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Uplift Load Carrying Capacity of Cylindrical and Belled Pile in Cohesive soil Bed.

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Abstract

Foundation of some structures like transmission towers, mooring systems for ocean surface or submerged platforms, tall chimneys, jetty structures etc. are subjected to uplift loads. Literature reflects that scholars have conducted pull out field prototype & model test and failure pattern of soil is studied for belled piles in loess soil & cohesionless soil. In this research work, the authors have carried out 36 tests on single pile and pile groups and uplift load carrying capacity is obtained by experimental investigation of single pile, triangular pattern (2x1) and square pattern (2x2) using the model piles of cylindrical and belled shaped in cohesive soil of soft consistency. The piles are having 20 mm shaft diameter and varying L/d ratio of 6, 8,10,15,18 & 20 for both cylindrical pile and belled pile. Belled portion is cast in belled pile with an angle of 70° with horizontal and having base diameter of 60 mm and height 55 mm. Spacing between two piles in various pile group was kept three times the piles shaft diameter (3d) in all experiments. Based on the experimental results as the L/d ratio increases uplift load carrying capacity increases. Uplift load carrying capacity of single pile, triangular pile group & square pile group of belled pile is 410%, 280% and 240% more than cylindrical piles. Uplift load carrying capacity of triangular pile group & square pile group increases by 182% and 273% for cylindrical pile and 104% and 141% for belled pile in comparison with single pile. Failure pattern of soil is obtained from experiments performed on belled pile and by using this failure pattern, theoretical uplift load carrying of belled pile is obtained.

Keywords: Uplift load carrying capacity, Cylindrical and Belled pile, Failure plane, Cohesive soil bed.

1.Introduction

Tall, heavy and many important structures are subjected to lateral loads like wind and wave loads and large moments are induced and piles are subjected to compressive and uplift loads. To counter this type of load in structures like tall chimneys, transmission line towers, mooring system for ocean surface or submerged platform or jetty structures belled piles are used [1].

Belled piles are piles with enlarged base which provide more area and anchorage compared to cylindrical pile and for resisting uplift load coming on them. Belled pile is rarely used in India and very less work is done in this area of finding the uplift load carrying capacity and failure pattern of the soil and more specifically in cohesive soil. The enlarged area of the belled pile provides the passive resistance to the uplift load which helps in increasing the uplift load carrying capacity of pile. The belled resist the uplift load by combined mechanism. The shaft of the belled pile provides the frictional resistance and the belled portion provides the end bearing resistance. So belled piles are very useful in resisting the uplift load by this combined mechanism.

Hamed Niroumand, Khairul AnuarKassim, Amin Ghafooripour, Ramli Nazir (2012)[2] in there paper studied about Dickin (1988),Majer (1955),Balla (1961)[3], Downs and Chieurzzi (1966), Meyerhof and Adams (1968)[4] and Clemence and Veesaert (1977) works, they have conducted experiments on cylindrical and belled pile in sand and they observed various failure pattern of soil and they have concluded that failure pattern depends upon various parameters as embedment length, bell angle base diameter of belled pile and shaft diameter of the pile. Chattopadhyay . B.C. (1994)[5] Liu Wenbai, Zhou Jian, Mongke Tei-Mohr (2004) [6], Qian Su, Xiaoxi Zhang, Pingbao Yin, Wenhui Zhao (2014)[7] Bai Yang, Jianlin Ma, Wenlong Chen, and Yanxin Yang (2016)[8] and Jeet. N. Thacker, Dr.A.K. Verma (2019)[1] all scholars have carried out experimental investigation to find the uplift load carrying capacity of cylindrical and belled pile.

Literature study shows that the many researchers have carried out experimental investigation on cylindrical piles and concluded that uplift load is resisted by skin friction between pile and its nearby soil Effects due to compressive load on piles is very well explored in comparison with uplift

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load on pile. Specifically, very less work is done on predicting uplift load carrying capacity of pile in cohesive soil with respect to sand.
This research aim at finding the uplift load carrying capacity of cylindrical and belled model pile and cohesive bed and to develop the mathematical equation of the uplift load carrying capacity by using the failure pattern of the soil caused by the belled pile during experiment.

2.Soil investigation

The cohesive soil used in the current thesis investigation is brought from local place from Vallabh Vidyanagar, Anand Engineering properties of soil is obtained by various soil tests performed on cohesive soil and results are presented in Table 2.1.

