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Comparative study of 2D and 3D analysis of soil nailed structures using numerical simulation: A case study of Bandipur, Tanahun

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Abstract
Soil nails are passive reinforcing elements that are inserted sub-horizontally into the ground to stabilize unstable soil mass and other underground or surface excavations in soil. Soil nailing technique are classified into different types based on how they are installed in the field. Driven nails are directly pushed into the structure along with the excavation works whereas in drilled and grout type soil nail, a hole is initially drilled at the excavated soil face and nails are installed afterwards and filled with grout at low pressure. This study conducts a comparative analysis between 2D and 3D analyses of driven and grouted nails using finite element analysis methods (FEM) in Plaxis 2D and Plaxis 3D respectively. Results of the simulations indicated that the use of 3D models is preferable for analysis of soil nail walls. In this work both driven and grouted soil nail are simulated in 2D and 3D using the embedded beam element and Factor of Safety (FoS), maximum deformation in the soil nailed wall, maximum axial tension force and overall stability of the structure is checked and observed at different stages of construction. Results shows that FoS given by 3D analysis is less in comparison to 2D analysis but the maximum deformations in the structure is more in 2D as compared by 3D in both driven and grouted nails.

Keywords
Soil Nail, 2D, 3D, Embedded beam, Stability, Finite Element Method, Factor of Safety(FoS)

1. Introduction

Soil Nailing is a method of soil stabilization, where a long slender elements are inserted at closed spacing on a in unstable soil slopes either by driving them directly or drilling and grouting methods. Soil nailing initially developed as "New Austrian Tunnelling Method," purely for tunneling works, in modern times is being widely used in various other underground and excavation works in the field of the civil engineering due to its flexibility, easy adaptability, quick construction rate. Different components of the soil nailing consists of Reinforcement bar (Nail or Tendon), Nail head, Grout, Centralizers, Temporary and Permanent facing [1].

Soil nailing technique has become popular in Europe in the 70s decade and its popularity has also extended to North America in 1980s. Then after, soil nailing has been used in the many soil and rock slopes in Asia too. In Hong Kong soil nailing is firstly used to provide the support on the deeply weathered rock zones [2]. This technique was extensively used in Japan in late 90s, around 4000km length of the soil nailing structure along the expressway were built in the Japan. We can also find the soil nail retaining wall to stabilize the roadway and railway slope in India [2]. Soil nail walls offer greater benefits compared to alternative top-down retaining systems in situations where the soil can temporarily withstand brief, vertical, or sub-vertical excavations without additional support.

Soil nailing techniques are primarily categorized based on installation methods namely drill and grouted soil nailing, driven soil nailing, self-drilling soil nail method, jet-grouted soil nail, and launched soil nail methods. Among these, the drill and grouted technique is the most prevalent in practical applications. In this method, a nail is placed into a pre-drilled hole, which is subsequently filled with grout at low pressure. This versatile approach is suitable for both permanent and temporary structures. On the other hand, the driven soil nailing technique involves simultaneously driving the nail into the structure during excavation. Typically drilled nails are employed for temporary purposes and walls of limited height, this method differs from the drill and grouted technique in its application and purpose.

Soil nailing is quickly becoming popular in Nepal too though not used extensively to the extent in which it should have been. The recent preference of nailing in roadway cuts is due its adoption of a "top-down" construction sequence. It is being effectively used to stabilize the road side slope in the Narayanghad-Muglin road extension project [3]. A study has also been carried to stabilize the failed and critical slope using the soil nailing technique in the Nepalthok-Khurkot section [4]. Currently soil nailing practice is performed in the Ring Road of the Kathmandu valley, Narayanghad-Muglin road, Pasang Lambhu highway (Figure 1), Fast track and many others road and large hydropower projects. Numerical software based modeling have been performed to analyze behaviour of soil nail walls using finite element methods. These studies aimed to assess how the orientation of the nail layout affects the safety and deformation response of the structure when subjected to various loads. Various numerical study had been carried out in order to perform the numerical analysis of the soil nail wall using finite element methods. Study had been carried out to determine the influence of the orientation of the nail layout on the safety and deformation of the structure.

