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Slope Stability Analysis of Hill Side Steep Cut Slope and Its Stabilization by the Method Soil Nailing Technique, A Case Study of Narayanghat-Mugling Road Section

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Abstract

On hill roads of Nepal, soil nailed walls provide more economical design in the steep cut slopes as they minimize the quantity of excavation, occupy less space, have easier construction sequence and stabilize cut slopes of higher height compared to those of traditional gravity walls. This paper attempts to give a clear insight of the stability analysis of steep cut slope sections of Narayanghat-Mugling road by performing numerical simulations using Finite Element Method (PLAXIS 2D software) on unstable and reinforced soil nailed slopes, and thereby, find the optimized design for critical water table condition. Samples were tested in laboratory for soil classification and shear parameters. 40 numerical models in PLAXIS V8 were developed for sensitivity analysis of four parameters of soil nail i.e. diameter, inclination, length and spacing based on factor of safety and resulted length as the most sensitive parameter. Further, the result of this study is that with the increase in water table, the length of soil nail must be increased to ensure the stability condition. The optimized length of soil nail for 5m, 5.5m, 6m and 7m water table from bottom of the model are found to be 7.5m, 9m, 10.5m and 13.5m respectively along the slope to achieve the stability condition.

Keywords

Soil Nailing, Steep cut slopes, 2D numerical model, Finite Element Method, Sensitivity Analysis

1. Introduction

Soil nails can be effectively used as reinforcing technique on the hill side vertical or steep cut slopes during road construction especially in a mountainous country like Nepal where most of the roads are hill roads. Narayanghat-Mugling road, which lies in lesser Himalayas zone with young mountains and rugged topography, is taken as a case study for the analysis of the steep cut slopes. Existing 5.5m road is to be expanded to double lane 9-11m road to cater the heavy traffic and connect the East West highway to the capital. It is because of the fact that the width for the roadway is insufficient and traditional retaining walls require wider space and larger depth on the valley side, steep cutting is necessary on the hill side and thus the slope is unstable.

The major triggering factors for the failure of slope is due to earthquake and the effect of water table variation during monsoon. Also, the main causes for the slope failure are as a result of reduction in shear strength and increase in shear stress. These cut slopes can be effectively stabilized by the use of soil nailing technique. The study area lies at Chainage 27+100, 28+770, 28+280 and 27+530 of Narayanghat –

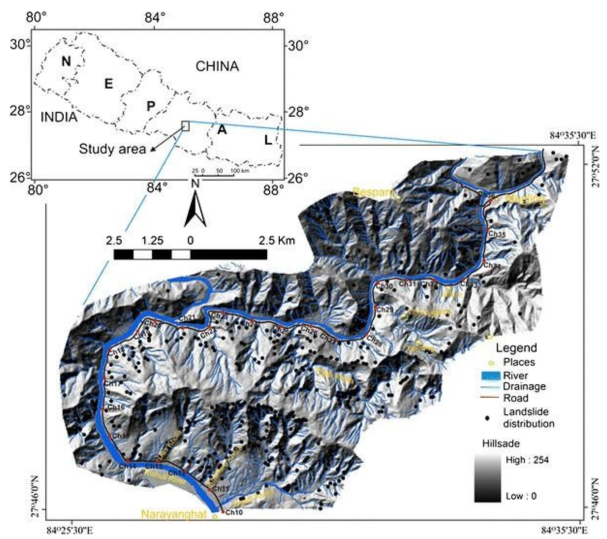

Figure 1: Map of Narayanghat - Mugling Highway

Mugling road in Chitwan district. However, the most critical section lies at Chainage 28+770 and is taken for modeling.

1.1 Soil Nailing

Soil nail is the reinforcing, passive elements that are drilled and grouted sub-horizontally in the ground to support excavations in the soil, or in soft and weathered rock (FHWA)[1]. This measure is used to stabilize the vertical or nearly vertical cut slope, was first used in 1972 in France, and is rarely used technique in Nepal. The basic procedure for installing a soil nail includes drilling a hole, placing steel bar in the hole, grouting the hole and finally perform facing operation.

The working sequence is done from top to bottom. Soil nail increases the overall shear strength of the in-situ soil by developing tension in the nail and restrain displacement of soil (Sahoo et. al.)[2]. Babu et al.[3] concluded that soil nail can be taken as feasible, efficient and economical alternative to the conventional retaining structures under seismic conditions for vertical cuts.

