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Finite Element Modelling and Study of Soil Nailed Slope- A Case Study of Silty Sandy Slope at Khadkadil, Bhaktapur

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Abstract
Nepal is vulnerable to hazard with frequent occurrence of landslide resulting in loss of properties and lives. There are several cases of incidents related to slope failure every year. Nepal has been using conventional methods for slope protection works like cantilever retaining wall, counterfort retaining wall, Random Rubble Masonry (RRM) Wall, gabion walls. They can be economically justified for small slope height. But they are quite costlier for bigger slope height. Some alternative slope protection measures is a matter of study for geotechnical engineers and experts. One of the best alternative can be soil nailing due to its easiness, effectiveness, timely construction and mainly cost optimization. In this paper, soil nailing was studied in three different soil types namely sandy, silty sandy and clayey silty slopes by varying slope angle and soil nail's inclination, spacing and length. Soil nail inclination has significant effects on slope stability. Steep slope requires gentle angle of slope inclination and vice versa. For slope with steepness of 30°, 45°, 60°, the best factor of safety was found with soil inclination of 50°, 40°, 20° respectively. The best range for soil nail spacing was found at 1m to 2m and significantly decreases with spacing of 1m. FOS increases with increase in length/height (L/H) ratio of soil nail. It should be long enough (beyond) failure surface to ensure sufficient bond strength.

Keywords
Landslide, Slope Stability, Finite Element Method, Soil Nails, Models, Factor of Safety, Spacing

1. Introduction

Nepal is hotspot of natural disaster with frequent occurrence of landslide due to intense rainfall, river flood, surcharge loads, shock or cyclic load, development activities, weathering or combination of them. Most of the infrastructures are constructed along hills and river valleys that possess threat of landslide in future. One of the main reasons for regular traffic jams, property damage, and human fatalities in Nepal is slope collapse failure. A mass of rock, rubble, or dirt sliding down a slope is referred to as a landslide. Most of Nepal's mountainous road slopes often experience mass movements in the form of creep, landslides, subsidence, etc. Slope failure is a situation in which a slope shifts relatively rapidly because the earth's ability to support itself has been compromised by rainfall, an increase in the amount of subsurface water, or other similar occurrences. Every year, landslides across the region cause significant loss of both human life and property during and after the intense monsoon. Both scholars and engineering professionals have long struggled with the instability issues that both engineered buildings and naturally occurring slopes face. The failure of slope may occur due to intense rainfall, river flood, surcharge loads, shock or cyclic load, weathering or combination of them. The rainfall pattern in Nepal is irregular; because of this reason, Nepal has been facing the landslides or instability problems especially along the highway areas. Development activities as well as services like regular traffic movement, power production, water supply and irrigation etc. are affected by unstable ground. In such circumstances, slope stability issues draw primary attentions of all concerned people and demand the evaluation of slope stability condition and adaptation of proper remedial measures. Soil Nailing has now been the effective method for soil stabilization since it involves less disturbance to surroundings, less time for construction and less costs as well. It was first developed in early 1960s. NATM was the premier prototype to use steel bars and shotcrete for reinforcing slope. Soil Nails increase the slope stability by increasing normal force on shear plane and thus increasing shear resistance along slip plane and by reducing the driving force along slip plane.

2. Problem Statement

Nepal is vulnerable to hazard with frequent occurrence of landslide resulting in loss of properties and lives. There are several cases of incidents related to slope failure every year. Nepal has been using conventional methods for slope protection works like cantilever retaining wall, counterfort retaining wall, random rubble masonry (RRM) wall, plum concrete wall, gabion walls. They can be economically justified for small slope height. But they are quite costlier for bigger slope height. Some alternative slope protection measures is a matter of study for geotechnical engineers and experts. One of the best alternative can be soil nailing due to its easiness, effectiveness, timely construction and mainly cost optimization. Soil nailing techniques are now being used in Nepal too but we still lack our own Design Guidelines for soil nails. So this research can help to prepare standard design templates for soil nailed structures relevant to Nepali soils.

