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Three Dimensional Analysis of Piles on Sloping Ground Subjected to Passive Load Induced by Surcharge

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Abstract

Pile foundations are slender structural elements used to transfer loads from structures into deep hard strata below the ground level. It is time consuming and expensive to carry out field test over the piles in larger lengths. Computer simulations of Finite Element/Finite Difference Modelling will allow for in depth studies to analyze the pile – soil interaction of laterally loaded piles on sloping ground under passive loading. This paper presents a three dimensional finite difference analysis for the lateral response of pile located at the horizontal ground and crest of slopes of 33 degrees 40 min, 26degrees 33min, 18 degrees 27min with relative densities of 30%, 45%, and 70%. The soil stratum is represented as elastic-plastic Mohr-Coulomb model and pile is represented as beam element. The results of Model test are analyzed and compared. Based on the results of model test, conclusions are drawn regarding the application of the analytical method to study the effect of slope on laterally loaded pile under surcharge load. An equation is developed to calculate the depth of fixity for single pile in sloping ground considering the effect of slope, relative density and embedded length of the pile using the finite difference analysis results.

1. Introduction

Pile foundations can be used to transmit both vertical and horizontal loads. Many pile foundations supporting structures such as wharfs and jetties along the coast, offshore structures, bridge foundations, tall structures like chimneys, TV towers, and high rise buildings are subjected to significant lateral forces. The lateral forces are mainly because of the action of wind and earth pressures which are due to lateral soil movement in case of structures along the coast. While in the case of coastal and offshore structures, the predominant forces leading to lateral movements are mainly due to waves, currents, winds, berthing forces, mooring forces, lateral earth pressure which are because of unstable slope as a result of dredging or siltation, etc.

Many analytical approaches have been developed in recent years for the response analysis of laterally loaded piles. The various analytical and numerical methods that are commonly employed to study the static and dynamic behaviour of laterally loaded piles are (a) Beam – on Winkler foundation approach (b) Elastic Continuum approach; (c) Boundary Element method; (d) Finite Element approach; (e) Finite difference approaches, etc. Most of the approaches consider either the theory of subgrade reaction or the theory of elasticity (Pise, [1]). However, the load – deflection behaviour of laterally loaded piles is highly nonlinear in nature, and hence requires a nonlinear analysis. Several empirical and numerical methods have been proposed for analyzing the response of single and pile groups to lateral loading from horizontal soil movement. Most of the numerical

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methods that have been proposed utilize the finite-element method (Carter [2]; Broms et al. [3], Bransby and Springman [4] and Goh et al. [5]) or the finite difference method (Poulos and Davis [6]). In the approach taken by Poulos and Davies [6], the solution is based on a point load in an elastic half-space (Mindlin's solution) and empirically to account for the presence of rigid bearing layer.

Prakash and Kumar [7] developed a method to predict the load deflection relationship for single piles embedded in sand and subjected to lateral load, considering soil nonlinearity based on the results of 14 full-scale lateral pile load tests. Kim and Barker [8] studied the effect of live load surcharge on retaining walls and abutments. Besides, Cai and Ugai [9] have studied the behaviour of piles under lateral soil movement. However, the studies on behaviour of piles on sloping ground and subjected to passive loading induced by surcharge are limited. Accordingly, a finite difference study has been carried out to determine the effect of slope, relative density and embedded length of pile on the depth of fixity of the pile.

2. Numerical Modelling

Numerical models involving FDA can offer several approximations to predict true solutions. The problem being modelled is often complex and has to be simplified to obtain a solution. Here finite difference analysis package FLAC 3D is used for the analysis. An explicit time-marching finite difference solution scheme is used for the analysis and the calculation sequence is

(1) Nodal forces are calculated from stresses, applied loads and body forces

(2) The equations of motion are invoked to derive new nodal velocities and displacements

(3) Element strain rates are derived from nodal velocities

(4) New stresses are derived from strain rates, using the material constitutive law

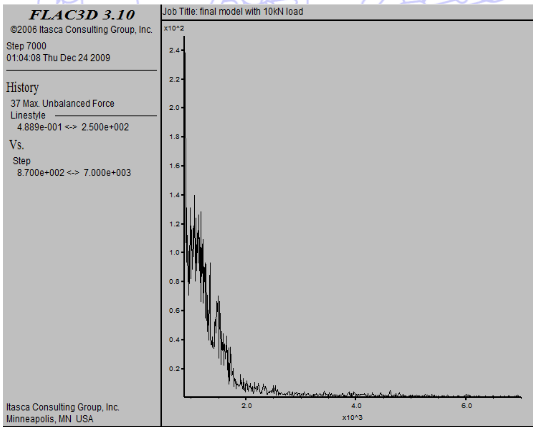

Fig. 1 Maximum Unbalanced Force vs Number of Steps

This sequence is repeated at every time interval, and the maximum out-of-balance force in the model is monitored. This force will either approach zero, indicating that the system is reaching an equilibrium state, or it will approach a constant, nonzero value, indicating that a portion (or all) of the system is at steady-state (plastic) flow of material. A model is in exact equilibrium if the net nodal-force vector (the resultant force) at each grid point is zero. Fig. 1 shows the variation of the unbalanced force for incremental time interval.

3. Constitutive Modeling

3.1. Mohr – Coulomb Soil Model

Mohr Coulomb's model can be considered as a first order approximation of real soil behaviour. This elastic perfectly plastic model requires 5 basic input parameters, namely a Young's Modulus E, a Poisson's ratio μ, a cohesion c, a friction angle φ and a dilatancy angle Ψ. This is a well known and a basic soil model. The soil nodes and pile nodes are connected by bilinear Mohr-Coulomb interface elements. This allows an approximate representation of the development of lateral resistance with relative soil-pile movement and ultimately the full limiting soil pressure acting on the piles.

3.2. Interaction between the Soil and Pile

Two noded, linear elements represent the behaviour of beams, and piles. Piles interact with the grid via shear and normal coupling springs. The coupling springs are nonlinear, spring-slider connectors that transfer forces and motion between the pile and the grid at the pile nodes (by way of the link emanating from each pile node). The spring constants are calculated using the Vesic equation,

$$k_s = \frac{1.3}{D}\sqrt[12]{\frac{E_s \times B^4}{E_b \times I}}\,\frac{E_s}{1-\mu^2} \tag{1}$$

where *D* is the diameter of pile (m), *Es* is the modulus of elasticity of soil (N/m2), E_b is the modulus of elasticity of pile (N/m2), *B* is the lateral dimension of pile (m), μ is the Poisson's ratio of soil

3.3. Model Description

Soil block is modelled by using eight nodded brick shaped elements (Fig. 2) of elastic plastic Mohr-Coulomb model. Piles/beams are modelled as two nodded structural finite element segments with 12 degree of freedom (Fig. 3). The dimensions of the model are 1.3m x 0.6m x 0.9m. The soil is sandy soil and a hollow aluminum pile of 700mm length and 25mm outer diameter which is located at 0.75m along the length and 0.3m along the width of the soil block. The pile is embedded in the soil to a depth of 550mm and 150mm projecting outside the soil.

