Indian Geotechnical Journal, 38(3), 2008, 278-294

Lateral Load Capacity of Single Pile Located at Slope Crest

N. Almas Begum*, P. Seethalakshmi and K. Muthukkumaran*****

Introduction

Pile foundations are subjected to lateral loads and moments, which come up due to wind loads and seismic forces in buildings, earth pressure in retaining walls and abutments and water pressure (wave forces, current forces) in water front structure. Many transmission towers, high rise buildings, bridges, coastal and offshore structures constructed on slope are supported by pile foundation. These structures may be subjected to large lateral loads such as heavy wind and earthquake forces. When piles are constructed in sloping ground, the behaviour of piles under lateral load differs from piles in horizontal ground. The lateral resistance of pile on sloping ground is lower due to the reduction of passive resistance mobilized in front of pile when compared with pile located on horizontal ground. And also the initial horizontal confining pressure acting on the piles on the slope is smaller than in horizontal ground.

A number of different approaches are available to determine the behaviour of laterally loaded piles on horizontal ground. However, for the piles on sloping ground, very limited research has been carried out. The governing criterion in designing pile foundation to resist lateral loads in most of the cases is the maximum deflection of the foundation rather than its ultimate capacity. The maximum deflection at the pile head and the distribution of bending moment along the pile are important criteria for the successful design of piles that support lateral loads. Knowing the maximum deflection at the pile head is important to satisfy the serviceability requirements of the super structure while the bending moment is required to obtain the structural details of pile.

Literature Survey

Matlock and Reese (1960) gave a generalized solution for the laterally loaded pile. Basic equations and method of computations were given for both elastic and rigid behaviour. Soil modulus variation with depth in different forms was considered. Broms (1964a, 1964b) developed solutions for the ultimate lateral resistance of a pile assuming the distribution of lateral soil pressure and

---

* Ph. D scholar, Department of Civil Engineering, National Institute of Technology, Tiruchirapalli. Email: n_almas@rediffmail.com

** Ex Post Graduate Student, Department of Civil Engineering, National Institute of Technology, Tiruchirapalli.

*** Lecturer, Department of Civil Engineering, National Institute of Technology, Tiruchirapalli. Email: kmk@nitt.edu

considering statics of the problem. Also two modes of failure and yielding of the soil along the length of the pile were considered.

Many analytical approaches have been developed in recent years for the response analysis of laterally loaded piles. Poulos and Davis (1980) modified the elastic solution to account for nonlinearity using yield factors. The modulus of subgrade reaction approach was extended to account for the soil nonlinearity. This was done by introducing p-y curves (Matlock 1970, Reese et al. 1974). Chae, et al. (2004) described the results of several numerical studies performed with a three – dimensional finite element method (FEM) of model tests and a prototype test of a laterally loaded short rigid piles and pier foundation located near slopes. Measurements on model tests and field tests were compared.

Experimental studies were performed to examine the performance of piles under lateral loads. Based on the results of fourteen full scale lateral pile load tests, Prakash and Kumar (1996) developed a method to predict the load – deflection relationship for single piles embedded in sand by considering the nonlinearity of the soil. Gandhi and Selvam (1977) conducted experiments on group of aluminium pipe piles, driven in sand with 60% relative density in different configurations under fixed head conditions. They have studied the effect of spacing on efficiency of group piles. Kim et al. (2004) described the results of a model testing of single pile embedded in Nak – Dong River sand located in South Korea, under monotonic lateral loadings. p – y curves for laterally loaded piles in Nak-Dong river sand were developed and p – y curves were also evaluated on the effects of relative density, pile head restraint conditions and pile installation method.

However, all these studies with the exception of Chae, et. al. (2004), have been directed towards the response of single pile or group of piles subjected to lateral load in horizontal ground with little attention being paid to pile subjected to lateral load in sloping ground.

Experimental Program

The model pile load tests were conducted in a test tank of dimension 2m x 1m x 1m filled with dry river sand shown in Figure 1.

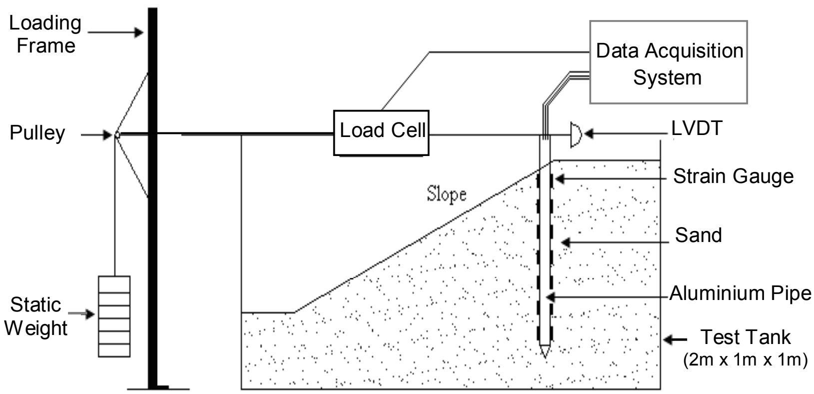

Fig. 1 Experimental Setup

The size of the tank was designed such that to avoid the influence of boundaries in the result. Calculations for fixing the dimensions of the tank were based on the Rankine's theory and zone of influence of the pile by knowing the depth of fixity z_f as suggested by Davisson and Robinson (1965) using the Eqn. 1.

Depth of point of fixity 'z_f' = 1.8T (1)

where, $T = (EI/\eta_h)^{(1/5)}$ (2)

T is the stiffness factor and EI is the flexural rigidity of the pile.

