Stabilization of Slopes Using Soil Nailing: Comparative Study of the Design by Conventional Method and Numerical Simulation

Ankit Kushwaha and P.K. Jain

PG Student, Department of Civil Engineering, Maulana Azad National Institute of Technology, Bhopal-462003
E-mail: ankit.manu26@gmail.com

Professor, Department of Civil Engineering, Maulana Azad National Institute of Technology, Bhopal-462003
E-mail: pkjain2808@gmail.com

ABSTRACT: The conventional design method (FHWA, 2003) and Numerical modeling (PLAXIS 2D) has been adopted for the design of soil nail stabilized slope, and a comparison between the two methods is made by varying the design parameters. A 10m vertical wall in lateritic soil with nails installed horizontally is considered, and a parametric study is performed on it. Variation in material properties such as cohesion, unit weight, and angle of shearing resistance was made and the output in terms of maximum lateral displacement and the Global Factor of Safety was obtained. It is noted that the conventional method assumes a constant value of output parameters (Maximum lateral displacement and Global Factor of Safety) whereas the results obtained from PLAXIS 2D show significant variation in the output parameters. Effect of varying geometric parameters such as back slope angle, the vertical spacing of nails, and facing thickness is also observed by PLAXIS 2D and presented.

Keywords: *Slope stabilization; Soil Nailing; Conventional Method; FHWA 2003; Numerical Simulation; PLAXIS 2D.*

Introduction

Soil nailing is the procedure of putting closely spaced steel bars (nails) that are thereafter encased in grout to passively reinforce existing ground (i.e., no post-tensioning). To provide continuity, shotcrete or concrete is put to the front of the excavation as the work goes from top to bottom. Stiff to hard fine-grained soils, such as stiff to hard clays, sandy clays, silty clays, sandy silts, and clayey silts, are favored for soil nailing. Gravels and sand with a high to very high density and some visible apparent cohesion perform well for soil nailing too.

The performance of soil nails is influenced by a complex mutual interaction between their main components, which is not taken into account by conventional soil nailing design approaches, which are based on limit equilibrium methods. As a result, in real-world applications, rigorous computational codes based on numerical techniques like the finite element method, discrete element method (for example Kim et al. 1997 [11]), & finite difference method are frequently used to carry out numerical simulations. It is well known that the choice of the proper relevant model parameters and the constitutive soil model employed have a major impact on the accuracy of numerical simulations.

Basic Elements of Soil Nailing

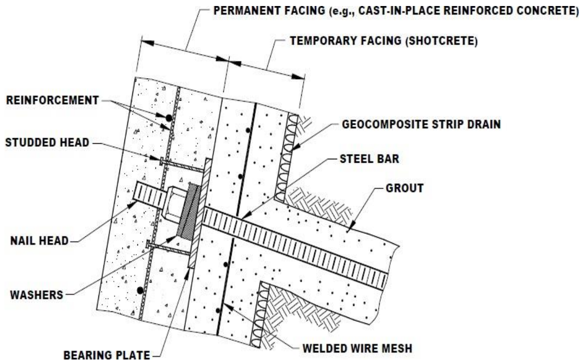

Fig 1: General cross-section of a soil nail wall (Byrne et al., 1998) [4]

- **Tendons** – The solid reinforced steel bars are the most important part of the soil nail wall system. These components are grouted in place after being put in pre-drilled drill holes. In reaction to the deformation of the retained materials during future excavation activities, nails are subjected to tensile stress.

- **Grout** – After the nail is in place, the pre-drilled borehole is filled with grout. The grout's main purpose is to transfer stress out from the ground to the nail. The soil nail is also protected from corrosion to a certain extent by the grout.

- **Nail head** – The screwed side of the soil nail that protrudes from the wall facing is known as the nail head.

- **Bearing plate, hex nut and washer** – These components are utilised to link the soil nail to the facing and are fastened to the nail head.

- **Permanent and temporary facing** – In most cases, the facing provides structural connection. The temporary facing supports the exposed soil by acting as a bearing surface for the bearing plate. Before the excavation grades are advanced, this face is placed on the unsupported excavation. After the soil nails are in place and the hex nut is tightened, the permanent facing is applied over the temporary facing.

