

# STUDIES ON THE GEOMETRICAL FEATURES OF UNDERREAMED PILES BY THE FINITE ELEMENT METHOD

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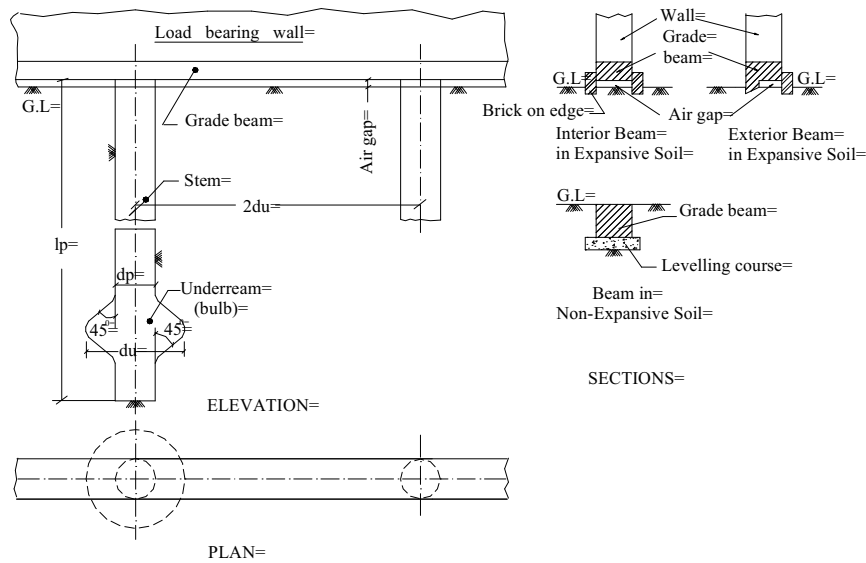
**ABSTRACT:** Most of the studies on underreamed piles have been on the experimental side only, while theoretical studies, using the Finite Element Method, have been mostly confined to straight-shafted (prismatic) piles. In a study with emphasis on the geometrical features of the underreamed pile, no other method is as versatile as the Finite Element Method. The present investigation makes use of the finite element analysis for the underreamed pile problem with special reference to its geometrical features, using the advanced software package ANSYS. The content of this paper is limited to 2-D axisymmetric nonlinear analysis for axial compression and tension, in non-expansive clays, with respect to the geometrical parameters which include the number, size, location and shape of the bulb, and 3-D analysis for the group capacity of two piles. On the material side, while the pile is treated as linear, the soil and the pile-soil interface are nonlinear, the former following the Drucker-Prager constitutive model. The nonlinear analysis is 'incremental-iterative-mixed' leading to high accuracy. The results of the analyses will be of sustained interest to designers of underreamed piles.

(Key Words: Clay, Pile, Underream, Geometry, Analysis, Finite Element Method)

## INTRODUCTION

Piles with enlarged base or 'underreams' (Fig.1) have been known since the early 40's. Such piles were first used in Texas, U.S.A., where expansive soils occur in abundance. They were intended primarily to resist the uplift forces developed on them due to the heaving of the ground. In India they are extensively used since the 50's to anchor building foundations in the expansive black cotton soils, at a depth where ground movements due to changes in moisture content are negligible. Considerable research has been carried out in later years, and there has been marked development in their design and use. In recent years work has been done on piles with two or more bulbs, and presently multi-bulb piles are in use. A systematic study of these piles was first attempted in South Africa by Jennings and Henkel (1949). This was followed by a report from Australia by Tasker et al.(1950) which gave an empirical expression for the anchoring capacity. Golait (1976) has done an extensive study on underreamed piles and a special load cell was designed for testing the anchorage offered by underreamed piles.

Currently, guidelines for design and construction of underreamed piles are available in a handbook by Sharma et al.(1978). Chummar(1986) and Sharma(1986) discuss the use of underreamed piles in India, with special reference to construction practices and situations where they are superior to other foundations. In favourable soil conditions such as stiff to hard clays, multi-underreamed drilled shafts may provide cost savings due to increased capacity when compared with single underreamed drilled shafts. Short bored underreamed piles have been popularized in India by Central Building Research Institute, Roorkee, primarily for use in 'black cotton soils', but they have since found wider application in various soil conditions, under a variety of situations. In India, the use of underreamed pile is governed by the code IS:2911 (Part III) – 1980.



**Fig. 1. Underreamed Pile (IS: 2911 (Part III) – 1980)**

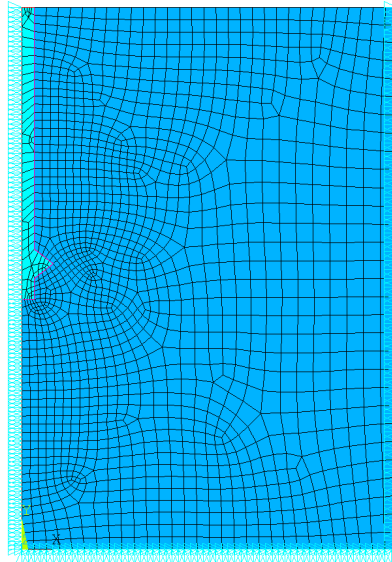
Study of anchor foundations is becoming more and more important in the wake of the rapid infrastructure development and industrialization of the country. They are used for high tension electric transmission towers, masts for radio transmission lines and television towers, support for suspended brackets on roads, etc. Babu Shanker (1965) presented an approach for the prediction of the bearing capacity of underreamed piles. Model steel piles have been tested with varying lengths and underreaming ratios in order to investigate the proportions of total load taken by the narrow pile stem and its expanded base. Pull-out tests have also been conducted on underreamed piles to study the anchorage resistance offered by the expanded base. Jha (1967) has tried to predict the ultimate bearing capacity, relative displacement and shape of the failure surface by performing experiments using smaller models. From the data for the full scale static tests of 6 to 22m long piles, it was found that, as the  $(l/d)$  ratio increases, where  $l$  is the length of the pile and  $d$ , the diameter of the stem, the load transmitted through a pile underream having the same size decreases proportionately (Grigoryan and Chakhvadze, 1986).

