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Analysis of Maximum Economic Length of Soil Nail for Slope Stability

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Abstract
Slope stability is of utmost importance in geotechnical engineering, necessitating effective reinforcement methods to mitigate failures. This study examined the advantages, limitations, and overall suitability of soil nails and cable anchors in stabilizing slopes. Numerical modeling and analysis were performed using the Rocscience Slide2 program. The study analyzed soil nails and cable anchors for slopes of 10 m to 60 m height, slope angle from 35° to 90°, and friction angle from 27° to 36°. The findings reveal that the maximum economic length of soil nails decreases as slip surface depth, slope height, and slope angle increase. Additionally, the friction angle of the soil has a negligible effect on the maximum economic length of the soil nail.

1. Introduction

Slope stability is a critical concern in geotechnical engineering as it directly impacts the safety and performance of infrastructure projects. Unstable slopes pose significant hazards such as landslides, rockfalls, and slope failures. To mitigate these risks, geotechnical engineers must perform rigorous analyses and implement appropriate safety measures. The stability of a slope is calculated based on the factor of safety (FOS), where an FOS greater than 1 indicates that the resisting force due to soil shear strength is higher than the driving force due to the self-weight of the sloping ground, and vice versa [1]. By Mittal and Biswas [2], the factor of safety (FOS) exhibits an upward trend with higher values of the internal friction angle (ϕ) and cohesion (c) of the soil, as well as with longer and larger-diameter nails. In contrast, decreasing the slope inclination contributes to an increase in the factor of safety. Duncan and Wright[3] mentioned several techniques to enhance the safety of a slope. These methods include drainage, using cables, stabilizing piles for the slope, and soil treatments like unloading at the crest and adding buttresses at the toe. Reinforcement methods play a crucial role in mitigating slope failures by improving stability and reducing risks [4]–[8].

Table 1. Advantages and limitations of soil nail and cable anchor

Soil Reinforcement	Advantages	Limitations
Soil Nail	Low installation cost Flexible design Long term performance Minimize surface cracking [8]	High corrosion Limited tensile resistance Difficult to construct under groundwater [15]
Cable Anchor	Effective performance under groundwater High load-carrying capacity Prevent excessive soil displacement [7]	Higher installation cost Not suitable for highly cohesive soil [7]

1.1. Soil Nail

Soil nailing is a widely used method for slope reinforcement, involving the insertion of closely spaced nails or steel bars into a slope to enhance stability [8]. It relies on the interaction between soil and reinforcing elements to increase shear strength and control deformations. Soil nailing is commonly employed for stabilizing existing slopes, offering advantages over other retaining wall systems [8], [9]. By improving shear strength and providing tensile resistance, soil nailing effectively enhances slope stability and mitigates the risk of failures. The stability of a soil-nailed slope depends on; shape, slope angle, angle of the back slope, groundwater level, nail length, inclination, and nail spacing pattern.

Optimal soil nail spacing typically ranges from 1 m to 2 m [10]. The role of each nail in slope stability differs according to its location and angle [11] Research by [12] on a 15-m nailed wall in cohesive soil revealed that the upper nail does not significantly contribute to maintaining and stabilizing the slope system. The force exerted by the nail increases briefly and then remains relatively constant. The highest deformation takes place at the summit of the slope. Additionally, Pham [13] found that soil nails installed in the upper part of the slope are more effective in enhancing stability, while those placed in the lower part contribute more to reducing horizontal displacement. Furthermore, it has been noticed that longer nails result in reduced horizontal deflection and vertical settlement [14]. The length of nails used in a soil slope is determined by the active and resistant zones, where the active zone's width is generally about 0.3 to 0.35 times the slope height [15].

1.2. Cable Anchor

Cable anchors, also known as rock or soil anchors, are another commonly used reinforcement method in slope stability, where high-tensile steel cables are installed into the slope and anchored to a stable zone. These anchors provide additional resistance to sliding forces and enhance the stability of slopes [7], [16]. They have been successfully applied in numerous slope stabilization projects, such as rock slopes, cliff faces, open cuts, and deep excavations. Cable anchors are particularly advantageous in scenarios where traditional stabilization methods may be less effective due to challenging geological conditions or where minimal visual impact on the landscape is desired.