The values of coefficient of horizontal modulus variation 'η_h' for sand (Terzaghi 1955) is 2.5MN/m^3, 7.5MN/m^3 and 20MN/m^3 for loose, medium and dense sand respectively. The failure mechanism and zone of influence for the present model study is shown in Figure 2. The minimum length of the test tank was estimated for different relative densities which are presented in Table 1. Therefore length of the test tank should be greater than minimum length specified in the Table 1. Accordingly the test tank size of 2mx1mx1m was chosen. The pile is modeled as the preinstalled model pile. The model pile tip was placed with a minimum clearance of at least 4 times the pile diameter from the bottom of the tank. Lateral loads were applied to the pile by using mechanical dead weights at an eccentricity of 75mm above the ground surface and was measured by load cell. The horizontal displacement of the pile head was measured using LVDT and the bending strain along the length of the pile was measured by strain gauges.

Table 1 Minimum Length of Test Tank Required

Denseness of Sand	*Minimum Length of Test Tank (mm)*
Loose Sand	830
Medium Dense Sand	666
Dense Sand	548

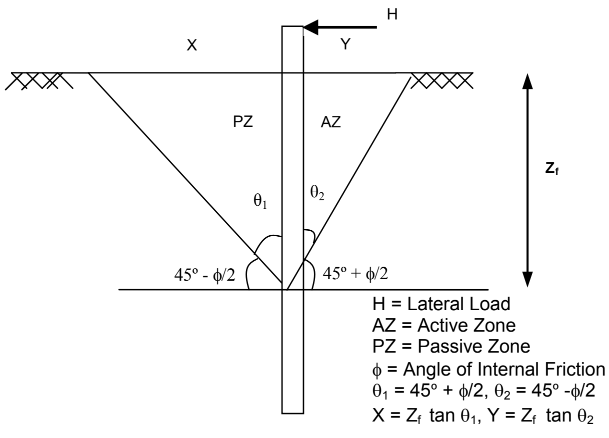

Fig. 2 Zone of Influence

Model Study

The dimensions of the model pile were determined by a dimensionless analysis (Buckingham π theorem). This gives the relation between the number of basic dimensions in a phenomenon, number of dimensionless parameters defining the phenomenon and the number of variables.

For a pile subjected to lateral load, the solution of lateral deflection (y) expressed as a function of quantities like pile diameter (D), pile length (L), load (W), young's modulus of elasticity (E) and moment of inertia (I). This means that the pile bending phenomenon is expressible in terms of the above six variables. According to π theorem two of the variables 'W' and 'L' may be common to all the π terms. Since the number of variables (n) is six and among these the number of common variables is two (m), the number of π terms (n-m) is four. For complete similitude the four π terms obtained must be equal for the model and prototype structure.

$$D_s = k\ D_m \tag{3}$$

$$W_s = k^2 * (E_s/E_m) * W_m \tag{4}$$

$$I_s = k^4 * I_m \tag{5}$$

$$y_s = k * y_m \tag{6}$$

where,

k – scale factor = L_s / L_m

W – load applied on the pile (N)

E – Modulus of elasticity of the pile (N/mm^2)

y – lateral deflection of the pile (mm)

I – moment of inertia of the pile material (mm^4)

L – embedment length of pile

Suffixes, 's' represent the prototype pile and 'm' represent the model pile.

For any applied lateral load on the model pile (W_m) is the function of scale factor (k) and ratio of modulus of elasticity (E_s/E_m) in the prototype. For instance, in the present study the model aluminium pile ($E_m = 0.5x10^5 N/mm^2$) is subjected to a lateral load of 10N, the corresponding lateral load (Eqn. 5) on a M_{20} concrete prototype pile of 40 scale factor is 7155.4N. However, the corresponding lateral deflection in prototype is only the function of scale factor, which is 40 times the lateral deflection of the model pile.

Therefore, the present model pile results can be used for any prototype piles with a suitable scale factor and Young's modulus of the prototype pile.

Pile Instrumentation

An aluminium pipe having an outer diameter (D) of 25.4mm with 1mm wall thickness was used as the model pile. Pile was instrumented for measuring bending stress by pasting electrical resistance type strain gauges having gauge length of 3 mm, gauge factor (K) equal to 2 and the resistance (R) equal to 120 ohms. The strain gauges were pasted with its axis parallel to the pile axis. They formed quarter bridges with the dummy gauges placed in a separate strain gauge box. The strain gauges were placed at a minimum spacing of 50mm apart with top gauge 25mm below the pile cap. Small holes were made on the side of the pile slightly above each gauge location to pass the wires inside the pile. Strain gauges were coated with silicone gel for protection. The bottom of the pile was closed by a 60° conical shoe. The model pile is modeled as an equivalent prototype pile (1:40) scale with an outer diameter of 1018mm.

Strain gauges were calibrated for bending moment along the pile length by conducting a simple bending test of considering simply supported ends and it is given in Eqn .7.

$$M = C * \varepsilon \qquad (7)$$

where,

M – bending moment at various depths (N-mm)

C - bending constant (1 micro strain = 30.67 N-mm per micro strain)

ε – strain (micro strain)

The strain response was found to be linear with the bending moment for the applied load for all the strain gauges pasted in the pile. The calibration constant was obtained from the slope of the straight line. An average value of linear response of all the strain gauges has been taken as bending constant and found to be 30.67 N-mm per micro strain (1 x 10^{-6} mm/mm). A typical response of a strain gauge is shown in Figure 3.