The schematic view of the model is explained in Fig. 4 and the finite difference discretization of the model is shown in Fig. 5. The influence of various soil and pile parameters such as relative density of sand, length to diameter ratio of pile and slope of ground are studied for a series of static surcharge loads. In order to study the effect of slope, the slope is provided in such a way that the pile rests on the crest of the slope and the surcharge load is also applied from the crest of the slope as a uniformly distributed load over an area of 0.45m x 0.35m.

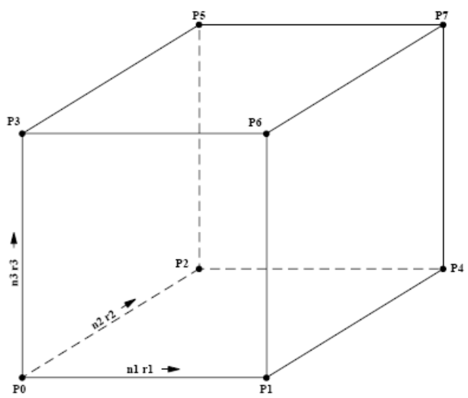

Fig. 2 8 Nodded brick element

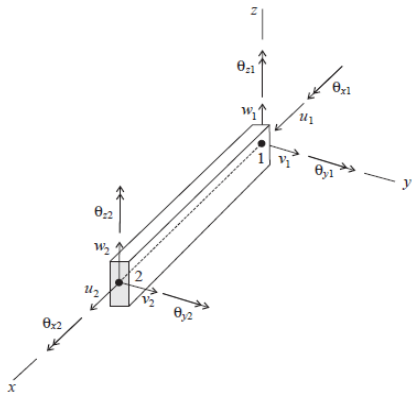

Fig. 3 Two nodded pile SEL coordinate system and 12 degrees of freedom of the beam finite element

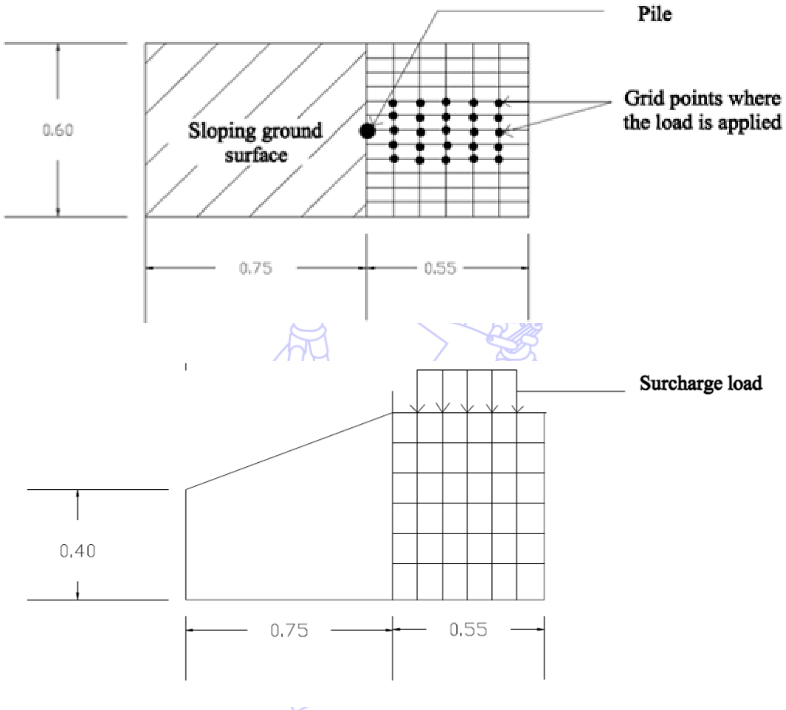

Fig. 4 Schematic view of the Model Analysis

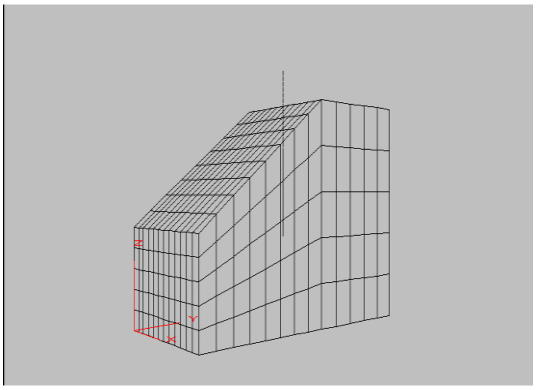

Fig. 5 Discretized finite element model

4. Material Properties

4.1. Soil and Structural Properties

The analyses are conducted with sand of various relative densities of 30%, 45% and 70%. The input parameters for soil and structural elements are taken from Muthukkumaran et al. [10]. The input values of soil and structural elements are presented in Table-1 & 2 respectively.

Table 1 Soil Properties [10]

Description	Relative density			Unit
	30%	45%	70%	
Dry Soil Weight	16	17	18.5 × 10^3	N/m^3
Young's Modulus	30,000	45,000	60,000000	N/m^2
Poisson's Ratio	0.333	0.319	0.291	-
Cohesion	0	0	0	N/m^2
Friction Angle	30	32	36	degree
Bulk modulus	3.0x10^7	4.14x10^7	4.7x10^{10}	N/m^2
Shear modulus	1.1x10^7	1.7x10^7	2.3x10^{10}	N/m^2

Table 2 Pile Properties [10]

Description	Pile	Unit
Young's modulus	7.65x10^7	N/m^2
Poisson's ratio	0.33	
Cross sectional area	7.54x10^{-5}	m^2
Polar moment of inertia	1.09x10^{-8}	m^3
Moment of inertia	5.43x10^{-9}	m^4
Perimeter	0.07854	m

5. Model Validation

In order to validate the generated FD model for its applicability in the problems involving effect of slope on laterally loaded piles, the experimental model study of Muthukkumaran et al. [10] is chosen and FD analysis is carried out for the same model with same pile and soil properties and compared the results.

