unit weight of soil.
- N_γ & N_q = bearing capacity factors depending upon the angle of internal friction.
- d_r = depth of the centre of different under-reamed bulbs below ground level.
- d_f = total depth of pile below ground level.
- K = earth pressure coefficient (usually taken 1.75 for sandy soils).
- δ = angle of wall friction (may be taken equal to the angle of internal friction ϕ degrees)
- d_1 = depth of the centre of the first under-reamed bulb.
- d_n = depth of the centre of the last under-reamed bulb.

The actual uplift capacity obtained from the experiments and as estimated from the BIS method are given in Tables 1 and 2, respectively, and when the values are compared, the BIS values are higher, resulting to an error on the unsafe side by the designer. Therefore, a modified expression as given below is suggested over BIS expression.

Table 1 Ultimate Uplift Pile Load Capacity From Experiments

Pile stem diameter (mm)	Ultimate Uplift Load Capacity (kg)					
	Simple Pile	Pile with Single bulb	Pile with Double bulb at different spacing			
			1.0 Du	1.25 Du	1.5 Du	1.75 Du
20	35	101	111	118	124	128
25	39	115	121	126	130	135
30	46	148	152	156	158	161

Table 2 Ultimate Uplift Pile Load Capacity as Per BIS Code Provisions

Pile stem diameter (mm)	Ultimate Uplift Load Capacity (kg)					
	Simple Pile	Pile with Single bulb	Pile with Double bulb at different spacing			
			1.0 Du	1.25 Du	1.5 Du	1.75 Du
20	16.11	69.40	114.42	112.40	110.41	108.44
25	20.13	102.46	169.92	166.30	162.72	159.18
30	24.16	141.37	234.34	228.45	222.63	216.87

Table 3 Ultimate Uplift Pile Load Capacity As Per Suggested Expression

Pile stem diameter (mm)	Ultimate Uplift Load Capacity (kg)					
	Simple Pile	Pile with Single bulb	Pile with Double at different bulb spacing			
			1.0 Du	1.25 Du	1.5 Du	1.75 Du
20	17.97	70.28	71.71	71.08	70.48	69.90
25	22.75	105.27	109.32	108.42	107.57	106.73
30	27.76	145.27	153.69	152.39	151.37	150.32

$$Q_u = A_a \left[1/2\, D_u \gamma n N_\gamma + \gamma N_q (d_n)\right] + 1/2\, \pi D \gamma K \tan\delta \left(d_1^2 + d_f^2 - d_n^2\right) + W \quad (2)$$

where W is the weight of the pile. All remaining terms of the expression are same as given in Eq. (1). In the above expression, the first component accounts for bearing and the second component for the skin friction.

The higher value of uplift capacity estimated for all the three sets of piles as per BIS expression may be attributed to the consideration of number of under-reamed bulbs in the first component. But in practice, the full mobilization of uplift capacity is possibly mobilized only in the last bulb and partial mobilization on all other bulbs. Therefore, in the suggested expression only one bulb is considered and its the uplift capacity calculated. However, the expression requires some more modification or a contribution factor for partial mobilisation of uplift capacity other than in the last bulb, but this requires further investigation. The uplift capacity expression given in BIS method does not take the self weight of pile. However, it also contributes in development of uplift capacity which has been accounted in the suggested expression. The uplift capacity values calculated using the suggested expression are tabulated in Table 3.

ANALYSIS AND DISCUSSIONS

In this investigation, the uplift capacity of the under-reamed piles was determined through laboratory tests. There are three set of different diameters of pile considered such as 20, 25, 30 mm (six in each set). The results of the tests are reported in Table 1 and in Figs. 1 to 3. It is observed from Table 1 that there is marked increase in uplift capacity of pile without and with a bulb. The uplift capacity increased due to the increase in the diameter of pile. The percent increase of uplift capacity of pile due to the presence of a bulb are 188, 195 and 222 due to increase in diameter of 20, 25, 30 mm, respectively. This infers that under-reamed piles can carry heavier tension loads. There is no significant variation in uplift capacity of pile with single bulb pile and double bulbs of various spacing. This is quite contrast to compressive load bearing capacity of under reamed piles, where there is significant influence of number of bulbs and spacing (Mohan et al., 1966; De, 1978; Poulos, 1969; Poulos and Davis, 1980; Cooke and Whitakar, 1961). In case of the pile under compression loading, the pile capacity is derived from both skin friction and bearing all the bulbs contribute for mobilization of pile capacity by not allowing any displacement of pile at tip. As the pile capacity under tension loading is derived only form skin friction, the variation in uplift capacity may not be significant due to number of bulbs and its spacing.

As the pile diameter increases, the uplift capacity also increases. However, this increase is not proportional to the increase in the pile diameter. The variation in uplift capacity of the pile is marginal due to different spacing of bulbs, indicating the uplift capacity of the pile is independent of bulb spacing in case of double under-reamed piles as per this investigation.

It can be observed from Figs. 1 to 3, that the pile displacement increases as the load increases, irrespective of the spacing of the bulbs. The pile displacement is lower due to the presence of bulb. The pile displacement decreases as the load and bulb spacing increases.

It can be observed from Tables 1, 2 and 3 that the modified expression yielded the value of uplift capacity close to the observed experimental uplift values, and BIS code expression resulted in higher uplift values than both experimental and modified values in all the three sets of pile tests. For the plain pile, the experimental values of uplift are higher than the BIS code expression values in all three sets of pile tests. In case of single under-reamed piles, the uplift capacity values are higher, almost three times that of the plain pile for same length and diameter, due to the presence of the under-ream bulb. The uplift values in both expressions (BIS code and suggested) are slightly higher than the experimental values.

