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Stability analysis of soil-nailed slopes using the Spencer Method

Análise de estabilidade de taludes pregados com solo utilizando o Método Spencer

Análisis de estabilidad de taludes clavados en el suelo utilizando el Método Spencer

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ABSTRACT
This study analyzes the stability of a 12-meter-high slope reinforced with soil nails, using the Spencer limit equilibrium method. The evaluation of safety factors was performed under various loading conditions, including self-weight, road surcharge, water table presence, and seismic activity. The results show that soil nailing significantly improves slope stability, with the safety factor increasing from 0,48 to 1,48 under self-weight loading. Numerical simulation software was used for the modeling and calculations, yielding accurate results that are highly suitable for designing retaining structures. This research demonstrates the effectiveness of soil nailing as a reinforcement method, highlighting its ability to enhance stability in slopes subjected to different types of loading. The study also emphasizes the importance of considering multiple factors, such as hydraulic pressures and seismic effects, when designing slope stabilization systems. The reliable outcomes obtained from numerical analysis reinforce the role of advanced simulation tools in ensuring slope safety, particularly in areas prone to environmental or man-made stressors.

Keywords: Stability. Soil Nails. Spencer Limit Equilibrium Method. Stabilization.

RESUMO
Este estudo analisa a estabilidade de um talude de 12 metros de altura reforçado com grampos de solo, usando o método de equilíbrio limite de Spencer. A avaliação dos fatores de segurança foi realizada sob várias condições de carga, incluindo peso próprio, sobrecarga da estrada, presença de lençol freático e atividade sísmica. Os resultados mostram que o grampo de solo melhora significativamente a estabilidade do talude, com o fator de segurança aumentando de 0,48 para 1,48 sob carga de peso próprio. Software de simulação numérica foi usado para modelagem e cálculos, produzindo resultados precisos que são altamente adequados para projetar estruturas de contenção. Esta pesquisa demonstra a eficácia do grampo de solo como um método de reforço, destacando sua capacidade de aumentar a estabilidade em taludes sujeitos a diferentes tipos de carga. O estudo também enfatiza a importância de considerar múltiplos fatores, como pressões hidráulicas e efeitos sísmicos, ao projetar sistemas de estabilização de taludes. Os resultados confiáveis obtidos da análise numérica reforçam o papel de ferramentas avançadas de simulação para garantir a segurança do talude, particularmente em áreas propensas a estressores ambientais ou artificiais.

Palavras-chave: Estabilidade. Grampos no Solo. Método do Equilíbrio Limite de Spencer. Estabilização.

RESUMEN
Este estudio analiza la estabilidad de un talud de 12 metros de altura reforzado con clavos de suelo, utilizando el método de equilibrio límite de Spencer. La evaluación de los factores de seguridad se realizó bajo varias condiciones de carga, incluyendo peso propio, sobrecarga de la carretera, presencia de nivel freático y actividad sísmica. Los resultados muestran que el uso de clavos de suelo mejora significativamente la estabilidad del talud, con un factor de seguridad que aumenta de 0,48 a 1,48 bajo carga de peso propio. Se utilizó un software de simulación numérica para el modelado y los cálculos, obteniendo resultados

precisos que son muy adecuados para el diseño de estructuras de contención. Esta investigación demuestra la eficacia del uso de clavos de suelo como método de refuerzo, destacando su capacidad para mejorar la estabilidad en taludes sometidos a diferentes tipos de carga. El estudio también enfatiza la importancia de considerar múltiples factores, como las presiones hidráulicas y los efectos sísmicos, al diseñar sistemas de estabilización de taludes. Los resultados confiables obtenidos a partir del análisis numérico refuerzan el papel de las herramientas de simulación avanzadas para garantizar la seguridad de los taludes, en particular en áreas propensas a estresores ambientales o artificiales.

Palabras clave: Estabilidad. Clavos de Suelo. Método de Equilibrio Límite de Spencer. Estabilización.