Fig. 6 shows the bending moment variation, it is observed that the value of the Maximum bending moment obtained by FDA is having good agreement with the experimental results and the location of the maximum bending moment is also at the same depth in both FD and experimental results. Fig. 7 shows the variation of maximum bending moment with different relative density. The FDA results are compared with experimental results and it is observed that the variation of bending moment obtained through finite difference analysis is almost close to the results of experimental results.

From these two figures, it is observed that the results obtained by finite difference analysis is having good agreement with Muthukkumaran et al. [10] and hence the developed FD model can be used for further parametric study. The following parameters are considered to study the effect of slope on laterally loaded pile due to surcharge load.

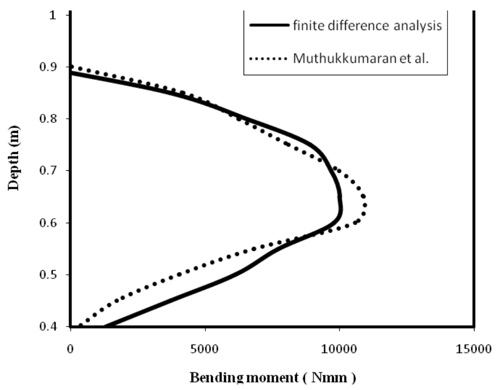

Fig. 6 Bending moment vs Depth curve for 1V:2H slope

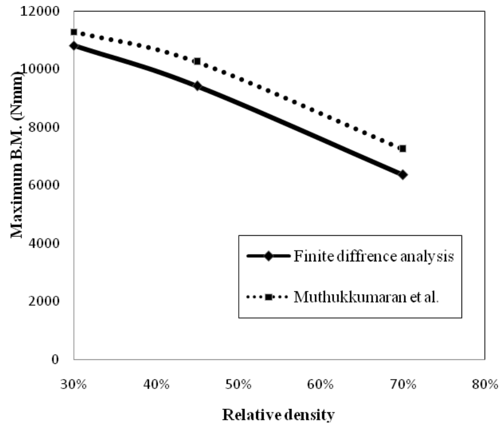

Fig. 7 Relative Density vs Maximum Bending moment for 1V:2H for 20kN load

From these two figures, it is observed that the results obtained by finite difference analysis is having good agreement with Muthukkumaran et al. [10] and hence the developed FD model can be used for further parametric study. The following parameters are considered to study the effect of slope on laterally loaded pile due to surcharge load.

6. Parameteic Study

6.1. List of Analysis Carried Out

List of analysis carried out for the various parameters is shown in the table 3. According to Broms [11], the depth of the pile is greater than 4T for long elastic pile behaviour, where T is the stiffness factor which is based on relative density of the soil and stiffness of the pile. Therefore, the embedment depths are choosen as 550mm, 625mm and 750mm such that the L/D ratios 22, 25 and 30 and relative densities of 30%, 45% and 70% in the present study.

Table 3 List of Analysis carried out

Soil surface	L/D ratio	Relative density (%)
Horizontal	22	30,45,70
	25	30,45,70
	30	30,45,70
1V:3H	22	30,45,70
	25	30,45,70
	30	30,45,70
1V:2H	22	30,45,70
	25	30,45,70
	30	30,45,70
1V:1.5H	22	30,45,70
	25	30,45,70
	30	30,45,70

6.2. Results And Discussions

Fig. 8 to 15 show the variation of displacement along the pile depth. From all the figures, it is seen that the maximum lateral displacement of the pile is maximum at the top and as the slope of the soil increases, the displacement of the pile also increases due to the reduction in the passive resistance in front of the pile. Fig. 16 shows the effect L/D ratio on the pile lateral displacement for 1V:1.5H slope with 30% relative density of 127000 N/m2 applied surcharge pressure. As L/D of the pile increases from 22 to 30, the maximum displacement of the pile is reduced 41%. Fig. 17 shows the effect of L/D ratio on the displacement of pile for zero slopes with 70% relative density and 127000 N/m2 applied surcharge pressure and it is observed that as the L/D ratio increases from 22 to 30, the maximum displacement reduces 48%.

