Numerical Simulation of Soil Nailed Structures

Midhula Jayanandan
Department of Civil Engineering
NIT Calicut
Kerala , India

S. Chandrakaran
Department of Civil Engineering
NIT Calicut
Kerala , India

***Abstract*— Soil nailing is an in-situ earth retaining technique excessively used all over the world for the various slope stability applications. In this study, PLAXIS 2D is employed for the comprehensive study of nailed soil structures. A model is generated for a 10m vertical cut in lateritic soil with horizontal nails installed. A critical comparative study is accomplished for the cut with and without nails. On quantifying the improvement of the slope stability after nail installation, it is observed that lateral deformation is reduced by about 41 percent and factor of safety is increased by almost 1.2 times that of slope without nail. A detailed parametric study is conducted to substantiate the general characteristics of a soil nail system. Subsequently the response of the system for the effect of berm provision in the construction, nail configuration, and base heave are also included herein this work.**

Keywords—In-Situ Earth Retaining Technique, PLAXIS 2D, Base Heave

I. INTRODUCTION

Soil nailing consists of the passive reinforcement (i.e., no post-tensioning) of existing ground by installing closely spaced steel bars (i.e., nails), which are subsequently encased in grout[9]. The technique is also used for construction of permanent retaining walls, slope stabilization, underpinning, and protection of existing cuts[15]. Soil nailing is also used as temporary shoring for basement excavations and as permanent and temporary earth support for excavations associated with railroads and tunnels [5]. As construction proceeds from the top to bottom, shotcrete or concrete is also applied on the excavation face to provide continuity.

Conventional soil nailing design procedures based on limit equilibrium methods fail to address the complex mutual interaction between its main components which affects the performance of soil nail [9]. Consequently, in practice, often numerical simulations are performed using rigorous computational codes based on numerical techniques such as finite element method[8,10], discrete element method (e.g. Kim et al. 1997) and finite difference method[2]. It is well established that the accuracy of numerical simulations depends significantly on the constitutive soil model used and the selection of the appropriate corresponding model parameters.

II. APPLICATION OF PLAXIS 2D FOR SIMULATION OF A SOIL NAILED SLOPE

For the numerical simulation, two-dimensional finite element code PLAXIS is used. The Mohr-Coulomb model is used to model soil and for nails along with facing elements, an elastic model is used. Beam elements are used to model nails and facing elements. Input parameter definitions in PLAXIS require averaging the effect of a three-dimensional problem to a two-dimensional problem.

At this stage, the soil parameters and other pre-determined variables are used as inputs to run the slope stability analysis using PLAXIS software. Table I provides the typical values of various properties of in-situ soil, nails and facing elements used for simulation.

TABLE I. Parameters of soil nail wall used for numerical simulation

Input	Properties	Value
Soil properties	Unit weight of soil, γ_{unsat}	15 kN/m^3
	γ_{sat}	17kN/m^3
	Friction angle, ϕ	30^o
	Cohesion , c	80 kN/m^2
	Young's modulus of soil, E	40000 kPa
	Permeability, k_x	10 m/day
	k_y	10m/day
	Poisson's ratio,υ	0.25
Wall Geometry	Wall Height, H	10 m
	Wall inclination, α	90^o
	Backslope angle, β	0^o
Nail properties (grouted nail)	Length of reinforcement, L	7m
	Diameter of reinforcement	20 mm
	Drill Hole diameter, D_{DH}	100 mm
	Nail inclination, η	0^o
	Horizontal and vertical spacing (S_H x S_V)	1 m x 1m
	Yield strength of nail (Fe 415)	415 MPa
	Elasticity modulus of reinforcement, E_n	200 GPa
Facing properties(shotcrete)	Thickness of facing	100 mm
	Elasticity modulus of grout (M20 concrete) E_g	22 GPa

The geometry of the soil nailed slope used for the numerical simulation is given in the Fig.1. The figure is the general representative of the model and its geometrical and material parameters are varied subsequently during the parametric studies. The placement of the boundaries so that there is minimum influence on the results of the numerical simulation of soil nail wall is important. It is suggested that bottom of the mesh is best placed at a depth where soil becomes notably harder [4]. The soil nailed slope is constructed by excavating soil in several stages with each stage of excavation being 1m in height. The first row of nails is placed at a distance of 0.5m from top of excavation and the succeeding rows are placed at a vertical spacing of 1m.