3. Experiment methodology

Concrete piles of different L/d ratios 6,8,10,15,18 and 20 of cylindrical and belled pile were cast for studying the behaviour under uplift load. The pile shaft diameter (D) is kept 20mm for all the types of cylindrical and belled piles, the diameter and height of the belled portion is 60mm and 50mm respectively with a bell angle of 70^o with the horizontal. Experiments were conducted on single pile, pile groups of triangular pattern arrangement with 3 piles (2x1) and square pattern arrangement with four piles (2x2). Spacing between two piles is kept as 3D for cylindrical as well as belled piles.
One end of flexible wire hose is tied to the pile cap and another end is attached to tension proving ring through which the uplift load is applied on the piles by using pulley arrangement Uplift load is measured by tension proving ring and very sensitive dial gauge is attached to the pile cap to record the upward displacement. This developed system is shown in the Fig. 3.4. The uplift load is applied through the center of the pile cap on longitudinal axis of pile. Two Steel tanks of different sizes are used for the testing of the model piles from which one is of 500mm x 500mm x 500mm and other one is 750mm x 750mm x 750mm [1].

Table 2.1: Engineering properties of soil

Parameters	Result	Description
Soil Classification		
1) % Fines	68%	Percentage of fines > 50 %. Hence soil is cohesive soil
2) % sand	32 %	
Consistency limits		Plasticity Index is above A-line. Liquid limit < 35 % Hence soil is classified as Low compressible clay (CL).
1) Liquid limit	33.7 %	
2) Plastic limit	17.59 %	
Plasticity Index = Liquid limit – Plastic limit	16.1 %	
A – Line	10 %	
Specific gravity	2.65	
Field bulk unit weight	1.99gm/cc	
Field dry unit weight	1.69gm/cc	
Unconfined Compression test (q_u)		
q_u at w = 20%	25 kpa	Consistency is SOFT

Fig 3.1: Belled portion of a belled pile

Fig 3.2: Triangular pattern arrangement with 3 cylindrical piles (2x1)

Fig 3.3: Triangular pattern arrangement with 3 belled piles (2x1)

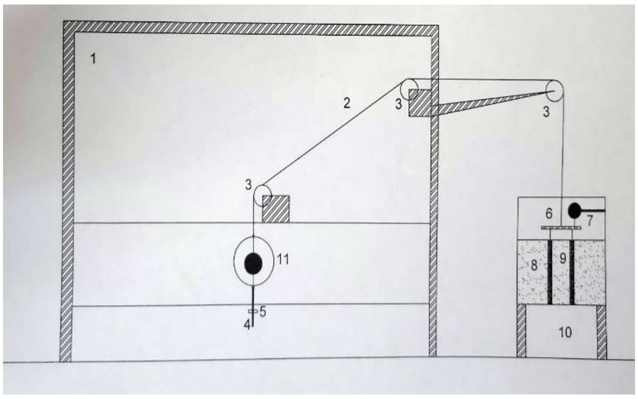

Fig 3.4: Experimental setup drawing (1) Loading frame (2) Wire hose (3) Pulley (4) Long bolt (5) Nut (6) Pile cap (7) Dial gauge (For recording uplift displacement) (8) Cohesive soil bed (9) Pile (10) Soil tank (11) Tension proving ring (For recording uplift load)

Piles are first placed in the position and then soil is placed and compacted in layers. The cohesive soil bed is prepared up to the level of pile top. Cohesive soil bed prepared at particular moisture content and unit density and it is maintained throughout the experimental investigation.

4. Results

In this experimental investigation (36 tests) carried out on cylindrical and belled pile of various L/d ratios and pile group arrangements, uplift load carrying capacity and upward displacement are compared for different pile group arrangements and in between cylindrical and belled pile.
All experiments are conducted at water content and density of cohesive soil bed as 20% and 20.28 KN/m^2.

Table 4.1: Comparison of uplift load carrying capacity of a single cylindrical and belled pile.