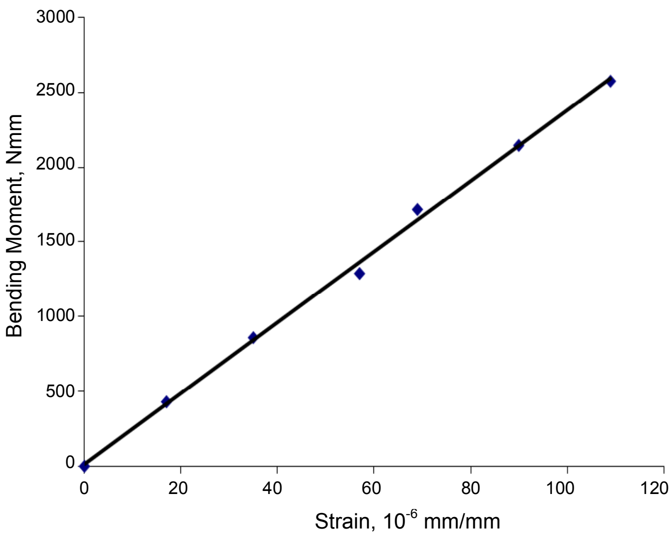

Fig. 3 Calibration of Strain Measuring Device for a Single Strain Gauge

Soil Description and Sample Preparation

The dry river sand was used for testing. It is classified as poorly graded sand (SP) of which the uniformity coefficient obtained as 2.7 and the co-efficient of curvature was 1.2. The other typical properties of the sand were effective size (D_{10}) = 0.23mm, average size (D_{50}) = 0.50mm, specific gravity of sand (G_s) = 2.68, maximum unit weight (γ_{max}) = 18.74 kN/m^3, minimum unit weight (γ_{min}) = 14.72 kN/m^3. A model soil bed with three kinds of relative density 30%, 45%, 70% and three types of slope of zero slope (horizontal ground), 1V:1.5H, 1V:2H slope were used. Sand raining device was used to achieve the uniform density. This arrangement contains a hopper connected to a 750 mm long pipe and an inverted cone at the bottom, with a holding capacity of about 78N of sand. The sand poured through a 31mm internal diameter pipe and was dispersed by 60^o due to the inverted cone placed at the bottom. By varying the height of free fall of dispersed sand particles, the density of the sand was varied. The height of free fall from the bottom of the pipe was maintained constant using an adjustable length pointer fixed at bottom. This arrangement was calibrated by number of trials to get height of fall required for relative density corresponding to 30%, 45%, and 70%. The relationship between the height of freefall and relative density is obtained as shown in Figure 4. From the graph, the height of fall corresponding to relative densities of 30%, 45%, 70% were found to be 5cm, 20.5cm, and 71cm respectively.

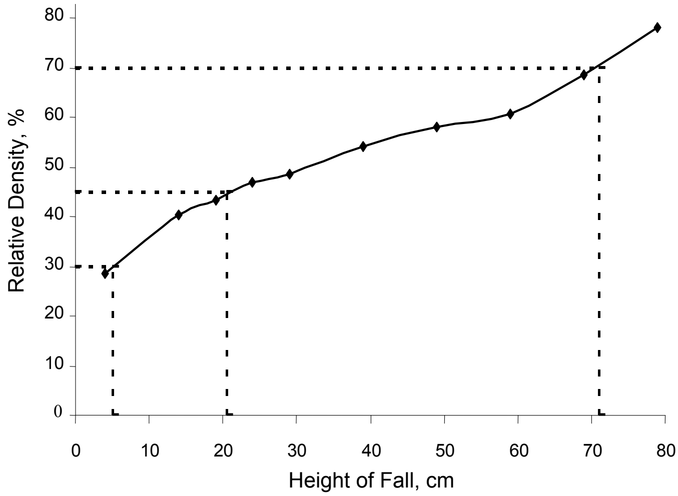

Fig. 4 Density Calibration

Measurements

The horizontal displacement of the pile head and the strain at various levels in the piles were measured for each tests. Vertical settlement was also measured for one test and it was negligible. LVDT was used to measure the horizontal displacement. A manual compensating strain meter with quarter bridge circuit was used to measure bending strain along pile length at various elevations. Lateral deflection and strain readings were recorded for each increment of load.

Pile was loaded up to allowable limit. It was observed that there was no increase in lateral movement of pile head for sustained load in sand. The lateral load was applied till the lateral deflection reaches 20% of pile diameter (5mm) the corresponding load was taken as lateral load capacity of the pile.

Tests Carried out

A series of experimental tests were carried out by varying the parameters such as slope, L/D ratio and relative density of the soil as shown in the Table 2.

Table 2 List of Experiments

Soil Surface	*L/D Ratio*	*D_r (%)*
HORIZONTAL	25	30,45,70
	30	30,45,70
	35	30,45,70
1V:1.5H	25	30,45,70
	30	30,45,70
	35	30,45,70
1V:2H	25	30,45,70
	30	30,45,70
	35	30,45,70

Results and Discussion

Lateral Load Behaviour

The lateral load behaviour of the pile was studied by using lateral load – deflection curves. The curves were drawn between the lateral load applied and the lateral deflection at the soil surface. Lateral load was applied at the distance of 75mm above the ground surface and lateral deflections were measured at the soil surface. Tests were done on the pile of embedment length (L) to the diameter (D) ratios of 25, 30 and 35 on sandy soil of relative densities of 30%, 45% and 70% on both the horizontal ground and the sloping ground of 1V:1.5H and 1V:2H. In the present study, the lateral load was applied till the lateral deflection reaches 20% of pile diameter (5mm) and the corresponding load taken as allowable lateral load capacity of the pile.

