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A Study on Behavior of Vertical Pile in Sand under Uplift Load

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ABSTRACT: The significant design parameter for supporting the piles and the ground anchors for tension loads and compressive loads is shaft resistance. Steel pipe piles often mentioned as cylindrical piles are used often in offshore projects and in harbor structures. Since the end condition of the cylindrical piles (open and closed end) plays a significant change in the shaft capacity of the pile, an experimental study is proposed to predict the load displacement characteristics of single vertical pile subjected to uplift load. The pile is embedded in sand with varying relative densities. The analytical study was developed based on the failure mechanism from limit equilibrium technique. The present study takes into account of significant parameters such as length, diameter and as surface characteristics of pile. The axial load-displacement behavior of vertical pile is studied under the different length to diameter (L/d) ratio which is adopted for the experimental analysis. The uplift co-efficient (K_u) is evaluated by using ultimate uplift capacity load. The obtained experimental results were compared with the reported data to elucidate the significance of the work done.

ABSTRACT: Uplift coefficient, Load-displacement response, Soil-pile interface reaction, Load transfer mechanism, Internal friction angle.

1. INTRODUCTION

Pile foundation belongs to the category of deep foundation. A pile is a slender column structure buried underneath the ground surface. In the construction of various types of foundations, piles are often used to transmit vertical downward load to an adequate stronger soil strata at greater depth. Piles are also used in the construction of foundation subjected to uplift forces. The skin friction is developed along with the soil pile interface which counteracts the uplift forces. A number of structures such as transmission towers, submerged pipelines, suspension bridges, floating offshore platforms, mooring systems for ocean surfaces and tall chimneys are typically subjected to overturning moments due to wave pressure, wind and ship impact etc., These overturning moments are transmitted to structure's foundation in the form of compression on some elements and pullout or tension on the medium of foundation. In this investigation the load displacement behaviour of vertical pile has been investigated under vertical uplift loads. Numerous studies of load displacement performance of pile have been reported in this literature. On the basis of these researches, a number of limit equilibrium equations and theoretical predictions are proposed. **Meyerhof (1973)** developed a simple theoretical expression for evaluation of the ultimate uplift capacity of vertical piles which is embedded in sand. According to Meyerhof's theory;

$$Q = K_u \, \sigma_v \, As \tan \delta \qquad (1)$$

Where Q = uplift capacity, K_u = uplift coefficient, σ_v = average effective overburden pressure, As = surface area of the pile, δ = angle of internal friction at the soil-pile interface.

The average effective overburden pressure is: $\sigma_v = (1/2)\, \gamma'\, L$ (for submerged sand) and $\sigma v = (1/2)\, \gamma\, L$ (for dry sand), where γ'= effective unit weight of sand, γ = dry unit weight of sand and L = embedment length of the pile. B.C. Chattopadhyay and P.J. Pise (1986) developed a generalized theory to estimate uplift capacity of vertical pile which is embedded in sand. The failure surface of the pile embedded in sand is assumed as curved, which passes through the surrounding soil medium. The net uplift capacity of vertical pile embedded in sand is estimated as

$$P_{nu} = A_1 \gamma \pi \, dL^2 \qquad (2)$$

Where A1 = net uplift capacity factor and depends on L/d ratio, δ and Ø. Rove and Davis (1982) has analysed a numerical analysis to determine the behavior of anchor plate using elasto - plastic finite element computations. He considered the parameters in his study such as, anchor embedment, dilatancy, soil-pile friction angle, roughness and initial stresses of anchor plate etc., Ultimate capacity of the anchor q_u was expressed as:

$$Q_u = \gamma \, h \, F_\gamma' \qquad (3)$$

Where γ is the unit weight of soil, h is depth of anchor and F_γ' is an anchor capacity factor which is a function of anchor orientation, embedment ratio, angle of internal friction, dilatancy initial stress state and anchor roughness. Fγ' may be approximately expressed as

$$F_\gamma' = F_\gamma \, R_\Psi \, R_R \, R_K \qquad (4)$$

Where F_γ is the anchor capacity factor for the basic case of a smooth anchor resting in a soil which deforms plastically at constant volume (Ψ=0) and with a coefficient of earth pressure at rest k_o = 1.0. R_Ψ, R_R and R_K are correction factors for the effect of soil dilatancy, anchor roughness and initial stress state respectively. Murray and James D Geddes (1987) has made a limit equilibrium analysis for strip anchors. The ultimate uplift resistance P_u is given by the following equilibrium expression:

$$P_u / \gamma \, B \, H = 1 + (H/B)\,(\sin \varphi + \sin \varphi/2) \qquad (5)$$