- **Geo-composite strip drainage** – Before applying the temporary facing, the geo-composite strip drainage system media is placed to enable the collection and conveyance of any seepage water which might migrate to the temporary face.

Behaviour And Mechanism Of Soil Nailing

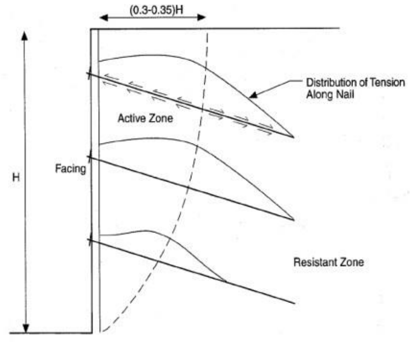

Fig 2: Conceptual soil nail behaviour (Byrne et al, 1998) [4]

Soil nails are passive additions that increase the soil's shear resistance. The active and passive regions of the soil nail system are split. The active portion of the slope deforms during failure, resulting in longitudinal displacement along soil nails positioned across the slip plane. This causes tensile pressures to develop in the passive zone of the soil nail, preventing the active zone from deforming. The normal force acting on the slip plane increases as a result of the tension force, reducing the pushing shear force. The soil nails are embedded in a passive zone, which prevents the nail from being pulled out of the slope by friction between the nails and the soil. The needed quantity of nail length should be put in the resistive zone based on the two mechanisms mentioned above. The cumulative effect of nail head strength and tension force generated in the active zone must also be sufficient to give the appropriate nail tension at the slip surface.

Difference Between Conventional Method And NumericalSimulation

There are many approaches with the help of which the design of a stable soil nailed slope can be achieved. In the present study, two approaches have been considered namely FHWA, 2003 which has been referred to as a conventional design procedure and numerical simulation which has been achieved with the assistance of PLAXIS 2D software. The design principles presented in the FHWA approach are based on ASD (Allowable Stress Design) procedure. It also introduces new simplified charts that could be used in the preliminary design phase. On the other hand, PLAXIS 2D employs LRFD (Load and Resistance Factor Design) analysis for the simulation of the model. The software is embedded with features to find solutions for different aspects of complex geotechnical structures using theoretically sound and robust computational procedures. For all designs, regardless of load type, ASD uses a constant factor of safety, whereas LRFD compels a higher safety factor for loads with greater variability (less predictability). The behaviour at the point of failure, such as ductility and warning before failure, is taken into account in the LRFD technique; however it is not possible in the ASD method because the structure is analyzed at the service stage.

In the analysis and design of soil nailing with marginal conservatism, Jewell and Pedley, 1992 [9] (vide Babu and Singh (2009) [3]) determined that the effects of shear and bending resistances could be ignored. Soil nailing analysis and design have been radically simplified in practice, ignoring the effects of bending and shear resistances of soil nails, and the shear and bending strengths of the soil nails have been conservatively disregarded in the conventional design procedure due to this relatively modest contribution.

Users of PLAXIS 2D for the study of soil nail structures have been documented to utilize both geogrid elements (for example Plaxis, 2002 [13]; Liew and Khoo, 2006 [12]) and Plate element (e.g. Babu and Singh, 2009 [3]; Fan and Luo, 2008 [5]) structural components to model nails, according to the literature. It's worth noting that the bending stiffness of soil nails is completely ignored when using geogrid structural components; on the other hand, plate elements account for it. As a result, in this study, the plate element is taken into account while designing a nail in a soil-nailed wall.

Modeling Features

For this study, different parameters of soil and other variables are pre-determined from the case study in Jayanandan and Chandrakaran, 2015 [8] and are therefore needed to run the slope stability analysis via both the methods are provided in Table 1. Figure 1 shows the geometry of the soil nailed slope utilized in the numerical simulation. The figure represents a generic representation of the model, with geometrical and material parameters changing over time throughout parametric investigations. It's crucial to position the boundaries in such a way that they have the least possible impact on the results obtained from the PLAXIS 2D of the soil nail wall. The bottom of the mesh should be set at a depth where the earth becomes noticeably tougher. The soil nailing slope is built by excavating earth in numerous stages, each one measuring 1 metre in height. The 1st row of nails is installed at a distance of 0.5m from the top of the excavation, and the subsequent rows are installed at a vertical spacing of 1 metre. The effect of varying material parameters (cohesion, angle of shearing resistance, unit weight) and geometrical parameters (Back slope angle, vertical spacing of nail and facing thickness) is observed with respect to the resulting maximum horizontal displacement and the FOS against global stability. The conventional method considers the Global FOS as 1.35 for the design and the maximum horizontal displacement as 0.02% of the wall height despite the change in parameters whereas the numerical simulation by PLAXIS 2D provides more accurate results.