Figure 5 shows the comparison of lateral load capacity of pile with deflection for L/D ratio of 30 and relative density of 45%. When ground surface changed from horizontal to 1V:1.5H slope or 1V:2H, the lateral load capacity was significantly reduced. This reduction was due to the reduction in passive resistance of the soil in front of the pile. The increase in slope from horizontal to 1V:2H reduces the lateral load capacity by 18% for relative density of 45% and for L/D ratio of 30. When the ground surface changes from horizontal to 1V:1.5H, the lateral load capacity reduces by 31% for relative density of 45% and for L/D ratio of 30.

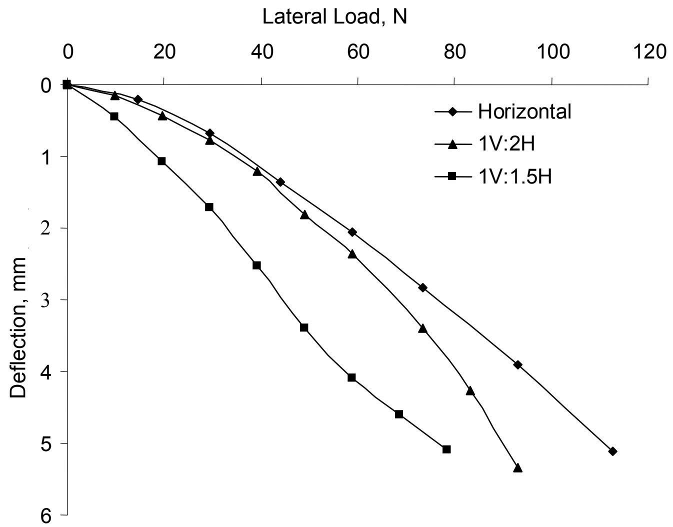

Fig. 5 Load Displacement Curve (L/D = 30, D_r= 45%)

Figure 6 shows the load – deflection curve for 1V: 2H ground with piles of different L/D ratios of 25, 30 and 35 and on relative density of 45%. And Figure 7 shows the load – deflection curve for 1V: 2H ground with sand of different relative densities of 30%, 45%, and 70% and on L/D ratio of 30. The lateral load capacity was found to increase with the increase in relative density of the soil along with the L/D ratio of the pile material. This is due to the increase in the relative stiffness of the pile and the soil.

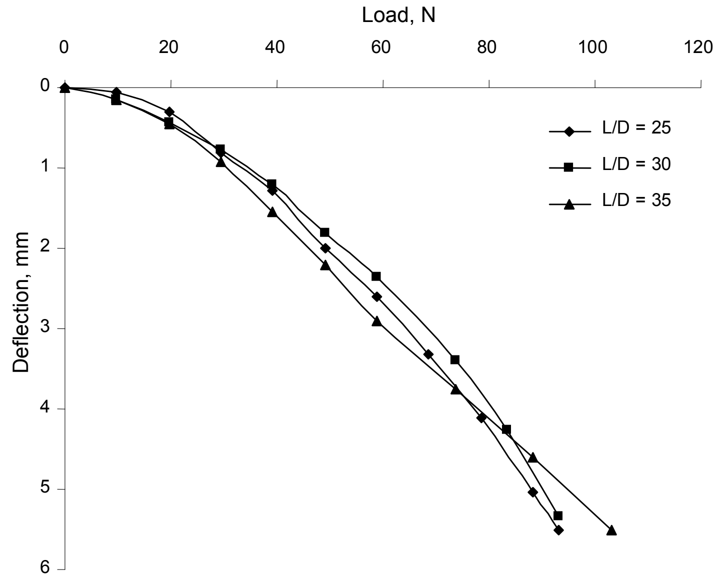

Fig. 6 Load Displacement Curve (1V:2H, D_r= 45%)

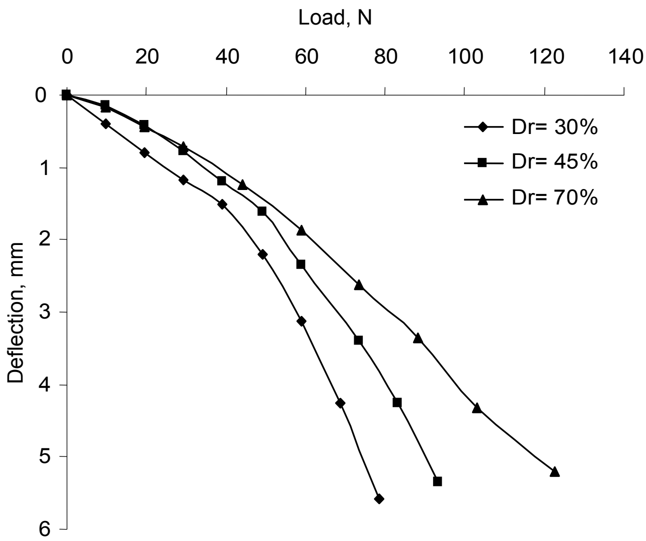

Fig. 7 Load Displacement Curve (1V:2H, L/D = 30)

Effect of Slope

Figure 8 and Figure 9 shows the comparison of lateral load capacity of pile with slope for different L/D ratios and relative densities. When ground surface changed from horizontal to 1V:1.5H slope or 1V:2H, the lateral load capacity was significantly reduced. This reduction was due to the reduction in passive resistance of the soil in front of the pile.

