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Comparative Study on the Behavior of Under-Reamed Piles Under Vertical Uplift Loads in Sand

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Abstract

Under-reamed piles are bored cast in-situ concrete piles having one or multi bulbs formed by enlarging the pile base. This paper presents a comparative study of a number of previous theories with field data and experimental results of single under-reamed piles embedded in loose, medium and dense sand with bulb diameter ratios 2 and 3, to predict the uplift factor. Also, a brief review was performed on under-reamed piles under uplift loads in sand soil. Many factors, such as embedment ratio, bulb diameter ratio, bulb number, relative density, etc., influence on the uplift capacity of the reamed piles. The observation of the variation of failure mechanism is correlated with the effect of different parameters. The predicted uplift factors were various, due to the theories were derived from the capacity of anchors and belled piles. The comparative results were documented in this paper.

Keywords: *Under-Reamed Piles, Pile Geometry, Failure Mechanism, Uplift Factor and Comparative Study.*

1. Introduction

Under-reamed Piles are one of the deep foundation types which used widely for different types of soils such as sandy soils, clayey soils and also expansive soils. When the soils exposed to volumetric changes due to moisture variation underneath the ground surface this expansion and shrinkage can cause distress which is very critical as far as bearing of the foundation is concerned. So, it is found that under-reamed piles are considered as most safe and economical foundation for such expansive soils. Under-reamed piles are generally designed in such a way that, they can support load from the structure and transmit to the soil without causing any soil failure and settlements [1]. In deep deposits of expansive soils, the minimum length of piles, irrespective of any other consideration shall be 3.5 m below the ground level. If the expansive soil deposits are of shallow depth and overlying non-expansive soil strata or hard strata, piles of smaller length can also be provided.

The under-reamed piles are effectively used in machine foundations, under bridges, electrical transmission tower foundations and water tanks. Although, the Indian Standard IS 2911 (Part III) - 1980 [1] covers the design and construction of under-reamed piles having one or multi bulbs but the under-reamed piles are not concluded in other codes. Corresponding to the code, the diameter of under-reamed bulbs can change from 2 to 3 times the shaft diameter depending upon the feasibility of construction and design requirements. The center to center spacing for these piles should not be less than $2D_p$, where D_p is the pile diameter. The code suggests a vertical spacing between two bulbs varied from 1.25 D_u to 1.50 D_u, where D_u is the bulb diameter. This code also gives mathematical expressions for calculating the bearing and uplift capacities. The load carrying capacity of this type of pile foundation can be increased by making more bulbs at base.

Under-reamed piles date back to early 1940s. They were first used in Texas state in USA where smectic clay is abundant. They were intended mainly to resist the uplift forces created on them due to the heaving of the ground. In South Africa in 1949 by Jenkins and Henkel, the first systematic studies on these piles were performed. The research of Jenkins was followed by the Australian researcher Tusker. In India, under-reamed piles are significantly used since the 50’s to anchor building foundations in the expansive black cotton soils, at a depth where ground movements due to variations in moisture content are insignificant.

The machinery used for the installment of under-reamed pile is developed by C.B.R.I. Rurki and easy to use and it is light weighted. The main component parts are spiral Auger, under-reamer and boring guide.

1.1 Advantages and Disadvantages of Under-Reamed Piles

Table 1: Advantages and disadvantages of under-reamed piles [2]

Advantages	**Disadvantages**
• It decreases the vertical settlement and also differential settlement. • It is used when soil tends to swell and shrink due to moisture variation. • The provision of bulbs is of special advantage in under-reamed piles to resist uplift and they can be used as anchors. • The cost advantages of under-reamed piles are due to the reduced pile shaft diameter, resulting in less concrete needed to replace the excavated material. • When the number of bulbs is increased from one to two, the load carrying capacity of the under-reamed pile is increased. • Provision of under-reams or bulbs has the advantage of increasing the bearing and uplift capacities.	• At a depth, where nature of soil varies with a climatic condition, under-reamed piles are not suitable for waterlogged soil, as they take load by friction. • These piles need strict quality control and regular supervision during the construction. • Most of the times, under-reamed piles are driven manually with hand operated machine. • The material used in the under-reamed pile is concrete cast in place only because of the implementation requirements to form the bulbs.

1.2 Classification of Under-Reamed Piles

The under-reamed piles are classified according to number of bulbs, material and load transfer as following, respectively:

1- The under-reamed piles are classified according to number of bulbs to pile with single bulb, pile with double bulbs and pile with multi bulbs.
2- The under-reamed piles are bored cast in situ piles.
3- Under-reamed piles resist the pullout load through the self-weight of the pile, weight of soil inside the failure surface and the shearing resistance of the failure surface [3]. But the under-reamed piles resist the compression load through point bearing resistance at the pile tip, skin friction resistance along the pile shaft and skin friction on the soil cylinder between the consecutive bulbs.

2. Failure Mechanism of Under-Reamed Piles

Majer [4], one of the earliest researchers, assumed the failure mechanism is a vertical slip surface above the anchor as shown in Fig. 1. According to him, the pullout capacity is mainly the total of weight of soil above the anchor and shear resistance along the perimeter of the vertical slip surface.

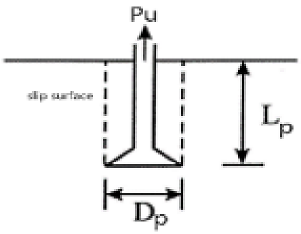


Fig. 1 Vertical slip surface model [4].

Balla [5], assumed that the slip surface above small model anchors was a tangential curve. Also, the failure surface for shallow footings embedded in dense sand was almost circular in elevation and the tangent to the surface of ground contact was at an angle of roughly (45°-Ø/2) to the horizontal as drawn Fig. 2. where, Ø is the angle of internal friction.

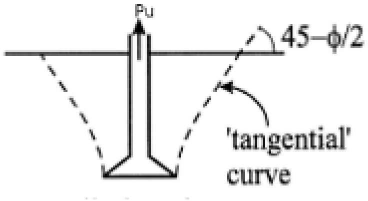


Fig. 2 Curved slip surface model [5].

Mac Donald [6], who had done model test in sand, illustrated that the failure surface was almost vertical for greater depths and the failure plane was approximately parabolic for shallow depths. The theory developed by Mac Donald [6] assumed failure for the deep case was assumed to be cylindrical with a cylinder diameter of 1.75 times the base diameter. Meanwhile, failure for the shallow case is conical with inclination angle equal to half the angle of internal friction (Ø/2).

Downs and Chieurzzi [7], field test observations were done on reamed piers, hold on to the concept that the uplift capacity is derived from the self-weight of the pier plus the weight of the soil in an inverted cone above the ream as shown in Fig. 3.