Table 1: General Material Properties adopted for the study (Jayanandan and Chandrakaran, 2015) [8]

INPUT	PROPERTIES	VALUE
Properties of soil	Soil's Unit Weight	
	γ_{unsat}	15 KN/m^3
	γ_{sat}	17 KN/m^3
	Shearing resistance angle, ϕ	30°
	Soil Cohesion, c	80 KN/m^2
	Young's modulus of soil, E	40000 kPa
	Permeability, k_x	10 m/day
	k_y	10 m/day
	Poisson's ratio, μ	0.25
Geometry of wall	Height of wall, H	10 m
	Inclination of wall, α	90°
	Angle of backslope, β	0°
Properties of nail (Grouted Nail)	Reinforcement's length, L	7 m
	Reinforcement's diameter	20 mm
	Diameter of drill hole, D_{DH}	100 mm
	Inclination of the nail, ŋ	0°
	Vertical and Horizontal spacing	1m X 1m
	Yield strength of nail	415 MPa
	Elasticity modulus of reinforcement, E_n	200 GPa
Facing Properties (Shotcrete)	Facing's thickness	100 mm
	Elasticity modulus of grout, E_g	22 GPa

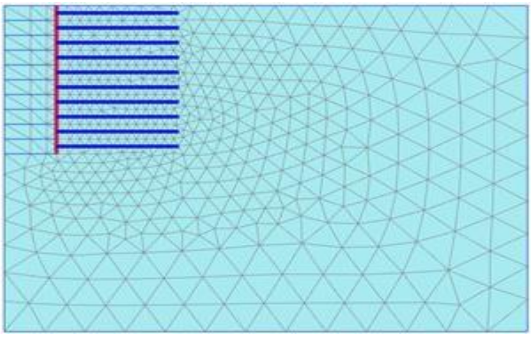

Fig 3: Finite element model depicting a soil nailed wall (H = 10m)

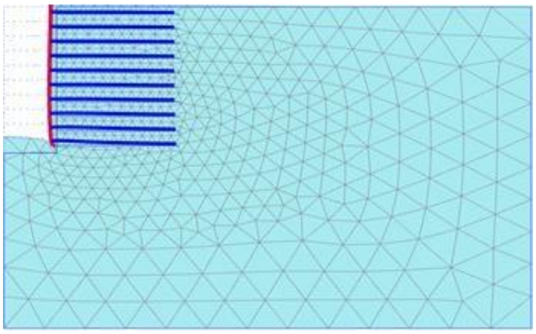

Fig 4: Deformed mesh of soil nailed wall

Results And Discussion

Material Parametric Study

The remainder of the properties, as well as the geometry of this case, are kept unchanged while executing a parametric analysis on any material property. The impact of various parameters on the soil nailed structure's stability is then determined. To conduct the investigation, the material qualities of in-situ soil are modified. What effect does the alteration in these in-situ soil characteristics has on the deformation and factor of safety of the soil nailed slope has been evaluated in this study.

- **Effect of change in Cohesion:** For the adjoining soil, the value of cohesiveness is modified between 20 KN/m^2 and 120 KN/m^2, whereas the remainder of the properties, as well as the geometry of the model, are kept unchanged. It is observed that the value of the maximum lateral displacement and global factor of safety, when calculated from conventional method remains unchanged that is their values remain as 20 mm and 1.35 respectively despite the change, whereas when calculated by numerical simulation, the lateral displacement decreases from 13.84mm to 9.58mm and Global FOS increases from 1.869 to 4.677 with the increase in cohesion between 20 KN/m^2 and 120 KN/m^2 of the soil.