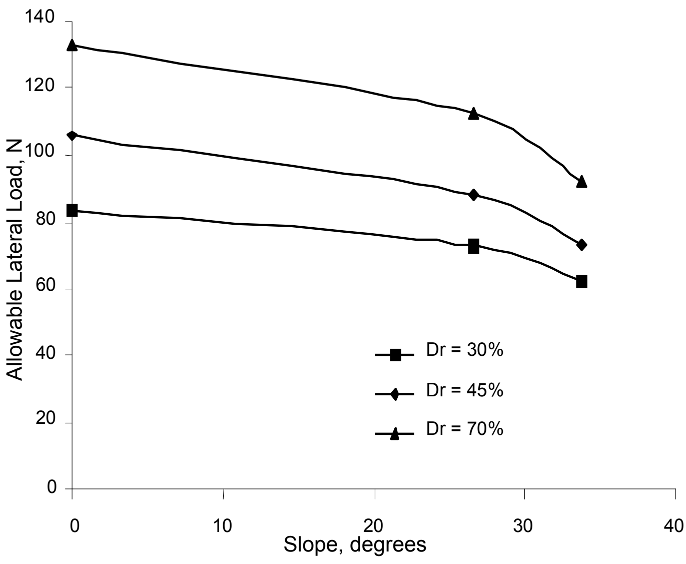

Fig. 8 Effect of Slope on Lateral Load for Relative Density

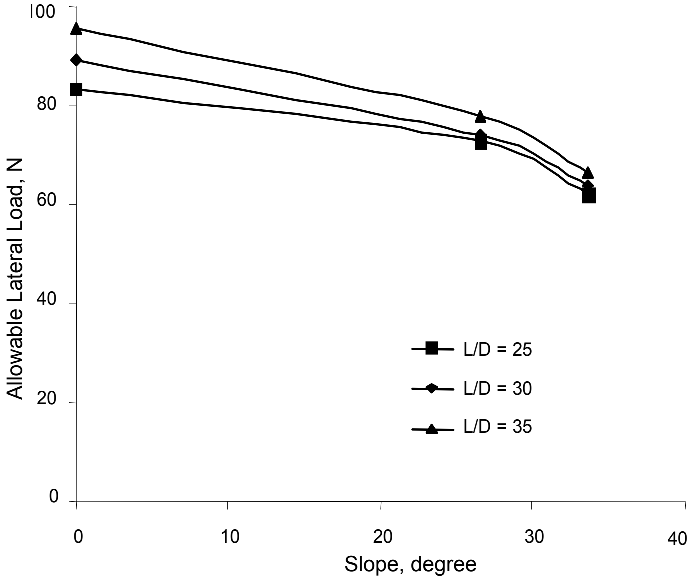

Fig 9 Effect of Slope on Lateral Load for L/D Ratio

Table 3 shows the reduction of lateral load capacity when the soil bed changed from horizontal to 1V:2H slope and from 1V:2H slope to 1V:1.5H slope with different relative densities of 30%, 45% and 70% and L/D ratio of 25, 30, and 35.

Table 3 Percentage Reduction in Lateral Load due to Effect of Slope

Relative Density (%)	*L/D = 25*		*L/D = 30*		*L/D = 35*	
	Horizontal to 1V:2H	*1V:2H to 1V:1.5H*	*Horizontal to 1V:2H*	*1V:2H to 1V:1.5H*	*Horizontal to 1V:2H*	*1V:2H to 1V:1.5H*
30	12%	15%	17%	14%	19%	15%
45	16%	17%	18%	16%	21%	14%
70	15%	18%	12%	19%	11%	14%

Effect of L/D Ratio

Figure 10 shows the comparison of lateral load capacity of pile with L/D ratio in horizontal ground, sloping ground of 1V:1.5H and 1V:2H for the relative density of 45%. It can be seen from the figure, the increase in L/D ratio increases the lateral load capacity. From the results it has been observed that the lateral resistance of the pile in the horizontal ground with L/D ratio of 25 is nearly equal to the lateral load carrying capacity of the pile embedded in the slope of 1V:2H having L/D ratio of 35 with the same relative density of the soil. This was due to increase in the passive resistance of the pile and the soil, due to increase in the embedded length of the pile. Table 4 shows the amount of increase in lateral load capacity for the three soil surface and relative density due to the increase in L/D ratio.

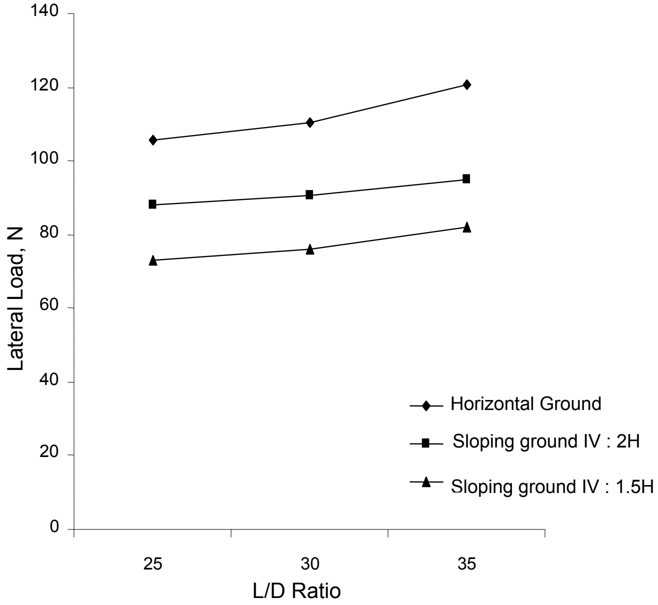

Fig. 10 Effect of L/D on Lateral Load for Relative Density 45%

Table 4 Percentage Increase in Lateral Load due to Embedment Length

Soil Surface	*D_r = 30%*		*D_r = 45%*		*D_r = 70%*	
	L/D Ratio 25-30	*L/D Ratio 30-35*	*L/D Ratio 25-30*	*L/D Ratio 30-35*	*L/D Ratio 25-30*	*L/D Ratio 30-35*
Horizontal	6%	7%	4%	8%	2%	2%
1V:2H	2%	5%	3%	5%	5%	3%
1V:1.5H	3%	4%	4%	8%	4%	9%

Effect of Relative Density

Figure 11 shows the comparison of lateral load capacity of pile with relative densities in horizontal ground, sloping ground of 1V:1.5H and 1V:2H for the L/D ratio of 30. From the analysis of the results, it is observed that the lateral load capacity of pile in the horizontal ground with 30% relative density, 1V:2H slope with 45% relative density and 1V:1.5H slope of 70% relative density are giving almost same capacity irrespective of L/D ratio. There fore the increase in relative density of the soil increases the lateral load capacity due to increase in the relative stiffness of the pile and the soil. Table 5 shows the percentage increase in lateral load capacity for the three soil surface and L/D ratio due to the increase in relative density.