Two-dimensional analysis study was done on a modeled soil nail wall in a Plaxis 2D by simulating the nail as both geogrid

Figure 1: Soil nailing being done at Pasang Lambhu Highway at Dhading District

and plate material [5]. Likewise, a different investigation conducted through the Finite Element Method (FEM)analysis recommended employing sophisticated models such as hardening models for simulating soft soil [5].

While 2D numerical analyses are capable of predicting displacements, they lack the ability to accurately represent the behavior of nails due to their simulation as continuous elements along the longitudinal direction resulting in some. To overcome this, there is a preference for 3D numerical analyses in principle, though they increased modeling efforts.

1.1 Research Objectives

1.1.1 Main Objective:

The general objective of this work is to carry out comparative analysis 2D and 3D modeling of the soil nailed walls by varying the nail and geometric parameters and to suggest the results.

1.1.2 Specific Objectives:

The specific objective of this research work are as follows:

- To perform the analysis in drill and grout and driven nails by varying different nail and wall geometrical parameters using 2D and 3D model.
- To compare the results between 2D and 3D simulation of soil nailed structures.
- To compare findings of FEM with previously established limit-equilibrium methods and former research papers.

1.1.3 Scope and Limitations:

- Study is limited to the soil obtained from the study area.
- Different parameters not available from the field and lab test results have been approximated using suitable available literatures.
- Real model construction, stagewise field measurement of deformations, pull out test and other field tests weren't possible to conduct.

2. Study area

The study area is located in Bandipur, Tanahun district, Gandaki Province, Nepal (Refer Figure 2). Study area lies the Lesser Himalayan Zone and is located at a distance of about 70 kms from the epicenter of 2072 Barpak earthquake. Subsurface exploration was done using Percussion Drilling of 100mm nominal diameter and laboratory tests were done on selected disturbed/ undisturbed soil samples. Direct shear tests results was used to find out the engineering properties of soil (Refer Figure 3).

Soil parameters used in the numerical modeling is taken from test results of this specific site and was found to have an average cohesion value of 0 kN/m^2 and friction angle 31.6°.

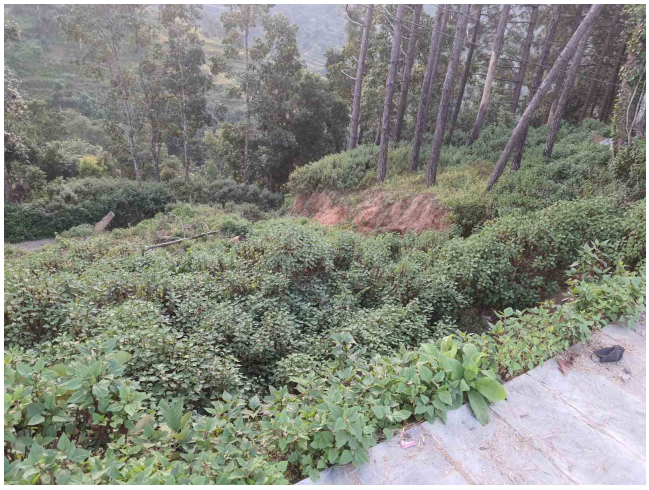

Figure 2: Bandipur site

Figure 3: Site exploration being conducted at site

3. Materials and Methods

3.1 Analysis of Soil Nail Wall

3.1.1 Limit Equilibrium Method of Analysis of Soil Nail Wall

Limit equilibrium method is one of the common methods of evaluating the global saftey of the Soil Nail Walls which considers the shearing, tension, pull-out resistance of the nail. Different methods of evaluating safety using limit equilibrium

method includes. Force elements used to find the global factor of safety using limit equilibrium methods [6].

3.1.2 Finite Element Method of Analysis of Soil Nail Wall

As the limit equilibrium method is unable to predict the deformation of the soil nail wall structure nowadays finite element method is used to predict the deformation of the soil nail wall. Different software like PLAXIS, ABACUS, PHASE etc. are the common Finite Element Software to simulate the soil nail wall.