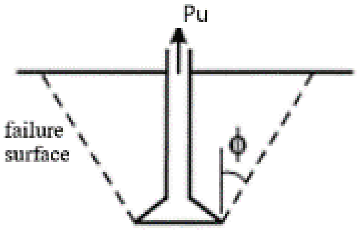


Fig. 3 Inverted truncated cone model [7].

Meyerhof and Adams [8], proposed a theoretical model for the problem by investigating the uplift capacity of plate anchors in laboratory experiments and available field test data. Although, they noticed that the problem was a complicated one, but simplified it to develop a generalized theory for predicting the uplift capacity of anchor plates. According to them the behavior of failure mechanism was divided into two categories where the failure surface extends to the ground surface in case of shallow embedment but in case of deep embedment it does not reach the surface as illustrated in Fig. 4, where a shallow embedment is shown on the left and a deep embedment is shown on the right.

Estimates of the critical embedment depths $(H/D_u)_{cr}$ are shown in Table 2 For values where $L_P/D_u > (H/D_u)_{cr}$, the pile is expected to behave in a deep manner, with the failure mechanism not reaching the soil surface. Correspondingly, for values of embedment $L_P/D_u \leq (H/D_u)_{cr}$, the pile is predicted to behave in a shallow manner, with the failure mechanism reaching the soil surface.

Where: P_p is total passive earth pressure inclined at average angle beta acting downward on the vertical plane through the footing edge; β is angle of P_p to the horizontal plane; P_o is surcharge pressure above the level of the failure surface; H is the vertical extent of failure mechanism from the base of foundation; W is the weight of the soil inside failure mechanism added to the pile self-weight.

Table 2: Critical values for H/D_u for various friction angles [8]

Ø	20°	25°	23°	35°	40°	45°	48°
$(H/D_u)_{cr}$	2.5	3.0	4.0	5.0	7.0	9.0	11.0

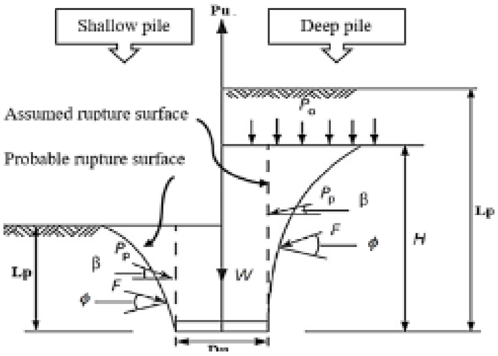


Fig. 4 Failure surface of a plate anchor under uplift load [8].

Clemence and Veesaert [9]**,** the angle in the inverted cone slip-surface model is equal to Ø/2 to the vertical, where Ø is the angle of internal friction as shown in Fig. 5.

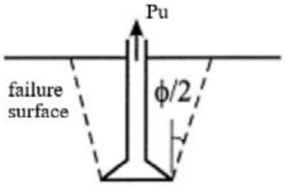


Fig. 5 Inverted truncated cone model [9].

Vermeer and Sutjiadi [10], detected that the angle of the inverted cone slip surface with the vertical is equal to the angle of dilatancy of the soil (ψ). In contrast of, it was noticed that the angle is equal to the angle of soil friction [11].

Dickin [12]**,** has noticed a number of existing design method giving the uplift capacity of horizontal anchors in sand. It was classified the assumed failure mechanism of most design methods into three groups which are inverted truncated cone model, vertical slip surface model and curved slip-surface model as shown in Fig. 6.

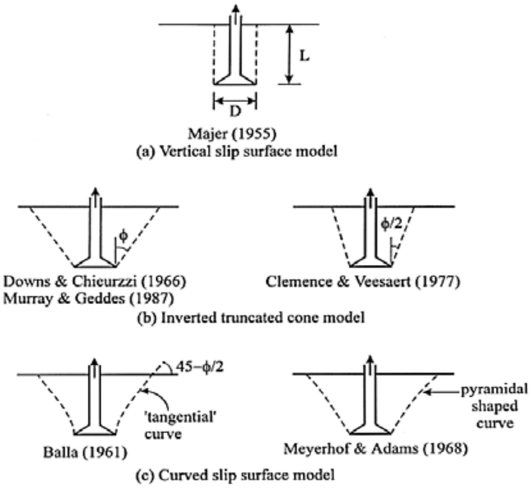


Fig. 6 Assumed failure mechanisms for belled piers subject to uplift loads [12].

Deb and Pal [13], studied the failure pattern of single belled pile with 2D model in sand soil under uplift load, experimentally. The study was concentrated on the behavior of anchors in shallow embedment depth. The variable parameters were used to notice the variation of nonlinear failure pattern in sand around 2D panels, embedment depth ratio (L_p/D_u) 3,4 and 5, diameter ratio (D_p/D_u) 0.28, 0.33, 0.38 and 0.46 and bulb angle with the horizontal (Ө) 45º, 54º, 63º and 72º. In order to visualize the pattern of failure surfaces clearly, 3-mm-thick layers of dyed sand are placed within 18 mm thick non-dyed sand layers maintaining the same density of sand. Fig. 7 shows the typical pictorial failure surfaces at case a: bulb angle 45º, diameter ratio 0.33 and embedment ratio 4 and at case b: bulb angle 45º, diameter ratio 0.33 and embedment ratio 5.

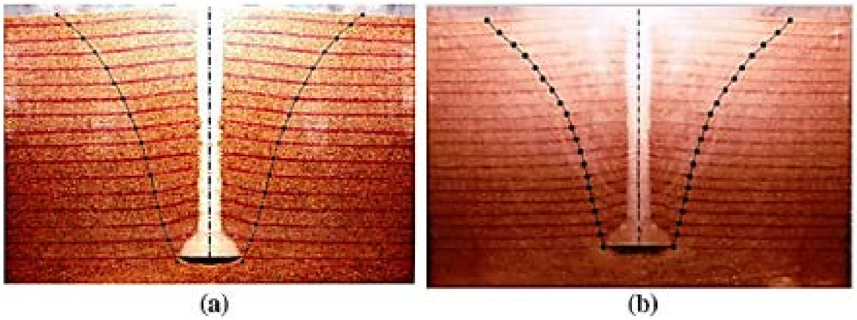

(a)
(b)

Fig. 7 Pictorial view of nonlinear failure points in sand around, (a) 2D:45-0.33-4 and (b) 2D:54-0.33-5 [13].