L/d ratio	Uplift load carrying capacity (N)		Difference (%)
	Cylindrical pile	Belled pile	
6	62	355	472
8	77	448	472
10	124	618	397
15	263	1159	339
18	324	1622	376
20	355	1776	399

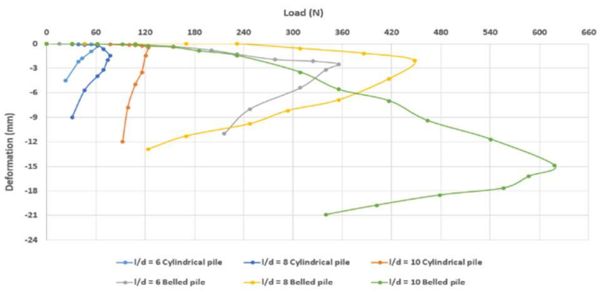

Fig 4.1: Uplift load carrying capacity (N) vs Upward displacement (mm) graph for single Cylindrical and Belled pile.

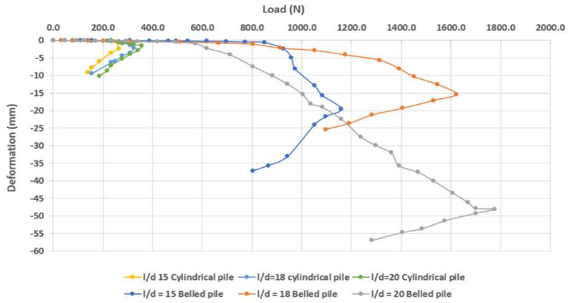

Fig 4.2: Uplift load carrying capacity (N) vs Upward displacement (mm) graph for single Cylindrical and Belled pile.

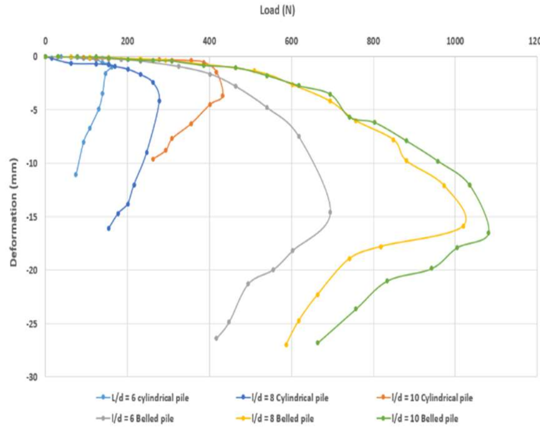

Fig 4.3: Uplift load carrying capacity (N) vs Upward displacement (mm) graph of triangular pattern arrangement for Cylindrical and Belled pile.

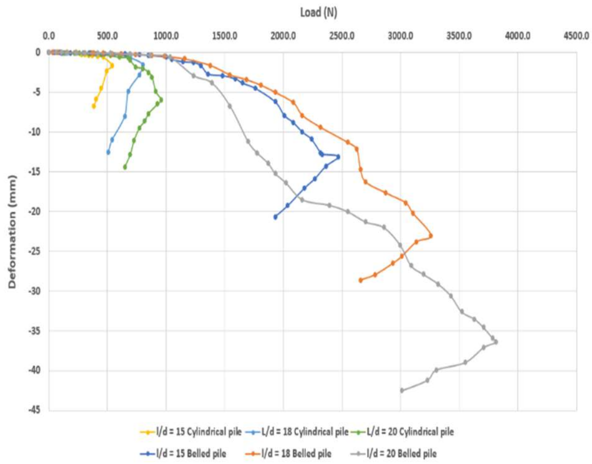

Fig 4.4: Uplift load carrying capacity (N) vs Upward displacement (mm) graph of triangular pattern arrangement for Cylindrical and Belled pile.

Table 4.2: Comparison of uplift load carrying capacity of a triangular pattern cylindrical and belled pile.

L/d ratio	Uplift load carrying capacity (N)		Difference (%)
	Cylindrical pile	Belled pile	
6	162	695	328
8	278	1019	266
10	433	1081	149
15	541	2471	357
18	803	3259	306
20	958	3815	298

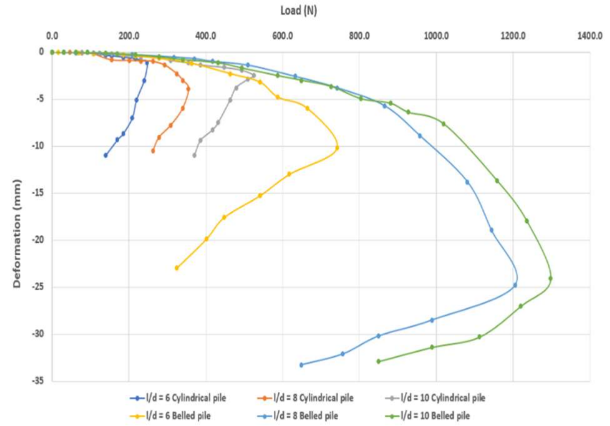

Fig 4.5: Uplift load carrying capacity (N) vs Upward displacement (mm) graph of square pattern arrangement for Cylindrical and Belled pile.

