A Model Study on Pile Behavior under Inclined Compressive Loads in Cohesionless Soil

Serin Issac
M Tech Student,
Department of Civil Engineering
Saintgits College of Engineering, Kottayam
Kerala, India

Swapna Thomas
Assistant Professor,
Department of Civil Engineering
Saintgits College of Engineering, Kottayam
Kerala, India

***Abstract*— Pile foundations are extensively used to support various structures built on loose/ soft soils where shallow foundations would undergo excessive settlements or have low bearing capacity. Piles are slender, having high length to width ratio, and are mainly designed to resist axial loads. However, some structures such as high rise buildings, offshore structures, tall chimneys, earth retaining walls are subjected to horizontal or lateral pressure caused by wind force, wave force, traffic movement, earthquake etc. Thus, piles are used as foundation to transmit vertical and lateral loads to the surrounding soil media. In many cases, they may be subjected to inclined compressive loading conditions also. These loads cause lateral and vertical displacements and rotation of the pile cap. These overall behaviors of the piles are estimated from the available conventional theoretical approaches. There are limited experimental studies available on behavior of vertical piles subjected to inclined compressive loads. This paper is an attempt to study the behavior of single pile in cohesionless soil, subjected to varying inclined load until failure with the angle of applied load varying from 0º to 90º from the vertical axis of the pile, through an experimental model study on model mild steel and concrete piles driven into dry river sand. Axial and lateral load carrying capacities of both piles of various slenderness ratios (10, 15, and 20) are found through the load – settlement diagrams and are compared. The effects of vertical and lateral components of inclined loads on horizontal and vertical displacement of the pile head are discussed. Also, the effects of pile material on the lateral load capacity of piles are studied.**

Keywords— ***Bearing Capacity, Cohesionless soil, Inclined Loads, Lateral loads, Model tests, Pile foundation***

I. INTRODUCTION

Pile foundations are generally adopted, when the soil conditions are poor. The purpose of a pile foundation is to transmit the loads of the superstructure to the deep underlying firm soil while preventing excessive structural deformations. Pile foundations of offshore structures, transmission towers, wind energy converters, are often subjected to inclined loads and moment from usual structural dead load and horizontal loads generated by wind, waves, earth pressure etc. For proper functioning of such structures, two criteria must be satisfied: (1) A pile should be safe against ultimate failure, (2) Normal deflection at working loads should be within the permissible limit. For design of such piles, a quantitative estimate of allowable inclined compressive load is needed. If a vertical pile is subjected to an inclined and eccentric load, the ultimate bearing capacity in the direction of the applied load is intermediate between that of ultimate lateral load and ultimate vertical load. When load acts vertical, it is resisted by pile through skin friction and base resistance but when load acts with inclination, the deficiency in the base resistance and to some extent in the shaft friction leads to decrease in carrying capacity of single pile. Analysis of piles subjected to inclined loading action is complicated due to large number of variables involved. Further, experimental studies on behavior of single pile subjected to inclined compressive loads are limited. The effect of angle of inclination of compressive load on horizontal deflection and vertical displacement of vertical piles of different length to diameter ratio are also rarely tested. A number of model tests have been conducted by Sharma and Pise (1994) and some other methods of analysis have been proposed by Meyerhof and Adams (1968), Chattopadhyay and Pise (1986), Rao and Kumar (1994), for the piles or anchors separately and that too in homogeneous media. The comparative study by Lianyang Zang et al. (2005) has shown that these studies produced significantly different ultimate resistance values of single as well as pile group. Behavior of vertical and batter piles subjected to inclined oblique loads have been reported by researchers like Madhusudan Reddy. K et al. (2011), Muthukkumaran et al. (2015) etc. Salini U. and Girish M. S (2009), Alice Johny and C. Prabha (2014), Jerin Wiba, V. Jeyanthi Vineetha (2014) studied the lateral load analysis results of single piles in cohesionless soils for range of soils. Their studies captured both the short pile and long pile behaviour observed for loose sands from dry state to submerged condition.