This paper presents the results of analyses conducted on the influence of the geometrical features of the underreamed pile on its ultimate load carrying capacity, besides the group capacity of two piles with varying spacing. The geometrical features include the length of the pile without and with bulb, location, number, size and shape of the bulb. The present study was preceded by a detailed study by the same authors (2001) for ultimate load carrying capacity – both in compression and tension – against factors such as different stem and underream diameters, in clay over a wide range of consistency. Prior to the latter, in order to validate the analysis, the authors verified some of the experimental results on underreamed piles in clays reported in literature which were found to agree within a margin of 10%. Indeed, the greatest advantage of the analytical approach is that, whereas the experimental results are at best confined to yielding the load-settlement diagram and the ultimate load, the analytical investigations yield a host of information, which among others include, besides the above, mesh deformation, displacement vectors, deformation contours in the medium, principal stress vectors, contact stresses, etc.

### **FINITE ELEMENT IDEALIZATION AND SOLUTION DETAILS**

The advanced engineering software package ANSYS with excellent pre- and post-processing features has been used for the analysis in the present study. 2-D axisymmetric analysis has been carried out by using 8-noded quadrilateral elements for both the pile and soil. The pile is considered as linearly elastic. While Drucker-Prager model is invoked for soil nonlinearity, the interface between the pile and the soil is analyzed by using a 3-noded line contact element, characterized by the coefficient of interface friction. For studying the group capacity, 3-D analysis has been carried out by using 10-noded tetrahedron element for

both the pile and the soil and 8-noded quadrilateral element for the interface. An ‘incremental-iterative-mixed’ method is used for the analysis, which gives highly reliable and accurate results. 25 increments of the given load, and within each increment 100 iterations, are specified in the solution for convergence. Automatic time-stepping option was used, which would change both increments and iterations according to convergence. In all cases a lateral extent of soil mass up to six times the bulb diameter and vertical extent up to four times the bulb diameter below bottom of the pile was modelled for the analysis (Fig.2).



**Fig. 2. Finite Element Mesh for the Underreamed Pile-Soil System**

The following material properties are used in the analysis.

<i>Pile:</i>	$E = 2.5 \times 10^7 \text{ kPa}$	
	$\gamma = 25 \text{ kN/m}^3$	
	$\mu = 0.15$	
<i>Soil:</i>	$E = 8000 \text{ kPa}$	$c = 50 \text{ kPa}$
	$\gamma = 17 \text{ kN/m}^3$	$\phi = 10^\circ$
	$\mu = 0.3$	$\psi = 10^\circ$
<i>Interface:</i>	$MU = 0.12$	

## RESULTS AND DISCUSSION

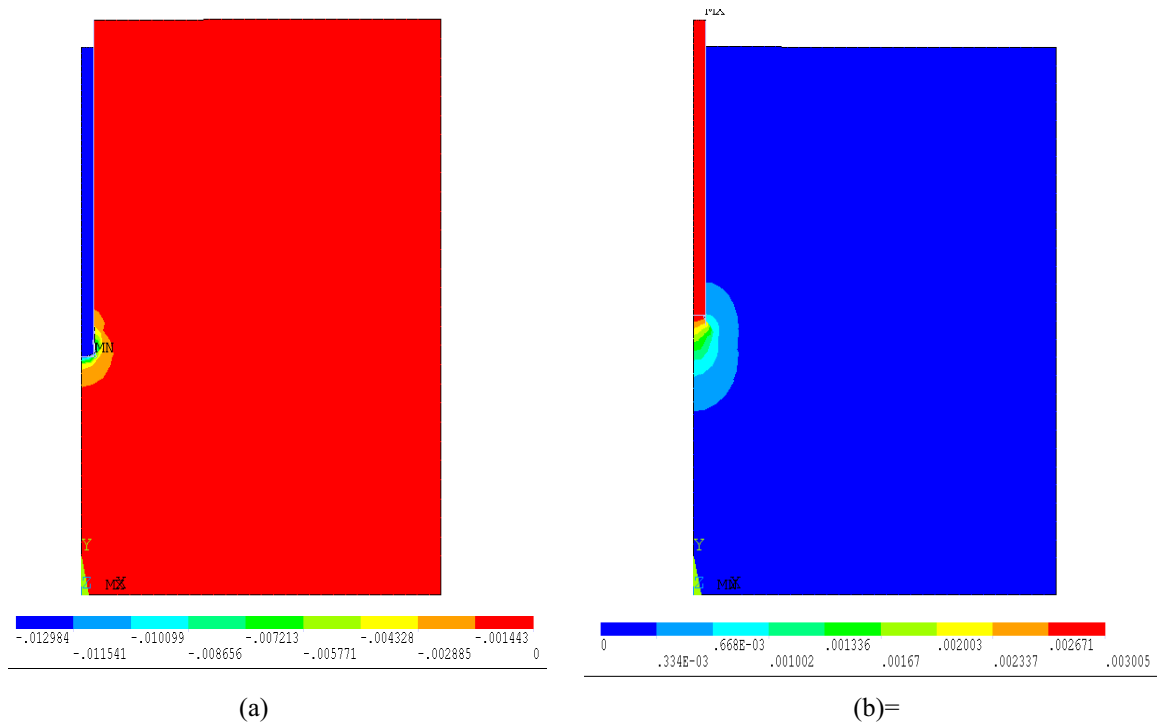
The results of the analysis and discussions on the same for each parameter are presented in the following. Since these are standard piles given in the Code (IS:2911 (Part III) – 1980), the results are presented directly without attempting any normalization.