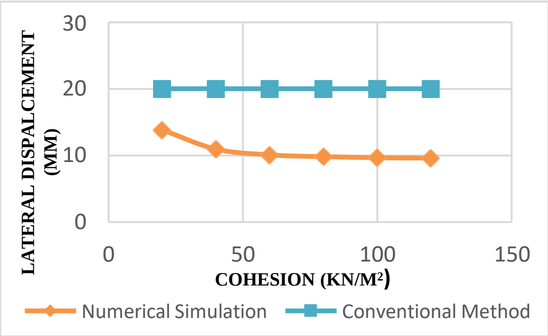

Fig 5: Effect of change in lateral displacement with cohesion

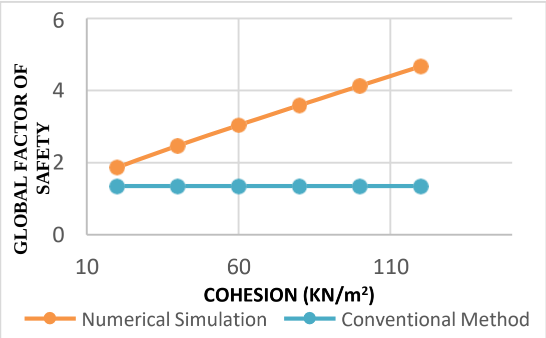

Fig 6: Effect of change in Global FOS with cohesion

- **Effect of change in angle of shearing resistance:** When the value of angle of shear resistance is modified, whereas the remainder of the properties, as well as the geometry of the model, are kept unchanged. It is observed that the value of the lateral displacement and global factor of safety, when calculated from conventional method remains unchanged that is their values remain as 20mm and 1.35 respectively despite the change whereas when calculated by numerical simulation, the lateral displacement decreases from 12.34mm to 8.603mm and Global FOS increases from 3.066 to 4.221 with the increase in the angle of shearing resistance from 20° to 40° of the soil.

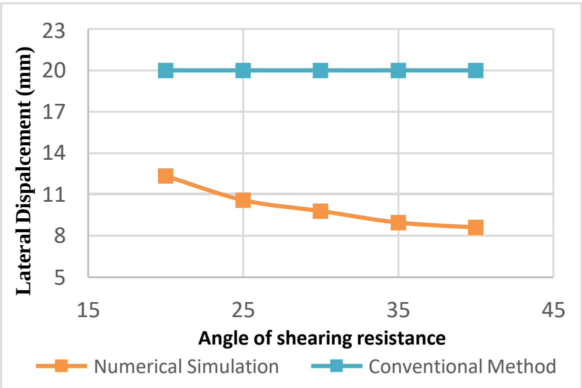

Fig 7: Effect of change in lateral displacement with angle of shearing resistance

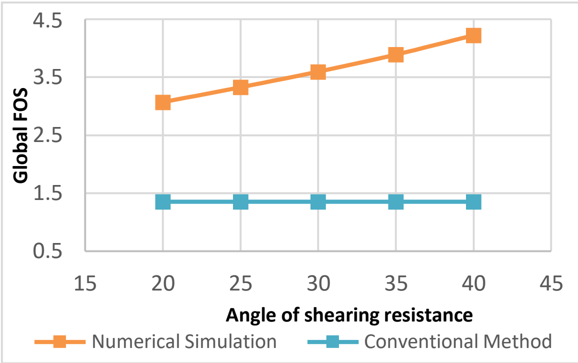

Fig 8: Effect of change in Global FOS with angle of shearing resistance

- **Effect of change in unit weight of soil:** When the value of unsaturated unit weight is modified, whereas the remainder of the properties, as well as the geometry of the model, are kept unchanged. It is observed that the value of the lateral displacement and global factor of safety, when calculated from conventional method remains unchanged that is their values remain as 20mm and 1.35 respectively despite the change, on the other hand when calculated by numerical simulation, the lateral displacement increases from 9.062mm to 13.73mm and Global FOS decreases from 3.718 to 3.065 with the increase in unsaturated unit weight from 14 KN/m^3 to 20 KN/m^3 of the soil.