Figure 2: Hill side cut slope of Narayanghat-Mugling Highway at chainage 27+100

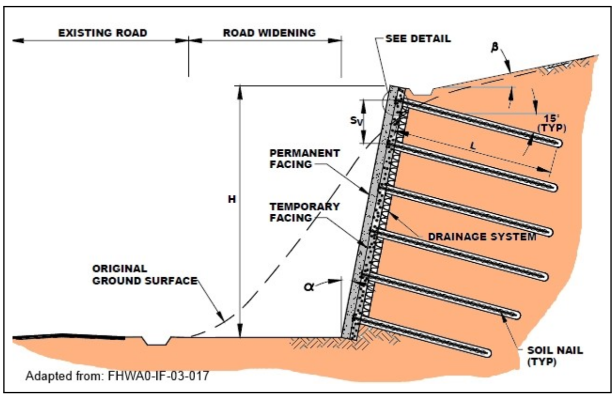

Figure 3: Soil nail wall on a hill side steep cut slope of road section

The major components of soil nail wall are: Tendons (steel bars), Grout, Corrosion protection, Shotcrete, Connection components, Drainage system. These components are shown in figure 4.

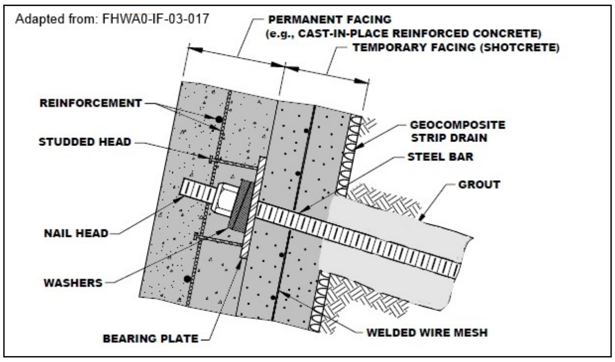

Figure 4: Details of soil nail wall

1.2 Failure Modes and Factor of Safety

Failure modes of soil nail walls are classified into three different categories as: external failure modes, internal failure modes and facing failure modes (FHWA,[4]) and are shown in figure 5. The minimum recommended FOS for external and internal stability are presented in Table 1.

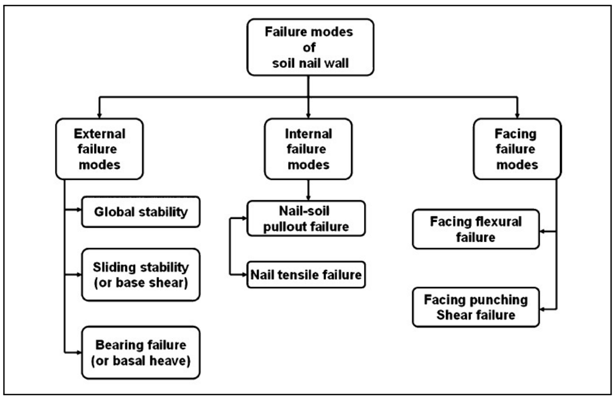

Figure 5: Principal failure modes of soil nail walls (FHWA)[4]

The recommended factor of safety, when uncertainty and consequence of failure are small under pore water pressure condition, is 1.35 or even smaller. (US Army[5])

Table 1: Minimum recommended factor of safety for soil nailing (FHWA)[4]

Type	Failure mode	Symbol	Factors of Safety	
			Temporary walls	Permanent walls
External stability	Global stability	FS_G	1.35	1.50
	Sliding stability	FS_{SL}	1.30	1.50
Internal stability	Pull-out resistance	FS_P	2.00	2.00
	Nail bar tensile strength	FS_T	1.80	1.80

1.3 Finite Element Method

This method is more powerful, accurate, reliable and versatile method to find the slope deformation and stress analysis. The soil mass is divided into small noded elements. This method utilizes the stress-strain relationship among the soil elements and helps better visualization of deformation of soil mass and no assumption for location of failure surface is made. This method has been widely accepted for the analysis of slope stability. Material is controlled by the infinitesimal incremental stress and strain relationship (Rawat et al.[6]). Strength reduction method, also called Φ-c reduction method is used to obtain the factor of safety of the slope. In this technique, the strength parameters 'tan Φ' and 'c" of the soil are reduced in steps until the soil mass fails. In this paper, we talk about the use of numerical model PLAXIS 2D based on FEM to analyse the slope.