Where B is the width of anchor plate and H is the depth of embedment. K.Illamparuthi, E.A.Dickin and K.Muthukrisnaiah (2002), has formulated a series of empirical equations from the similar relationships between N_{qf} and H/D and a series of equations was formulated for anchors in loose sand.

The breakout factor for any embedment ratio in loose sand for circular plate anchors are predicted using the following equations.

$$N_{qf} = e^{(33.5/28)\,(H/D)} \quad \text{for } 0 \le (H/D) \le 1.0 \qquad (6)$$

$$N_{qf} = (H/D)\, N_{qf} \quad \text{for } 1 < (H/D) \le 2.4 \qquad (7)$$

$$N_{qf} = (H/2D)\, (e^{((\tan\varphi \, \ln (H/D))}\, N_{qf} \text{ for } 2.4 < (H/D) \le 4.20 \qquad (8)$$

$$N_{qf} = ((H/D) + (H/D)\, (e^{\,(\tan\varphi \, \ln (H/D))}\,)\, N_{qf1} \quad \text{for } 4.2 < (H/D) < 6.0 \qquad (9)$$

$$N_{qf} = ((H/D) + (e^{\,\tan\varphi \, \ln (H/D)}))\, N_{qf1} \quad \text{for } 6.0 \le (H/D) \le 10.0 \qquad (10)$$

$$N_{qf} = (N_{qf10} + e^{\,(\tan\varphi \, \ln ((H/D)-10))})\, N_{qf1} \quad \text{for } 10.0 < (H/D) \le 12.0 \qquad (11)$$

Where N_{qf} is the breakout factor for any desired H/D ratio in loose sand. N_{qf1} is the breakout factor for H/D = 1.0 and N_{qf10} is the breakout factor for H/D=10.0. The following equation can be used to predict the breakout factor for any embedment ratio and angle of shearing resistance for anchor in dense sands.

$$N^{\varphi}_{qf} = N^{33.5}_{qf} (e^{(H/2D)(\varphi-33.5)/33.5}) \quad (12)$$

Where N^{φ}_{qf} is the breakout factor for any φ value and H/D value. Yang Xiao-li and Zar Jin-Feng (2008) has adopted a numerical simulation to predict the ultimate displacement of uplift pile expressed as

$$S= S_e + S_{(L)} \quad (13)$$

$$S = (PL/3\pi EaD^2) (\cos h (\mu L/D) / (\cos h (\mu L/D)-1)) \quad (14)$$

From their studies, it can be seen that the load displacement can be calculated, if the material parameters, geometry of the uplift pile and the parameters of the soil are known. Deshmukh V B and Devaikar D M (2011) has presented a theoretical analysis of net ultimate uplift capacity of horizontal strip anchors in cohesion less soil using kotter's equation. For cohesionless soil the net ultimate uplift capacity, P_{un} is obtained as;

$$P_{un} = 2 (W + R_v) \quad (15)$$

Where the net uplift force is resisted by vertical component, R_v of resultant soil reaction and weight W of soil in the failure wedge.

$$P_{un} = 2 ((\gamma H^2/2 \tan \alpha) + (0.5 \gamma BH) + (-(1/2) (H^2/\sin^2\alpha) \gamma \sin (\alpha+ Ø) \cos (\alpha+ Ø)) \quad (16)$$

Substituting for α = 90° - Ø/2 in the above equation and with further simplification the net uplift capacity is defined as

$$P_{nu} = \gamma H (2H \tan (Ø /2) + B) \quad (17)$$

This equation represents the net uplift capacity of a strip anchors in cohesionless soil.