1.3. Comparison of Soil Nail and Cable Anchor

Soil nailing and cable anchors are widely utilized for enhancing slope stability [5], [6]. Both soil nailing and cable anchors effectively enhance slope stability and contribute to deformation control. However, each of them has its advantages and limitations, as presented in Table 1.

The maximum economic length of soil nails is the maximum length at which it remains cost-effective than utilizing other reinforcement methods, such as cable anchors, to achieve the same factor of safety. Soil nails become less effective as their length exceeds a certain point, whereas cable anchors offer greater tensile capacity with increasing length, but at a higher cost. Consequently, determining the maximum economic length of soil nails for slope mitigation and landslide protection structures is still a matter of debate, and no research on this type of comparison has been done.

Understanding the relationships between soil nail length, slope geometry, and various parameters is crucial for designing economic and stable soil-nailed slopes. This research aims to determine the maximum economic length of soil nails in comparison with cable anchors for different slope heights, slope angles, friction angles, and depth of slip surface through numerical modeling using the Slide2 program.

Table 2. Soil properties used in numerical modeling

Soil Layer	**Unit Weight (kN/m^3)**	**Cohesion (kPa)**	**Friction Angle (°)**
Top Layer	18	5	27, 30, 33, 36
Bedrock (Impenetrable Layer)	25	500	40

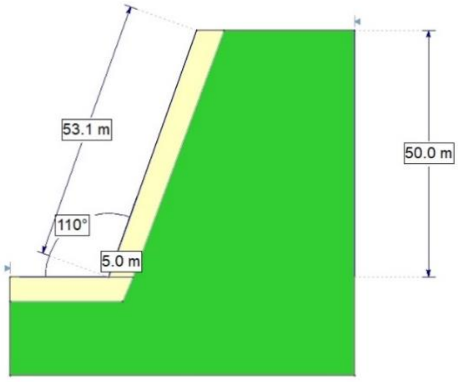

Figure 1. Slope model of 50 m slope height, 5 m depth of bedrock, and 70° slope angle

2. Methodology

2.1. Model Preparation

This section discusses the assumptions for modeling the slope and the properties and layout of soil nails and cable anchors. The numerical simulation of the slope was developed using the Rocscience Slide2 program version 6.020 [17]. The Mohr-Coulomb criteria were used in the numerical simulation of the slope as the shear strength of soil and rock can be defined by cohesion and friction angle[18].

The analysis considered materials with different friction angles of soil to determine the effect of friction angle on the maximum economic length of the nail. The properties of these soil layers are presented in Table 2. The slope model was analyzed using these soil properties to evaluate the performance of soil nailing and cable anchors as reinforcement methods. The typical slope model of 50 m height is shown in Figure 1.

The cost of soil nails and cable anchors was determined based on the district rate of Ilam District, Nepal, in the fiscal year 2022/2023 [19]. The cost per meter of cable anchor installation is 2.57 times more expensive than soil in eastern Nepal as per the Illam district rate. The model considered soil nails with a diameter of 32 mm, a tensile capacity, and a plate capacity of 250 kN. The length of the soil nails was chosen in multiples of 5 meters, based on their availability in the market for design purposes and the minimum recommended length of soil nails for soil nail walls is 5 m [20]. The out-of-plane spacing of the nailing is varied from 1 m to 2 m, as the recommended soil nail spacing ranges from 1 m to 2 m [10]. The analysis did not consider surface protection using a soil net or 3D mat. Cable anchors with a tensile capacity of 1027 kN were used in the analysis. These cable anchors were made of 7-stranded wires with a diameter of 15.2 mm. The bond length of the cable anchors was fixed at 30% of the total length. The support type of the cable anchor was modeled as a grouted tieback in the Slide2 program.