Kumar et al. [3], studied numerically the uplift behavior of the under-reamed piles and found that the failure mechanism consisted of two types based on the sand friction angle and the embedment ratio of the pile as illustrated in Fig. 8. From the study of the failure pattern, it was found that the balloon shape was defined for loose to very loose sand (Ø ≤ 35º) but for dense or very dense sand (Ø ≥ 40º), the inverted cone shape was defined. In the case of medium dense sand (Ø=35º), a transition from balloon shape to an inverted cone of failure mechanism was observed according to embedment ratio. Also, it is noticed that the failure mechanism for single and double under-reamed piles are similar and the inverted cone failure surface starts from the last bulb. In addition, the pile with double bulbs has less effect on failure mechanism than pile with single bulb. So, the uplift capacity for double under-reamed piles is slightly larger than single under-reamed pile. For single under-reamed piles embedded in loose sand, the balloon failure mechanism does not reach the surface with the increase in embedment ratio. Also, for double under-reamed pile embedded in loose sand, the failure mechanism is cylindrical for L_p/D_p=10 and transits to balloon shape for L_p/D_p=17.5 and does not reach the surface. Note, for all embedment ratios for dense and very dense sand, the truncated cone reaches the sand surface permanently. Finally, it was stated the inclination angle (α) of the line failure of inverted truncated cone with vertical and was found close to the dilation angle (ψ=Ø-30) selected for the analysis.

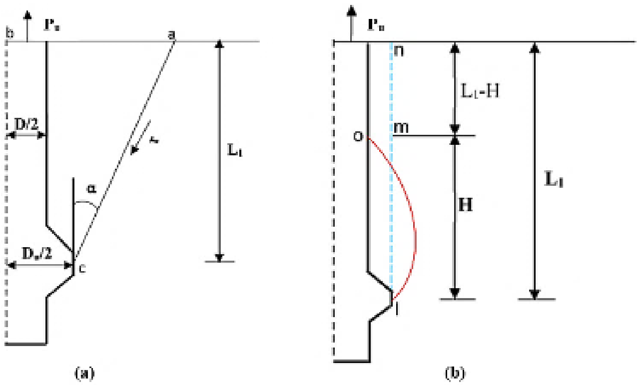


Fig. 8 Schematics of (a) inverted cone mechanism, (b) balloon shaped mechanism [3].

Finally, it is concluded that the failure mechanism of the under-reamed piles depends mainly on angle of internal friction of sand (Ø), base diameter ratio (D_u/D_p) and embedment depth ratio (L_P/D_p).

3. Factors Influencing the Behavior of Pullout Loaded Under-Reamed Piles

Embedment ratio (L_p/D_p), bulb geometry, bulb diameter ratio (D_u/D_p), bulb spacing ratio (S/D_u) and material of pile have great influence on the behavior of under-reamed pile foundation loaded vertically. However, the effect of soil type, characteristics of soil layers, amount of vertical load and size of group can never be neglected.

3.1 Number of Bulbs

Peter et al. [14], conducted research experimentally on concrete under-reamed piles, and performed various loading investigates on these piles. They plotted numerous stress-strain diagrams indicating lower strength of conventional piles under tensile loading in comparison with under-reamed piles.

Rahman and Sengupta [15], investigated experimentally the behavior of inclined and vertical under-reamed and conventional piles under vertical tension load in dry sandy soil with two relative densities (45 and 70%). Wooden piles with diameter of stem 20, 25 and 35 mm were used. The number of under-reamed bulbs was 0, 1 and 2 bulbs, the diameter of bulbs (D_u) were kept equal to ($2D_p$) where D_u is the diameter of the under-reamed bulb and D_p is the diameter of the stem pile. At D_r=45%, for vertical piles, the uplift capacity increased by about 20% (120-145 N) for single under-reamed pile as compared to conventional piles and by about 83% (120-220 N) for double under-reamed pile as compared to conventional piles. But, for vertical piles embedded in sand with D_r=70% for the same stem diameter and embedment ratio, the uplift capacity increased by about 22% (177-216 N) for single under-reamed pile as compared to conventional piles and by about 83% (177-324 N) for double under-reamed pile as compared to conventional piles.

Abbas [16], carried out an experimental investigation on the under-reamed piles under uplift load embedded in expansive soil and extended to sand soil as a stable zone. Depending on the experimental test results it is concluded that the soil swelling leads to upward movements of pile and the amount and rate of movement reduced when using double under-reamed piles as compared with single under-reamed piles with the same slenderness ratio as shown in Fig. 9.

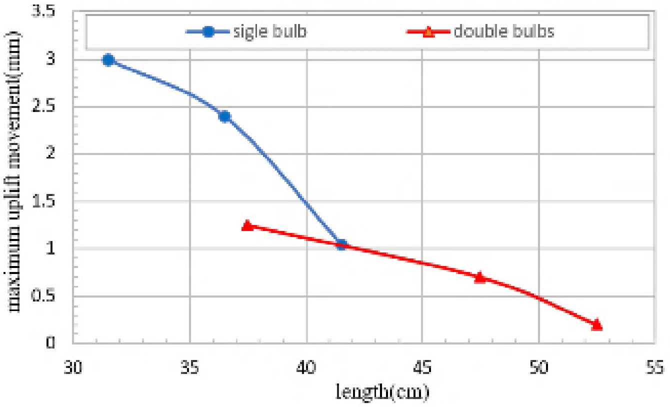
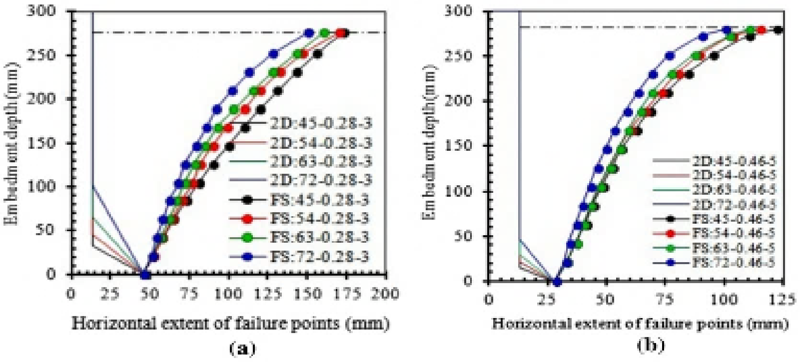


Fig. 9 Change of the maximum uplift movement with different lengths [16].

3.2 Base Angle of the Bulb

Nazir et al. [17], investigated the effect of base angle with the horizontal (ϴ) on the uplift capacity, where the base angle was taken equals 30°, 45° and 60°. Then, observed that with the increase of base angle of the enlarged base pier, the net uplift capacity decreases. In addition, in dense sand packing, the pullout load with a base angle ϴ =45° was 5 % lower than that for a base angle ϴ =30°.

Deb and Pal [13], experimentally, investigated the effect of various bell angles (ϴ) with the horizontal of 45º, 54º, 63º and 72º on the pullout behavior of single belled anchor in dry sand with relative density of 67.27%. finally, it was showed that, The higher the bulb angle with the horizontal, the lesser the ultimate uplift capacity irrespective of diameter ratio and embedment ratio. Where, the wedge weight and mobilized shear decrease. The maximum extents of failure at sand surface are generally shrinking with steeper bulb angles as illustrated in Fig. 10.