The present study has the following assumptions are as follows; The pullout or uplift force is resisted by pile shaft resistance only and no tip resistance assumed (Shubhra Goel, Nihar Ranjan Patra, 2007). The uplift displacement of pile is assumed that elastic extension and rigid body movement along the shaft failure of pile (Yang Xiao-li and Zar Jin-Frng, 2008) (K.Shanker, P.K. Basudhar and N.R.Patra, 2004).

2. EXPERIMENTAL SETUP

A pullout test apparatus is required for this study which is designed and fabricated. Care is taken to design the test setup to estimate the uplift capacity accurately. The experimental test setup is shown in Figure 1. The various components in the test setup are explained clearly.

2.1 Model Test Tank

The tests were conducted in a model steel tank size of 300 x 300 x 400 mm made up of steel. The effect of boundary conditions is taken care of by maintaining side and bottom clearance such as the zone of influence lies within the soil medium. The range is to be of 3-8 times the pile diameter diameter (B.Krishna and N.R.Patra, 2006; K.Shanker, P.K.Basudhar, N.R.Patra, 2007).

2.2 Foundation Medium

Sand was used as foundation medium. The specific gravity and uniformity coefficient of dry sand are 2.65 and 1.71 respectively. The sand grains are sub angular and e_{max} and e_{min} are 0.725 and 0.550 corresponding minimum and maximum dry densities of 14.730 kN/m^3 and 17.037 kN/m^3 respectively. The sand bed density of 15.470 kN/m^3 and 15.296 kN/m^3 are corresponding to medium dense sand and 15.168 kN/m^3 and 14.998 kN/m^3 are for loose sand conditions.

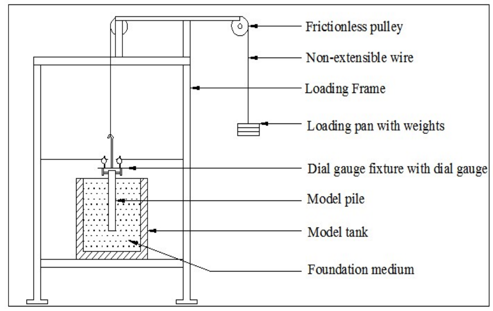

Figure 1 Experimental setup

2.3 Model Pile

Vertical piles with smooth and rough surface piles are used as model piles. The pile shaft was made of mild steel solid rods having diameter of 16mm and the L/d ratios of 6.25, 9.375, 12.5 and 15.625 are adopted. The model piles were tested in the medium dense and loose sand conditions.

2.4 Loading Arrangement

The loading arrangements are shown in Figure 1. Axial vertical pullout loads are applied to the piles through double pulley arrangement by using dead weights, loading pan, dial gauge fixture, bolt and nut arrangement (B.Krishna and N.R.Patra, 2006; L.Vanitha, N.R.Patra, S.Chandra, 2007). The dead weights are used to apply the pullout loads and the non-extensible 2mm diameter of wire is attached to the pile top through a bolt and nut arrangement (B.Krishna and N.R.Patra, 2006; L.Vanitha, N.R.Patra, S.Chandra, 2007). Two dial gauges are used for measuring the axial displacement of the pile; the sensitivity of the dial gauge is 0.01mm.

2.5 Testing Procedure

For all piles, the experimental testing procedure is same, which is described below. The model pile was prepositioned in the empty tank vertically. After proper placement of pile, sand was poured in the tank continuously through the slot of a hopper (having 5mm slot at one edge for uniformity) keeping height of fall about 300 mm and 250mm for medium dense and 200 mm and 150mm for loose sand condition packing moving horizontally by hand. This technique of sand pouring is termed as rainfall technique and this technique was reported to achieve good reproducible densities (B.Krishna and N.R.Patra, 2006; L.Vanitha, N.R.Patra, S.Chandra, 2007).