3. Research Objectives

Main Objective:

- To study the effect of variation in design parameters of soil and soil nailing on stability of reinforced soil slopes.

Specific objective:

- To identify the geo-technical parameters of the slope material.
- To develop finite element model to investigate the stability of the slope after incorporating soil nails.
- To conduct numerical parametric study by varying soil parameters, slope, nailing's dimensions: spacing, length, inclination, bond length.

4. Need and Importance

Slope instability is one of the major concern in infrastructure development in Nepal, especially in highway construction. To stabilize the slopes, soil nails are nowadays commonly used but there is no universally accepted methodology for their design and it often requires use of advanced modeling software.

One of the major objectives of soil nailing design is to determine their geometry: their bond length, spacing, inclination. The state-of-the-art practice for design of soil nails provide general guideline for selection of these parameters. The efficiency of the nails depend on the choice of these parameters.

Slope failures are complex events and the factors that affect slope stability are difficult to measure, particularly shear strength parameter values of the soil and ground water conditions. Ideally, the stability problems can be discovered and addressed before a slope failure occurs. However, once a failure occurs or a potential failure is identified, information and knowledge of the major factors resulting in the failure are required to develop an effective remediation plan. It is necessary to evaluate the stability of the concerned slopes, or to investigate the causes of the slope failures, in a rapid and effective way. This study aims at fulfilling these shortcoming and propose a framework to choose the nail design parameters for the most efficient design.

Slope stability refers to how much deformation a slope can endure before collapsing. This information matters to civil and geotechnical engineers involved in planning construction for roads, dams, embankments, and other excavated slopes, as failing to understand slope stability could result in landslides, unwanted movement, or injury to both property and individuals. A slope stability analysis (sometimes referred to a Landslide Hazard Analysis) is performed to assess soil mechanics and plan for future stabilization efforts.

In most applications, the primary purpose of slope stability analysis is to contribute to the safe and economic design of excavations, embankments, earth dams, landfills. Slope stability evaluations are concerned with identifying critical geological, material, environmental, and economic parameters that will affect the project, as well as understanding the nature, magnitude and frequency of potential slope problems. When dealing with slopes in general and slope stability analysis in particular, previous geological and geotechnical experience in an area is valuable also adds new knowledge for formulation of design guidelines.

5. Limitations

Slope failure is a contextual subject where the site condition is most important to identify the failure characteristics of the soil. This study focuses on sensitivity analysis for reinforced slopes using numerical modelling i.e. the use of soil nailing structures in stabilizing the slope. The use of PHASE2 and PLAXIS 2D for numerical modeling of slope is carried out from which we have tried to analyze the factor of safety while using different soil and nails parameters.

However, the use of PHASE2 and PLAXIS 2D only focus on 2-dimensional modeling of the soil using FEM. It also does not give precise results as compared to software with 3-dimensional modeling features. Similarly, in this study, dynamic conditions and earthquake loads have not been taken into account as it would be a time consuming effort and could not be completed within the stipulated time. The structural design part which may include corrosion analysis, shortcreting and strength of construction materials have also not been taken into account.

The aforementioned points have narrowed down the thesis for analyzing the soil in 2-dimensional condition and performing sensitivity analysis for reinforced slopes using numerical modelling i.e. the use of soil nailing structures in stabilizing the slope. However, while considering the expected results of this study, it would be a road map for soil nailing structures in different kinds of soil in varying slope condition.

6. Methodology

The methodology includes the primary as well as secondary data collection and their analysis. The ultimate aim of the thesis is to analyze the stability of landslide according to different parameters while using soil nailing, which affects the stability of the slope. Various land slope longitudinal profiles are plotted and according to their soil parameters, especially cohesion and friction angle, the model is analyzed using PHASE2 and PLAXIS 2D for modeling various excel linked engineering software are especially useful for quick calculation and data formatting & listing. Flow Chart of methodology has been shown below.