(a) (b)

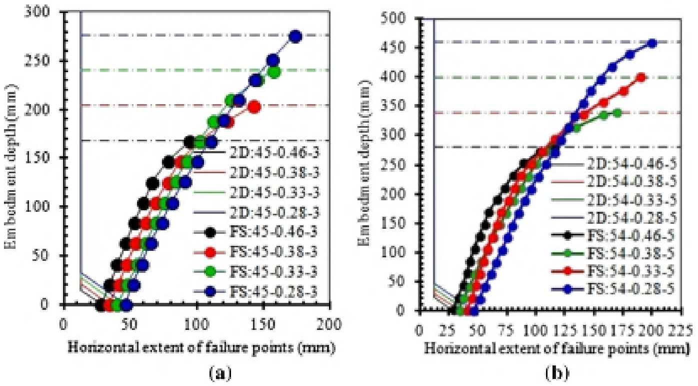
Fig. 10 Embedment depth versus horizontal extent of failure points, (a) around panels belonging to $(D_p/D_u) = 0.28$, $(L_p/D_u) = 3$, ϴ = 45°, 54°, 63°, 72 °and (b) around panels belonging to $(D_p/D_u) = 0.46$, $(L_p/D_u) = 5$, ϴ = 45°, 54°, 63°, 72° [13].

3.3 Bulb Diameter Ratio (D_u/D_p or D_p/D_u)

According to Patra et al. [18], the pullout capacity increased with the increase of bulb ratio where (D_u/D_p) was taken equal to 1, 2 and 3 as a variable parameter.

Nazir et al. [17], concluded that for the same base diameter, the pullout capacity reduces with the increase in stem diameter, irrespective of embedment length and base angle.

Deb and Pal [13], experimentally, investigated the effect of various diameter ratios on the pullout behavior of single belled anchor in cohesionless soil bed. The diameter ratios (D_p/D_u) taken were 0.28, 0.33, 0.38 and 0.46. The stem diameter (D_p) equals 26 mm and was constant for all tests. It was concluded that, for a certain bell angle and embedment depth, the uplift capacity decreases with the increase of diameter ratio (D_p/D_u), where the failure wedge is smaller, so the mobilized shear and weight of the wedge reduces. The maximum extents of failure at sand surface are generally shrinking with greater diameter ratios as illustrated in Fig. 11.



(a) (b)

Fig. 11 Embedment depth versus horizontal extent of failure points, (a) around panels belonging to ϴ= 45º, $(L_p/D_u) = 3$, $(D_p/D_u) = 0.28$, 0.33, 0.38, 0.46 and (b) around panels belonging to ϴ= 54º, $(L_p/D_u) = 5$, $(D_p/D_u) = 0.28$, 0.33, 0.38, 0.46 [13].

3.4 Vertical Spacing Between Bulbs for Double Reamed Piles

Gangadharappa et al. [19], conducted from the experimental investigation on pile models that there was no significant change in uplift capacity of under-reamed pile with spacing of the bulbs.

Kumar et al. [3], studied numerically the uplift capacity of the under-reamed piles in sand with L_p/D_p=10 and 17.5 and Ø=25º and 45º. The analysis was performed by taking the bulb spacing 1.0 D_u, 1.25 D_u, 1.50 D_u and 1.75 D_u. Finally, it was noticed that, the uplift capacity increases with the increase of bulb spacing from 1.0 D_u to 1.50 D_u but with an additional increase in the spacing to 1.75 D_u, the uplift capacity decreases. This observation is in contrast to that reported by Gangadharappa et al. [19] wherein a continuous increase in uplift capacity up to 1.75 D_u was stated.

3.5 Embedment Ratio of the Pile (L_p/D_p or L_p/D_u)

Dickin and Leung [20], concluded that failure displacement normalized to base diameter increased significantly with the increase of embedment ratio but decreased with the increase of sand relative density.

Patra et al. [18], investigated the behavior of under-reamed piles embedded in layered dry sand soil under axial pullout loads and embedded in homogeneous dry sand soil under inclined tension loads. The diameter of the model piles (D_p) was 12mm and 16mm and embedment depths 300mm, 320mm and 360mm with embedment ratios (L_p/D_p) 20, 25 and 30. The main findings of the test results are that, the relation between load and displacement was nonlinear and the uplift carrying capacity of pile increased with increasing the embedment ratio.

Nazir et al. [17], studied the effect of embedment ratio on the pullout capacity of the enlarged base pier. The diameter of pier shaft (D_p) was 30, 40 and 50 mm with base diameter (D_u) 75, 100, 125 and 150 mm and base angle (ϴ) equals 30°, 45° and 60°. Based on the laboratory investigations, it was found that with increasing the embedment ratio (L_p/D_u), the maximum uplift load increases. But, with the increase of base angle and shaft diameter the net uplift capacity decreases.

Deb and Pal [13], experimentally, investigated the uplift behavior of single belled anchor. The model piles embedded in dry sand with relative density of 67.27%. and embedment ratios (L_p/D_u) of 3, 4 and 5. The shaft diameter (D_p) equals 26 mm and was constant for all tests. The ultimate uplift capacity increases with the increase of embedment depth irrespective of diameter ratio (D_p/D_u) and bell angle (ϴ) due to the increase in failure wedge as illustrated in Fig. 12, where the shear mobilization and wedge weight increase. The maximum extents of failure at sand surface are generally expanding for greater embedment ratios as shown in Fig. 13.

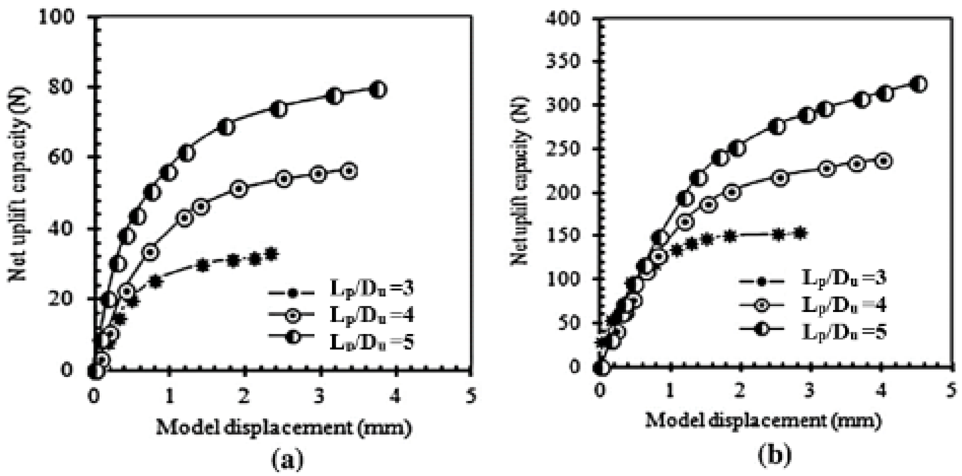


Fig. 12 Net uplift capacity versus model displacement, (a) for ϴ= 45º, D_p/D_u= 0.46 at (L_p/D_u) = 3, 4, 5 and (b) for ϴ= 72º, D_p/D_u= 0.28 at (L_p/D_u) = 3, 4, 5 [13].