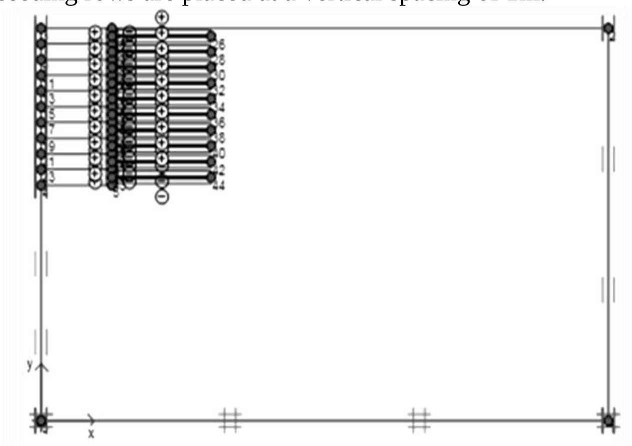

Fig. 1 Geometry of base model

III. COMPARATIVE STUDY OF AN EXCAVATION WITH AND WITHOUT SOIL NAILS

In the following section the stability analysis of a 10m vertical cut without nail having identical geometry and soil properties of that of the base model is carried out. The output parameters such as lateral displacement and factor of safety are noted. Then a comparative study is carried with results obtained for the base model wherein one row of soil nail is installed horizontally in each 1m lift of the 10m excavation.

TABLE II. Comparison of results of stability slope with nails and without nails

Output parameters	Excavation without nails	Excavation with nails(i.e 10 rows)
Lateral displacement (mm)	10.19	5.97
Factor of safety	1.755	3.736

From the results it is ensured that the introduction of nails in the excavation, increase the factor of safety substantially. The lateral deformation of the soil nailed wall is also found to decrease compared to the slope without nails. On quantifying the improvement of the slope stability, it is observed that lateral deformation reduced by about 41 percent and factor of safety increased by almost 1.2 times that of slope without soil nail.

IV. PARAMETRIC STUDIES ON SOIL NAILED SLOPE

A. Material Parametric Study

While conducting the parametric study on any material property, the rest of the properties along with the geometry of the model are kept constant. The influence of the different parameters on the stability of the soil nailed structure is then ascertained. Material properties of in-situ soil are varied to conduct the study. The effect on the deformation and factor of safety of the soil nailed slope is studied based on variation in these in-situ soil parameters.

Cohesion

The value of cohesion is varied for the surrounding soil keeping the value of other parameters constant. The base model used in the study is same as the one used in the previous analysis. The value of cohesion is varied in the subsequent models for the analysis.

The value of cohesion is increased from 20 kN/m^2 to 120 kN/m^2. The behaviour of the slope as the cohesion increases at the rate of 20kN/m^2, is observed.The effect of change of cohesion in lateral displacement and factor of safety can be noted from Fig.2 and Fig.3 respectively.