1.4 Research Review

Many researchers in the past had performed stability analysis of the slope using soil nails analytically or by numerical modeling. Patra et al.[7] applied LEM to find the optimum quantity of steel reinforcement for soil nails for required FOS by treating location, size (length and diameter) and orientation of the nails as variables. Babu et al. [3] performed numerical analysis of soil nail with FEM approach using PLAXIS 2D for seismic conditions (pseudo-static and dynamic). FOS for pseudo-static analysis is lower than dynamic. Babu et al. [8] performed reliability analysis of soil nail wall. Sahoo et al. [2] performed seismic 3D FE analysis with respect to material parameters obtained from shake table test. Rabie [9] used numerical methods for estimation of the Global factor of safety and failure surface along with traditional LEM for the design of hybrid MSE/SN walls. According to Rawat et al. , LEM (SLOPE/W) yields higher FoS than FEM (PLAXIS 2D). However, the result for most stable slope is observed at 15^o nail inclination in a trial of three nail inclinations (0^o, 15^o and 30^o) for both two methods for soil nail.

1.5 Laboratory Testing

The collected samples from the field was brought to Central Material Testing Laboratory (CMTL), Institute of Engineering, Pulchowk Campus for laboratory testing to classify the soil and find the shear parameters which are useful to develop material model. The lab tests performed are as follows:

(a) Particle size distribution – Sieve Analysis

(b) Atterberg's limit – Liquid Limit (LL) and Plastic Limit (PL)

(c) Shear Parameters (c and ϕ) – Direct Shear Test

The details of the laboratory test results are shown in the table 2. All four soil samples are disturbed but representative and show the similar results in terms of soil classification and shear parameters. But the results of the sample of location 28+770 is taken into account for modeling as the failure envelope for the chainage lies at the lowest from the shear stress versus normal stress curve as shown in figure 6.

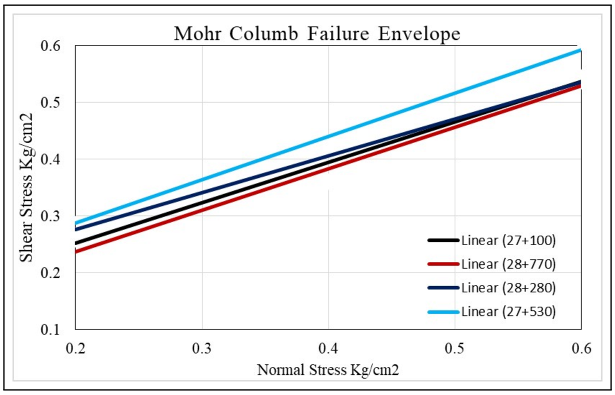

Figure 6: Shear stress versus normal stress curve

Table 2: Summary of soil classification of all samples

Unified Soil Classification System (USCS)				
Description	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**
Chainage	27+100	28+770	28+280	27+530
% Passing no. 200 sieve (0.075mm)	23.83	38.55	39.61	26.16
% Passing no. 4 sieve (4.75mm)	66.74	71.45	70.76	62.49
% Coarse (gravel)	33.26	28.55	29.24	37.51
% Sand	42.92	32.9	31.15	36.34
D_{10}	0.024	0.018	0.018	0.022
D_{30}	0.37	0.045	0.044	0.13
D_{60}	2.3	1.2	2	4
Coefficent of uniformity (Cu)	95.83	66.66	111.11	181.81
Coefficent of curvature (Cc)	2.48	0.094	0.054	0.192
Liquid Limit (LL)	27.5	27.44	48.01	32.32
Plastic Limit (PL)	23.23	20.52	40	27.77
Plasticity Index (PI)	4.27	6.92	8.01	4.55
PI from A-line	5.47	5.43	20.44	8.99
Soil classification	Silty sand with gravel (SM)	Clayey sand with gravel (SC)	Silty sand with gravel (SM)	Silty sand with gravel (SM)

2. Details of Numerical Model

Two dimensional numerical models in PLAXIS V8 for the simulation of unreinforced as well as steep nailed soil slope are developed for the geometric model obtained from the field measurement. Soil nails and facing element are modeled as elastic plate element (Singh & Babu, [10]. Soil nails are injected in drill holes in conjunction with grout material. Slope facing is done on reinforced cement concrete with proper bolt connection.