### Length of the pile without bulb and with bulb

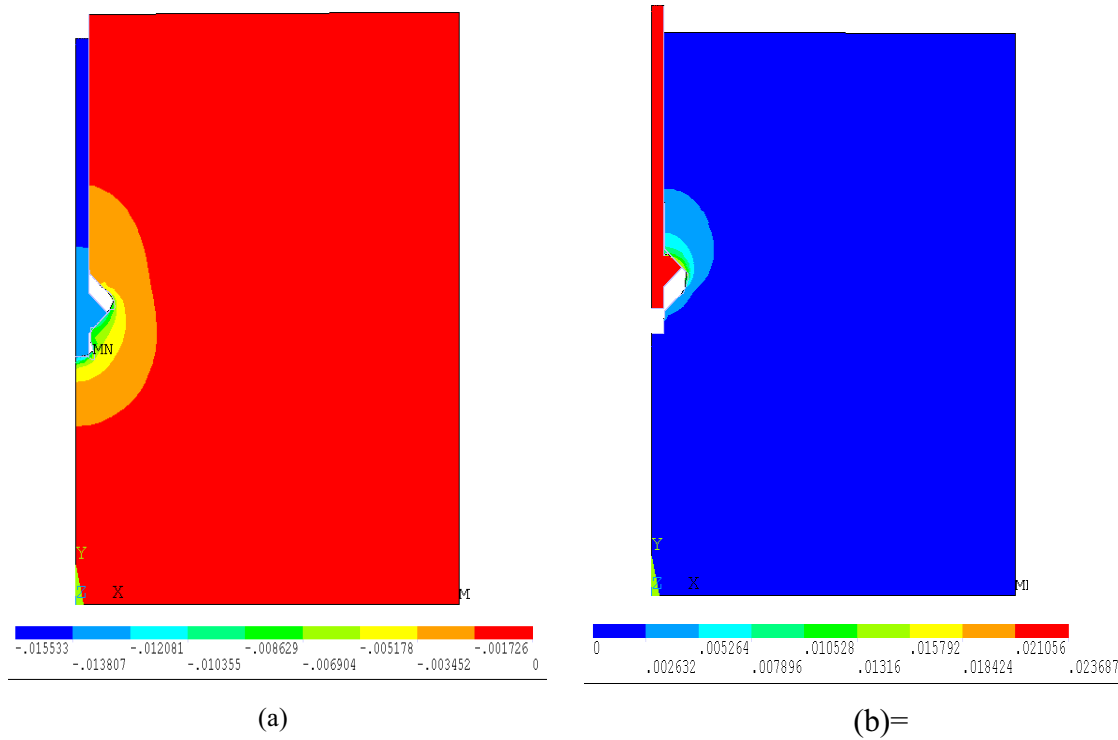
In this study a bulb of dia 0.75m is provided on the stem – at standard height from the tip – whose length is made to vary. Two sets of data, one with bulb and one without, have been used for the analysis. The results from the analyses are entered in Table 1 which show that ultimate load is generally insensitive to change in length, especially in the case of underreamed piles. The ultimate loads, however, are substantially in favour of the underreamed pile when compared to prismatic pile, even when considering the additional material input for the bulb. Figs. 3 and 4 give the post-processing results for prismatic pile and underreamed pile, for the pile of 3.5m length, at half the ultimate load, in both compression and tension.

**Table 1. Length of Pile: Ultimate Load in Compression and Tension=**

Length of pile= (m)= (1)=	Prismatic (without bulb)=					Underreamed (with bulb)=				
	Com= press= ion= (kN)= (2)=	Settl= eme= nt at= P <sub>u</sub> /2= (mm)= (3)=	Tens= ion= (kN)= (4)=	Upli= ft at= P <sub>u</sub> /2= (mm)= (5)=	Total= volume= of= materi= al (m <sup>3</sup> )= (6)=	Com= pressi= on= (kN)= (7)=	Settl= ement= at P <sub>u</sub> /2= (mm)= (8)=	Tens= ion= (kN)= (9)=	Upli= ft at= P <sub>u</sub> /2= (kN)= (10)=	Total= volume= of= material= (m <sup>3</sup> )= (11)=
3.0=	61=	11.7=	15.0=	2.39=	0.212=	223.2=	15.0=	201=	16.5=	0.284=
3.5=	61.5=	12.5=	16.5=	2.97=	0.247=	222.5=	15.5=	202=	17.3=	0.319=
4.5=	80.0=	10.6=	24.6=	2.47=	0.318=	222.0=	14.6=	201=	23.5=	0.390=
6.0=	60.0=	6.4=	17.0=	2.20=	0.424=	222.4=	13.5=	200=	23.6=	0.496=



**Fig. 3. Y-displacement for Prismatic Pile at P<sub>u</sub>/2=**  
**(a) Compression (b) Tension=**



**Fig. 4. Y-displacement for Underreamed Pile at  $P_u/2$   
 (a) Compression (b) Tension**

**Location of the bulb**

A pile of length 4.5m but with standard values of 0.3m and 0.75m respectively for  $d_p$  and  $d_u$ , has been used for these studies, with the height of the centre of the bulb (underream) from the tip as the parameter. The results pertaining to the location of the bulb on the stem are given in Table 2. It is seen that the ultimate capacity is highest for the bottom-most location of the bulb, decreasing thereafter to a constant value after some height.