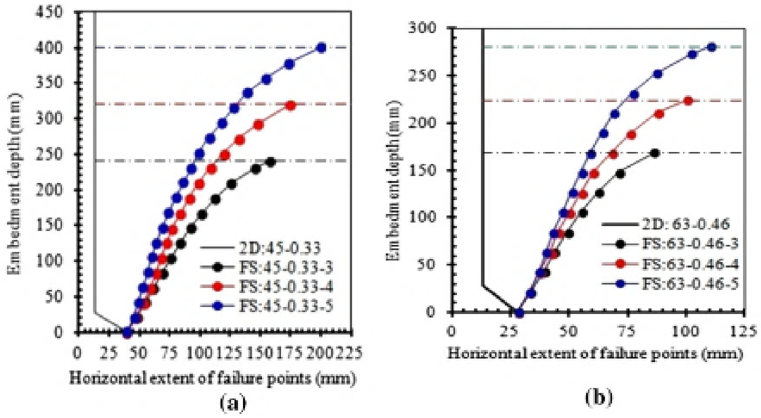


Fig. 13 Embedment depth versus horizontal extent of failure points, (a) around 2D:45-0.33, at (L_p/D_u) = 3, 4, 5 and (b) around 2D:63-0.46 at (L_p/D_u) = 3, 4, 5 [13].

Abbas [16], found that the amount and rate of movement of the under-reamed piles embedded in expansive soil overlying sand soil reduced by increasing length of the pile.

3.6 Relative Density of Sand (D_r)

Niroumand et al [21], studied uplift capacity of enlarged base piles in sand. Then it was concluded that the ultimate uplift capacity is dependent on the relative drained/undrained shear strength of cohesionless soil, the depth ratio of embedment and soil thickness ratio.

Nazir et al. [17], studied the capability of enlarged base pier in resisting uplift capacity and factors affect the performance. The tests were run in both loose and dense sand with relative density 35% and 85%, respectively. The results showed that the maximum uplift load in dense sand is higher than in loose sand by 60% and the failure mechanism took longer to develop.

Rahman and Sengupta [15], experimentally, studied the behavior of vertical under-reamed and conventional piles under vertical pullout load in dry sand with two relative densities (45 and 70%). Then, concluded that with the increase of relative density from 45% to 70%, the pullout capacity for conventional, single under-reamed and double under-reamed pile increased by approximately 47.5% (120-177N), 49% (145-216N) and 47% (220-324N), respectively.

3.7 Soil Layering Effects

Patra et al. [18], experimentally, investigated the behavior of under-reamed piles embedded in layered dry sand soil under axial pullout loads. The relative densities for medium dense and dense sand were 52% and 80%, respectively. Finally, it was noticed that the ultimate uplift capacity was larger for medium dense over dense condition than dense over medium dense condition.

Schafer and Madabhushi [22], Experimentally investigated using half-space small-scale 1g model the uplift behavior of enlarged base piles in layered strata (loose sand and clay overlying dense sand). Finally: the researchers concluded that when the loose sand overlying on dense sand the peak uplift capacity of the under-reamed pile foundation increase but does not affect the displacement required. Substituting this upper loose sand layer with clay can further increase the uplift capacity especially for high rates of loading where the undrained behavior of clay is raised.

Abbas [16], noticed that decreasing the uplift movement can be improved when the under-reamed pile embedded in expansive soil layer extends to sandy soil or non-expansive soil layer for adequate depth. Also, the maximum reduction in uplift movement reached 99% when under-reamed pile extended to sandy soil. The uplift movement of expansive soil bed increases non-linearly with time until maximum value continuously.

4. Comparative Study Between Theoretical Uplift Breakout Factors and Published Field Results for Single Under-Reamed Piles

Theories of calculating uplift capacity of under-reamed pile are derived from researches performed by multiple researchers [4], [5], [8], [20], [23] and [24]. Improvement the method of design has been made from time to time by taking into account additional factors to generate more accurate and complete design. Generally, under-reamed piles obtain uplift capacity through the own-weight of the pile and the frictional resistance along the failure surface and the weight of soil within the failure zone above the base.

4.1 Uplift Factor (Normalized Net Uplift Capacity)

Simple expressions and design charts were provided by investigators to accelerate the determination of the uplift capacity. It can be expressed in terms of a dimensionless uplift factor of piles embedded in sand (N) and calculated by using the formula of equation:

$$N = \frac{P_{un}}{\gamma\ A\ L_p} \tag{1}$$

$$P_{un} = P_u - W_p \tag{2}$$

Where: N, is the uplift factor,
P_u , is the gross uplift capacity of the under-reamed pile,
P_{un}, is the net ultimate uplift capacity and defined as the gross uplift capacity of the under-reamed piles (P_u) minus the pile weight (W_p) as noticed in equation
W_p, is the self-weight of the under-reamed pile,
L_p, is the embedment length,
γ, is the soil unit weight and
A, is the plan area of pile ream $A = \pi \frac{D_u{}^2}{4}$.

4.2 Validation of Theoretical Analysis with Field Data:

Some of available formulae from literature listed in Table 3 are used to validate the theoretical analysis with previous field data available in literature to compute the uplift factor. For this analysis, field test data of some previous researchers [7], [25], [26], [27] and [28] were selected. A total of 21 field tests reported in Ilamparuthi et al. [28] were selected for validation. It is pertinent that the range of friction angle (Ø) (24.70º-48º) covers loose to dense sand and embedment ratio (L_p/D_u) (1.38-5.33).

It is pertinent to mention here that a comparison of uplift factors for a belled pile, obtained using plate anchor theory reported by several researchers, was already performed [24]. Hence such rigorous comparison is avoided in the present study. The uplift factors from field tests (N_{field}) were compared exclusively with those based on plate anchor and belled theory by (1) Meyerhof and Adams based on the limit equilibrium method [8], (2) Clemence and Veesaert [9], (3) Ovesen [23], (4) Murray and Geddes [11] and (5) Kumar et al. [3]. The expressions proposed by these researchers are variable in terms of geometrical parameters of the under-reamed pile.
The values of predicted uplift factor (Npredicted), field uplift factor (Nfield) and the variation are listed in Table 4. The variation of (Npredicted) with respect to (Nfield) is calculated as follows:

$$Variation\ \% = \frac{N_{field} - N_{predicted}}{N_{field}} * 100 \tag{3}$$

The comparison of uplift factor obtained using the analytical equations with the field data is shown in Table 4.
From the study of Table 4 it is observed that:

1. According to Meyerhof and Adams [8], 52.38% of (N_{field}) values are within +26.08 to -16.71% variation and the remaining 47.62% results are within +33.28 to 42.94% variation with respect to ($N_{predicted}$). Also, 85.71% of the results are within (+11.31 and 42.94%) and underestimated.