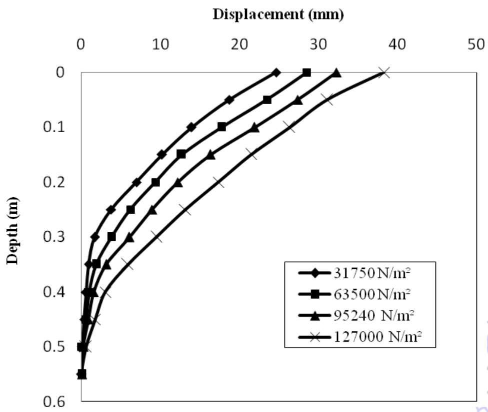

Fig. 8 Displacement vs Depth curve for zero slope and 30% relative density

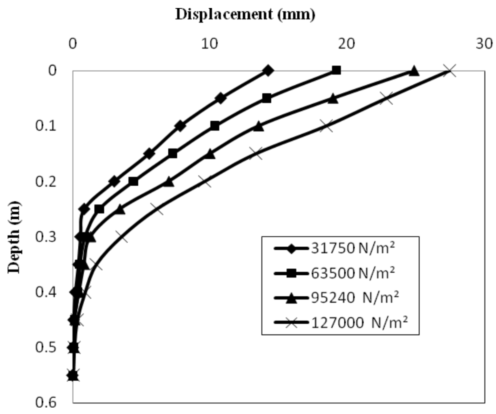

Fig. 9 Displacement vs Depth curve for zero slope and 70% relative density

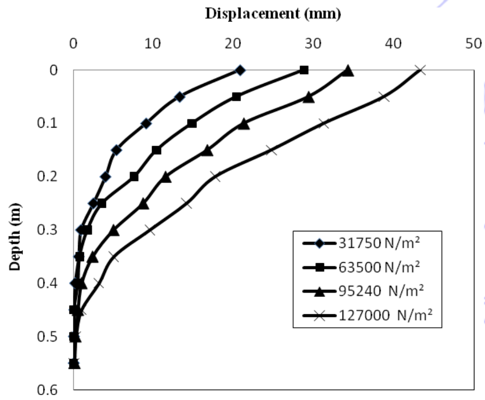

Fig. 10 Displacement vs Depth curve for 1V:3H Slope and 30% relative density

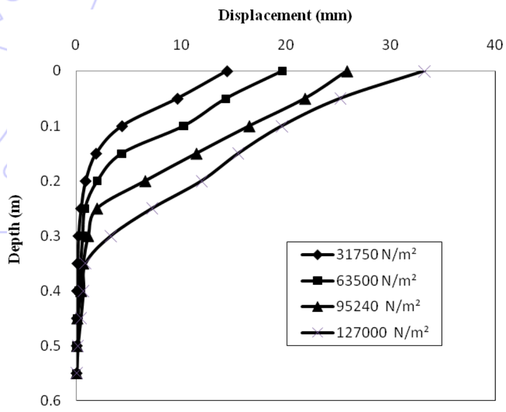

Fig. 11 Displacement vs Depth curve for 1V:3H slope and 70% relative density

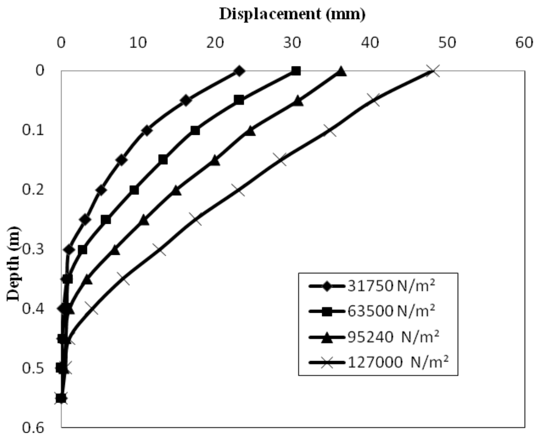

Fig. 12 Displacement vs Depth curve for 1V:2H slope and 30% relative density

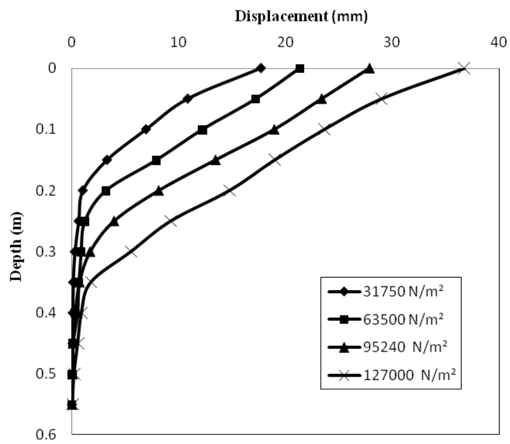

Fig. 13 Displacement vs Depth curve for 1V:2H slope and 70% relative density

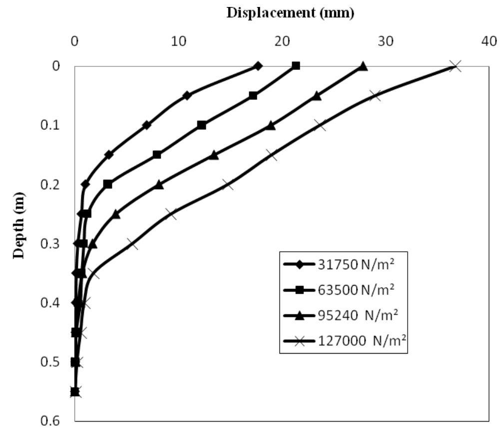

Fig. 14 Displacement vs Depth curve for 1V:1.5H slope and 30% relative density

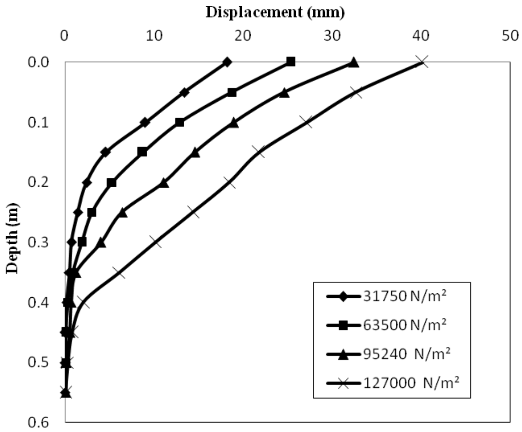

Fig. 15 Displacement vs Depth curve for 1V:1.5H slope and 70% relative density

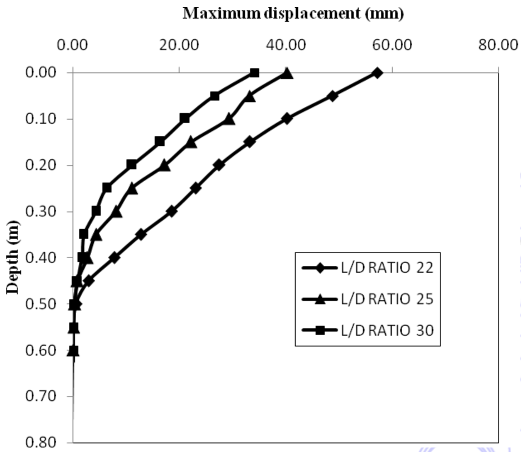

Fig. 16 Displacement vs Depth curve for 1V:1.5H slope with 30% relative density and 127000 N/m^2

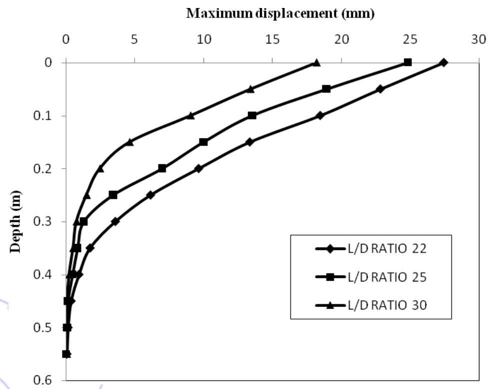

Fig. 17 Displacement vs Depth curve for zero slope with 70% relative density and 127000 N/m2

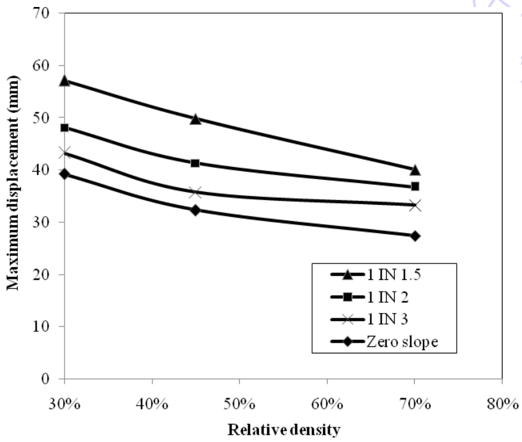

Fig. 18 Relative density vs Displacement for applied surcharge pressure 12700 N/m^2

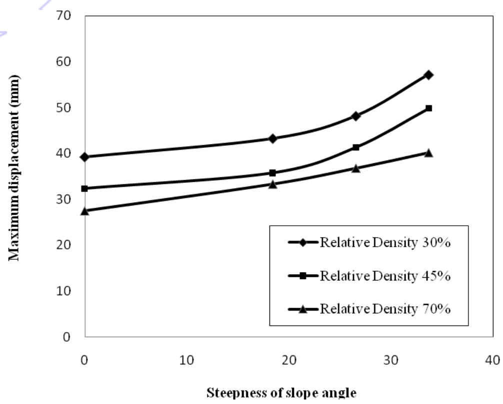

Fig. 19 Steepness of slope vs Displacement for applied surcharge pressure of 12700 N/m^2

Fig. 18 shows the effect of relative density on maximum displacement is zero, 1V:3H, 1V:2H and 1V:1.5H slopes with 20kN surcharge load. The maximum displacement of 57mm is observed for 30% relative density with 1V:1.5H slope and a minimum displacement of 27mm observed for 70% relative density with zero slope. Increase in relative density from 30% to 70%, decreases the maximum displacement by 42%, 31%, 30% and 43% for 1V:1.5H, 1V:2H, 1V:3H and 0 slopes respectively.