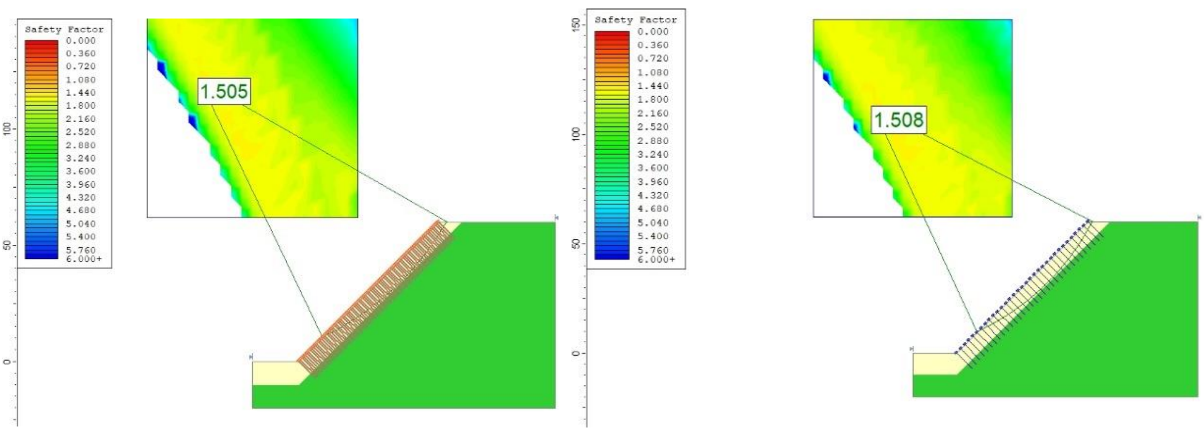

Figure 2. Slide analysis with FOS 1.5 at dry condition for soil nail (left) and cable anchor (right)

The inclination of soil nails and cable anchors significantly affects slope stability. Typical nail inclination should be 60°, 50°, and 40° to the horizontal, for slope with steepness of 30°, 45° and 60° respectively [21], [22]. Cable anchors are installed at an angle of 10°- 45° with horizontal. [23] However, in this study, soil nails and cable anchors are inclined normally with the slope surface to maintain consistency so that the effect of the length of the nail and cable on slope stability can be accurately determined. To limit the depth of the slip surface, an impenetrable bedrock layer with high strength was utilized, restricting the slip surface depth to specified values of 5, 10, and 15 meters. These design considerations and parameters were incorporated to assess the performance and effectiveness of soil nailing and cable anchors in stabilizing the slopes under different conditions.

2.2. Analysis

In this section, the detailed procedures used for slope stability analysis are discussed The factor of safety of 1.5 was adopted for the dry condition, as a factor of safety of 1.5 is generally used for the analysis of slope[24]–[26]. The research did not include an analysis of rainfall conditions because of the complex variability in the slope's saturation level and hydraulic conductivity [26]. These factors are influenced by variables such as rainfall history and upslope topography. Circular slip surfaces were used for the calculation of the slip surface. Various researchers have found that utilizing a circular slip surface for analyzing undisturbed cuttings is more appropriate than a noncircular slip surface. This approach has resulted in a reduction in analysis time by more than threefold [16]. The factor of safety was determined using Bishop's simplified method as this method is suitable for circular slip surfaces [27]. The slope limit was assumed to be constant throughout the slope surface for the analysis.

The analysis was performed for different depths of 5, 10, and 15 meters, various slope angles ranging from 35° to 90°, and different slope heights from 10 m to 60 m to assess the stability of the slope under different conditions. The other methods of mitigation measures like retaining walls and bioengineering are more economical than soil reinforcements for gentle slopes [27]. The analysis for the economic length of soil nail proceeded as:

- Step 1: A numerical model was developed with a slope angle of 45° and a slope height of 50 m.
- Step 2: In this step, soil nailing was employed as slope reinforcement, and the factor of safety was calculated. The nail length and spacing were adjusted until a factor of safety of 1.5 was achieved, as depicted in Figure 2 (left).
- Step 3: Next, cable anchors were introduced in place of the soil nails, and cable anchor nails and spacing were varied to achieve a factor of safety of 1.5 as shown in Figure 2 (right).
- Step 4: Various slope models were created by varying the slope angle from 35° to 90° degrees while maintaining the slope height at 50 m. The process outlined in Step 2 and Step 3 was repeated for each of these slope models.
- Step 5: The procedure of step 4 was replicated for slope heights ranging from 10 m to 60 m, with a consistent factor of safety of 1.5.
- Step 6: The cost ratio of cable anchors to soil nails was computed for different slope angles, nail lengths, and slope heights.
- Step 7: The cost ratios for various lengths of soil nails and cable anchors are interpolated to determine the length at which the cost of using a soil nail is equal to or greater than the cost of using a cable anchor. This calculation identifies the maximum economic length of the soil nail.