3.2 Wall Geometry

Table 1: Soil Nail excavation wall geometry, Nail, Grout and facing

Parameter	Value
Vertical Height of Wall H (m)	12
Face batter angle α(deg)	15
Backslope angle β(deg)	15
Material Property	Elastic
Yield Strength of Nail tendon f_y (Mpa)	415
Elastic modulus of Nail E_n (Gpa)	200
Elastic modulus of Grout material E_g(Gpa)	22
Elastic modulus of Shotcrete E_s (Gpa)	22
Daimeter of Drill hole (mm)	100
Facing thickness t (mm)	200
Live load during Construction (kN/m^2)	8

3.3 Soil Properties

Mohr Coulomb model is used here for the numerical analysis. It is an elastic perfectly plastic model, which considers both Hooke's law and the Coulomb's failure criterion. It is a first order model for representing soils which requires the following basic input parameters.The parameters include Young's modulus E and Poisson's ν for soil elasticity, soil friction angle ϕ and soil cohesion c for soil plasticity, and the dilatancy angle ψ. In this MC model since linear elastic prefailure stiffness behavior is supposed, this model does have its shortcomings in terms of prediction of the deformation behavior before failure [7].

Table 2: Soil Parameters used in Numerical Analysis using Mohr-Columb's (MC) model

Parameter	Value
Cohesion, c (kN/m^2)	10
Friction angle, ϕ (deg)	27
Dilatancy angle, ψ (deg)	0
Unit Weight of nail, γ_n (kN/m^3)	19
Young's Mod. of Elasticity, E (kN/m^2)	20000
Poisson's ratio, ν	0.3 [1]

3.4 Nail Parameters

3.4.1 Drill and Grout Nail

1. Length of the soil nail is taken equal to H i.e 12 m.
2. Spacing of the soil nail is 1.5m in both horizontal and vertical directions.
3. Diameter of the soil nail taken as 25 mm in this study.
4. Inclination of the soil nail wall is taken as 15°.

3.4.2 Driven Soil Nail

1. Length of the soil nail is taken equal to height of excavation i.e 6 m.
2. Spacing of the soil nail is taken as 0.6 m in both horizontal and vertical directions.
3. Diameter of the soil nail taken for analysis is taken as 32 mm as per DoR guidelines.
4. Inclination of the soil nail wall is taken as 0 degrees i.e vertical wall face.

Table 3: Nail Parameters used in Numerical Analysis

Parameter	Value
Diameter of nail, d (mm)	25
Spacing of Nail, $S_h \times S_v (m \times m)$	1.5×1.5
Unit Weight, γ_{nail}(kN/m^3)	78.5
Skin Friction for Driven Nail below 8m (kN/m)	28.15 [1]
Skin Friction for Driven Nail above 8m (kN/m)	17.32 [1]
Skin Friction for Drilled Nail (kN/m)	43.32 [1]

4. Numerical Modelling

For the purpose of numerical simulation, in case of drill and grout soil nail wall height of 12 m with 15° inclined face and horizontal backfill as shown in Figure 4 and 5 and in case of driven soil nail wall, a height of 6 m with vertical face and horizontal backfill as shown in Figure 6 and 7 were modeled,designed and analyzed in the study. Design of the soil nail wall is done as per the allowable stress design procedure given in standard literature [8]. Each type of soil nail models are modelled in both 2D and 3D using the Plaxis 2D and 3D software respectively. In both analysis we used to simulate the long term behavior of the soil nailed wall using drained conditions. PLAXIS 2D software is used to emulate the finite element based 2D simulations of the soil nail wall assuming it be a plane strain problem. In case of 3D analysis Plaxis 3D is used to carryout the simulation considering the 3D behavior of the soil nailed walls and its components. The width of the 3D model is taken as 5 m to limit the effects of boundary conditions.

In both 2D and 3D model analysis, calculations are performed considering the soil to show behavior as predicted by MC-model soil. Soil nails were modeled as the embedded row beam

element. The values of global stability (FoS), displacements of the excavation base, lateral deformations and axial forces in the nails after each construction stage is observed and conclusions are drawn from those results.