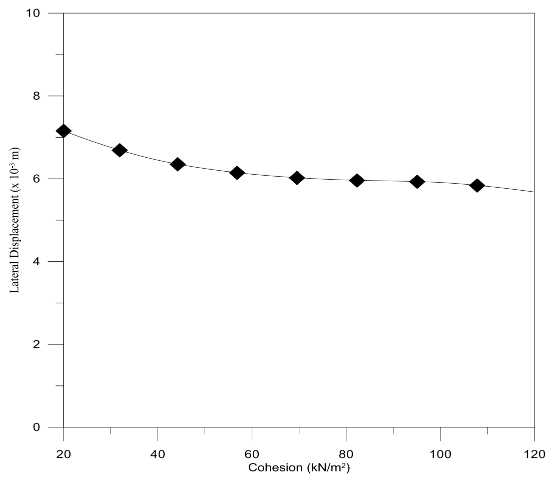

Fig.2 Effect of change of cohesion in lateral displacement

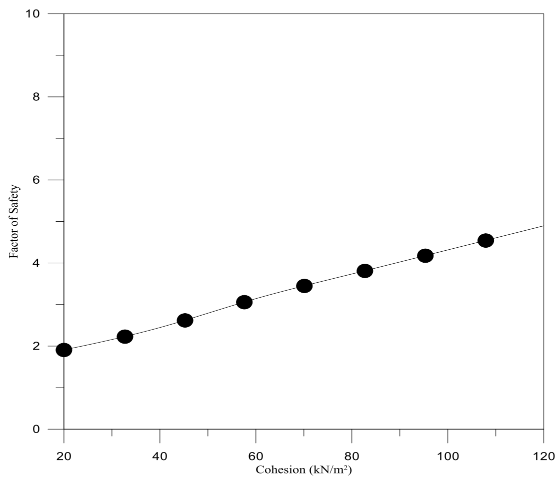

Fig.3 Effect of change of cohesion in factor of safety.

There is a steady increment in the FOS complimented with slight decrease in lateral deformation of soil nailed slope.

Angle of Internal friction

The value of angle of internal friction is increased from 25^o to 40^o. The behaviour of the slope as angle of internal friction increased by 5 degrees is observed. There is an increase of FOS from 3.46 to 4.73 and a reduction in lateral displacement from 7.77mm to 3.95mm. In general, FOS increase with an increase in the angle of internal friction of the surrounding soil. The lateral deformation of soil nailed slope is observed to decrease further indicating more stability with increase in angle of internal friction.

Unit Weight of Soil

The value of unsaturated unit weight of the soil is increased from 14 kN/m^3 to 20kN/m^3. The behaviour of the slope is observed as γ_{unsat} is increased by 1 kN/m^3. The effect of change of γ_{unsat} in lateral displacement and factor of safety are studied. An increase in maximum lateral deformation is noted from 5.14mm to 8.15mm. Factor of safety reduced from 4.09 to 3.14. As the unsaturated unit weight of the in-situ soil increase, there is a detrimental effect on the stability of the soil nailed slope.

B. Geometric Parametric Study

In geometric parametric study, any one of the geometrical property is varied, keeping rest of the properties constant. The properties of both wall and nail are varied and corresponding influence on the deformation and factor of safety are studied.

Backslope angle

The effect of backslope angle on the horizontal deformation and factor of safety are studied. The results clearly indicate that as backslope increases, slope becomes more unstable. As the backslope angle increases, the lateral deformation increases and factor of safety decreases. The backslope batter is increased from 0^o to 30^o and soil nailed slope behaviour is studied. Minimum lateral deformation and maximum FOS are obtained for a backslope angle of 0^o. In other words, a horizontal backslope is always advisable for an excavation.

Length of Nail

The influence of the nail length on the horizontal deflection profile and factor of safety are studied. It can be seen that horizontal deflection decreases with increasing nail length, and longer nails can effectively limit the horizontal deformation close to the ground surface. Factor of safety is found to show an increasing trend with increasing nail length. The observations obtained substantiated the results of many previous works [6,7,10]

Vertical Spacing of Nails

The influence of the vertical nail spacing on the horizontal deflection and factor of safety are studied. The deformation decreases with decreasing nail spacing, and the factor of safety increases significantly near the vertical cut as the nail spacing decreases. The vertical spacing is increased from 0.5m to 2m with an increment unit of 0.5m which resulted in an increase in maximum lateral displacement from 5.9mm to 6.6mm and a slight decrease in FOS from 3.83 to 3.54. But it is noticed that the effect of horizontal spacing on stability of nailed slope is more profound than effect of vertical spacing [13].

Excavation Height

The horizontal deflection increases as the excavation height increases. On calculating the ratio between the maximum deflection and the excavation height, it increases with the excavation depth, which means that the maximum deflection increases significantly as the excavation depth increases. Therefore the required reinforcement is more than linearly proportional with the excavation depth. Similarly more the excavation height, lesser is the factor of safety. The effect of excavation depth on lateral displacement and factor of safety are studied. Beyond a particular depth of 14m, excavation is found to be unstable for the given soil condition**s** [10].