It is to be pointed out in this connection that in the manual method of construction of underreamed piles, illustrated by Kurian (1992), a length of the stem projects below the underream, which corresponds to the space occupied by the bucket which receives the soil scraped out from the enlarged part of excavation forming the bulb. Such a projection can however be avoided if one resorts to more mechanised methods of construction as practised in the west. Fig. 5 gives post-processing result at half the ultimate load in both compression and tension for the bottom-most location of the bulb.

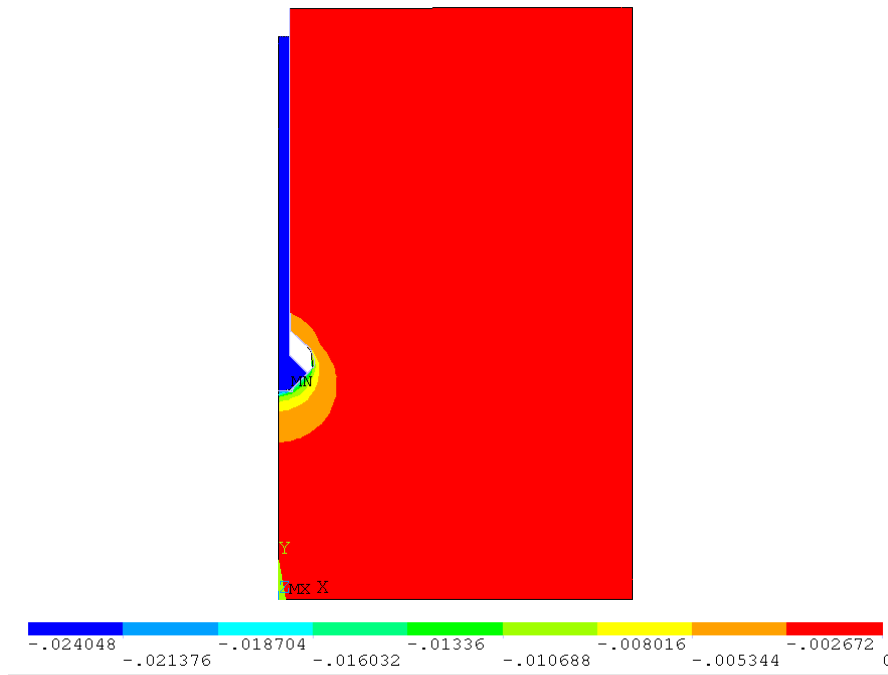
**Number of bulbs**

A pile of length 4.5m but with standard values of 0.3m and 0.75m respectively for  $d_p$  and  $d_u$ , has been used for these studies. Here, a maximum of 3 bulbs were used for the analysis. Any *benefit* (in load-carrying capacity) in this case is at the *cost* of the extra material input in the form of bulb. In such a situation, it should be remembered that the scheme is attractive only if the benefit *outweighs* the cost.

The results from the above analyses are presented in Table 3. It is seen that the increase in the ultimate load carrying capacity is commensurate with the additional material input. Load-settlement and load-uplift diagrams for single underreamed pile are given in Figs 6 and 7. The post-processing result is given in Fig. 8 for 3 bulbs, at the ultimate load.

**Table 2. Location of Bulb on Stem: Ultimate Load in Compression and Tension**

Height of underream from bottom of the pile – h (m) (1)	Ultimate load in compression (kN) (2)	Ultimate load in tension (kN) (3)
0.275	242.8	202.5
0.350	236.5	204.5
0.475(std.)	222.0	201.0
0.600	222.0	199.4
0.725	222.0	199.8



**Fig. 5. Y-displacement at  $P_u/2$  in Compression for  $h=0.275m$**

**Size of the bulb**

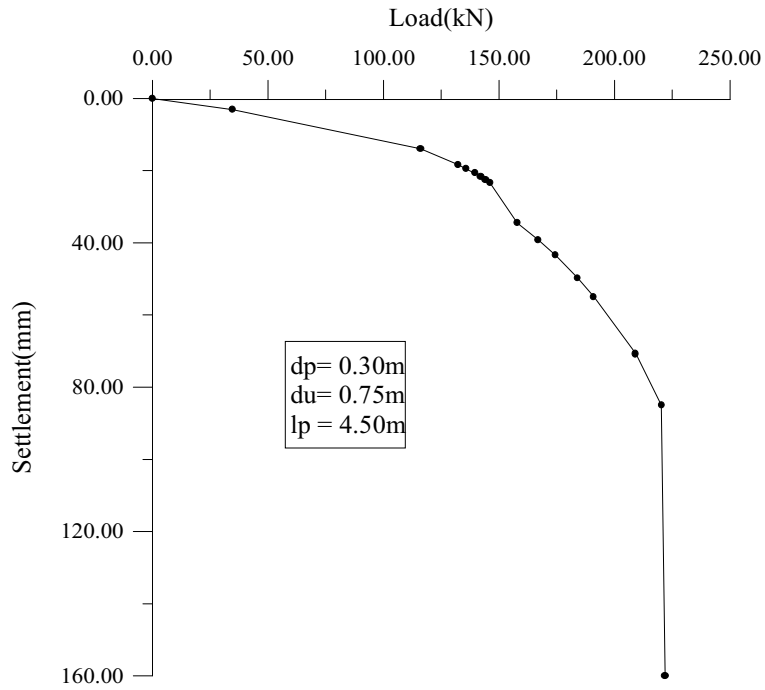
In this, keeping the length of the pile as 3.5m, with  $d_p$ , 0.3m, the diameter of the underream is varied from 0 (no bulb) to 1.2m. It is of interest to know the gain in the ultimate load against the corresponding increase in material input when underreams of increasing diameters are considered. These results are presented in Table 4. The gain in strength is marked if larger bulbs did not pose problems as regards stability and retention of the enlarged excavations in construction. It is perhaps more relevant to consider the increase in strength against the increase in bearing area in this case, which is also entered in Table 4.