The present work involves separate analysis of axial and lateral pile capacities. An attempt is made here to study the behavior of single model steel and concrete piles in cohesionless soil, subjected to varying inclined load until failure with the angle of applied load varying from 0º to 90º from the vertical axis of the pile, through an experimental model study.

II. EXPERIMENTAL INVESTIGATION

A. Foundation medium

The foundation medium used for the study is dry sand obtained from the river Bharathapuzha in Palakkad district, Kerala, India. The physical properties of sand were determined using various laboratory experiments such as specific gravity test, density test, sieve analysis and direct shear test. The results obtained are shown in Table 1.

TABLE 1: PROPERTIES OF SAND

PROPERTY	VALUE
Specific Gravity (G)	2.66
Maximum Dry Density (γ_{max})	1.457 g/cc
Minimum Dry Density (γ_{min})	1.341 g/cc
Particle size at 10% finer, D_{10}	0.450 mm
Coefficient of curvature (Cc)	1.08
Uniformity coefficient (Cu)	2.55
Cohesion (C)	0
Angle of internal friction (φ)	31°

B. Model Piles

A steel pile and a concrete pile are used as the model piles. The range of prototype dimensions represented by the model piles for different scale factors is calculated using the following formula (Wood et al. 2002; Wood 2004)

$$(EI)_P / (EI)_m = n^{4.5}$$

Where, n = scale factor, $(EI)_P$ = Flexural rigidity of prototype pile and $(EI)_m$= Flexural rigidity of model pile. L/D ratios of 10, 15, and 20 are used in the present investigation for simulating piles in the model experiments. Rigid rough Mild Steel (MS) solid tubes and precast concrete tubes having diameter 20 mm with lengths of 200mm, 300mm and 400mm to achieve desired slenderness ratios of 10, 15 and 20 respectively were used as model piles. The Mild steel piles were slightly roughed to ensure better interaction with the sand particles. The concrete piles were casted in a PVC pipe, using cement and sand in the ratio of 1:1.5 and 0.5 water-cement ratio, providing a reinforcement of 6 mm diameter steel bar at the center. The casted piles were cured for 28 days and were taken out of the casing for testing.

C. Experimental setup

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/ inclined 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). In the present study, the model pile diameter is 20 mm and hence the size of the tank in the plan should be larger than 200 mm for a single pile. Accordingly, the dimensions of the model steel tank are fixed as 1.0 × 1.0 × 0.75 m (depth) to avoid the boundary effects while testing the model pile under axial, lateral and inclined loads.

Model tests were carried out using model Mild Steel solid piles and model concrete piles, embedded in sand medium. The test tank of size 100 cm x 100 cm x 75 cm was fabricated as water tight using mild steel materials. The tank is provided with a detachable frame with the provision of applying loads at various inclinations of 0°, 15°, 30°, 45°, 60° and 90°. The vertical and horizontal settlement measuring dial gauges were also dully attached to the loading frame. The tests were conducted in dry soil conditions. A schematic view of the experimental assembly is shown in *Fig.1*. Placement density of the sand during testing was 1.4 g/cc. Sand was poured in the tank evenly keeping the height of fall constant throughout the time of fall. Further sand pouring was continued to top level surface and then compacted to achieve the placement density. Pile was then fully embedded in sand in vertical position in model tank was subjected to inclined.

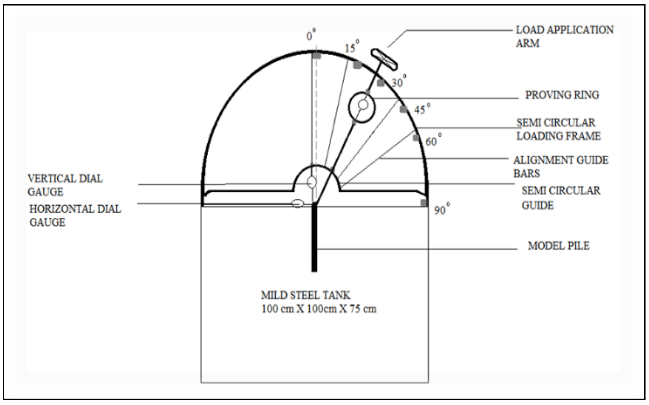

Fig.1. Schematic view of the experimental assembly

The *Fig.2* shows the pictorial representation of this test setup. Loading was applied at the pile head by wheel axle arrangement for load inclination angle ranging from 0° to an angle of 60° with the vertical axis of the pile. Vertical and the horizontal displacements of the pile top were measured with dial gauges of sensitivity 0.001 mm. Loads were applied in small increments till the ultimate capacity of the pile was reached with little subsequent increment of the applied load.