Since soil nails (which are circular in cross-section) are modelled as plate element of rectangular in shape, the equivalent axial and bending stiffness has to be calculated for correct simulation of soil nails (Singh & Babu)[10].

Equivalent modulus of elasticity of grouted soil nail,

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

where, E_g is modulus of elasticity of grout material, E_n is modulus of elasticity of nail, $A = \frac{\pi}{4}D_{DH}^2$ is the total cross sectional area of grouted nail, $A_g = A – A_n$ is the cross sectional area of grout cover, $A_n = 0.25\pi d^2$ is cross sectional area of reinforcement bar and D_{DH} is the diameter of drill hole.

The axial stiffness is given by,

$$EA = \frac{E_{eq}}{S_h}\left(\frac{\pi}{4}D_{DH}^2\right) \tag{2}$$

Bending stiffness is given by,

$$EI = \frac{E_{eq}}{S_h}\left(\frac{\pi}{64}D_{DH}^4\right) \tag{3}$$

where, S_h is horizontal spacing of soil nails.

In addition, Equivalent plate thickness in meter is determined automatically by PLAXIS,

$$d_{eq} = \sqrt{12\left(\frac{EI}{EA}\right)} \tag{4}$$

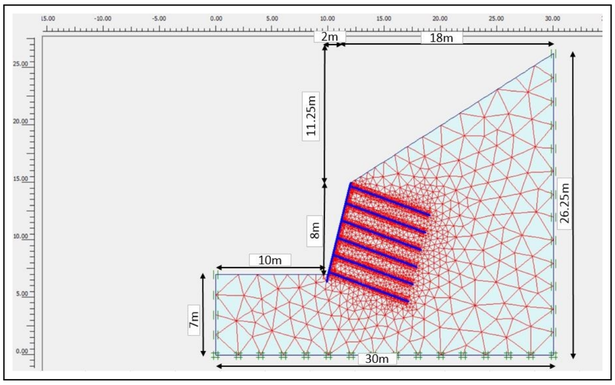

Figure 7: Geometric model of normal reinforced soil section

2.1 Geometric Model

Model parameters for soil nails are taken from HKIE[11] and FHWA[1]. The geometric model is shown in figure 7. The model is restrained for horizontal and vertical displacement on the bottom boundary, the left and right boundaries are restrained horizontally. The model is assumed as plane strain problem. The model is discretized with medium mesh density on the soil cluster, the lines are refined around the soil nail and slope facing and the meshing is done by 15-nodded triangular element. Phreatic lines are assumed to be parallel to the upper slope line of the model.

Table 3: Geometric model parameters of soil nail and facing elements

Parameters	Input Value (At normal condition)
Soil nail	Plate element, Elastic
Diameter (d), mm	25
Length (l), m	7.5 [0.9H, (FHWA)[1]]
Spacing (S_h & S_v), m	1.5 [(5ft., (FHWA)[1]]
Inclination (i), (Degree)	20^o (Rawat)[6]
Diameter of drill hole (D), mm	100
Slope Facing	Grillage facing type
Area (A), m^2	0.18 (HKIE)[11]
Perimeter, P (m^2/m/m)	0.533 (HKIE)[11]
Moment of Inertia, I (m^4)	$1.35 * 10^{-3}$

2.2 Material Model

Table 4: Material Model Parameters for soil

Parameters	Input Value
Cohesion, c (kPa)	9.07
Angle of internal friction, ϕ (Degree)	36^o
Modulus of Elasticity, E (kPa)	100000
Poisson's ratio, ν	0.3
Dilation angle, ψ (Degree)	6^o
Unit weight (unsaturated), $\gamma_{unsat}(kN/m^3)$	18
Unit weight (saturated), $\gamma_{sat}(kN/m^3)$	20
Material type	Drained
Permeability, k_x (m/day)	1
Permeability, k_y (m/day)	1

The failure criterion of soil model is assumed as Mohr-Coulomb (elastic-perfectly plastic) (Griffths[12]). The material model for soil, soil nail and facing element are presented on tables 4 and 5.

