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An experimental study of static lateral and uplift capacity of single pile in sand

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Abstract

Some structures like high-rise buildings, transmission towers, offshore structures, and the like are generally supported by pile foundations. Piles of such structures are subjected to large lateral loads and overturning moments due to wind, waves, or both, in addition to vertical compressive load. So, safe design of piles under combined loading (lateral- compressive and lateral-uplift) has become the key concern for geotechnical engineers. Although some works have been done on individual lateral, uplift and compressive loading but behavior of piles under combined lateral and uplift load is not well addressed in literature. With this in view, in the present study, experiments have been carried out on a model mild steel single pile, embedded in homogeneous sand bed prepared by pouring locally available sand (made uniform through sieving) with the help of rainfall technique, to investigate the pile behavior under independent lateral loads (6 tests) and independent uplift loads (6 tests). A parametric study has then been done to find the influence of RD of sand bed and L/D of model piles on ultimate lateral capacity obtained with different values of uplift applied on the model piles. It has been observed from the results that the value of ultimate lateral capacity of piles increases with the increase in both length-to-diameter ratio (L/D ratio) of model piles and relative density (RD) of the homogenous sand bed. This study highlights lateral response of a pile with different uplift loads for varying L/D ratio and relative density of homogeneous sand bed. The dimensions of the mild steel pile cap are120 mm × 120 mm × 10 mm and it is used along with the piles welded over the piles at the top.

Keywords: Pile; Homogeneous sand; Model pile; Relative density; L/D ratio; Lateral load; Uplift load; Combined load

1. Introduction

Geotechnical engineers often have to design piles for high-rise buildings, transmission towers, and offshore structures and also for mooring systems. In these cases, some piles are subjected to lateral forces along with uplift and some are subjected to vertical compression and lateral forces due to wind and wave action, earthquakes etc. The sources of lateral and uplift load are different for different structures. For example, bridge abutments and piers are subjected to traffic and wind movement leading to lateral forces. So the piles underneath are subjected to lateral load along with vertical compression. High rise building and towers are subjected to lateral load due to wind and earthquake forces. This lateral load is accompanied by uplift due to transfer of overturning moments through piles in the form of push and pull. When piles have to support deep underground tanks, they are subjected to uplift with lateral loads coming due to earthquake. Thus it appears that knowledge about lateral response of pile under the simultaneous action of uplift is very important for safe design of such structures.

Studies on pile foundations under individual lateral load and uplift are being carried out since long time. Reese and Matlock (1956) [17], Matlock and Reese (1960) [7], Bowles (1974) [1], Prakash and Kumar (1996) [10], Phanikanth *et al.* (2010) [11] etc. studied the pile behaviour under individual lateral loading. Again, Nicola and Randolf (1993) [9], Livneh and Nagger (2008) [5], Verma and Joshi (2010) [19] Parthipan and Kumar (2017) [13], studied the pile behaviour under uplift. However, only a few researchers like Reddy and Ayothiraman (2015) [16], Parekh and Thakare (2016) [15] studied pile behavior in homogeneous soil under combined lateral and uplift loading. The load transfer mechanism for individual uplift and individual lateral load are well known. But, to gain an insight into the behaviour of piles under combined lateral and uplift load, still there is a scope of research. This is also required for appropriate pile design of offshore structures and some onshore structures without which construction of these structures may not be appropriate.

2. Research Methodology

This research methods deals with the test program, materials and equipment used in the test, the properties of the individual materials, test procedure and finally the test programs done; adopted in the present experimental investigation. Model experiments are carried out in the laboratory to measure the pile behavior under independent lateral loads, independent uplift loads, and combined loads (uplift plus static lateral load). Models are so chosen that the response measured from the small-scale models can be used to interpret the behaviour of piles under combined lateral and uplift load within the range of the parameters adopted in the study.

2.1. Test Program

The test program of three different types of tests; such as, individual static lateral tests, individual static uplift tests and combined lateral and uplift tests are shown below in Table 1 and Table 2. A total of 6 tests are conducted for individual static lateral tests and again, a total of 6 tests are conducted for individual static uplift tests also as per Table 1.

Table 1: Test Program of Independent Lateral and Uplift Load Tests

Type of Sand Bed	Relative Density of Sand (%)	L/D Ratio	Total No. of Static Lateral Load Test Without Uplift Load	Total No. of Static Uplift Load Test Without Lateral Load
Homogenous	45	20	6	6
		25		
	70	20		
		25		
	85	20		
		25		

2.2. Equipment and Material Used

The following materials are used in the proposed research work recommended by the different specifications of Indian Standards.