Fig.2. Pictorial view of the experimental assembly

III. RESULTS AND DISCUSSIONS

Due to application of oblique load P_θ on pile head, it is subjected to a vertical component, P_v and a horizontal component, P_h. From geometry, these components can be expressed as:

$$P_v = P_\theta \cos\theta$$
$$P_h = P_\theta \sin\theta$$

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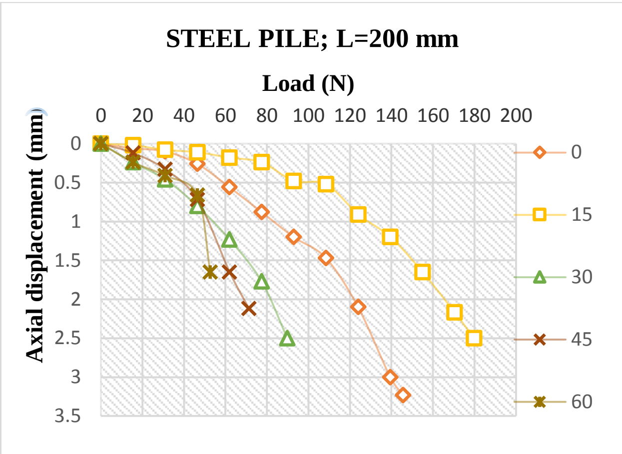
It can be seen that, as θ increases, P_v decreases and P_h increases. Thus, with the increase of tilt of load with the vertical direction the horizontal component dominates the vertical load component. Depending on the relative magnitudes of the ultimate axial capacity and lateral ultimate resistance of a vertical pile, the axial component may attain critical value equal to ultimate load carrying capacity of pile axially. In this case, the horizontal component remains smaller than the ultimate horizontal load carrying capacity causing axial failure of the pile. Results of load versus axial and lateral movement of the pile head were plotted. The failure load was taken to be that load at which the load vs. pile head displacement curve passes in to steep and fairly straight tangent.

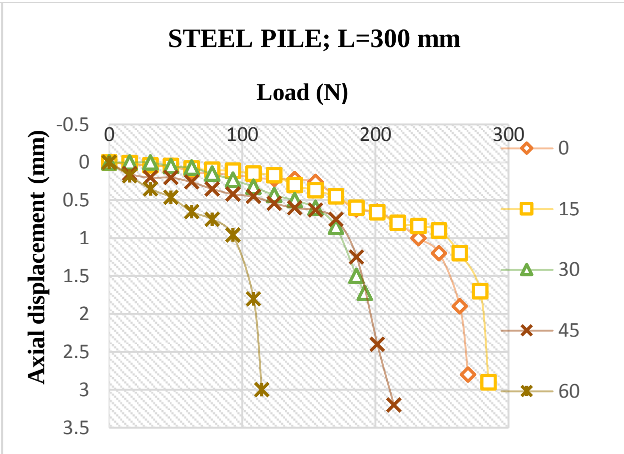
A. Ultimate Axial Capacity of the Piles

In order to obtain the axial load bearing capacity of the Steel Piles and Concrete Piles subjected to various load inclinations, plots of vertical component of the loads versus the vertical settlement of the pile head are drawn for all pile slenderness ratio at load inclinations of 15°, 30°, 45° and 60°.