1 INTRODUCTION

Landslides are phenomena that pose major risks to infrastructure and residential safety, especially in mountainous regions. Hence, slope stabilization is crucial for protecting road and railway infrastructures. Among the stabilization techniques, the use of soil nails has proven effective, increasing shear resistance and overall slope stability [3].

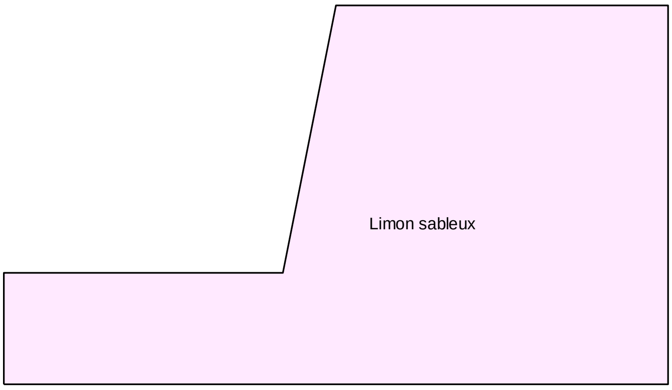
The Spencer limit equilibrium method is one of the most reliable techniques for evaluating slope stability. This method accounts for inter-slice forces and allows the calculation of safety factors under various loading conditions [7]. The objective of this study is to analyze the stability and reinforcement of a 12-meter-high slope using soil nails, by applying Spencer's method under different loading scenarios, such as self-weight, surcharge, water table, seismic effects, and their combinations.

2 MATERIALS AND METHODS

2.1 REFERENCE PROFILE OF THE ANALYZED SLOPE

The analyzed slope is a 12-meter-high structure with an inclination of 80,54° (Figure 1). The first step involved modeling the structure by considering soil parameters, boundary conditions, and gravity. An automatic mesh was generated for the 2D calculations [5].

Figure 1. Geometry of the studied profile.



Source: Authors.

The soil behavior was represented using the elastoplastic Mohr-Coulomb model. The mechanical properties of the soil, such as cohesion (c), internal friction angle (φ), and unit weight, are presented in Table 1 [1].

Table 1. Mechanical properties of the soil

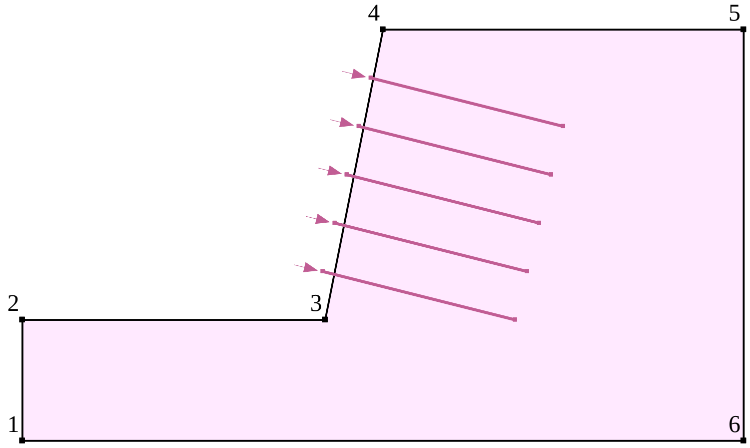
Parameter	**Value**
Cohésion (c)	25 kPa
Internal friction angle (φ)	30°
Unit weight	18 kN/m³

Source: National Laboratory of Housing and Construction (LNHC) .

2.2 MODELING OF THE REINFORCED SLOPE

As the slope was unstable under self-weight loading (safety factor of 0,48), soil nailing reinforcement was implemented. Five rows of soil nails were installed with a spacing of 2m to ensure an optimal distribution of reinforcement forces (Figure 2) [4].

Figure 2. Slope reinforced with soil nails



Source: Authors.

The characteristics of the soil nails used are detailed in Table 2.

Table 2. Characteristics of the soil nails

Parameter	**Value**
Length (m)	8 to 8,5
Inclination (°)	14
Diameter (m)	0,30 to 0,35

Source: Authors.