For the grouted nails, it is essential to calculate an equivalent modulus of elasticity E_{eq} which is calculated by taking into effect the contribution of elastic stiffness modulus of both grout and nail materials.From the fundamentals of mechanics of materials, E_{eq} can be determined as

$$E_{eq} = E_n\left(\frac{A_n}{A}\right) + E_g\left(\frac{A_g}{A}\right) \quad (1)$$

where,
E_{eq}= Equivalent modulus of Elasticity of drill and grout Nail
E_n= Modulus of Elasticity of Nail
E_g= Modulus of Elasticity of Grout
A_n= Cross Sectional area of Nail
A_g= Cross Sectional Area of the grout ($A_g = A - A_n$)
A= Cross section of the hole

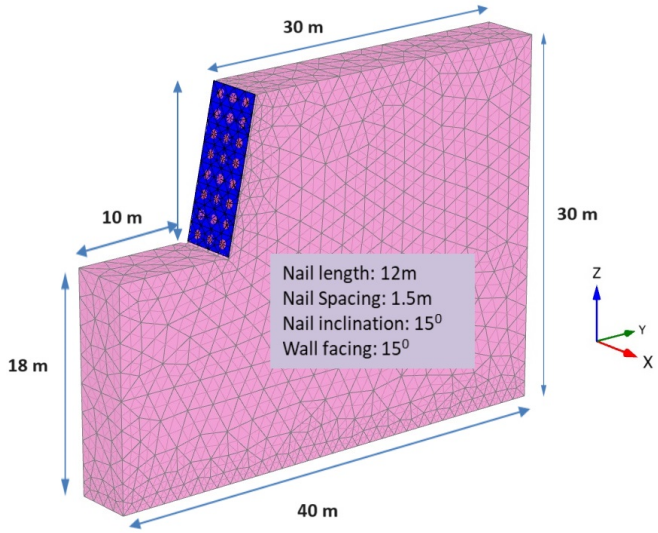

Figure 4: 3D model of drill and grout type nail

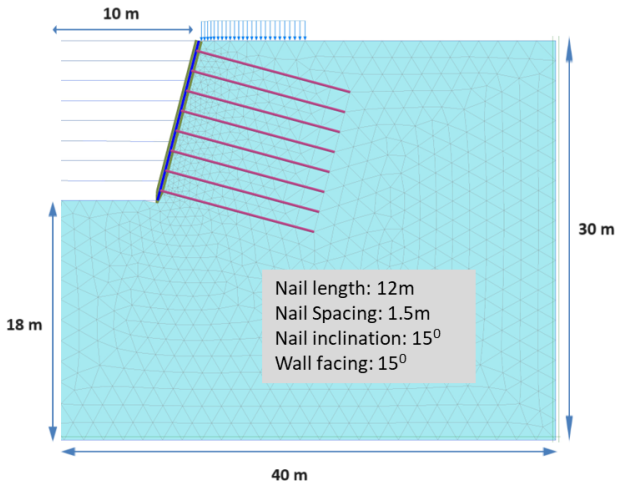

Figure 5: 2D model of drill and grout type nail

A surcharge load of $8kN/m^2$ is applied on the top of the wall to 8m beyond to simulate the effect of live load due to the