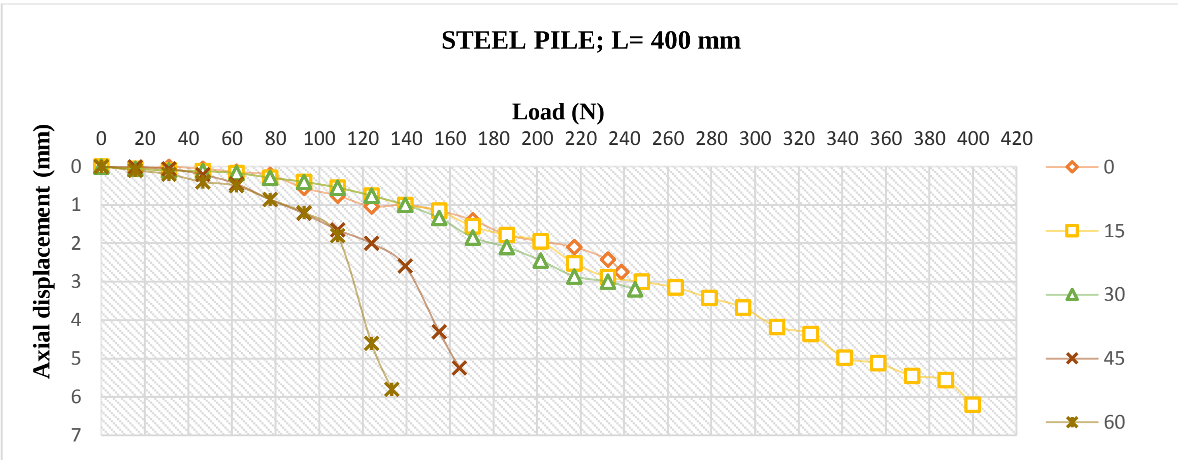
All loads applied at inclinations have vertical components, P_v, whose values are different from that under purely axial conditions. The values of the vertical component of the inclined load and their corresponding axial displacements for varying load inclinations for piles of lengths 200mm, 300mm and 400mm are plotted in graphs. The curves of vertical component of the load versus vertical settlement of the steel piles and concrete at 15°, 30°, 45° and 60° as shown in *Fig.3 (a), (b) and (c)* and *Fig.4 (a), (b) and (c)* are different from pile's vertical settlement under axial loading condition (at θ = 0°) i.e. when no horizontal components are present. This indicates that presence of lateral component of the applied load modifies the vertical load displacement response. It is observed that the presence of horizontal component of the applied load, when the inclination of loading with the vertical axis of pile approaches an angle around 15° caused an increase in vertical load carrying capacity of the pile and at 60° a decrease in the vertical load carrying capacity.