Facing Stiffness

A proper choice of flexural rigidity for the facing can be made from the parametric studies. This enables the designer to choose appropriate facing material keeping in view cost and performance considerations. Hence the effect of stiffness of facing is examined here, for varying facing thicknesses. Simulations are performed for 75, 100, 150 and 200mm thick, with all other parameters constant. Fig.4 and Fig.5 show that there is no significant difference in the observed deformations and factor of safety for different values of facing thickness. Similar results are obtained by G L S Babu and B R S Murthy [2]. The results suggest that in practice, 75 mm thick facing is sufficient.

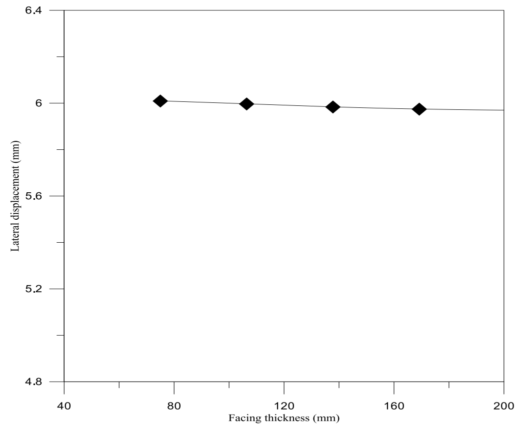

Fig.4 Effect of change of facing thickness in lateral displacement

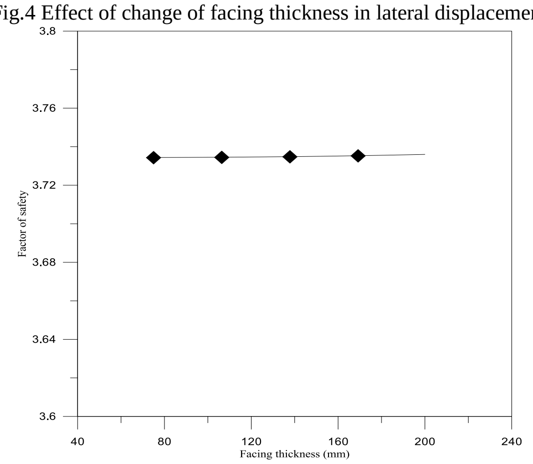

Fig.5 Effect of change of facing thickness in factor of safety.

MISCELLANEOUS CONDITIONS

Simulation of Excavation Stages:

The effect of the construction sequence is presented in the following subsections with respect to global FOS for two cases: (1) a vertical excavation and (2) an excavation with berms. Three sequences are included in both the cases by differing the depth of excavation (0.5m, 1m, 2m) in each stage. For this subsection the vertical spacing of nails is taken as 0.5m. From the Fig.6 and Fig.7, it is clear that the global FOS decreases as construction proceeds and the FOS for vertical excavation is less compared to that of excavation with berms. The possible reason for this is that, as soon as the 0.5m depth is excavated and the nail is inserted, the soil's resistance to deformation in the excavated zone is developed as a result of interfacial friction between the soil and the nail contributing to improved global FOS. For 0.5m excavation depth a similar effect is available at every level of excavation as the sequence is continued. In case of 2m excavation depth, deformation corresponding to a 2m depth of excavation will have already occurred, and even if the nails are inserted at this stage, the deformation that contributes to the mobilization of tensile forces is less and therefore the global safety factor is less. It is also observed that the global safety factor drastically decreases upto 50 percent of the construction stage, this is because of the large deformation occurring in the soil.