Table 3. Variation in the number of nail and cable anchors with slope height

Slope Height	Number of Nails	Nail Number Ratio	Number of Cable Anchors	Cable Anchor Number Ratio
10	20	4.50	10	4.00
20	88	2.51	40	2.27
30	221	1.48	91	1.41
40	328	1.40	129	1.34
50	460	1.29	172.5	1.25
60	592	-	215	-

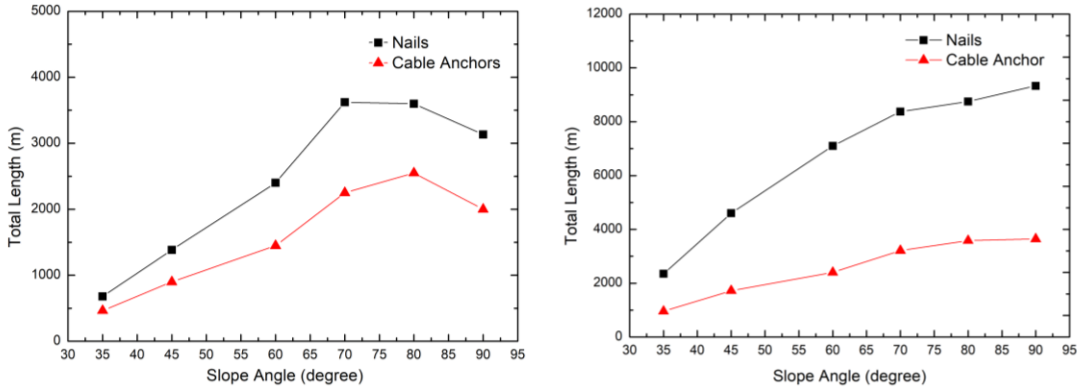

Figure 3. Total length variation with slope angle for 5 m deep slip surface (left) and 10 m deep slip surface (right)

3. Results and Discussions

In this section, the result of the slope stability analysis using the slide2 program is presented and discussed.

3.1. Number of Soil Nail and Cable Anchor

The number of soil nails and cable anchors needed for slope stability increases with the slope height, but the increment is not linear. The nail number ratio (cable anchor number ratio) compares the required nail numbers (cable anchor numbers) between different slope heights. For a 20 m slope, it's the number of nails needed for a 30 m slope divided by those needed for the 20 m slope. The nail (cable anchor) number ratio shows a higher value when the slope height increases from 10 m to 20 m and 20 m to 30 m but gradually decreases as the height increases further as shown in Table 3. The cable anchor number ratio is lower than the nail number ratio for all slope heights.

3.2. Slope Angle

The relationship between the slope angle and the required length of soil nails and cable anchors shows distinct patterns. For a 5-meter-deep slip surface, the total length of soil nails increased by 360%, starting from 680 meters for a 35° slope to 3131 meters for a 90° slope as shown in Figure 3 (left). In the case of a 10-meter-deep slip surface, the total length of soil nails increased by 297% as the slope angle progressed from 35° to 90° slope as shown in Figure 3 (right). As the slope angle increases, the number and length of soil nails and cable anchors also increase.

3.3. Soil Friction Angle

With the increase in the friction angle of the soil, both the shear strength and factor of safety of the slope increases [2],[27]. However, interestingly, the change in the friction angle of the soil doesn't have any noticeable effect on the maximum economic length of the soil nail, keeping all other soil properties constant as shown in Figure 4. For a 1° increase in the friction angle, the safety factor increases by 0.035, assuming the number of soil nails and cable anchors remains constant.