2.2.1. Sand

The soil condition at the site for any proposed structure depicts the choice of suitable foundation to support various structures. Locally available sand will be considered in the present investigation, which has been sieved through 1.18 mm and 0.425 mm IS sieve to simulate the gradation of Ennore sand as far as possible. The engineering properties of the materials passing through 1.18 mm sieve and retained on 0.425 mm IS sieve are determined through laboratory tests as per the standard procedures recommended by the IS:2720-Part 8. The gradation curve is shown in Fig. 1 and the summary of engineering properties of sand is presented in Table 2. All the sand used in the test are kept in covered air tight big size plastic container drums for keeping them atmospheric moisture free as shown in Fig. 2 below.

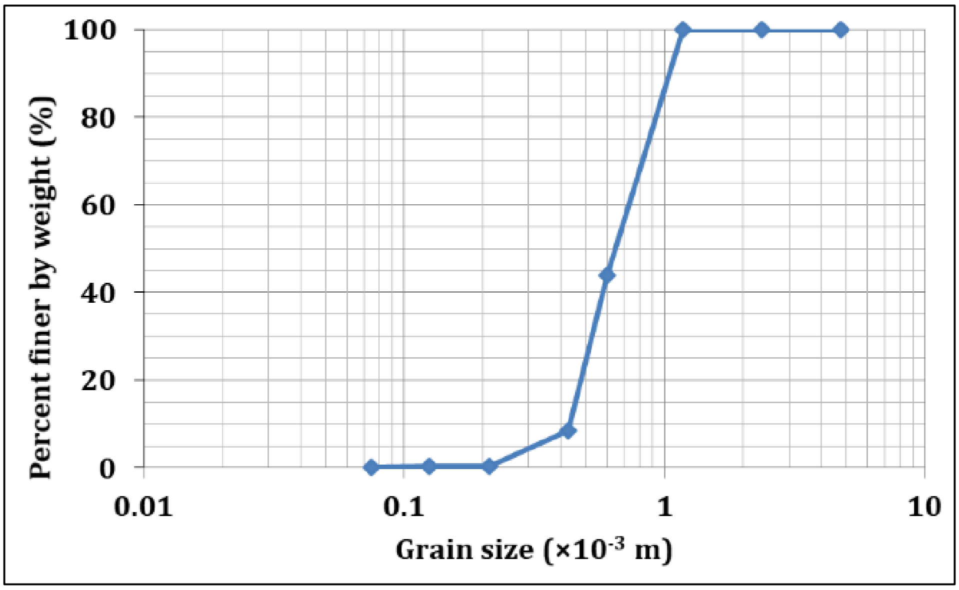

Fig 1: Gradation Curve of Sand

Table 2: Summary of Properties of Sand

Description	Value
Maximum dry density, ρ_{max}	17kN/m^3
Minimum dry density, ρ_{min}	13.7kN/m^3
Specific gravity, G_s	2.696
Void ratio (loosest), e_{max}	0.992
Void ratio (densest), e_{min}	0.605
Uniformity coefficient, C_u	1.55
Coefficient of curvature, C_c	0.903
Effective Size, D_{10}	0.49 mm

Fig 2: Sand (Size range: 1.18 mm to 0.425 mm)

2.2.2. Model Pile and Pile Cap

For conducting model tests, mild steel hollow pipes having an external diameter of 25 mm with 2 mm thickness are used. L/D ratios of 20 and 25 having effective lengths of 500 mm and 625 mm are used in the present investigation for simulating piles in the model experiments. The range of prototype dimensions represented by the model pile for different scale factors is calculated using the following formula (Wood *et al*. 2002) [21]:

$$\frac{(EI)_p}{(EI)_m} = n^{4.5}$$

Where, n = scale factor; $(EI)_p$ and $(EI)_m$ = flexural rigidity of prototype pile and model pile, respectively. The summary of properties of material of mild steel pile and pile cap are presented in Table 3, using the instruments and machineries of the Mechanical Engineering Department of Jadavpur University, Kolkata, West Bengal.