This rainfall technique is further continued till the required embedment length was reached. The surface of the sand medium was leveled carefully. This method of sand pouring gave a predetermined dry density of 15.470 kN/m^3 (RD=53.85%) and 15.296 kN/m^3 (RD=40.37%) for medium dense sand and 15.168 kN/m^3 (RD=27.49%) and 14.998 kN/m^3 (RD=20.52%) for loose sand conditions. The pile was tested under axial pullout loads by means of double pulley arrangement. The flexible and non-extensible wire rope is passing over the pulleys are connected to the top of the pile head through a hook and another end is attached to a loading pan (B.Krishna and N.R.Patra, 2006); (L.Vanitha, N.R.Patra, S.Chandra, 2007).

The position of first pulley is fixed according to the alignment of the wire rope and pile axis as per the vertical position of the pile. Two dial gauges were fixed equidistant from pile axis on dial gauges fixture. The static load was applied by dead weights in the loading pan starting the smallest with gradual increase in stages. Dial gauge readings were observed for both dial gauges for each increment of axial displacement of pile corresponding to the pullout load applied.

3 RESULTS AND DISCUSSION

3.1 Load versus displacement response

The load-displacement curves are plotted for medium dense and loose sand conditions for smooth and rough piles are shown in Figure 2 to Figure 9. The load displacement diagrams are practically linear in the early stages and tend to be non-linear. The axial displacement for all the piles is in the range of 0.72mm to 1.52mm. It is observed that the displacement range of 0.04d to 0.1d for medium dense and loose sand conditions. The failure is considered when the pile moves out of the soil.

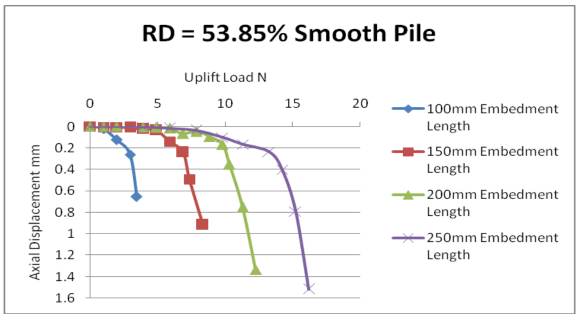

Figure 2 Uplift load versus Axial displacement for Smooth Pile (RD=53.85%)

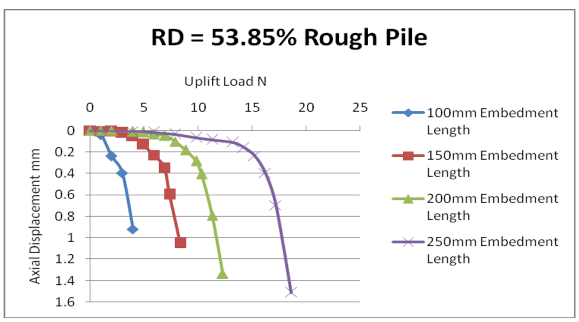

Figure 3 Uplift load versus Axial displacement for Rough Pile (RD=53.85%)

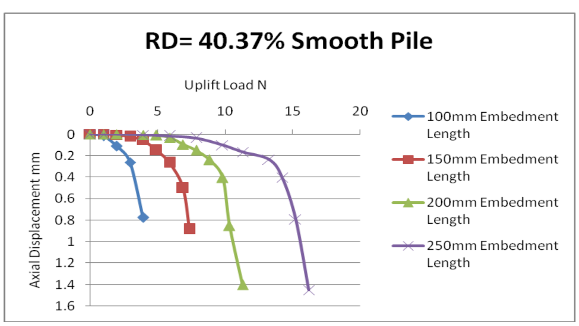

Figure 4 Uplift load versus Axial displacement for Smooth Pile (RD=40.37%)