**Table 3. Multi-underreamed Piles: Ultimate Load in Compression and Tension=**

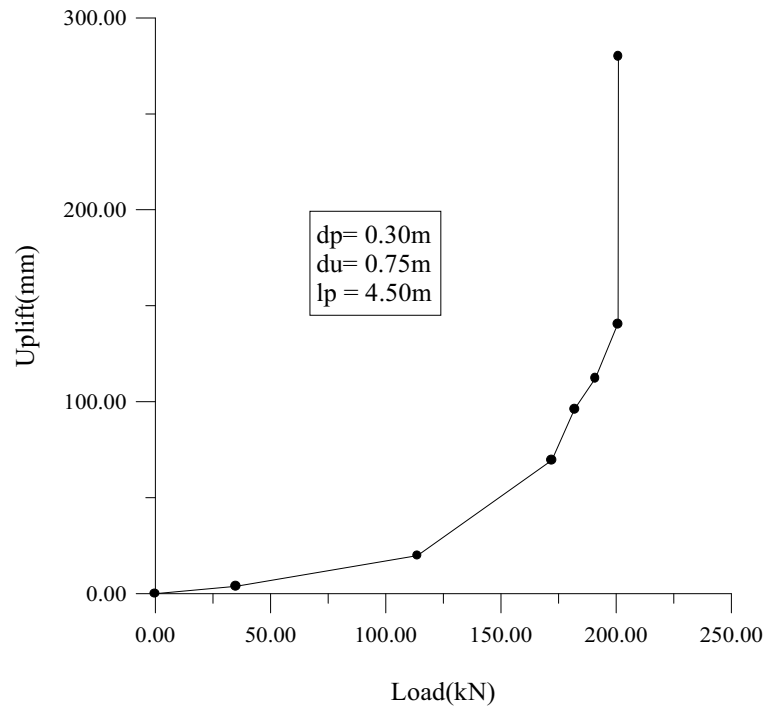
Number of bulbs=	Ultimate load in compression= (kN)=	% increase=	Ultimate load in tension= (kN)=	% increase=	Total volume of material= (m <sup>3</sup> )=	% increase in volume=
(1)=	(2)=	(3)=	(4)=	(5)=	(6)=	(7)=
1=	222.0=	0.0=	201.0=	0.0=	0.390=	0.0=
2=	430.0=	93.7=	388.0=	93.0=	0.462=	18.5=
3=	561.0=	30.5=	557.4=	43.7=	0.534=	37.0=

**Table 4. Diameter of Bulb: Ultimate Load in Compression and Tension=**

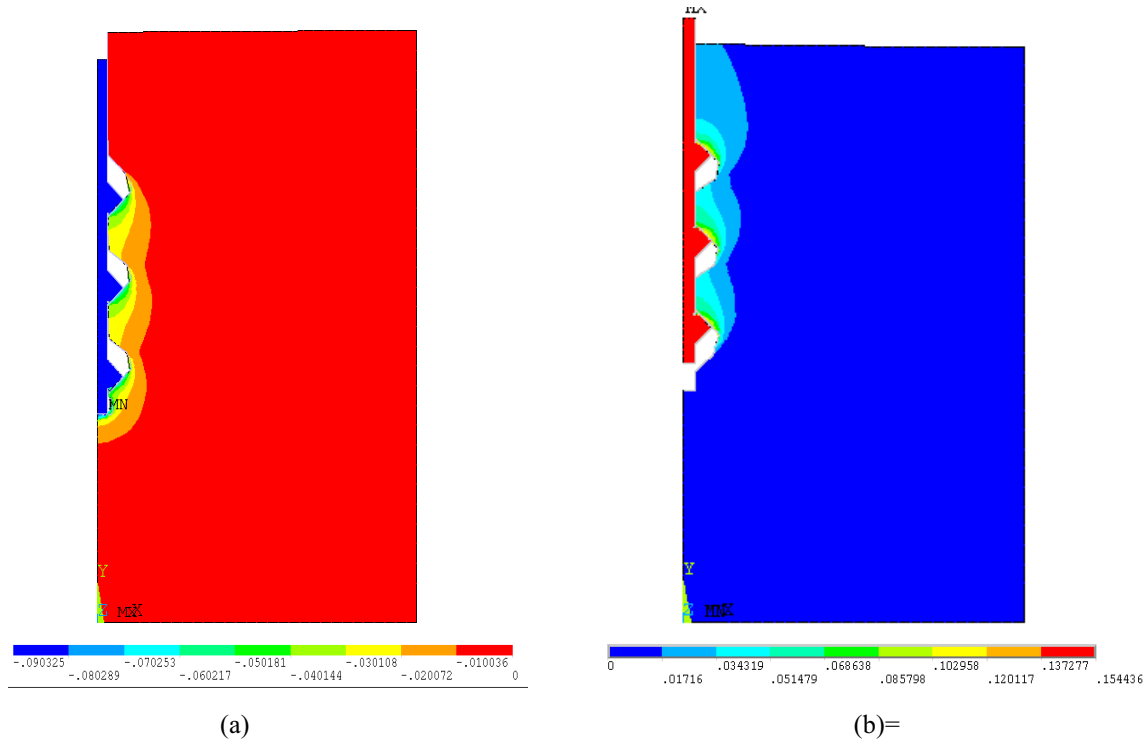
Dia of bulb = du=	Ultimate load in compression=	% increase=	Ultimate load in tension=	% increase=	Total volume=	Increase in volume (due to bulb)=	% increase in volume=	Total plan area=	% increase in plan area=
(m)=	(kN)=	(3)=	(kN)=	(5)=	(m <sup>3</sup> )=	(m <sup>3</sup> )=	(8)=	(m <sup>2</sup> )=	(10)=
(1)=	(2)=	(3)=	(4)=	(5)=	(6)=	(7)=	(8)=	(9)=	(10)=
0.3 (no bulb)=	61.5=	0.0=	17.5=	0.0=	0.247=	0.000=	0.0=	0.071=	0.0=
0.525=	84.0=	36.5=	81.0=	363.0=	0.262=	0.015=	6.07=	0.216=	204.2=
0.750=	222.5=	262.0=	202.1=	1055.0=	0.319=	0.072=	29.1=	0.442=	522.5=
0.975=	374.3=	508.0=	365.2=	1987.0=	0.435=	0.188=	76.1=	0.747=	952.1=
1.200=	582.0=	846.0=	552.0=	3054.0=	0.629=	0.382=	154.6=	1.131=	1493.0=