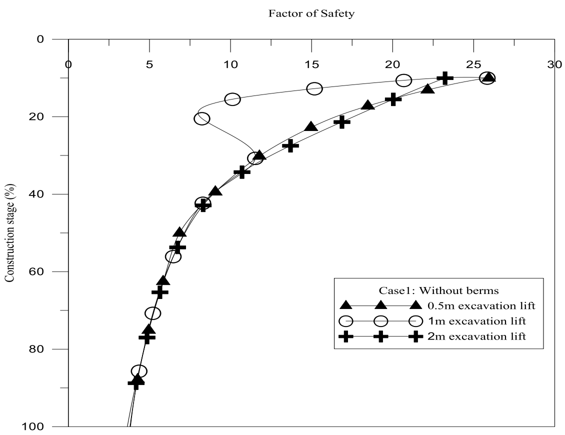

Fig.6 Trend of safety factor for vertical soil nailed slope

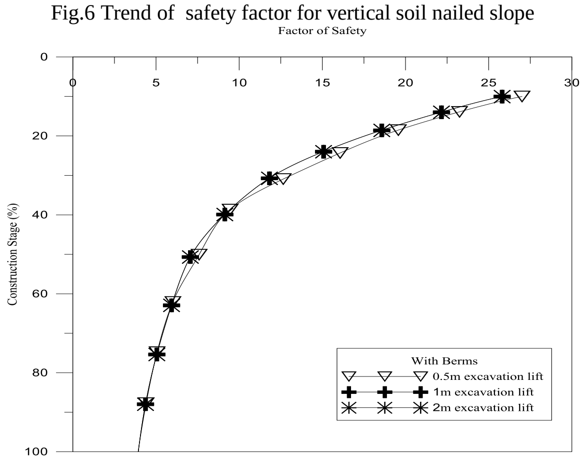

Fig.7 Trend of safety factor for soil nailed slope with berms

Effect of orientation of nails on stability of soil-nailed slopes:

Contribution of nails to the additional shear resistance in soil mass is primarily governed by the mobilization of tensile forces in nails based on the mechanism of soil- nail interactions. The FE analyses are conducted to investigate the effect of nail's orientation on the overall stability[1,8]. Fig 8 shows the effect of nail orientation for various slope angles on the factor of safety of the excavation. The factor of safety for vertical soil-nailed walls decreases with an increase in nail's orientation. Factor of safety is found to decrease as the face of the excavation becomes steeper. Additionally, the optimal nail orientations for slope angles 80°, 70° and 60° are obtained as 22°, 31°, and 43° respectively.

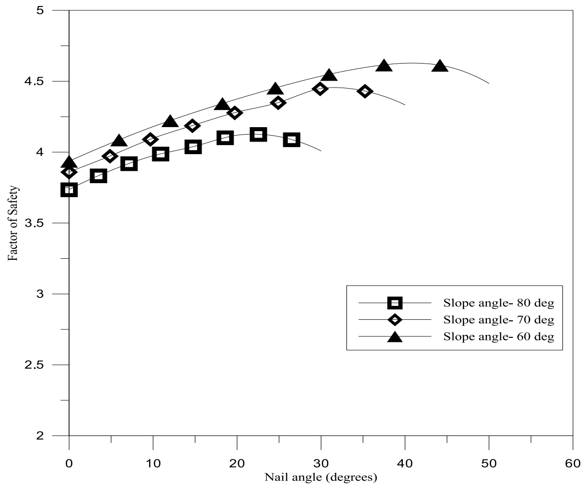

Fig.8 Optimal nail orientations for soil- nailed slopes

Base Heave

Base heave or the bearing capacity failure is one of the external failure modes for soil nail walls. Because of the wall facing does not extend below the bottom of excavation, the unbalanced load due to the excavation may cause the bottom of the excavation to heave and simulate a bearing capacity failure of foundation. Fig.9 shows the base heave at the bottom of excavation for the base model. Fig.10 and Fig 11 show the effect of nail spacing and lift thickness on upward heave in front of the soil nail wall face with construction stage.

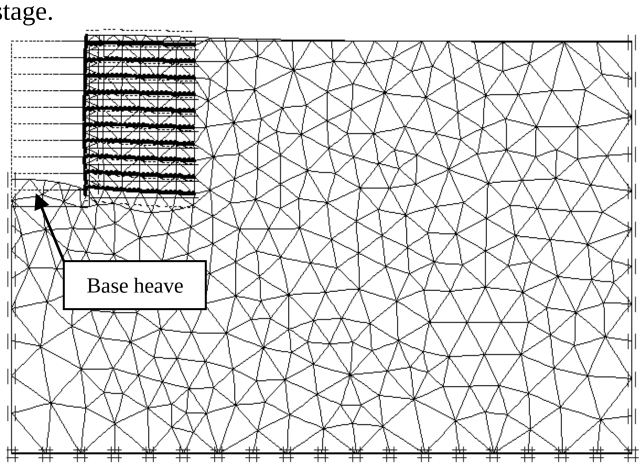

Fig.9 Base heave at the bottom of excavation for the base model

From the Fig.10 and Fig.11, it is clear that base heave increases as the construction proceeds. It is also understood that vertical spacing between nails does not have any significant effect on the excavation base heave. But as the lift thickness increase there is considerable change in the value of base heave.