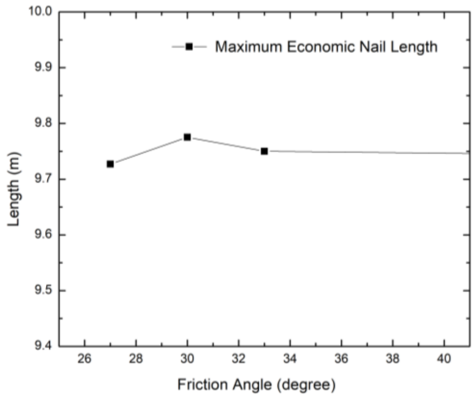

Figure 4. Variation of maximum economic nail length with soil friction angle

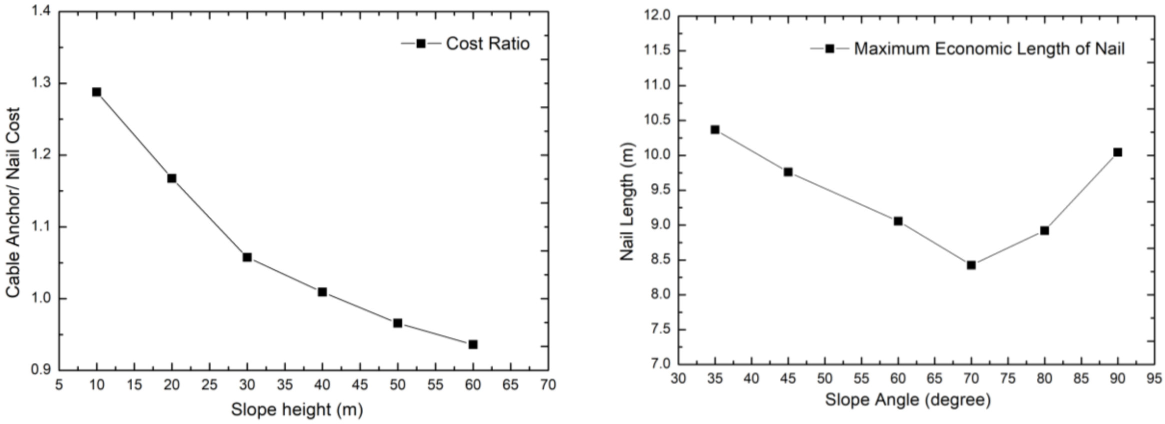

Figure 5. Cost ratio for different slope heights (left), and maximum economic length of nail (right)

3.4. Slope Height

The maximum economic length of a soil nail is also dependent on the height of the slope. For slopes with smaller heights, soil nails are more economical than cable anchors up to a slope height of 40 meters. Beyond this slope height, the cost of cable anchor installation becomes lower than that of soil nails. For a 50 m high slope, the cost of using cable anchors is 0.97 times the cost of using soil nails, and for a 60 m high slope, it's 0.94 times, as presented in Figure 5 (left). This cost relationship is a critical consideration when selecting the most cost-effective reinforcement method for stabilizing slopes of varying heights.

3.5. Maximum Economic Length of Soil Nail

The research reveals that for a slope angle of 35°, the maximum economic length of the soil nail is determined to be 10.4 meters for a slope height of 50 m. The maximum economic length of the nail decreased as the slope angle increased and is minimum for a slope angle of 70° as shown in figure 5 (right). After this, the maximum economic length of the soil nail increases, forming a U curve.

The maximum economic length of soil nails for different slope heights and angles is provided in Table 4. These empirical findings indicate that soil nails exceeding a length of 13.8 meters are deemed cost-effective when compared to the utilization of cable anchors across all slope angles and all slope heights. Moreover, for steep slopes with higher slope heights, soil nails longer than 10 meters are considered cost-effective. These results, supported by numerical analysis, contribute valuable insights for practitioners and designers in making informed decisions regarding the selection of reinforcement methods for slope stabilization projects.

Table 4. Maximum economic length of soil nail for different slope angle

Slope Angle (°)	**Slope Height (m)**					
	10	**20**	**30**	**40**	**50**	**60**
35	13.8	12.5	11.3	10.8	10.4	10.0
45	13.0	11.7	10.6	10.2	9.8	9.4
60	12.0	10.9	9.9	9.1	9.1	8.7
70	11.2	10.1	9.2	8.8	8.4	8.1
80	11.8	10.7	9.7	9.3	8.9	8.6
90	13.3	12.1	11.0	10.5	10.0	9.7

4. Conclusion

The comprehensive analysis of soil nails and cable anchors under various conditions revealed several key findings. The maximum economic length of soil nails decreases as the slope angle increases up to 70° and then increases again. The maximum economic length of soil nails is 13.8 meters for a slope of 10 m height with a 35° slope angle and 8.1 meters for a slope of 60 m height with a 70° slope angle. In cases where a deeper slip surface is present, cable anchors should be utilized.

Cable anchors have higher installation costs than soil nails and in the case of eastern Nepal, the per meter cost of a cable anchor is 2.57 times more expensive than soil nails. The cost-effectiveness of soil nails and cable anchors is influenced by the height of the slope and the cost of using soil nails goes on increasing when the height of the slope increases. Although an increase in soil friction angle increases the factor of safety of the slope, its impact on the maximum economic length of the soil nail is minimal. The number of nails and cable anchors increases at a decreasing rate as the slope height increases.

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