Finite element modelling of soil nailing inclination effect on slope stability: Cibeureum slope case study

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Abstract

On November 21, 2022, a 5.6 magnitude earthquake caused a landslide on one of the slopes in Cibeureum, Cianjur district. To repair the slope, reinforcement is necessary to achieve stability values that can withstand future earthquakes. One method for enhancing slope stability is soil nailing. Various soil nailing installation angles were analyzed to find the optimal design for the Cibeureum slope. Using the Plaxis 2D V20 program, the safety factor of the original slope without an earthquake was found to be 1.62. Increasing the installation angle of the soil nails from 10°, 15°, to 20° improved the safety factor, but the increase was not significant because the initial installation point was far from the slip line, requiring a nail length of 50 meters. The best configuration, yielding the highest safety value, was achieved with a modified slope angle of 19° and soil nails with a 50 m length installed at a 20° angle. This configuration produced a safety factor of 2.55 without an earthquake and 1.102 with an earthquake, as calculated using the Plaxis 2D V20 program.

Introduction

On November 21, 2022, Cianjur Regency experienced a 5.6 magnitude earthquake, resulting in the deaths of 334 people and causing significant damage to multi-story buildings, ground movements, and cracks (Yusri et al., 2023; Mulyana et al., 2023). In addition to the loss of life and infrastructure damage, the earthquake triggered landslides on the Cibeureum slope. Landslides occur when masses of soil or rock move under the influence of gravity, often caused by factors such as rainfall, climate, and slope angle (Sulistyowati et al., 2022; Fauzi and Hamdan, 2019; Hamdan and Pratiwi, 2017). The presence of landslide hazards necessitates slope stability analysis to prevent future landslides and reinforce the slope (Kusuma and Mina, 2020). Numerous studies have been conducted on slope stability, such as using sheet piles and embankment soil (Setyanto et al., 2016). Slope reinforcement techniques like retaining walls and bored piles with a diameter of 80 cm have also been shown to increase the safety factor by 242.2% compared to existing conditions (Hamdan and Pratiwi, 2017). Soil nailing has emerged as a preventive measure for slope failure that is more economical, faster to implement, and feasible in constrained work areas with minimal heavy equipment requirements. An illustration of soil nailing is shown in Figure 1 below.

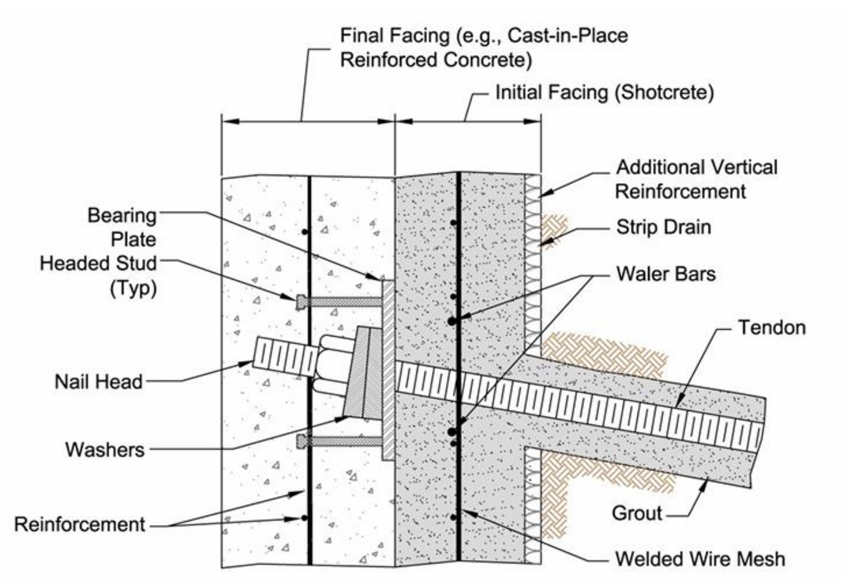

Figure 1. Detailed Image of Soil Nailing (Federal Highway Administration, 2015)

One of the methods for analyzing slope stability is through geotechnical finite element analysis using a computer program called Plaxis 2D V20. This program allows for the assessment of slope stability, including soil nailing reinforcement, by employing the finite element method and various soil models to simulate soil behavior (Badan Standardisasi Nasional, 2017; Mangnejo et al., 2019; Dewedree and Jusoh, 2019; Elahi et al., 2022). The use of Plaxis 2D in modeling soil nailing, as demonstrated in toll road projects, has proven to significantly enhance slope stability (Standyarto et al., 2023). This research aims to evaluate the stability of the Cibeureum slope by analyzing soil nailing reinforcement at various installation angles using Plaxis 2D V20, with the goal of achieving an optimal slope design.

