Numerical Simulation of Soil Nailed Structures

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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 berms 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, γs             | 15 kN/m³    |
|                        | Friction angle, φ                  | 30°         |
|                        | Cohesion, c                        | 80 kN/m²    |
|                        | Young’s modulus of soil, E         | 40000 kPa   |
|                        | Permeability, kₚ                   | 10 m³/day   |
|                        | Backslope angle, β                 | 0°          |
| Wall Geometry          | Wall Height, H                     | 10 m        |
|                        | Wall inclination, α                | 90°         |
|                        | Backslope angle, β                 | 0°          |
| Nail properties (grouted nail) | Length of reinforcement, L         | 7m          |
|                        | Diameter of reinforcement          | 20 mm       |
|                        | Drill Hole diameter, Dₜ             | 100 mm      |
|                        | Nail inclination, η                 | 0°          |
|                        | Horizontal and vertical spacing (Sₜ x Sᵥ) | 1 m x 1m   |
|                        | Yield strength of nail (Fe 415)    | 415 MPa     |
|                        | Elasticity modulus of reinforcement, Eₚ | 200 GPa    |
| Facing properties (shotcrete) | Thickness of facing                | 100 mm      |
|                        | Elasticity modulus of grout (M20 concrete) Eₕ | 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/m² to 120 kN/m². The behaviour of the slope as the cohesion increases at the rate of 20kN/m², 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° to 40°. 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 deformation 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 $\gamma_{unsat}$ is increased by 1 kN/m$^3$. The effect of change of $\gamma_{unsat}$ 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 $0^\circ$ to $30^\circ$ and soil nailed slope behaviour is studied. Minimum lateral deformation and maximum FOS are obtained for a backslope angle of $0^\circ$. 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 conditions [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.
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.

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.

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.6 Trend of safety factor for vertical soil nailed slope

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

Fig.8 Optimal nail orientations for soil-nailed slopes

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](image1)

![Fig.11 Effect of lift thickness on upward heave with construction stage.](image2)

**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 80°, 70° and 60° 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.

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