2.3 SPENCER METHOD FOR STABILITY ASSESSMENT

The Spencer method enables stability analysis by considering shear and normal forces acting along potential slip surfaces. The safety factor (FS) is calculated as follows [2][6]:

$$FS = \frac{\sum[(N - U.L).tan\emptyset + c.L]}{\sum(S + W.a_h)} \quad (1)$$

Where:

- N is the total normal force
- U is the pore water pressure, and L is the length of the slip surface at that slice.
- (R_n) is the normal force,
- (c) is cohesion, and (φ) is the internal friction angle.
- (S) is the shear force, and a_h is the acceleration due to gravity

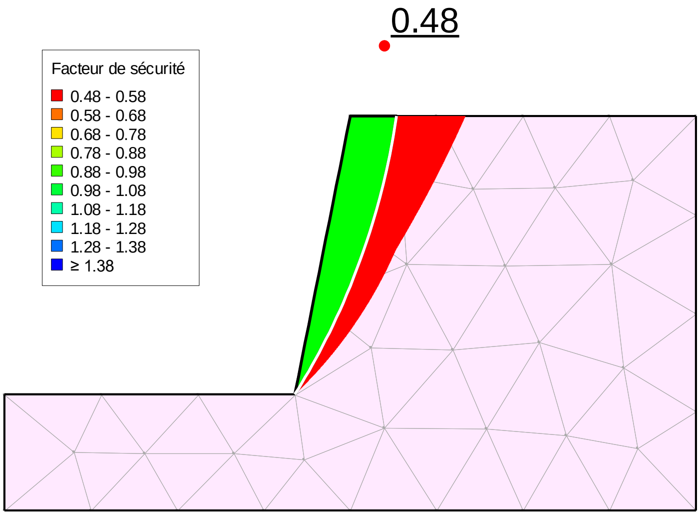
3 RESULTS

Figure 3 illustrates in detail the different slip lines corresponding to the minimum calculated safety factors.

It is significant to note that the safety factor increased considerably, from 0,48 to 1,48 after reinforcement (Figure 4).

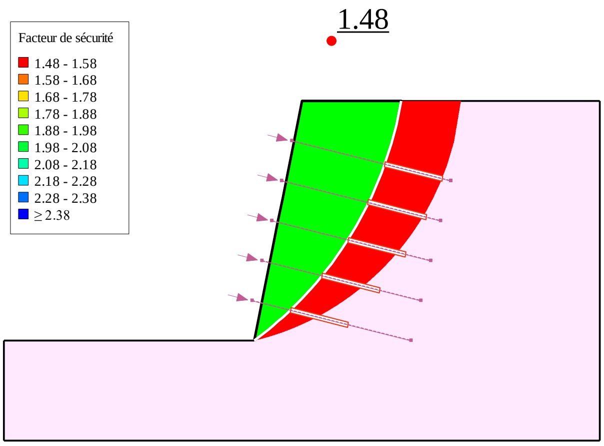
This clearly indicates that the slope, once reinforced with soil nails, reached a sufficient level of stability to effectively resist self-weight loading.

Figure 3. Slip Circle and Safety Factor by SPENCER for Unreinforced Slope under Self-Weight



Source: Authors.

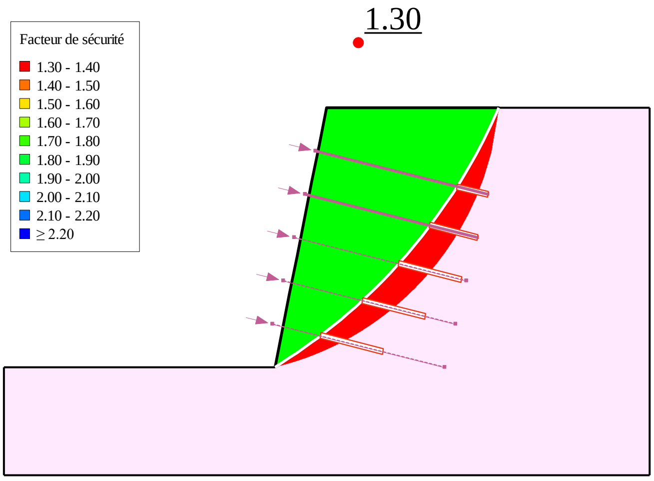
Figure 4. Slip circle and safety factor using the SPENCER method for the slope reinforced with soil nails



Source: Authors.