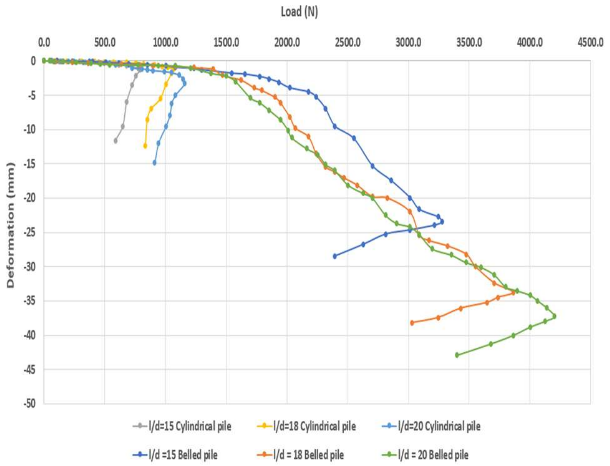

Fig 4.6: Uplift load carrying capacity (N) vs Upward displacement (mm) graph of square pattern arrangement for Cylindrical and Belled pile.

Table 4.4: Comparison of uplift load carrying capacity between single pile and triangular arrangement piles for cylindrical pile.

L/d ratio	Uplift load carrying capacity (N)		Difference (%)
	Single pile	Triangular arrangement piles	
6	62	162	161
8	77	278	261
10	124	433	249
15	263	541	105
18	325	803	147
20	355	958	169

Table 4.3: Comparison of uplift load carrying capacity of a square pattern cylindrical and belled pile.

L/d ratio	Uplift load carrying capacity (N)		Difference (%)
	Cylindrical pile	Belled pile	
6	247	741	199
8	355	1205	238
10	525	1298	146
15	788	3275	317
18	1066	3862	262
20	1159	4202	262

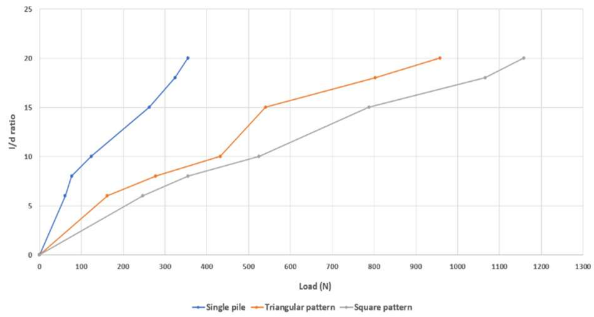

Fig 4.7: Ultimate uplift load carrying capacity (N) vs L/d ratio graph for cylindrical pile for various pile group arrangement.

Table 4.5: Comparison of uplift load carrying capacity between single pile and square arrangement piles for cylindrical pile.

L/d ratio	Uplift load carrying capacity (N)		Difference (%)
	Single pile	Square arrangement piles	
6	62	247	298
8	77	355	361
10	124	525	323
15	263	788	199
18	325	1066	229
20	355	1159	226

Table 4.6: Comparison of uplift load carrying capacity between single pile and triangular arrangement piles for belled pile.

L/d ratio	Uplift load carrying capacity (N)		Difference (%)
	Single pile	Triangular arrangement piles	
6	355	695	96
8	448	1019	127
10	618	1081	75
15	1159	2471	113
18	1622	3259	101
20	1776	3815	115

Table 4.7: Comparison of uplift load carrying capacity between single pile and square arrangement piles for belled pile.