2. According to Clemence and Veesaert [9], the results of variation are between (+16.06 and 58.28%). Notably, the present equation overestimates the field uplift capacity. So, the angle of the inverted cone is more than Ø/2 which is in contrast with assumption of failure surface.
3. According to Ovesen [23], 23.80% of (N_{field}) values are overestimated and the rest results are in contrast. Also, 71.43% of (N_{field}) values range between (-6.00 and 25.65%) variation.
4. According to Murray and Geddes [11], 85.71% of (N_{field}) values are within +16.90 to -17.41% variation and the remaining 14.29% results are overestimated and within -49.68 to -54.29% variation with respect to ($N_{predicted}$). Nevertheless, this equation can predict the uplift capacity of field under-reamed piles with reasonable accuracy even with the variation in Ø from 24.7° to 48° and (L_p/D_u) from 1.38 to 5.33.
5. According to Kumar et al. [3], the results are underestimated and indicate that for dense sand the angle of failure mechanism is more than dilatancy angle and assumed cylindrical surface in loose sand is not accurate for the present case studies.

Table 3: Some of previous formulae for design of under-reamed piles

Researcher	Method of Analysis	Formulation
Majer [4]	Vertical slip surface	$\mathrm{N} = 1 + 2\mathrm{K}\left(\frac{\mathrm{L_p}}{\mathrm{D_u}}\right)\tan\emptyset$ where K is the coefficient of lateral stress in soil
Meyerhof and Adams [8]	Pyramid- shaped slip surface	$\mathrm{N} = 2\left(\frac{\mathrm{L_p}}{\mathrm{D_u}}\right)\mathrm{K_u}\tan\emptyset\left[\mathrm{m}\left(\frac{\mathrm{L_p}}{\mathrm{D_u}}\right)+1\right]+1$ Where: K_u =0.9 for 30° < Ø < 45° and m is the shape factor, dependent on Ø and varies from 0.15 to 0.5
Clemence and Veesaert [9]	Inverted cone slip surface; cone angle with vertical = Ø /2	$N = \left[1+\left(\frac{\mathrm{L_p}}{\mathrm{D_u}}\right)\tan\left(\frac{\emptyset}{2}\right)\right]^2 + 4\mathrm{K_\circ}\tan\emptyset\cos^2\left(\frac{\emptyset}{2}\right)\left[\frac{1}{2}\left(\frac{\mathrm{L_p}}{\mathrm{D_u}}\right)+\frac{1}{3}\left(\frac{\mathrm{L_p}}{\mathrm{D_u}}\right)^2\tan\left(\frac{\emptyset}{2}\right)\right]$ Where: $K_\circ$ is the coefficient of lateral earth pressure at rest (1-sin Ø)
Ovesen [23]	Derived from centrifugal model tests on horizontal anchor plates	$N = 1 + (4.32\,tan\emptyset - 1.58)\left(\frac{L_p}{D_e}\right)^{1.5}$ Where: $D_e = \sqrt{\frac{\pi {D_u}^2}{4}}$ (Equivalent width of a square anchor)
Murray and Geddes [11]	Inverted cone slip surface; cone angle = ϕ	$N = 1 + \left(\frac{\mathrm{L_p}}{\mathrm{D_e}}\right)\tan\emptyset\left[2+\frac{\pi}{3}\left(\frac{\mathrm{L_p}}{\mathrm{D_e}}\right)\tan\emptyset\right]$ Where: $D_e = \sqrt{\frac{\pi {D_u}^2}{4}}$ (Equivalent width of a square anchor)
Kumar et al. [3]	Inverted cone slip surface for Ø ≥ 40° (dense sand); cone angle = α	$N_g = \left[1+\frac{2L_\mathrm{p}}{D_u}\left(tan\alpha+\frac{1}{2}ksin\delta_f\right) + \left(\frac{2L_p}{D_u}\right)^2 tan\alpha\left(\frac{1}{3}tan\alpha+\frac{1}{2}k\,sin\delta_f\right)\right]$ Where: $\alpha = -1.14\frac{L_1}{D_u} - 0.437\frac{\emptyset}{\psi} + 0.467\psi + 13.92$ $\psi = \emptyset - 30$ and $\delta_f = \emptyset$ K, was taken as per the recommendation of bored pile code (IS 2911 Part I /sec 2 2010). varies from (1 to 1.75) for ($\emptyset = 30^\circ - 45^\circ$) Where, N_g the gross normalized uplift capacity
	Balloon-shaped mechanism simplified to cylindrical shape for Ø ≤ 35° (loose sand)	$N_g = \left[1 + ktan\delta_f\,\frac{2H}{D_u}\left(2-\frac{H}{L_\mathrm{p}}\right)\right]$ Where: $\frac{H}{D_u} = 0.66(2.74)^{\emptyset}\left(\frac{L_\mathrm{p}}{D_u}\right)^{0.86}$

Table 4: Comparison between theoretical and field uplift factors for reamed piles