Fig. 19 shows the effect of slope on maximum displacement for 30%, 45% and 70% of relative density. The maximum displacement is observed to increase by 45%, 54% and 46% for 30%, 45% and 70% relative density respectively. This is due to the decrease in lateral resistance offered by the soil in front of the pile with increase in slope.

Fig. 20 shows the displacement contour for the pile rests on the crest of the slope of 1V:2H before analysis and Figs. 21 and 22 shows the displacement contours for a surcharge pressure of 95240 N/m^2 applied at the crest of the slopes of 1V:2H and 1V:1.5H respectively.

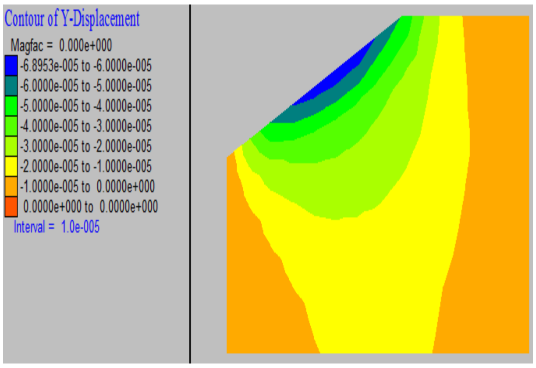

Fig. 20 Y Displacement Contour for Pile Resting on 1V:2H Slope before Analysis

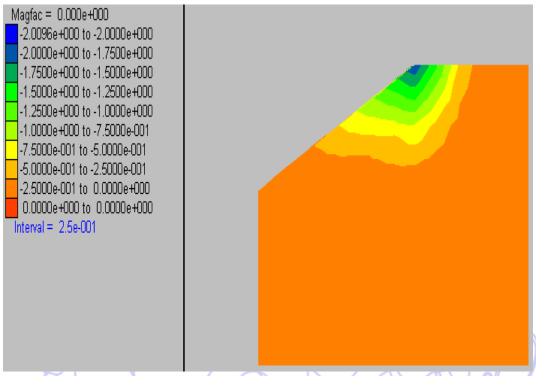

Fig. 21 Y Displacement Contour for Pile Resting on 1V:2H Slope after application of surcharge pressure of 95420N/m^2 after Analysis

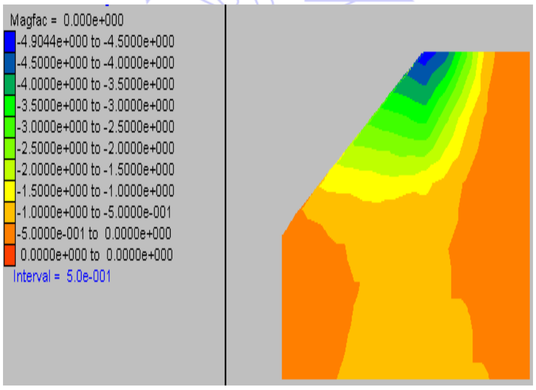

Fig. 22 Y Displacement Contour for Pile resting on 1V:1.5H Slope after application of 95420N/m^2 after Analysis

The typical bending moment variation along the depth of pile for different relative densities and slopes are shown in fig. 23 to 30. From all the figures, it is seen that the increase in surcharge load will increase the bending moment. This is due to increase in lateral soil movement. Maximum bending moment of 10.9N-m is observed for 30% relative density with 1V:1.5H slope and minimum bending moment of 3.04N-m is observed for 70% relative density with zero slopes. The maximum bending moment is observed to occur at a depth of 14D for zero slope and 15D for 1V:3H and 16D for 1V: 2H and 1V: 1.5H slope.