L/d ratio	Uplift load carrying capacity (N)		Difference (%)
	Single pile	Square arrangement piles	
6	355	741	109
8	448	1205	169
10	618	1298	110
15	1159	3275	183
18	1622	3862	138
20	1776	4202	137

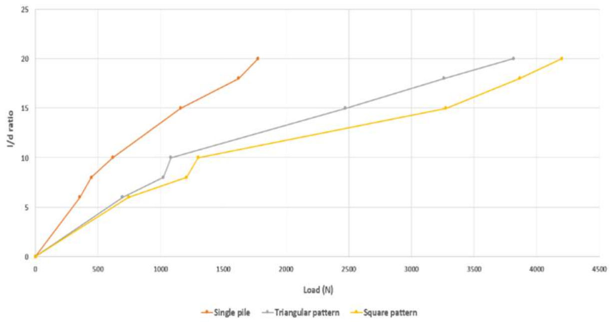

Fig 4.8: Ultimate uplift load carrying capacity (N) vs L/d ratio graph for belled pile for various pile group arrangement

Table 4.8: Comparison of upward displacement (At ultimate uplift load of single cylindrical pile) between single cylindrical and belled pile for various L/d ratio.

Pile configuration	L/d ratio	Cylindrical pile (mm)	Belled pile (mm)	Difference %
Single pile	6	0.3	0.058	80.67
	8	1.5	0.005	99.67
	10	0.5	0.29	42
	15	2.3	0.0045	99.8
	18	2	0.3	85
	20	1.5	0.28	81.33

Table 4.9: Comparison of upward displacement (At ultimate uplift load of triangular pattern arrangement cylindrical pile) between triangular pattern arrangement cylindrical and belled pile for various L/d ratio.

Pile configuration	L/d ratio	Cylindrical pile (mm)	Belled pile (mm)	Difference %
Triangular pattern arrangement	6	1	0.21	79
	8	4.2	0.34	91.9
	10	3.68	0.95	74.18
	15	1.65	0.18	89.09
	18	1.5	0.31	79.33
	20	5.95	0.54	90.92

Table 4.10: Comparison of upward displacement (At ultimate uplift load of square pattern arrangement cylindrical pile) between square pattern arrangement cylindrical and belled pile for various L/d ratio.

Pile configuration	L/d ratio	Cylindrical pile (mm)	Belled pile (mm)	Difference %
Square pattern arrangement	6	1.1	0.58	47.27
	8	3.9	0.65	83.33
	10	2.5	1.9	24
	15	1.35	0.49	63.7
	18	1.2	0.86	28.33
	20	3.3	1.35	59.09

4.1. *Analysis of failure plane caused by belled pile*

Total of 18 experiments are conducted on belled of for 6 l/d ratio with 3 different pile arrangement and out of them failure of 9 experiments are discussed below. The experiments were carried out till the belled pile is completely pulled out of the soil. The failure of the soil is then observed and the amount of soil which is mobilized is noted. Dimensions of the mobilized soil are measured for each experiment, then using these dimensions' failure plane is generated and it is shown in the fig 4.11 to 4.16. Volume of the mobilized soil and the lateral area of the failed soil is calculated by using the dimensions of the mobilized soil.

When uplift load is applied to a cylindrical pile, soil surrounding the pile is not at all mobilized, the soil is simply resisting the load by friction between the cylindrical pile and cohesive soil.

When belled pile is pulled out soil around the pile is disturbed and it is coming out with the pile. As the belled pile initialize the upward displacement the soil above the belled portion of the belled pile exerts passive resistance and the belled portion acts as an anchor. Belled pile resists the load by combined mechanism of passive and frictional resistance.

Cracks are first observed and lifting of the soil along with the belled pile during the experiment as shown in the fig 4.9. actual failure plane and the volume of soil which is mobilized is shown in the fig 4.10.

Table 4.11: Dimensions of the mobilized soil for single belled pile.

L/d ratio = 6	Diameter (m)	0.06	0.08	0.12	0.24
	Height (m)	0	0.04	0.06	0.12
L/d ratio = 8	Diameter (m)	0.06	0.08	0.14	0.28
	Height (m)	0	0.07	0.1	0.16
L/d ratio =10	Diameter (m)	0.06	0.1	0.15	0.32
	Height (m)	0	0.11	0.14	0.2

Table 4.12: Dimensions of the mobilized soil for triangular pattern arrangement belled pile.

L/d ratio = 6	Diameter (m)	0.12	0.16	0.22	0.38
	Height (m)	0	0.04	0.06	0.12
L/d ratio = 8	Diameter (m)	0.12	0.15	0.21	0.4
	Height (m)	0	0.06	0.09	0.16
L/d ratio =10	Diameter (m)	0.12	0.14	0.2	0.44
	Height (m)	0	0.08	0.12	0.2

Fig 4.9: Lifting of the soil along with the belled pile

Fig 4.10: Actual failure plane observed after complete pull out test on belled pile.