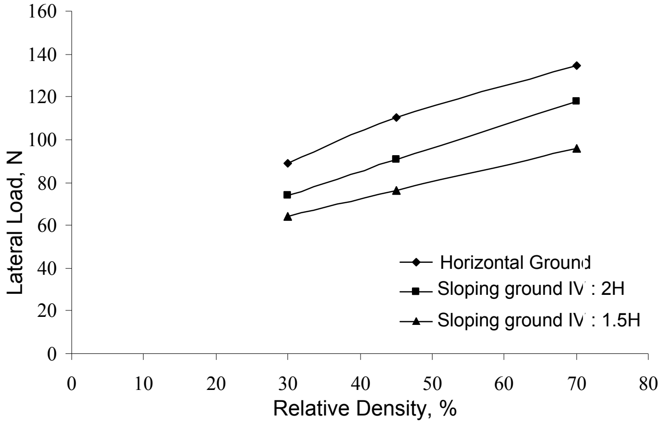

Fig. 11 Effect of Relative Density on Lateral Load for L/D of 30

Table 5 Percentage Increase in Lateral Load due to Relative Density

Soil Surface	*L/D = 25*		*L/D = 30*		*L/D = 35*	
	D_r 30%-45%	*D_r 45%-70%*	*D_r 30%-45%*	*D_r 45%-70%*	*D_r 30%-45%*	*D_r 45%-70%*
Horizontal	21%	20%	19%	18%	20%	12%
1V:2H	17%	21%	18%	23%	18%	22%
1V:1.5H	15%	21%	16%	21%	19%	22%

Correction Factor for the Allowable Lateral Load

The expression for the correction factor for the sloping ground including the effect of relative density and embedment length was given below. Experimentally, the correction factor is the ratio between the allowable load for the sloping ground for particular relative density and L/D ratio to the allowable load for the horizontal ground for maximum relative density and L/D ratio. This expression for the correction factor was obtained by multiple regression analysis by treating experimental reduction factor R_l as dependent quantity and the parameters such as slope, L/D ratio and relative density as independent quantities and is given in the Eqn. 8 and shown in Figure 12.

$$R_l = 0.2765 - 0.3685 * S + 0.0064 * L/D + 0.0072 * D_r \leq 1 \quad (8)$$

where

S = Slope (Radians)

D_r = Relative Density (%)

L = Length of the pile

D = Diameter of the pile

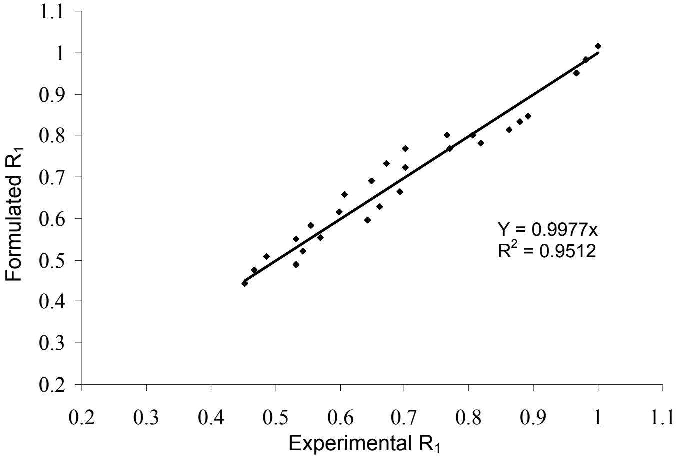

Fig. 12 Correction Factor

The allowable lateral load for the sloping ground was obtained by multiplying the factor 'R_l' with the allowable lateral load for the horizontal ground.

$$P_{a(\text{Sloping Ground})} = R_l * P_{a(\text{Horizontal Ground})} \quad (9)$$

Bending Moment Behaviour

Figure 13 and Figure 14 shows the typical curves for bending moment against depth for sloping ground of 1V:2H and 1V:1.5H for the pile of L/D ratio of 25 and on relative density of 30%. From the results, it was found that maximum bending moment increase with increase in the applied lateral load. The depth, at which maximum bending moment occurs, increases with increase in the slope of the ground surface. This is due to the decrease in the resistance at the top portion of the soil mass as there is reduction in the soil mass in the sloping ground.

Figure 15 and Figure 16 shows the comparison of maximum bending moment corresponding to applied load of 60N to pile with slope for different L/D ratio and relative densities for various ground. When ground surface changes from horizontal to 1V:1.5H slope or 1V:2H, maximum bending moment was significantly increased. The increase in slope from horizontal to 1V:2H increases the maximum bending moment by 15%, 38% and 16% for relative densities of 30%, 45% and 70% respectively for L/D ratio of 25. When the ground surface changes from 1V:2H to 1V:1.5H, the maximum bending moment increases by 10%, 6%, and 11% for relative densities of 30%, 45%, and 70% respectively for L/D ratio of 25.