**Fig. 6. = Load vs. Settlement for Underreamed Pile with One Bulb=**



**Fig. 7.= Load vs. Uplift for Underreamed Pile with One Bulb=**



**Fig. 8. Y-displacement at  $P_u$  for Underreamed Pile with 3 bulbs**  
**(a) Compression (b) Tension**

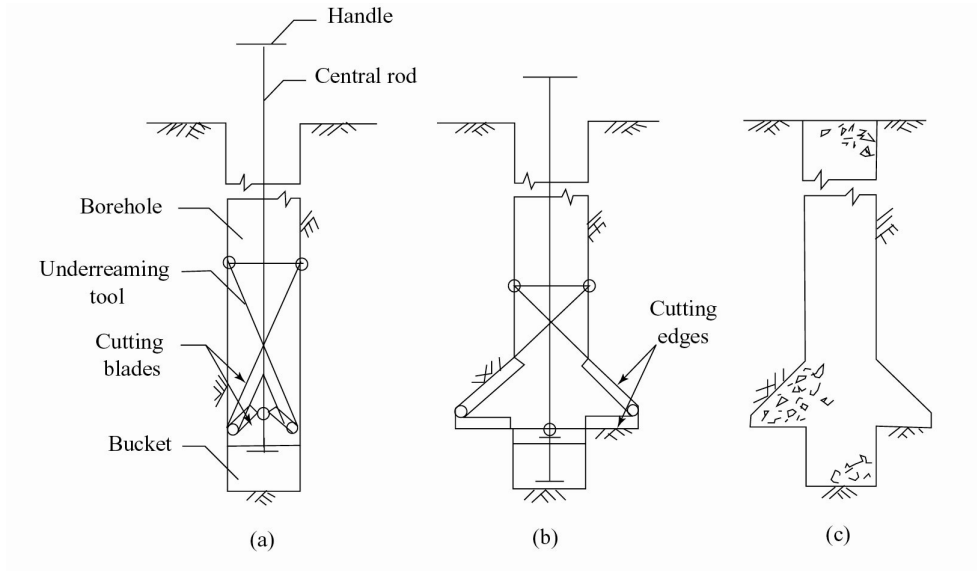
### Shape of the bulb

Since the Finite Element Method is ideal for considering shapes, it was thought fit to consider a spherical bulb of equivalent volume as the standard double conical shape, besides single cones at top and bottom each at half the material input. These results are presented in Table 5.

While the ultimate load given by the spherical shape is lesser, presumably due to reduced bearing area, it is of considerable interest to note that half bulbs (single cones) give comparable strengths as full bulbs with the one at top well exceeding that of the full bulb, at half the material input.

In a detailed analytical study on the bearing capacity and settlement characteristics of *shell foundations* of various types, verified by test results, Kurian and Jayakrishna (2001) have found that inverted conical shells give lesser bearing capacity than their flat counterparts. While this finding throws some light on the decrease of load carrying capacity with the inverted half cone at the bottom, in compression, the presence of the inverted half cone at the bottom, leaving the top flat, does not show a corresponding increase in anchoring capacity in tension.

It may be noted in this connection that in the mechanized construction of piles with enlarged conical base as practised in the west, the same is invariably confined to the single upright cone. Fig.9 shows the design of a manual underreaming tool for cutting a half bulb at top corresponding to the design for cutting the double cone, illustrated by Kurian (1992). An added advantage in this case is that since the bucket is of half the height, the underream is lowered on the stem, which has the potential of raising its ultimate capacity. Settlement at the ultimate load for the half bulb at the top is given in Fig. 10 from post-processing



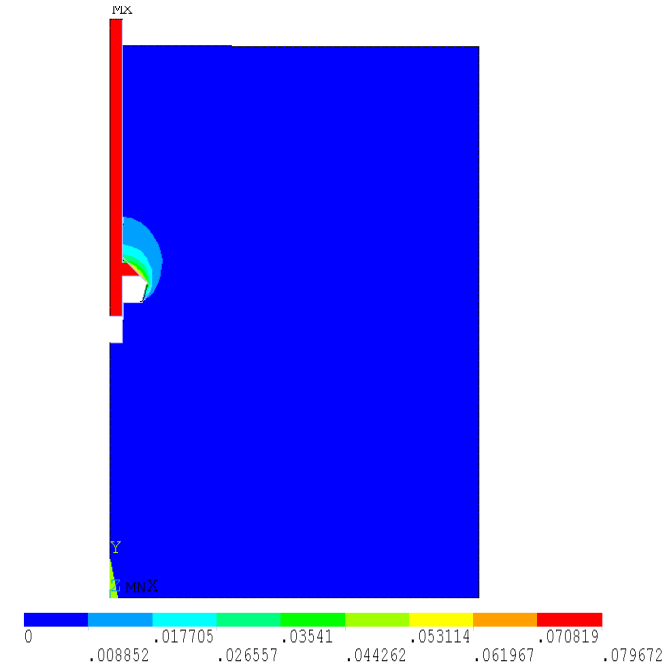
**Fig. 9 Underreamed Pile with Half Bulb at Top (a) Borehole with the underreaming tool in the collapsed position, (b) Underreaming completed, (c) Hole concreted.**