(a) L = 200 mm

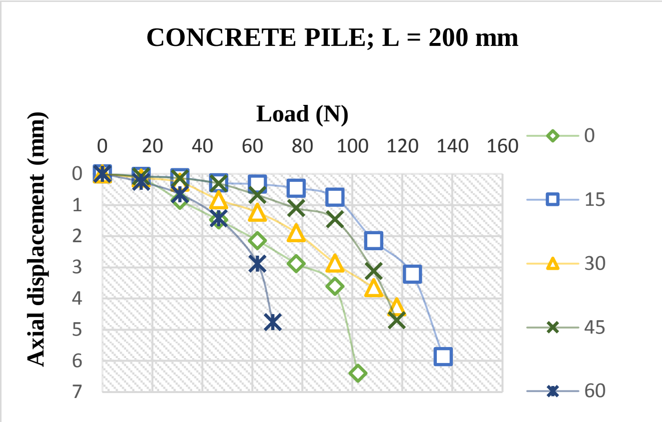


(b) L = 300 mm

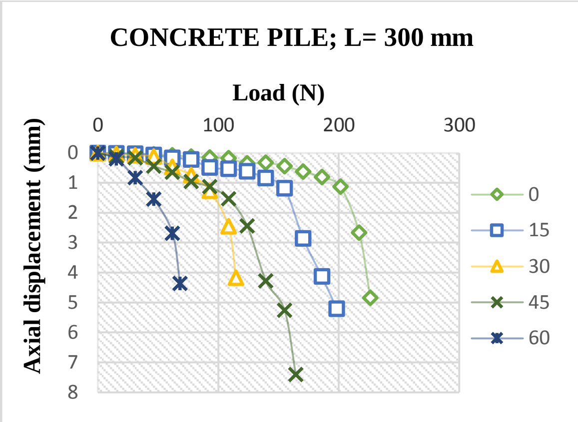


(c) L = 400 mm

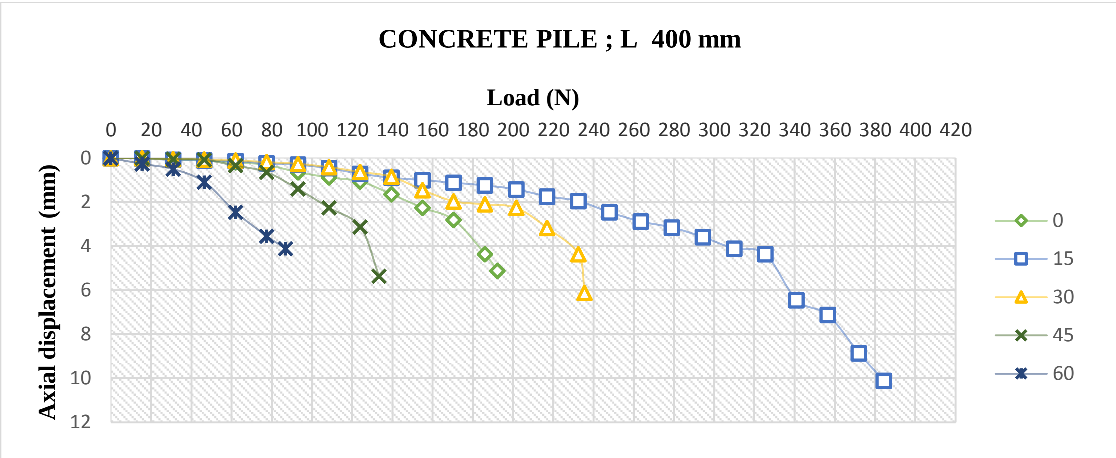
Fig.3: Vertical component of the load vs Axial displacement of steel piles



(a) L = 200 mm



(b) L = 300 mm



(c) L = 400 mm

Fig.4: Vertical component of the load vs Axial displacement of concrete pile

TABLE 2: COMPARISON OF AXIAL CAPACITIES OF PILES (N)

LENGTH OF PILE (mm)	STEEL PILES (N)	CONCRETE PILES (N)
200	108	120
300	165	180
400	295	310

From Table 2, it is observed that the axial load capacity of concrete pile is more than steel pile. The increase in the axial load capacity in case of Concrete pile is due to increase in frictional resistance compared to the steel piles. Concrete piles are capable of resisting the applied axial load through skin friction, initially to a great extent, due to adhesion between the pile surfaces and surrounding sand medium. Also, the load carrying capacity of the piles are found to be increasing with its slenderness ratio. This is because the passive resistance has been mobilized with increase in pile length.

B. *Ultimate Lateral Capacity of the Piles*

In order to obtain the lateral load bearing capacity of the Steel Piles and Concrete Piles subjected to various load inclinations, plots of horizontal component of the loads versus the lateral settlement of the pile head are drawn for all pile slenderness ratio at load inclinations of 15°, 30°, 45° and 60° as shown in *Fig.5 (a), (b)* and *(c)* and *Fig.6 (a), (b)* and *(c)* are different from pile's lateral settlement under lateral loading condition (at θ= 90°) i.e. when no vertical components are present. Further it is observed that the presence of axial component of the applied load, when the inclination of loading with the vertical axis of pile approaches an angle around 60° to 90° caused an increase in lateral load carrying capacity of the pile and at 15° a decrease in the lateral load carrying capacity.