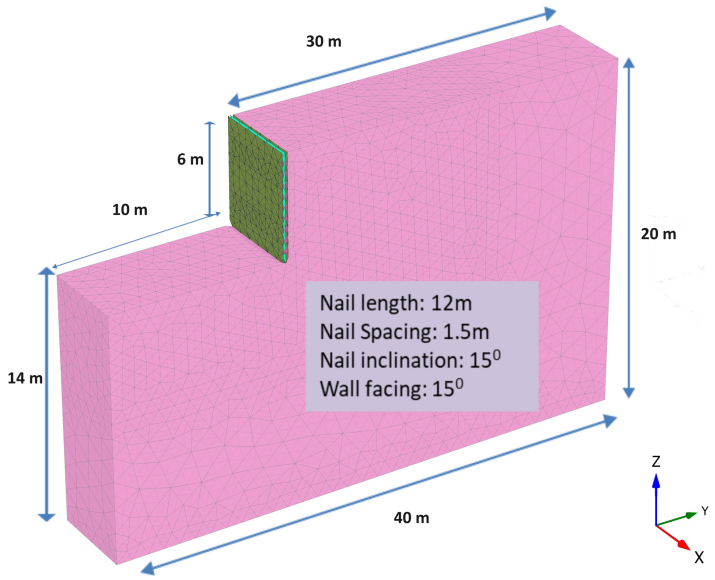

Figure 6: 3D model of driven type nail

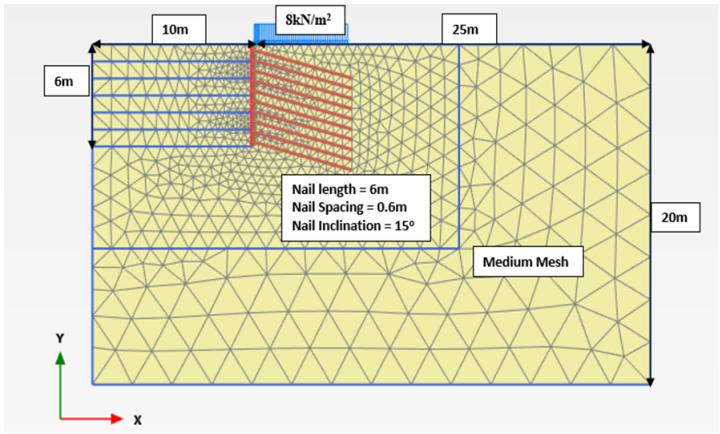

Figure 7: 2D model of driven type nail

operation of the construction equipment during soil nail construction procedure. A global medium mesh is chosen for the analysis. The top boundary is set free in both the horizontal and vertical direction, right and left boundaries are fixed only in the horizontal direction and bottom boundary is set fixed in both directions. Now, a required number of stages for the analysis are defined which is analogues with the field stage construction procedure which is defined in the stage construction tab in the Plaxis. The construction stages were completed in 8 steps (1.5 m depth excavation in each phase) in case of drill and grout type soil nail and in 6 steps (1 m depth excavation in each phase) in case of driven type soil nail.

At first initial condition is simulated in the K_o procedure, then the stage wise construction is performed under 'plastic type' calculation methods up to the required level. Safety calculation is performed to find out the factor of safety as per requirement. Global factor of safety is performed at the end of the simulation process. If it is necessary to calculate the intermediate factor of safety then safety calculation is performed by following the required stage. Point at the top of the wall is selected to know the lateral deformation on the wall due to the excavation process.

5. Results and Discussion

From the analysis in Plaxis 2D and 3D of the same arrangement for both drilled and grout and driven nails we observed that the maximum displacement shown by 2D analysis is more compared to 3D for each construction stage with an average value of 24.68% in case of grouted nails and 50% in case of driven nails which implied that effect of 2D and 3D analyis is more prominent in driven nails compared to drill and grout nail which is shown in Figure 8 and 9. Also, there is a significant difference between the displacements predicted by 2D and 3D analysis as the depth of the excavation increases. In the safety analysis the FoS predicted by 2D model is more than that predicted by the 3D model in case of driven nails. In case of driven nails the axial forces developed in 2D analysis is greater than that predicted by 3D analysis by around 25% The results of the safety analysis and FoS predicted by 2D model is more than that predicted by the 3D model which is shown in Figure 10.

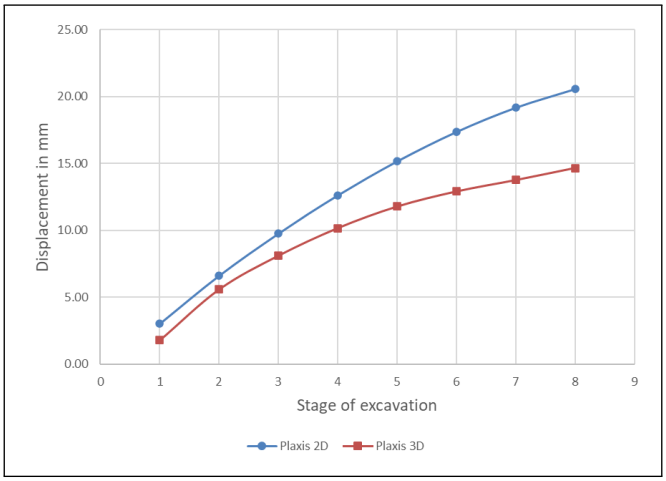

Figure 8: Comparison of max. displacements between 2D and 3D analysis in drill and grout soil nails for 12 m wall height