#### **Pile spacing in group of two**

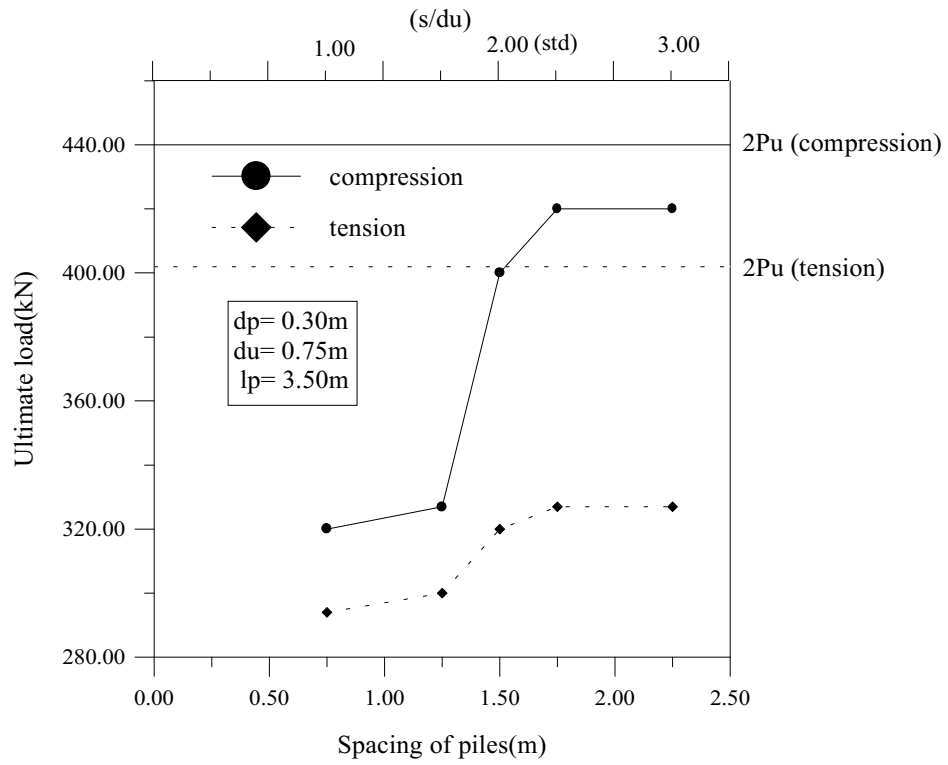
The behaviour of a group of two piles, with dimensions,  $d_p=0.3\text{m}$ ,  $d_u=0.75\text{m}$  and  $l_p=3.5\text{m}$ , at variable spacing (centre to centre) has been studied. Referring to the results presented in Fig.11, one notices the sharp fall in ultimate load carrying capacity of the group when the spacing decrease below  $2.33d_u$ , particularly in compression. This is presumably due to the increasing interference between the corresponding zones of influence with decreasing spacing. One also notices that the group capacities are only 91% and 80% of the sum of the individual capacities even at the standard spacing of  $2d_u$  in compression and tension respectively. Figs. 12 and 13 are included to show some of the typical post-processing results.

**Table 5. Shape of Bulb: Ultimate Load in Compression and Tension**

Shape of bulb (1)	Ultimate load in compression (kN) (2)	Ultimate load in tension (kN) (3)	Volume of bulb ( $\text{m}^3$ ) (4)
Full bulb – double cone	222.5	202.1	0.072
Half bulb (above)	270.0	220.0	0.036
Half bulb (below)	223.0	214.0	0.036
Full bulb – spherical	138.0	115.4	0.072



**Fig. 10. Y-deformation at  $P_u$  for Half Bulb above in Tension=**



**Fig. 11. Variation of Ultimate Load with the Spacing of Piles=**

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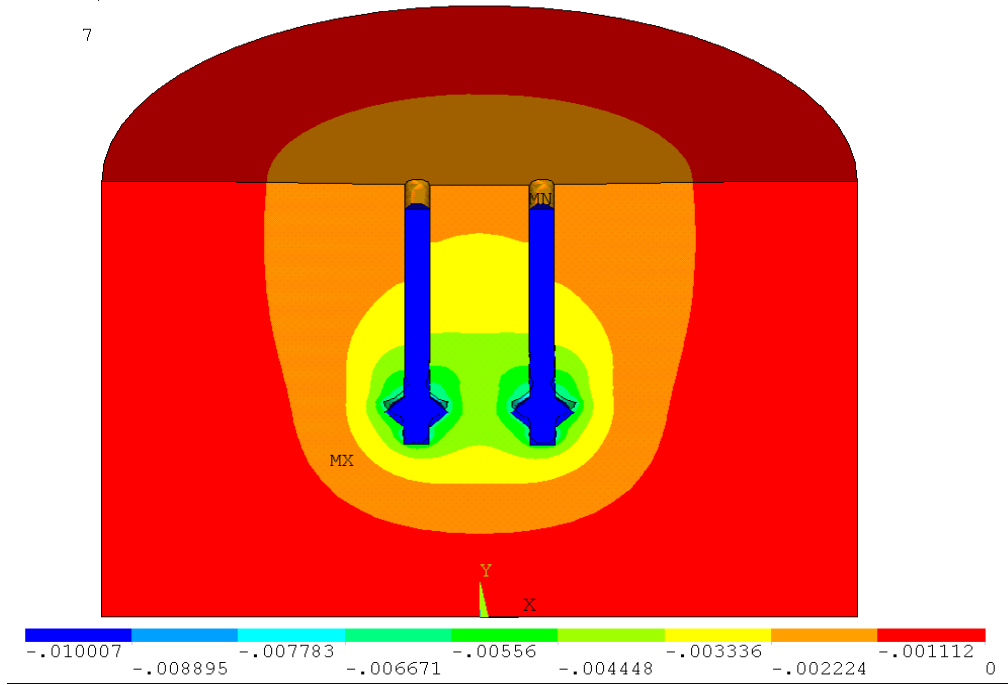