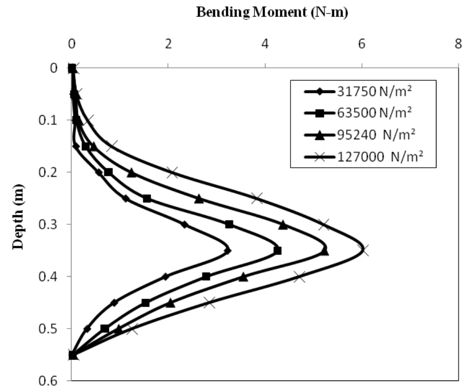

Fig. 23 Bending Moment vs Depth curve for zero slope and 30% relative density

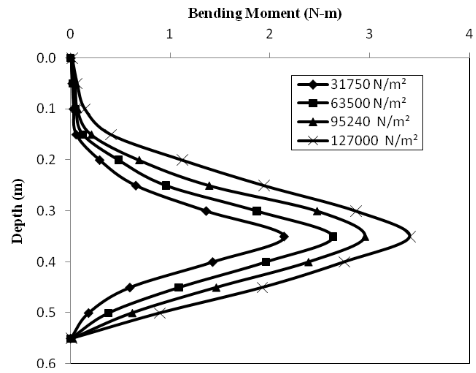

Fig. 24 Bending Moment vs Depth curve for zero slope and 70% relative density

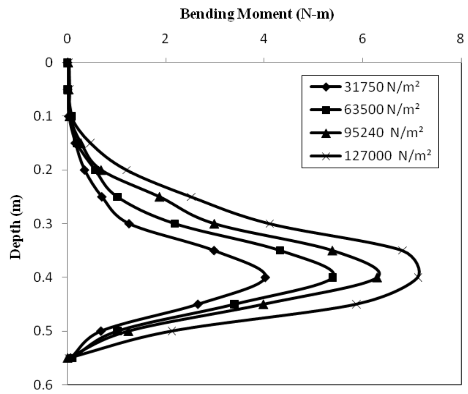

Fig. 25 Bending Moment vs Depth curve for 1V:3H and 30% relative density

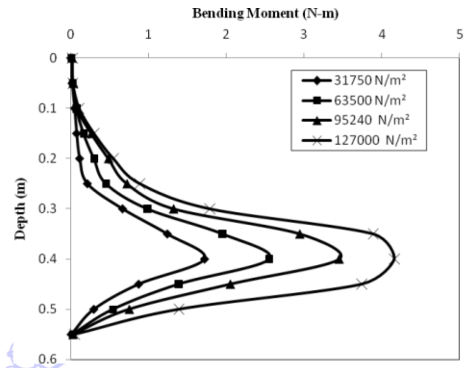

Fig. 26 Bending Moment vs Depth curve for 1V:3H and 70% relative density

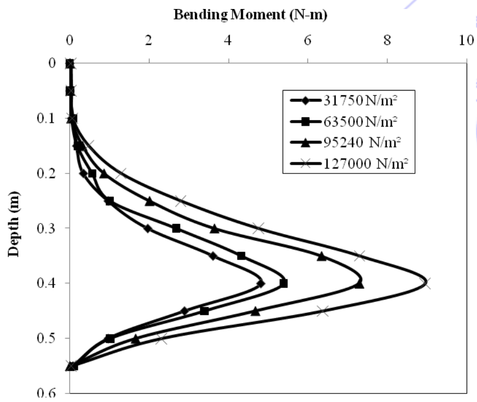

Fig. 27 Bending Moment vs Depth curve for 1V:2H and 30% relative density

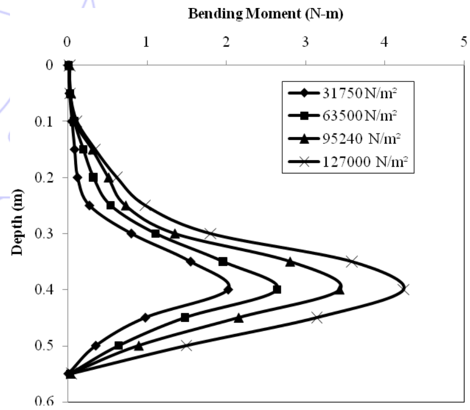

Fig. 28 Bending Moment vs Depth curve for 1V:2H and 70% relative density

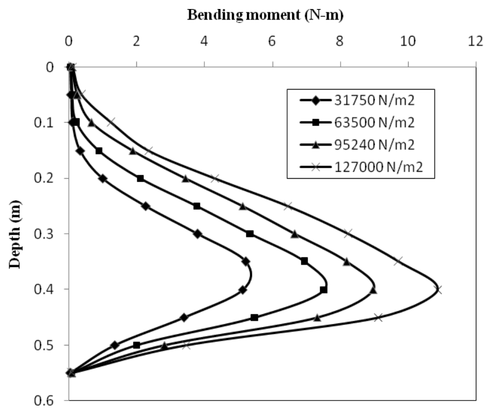

Fig. 29 Bending Moment vs Depth curve for 1V:1.5H and 30% relative density

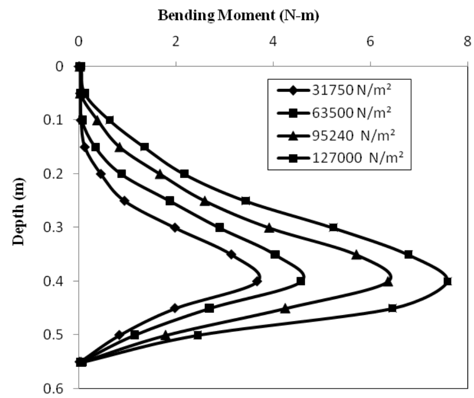

Fig. 30 Bending Moment vs Depth curve for 1V:1.5H and 70% relative density

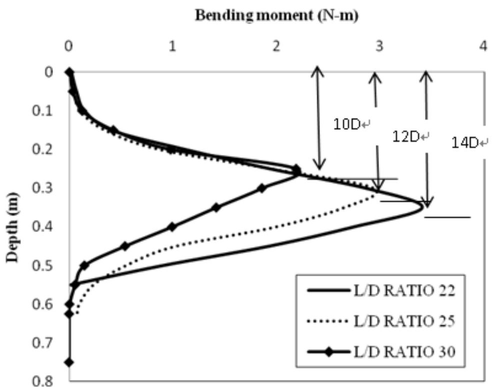

Fig. 31 Bending Moment vs Depth curve for zero slope and 30% relative density for applied pressure of 127000 N/m^2

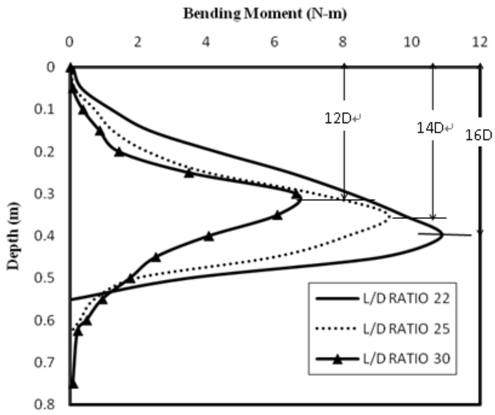

Fig. 32 Bending Moment vs Depth curve for1V:1.5H slope and 30% relative density for applied pressure of 127000 N/m^2

Fig. 31 shows the bending moment variation along the depth of the pile for zero slope with 70% relative density and applied surcharge pressure of 127000 N/m^2. As the embedded length of the pile increases the depth of fixity and maximum bending moment is reduced. The occurrence of depth of fixity is 14D, 12D and 10D in case of L/D ratio of 22, 25 and 30.

Fig. 32 shows the bending moment variation along the depth of the pile for 1V:1.5H slope with 30% relative density and applied surcharge pressure of 127000 N/m^2. The depths of fixities are 16D, 14D and 12D for L/D ratio of 22, 25 and 30 respectively.

The stress contour for the pile resting on the crest of 1V:1.5H before analysis and after applying surcharge pressure of 95240 N/m^2 at the crest of the slope is shown in the Fig. 33 and 34 respectively.