Correlations for determining soil parameters

In geotechnical engineering, empirical correlations are commonly employed as preliminary estimates and for comparing values obtained from both laboratory and field tests. The N-SPT value correlation is an empirical method used to optimize testing when field investigation data is limited (Warman, 2019). The estimated values of the Elasticity Modulus are presented in Table 1.

Table 1. Estimated elasticity modulus (Look, 2014)

Type	Strength of soil	E (MPa) Short term	E (MPa) Long term
Silt	Soft	<10	<8
	Stiff	10-20	8-15
	Hard	>20	>15
Clay	Very soft	<3	<2
	Soft	2-7	1-5
	Firm	5-12	4-8
	Stiff	10-25	7-20
	Very stiff	20-50	15-35
	Hard	40-80	30-60

Bowles (1984) provides the correlation between N-SPT and Unit Weight shown in Table (2) below (Maulidha et al., 2022)

Table 2. Correlation of N-SPT with unit weight of cohesive soil (Bowles, 1984)

N (blow)	γ (kN/m^3)
<4	14-18
4-6	16-18
6-15	16-18
16-25	16-20
>25	>20

Bowles (1977) provides the correlation between type soil and Poisson’s ratio shown in Table (3) below (Rahman, 2020).

Table 3. Estimated poisson's ratio (Bowles, 1977)

Type of Soil	Poisson's Ratio (μ)
Saturated clay	0,4 – 0,5
Unsaturated clay	0,1 – 0,3
Sandy clay	0,2 – 0,3
Silt	0,3 – 0,35
Dense sand	0,2 – 0,4
Coarse sand	0,15
Fine sand	0,25
Rock	0,1 – 0,4
Loess	0,1 – 0,3

Terzaghi and Peck (1967) provides the correlation between N-SPT and Cohesion shown in Table (4) below (Warman, 2019).

Table 4. Correlation of N-SPT with cohesion of clay soil (Terzhagi and Peck, 1967)

Consistency	N	Cohesion (kN/m^2)
Very soft	0-2	<12
Soft	2-4	12-25
Medium	4-8	25-50
Stiff	8-15	50-100
Very Stiff	15-30	100-200
Hard	>30	>200

Bowles (1984) provides the correlation between N-SPT and unit weight saturated shown in Table (5) below (Rahman, 2020).

Table 5. Correlation of N-SPT with unit weight saturated of cohesive soil (Bowles, 1984)

N (blow)	γ (kN/m^3)
0-2	<15,7
2-4	15,7 – 18,8
4-8	17,3 – 19,6
8-16	18,1 – 20,4
16 - 32	18,8 – 22.0
>32	>20,4

Traffic Load

The traffic load is applied across the full width of the road, with the load value adjusted based on the road class. The relationship between road class and traffic load is presented in Table 6.

Table 6. Traffic Load (Badan Standardisasi Nasional, 2017)

Class	Within Road (kPa)	Outside Road (kPa)
I	15	10
II	12	10
III	12	10

Technical Requirements for Soil Nailing

Nail bars should be installed at angles between 10° and 20° below the horizontal plane. A steeper inclination can reduce the nail's effectiveness in resisting lateral forces, while an inclination of less than 10° may lead to voids forming in the grout. Additionally, the nail bar length should range from 0.6 H to 1.2 H, where H represents the height of the slope (Badan Standardisasi Nasional, 2017).

Plaxis 2D Program

The graphical modeling process in Plaxis 2D is intuitive, allowing for the quick creation of complex finite element models, while also offering features that present more detailed results. As a finite element method, Plaxis 2D automatically identifies failure zones where the soil's shear strength is insufficient to withstand applied shear stresses (Griffiths, 1999). The safety factor in Plaxis 2D is calculated using the ϕ-c reduction method, which uniformly reduces shear strength parameters until failure occurs (Jurgens and Henke, 2021). For a visual representation of this method, refer to Figure (2).