For relative density of 30%, the maximum bending moment increases by 15%, 17%,13% for L/D ratio of 25,30,35 respectively, when the ground surface changes from horizontal to sloping ground of 1V:2H and increases by 10%,16%,21% for L/D ratio of 25,30,35 respectively for increase in slope from 1V:2H to 1V:1.5H.

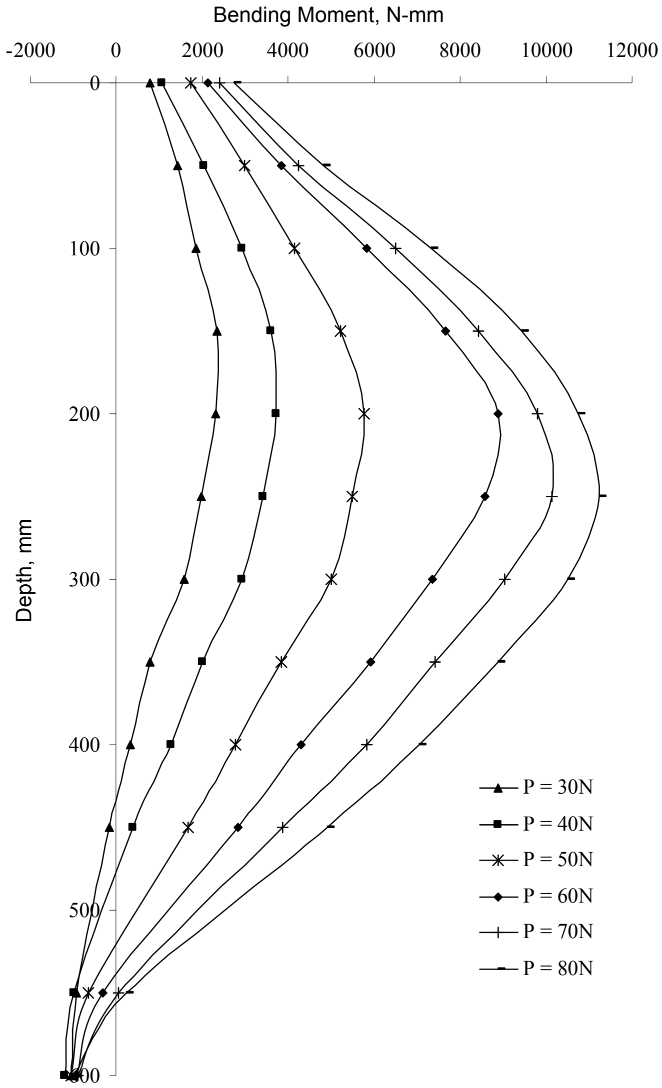

Fig. 13 Bending Moment Variation against Depth for Various Loading Condition (1V:2H, L/D = 25, D_r = 30%)

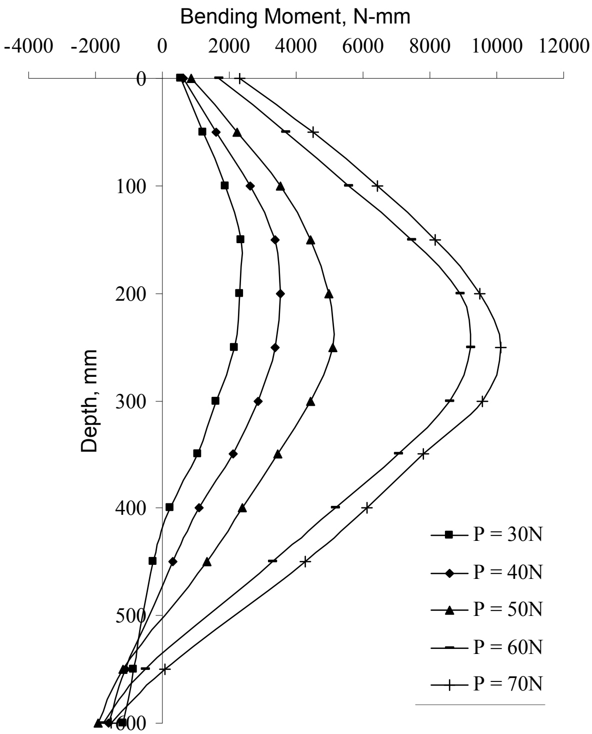

Fig. 14 Bending Moment Variation against Depth for Various Loading Condition (1V:1.5H, L/D= 25, D_r = 30%)