Fig. 12. Y-deformation at  $P_u/2$  for Spacing of 1.5m in Compression=

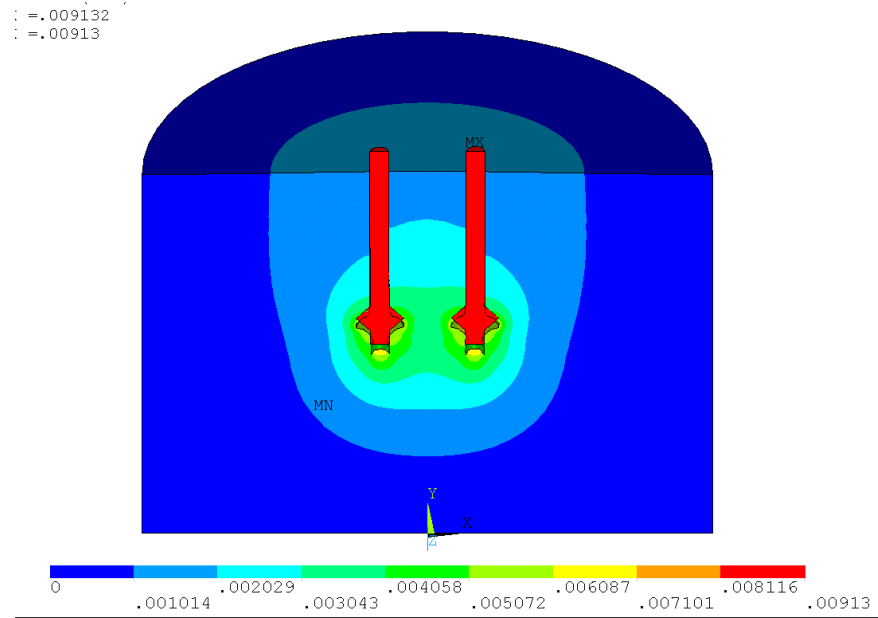


Fig. 13. Y-deformation at  $P_u/2$  for Spacing of 1.5m in Tension=

## CONCLUSIONS=

The conclusions drawn from the above studies have been stated below in a quantitative form to the extent possible. At any rate, they are indicative of the general trend of the results.=

- 1.= An advanced Package like ANSYS 5.7 with excellent pre- and post- processing features, can yield= a vast number of results from each analysis, unlike experimental results.=
2. The most valuable conclusion from the case of no bulb (prismatic pile of diameter 0.30m), is the increase in the capacity by 262% in compression and by 1124% in tension, when the pile is underreamed, for a volume increase of 29%. These results alone establish the case for the underreamed pile.=
3. For a given soil ( $c=50$  kPa) and pile (stem dia=0.30m), the influence of location of the bulb is not significant beyond the standard height 0.475m (applying to  $d_p=0.3$ m) from the base of the pile for the location of the underream. However this capacity is 8.6% lesser compared to the case of the underream located at the bottom of the pile. This leads to the observation that the standard location= using manual construction, leaving space for the bucket at the bottom, is reasonable.=
4. The observation in the case of multi-underreamed piles is that, the capacity increases by 153% in compression and 177% in tension when the number of bulbs increases from 1 to 3, against a corresponding increase in the volume of material by 37%. This leads to the conclusion that multi= underreamed pile is a highly cost-effective proposition in terms of material input.=
5. As regards the size of the bulb, there is an increase in capacity by 846% in compression and 3054% in tension, when the diameter of the bulb varies from 0.30 to 1.20m (i.e., by 300%). The corresponding increase is 155% in volume of material and 1493% in bearing area. However large= underreams disproportionate to the stem cannot be attempted as they pose difficulty in construction, with regard to keeping the underream cavity stable.=
6. The shape of the underream has revealed an interesting result. With half bulb (single upright cone)= at the top alone, the maximum capacity in compression is found to exceed that of the full underream (double cone) by 21%, indicating thereby a gain in strength with reduced material= input (i.e., by 50% for the bulb). For the same material input as the double cone bulb, the spherical shape, which suffers an area reduction of 32%, is found to be less effective with the capacity in= compression falling by 38%.=
7. In studying group action using two underreamed piles ( $d_p=0.30$ m,  $d_u=0.75$ m), considering= different spacings between the piles, the maximum group capacity is reached at a spacing of 1.75m (2.33 $d_u$ ), beyond which it remains constant. However, the group capacity at this spacing= itself is 4.5% less than the sum of individual capacities in compression and 18.25% in tension,= respectively.=

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## APPENDIX II. NOTATION

$c$  = cohesion;

$d_p$  = diameter of pile;

$d_u$  = diameter of underream;

$E$  = Young's modulus;

$l_p$  = length of pile;

$\mu$  = coefficient of interface friction;

$P_u$  = ultimate load;

$Y$  = vertical deformation;

$\gamma$  = unit weight;

$\mu$  = Poisson's ratio;

$\phi$  = angle of internal friction;

$\psi$  = dilation angle;