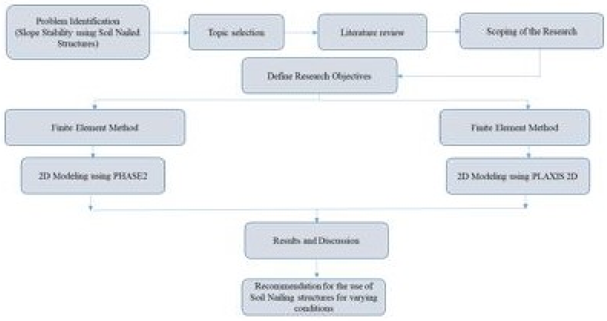

Figure 1: Flow Chart of Methodology

Here problem is identified at first and then followed by literature review. Since Nepal doesn't have its own Code for Design of Soiled Nailed Slope, so codes from India, USA, Australia and other research papers have been used at literature review. Then different soil parameters were determined from field by SPT, Piezometer and other necessary tests at site and lab. Obtained results were used for Finite Element Analysis by PHASE2 and PLAXIS 2D.

7. Literature Review

7.1 Concepts of Slope Failure

A slope failure is a phenomenon that a slope collapses abruptly due to weakened self-retain ability of the earth under the influence of a rainfall, earthquake, or other causes. Following are the various type of slope failures for engineering soils as proposed by [1]

- Earth/Debris Fall
- Earth/ Debris Topple
- Earth/ Debris Slump
- Earth/ Debris Block Slide
- Earth/ Debris Slide
- Earth/ Debris Flow
- Debris Avalanche
- Soil Creep
- Combination of two more principal types of movement

The movement of the mass movement can be falls, topples, rotational, lateral spread, complex and compound. The failure mechanism of soil slope is assumed to occur along a curved or plane surface, but in reality, the mechanism is quite complex. Slope Failure either occurs due to increase in shear stress or due to decrease in shear strength of soil. The reasons for decline in shear strength of soil are increase in water pressure, cracking, swelling, creep, leaching, weathering and cyclic loading. Likewise the reasons for increase in shear stress of soil are increase in loads at soil's top, water pressures in fracture, increase in soil weight, excavation, drop in water level at base of slope and earthquakes. FEM (Finite Element Method) is a popular method for slope stability analysis since it incorporates mechanism of soil failure to great extent. It considers stress-strain behavior and displacement which is more accurate, versatile and requires fewer assumptions as compared to limit equilibrium approaches. A finite element analysis is employed to study the effect of shear strength spatial variability on the stability of undrained engineered slopes[2]. This model can be used to account for seepage induced failures, different soil behaviors and engineering structures like soil nails, geo-textiles, drains, retaining walls. Shear strength reduction technique is used to analyze slope stability in FEM.

There are many methods for slope stabilization and soil nailing is one of them. Soil nailing is a ground stabilization technique that can be used on either natural or excavated slopes. It prevents slipping, overturning and overall failure of the critical surface by mobilizing shear strength (i.e., bond stress), tensile strength of nailing. A typical section of soil nailing is shown below.

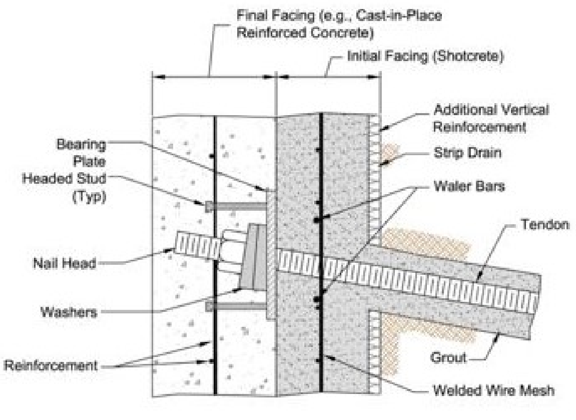

Figure 2: Typical Section of Soil Nail Wall[3]

Major components of soil nailing are listed below with their functions.