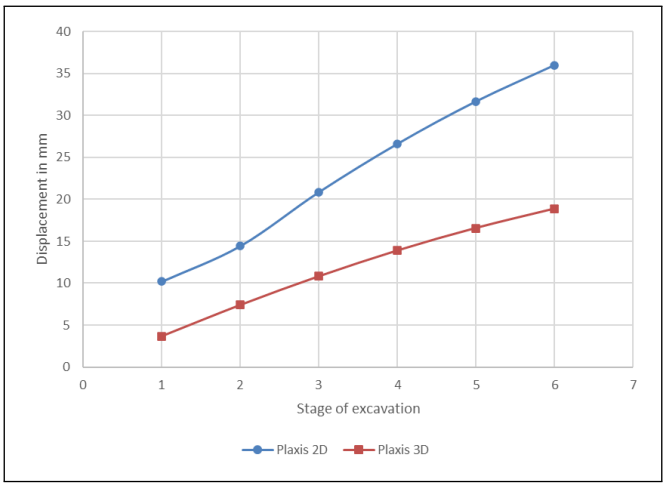

Figure 9: Comparison of max. displacements between 2D and 3D analysis in driven nails for 6 m wall height

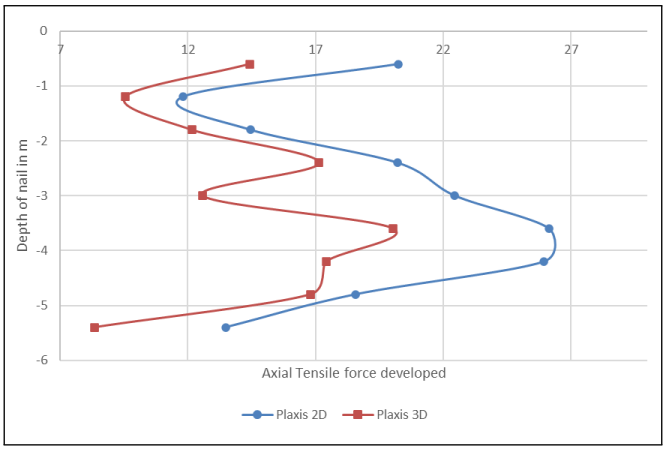

Figure 10: Comparison of max. Axial Tensile force in 2D and 3D analysis in driven soil nails

The results of the safety analysis and FoS predicted by 2D model is more than that predicted by the 3D model which is shown in Table 4.

Table 4: Comparison of max. displacements (in mm) between 2D and 3D analysis in driven soil nails

Stage	2d analysis	3d analysis	% difference	Remarks
1	10.19	3.688	63.81%	$\|u\|$
2	14.44	7.409	48.70%	$\|u\|$
3	20.87	10.82	48.16%	$\|u\|$
4	26.63	13.89	47.84%	$\|u\|$
5	31.69	16.57	47.71%	$\|u\|$
6	36.01	18.87	47.60%	$\|u\|$
FOS	1.824	1.487	18.48%	M_{sf}

5.1 Validations

1. Similar results can be seen in the results obtained in study conducted by Stauffer where the author has used the results of 3D numerical analyses on soil-Nailed Slopes by Finite Element Method to validate the previously performed 2D analysis [9].

2. Analysis of Clay Slopes Using 2D and 3D FEM Study shows that results of 3D analysis simulates the real behavior of slopes having infinite length more better and gives realistic results in comparison to the simplified 2D analysis [10].

3. A research on 3D Modeling of Soil Nailed Excavations suggests that 2D models are in fact too rigid due to the approximation of nails by planar inclusions [11].

6. Conclusion and Recommendation

Following conclusion are drawn from this study.

1. The difference in results between the 2D and 3D models is more prominent in driven nails compared to drill and grout nail.

2. In case of driven nails the axial forces developed in 2D analysis is greater than that predicted by 3D analysis by around 25
3. The displacement behavior predicted by 2D analysis is more conservative by 42.5% in case of driven and 50.3% in case of drill and grout nails in comparison to 3D analysis.
4. The FOS predicted by 2D analysis is more in comparison to 3D analysis by 18.5%.
5. It is recommended to use 3D analysis for analysis of soil nail structures for a more economic and efficient design.

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