Table 5: Model parameters of soil nail, grout and facing element

Parameters	Input Value
Soil nail	Plate element, Elastic
Modulus of Elasticity of nail, E_n (kPa)	$2.10 * 10^8$
Modulus of Elasticity of grout, E_g (kPa)	1.38*10^7 [13] (Allan & Philippacopoulos
Facing Element	Plate element, RCC grade M30
Modulus of Elasticity of concrete, E_c (kPa)	$2.22 * 10^7$
Poisson's ratio of concrete, ν	0.15

2.3 Sensitivity Analysis

Sensitivity Analysis is performed among the four parameters (i.e. diameter, inclination, length and spacing) by varying each parameter 50% above and below by 10% increment and decrement from the original (normal) value keeping other three parameters constant, using PLAXIS V8 as numerical modeling tool. One of the parameters which gives the highest variation in FOS values with respect to the FOS value of normal soil nailed wall, is taken as the most sensitive parameter, which is further used for numerical analysis of the soil-nailed slope with water table variation as shown in table 6.

Eleven numerical models were generated for modeling of soil nailed walls for 7.5m, 9m, 10.5m, 12m and 13.5m nail length by varying water table of 5m, 5.5m, 6m and 7m from the bottom of the model.

3. Results and Discussion

From the numerical analysis, the factor of safety ($\sum M_{sf}$) value of unreinforced slope is found to be 0.727 and hence, the slope is unstable. Normal reinforced soil nailed slope gives factor of safety ($\sum M_{sf}$) value of 1.69 which is stable condition.

3.1 Effect of nail diameter

Nail diameter is varied from 12.5mm to 37.5mm (i.e. 0.5d to 1.5d). The factor of safety increases upto 25mm diameter (i.e. 1.690) and then decreases.

3.2 Effect of nail length

Nail length is varied from 3.75m to 11.25m (i.e. 0.5l to 1.5l) and factor of safety increases linearly. The maximum FOS value of 1.862 is found at 11.25m.

3.3 Effect of nail spacing

Nail spacing is varied from 0.75m to 2..25m (i.e. 0.5s to 1.5s) and factor of safety first increases upto 1.05m spacing (i.e. 1.728) and then decreases.

Table 6: Parameters variation for optimization

Parameters	Values
Length	Varying from 7.5m to 13.5m
Inclination	16^o constant (obtained from sensitivity analysis)
Spacing	1.5m vertical and horizontal
Water Table	5m, 5.5m, 6m and 7m from bottom of model

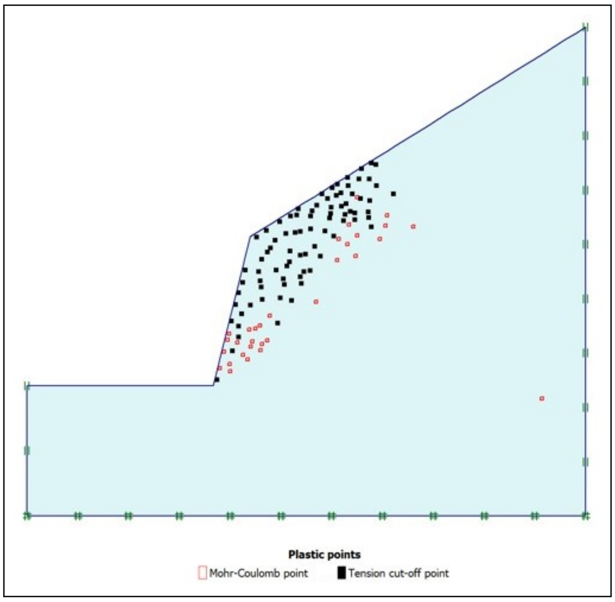

Figure 8: Plastic points of the model

3.4 Effect of nail inclination

Nail inclination is varied from 10^o to 30^o (i.e. 0.5i to 1.5i) and factor of safety first increases upto 16^o inclination (i.e. 1.709) and then decreases.

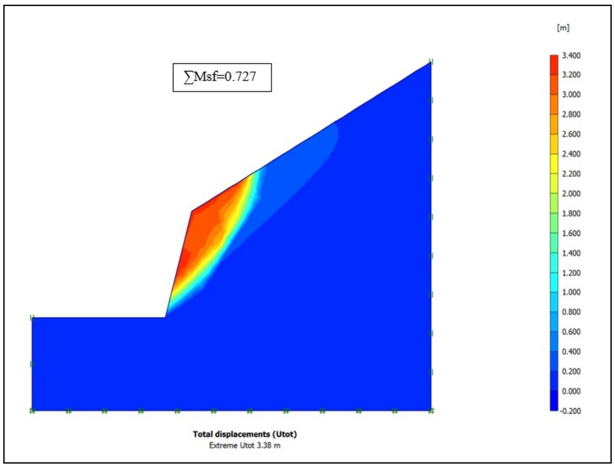

Figure 9: Slip surface at failure from PLAXIS

According to Rawat [6], the result for most stable slope increases from 0^o to 15^o and decreases from 15^o to 30^o nail inclination in the trial of three nail inclinations (0^o, 15^o and 30^o) for both 45^o and 60^o slope angles and for both LEM and FEM for soil nail.