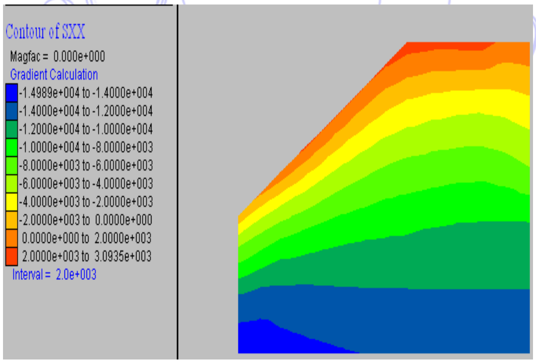

Fig. 33 Stress Contour for Pile Resting on the Crest of 1V:1.5H Slope before Analysis

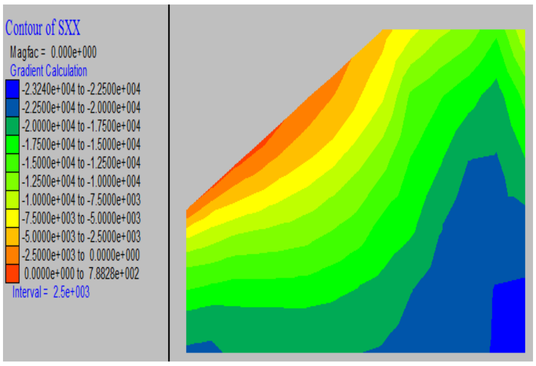

Fig. 34 Stress Contour for Pile Resting on Crest of 1V:1.5H Slope after the application of Surcharge pressure of 95240 N/m^2

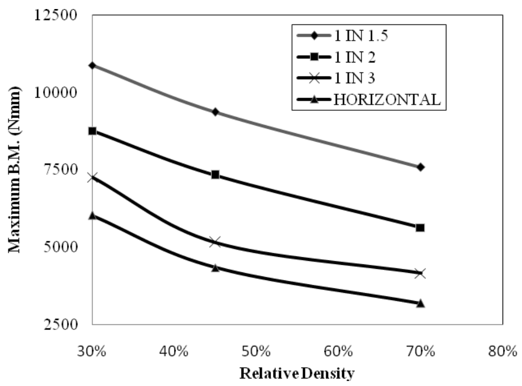

Fig. 35 Relative density vs Max. Bending moment for surcharge pressure of 127000 N/m^2

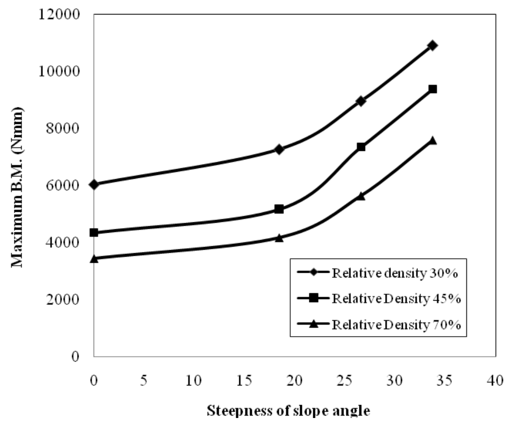

Fig. 36 Steepness of slope angle vs Maximum bending moment for applied surcharge pressure of 127000 N/m^2

Fig. 35 shows the effect of relative density on maximum bending moment. It is observed that the increase in relative density, the maximum bending moment decreases irrespective of the ground surface. The Increase of relative density from 30% to 70%, the maximum bending moment decreases by 30%, 35%, 43% and 46% for 1V:1.5H, 1V:2H, 1V:3H and 0 slopes respectively.

Fig. 36 shows the effect of slope on maximum bending moment. It is observed that the increase in steepness of slope, the maximum bending moment increases irrespective of the relative density. The ratio of change of maximum bending moment from 1V:3H to 1V:1.5H slope is very significant than horizontal ground to 1V:3H slope.

As the steepness of the slope increases, the lateral resistance of the soil reduces and results in arching of soil which is more common in case of ground surface with steeper slopes. As the increase in steepness of slope from zero to 1V:1.5H, the maximum bending moment increases by 45%, 53% and 55% for 30%, 45% and 70% relative density respectively.

7. Developing An Equation For Predicting The Depth Of Fixity For Single Pile In Sloping Ground

The finite difference analysis was carried out for four equal surcharge load increments from 5kN to 20kN and it was found that the slope of the ground, embedded length of the pile and soil stiffness affects the behavior of the pile significantly. As per IS 2911, the depth of fixity calculations are based on the eccentricity (e) and stiffness factor (T) and are applicable only for the pile in horizontal ground and subjected to direct lateral load.

Whereas the depth of fixity is also the function of depth of embedment and it is necessary to include the effect of embedment length. Therefore, proposing an expression for predicting the depth of fixity for piles considering the effect of embedded length of pile (L_e), slope of ground surface (S), soil pile relative stiffness (T) and subjected to surcharge pressure would be help full for the design engineers to determine the maximum bending moment for which the pile is to be designed. Table 4 shows the L_f/T values obtained from the finite difference analysis for the change in values of the various parameters.

Table 4 Values of Lf obtained from analysis results

Le	T	Slope	Lf (Actual)
0.55	0.04389	0.667	0.4
0.625	0.04389	0.667	0.35
0.75	0.04389	0.667	0.3
0.55	0.03527	0.667	0.4
0.625	0.03527	0.667	0.35
0.75	0.03527	0.667	0.3
0.55	0.02897	0.667	0.4
0.625	0.02897	0.667	0.35
0.75	0.02897	0.667	0.3
0.55	0.04389	0.5	0.38
0.625	0.04389	0.5	0.34
0.75	0.04389	0.5	0.29
0.55	0.03527	0.5	0.39
0.625	0.03527	0.5	0.36
0.75	0.03527	0.5	0.28
0.55	0.02897	0.5	0.4
0.625	0.02897	0.5	0.36
0.75	0.02897	0.5	0.29
0.55	0.04389	0.333	0.37
0.625	0.04389	0.333	0.33
0.75	0.04389	0.333	0.28
0.55	0.03527	0.333	0.38
0.625	0.03527	0.333	0.33
0.75	0.03527	0.333	0.27
0.55	0.02897	0.333	0.37
0.625	0.02897	0.333	0.31
0.75	0.02897	0.333	0.27
0.55	0.04389	0	0.35
0.625	0.04389	0	0.3
0.75	0.04389	0	0.25
0.55	0.03527	0	0.35
0.625	0.03527	0	0.3
0.75	0.03527	0	0.25
0.55	0.02897	0	0.35
0.625	0.02897	0	0.3
0.75	0.02897	0	0.25

Multiple regression analysis is carried out by using L_f/T as dependent variable and slope (S), L_e and T as dependent variable and an equation is developed for predicting the values of L_f.

$$\mathbf{L_f = (0.621 + 0.078251 \times S - 0.0640 \times T - 0.497 \times L_e) \times T \quad (m)} \tag{2}$$

where *Le* is the embedded length of pile (m), *S* is the slope of the ground in radians, *T* is the Relative stiffness (m) = $\sqrt[5]{\frac{EI}{K}}$, K=2600 kN/m3 for relative density 30% (As per IS 2911), K=7750 kN/m3 for relative density 45% (As per IS 2911), K=20750 kN/m3 for relative density 70% (As per IS 2911) , L_f is the depth of fixity (m)

Fig. 37 shows the scatter plot between the L_f/T predicted using equation (2) and L_f/T obtained using finite difference analysis, the value of R^2 is equal to 0.9716 and the maximum error is 7.94%. Hence, it is concluded that the developed equation can be used to obtain the depth of fixity of the pile for bending moment calculations.