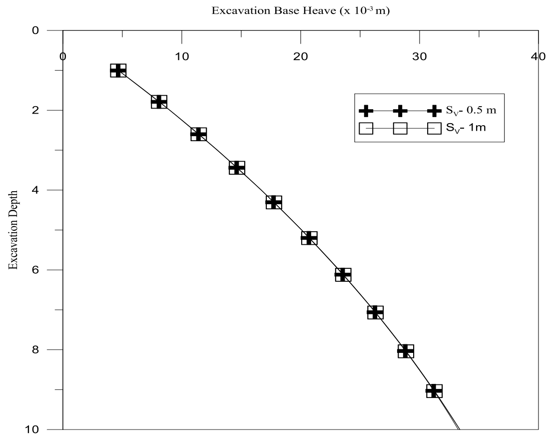

Fig.10 Effect of nail spacing on upward heave with construction stage

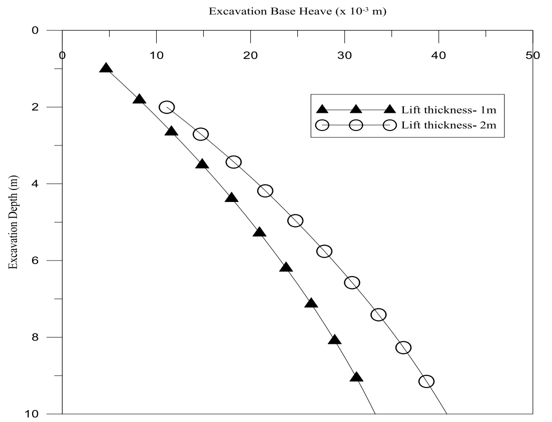

Fig.11 Effect of lift thickness on upward heave with construction stage.

Use of alternative reinforcement materials

The reinforcement can be used as either a permanent component of a reinforced soil structure or simply to provide a temporary increase in soil strength to allow the construction of an adjacent structure. The observed increase in the soil shear strength of a reinforced soil is always a direct result of relative soil-reinforcement displacement. The main properties of some available alternative reinforcement materials are listed below in the Table III.

TABLE III. Properties of alternate reinforcement materials

Reinforcement	Properties	Value
Carbon Fibre Reinforced Polymer	Modulus of Elasticity	150 GPa
	Diameter	20mm
Stainless Steel	Modulus of Elasticity	190 GPa
	Diameter	20mm
HDPE strips	Modulus of Elasticity	1 GPa
	Thickness	3mm
	Length	3m

The solid high yield deformed steel bars are commonly used as soil-nail reinforcement. Some other candidate materials are also considered for the reinforcement effect. The effect of various reinforcement materials on factor of safety and lateral displacement are studied in this section.

TABLE IV. Effect of various alternate reinforcement materials on Factor of Safety

Sl No	Reinforcement material	FOS
1	Carbon Fibre Reinforced Polymer	2.96
2	Stainless Steel (Grade 304)	3.45
3	HDPE strips	2.57

On examining the results in Table IV obtained after simulation, the usage of these candidate materials as soil nails is completely justified. The values of factor of safety obtained for various alternate reinforcement materials are within the palatable range comparing with the originally used deformed steel bars. Stainless steel shows very good result relative to other candidate materials. It shows higher factor of safety and lesser lateral displacement. But it is conspicuously observed that the high steel deformed bar is the most competent reinforcement material and is thus the commonly used reinforcement material.

CONCLUSIONS

Soil nailing is an accepted, economical, top-down construction technique that increases the overall shear strength of unsupported soils in situ through the installation of closely spaced reinforcing bars (nails) into the soil/rock. The finite element based software PLAXIS 2D is employed for the numerical simulation of the soil nailed structures.