Authors	D_u (m)	L_p (m)	L_p / D_u	Ø (°)	N_{field}	Meyerhof and Adams [8]	Variation %	Clemence and Veesaert [9],	Variation %	Ovesen [23]	Variation %	Murray and Geddes [11]	Variation %	Kumar et al. [3]	Variation %
Downs and Chieurzzi [7]	0.61	3.08	5.05	24.7	11.86	7.30	38.45	8.90	24.96	6.54	44.86	13.37	-12.7	3.37	71.59
	0.75	2.77	3.71	24.7	9.13	5.21	42.94	6.20	32.1	4.47	51.05	8.65	5.26	2.49	72.73
	1.02	2.83	2.79	24.7	6.86	3.95	42.42	4.60	32.95	3.26	52.48	6.03	12.1	1.89	72.45
Konstantinidis et al. [27]	0.91	3.20	3.52	48	19.71	22.85	-15.9	10.0	49.27	26.43	-34.1	29.95	-51.9	8.75	55.61
	0.91	2.50	2.08	48	17.51	15.53	11.31	7.31	58.26	18.56	-6	20.17	-15.2	6.83	61
Tucker [28]	1.22	1.68	1.38	38	4.73	3.76	20.51	3.14	33.62	4.48	5.29	4.96	-4.87	2.20	53.49
	1.30	2.00	1.54	42	7.95	5.06	36.36	3.64	54.22	6.29	20.89	6.66	16.23	3.07	61.39
	1.30	2.03	1.56	40	6.29	4.65	26.08	3.60	42.77	5.79	7.95	6.23	0.96	2.73	56.6
	1.22	1.73	1.42	40	6.69	4.20	37.22	3.30	50.68	5.14	23.17	5.56	16.9	2.48	62.93
	1.27	2.18	1.71	40	4.67	5.15	-10.3	3.92	16.06	6.52	-39.6	6.99	-49.6	3.00	35.77
	1.32	2.11	1.60	42	7.09	5.28	25.53	3.77	46.83	6.6	6.92	6.98	1.56	3.19	55.01
	1.37	2.53	1.84	40	7.27	5.59	23.11	4.21	42.1	7.16	1.52	7.67	-5.51	3.23	55.58
	1.52	2.44	1.60	42	4.55	5.31	-16.7	3.78	16.93	6.63	-45.7	7.02	-54.3	3.20	29.68
	1.52	2.29	1.50	42	6.47	4.99	22.88	3.57	44.83	6.12	5.41	6.49	-0.31	3.00	53.64
	0.91	3.2	3.50	36	13.10	9.96	23.97	7.92	39.55	13.31	-1.61	15.38	-17.4	4.45	66.04
	1.13	2.35	2.08	36	6.51	5.24	19.51	4.43	31.96	6.6	-1.39	7.42	-14	2.63	59.61
Kwasniewski et al. [26]	0.90	2.00	2.22	30	6.16	4.08	33.77	4.22	31.5	4.64	24.68	6.07	1.47	2.57	58.28
	0.70	1.90	2.71	28	6.93	4.51	34.93	4.90	29.3	4.85	30.02	7.01	-1.16	2.59	62.63
	0.70	1.30	1.85	32	5.74	3.83	33.28	3.71	35.37	4.4	23.35	5.40	5.93	2.54	55.75
	0.70	1.50	2.14	32	7.02	4.39	37.47	4.25	39.46	5.22	25.65	6.39	8.98	2.94	58.12
Baker and Kondner [25]	0.305	1.63	5.33	37	33.40	19.48	41.68	14.09	57.82	25.82	22.70	31.54	5.57	6.69	79.98

5. Comparative Study Between Theoretical Uplift Breakout Factors and Experimental Results for Single Under-Reamed Piles in Sand

5.1 Experimental Set-Up and Test Procedure

Experiments were conducted in a cylindrical PVC tank of 310 mm diameter and 1000 mm deep with thickness 9 mm. Sand was used as a foundation medium with specific gravity and uniformity coefficient equal 2.66 and 3.63, respectively. The sand was classified to poorly graded sand (SP) as per the Unified Soil Classification System (USCS). The maximum and minimum dry unit weight of sand were found to be 18.20 and 15.60 kN/m^3 respectively, and the corresponding values of minimum and maximum void ratios were 46.1% and 70.6% respectively. The sand densities during the experiments were 16.3, 16.8 and 17.62 kN/m^3 respectively for loose (D_r=30%), medium (D_r=50%) and dense (D_r=80%) sand. A sand-placing technique was used for the previous densities.

Smooth mild steel with shaft diameter (D_p=20 mm) and embedment depth (L_p=500 mm) were used in the investigation. The model piles were manufactured using CNC machine and shown in Fig. 14. The bulbs are in spherical shape with diameter (D_u) equals 2D_p and 3D_p. Also, spacing from pile tip to the centre of the bottom bulb equals ($0.55D_u$) for all model piles. The top portion of the piles were screwed to fasten them with the pile cap. In addition, the pile was suspended vertically at the centre of the empty tank before pouring the sand.

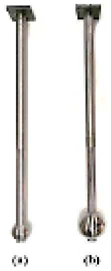


Fig. 14 Model Single under-reamed piles: (a) D_u/D_p=2 and (b) D_u/D_p=3.

Axial uplift loads in homogeneous sandy soil were applied vertically on the pile top through a smooth double pully arrangement. Flexible steel wire was attached to the top of the pile cap. The dead weights were applied in the loading hanger in stages with constant increments. Vertical displacement was recorded using dial gauge corresponding to each load increment when it became stable. Fig. 15 shows the experimental setup.

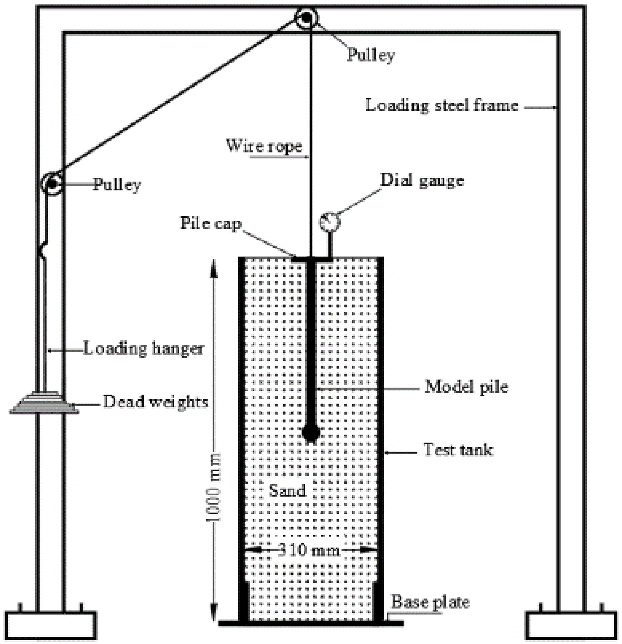


Fig. 15 Schematic diagram of experimental set-up.

5.2 Experimental Results and Discussion

An experimental investigation was carried on under-reamed pile with single bulb embedded in sand soil. Six experiments were performed using single under-reamed pile with two bulb diameter ratios, D_u/D_p = 2 and 3embedded in sand with three relative densities, D_r=30, 50 and 80%.

The basic observations from the experimental investigations were the applied load and the axial vertical displacement. Fig. 16 shows the relation between breakout factors and normalized vertical displacement. The figures are linear in the first stages of loading, then become non-linear.

The ultimate load was defined as the load corresponding to point on load-displacement curve at which the curve becomes steep and straight [30].

Fig. 16 (a and b) show that the uplift factor increases with the increase of the sand relative densities as it was expected. In addition, the uplift capacity was higher in case of D_u/D_p =3 than D_u/D_p =2, for all sand relative densities.