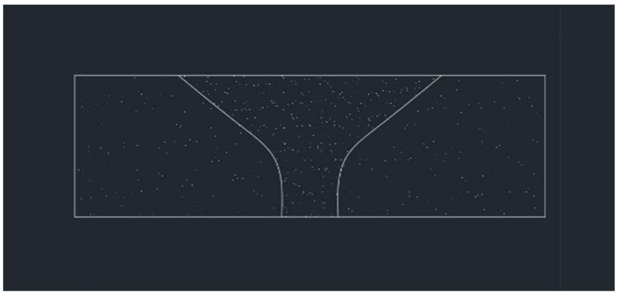

Fig 4.11: Failure plane of the soil observed for single belled pile having L/d = 8

Fig 4.12: Volume and lateral surface area of the mobilized soil for single belled pile having L/d = 8

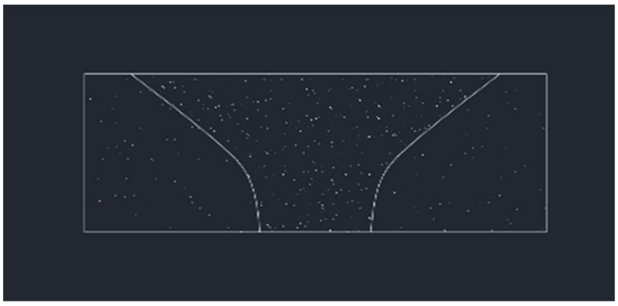

Fig 4.13: Failure plane of the soil observed for triangular pattern belled pile arrangement having L/d = 8

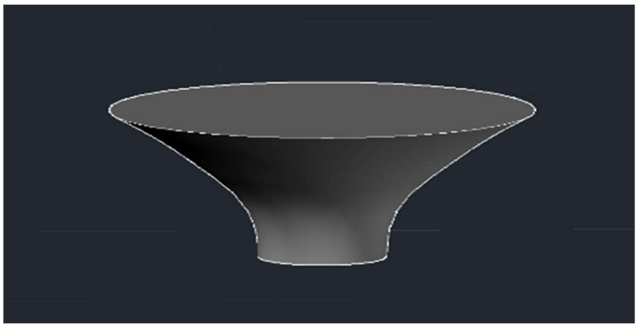

Fig 4.14: Volume and lateral surface area of the mobilized soil for triangular pattern belled pile arrangement having L/d = 8.

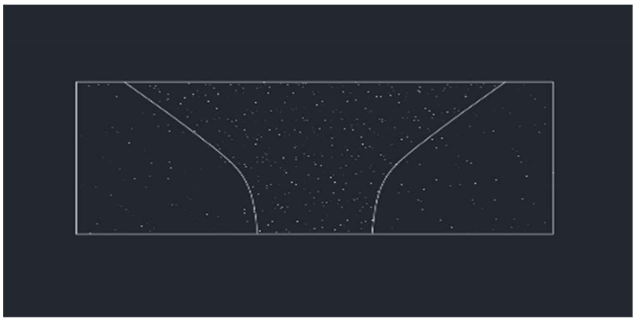

Fig 4.15: Failure plane of the soil observed for square pattern belled pile arrangement having L/d = 8

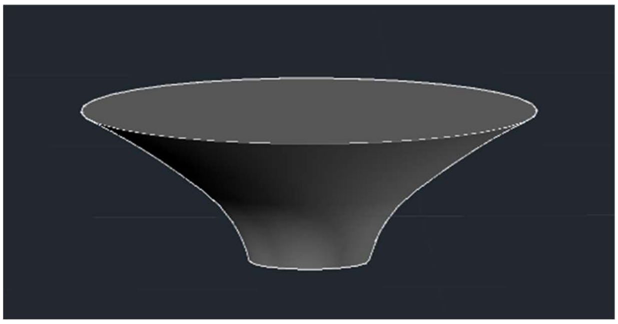

Fig 4.16: Volume and lateral surface area of the mobilized soil for square pattern belled pile arrangement having L/d = 8

Table 4.13: Dimensions of the mobilized soil for square pattern arrangement belled pile.