A comprehensive parametric study is conducted to study the characteristics of soil nailed structures with variation in the properties of in-situ soil, nail and facing. On inclusion of nails, the FOS exhibited a drastic increase accompanied with an abated lateral deformation indicating an increase in the stability of excavation. It is found that the presence of berms enhance the stability of an excavation. It is observed that the best performance in the factor of safety is dependent on the nail orientation and the optimum nail orientation for slope angles of 80º, 70º and 60º are obtained. The effect of vertical spacing and lift thickness on base heave, one of the failure mode of nailed structures is studied. From this study it is affirmed that PLAXIS 2D can be accustomed for predicting the general behaviour of soil nailed structures.

ACKNOWLEDGMENT

The author expresses her heartfelt gratitude to Dr. S Chandrakaran, Professor & Project Supervisor, Environmental Geotechnology Engineering, Civil Engineering, National Institute of Technology, Calicut for his invaluable guidance, supervision, constant encouragement and dedicated cooperation throughout the project. She expresses her sincere thanks to Dr. T.P. Somasundaran, Professor & Head of the Department, Civil Engineering for providing necessary facilities for the completion of this work. Additional support is provided by the members of the Civil Engineering Laboratory at NIT Calicut for providing the required instrumentation and technical support throughout the completion of the work.

REFERENCES

1. Andre P. Lima, M. S. G Denise and S. F. J. S. Alberto (2003), “Deformability analysis of nailed soil Slopes”, XII Panamerican Conference on Soil Mechanics and Geotechnical Engineering, Cambridge, USA, ISBN 3-7739-5985-0 v.1, pp. 2127-2132.
2. Babu, G. L. S., Murthy, B. R. S. and Srinivas, A., (2002), “Analysis of construction factors influencing the behavior of soil nailed earth retaining walls”, Ground Improvement, 6, No. 3, pp. 137 – 143.
3. Babu, G. L. S. and Singh, V. P., (2010), “2D Numerical simulations of soil nail walls”, Geotech Geol Eng (2010) 28, pp. 299–309.
4. Briaud, J.L. and Lim, Y., (1997), “Soil nailed wall under piled bridge abutment: simulation and guidelines.” J. Geotech. Geoenviron. Eng, Vol 123(11), pp.1043–1050.
5. Chassie, R.G., (1993), “Soil nailing overview and soil nail wall facing design and current developments,” presented at the Tenth Annual International Bridge Conference, Pittsburgh, PA.
6. Du, Y. J., Ma L. , Shen S.L. and Sun W.J., (2011), “A case study of the behavior of soil-nail supported deep mixed wall in the soft deposit of Shanghai” , Lowland Technology International ,International Association of Lowland Technology (IALT), ISSN 1344-9656, December ,Vol. 13, No. 2, pp.1-8.
7. Ilamparuthi, K. and Aishwarya, T, “Study on soil nailing based on parametric analysis”,Anna University, India.
8. Fan, C. C. and Luo, J. H., (2008), “Numerical study on the optimum layout of soil nailed slopes” Computers. Geotech., Vol. 35(4), pp. 585–599.
9. FHWA., (2003), “Geotechnical engineering circular No. 7- soil nail walls”, Report FHWA0- IF-03-017, U. S. Department of Transportation, Federal Highway Administration, Ishington D. C.
10. Mingju Zhang, Erxiang Song and Zhaoyuan Chen (1999), “Ground movement analysis of soil nailing construction by 3-D FEM”, Computers and Geotechnics, Vol 25(4), December 1999, pp.191-204.
11. PLAXIS., (2002), “PLAXIS practice I.” Plaxis Bulletin, June, No. 12, pp.14-17.
12. PLAXIS.,(2006), PLAXIS user manual, Delft University of Technology & PLAXIS BV The Netherlands.
13. Rotte, V. M., Viswanadham, B. V. S., Chourasia, D., (2011),“Influence of slope geometry and nail parameters on the stability of soil-nailed slopes”, Interntl Journal of Geotech Engg, Vol. 5 (3), pp.267.
14. Schlosser, F.,(1991), “Discussion – The multicriteria theory in soil nailing.”Groun. Eng, November, pp.30-33.
15. Tuozzolo, T.J., (1997), “Stabilizing the stacks - a hybrid soil nailing system provides permanent underpinning for a historic college library”, Civil Engineering Magazine, December 1997.