Table 3: Summary of Properties of Material of Pile and Pile Cap

Description	Value
Density	9.23×10^{-8}kN/mm^3
Young's Modulus	6.52×10^{7}kN/m^2
Shear Modulus	2.71×10^5 N/mm^2
Poisson's ratio	0.22

The dimensions of the mild steel pile cap are 120 mm × 120 mm × 10 mm and it is used along with the piles welded over the piles at the top. Two U-hooks are welded on top side and left side of the pile cap so that the loading strings can be attached to it safely for hanging the dead weights by them. Both the U-hooks are used to load weights needed initiating both the lateral force and uplift force in the test program. The model pile along with pile cap attached to U-hooks is shown in Fig. 3 below and also three different types of pile having L/D ratios of 20 and 25 are also shown below in Fig. 4.

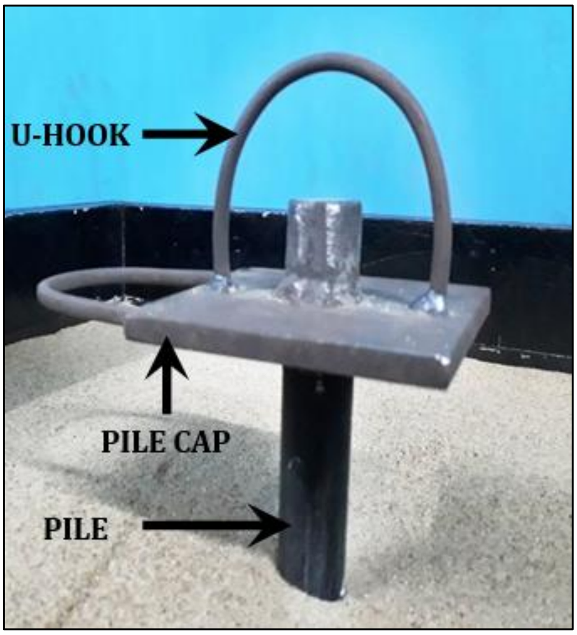

Fig 3: Pile and Pile Cap

Fig 4: Different Types of Pile

3. Experimental Setup

The experimental set up will consist of the following components listed below.

3.1. Test Tank

In general, the dimensions of the model test tank are decided based on the effective stressed zone of soil mass from the edge of the foundation. For a laterally loaded single pile, it is inferred from the literature that the boundary effect is more predominant within 10 times the pile diameter from the pile periphery (Matlock 1970; Rao *et al*. 1996, 1998) [8, 19]. The test tank used in the present experiment is show in Fig. 5 below which is made by hard seasoned wood consisting of five detachable blocks or parts.

Fig. 5: Test Tank

In the present study, the model pile diameter is 25 mm and hence the size of the tank in the plan should be larger than 250 mm for a single pile. For piles subjected to uplift load, the zone of influence is 3 to 8 times pile diameter from the edge of the pile at ground surface (Kishida 1963) [4]. Hence, the minimum size of the tank should be 425 mm (8D + 8D + D = 17D). Accordingly, the dimensions of the model test tank are fixed as 1000 mm × 1000 mm × 2250mm (depth) to avoid the boundary effects while testing the model pile under lateral and uplift loads.

4. Results & Discussion

Based on the experimental investigation an attempt has been made in this section to examine the effect of L/D ratio and relative density (RD) on ultimate lateral capacity of model piles with and without action of uplift.

In this section the experiments have been carried out on model piles with application of only lateral load, only uplift and combination of both. Pile behavior for these three cases has been discussed one by one in the following sections.

4.1. Ultimate Lateral Capacity with No Uplift

In this section, the effect of only lateral load without uplift has been studied. The results have been presented in Table 4. The variation of ultimate lateral capacity with L/D of piles and RD of sand of foundation bed has been studied in the following sections for homogeneous sand beds (RD=45%, 70% and 85%).

4.1.1. Ultimate Lateral Capacity (L_u) Vs. L/D

It is observed from Table 4, that when RD remains the same, ultimate lateral capacity (L_u) increases with L/D. For RD = 45% the L_u increases by 26%, for RD = 70% the L_u increases by 51% and further for RD = 85% the L_u increases by 71% for increase of L/D from 20 to 25. This is attributed to increase of stiffness of the soil-pile system. L_u has been plotted against L/D for various values of RD in Fig. 6 below.