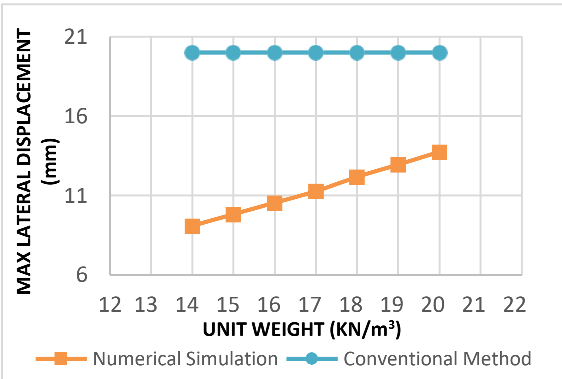

Fig 9: Effect of change in lateral displacement with unit weight

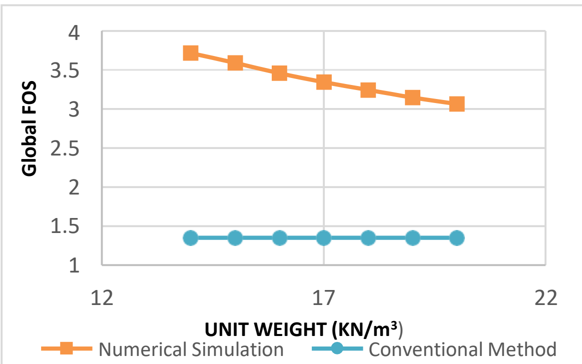

Fig 10: Effect of change in lateral displacement with unit weight

Geometric Parametric Study

While keeping the remaining of properties identical, In this study, the effect of variation of many of the geometrical properties by numerical simulation is observed and reported. The attributes of both the wall and the nail are modified, and the impact on deformation and the global factor of safety is investigated.

- **Back slope Angle:** The impact of back slope angle on horizontal deformation and safety factors is investigated. The findings show that as the back slope increases, the slope becomes more unstable. The lateral displacement increases as the back slope angle increases, and the factor of safety reduces. The back slope batter is increased from 0 to 30 degrees, and the behavior of soil nailed slopes is investigated. For a backslope angle of 0 degrees, the minimum lateral displacement i.e., 9.796 mm and maximum FOS of 3.592 are obtained. In other terms, an excavation should always have a horizontal backslope.

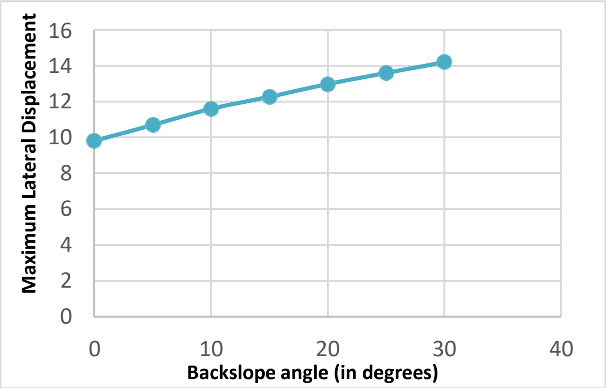

Fig 11: Effect of change of backslope angle in Max Lateral displacement

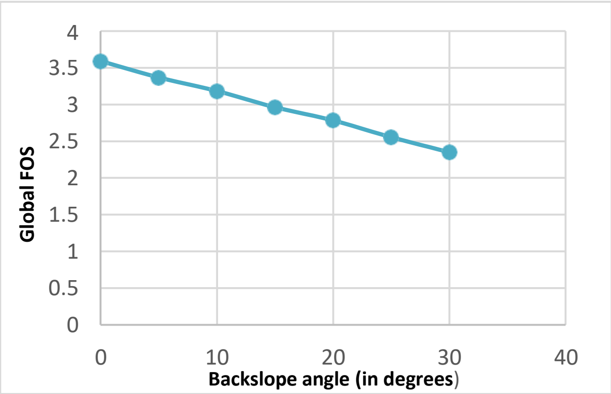

Fig 12: Effect of change of backslope angle in Global FOS

- **Vertical nail spacing:** The effect of vertical nail spacing on horizontal deflection and safety factor is investigated. The factor of safety increases dramatically near the vertical cut as the nail spacing reduces, and the deformation lowers as the nail spacing decreases. The vertical spacing was raised from 0.5m to 2m with a 0.5m increase per step, resulting in a 9.671mm to 10.186mm increase in maximum lateral displacement and insignificant fall in FOS from 3.689 to 3.388.