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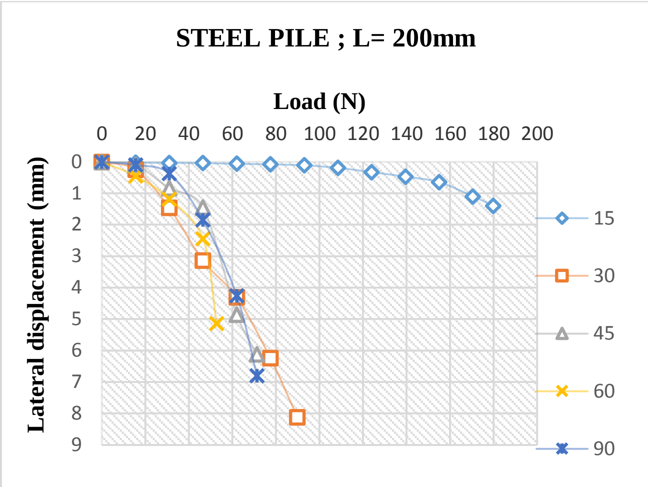
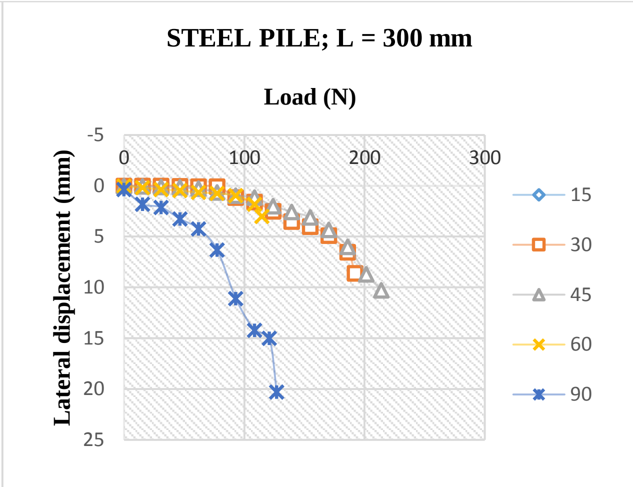
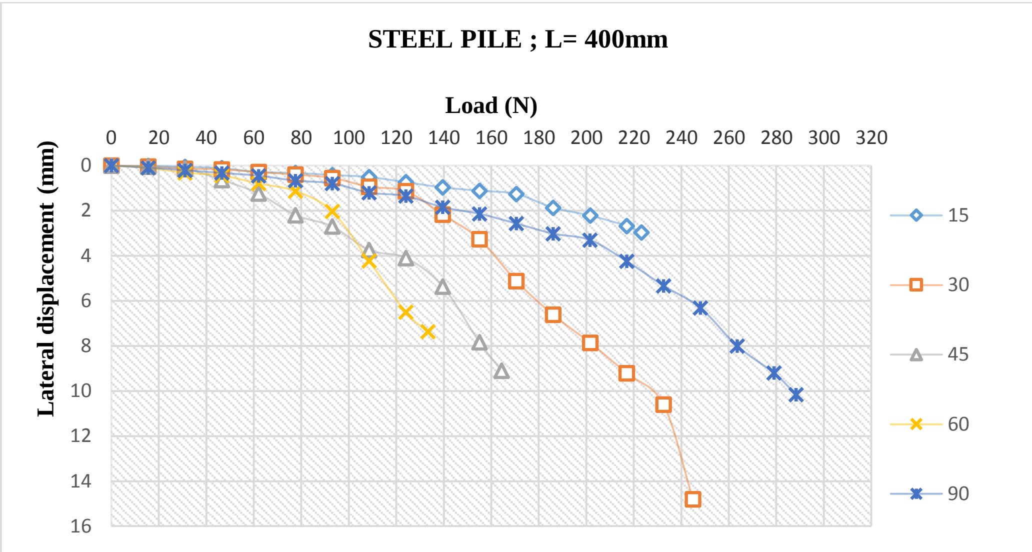