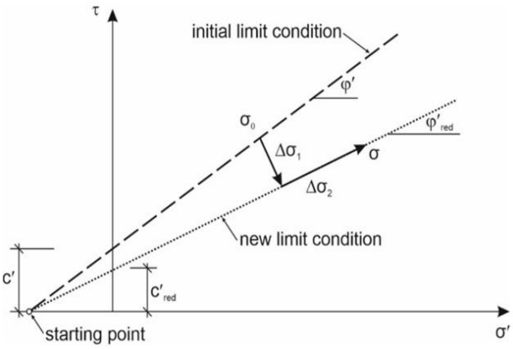

Figure 2. ϕ-c Reduction Method (Jurgens and Henke, 2021)

The pseudostatic method models the impact of an earthquake as horizontal and/or vertical acceleration. The seismic coefficient applied in this method is based on the peak ground acceleration (PGA). For horizontal seismic coefficient calculations, the value used is typically 0.5 times the PGA (Badan Standardisasi Nasional, 2017).

Research Method

The research was conducted on the Cibeureum slope in Cianjur Regency, which experienced landslides following the earthquake on November 21, 2022. The research location, along with sections and details of the research object, are illustrated in Figure (3), Figure (4), Figure (5), and Figure (6) below.

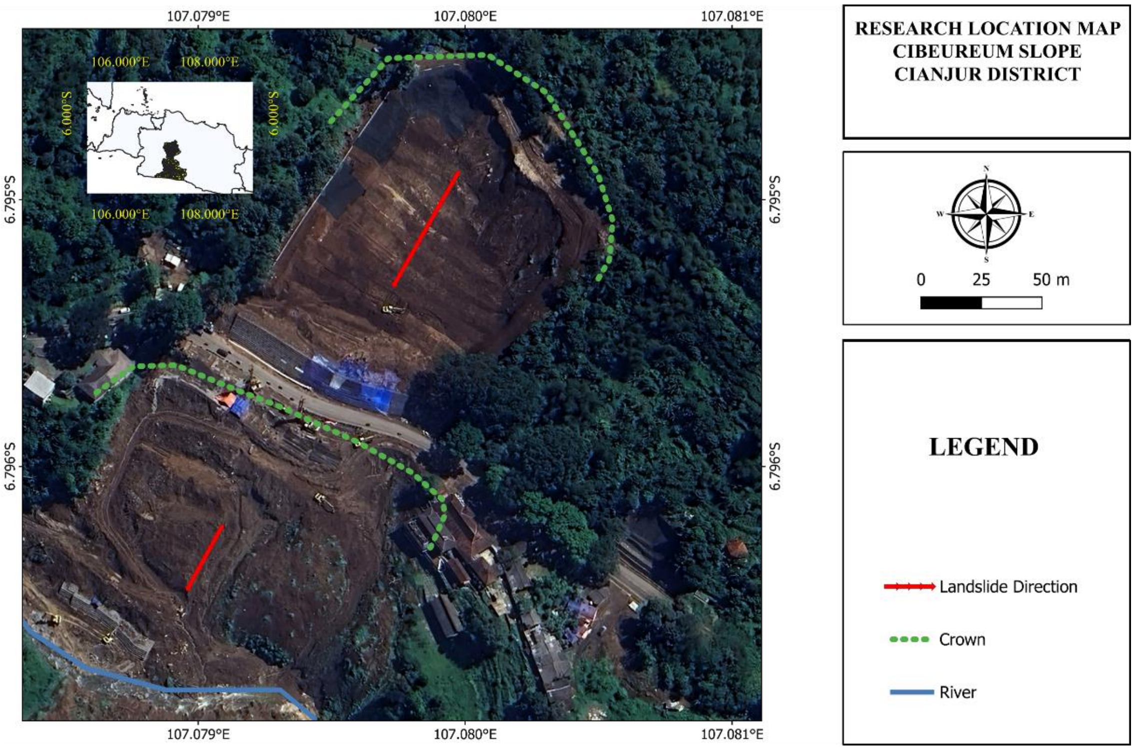

Figure 3. Case study location

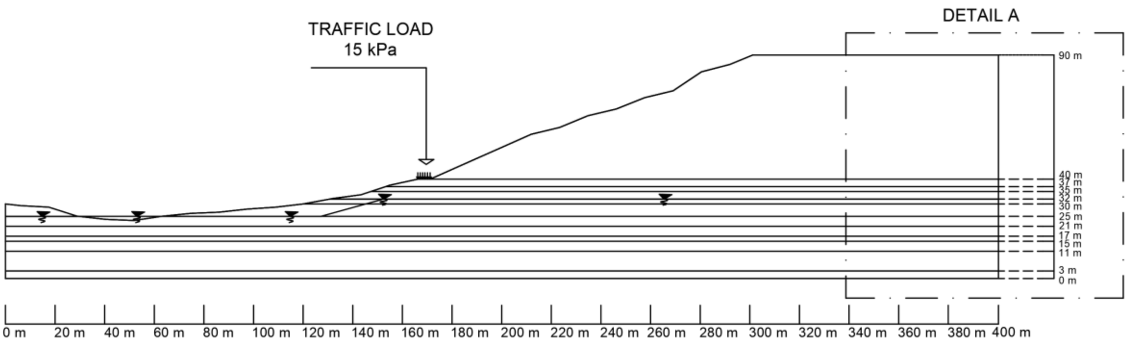

Figure 4. Slope modeling

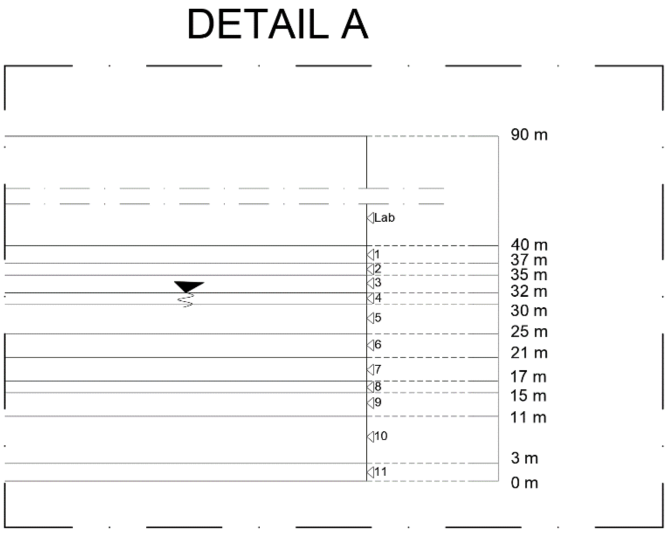

Figure 5. Detail a slope modeling

The Input Parameters

The primary data used in this research are the soil properties obtained through direct laboratory testing. The test results, referred to as the lab layer, are presented in Table (7).

Table 7. Results of laboratory testing of soil layers

Variable	Result
γ_{sat} kN/m^3	15.90
γ_{unsat} kN/m^3	15.80
c kPa	20.36
φ °	24.50

For the subsequent soil layer, the correlation of N-SPT results is used, as presented in Table (8).

Modelling Slope on Plaxis 2D

Based on the model shown in Figures (4), (5), and (6), along with the soil parameters for each layer in Tables (7) and (8), the Plaxis 2D modeling is illustrated in Figure (7) below.

Table 8. Layer Parameters Resulting from N-SPT Correlation

No.	γ_{sat} kN/m^3	γ_{unsat} kN/m^3	E Mpa	c' kPa	φ °
1	16.00	15.00	2	15	25
2	16.00	15.00	3	20	25
3	18.00	16.00	10	50	25
4	19.00	16.00	10	50	25
5	20.00	18.00	20	120	25
6	19.00	16.00	10	70	25
7	20.00	16.00	20	120	25
8	19.00	16.00	10	70	25
9	23.00	21.00	40	200	25
10	23.00	21.00	40	200	25
11	23.00	21.00	50	200	25