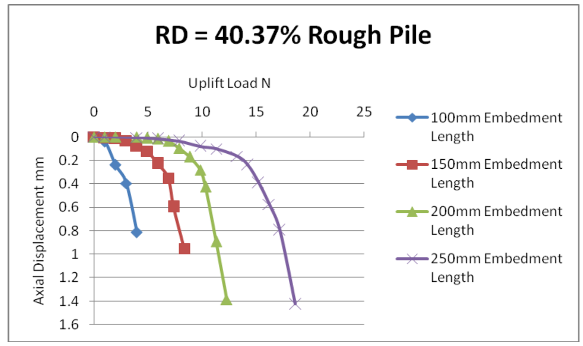

Figure 5 Uplift load versus Axial displacement for Rough Pile (RD=40.37%)

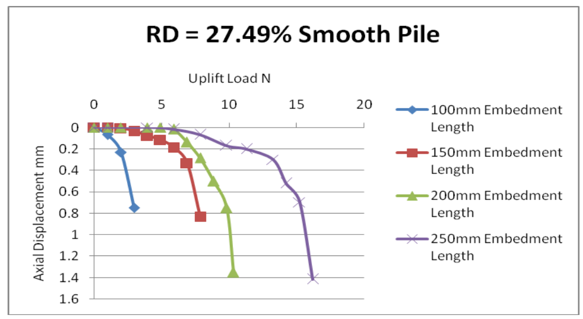

Figure 6 Uplift load versus Axial displacement for Smooth Pile (RD=27.49%)

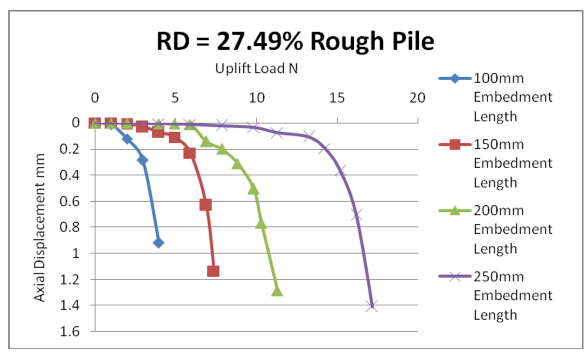

Figure 7 Uplift load versus Axial displacement for Rough Pile (RD=27.49%)

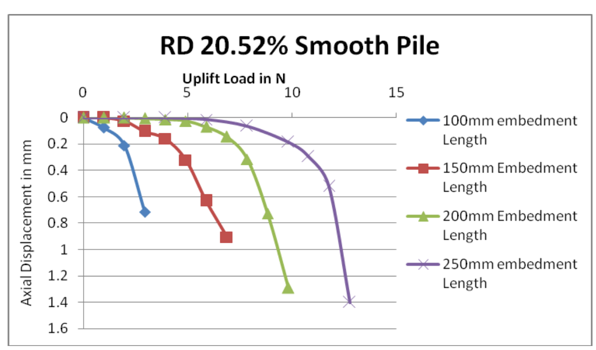

Figure 8 Uplift load versus Axial displacement for Smooth Pile (RD=20.52%)

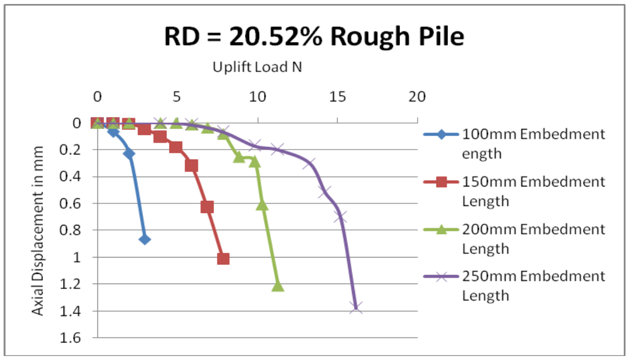

Figure 9 Uplift load versus Axial displacement for Rough Pile (RD=20.52%)

3.2 Variation of uplift capacity with L/d ratio

Figure 10 and Figure 11 shows the variation of uplift capacity with L/d ratio for medium dense condition of sand and Figure 12 and Figure 13 shows the loose condition of sand. The uplift capacity of the pile increases with increase in L/d ratio of the pile from 6.25 to 15.250. The length of the pile increases, there is a proportionate increase in the skin friction component because of increasing the contact area between soil and pile.