An illustration for calculating the depth of fixity based on the developed equation (2) and also based on IS2911 [12] has been given in the Annexure 1. It is found that the developed equation including the effect of depth of embedment is almost three times more than the IS 2911 method. The calculated depths of fixities are verified with actual bending moment plot and it is confirmed as per the calculated values.

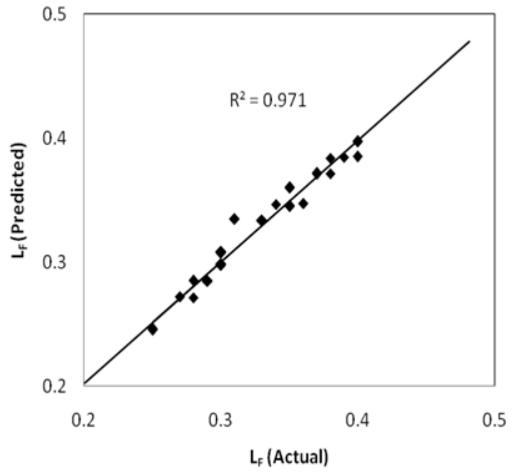

Fig. 37 Scatter plot for depth of fixity

8. Conclusions

The results obtained from the numerical model using the finite difference program FLAC 3D are compared with existing experimental results and the FDA results have a good agreement with the existing results and therefore the numerical model can be applied to study the effect of slope on laterally loaded piles. The same numerical model was used for the study of lateral response of pile located at the crest of slopes undergoing passive loading under various slopes of 0 degree, 33 degree 40 min, 26 degree 33min, 18 degree 27min, relative densities of 30%, 45%, and 70% and L/D ratios of 22, 25 and 30. Based on the study, the following major conclusions are drawn.

(1) The increase in ground slope from 0 to 1V:1.5H the depth of fixity is increased by 1.5D, 0.85D and 0.7D (D is diameter of the pile) for 30%, 45% and 70% relative densities respectively.

(2) The increase in ground slope has very significant effect in the lateral load capacity and lateral deflection of the pile. Since the lateral resistance offer in front of the pile is very less compared to horizontal ground and subsequently it leads to the arching effect in the soil, the lateral load capacity has reduced significantly.

(3) As relative density of the soil increases the pile lateral load capacity has increased significantly. It is also found that irrespective of the slope, the increase relative density decreases the maximum bending moment and increases the lateral capacity.

(4) The increase in L/D ratio has very significant effect in the lateral load capacity and bending moment. The increase in L/D ratio from 22-30, and reduces the bending moment by almost half times in 1V:1.5H slope with 30% relative density. This effect is slightly less for higher relative density soil with same slope. This is due to the reason that as the embedded length of the pile increases the pile stiffness and the anchoring effect produced by the pile, there is reduction in the pile bending moment and displacement.

(5) Based on the FD analysis results, an equation has been developed to estimate the depth of fixity of single piles located at the crest of slope and subjected to passive loading. The developed equation applicability has been checked with IS 2911 results. However, the design equation is applicable for piles in sloping ground of various embedment depths its' application is limited to only single piles subjected to surcharge pressure and located at the slope crest.

9. Acknowledgements

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Appendix A

A.1. Calculating the depth of fixity as per IS 2911

Rigidity modulus of the pile, EI = 0.4236 Nm2

Depth of free standing pile, L_1 = 0 m

Depth of embedment of pile, L_e = 1 m

Slope, S = 0

Subgrade reaction, ηh = 2.6 x 10^6 N/m3

$T = (EI/K_1)^{1/5}$

$= ((0.4236)/(2.6 \times 10^6))^{1/5}$

$= 0.0438$ m

Le > 4T for the applicability of IS 2911 design chart

Here 4T = 4 x 0.0438m = 0.1752 m < 1 m, hence IS method is applicable

From the graph given in IS 2911 for free headed pile in horizontal ground,

For $L_1/T = 0$, $L_f/T = 1.92$

$L_f = 1.92 \times 0.0438$

$= 0.0841$ m

A.2. Calculating the depth of fixity as per the equation developed (eqn (1))

Depth of fixity, L_f = $(0.621 + 0.078251 \times S - 0.06402 \times T - 0.49694 \times L_e)$

L_f = $(0.621 + 0.07825 \times 0 - 0.064 \times 0.0438 - 0.4969 \times 1)$

= 0.1213 m

A.3. CONSIDERING THE EFFECT OF SLOPE

A.3.1. When the pile rests on the ground with a slope of 1:3

As per IS 2911 method, Slope of the ground does not affect the depth of fixity

Therefore, L_f = 1.92×0.0438

= 0.0841 m

As per Design equation developed

Depth of fixity, L_f = $(0.621 + 0.078251 \times S - 0.06402 \times T - 0.49694 \times Le)$

L_f = $(0.621 + 0.07825 \times 0.3334 - 0.06402 \times 0.0438 - 0.4969 \times 1)$

= 0.146 m

A.3.2. When the pile rests on the ground with a slope of 1:1.5

As per IS 2911 method, Slope of the ground does not affect the depth of fixity

Therefore, L_f = 1.92×0.0438

= 0.0841 m

As per Design equation developed

Depth of fixity, L_f = $(0.621 + 0.078251 \times S - 0.06402 \times T - 0.49694 \times Le)$

L_f = $(0.621 + 0.07825 \times 0.667 - 0.06402 \times 0.0438 - 0.4969 \times 1)$

= 0.173 m

A.4. CONSIDERING THE EFFECT OF EMBEDDED LENGTH OF PILE

When the embedment length of pile changes from 1m to 0.75m

As per IS 2911 method Embedment length of pile does not affect the depth of fixity

Therefore, L_f = 1.92×0.0438

= 0.0841 m

As per Design equation developed

Depth of fixity, L_f = $(0.621 + 0.078251 \times S - 0.06402 \times T - 0.49694 \times Le)$

L_f = $(0.621 + 0.07825 \times 0.667 - 0.06402 \times 0.0438 - 0.4969 \times 0.75)$

= 0.251m