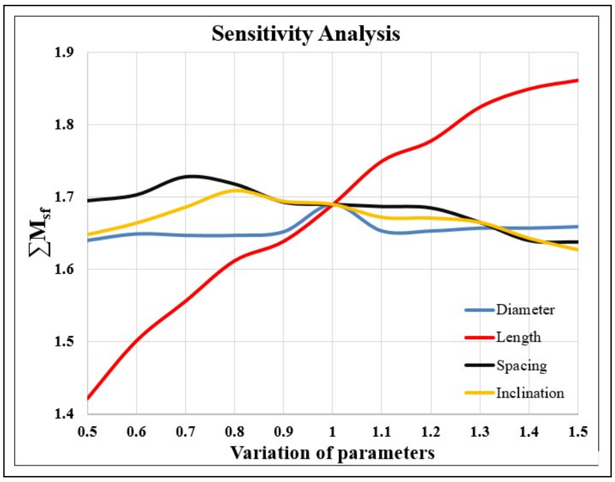

Figure 10: Summary of the $(\sum M_{sf})$ versus soil nail parameters

From sensitivity analysis, among the four parameters of soil nail, length is found to be the most sensitive parameter as the variation of factor of safety due to length is higher than due to other three parameters, which is shown in the figure 10.

The presence of water in soil mass reduces effective stress and shear strength due to increase of hydrostatic pressure (pore water pressure) and the factor of safety is highly reduced than normal condition. Figure 12, 13, 14 and 15 show the generation of water pressure by phreatic level for 5m, 5.5m, 6m and 7m (at road surface) water table from bottom of model in PLAXIS.

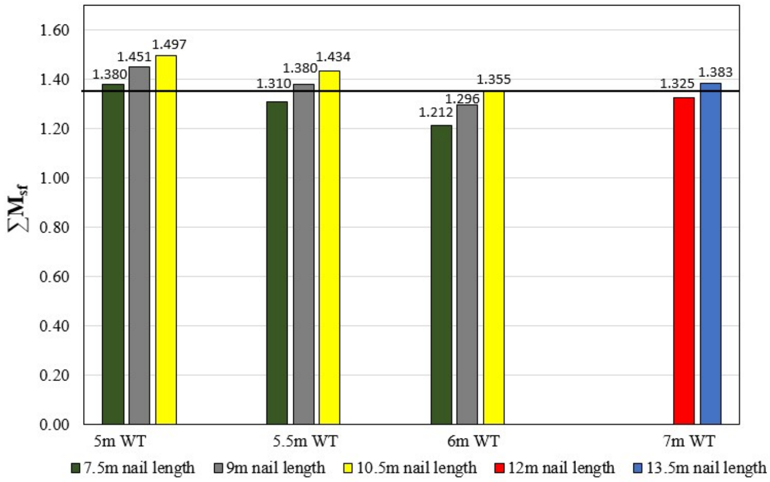

Figure 11: FOS values for 5m, 5.5m, 6m and 7m water table measured from bottom of model with the use of 7.5m, 9m, 10.5m and 13.5m nail length