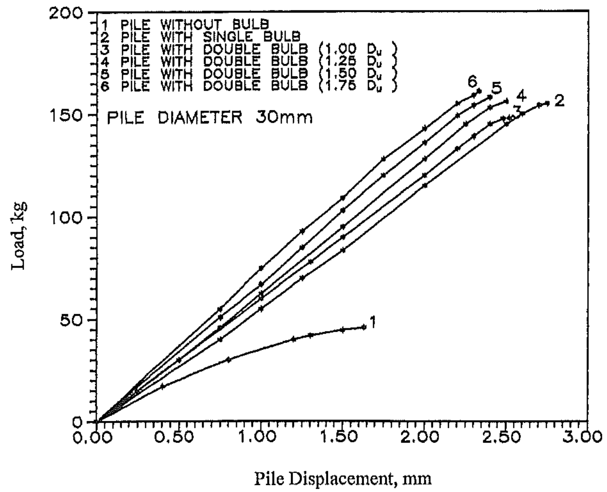

Fig. 1 Variation Pile Displacement with Load

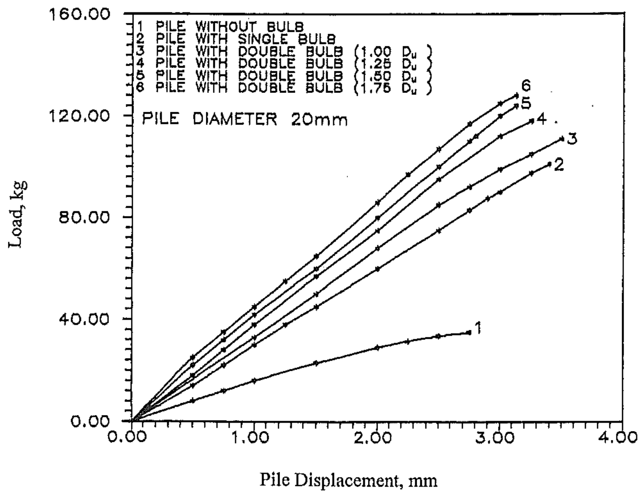

Fig. 2 Variation Pile Displacement with Load

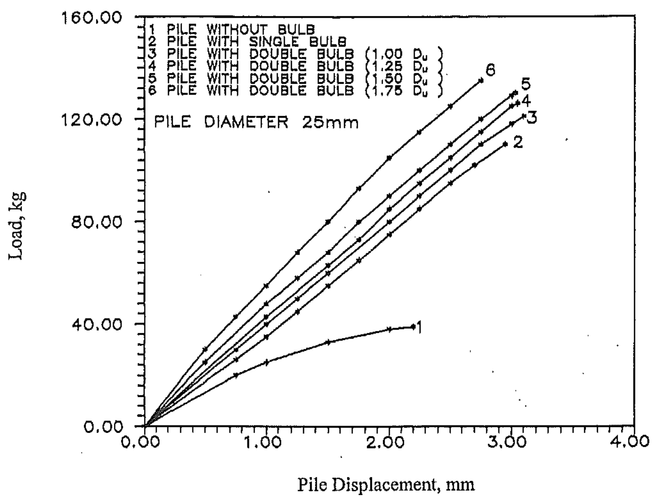

Fig. 3 Variation Pile Displacement with Load

The uplift capacity of piles with single and double bulbs exhibits higher values than plain piles due to the increase in bearing area provided by the additional number of bulbs. It is experimentally seen that the uplift capacity varies marginally with the spacing for bulbs from 1.0 D_u to 1.75 D_u.

In the design of under-reamed piles for uplift loading, the values calculated from the suggested expression seems to yield close values to experimental values. Therefore, it is suggested to use this modified expression for combining the uplift capacity of under-reamed piles in the cohesionless soils, for design purposes.

CONCLUSIONS

Based on the investigations the following conclusions were drawn. The use of under-reamed piles for foundations increases the strength in compression and in tension, and the design is mostly based on empirical expression arrived from experience. In the present study, the influences of the above two factors on the uplift capacity of the under-reamed piles has been investigated.

In this study, being essentially a laboratory investigation on under-reamed piles, pile models with bulbs with different diameters and spacing of bulbs were made from mild steel, installed in cohesionless soil test bed and were tested with tensile loading arrangement. Plain piles of the same diameters were also similarly tested for the purpose of comparison with the response of under-reamed piles. The tensile tests on these 18 pile models having different diameters and bulb spacing revealed that:

1. By providing under-reamed bulbs, the uplift capacity increases.
2. The uplift load carrying capacity is maximum and displacement is minimum for a single under-reamed pile, when the bulb is at the bottommost possible position.
3. The ultimate uplift load capacity is not significantly influenced by the spacing between the bulbs.
4. The ultimate uplift capacity increases with the increase in diameter, but is not proportional to the increase in the diameter.
5. The uplift load capacities increased with the number of bulbs. However, from the point of overall economy of construction, a number of bulbs of more than two do not seem to be advisable.
6. The rate of pile uplift per unit load decreases with the number of bulbs.
7. The BIS code 2911 (part III) method overestimates the uplift capacity of the under-reamed piles, and the designer is likely to err on the unsafe side.
8. The BIS code method when modified to the following form:

$$Q_u = A_a \left[1/2\, D_u \gamma n N_\gamma + \gamma N_q (d_n)\right] + 1/2\, \pi D \gamma K \tan\delta \left(d_1^2 + d_f^2 - d_n^2\right) + W$$

seems to yield uplift values which almost coincide with the experimental uplift values. Therefore, it is suggested that the designer shall use the above expression which is a modified form of the BIS method for under-reamed piles subjected to tensile loads like in situations such as transmission towers, chimney foundation, etc.,

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