- Steel Reinforcing Bars: To provide tensile strength to the soil
- Grouts: to fill the annular space between the nail bar and the surrounding ground, and for concreting of the temporary facing
- Centralizers: to ensure minimum thickness of ground around soil nails/ tendons
- Nail Heads; to provide nail bearing strength and transfer bearing loads from soil to soil nails.
- Temporary and permanent Facing: to provide support the exposed slope surface, prevent corrosion, and acts as bearing surface for bearing plates.
- Drainage: to collect and transmit seepage water

7.2 Concept of Soil Nailing

Soil and nail contact caused by ground deformation causes soil nails to acquire tensile force, which in turn causes soil nails to develop their reinforcing activity. This produced tension force is the primary source of resistances. Shear and bending have traditionally been thought to contribute little to its resistance [4]. The effect of soil nailing is to improve slope stability by:

- increasing the normal force on the shear plane to increase shear resistance along the slip plane in friction soil.
- lowering the driving force along the slip plane in both cohesive and frictional soil.

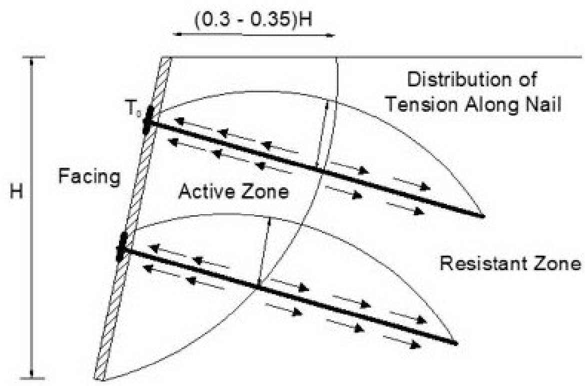

Figure 3: Mechanism of Soil Nailing[5]

7.3 Favorable Conditions for Soil Nails

- Dense to very dense granular soils with apparent cohesion
- Weathered rock with adverse weakness planes
- Stiff to hard fine-grained soils

- Engineered fills
- Residual soils
- Glacial tills

7.4 Unfavorable Conditions for Soil Nails

- Granular soils with high groundwater
- Soils with cobbles and boulders
- Soft to very soft fine grained soils
- Collapsible soils
- Organic soils
- Loess
- Expansive soils

7.5 Modeling by FEM

PLAXIS 2D and Phase2 are designed to simulate nailed walls using appropriate boundary conditions, geometry and material models, meshes, groundwater conditions, and pseudo-static conditions. As a result, we can create stress and deformation analysis, as well as global stability analysis. The computational procedure in PLAXIS 2D gives the value of the incremental multiplier σMsf when the result converges when failure is reached. This incremental multiplier value is treated as the Factor of Safety (FOS) value for unreinforced and reinforced slopes.

7.5.1 Mohr-Coulomb Model Description

There are various criteria by which failure can be defined in FEM. Some of these criteria are based on strain level, but most are based on shear stress and shear strength. The Mohr-Coulomb failure criterion is most commonly used in soil mechanics. The shear strength of soil is given by

$T_f = c' + \sigma' \tan \phi'$

Here, T_f is shear strength at failure, c' is effective cohesion, σ' is effective stress at failure and ϕ' is effective angle of friction [6]. The Mohr-Coulomb model is a full elastoplastic model. It is widely used in geotechnical applications for sandy, silty soils [7].

7.5.2 Shear Strength Reduction (SSR) Technique

The shear strength reduction method is a new method in the finite element method for obtaining the safety factor of ground slopes. The finite element method was first applied to geotechnical engineering in 1966 [8]. Slope stability analysis first appeared in the literature in the mid-1970s. According to the SSR method, the shear strength of the soil decreases and the slope approaches the verge of collapse [9]. In the finite element method, such a state is detected by the inability to reach equilibrium. SSR technology assumes the elastoplastic behavior of the slope material. Material strength is reduced to the point of failure.

