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Optimization of soil nailing designs through probabilistic approach

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ABSTRACT: Soil nailing is an effective and economical method for stabilizing excavations and cut slopes. However, like many other geotechnical designs, soil nailing is generally designed in a deterministic approach that does not adequately account for the inherent uncertainties in soil properties. In geotechnical engineering, the uncertainty in soil parameters can significantly influence system performance. Although assuming unfavourable soil properties and increasing the factor of safety (FS) can mitigate the effects of uncertainty, this approach often leads to conservative designs with higher costs. Therefore, in this study we propose a probabilistic framework for optimizing soil nailing designs taking an actual case history as an example. The total expected cost of construction, which is evaluated by an objective function formulated as the summation of initial construction cost and the cost associated with potential failure risks, is optimized during the process. The cost of failure is calculated as the product of the failure probability and the rehabilitation cost. The total length of the soil nails is treated as the design variable, while soil strength parameters are modelled as random variables. The deterministic FS for randomly selected soil parameters is computed using the limit equilibrium method for the soil-nailed slope. The probability of failure, or reliability, of the soil nailing design is evaluated through Monte Carlo simulations, with account for the variability of soil parameters across different soil nailing configurations. Finally, the optimal soil nailing arrangement is identified by minimizing the total expected cost, balancing both construction and risk costs.

KEYWORDS: Soil nailing, probabilistic slope stability, geotechnical uncertainty, design optimization.

1 INTRODUCTION

1.1 *Uncertainty in geotechnical engineering*

Uncertainty is a key, yet often neglected, characteristic in geotechnical engineering. While various categories of uncertainty exist, the inherent variability of soil and rock properties is a primary source that can be quantified and incorporated into engineering design. Unlike manufactured materials like concrete and steel, the properties of geomaterials exhibit significant spatial variability due to complex natural formation processes.

Although this uncertainty significantly affects system performance, conventional design practice often relies on a deterministic approach using conservative, single-point estimates for material properties. This typically produces safe but potentially over-designed and uneconomical solutions (Baecher and Christian, 2003).

1.2 *Probabilistic design approach for slope stability*

Probabilistic methods, which explicitly incorporate uncertainty, offer a more rational design alternative. These methods have seen growing application, although their use remains limited compared to deterministic approaches, partly due to requirements for more extensive data and computational effort. In slope stability, a deterministic analysis yields a single Factor of Safety (FS), whereas a probabilistic analysis produces a probability of failure (p_f). While the FS provides a measure of safety, it does not explicitly quantify the likelihood of failure. In contrast, pf offers a direct measure of this likelihood, which is invaluable for design optimization and risk-informed decision-making.

1.3 *Total expected cost*

In the deterministic design approach, the total cost is merely the initial cost of construction. While in the probabilistic design approach, the uncertainty of the failure is accounted by adding the cost of failure to the initial construction cost. The cost of failure is taken as the product of probability of failure and the associated rectification/consequence cost. This framework allows for design optimization by minimizing the total expected cost (Zevgolis & Bourdeau, 2010 and Zevgolis et al., 2018).

1.4 *Soil nailing*

Soil nailing is a widely used effective and economical solution for stabilizing steep and high slopes and excavations. Soil nails are activated when the slope experiences some movement. Tensile stress developed in a soil nail reduces the shear stress to be mobilized on the slip surface and increases the shear resistance force by increasing the normal stress on the failure surface. Both these phenomena increase the safety margin of a slope.

However, like many other geotechnical designs, soil nailing is typically designed deterministically, without accounting for the inherent uncertainties in soil properties.

1.5 *Objective*

The objective of this paper is to propose a probabilistic design framework for optimizing soil nailing designs by minimizing the total expected cost maintaining adequate p_f. A case history from Sri Lanka is used to demonstrate the methodology.

2 METHODOLOGY

2.1 *Overview*

The study integrates detailed site characterization with probabilistic limit equilibrium analysis to optimize the soil nail design. Geotechnical investigations were performed to quantify the statistical properties (mean and coefficient of variation) of subsoil parameters. A slope model was then analyzed using the limit equilibrium method (LEM) to calculate the FS and Monte Carlo (MC) simulation to determine p_f.

2.2 *Site characterization*

A site investigation comprising five boreholes with Standard Penetration Tests (SPTs) at 1 m intervals was conducted. The friction angle (φ) for soil layers was derived from SPT results using established empirical correlations. The mean and coefficient of variation (CV) for φ were then calculated. For cohesion (c), the mean and CV were estimated based on regional experience and typical values reported in the literature for similar soils.

2.3 *Deterministic FS*

The deterministic stability analysis was performed using GeoStudio SLOPE/W (GEOSLOPE International Ltd., 2017), employing the Morgenstern-Price limit equilibrium method, which satisfies both force and moment equilibrium. The critical slip surface was identified using a grid-and-radius search for circular failure surfaces.