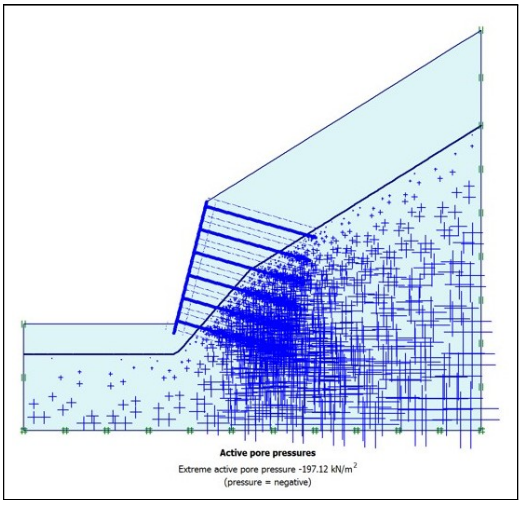

Figure 12: Water pressure generation by phreatic level for 5m

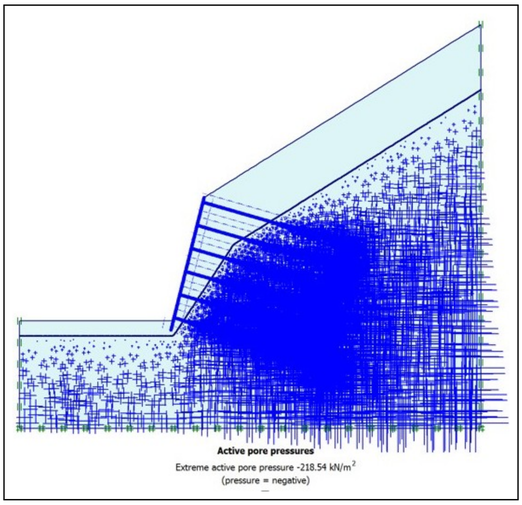

Figure 14: Water pressure generation by phreatic level for 6m from bottom of model

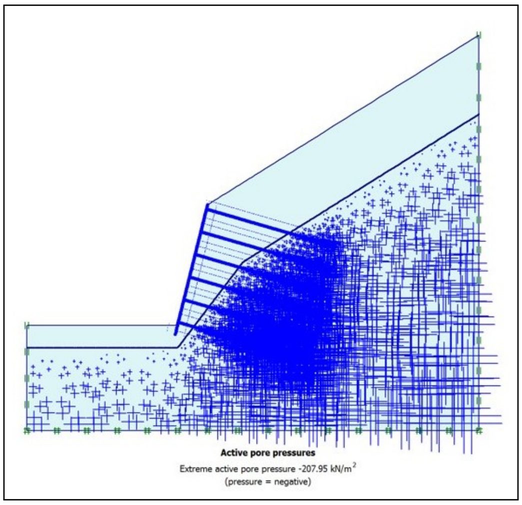

Figure 13: Water pressure generation by phreatic level for 5.5m

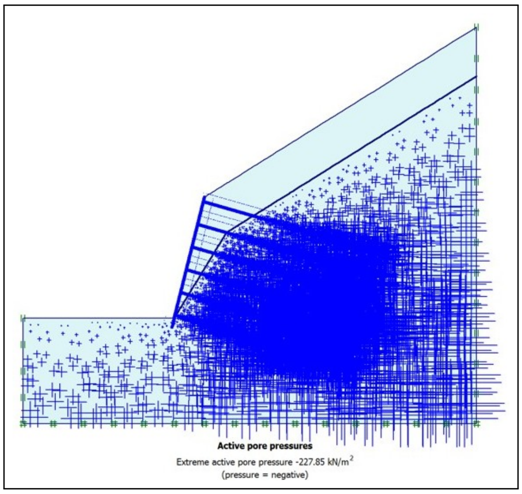

Figure 15: Water pressure generation by phreatic level for 7m from bottom of model

From figure 11, it is observed that 7.5m, 9m, 10.5m and 13.5m nail lengths are found to stabilize the slope with 5m, 5.5m, 6m and 7m water table from bottom of model respectively. The slope is unsafe due to 6m nail length.

4. Conclusion

From the FE analysis of the steep nailed soil slope models, based on the factor of safety values, some important conclusions drawn on the basis of the result are as follows:

Factor of safety increases with increase in length due to increase of axial nail force, shearing force and bending moments to resist the loading and deformation. Nail inclination variation from 10^o to 16^o increases the factor of safety which later decreases gradually on increase of nail inclination from 16^o to 30^o. Factor of safety increases with increase in spacing upto 1.05m and then decreases with the increase of the parameter. In addition, factor of safety increases with increase in diameter upto 25mm and then decreases with its gradual increase.

The critical water table condition of 5m from bottom of model is found to be stabilized by 7.5m nail length. While increasing the water table upto 5.5m from bottom of model, 9m nail length is required for the stabilization. For 6m water table from bottom of model, 10.5m nail length is required and for 7m water table from bottom of model, 13.5m nail length is required for stabilization. Hence the optimized length of nails for 5m, 5.5m, 6m and 7m water table from bottom of model are 7.5m, 9m, 10.5m and 13.5m respectively, which are inclined at 16^o to the horizontal, spacing of 1.5m and diameter 25mm of soil nails.

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