(a) L = 200 mm

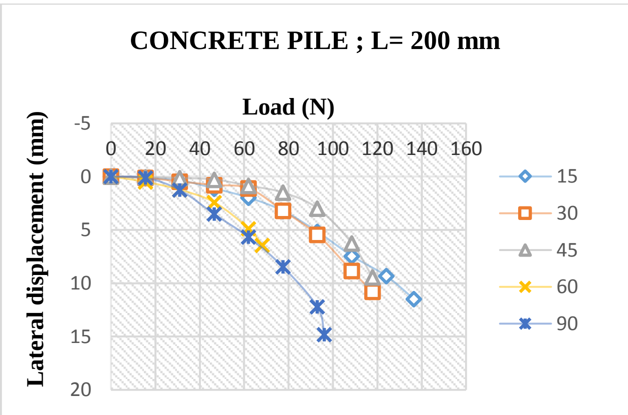


(b) L = 300 mm

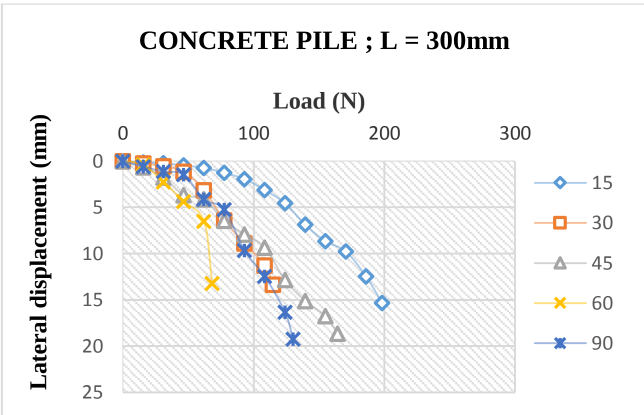


(c) L = 400 mm

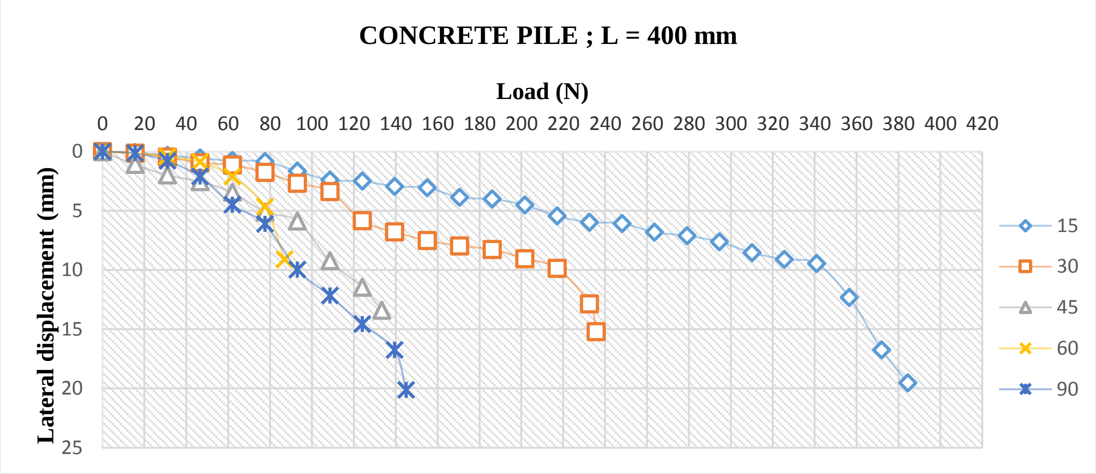
Fig.5: Horizontal component of the load vs Lateral displacement of steel pile



(a) L = 200 mm



(b) L = 300 mm



(c) L = 400 mm

Fig.6: Horizontal component of the load vs Lateral displacement of concrete pile

TABLE 3: COMPARISON OF LATERAL CAPACITIES OF PILES (N)

LENGTH OF PILE (mm)	STEEL PILES (N)	CONCRETE PILES (N)
200	72	62
300	120	110
400	200	140

From the above table, it is observed that the lateral load capacity of mild steel pile is more than that of concrete pile. Therefore, it is evident that with increase in the slenderness ratio, the lateral load capacity in case of Steel pile is found to increase more than that in concrete due to the increase in the weight and stiffness (EI) of the pile.

IV. CONCLUSION

The behavior of single model steel and concrete piles in cohesionless soil, subjected to varying inclined loads until failure was studied. Experimental values of the ultimate vertical load carrying capacity and lateral load carrying capacity of pile embedded in sand are observed under varying inclined loads were plotted. The vertical settlement and the lateral deflection of pile under inclined compressive load depend on both axial and normal components of the applied load. The load-vertical displacement and the load-lateral movement of pile head (in direction of load) curve revealed that they are unequal with the curves obtained for the case of applied purely vertical load (θ=0°) and purely lateral load (θ=90°).