For Mohr-Coulomb materials, a procedure to systematically search for the critical safety factor F that brings the previously stable slope to the verge of failure is presented below [8]

8. Data Collection and Modelling

8.1 Study Area

The landslide prone site is located at 27.703146°N, 85.414326°E, along the Sallaghari-Duwakot -Khadkadil-Bir Hospital-Mulpani Pul road. It is situated at Changunarayan Municipality, ward No. 1, Bhaktapur district of Bagmati Province of Nepal. At present, we can observe only some mass flow and has only little disturbance to road traffic so far. But it has potential for large threat, if not treated in time.

8.2 Material Models

S.N	Parameters	Unit	Top Layer	Middle Layer	Bottom Layer
1	Modulus of Elasticity (E)	KPa	8700	9000	10200
2	Poisson's Ratio (u)	-	0.30	0.30	0.30
3	Unit Weight	KN/m³	19.65	19.50	18.16
4	Cohesion (c)	KN/m²	0	0	0
5	Angle of Friction (φ)	Degree	28	31	33
6	Dilation Angle (ψ)	Degree	0	0	0
7	Failure Criteria		Mohr Coulomb	Mohr Coulomb	Mohr Coulomb

Table 1: Soil Parameters

Soils Used: Silty Sand

Soil Slopes: 30°, 45°, 60°

S.N	Parameters	Unit	Nails
1	Diameter(D)	mm	32
2	Axial Stiffness (EA)	KN/m	2.11X10^5
3	Flexural Rigidity (EI)	KNm2/m	131.64
4	Nail's Vertical Spacing	m	1,1.5,2,2.5,3
5	Length of Nails	M	7.5,10,12.5
6	Angle of Inclination of nail	Degree	10,20,30,40,50,60,70
7	Poisson's Ratio		0.17

Table 2: Soil Nail's Parameters

8.3 Boundary Conditions

- Side boundaries considered as roller (Ux=0)

S.N	Parameters	Unit	Facing
1	Thickness(D)	mm	200
2	Axial Stiffness (EA)	KN/m	4.4X10^6
3	Flexural Rigidity (EI)	KNm2/m	1.47X10^4
4	Poisson's Ratio		0.25