L/d ratio = 6	Diameter (m)	0.12	0.17	0.23	0.44
	Height (m)	0	0.04	0.06	0.12
L/d ratio = 8	Diameter (m)	0.12	0.18	0.25	0.46
	Height (m)	0	0.06	0.09	0.16
L/d ratio =10	Diameter (m)	0.12	0.15	0.24	0.5
	Height (m)	0	0.06	0.1	0.2

4.2. Derivation of uplift load carrying capacity of pile

Uplift load carrying capacity of of belled pile is obtained by using the volume of soil which is mobilized along with the belled pile and the shear failure area (lateral surface area).It is very difficult to measure the area and volume of the actual mobilized soil, so to make it convinient for calculation virtual cone is made by using the base diameter and top diameter of the mobilized soil.Volume and lateral surface area of cone are calculated and then multiplied by volume correction coeffiicent and area correction coefficient respectively to achieve the actual volume and lateral surface area of the mobilized soil.

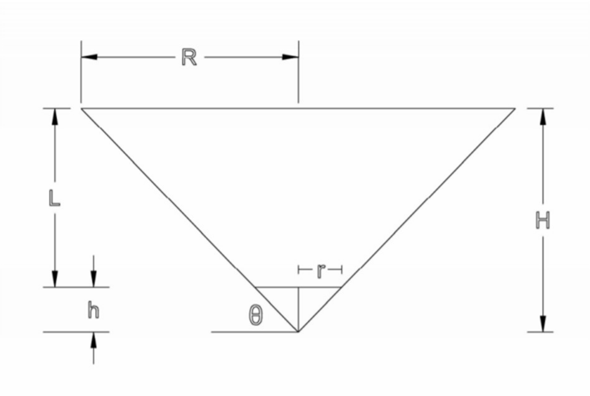

Fig 4.17: Virtual cone of mobilized soil

Qup Uplift load carrying capacity of belled pile.
R Radius at the top surface of the mobilized soil.
r Radius at the base surface of the mobilized soil.
L Length of the belled pile.
h Height of the virtual cone from its vertex to bottom surface of the mobilized soil.
θ Angle between the mobilized soil and the horizontal axis.
V_V Volume of the mobilized soil.
A_{LV} Lateral surface area of the mobilized soil.
C_V Volume correction coefficient.
C_A Area correction coefficient.
c Cohesion of soil.
D Coefficient of frictional resistance.
Vp Volume of belled pile with pile cap.
γc Density of concrete.
γs Density of soil.

- $\tan\theta = h / r$
- $\mathbf{h = r \tan\theta}$ **Equation. 1**

- $\tan\theta = H / R = (L + h) / R$

- $R = (L + h) / \tan\theta$
- $\mathbf{R = (L + r \tan\theta) / \tan\theta}$ **Equation. 2**

- $H = L + h$
- $\mathbf{H = L + r \tan\theta}$ **Equation.3**

Volume of virtual cone:

- $V_V = \frac{1}{3}\pi R^2 H - \frac{1}{3}\pi r^2 h$

- $\mathbf{V_V = \frac{1}{3}\pi (R^2 H - r^2 h)}$ **Equation. 4**

Substituting equation 1,2 and 3 in equation 4

$$\mathbf{V_V = \frac{1}{3}\pi [\{(L + r \tan\theta) / \tan\theta\}^2 (L + r \tan\theta) - r^3 \tan\theta]}$$

Equation. 5

Lateral Surface area of a virtual cone:

- $A_{LV} = \pi R \sqrt{(H^2 + R^2)} - \pi r \sqrt{(h^2 + r^2)}$

- $\mathbf{A_{LV} = \pi [\{(L + r \tan\theta) / \tan\theta\} \sqrt{[(L + r \tan\theta)^2 + \{(L + r \tan\theta) / \tan\theta\}^2]} - r^2 \sqrt{(\tan^2\theta + 1)}]}$

Equation. 6

Uplift load carrying capacity of belled pile = Weight of belled pile with pile cap + Weight of failed soil + Frictional resistance

- $\mathbf{Qup = [Vp * \gamma c] + [\frac{1}{3}\pi [R^2 H - r^3 \tan\theta]] * \gamma s * C_V + [\pi [R \sqrt{[H^2 + R^2]} - r^2 \sqrt{(\tan^2\theta + 1)}]] * C_A * c * D}$

Equation. 7

Above formula (Equation.7) is the derived formula to find the theoretical uplift load carrying capacity of belled pile. For each case value of C_A, C_V and θ are obtained and plotted below in fig by comparing actual mobilized soil and virtual mobilized soil. The value of frictional resistance coefficient (D) is calculated for each pile arrangement pattern. This formula is derived on the basis of limited study on uplift load carrying capacity of belled pile in cohesive bed of soft consistency. Diameter of the belled portion is considered 3 times the diameter of pile shaft.