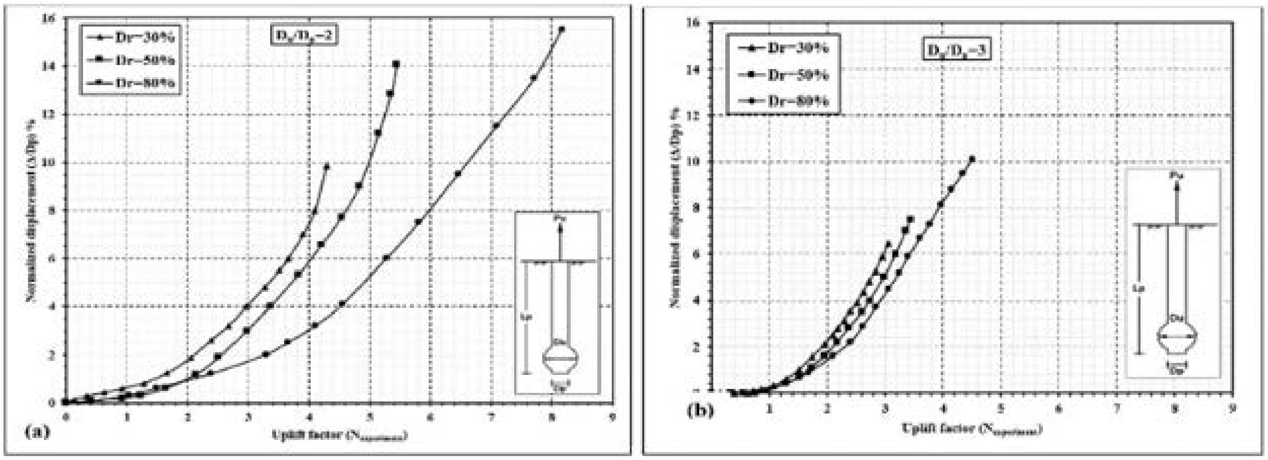


Fig. 16 Uplift factor versus normalized displacement curves for model piles embedded in loose, medium and dense sand, (a) D_u/D_p =2 and (b) D_u/D_p =3.

5.3 Validation of Theoretical Analysis with Experimental Results

Comparison between breakout uplift factors from the present experiments and predicted capacities from theoretical equations mentioned earlier in this paper are made below in Table 5.

All the theoretical equations overestimated the capacity of single under-reamed pile embedded in loose, medium and dense sand as shown in Table 5. In contrary, the theory of Majer (1955) [4] gives reasonably good predictions of uplift capacity in case of dense sand with variation -4.05% and -26.72% corresponding to D_u/D_p= 2 and 3, respectively. Such difference is considered reasonable, as the theory was derived for different bulb shape. Also, Majer (1955) [4] gives the best prediction for uplift capacity of single under-reamed pile embedded in loose and medium dense sand compared with other theories.

$$Variation\ \% = \frac{N_{experiment} - N_{predicted}}{N_{experiment}} * 100 \qquad (4)$$

The reasons of overestimation of the predicted uplift factor are due to:

1- The design equation of Majer (1955) [4], Meyerhof and Adams (1968) [8], Clemence and Veesaert (1977) [9], Murray and Geddes (1987) [11] and Kumar et al. (2021) [3] were derived from small scale laboratory model tests. Although the equation of Ovesen (1981) [23] is derived from centrifugal model, the predicted value of the uplift factor was overestimated.
2- The bulb shape in the present investigation was spherical but the theoretical equations were derived for anchors and belled piles. So, the uplift capacity for the model pile is lesser than the predicted value from theoretical equations where the weight of soil inside the failure surface is lesser.
3- Although the failure mechanism depends mainly on embedment depth, relative density and bulb diameter ratio, but the theoretical equations assumed failure mechanism irrespective all the previous factors together.
4- The model pile is expected to behave in a deep manner according to Meyerhof and Adams (1968) [8], where $L_P/D_u > \mathbf{(H/D_u)_{cr}}$ for all sand relative densities, so the failure mechanism does not reach the soil surface.

Table 5: Comparison between theoretical prediction and uplift factors for model single under-reamed piles.

D_u / D_p	L_p / D_u	Ø (º)	$N_{experiment}$	Majer [4]	Variation %	Meyerhof and Adams [8]	Variation %	Clemence and Veesaert [9]	Variation %	Ovesen [23]	Variation %	Murray and Geddes [11]	Variation %	Kumar et al. [3]	Variation %
2	12.50	31.5	4.28	8.31	-94.3	45.81	-970	43.17	-909	57.56	-1245	95.87	-2140	15.85	-270
2	12.50	34	5.44	8.41	-54.8	59.80	-999	47.36	-771	71.69	-1218	114.02	-1996	19.73	-263
2	12.50	39	8.16	8.49	-4.05	71.60	-778	55.79	-584	102.66	-1158	159.30	-1852	12.50	-53
3	8.33	31.5	3.06	5.87	-91.84	23.98	-684	22.81	-645	31.79	-939	47.01	-1436	10.74	-251
3	8.33	34	3.44	5.94	-72.7	30.50	-787	24.81	-621	39.48	-1048	55.46	-1512	13.33	-288
3	8.33	39	4.50	5.99	-33	36.42	-709	28.80	-540	56.34	-1152	76.43	-1598	8.33	-85

6. Conclusions

In the present paper, factors influencing the uplift capacity, failure mechanism and comparative study between analytical and field data carried out to understand the behavior of the under-reamed piles under pullout load. From the literature survey, the following conclusions are represented.

1. Under-reamed piles are a modified pile foundation which can improve the pullout load capacity. Under-reamed pile requires lesser diameter and length to provide uplift resistance compared to regular pile, therefore the use of reamed pile is economical.
2. The deeper the under-reamed piles installed, the higher the ultimate pullout capacity due to the increase in failure wedge so, the wedge weight and shear mobilization increase.
3. The ultimate pullout capacity increases with increasing bulb diameter (D_u) irrespective of shaft diameter (D_p), but with increasing the shaft diameter and the bulb diameter is constant, the uplift capacity decreases.
4. The ultimate pullout capacity gradually decreases, with a gradual increase in ream angle with horizontal for specific embedment ratio and diameter ratio.
5. That failure displacement normalized to base diameter increased significantly with the increase of embedment ratio but decreased with the increase of sand relative density.
6. The pile stem roughness had an insignificant effect on the pullout capacity of under-reamed piles [20] and [3].
7. Failure mechanism of the under-reamed piles depends mainly on angle of internal friction of sand (Ø), base diameter ratio (D_u/D_p), bell angle and embedment depth ratio (L_P/D_p).
8. Also, the failure mechanism for single and double under-reamed pile is similar and the inverted cone failure surface starts from the last bulb.
9. Note, for all embedment ratios for dense and very dense sand, the truncated cone reaches the sand surface permanently.
10. For single and double under-reamed piles embedded in loose sand, the failure mechanism is in balloon shape and does not reach the surface with the increase in embedment ratio.
11. The predicted uplift factors found by using a few previous analytical equations are varied with the field data due to these equations were derived from small-scale laboratory model tests. Also, the simplification and assumption of failure mechanism.
12. The soil in the field might be heavily over compacted with associated high lateral pressures which would produce significantly higher failure loads [20].
13. Among the existing design methods, the design equation of Murray and Geddes [11] give closest uplift factor values to that from field data for both loose sand and dense sand.
14. The theory of Majer [4] gives reasonably good predictions of uplift capacity in case of dense sand with variation -4.05% and -33% corresponding to D_u/D_p = 2 and 3, respectively.

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