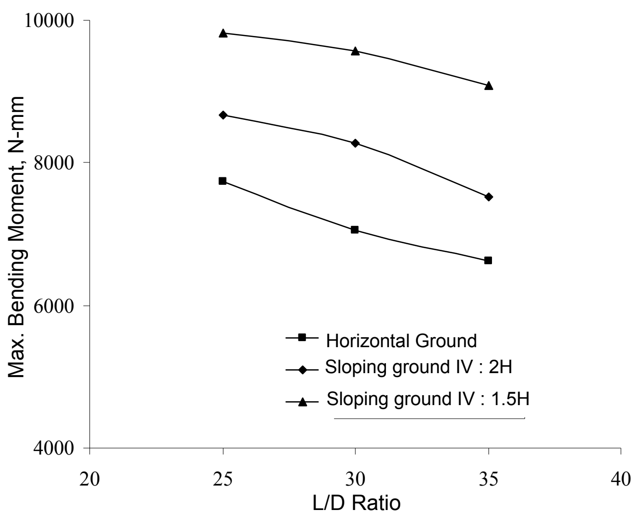

Fig. 15 Effect of L/D Ratio on Maximum Bending Moment for Various Grounds

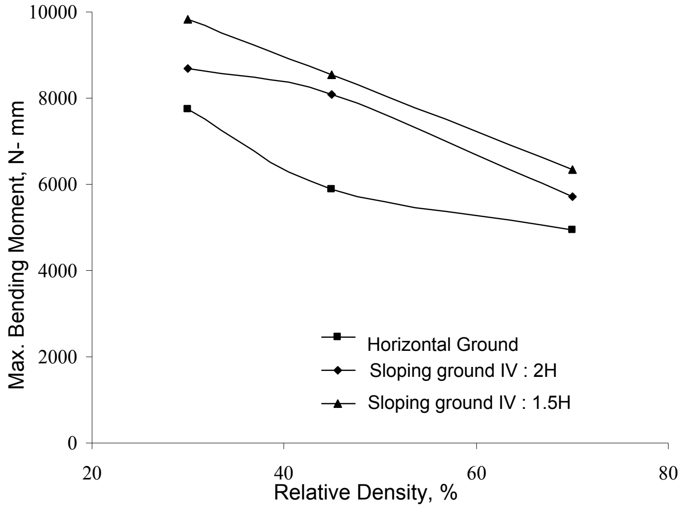

Fig. 16 Effect of Relative Density on Maximum Bending Moment for Various Grounds

Conclusions

Lateral load capacity is significantly reduced, when the ground surface changes from horizontal to 1V:2H slope by 12%, 17% and 15% for relative densities of 30%, 45%, and 70% respectively for L/D ratio of 25. From horizontal to 1V: 1.5H slope, the lateral load capacity is reduces by 15%, 17%, and 18% for relative densities of 30%, 45%, and 70% respectively for L/D ratio of 25.

Increase in relative density of the soil increases the lateral load capacity of the pile.

For increase in relative density of soil from 30% to 45% the lateral load capacity increases by 21% in horizontal ground, 17% in 1V : 2H sloping ground and 15% in 1V : 1.5H sloping ground for the L/D ratio of 25.

For the sloping ground of 1V:1.5H, the lateral load capacity increases by 3%, 4% and 4% for the relative densities of 30%, 45% and 70% when the L/D ratio increases from 25 to 30 and increases by 4%, 8% and 9% for increase in L/D ratio from 30 to 35.

Lateral load capacity of the sloping ground is obtained by applying the correction factor 'R_l' on horizontal ground, including the effects of slope, L/D ratio and relative density of the soil and by considering scale effect.

Maximum bending moment increases by 15%, 17% and 13% for L/D ratio of 25,30 and 35 respectively when the ground surface changes from horizontal to sloping ground of 1V:2H and 10%,16% and 21%, when the ground surface changes from 1V:2H to 1V:1.5H, for relative density of 30%.

Maximum bending moment decreases by 24%, 9% and 13% for horizontal ground, sloping ground of 1V:2H and 1V:1.5H respectively for increase in relative density from 30% to 45% and 16%, 30% and 26%, when the relative density increases from 45% to 70%, for the L/D ratio of 25.

Maximum Bending moment decreases by 2%, 9% and 2%, when the L/D ratio increases from 25 to 30 and 5%, 4% and 17% for increase in L/D ratio from 30 to 35 for the relative densities of 30%, 45% and 70% respectively for the sloping ground of 1V:1.5H.

References

Broms, B.B. (1964a): 'The Lateral Resistance of Piles in Cohesive Soils' *Journal of the Soil Mechanics and Foundation Div*., ASCE, 90(2), pp. 27 - 63

Broms, B.B. (1964b): 'The Lateral Resistance of Piles in Cohesionless Soils', *Journal of the Soil Mechanics and Foundation Div*., ASCE, 90(3), pp.123 – 156

Chae, K.S., Ugai, K. and Wakai, A. (2004): 'Lateral Resistance of Short Single Piles and Pile Groups Located Near slopes', *International Journal of Geomechanics*, 4(1), pp.93-103

Davisson, M.T. and Robinson, K.E. (1965): 'Bending and Buckling of Partially Embedded Piles', *Proc. of 6th Int. Conf. ISSMFE*, Montreal, 2, pp.243 – 246

Gandhi, S.R. and Selvam, S. (1997): 'Group Effect on Driven Piles under Lateral Load', *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 123 (8), pp. 702-709

Kim, B.T., Kyung Kim, N., Lee, W.J. and Kim, Y.S. (2004): 'Experimental Load – Transfer Curves of Laterally Loaded Piles in Nak – Dong River Sand' , *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 130(4), pp.416-425

Matlock, H. and Reese, L.C. (1960): 'Generalized Solution for the Laterally Loaded Piles', *Journal of the Soil Mechanics and Foundation Div*., ASCE, 86(5), pp.63 - 91

Matlock, H. (1970): 'Correlations for Design of Laterally Loaded Piles in Soft Clay'. *Proc. 2nd Annual Offshore Technology Conference*, Houston, Tex., Paper OTC 1204, pp.544-593

Poulos, H.G. and Davis, E.H. (1980): *Pile Foundation and Design*, John Wiley and Sons, New York.

Prakash, S. and Kumar,S. (1996): 'Nonlinear Lateral Pile deflection Prediction in Sands', *Journal of Geotechnical Engineering* 122(2): pp.130 – 138

Reese, L.C., Cox W.R. and Koop, F.D. (1974): 'Analysis of Laterally Loaded Piles in Sand', *Proc. 6th Annual Offshore Technology Conference*. Richardson, Tex., pp.473 – 483

Terzaghi, K. (1955): 'Evaluation of Coefficients of Subgrade Reaction'. *Geotechnique*, 5(4), pp. 297-326