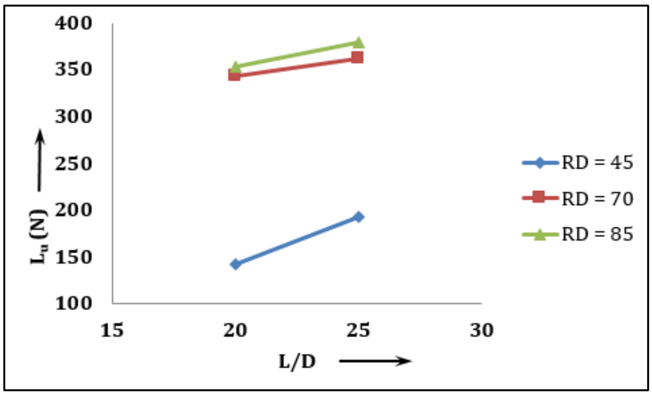

Fig 6: Variation of Ultimate Lateral Load (L_u) with L/D

It can be seen from the above Fig. 6 that, for higher RD values, the rate of increase is becoming less, indicating less increase of ultimate lateral capacity (L_u) for higher RD. This is probably due to the fact that with increase in RD value, soil stiffness is also increased but the pile stiffness is remaining constant.

4.1.2. Ultimate Lateral Capacity (L_u) Vs. RD

In Fig 7, ultimate lateral capacity (L_u) has been plotted against relative density (RD) for different L/D ratios. It appears from the figure that, as RD increases, L_u also increases for same L/D ratio. As RD increases from 45% to 70%, L_u increases by 58%. Again, when RD increases from 70% to 85%, L_u increases only by 2.5%. Thus, it is seen that, when RD is reaching the value of 70%, increase of L_u is becoming marginal for further increase in RD.

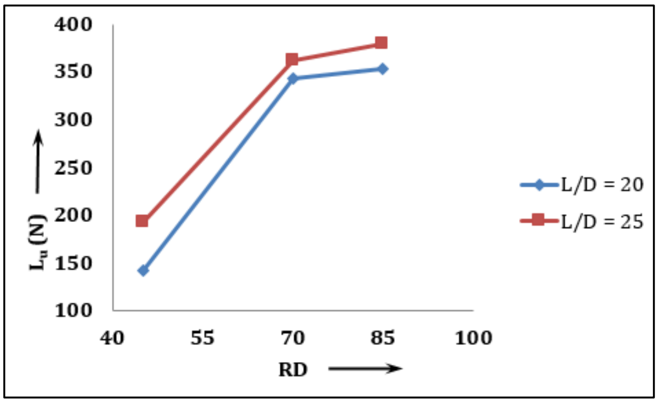

Fig 7: Variation of Ultimate Lateral Load (L_u) with RD

It is also seen that, beyond RD value of 70%, the curves are flatter in nature because the contribution of system stiffness is occurring due to dense compaction of soil. This is obvious since the pile dimensions are remaining the same with decrease of pile stiffness with increase in L/D.

4.2. Ultimate Uplift Capacity with No Lateral Load

In this section, the effect of uplift without lateral load has been studied. The results have been presented in Table 5.The variation of ultimate uplift capacity with L/D of piles and RD of sand of foundation bed has been studied in the following sections for homogeneous sand beds (RD = 45%, 70% and 85%).

4.2.1. Ultimate Uplift Capacity (P_u) vs. L/D
It can be inferred from Table 5. When RD remains unaltered, P_u increases with L/D. For increase in L/D from 20 to 25, P_u increases by 88%, 30% and 13% respectively, for RD value of 45%, 70% and 85%. P_u has been plotted against L/D ratio for various RD values in Fig. 8 below.

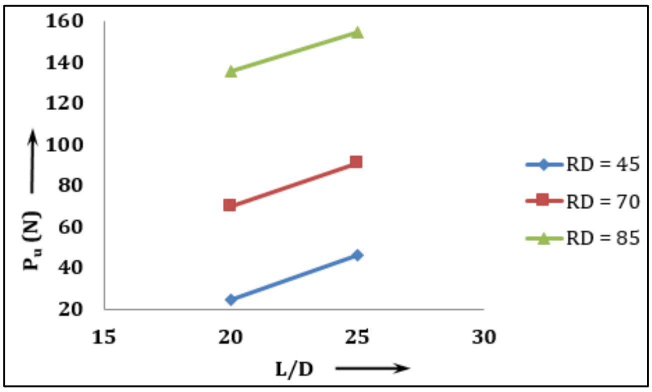

Fig 8: Variation of Ultimate Uplift Load (P_u) with L/D

It appears from the figure that, for higher RD, the curves are almost parallel, indicating increase of P_u is remaining same for all values of RD. This may be attributed to the fact, that for each value of RD, soil stiffness is remaining same but the pile stiffness is decreasing maintaining the same order as L/D ratio increases from 20 to 25 in each case. Thus, the major effect revealed in increase of P_u values occurs only due to depth of embedment accompanied by increase of L/D ratio since diameter of pile remains same.