To assess the effect of vehicular load on the roadway, it was replaced by an operational load of 40 kN/m². Figure 5 shows that the slope remained stable, with the safety factor being 1,30.

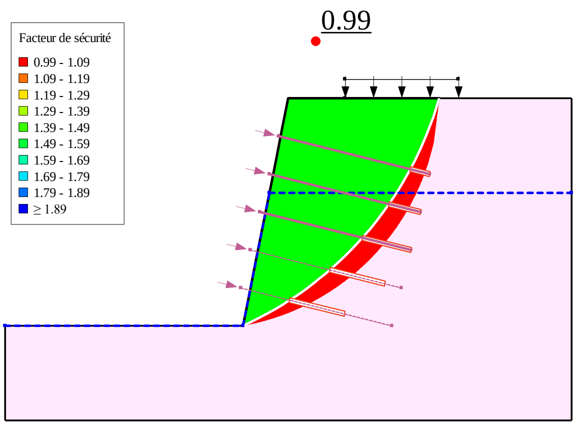
Figure 5. Slip circle and safety factor using the SPENCER method for the reinforced slope under road loading



Source: Authors.

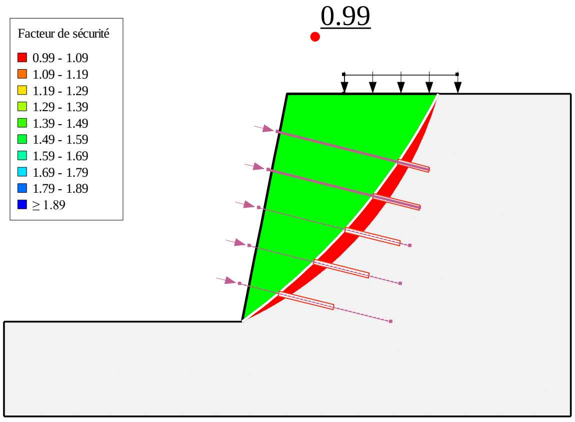
For the combined effect of all loads, the slope only loses equilibrium when either the water table reaches a height of 12 m or the horizontal seismic acceleration reaches 0,20g.

Figure 6. Slip Circle and Safety Factor by SPENCER for Soil-Nailed Slope with Load and 12m Water Table



Source: Authors.

Figure 7. Slip Circle and Safety Factor by SPENCER for Soil-Nailed Slope with 0,20g Seismic Load



Source: Authors.

4 DISCUSSIONS

The analyses were carried out under different loading scenarios:

- Self-weight loading only: The initial FS value was 0,48 (unreinforced slope) and increased to 1,48 after reinforcement (Figure 3 and Figure 4);
- Self-weight and road surcharge (40 kN/m²): The reinforced slope remained stable with an FS of 1,30 (Figure 5);
- Combined effect of self-weight, road surcharge, and water table: When the water table reached 12 m, the FS decreased but remained acceptable due to reinforcement (Figure 6);
- Seismic loading (horizontal acceleration of 0,20g): The slope remained stable with a sufficient FS (Figure 7).

5 CONCLUSION AND RECOMMENDATIONS

The results confirm that using soil nails significantly enhances slope stability, with the safety factor increasing from 0,48 to 1,48 under self-weight loading alone. This reinforcement also enables the slope to resist additional loads, such as road surcharges, rising water table, and seismic effects. Analyses conducted under different loading conditions indicate a significant increase in the safety factor, demonstrating that slopes reinforced with soil nails can withstand various load combinations.

RECOMMENDATIONS

- soil nails should be installed at an optimal inclination (around 14°) to maximize stability;
- an effective drainage system should be implemented to control the rising water table.

FUTURE WORK

- investigating the impact of soil property variability on soil nail performance.
- assessing reinforcement efficiency under extreme climatic conditions.

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