Table 3: Facing's Parameters

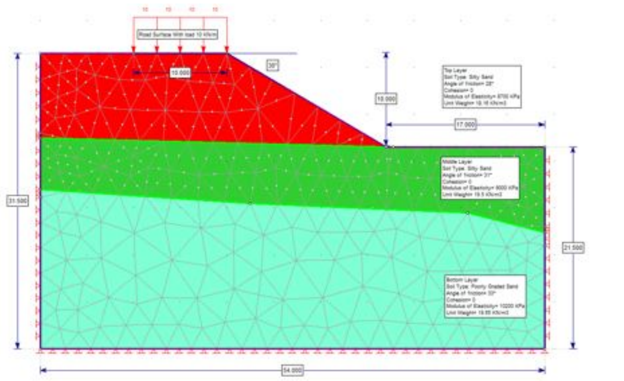

Figure 4: Finite Element Model of Slope

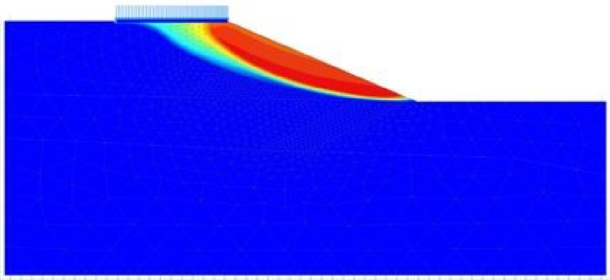

Figure 5: FEM Model Without Soil Nail

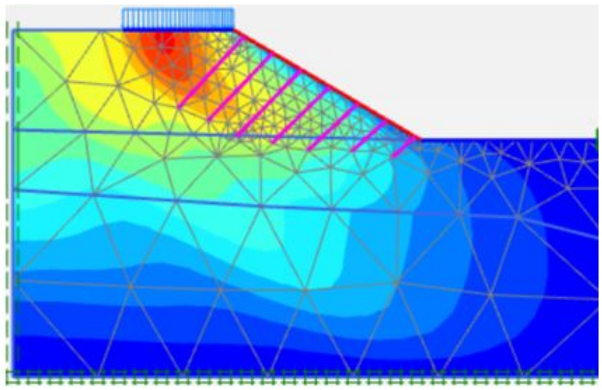

Figure 6: FEM Model With Soil Nail

- Bottom Boundaries considered as fixed (Ux and Uy=0)
- Surcharge Load = 10KN/m at top of slope
- Soil Model = Mohr's Coloumb
- Soil Nails and Facing Element = Plate Elements

9. Result and Discussion

9.1 Stability Analysis For Water table

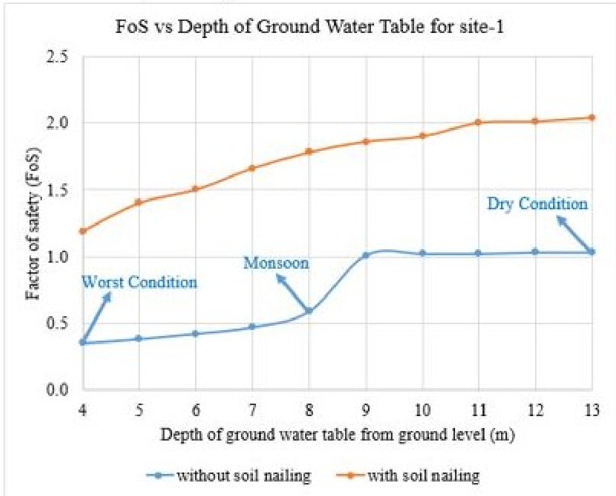

Figure 7: Stability Analysis for Water Table Variation

From the observation of site condition, dry condition was observed which resulted factor of safety of 1.03. During monsoon, water table was observed at 8m below ground level where factor of safety was found to be 0.59. When water table increases to 4m below ground water table (worst condition), factor of safety significantly decreases to 0.35. For water table less than 9m, the slope is vulnerable. After installation of soil nails, the factor of safety increases to 2.02 for dry condition, 1.78 at water table 8m and 1.19 for water table 4m below ground water table.

9.2 Stability Analysis for Soil Nail's Angle of Inclination and soil slope's angle

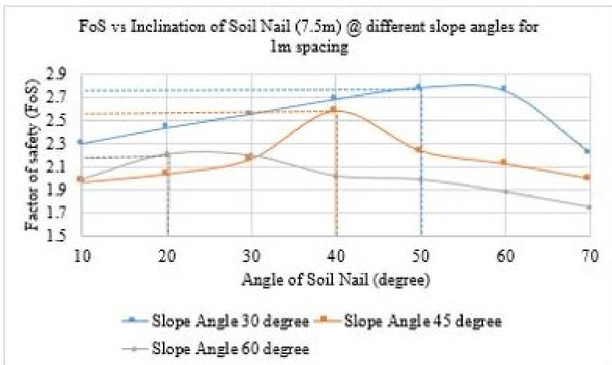

Figure 8: Stability Analysis for Soil Nail's Inclination

This shows the factor of safety for different angle of soil nail's inclination for 1m nail spacing and 10m nail length. For slope angle 30°, 40°, 60°, soil nail's inclination was analyzed for 10°, 20°, 30°, 40°, 50°, 60°, 70° with soil nail length 7.5m and 1m spacing. The maximum factor of safety obtained was 2.79 for 50° soil nail's inclination and 30° slope angle, 2.58 for 40° soil nail's inclination and 45° slope angle, 2.21 for 20° soil nail's inclination and 60° slope angle. This shows for slope angle 30°, the optimized soil nail's inclination is 50°, for slope angle 45°, the optimized soil nail's inclination is 40° and for slope angle 60°, the optimized soil nail's inclination is 20°.