The ultimate axial and ultimate lateral capacities may be considered corresponding to the load at failure of the pile. From the graphs plotted, it can be seen that the axial and lateral capacities of the pile increases with increase in the L/d ratio. This could be due to increase of the passive resistance with the increase in pile length. Also, on applying loads in various inclinations, increase in the inclined load carrying capacity of the vertical pile was found at lesser values of θ, mainly at 15°. The axial load capacities of concrete piles are found to be more than that of steel piles, whereas, lateral load capacities of steel piles were found to be more than that of concrete piles.

REFERENCES

[1] Alice Johny and C. Prabha (2014), "Laterally Loaded Pile in Cohesionless Soil", International Journal of Engineering Research & Technology (IJERT), Vol. 3 Issue 9, September- 2014, Pp. 931-934.

[2] Chattopadhyay, B.C. & Pise, P.J., (1986) "Ultimate Resistance of Vertical Piles to Oblique Pulling Loads", Proc. 1st East Asian Conference on Structural Engineering and Construction, Bangkok, Pp. 1632-1641.

[3] Jerin Wiba, V. Jeyanthi Vineetha (2014), "Behaviour of Laterally Loaded Piles in Cohesionless Soils", International Journal of Research in Engineering and Technology, Vol. 3 Issue 11, Pp. 179 - 181.

[4] Lianyang, Zhang, Francisco Silva, and Ralph Grismala, (2005) "Ultimate Lateral Resistance to Piles in Cohesionless Soils", Journal of Geotechnical and Geo-Environmental Engineering, Vol. 131, No. 1, January 1, Pp 78-83.

[5] Ling Zhang, Minghua Zhao and Xinjun Zou (2015), "Behaviour of Laterally loaded Piles in Multilayered Soils", ASCE journal.

[6] Madhusudan Reddy. K and R. Ayothiraman, (2011), "Experimental Studies on Behavior of Single Pile under Combined Uplift and Lateral Loading", Journal of Soil Mechanics and Foundation Division, ASCE, Vol.20.

[7] Matlock, H. and Reese, L. C., (1970), "Generalized solutions for laterally loaded piles", *Journal of Soil Mech. & Foundation Division, ASCE*, Vol. 86, Pp. 63-91.

[8] Meyerhof, G. G. and Adams (1968) "The Bearing Capacity of Rigid Piles under Inclined Loads in Sand: Vertical Piles", *Canadian Geotechnical Journal*, Vol. 9, Pp. 430-446.

[9] Muthukkumaran and N. Almas Begum (2015), "Experimental Investigation of Single Model Pile Subjected to Lateral Load in Sloping Ground", Springer- Geotechnical and Geological Engineering.

[10] Ranjan, N. P., and Jagannath, P. P. (2001), "Ultimate Lateral Resistance of Pile Groups in Sand", *Journal of Geotechnical and Geoenvironmental Engineering*, Vol.127, No.6, Pp. 481 – 486.
[11] Rao, S. N., Ramakrishna, V. V. G. S. T., and Balarama Raju, G. (1996), "Behaviour of pile supported dolphins in marine clay under lateral loading", *Journal on Geotechnical Engineering*, Pp.607–612.
[12] Salini U. and Girish M. S (2009), "Lateral Load Capacity of Model Piles on Cohesionless Soil", EJGE, Vol. 14, Pp. 1- 11.
[13] Sharma, B. (2011), "A model study of micropiles subjected to lateral loading and oblique pull", Indian Geotechnical Journal, Vol. 41(4), Pp. 196 -205.
[14] Wood, D. M. (2004), "*Geotechnical modelling*", Spon Press, Taylor and Francis Group, New York.
[15] Wood, D. M., Crewe, A., and Taylor, C. (2002), "Shake table testing of geotechnical models", *International Journal on Physical Modelling in Geotechnical Engineering*, Vol 2(1), Pp. 1–13.