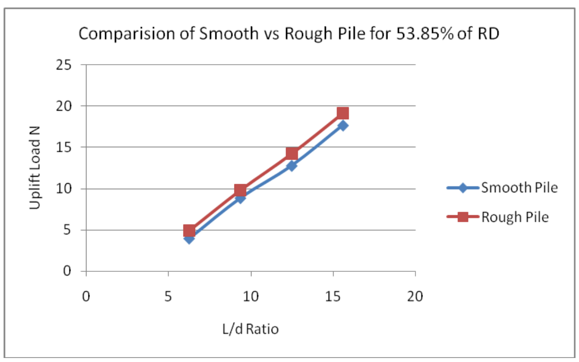

Figure 10 Comparison of results for Smooth and Rough piles (RD=53.85%)

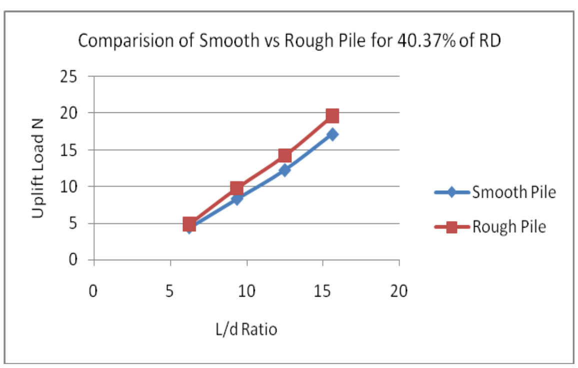

Figure 11 Comparison of results for Smooth and Rough piles (RD=40.37%)

3.3 Variation of uplift capacity with surface characteristics of the pile

The uplift capacity of the pile increases with the increase of surface roughness of the pile. The additional skin friction has been obtained from the experimental results because of more bondage between soil and pile materials.

For the loose condition of sand, the uplift capacity increases 4% to 13% with change in surface character for same diameter of pile for 20.52% and the uplift capacity increases 7% to 22% with change in surface character for same diameter of pile for 27.49%.

For the medium dense condition of sand, the uplift capacity increases 6% to 20% with change in surface character for same diameter of pile for 40.37% and the uplift capacity increases 5% to 18% with change in surface character for same diameter of pile for 53.85%.

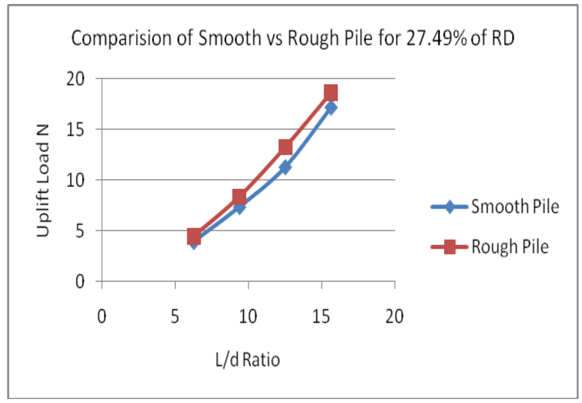

Figure 12 Comparison of results for Smooth and Rough piles (RD=27.49%)

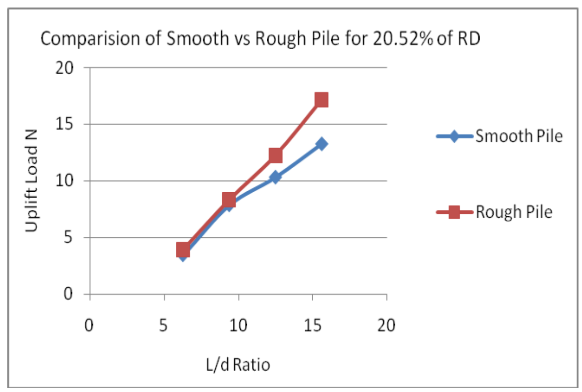

Figure 13 Comparison of results for Smooth and Rough piles (RD=20.52%)