4.2.2. Ultimate Uplift Capacity (P_u) vs. RD
Fig. 9 presents the variation of ultimate uplift capacity (P_u) with RD for different value of L/D. It appears from the figure that, P_u increases with RD for a particular L/D. In case of L/D = 20, when RD increases from 45% to 70%, P_u is increased by 187%. It further increases by 93% as RD increases from 70% to 85%. In case of L/D = 25, percentage increase in P_u is 97% and 69% respectively for increase in RD from 45% to 70% and 70% to 85%.

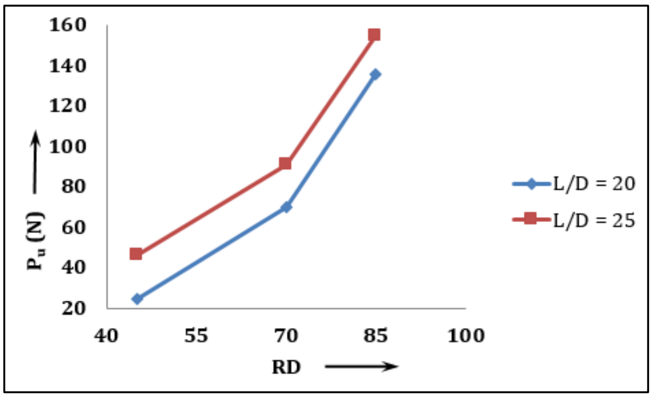

Fig 9: Variation of Ultimate Uplift Load (P_u) with RD

It is seen from Fig 9 that, rate of increase of P_u decreases beyond RD value of 70%, irrespective of L/D value; probably due to the fact that, contribution of system stiffness is due to dense compaction of soil as pile dimensions are remaining the same with decrease of pile stiffness with L/D.

Table 4: Experimental Results of Static Lateral Load Test

Sl. No.	Test No.	L/D Ratio	Relative Density (%)	Ultimate Lateral Load, L_u (N)	Pile Head Displacement, ρ_L (mm)
1	L_1	20	45	142.0	9
2	L_2	20	70	343.5	
3	L_3	20	85	352.5	
4	L_4	25	45	192.0	
5	L_5	25	70	362.0	
6	L_6	25	85	379.5	

Table 5: Experimental Results of Static Uplift Load Test

Sl. No.	Test No.	L/D Ratio	Relative Density (%)	Ultimate Uplift Load, P_u (N)	Pile Head Displacement, ρ_P (mm)
7	P_1	20	45	24.5	0.365
8	P_2	20	70	70.0	0.260
9	P_3	20	85	135.5	0.135
10	P_4	25	45	46.0	0.330
11	P_5	25	70	91.0	0.110
12	P_6	25	85	154.0	0.100

5. Conclusion
In order to gain an insight into the behaviour of piles under combined lateral and uplift loading, an experimental study has been carried out on 25 mm outer diameter (2mm thick) mild steel hollow model piles (L/D=20 and 25) embedded in three homogeneous sand beds (RD=45%, 70% and 85%). The desired relative density (RD) of sand has been achieved by pouring sand with rainfall technique. Loading arrangement for application of lateral and uplift loading has been made appropriately. Six tests have been carried out with lateral load and no uplift. Another set of six tests have been conducted by applying only uplift and no lateral load to find the ultimate uplift capacity. A parametric study has then been done to find the influence of RD of sand bed and L/D of model piles on ultimate lateral capacity with different values of uplift applied on the model piles.

The lateral load vs. lateral displacement and uplift load vs. uplift displacement characteristics is nonlinear in nature. In this experiment when RD of sand remains the same, L_u increases with L/D ratio of pile. In case of no uplift, increase of L_u is less for RD values beyond 70%. Again, as RD of sand increases, L_u also increases for the same L/D ratio. When RD remains unaltered, P_u increases with L/D ratio of pile. Furthermore, rate of increase of P_u decreases beyond RD value of 70% irrespective of L/D value of pile. It is also observed when RD is increased from 70% to 85%, increase of L_u is becoming marginal irrespective of L/D value of pile.

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