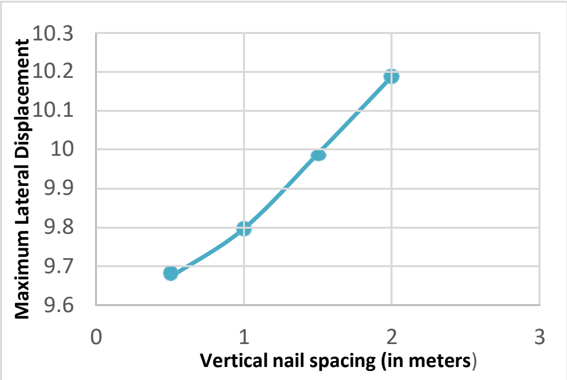

Fig 13: Effect of change of Vertical Nail spacing in Max Lateral displacement

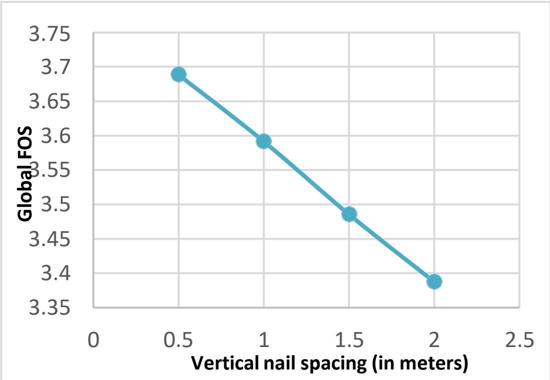

Fig 14: Effect of change of Vertical Nail spacing in Max Lateral displacement

- **Facing Stiffness:** An important geometrical parameter includes the facing thickness of the wall. It was observed that when the facing thickness increases from 75mm to 200mm, the maximum lateral displacement and the global FOS experiences no significant difference. Babu et al, 2002, also came up with similar results.

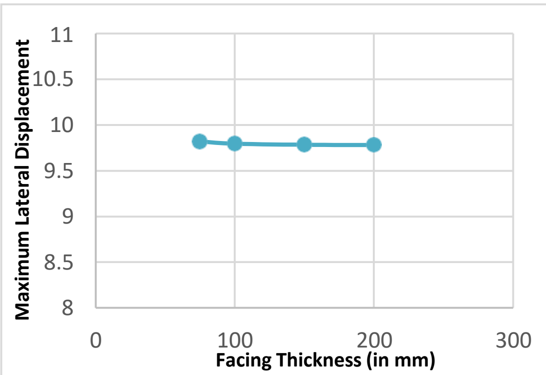

Fig 15: Effect of change of facing thickness in Max Lateral displacement

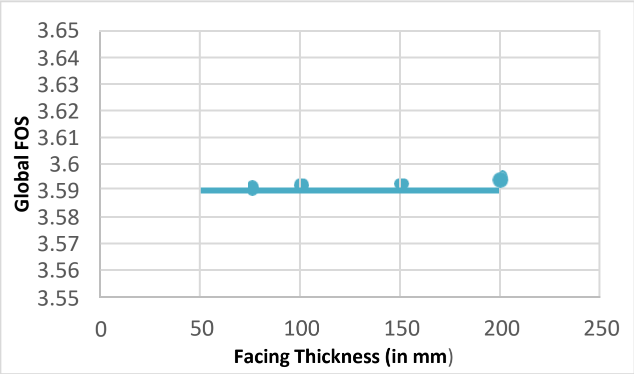

Fig 16: Effect of change of facing thickness in Global FOS

Conclusions

- With the change in cohesion and angle of shearing resistance of the in-situ soil, it is observed that the value of the maximum lateral displacement and global factor of safety, when calculated from conventional method remains unchanged whereas when calculated by numerical simulation, the lateral displacement decreases and Global FOS increases with the increase in the mentioned parameters.
- With the change in unit weight of the in-situ soil, it is observed that the value of the maximum lateral displacement and global factor of safety, when calculated from conventional method remains unchanged whereas when calculated by numerical simulation, the lateral displacement increases and the Global FOS decreases with the increase in the mentioned parameter.
- When the back slope angle and the vertical spacing between the nails increases, the maximum lateral displacement increases and the Global FOS decreases whereas the change in facing thickness has no significant effect on these.

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