3.4 Uplift co-efficient (Ku)

The uplift co-efficient is evaluated from the following expression,

$$Q_u = K_u \sigma_v A_s \tan \delta \tag{18}$$

The uplift capacity and axial displacement are obtained from the experimental study. The soil-pile friction angle (δ) is taken as 3/4 of the angle of internal friction (Ø) [(Shubhra Goel, Nihar ranjan Patra, 2007)]. The plot between L/d ratio and Ku corresponding smooth pile for both loose and medium dense condition is shown in Figure 14. The Ku value varies with increase in L/d ratio and increases with increasing angle of internal friction of sand. The plot between L/d ratio and Ku correspond rough pile for both loose and medium dense condition of sand is shown in Figure 15.

For same diameter of pile the uplift coefficient linearly varies with the increase in L/d ratio and changes the surface characteristics of pile. Table 1 and Table 2 show the uplift coefficient (Ku) and uplift load for medium dense (RD=58.61%, RD=40.37%) and loose sand (RD= 27.49%, RD=20.52%) conditions.

Table 1 Ku value for smooth and rough pile

L/D Ratio	Uplift Coefficient (Ku)							
	20.52		27.49		40.37		53.85	
	Smooth Pile	Rough Pile	Smooth Pile	Rough Pile	Smooth Pile	Rough Pile	Smooth Pile	Rough Pile
6.25	2.712	3.051	2.798	3.420	2.868	3.442	2.911	3.440
9.375	1.808	1.959	1.934	2.211	1.912	2.167	1.999	2.116
12.5	1.525	1.615	1.632	1.710	1.649	1.793	1719	1.852
15.625	1.247	1.301	1.442	1.542	1.514	1.606	1.524	1.608

Table 2 Uplift load value for smooth and rough pile

L/D Ratio	Uplift Load (Pu)							
	20.52		27.49		40.37		53.85	
	Smooth Pile	Rough Pile	Smooth Pile	Rough Pile	Smooth Pile	Rough Pile	Smooth Pile	Rough Pile
6.25	3.924	4.415	4.415	5.396	4.905	5.886	5.396	6.377
9.375	5.886	6.377	6.867	7.848	7.358	8.339	8.339	8.829
12.5	8.829	9.32	10.301	10.791	11.282	12.263	12.753	13.734
15.625	11.282	11.772	14.225	15.206	16.187	17.168	17.658	18.639

3.5 Comparison of predicted values with observed values

The L/d ratio versus uplift load obtained from this study is compared with the values evaluated from other theoretical results for loose sand conditions are shown in Figure 16 and Figure 17. The reasonable agreements are predicted from the existing previous studies and the results are compared with the present model study which is shown in Figure 18 and Figure 19 for medium dense sand condition.