To establish a conservative deterministic design, the design parameters for c and φ were taken at the 97.7th percentile lower-bound (μ - 2σ), a common practice in reliability-based design.

$$Determinstic\ Parameter = \mu - 2 * \sigma \qquad (1)$$

Where μ and σ are the mean and standard deviation values of the parameter. The target FS values, below which the slope is deemed to be unstable, for the deterministic design was set at 1.2.

2.4 *Probabilistic approach*

Normal probability distributions were assigned to the soil strength parameters (c and φ) of the topsoil and residual soil layers. Other sources of uncertainty, such as pore water pressures and soil nail properties, were treated as deterministic to simplify the analysis and focus on the impact of soil strength variability. The p_f was calculated using the built-in Monte Carlo simulation feature in SLOPE/W (GEOSLOPE International Ltd., 2017).

2.5 *Total expected cost*

The total expected cost (C_T) is the objective function to be minimized. It is formulated as the sum of the initial construction cost (C_0) and the cost associated with failure risk, following the framework proposed by Zevgolis & Bourdeau, (2010) and Zevgolis et al. (2018).

$$C_T = C_0 + p_f * C_R \qquad (2)$$

Here, C_R is the cost of repair or rehabilitation after a failure. For this study, C_R is taken as the cost to implement the soil nail arrangement that satisfies the deterministic target FS. Damages and change of slope profile due to failure was not considered.

The construction costs include two components as cost of soil nailing and cost of other associated works including, drainage improvements, facing structure, and other structures. While the cost for soil nailing is a variable cost, the other associated cost assumed to be remained constant across the different soil nailing arrangements.

Finaly, to facilitate comparison, C_T was normalized by the cost of the deterministic design (C_D).

$$^{C_T}/_{C_D} = {}^{C_0}/_{C_D} + p_f * {}^{C_R}/_{C_D} \qquad (3)$$

2.6 *Soil nailing arrangement*

In order to find the optimal soil nailing arrangement, with least total expected cost, various configurations of nail spacing and length were evaluated. Nails were installed in a rectangular grid with three horizontal spacings (SH) of 1.5 m, 2.0 m, and 2.5 m, while keeping similar horizontal spacing as 2.0 m. For each horizontal spacing the length of soil nails were incrementally increased in 2 m increments starting from 4 m. The length increment for a given soil nail was terminated when the nail reached its tensile capacity or the capacity of the nail reinforcement.

3 SITE CHARACTERIZATION

3.1 *Overview*

Avissavella – Hatton – NuwaraEliya road is a major connection road to central region of the country. Bridge No. 48/2 on this road near Ginigathhea area, which has an elevation about 470 m from mean sea level, is a very narrow bridge where two vehicles cannot be passed by. Also, the traffic demand on the said road is increasing rapidly with economic and population growth in the area. Based on that high demand, the bridge and the road was proposed to be widen. Some excavation was done at the toe of upper slope of the bridge on the purpose of widening the bridge. Ancient landslide above the bridge got reactivated with this toe excavation and the failure was propagated to upper slope. It was reported that there was no rain at the time of the initial failure. With the occurrence of rainfall in the area later, failure was further activated. Figure 1 and Figure 2 illustrates the location map of the landslide area and failure just after the rainfall event respectively.

More details on this landslide and mitigation are available in Lakruwan (2019), Lakruwan & Kulathilaka (2021a, 2021b),

Figure 1. Location map of the landslide

Figure 2. Photograph just after the failure

3.2 *Subsoil profile*

The subsoil profile derived from three boreholes drilled along the critical axis of the failure, which passes across the middle of the bridge, is presented in Figure 3. The other two borehole were located at offset axis parrel to the failure axis.

Table 1 presents the material parameters used for the analyses. The parameters were derived based on the investigation results, experienced gained in similar subsoil conditions, and typical values reported in the literature for similar soils.

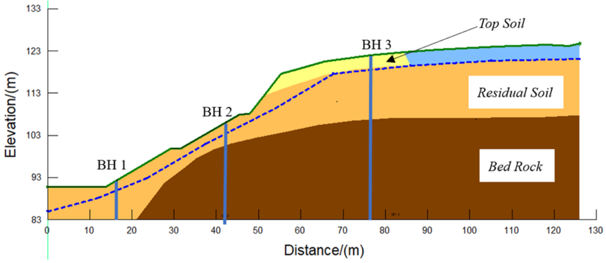

Figure 3. Subsoil profile

Table 1. Material properties for analysis.