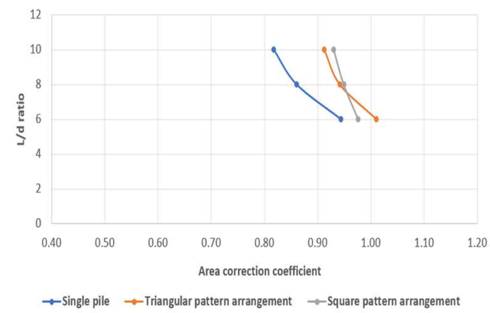

Fig 4.18: Area correction coefficient vs. L/d ratio of belled pile graph for single, triangular and square pattern pile arrangement

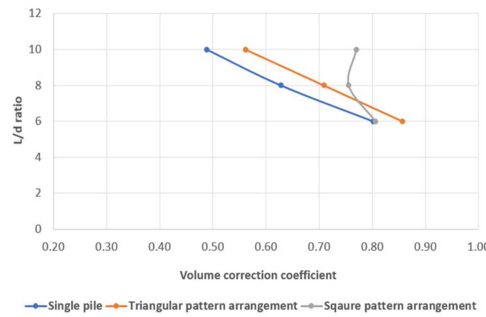

Fig 4.19: Volume correction coefficient vs. L/d ratio of belled pile graph for single, triangular and square pattern pile arrangement

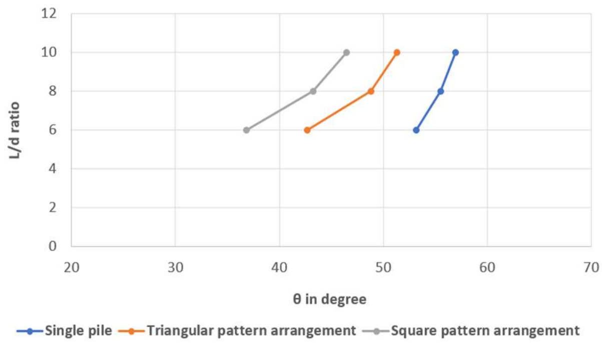

Fig 4.20: θ in degree vs. L/d ratio of belled pile graph for single, triangular and square pattern pile arrangement

5. Conclusions

- The uplift load carrying capacity of the pile increases as the L/d ratio increases in cylindrical pile as well as belled pile.
- The uplift load carrying capacity of cylindrical pile increases by 182% and 273% for triangular pattern and square pattern respectively over single pile.
- The uplift load carrying capacity of belled pile increases by 104% and 141% for triangular pattern and square pattern respectively over single pile.
- The uplift load carrying capacity of belled pile increases by 410%, 280% and 240% over cylindrical pile for single pile, triangular pattern and square pattern arrangement.
- Group efficiency of the pile group decreases as the L/d ratio increases in cylindrical and belled pile.
- Group efficiency of pile groups is more in cylindrical pile in comparison of belled pile.
- Upward displacement decreases by 81.41%, 84.07% and 50.95% of belled pile for single pile, triangular pattern and square pattern over cylindrical pile at ultimate uplift load of cylindrical pile for all L/d ratios.
- Only frictional resistance is resisting the uplift load in case of cylindrical pile.
- Failure angel θ increases as the L/d ratio and number of piles in a pile group increases for belled pile.
- Volume correction coefficient decreases as the L/d ratio increases and the no of piles in a pile group decreases for belled pile.
- Area correction coefficient decreases as the L/d ratio increases and the no of piles in a pile group decreases for belled pile.
- Uplift load carrying capacity of belled pile is dependent upon parameters as type of soil, water content, L/d ratio, Diameter of shaft and belled portion, pile spacing and number of piles in a pile group.
- Obtained average value of coefficient of frictional resistance (D) is 0.36.

Disclosures

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