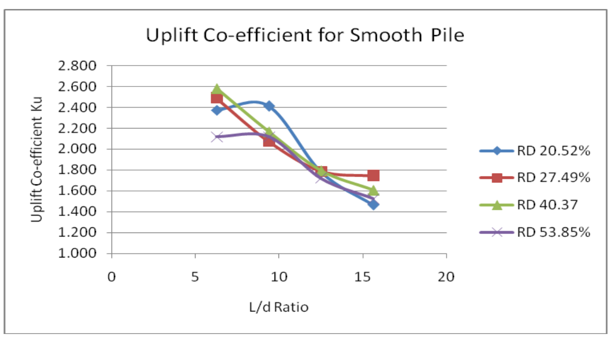

Figure 14 Uplift Co-efficient versus L/d ratio for smooth pile

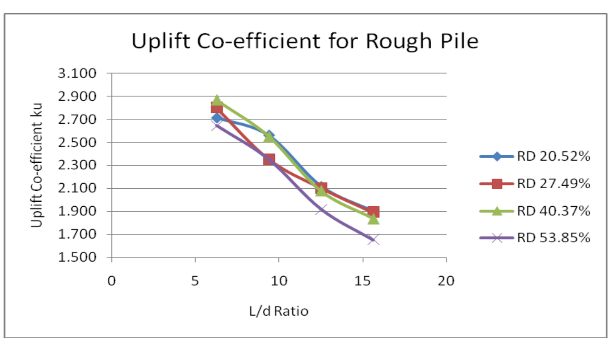

Figure 15 Uplift Co-efficient versus L/d ratio for rough pile

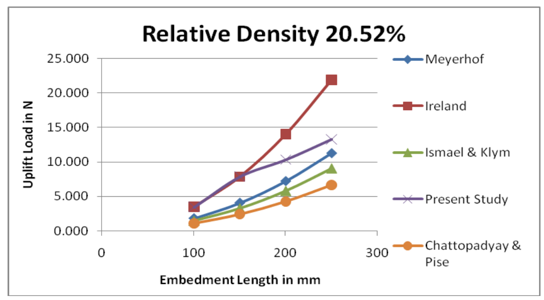

Figure 16 Comparison of results for smooth piles (RD=20.52%)

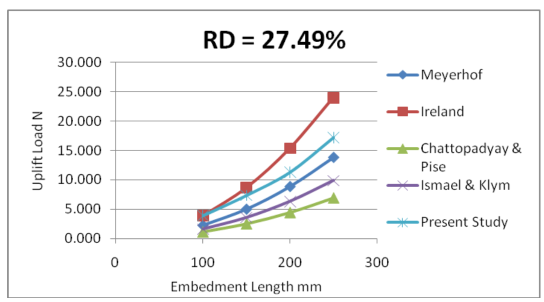

Figure 17 Comparison of results for smooth piles (RD=27.49%)

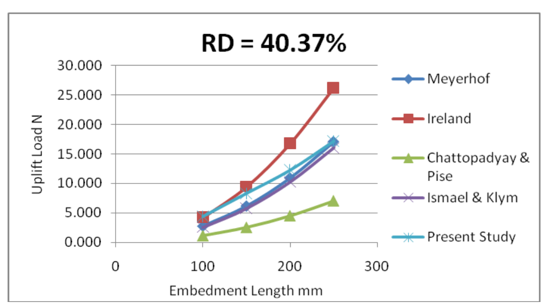

Figure 18 Comparison of results for smooth piles (RD=40.37%)

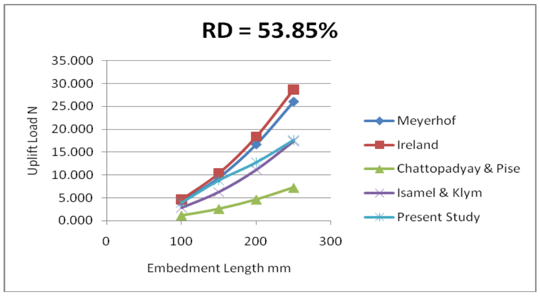

Figure 19 Comparison of results for smooth piles (RD=53.85%)

4. CONCLUSION

The test results of every vertical pile are obtained from the experimental investigation and summarized as, the uplift capacity of pile increases with the increase in length to diameter ratio of the pile. Axial displacement about 4% to 10% of pile diameter is required mobilize the shaft resistance. It is observed that, in all studies, the axial load displacement response is linear in the initial stages and thereafter it becomes non-linear. The uplift coefficient (Ku) value range is 1.2 to 3.4 for all type of piles in medium dense and loose condition of sand. The uplift coefficient value varies with increase in L/d ratio of the pile.

List of symbols

K_u	uplift coefficient
σ_v	average effective overburden pressure
As	surface area of the pile
δ.	angle of internal friction at the soil-pile interface
γ'	effective unit weight of sand
γ	dry unit weight of sand
L	length of the pile
L/d	Length / diameter ratio
A1	net uplift capacity factor and depends on δ, Ø and L/d ratio
h	depth of anchor
F_γ'	Anchor capacity factor
R_Ψ	Correction factors for the effect of soil dilatancy
R_R	Correction factors for the effect of anchor roughness.
R_K	Correction factors for the effect of initial stress
B	Width of anchor plate
H	Embedment depth
N_{qf}	the breakout factor
Ø	Angle of internal friction

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