Soil Layer		Parameter	Mean	CV
Top Soil	🟨	C	6 kPa	15%
		Φ	24°	15%
Residual Soil	🟧	C	10 kPa	15%
		Φ	30°	15%

4 RESULTS AND DISCUSSION

4.1 *Deterministic approach*

The minimum total length of soil nails required to achieve the target FS of 1.2 was determined by increasing the length of soil nails as stipulated in Section 2.6.

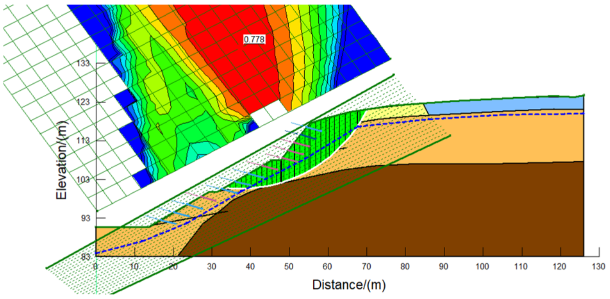

Figure 4. Critical slip surface corresponding to initial soil nailing arrangement (nail length = 4 m; horizontal spacing = 1.5 m)

Figure 4 illustrates that the critical slip surface does not passes through the underlaying bed rock layer, implying the four numbers of soil nails at the bottom berm do not contribute effectively to stability. Therefore, the cost for these soil nails was considered under the constant other associated cost.

Based on this analysis, the total soil nail length required to achieve the target FS of 1.2 is 113 m per meter width of slope.

4.2 *Sample size for MC simulation*

The reliability of MC simulations is highly dependent on the number of trials, especially for lowp_f, where uncertainty can be high for small sample sizes (Phoon et al., 2022 and Huang et al., 2016). However, GeoStudio SLOPE/W generates random sample in the same sequence in repetitions trails result in same p_f value. Consequently, a convergence study was performed to determine an adequate sample size for this analysis.

The convergence study was conducted while maintaining a p_f value about 0.2%. As suggested by Phoon et al. (2022) and Huang et al. (2016), the required number of samples to maintain CV of p_f value less than 10% is $100/p_f$. However, the calculated p_f was found to stabilize after 20,000 simulations as shown in Figure 5. Therefore, this sample size was adopted for the remainder of the MC simulations presented in this study to balance accuracy with computational effort.

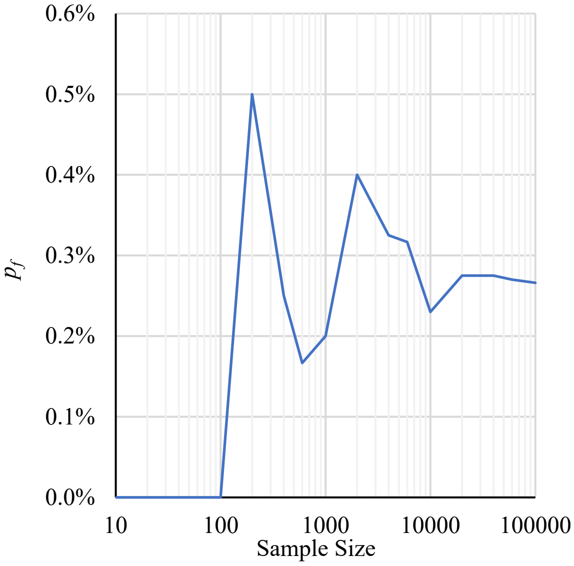

Figure 5. Variation of p_f with sample size of MC simulation.

4.3 *Failure probability*

Figure 6 illustrates the reduction of $p_f$as the nail length per unit width increases for three different horizontal spacings. Since three different horizontal spacings were considered, soil nail length per unit width of the slope was used for the comparison.

As expected, pf decreases with increasing nail length and the initial rapid reduction in p_f gradually reduces with the increment of the nail length. Furthermore, for a given total nail length, a wider horizontal spacing results in a lower p_f value. Therefore, wider spacings between the soil nails is economical. However, the possibility of local failure between soil nail columns shall be carefully evaluated before implementing wider horizontal spacings. Since the two-dimensional limit equilibrium stability analyses cannot accommodate for these local failures, this three-dimensional failure mechanism must be considered separately in a complete design.