9.3 Stability Analysis for Spacing of Soil Nails

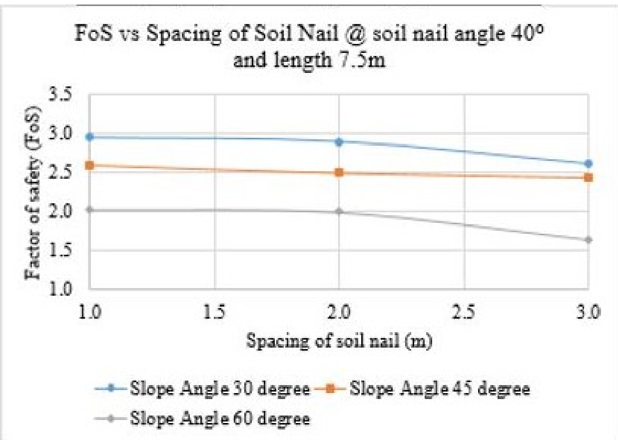

Figure 9: Stability Analysis for Soil Nail's Spacing

It shows the spacing of soil is influenced by soil nail spacing. It was found that the factor safety remains constant for spacing of 1m and 2m but shows significant changes for spacing 3m. The installation of closely spaced soil nails shows good results than widely spaced nails since closely spaced nails obtain required bond length and hence use their maximum allowable load. So the efficient soil nail spacing varies from 1m to 2m as suggested by [10].

9.4 Stability Analysis for Length of Soil Nails

It shows the FOS is influenced by length of soil nail. Nail length has significant effect for slope stability with deep seated slip surface as compared to shallow slip surface. It also shows that long nail tends to attain maximum allowable load with less nail inclination whereas short nails need higher soil nail inclination. Basically, increase in soil nail length increases the factor of safety as well. 7.5m nail's give good results but length can be increased depending on project's significance.

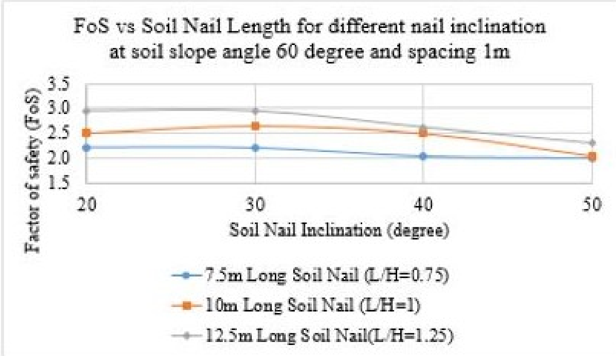

Figure 10: Stability Analysis for Soil Nail's Inclination

10. Conclusion

Soil nail inclination has significant effects on slope stability. Steep slope requires gentle angle of slope inclination and vice versa. The optimum angle of soil inclination are 50°, 40°, 20° for soil slope of 30°, 45° and 60°, respectively.

Similarly soil nail length has significant effect too. FOS increases with increase in length/height (L/H) ratio of soil nail. It should be long enough (beyond) failure surface to ensure sufficient bond strength. Long nail tends to attain maximum allowable load with less nail inclination whereas short nails need higher soil nail inclination.

Nail Spacing is indirectly proportional to slope stability. The factor safety remains constant for spacing of 1m and 2m but shows significant changes for spacing 3m. The installation of closely spaced soil nails shows good results than widely spaced nails since closely spaced nails obtain required bond length and hence use their maximum allowable load.

Increase in water table reduces the stability of slope. The natural condition for 30°, 45° and 60° soil slope has factor of safety just below one and after soil nail installations results in adequate factor of safety for higher values of water table as well.

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