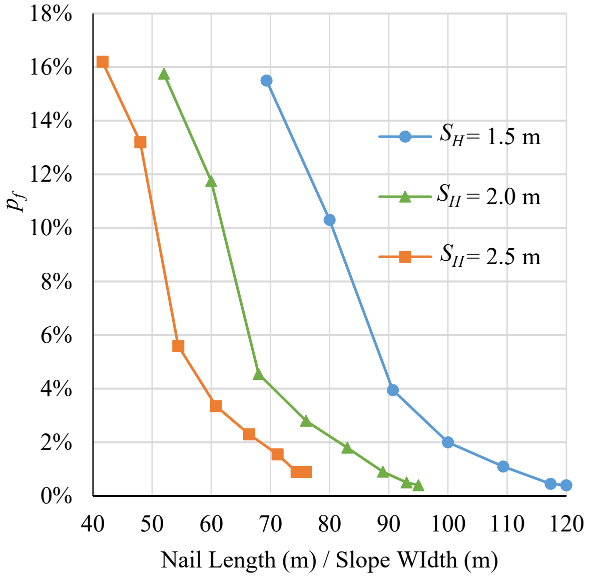

Figure 6. The p_f for different S_H

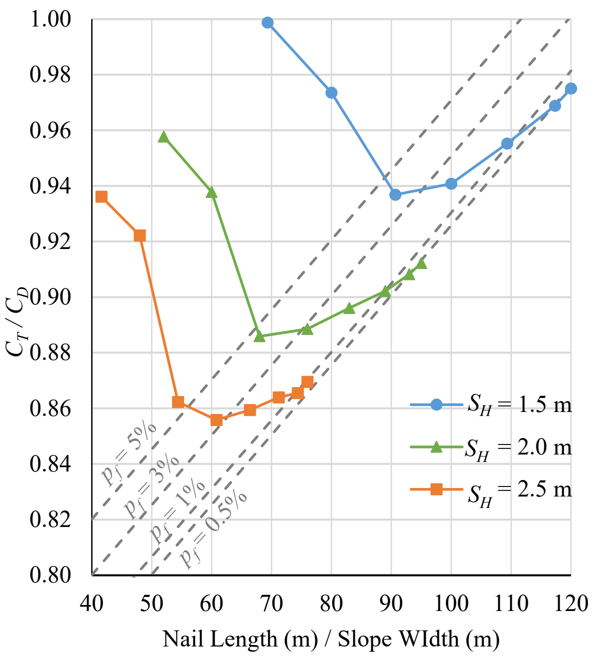

Figure 7. Optimization of soil nailing arrangement (dashed lines represent different p_f values)

Figure 7 presents the optimization curves based on the total expected cost function (Equation (3)) for soil nailing arrangements with three different S_H values. The dashed in the Figure 7 represents different p_f values.

Although the initial construction cost increases linearly with the nail length, the normalized total costs (C_T/C_D) exhibit clear convex distributions due to the non-linear variation of the repair cost. The lowest point on each curve represents the optimal design for that specific horizontal spacing, where the balance between construction cost and failure risk is optimized. For all spacings, the optimal p_f lies between 3% and 5%. To achieve a lower p_f values, a more robust and costly design with longer nails is required. Given that the total cost curves are relatively flat near the minimum, it is often sensible to select a design with a slightly lower p_f than the absolute optimum, as it can be achieved with only a minor increase in total cost. For the presented case study, the C_T can be reduced to about 86% of C_D while maintaining the p_f less than 1%.

It should be noted that, C_T only includes the construction and repair cost upon a failure. The other impacts due to failures such as, damages to road users and infrastructure, disruptions to transportation on the major road and surrounding communities, environmental impacts, and other economic losses have not been accounted for.

Following the similar trend as in p_f (Figure 6), wider spacings demonstrate lower C_T/C_D values. The potential local failures between nail columns shall be evaluated prior to decide on larger S_H values.

The optimum nailing arrangement shall be decided optimizing the cost, p_f, and potential local failures.

5 CONCLUSIONS

This study demonstrated the application of a probabilistic optimization framework for the design of a soil-nailed slope. By defining the total expected cost as the objective function, it was possible to move beyond conventional deterministic design and identify an optimal solution that rationally balances construction costs and failure risk.

The key findings are:

- A probabilistic approach provides a better understanding of slope safety than a deterministic single factor of safety value. The analysis revealed that a design considered "safe" under deterministic criteria (FS > 1.2) still carries a probability of failure, which can be incorporated into risk-based decision-making.
- The total expected cost, which combines initial construction costs associated with potential failure, serves as a robust objective function. The optimization curves derived from this function clearly identified an optimal design corresponding to a minimum total cost.
- For the case study presented, the optimal design configurations consistently corresponded to a probability of failure between 3% and 5%. This demonstrates that the most economical solution is not necessarily the one with the lowest initial cost or the lowest failure probability, but rather the one that achieves an effective balance between the two.
- Furthermore, the results showed that the total expected cost can be reduced to about 86% of the cost corresponding to the deterministic approach while maintaining the failure probability less than 1%.
- The framework highlights the trade-offs inherent in slope stability designs, where achieving an optimal balance between risk and cost is essential. This method allows designers and stakeholders to make informed decisions about the level of acceptable risk and total expected cost.

While this study focused on soil strength variability, the proposed framework is adaptable and can be extended to include other sources of uncertainty. The methodology provides a practical and rational approach for optimizing geotechnical designs, moving towards more economical and risk-informed engineering solutions.

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