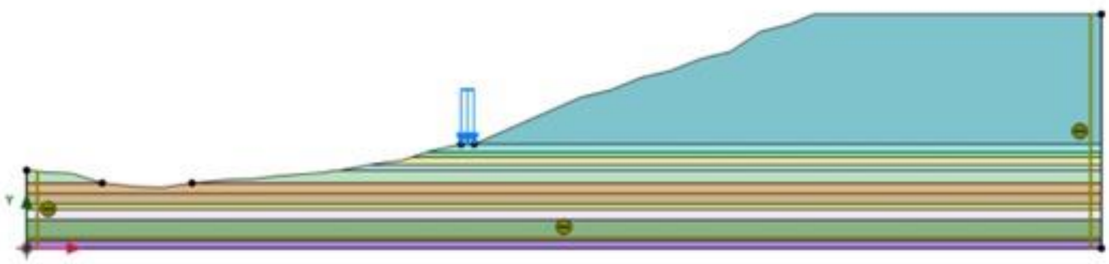

Figure 7. Modeling of existing slope in Plaxis 2D

Soil nailing parameters

Based on SNI 8460:2017, nail bars should be installed at angles between 10° and 20° below the horizontal plane. Accordingly, the design for the installation angle of soil nailing varies between 10°, 15°, and 20°. The soil nailing parameters used are detailed in Table (9) below.

Table 9. Soil Nailing Parameters

Parameter	Value	Unit
E	210000000	kN/m^2
γ	78.5	kNm^3
Diameter	0.043	m
Sv	1.3	m
L	50	m

Modelling soil nailing on slope

The modeling of slope reinforcement using soil nailing is based on Figure (7), along with the specified soil nailing parameters in Table (9). The design for slope reinforcement with soil nailing installed at a 10° angle is illustrated in Figure (8) below.

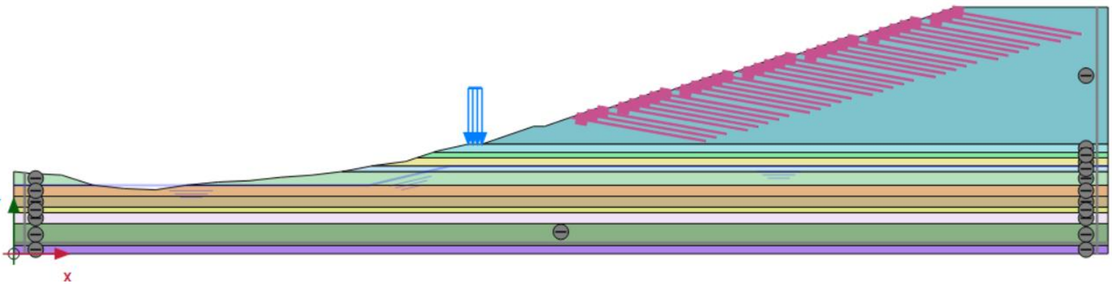

Figure 8. Modeling of slope reinforcement with soil nailing

Results and Discussion

Slope analysis using Plaxis 2D

Slope analysis using Plaxis 2D was conducted for multiple slope conditions. These conditions include the existing slope without and with seismic load, as well as the slope reinforced with soil nailing installed at angles of 10°, 15°, and 20°, both with and without seismic load. The modeling results in Plaxis 2D display the slip surfaces for each scenario as follows.

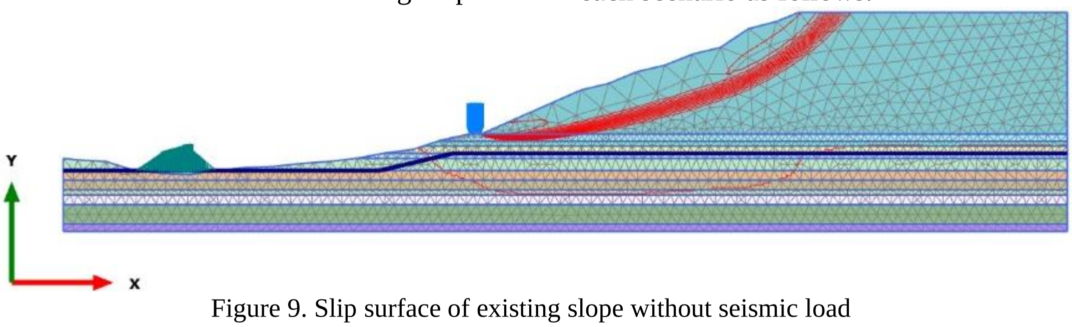

Figure 9. Slip surface of existing slope without seismic load

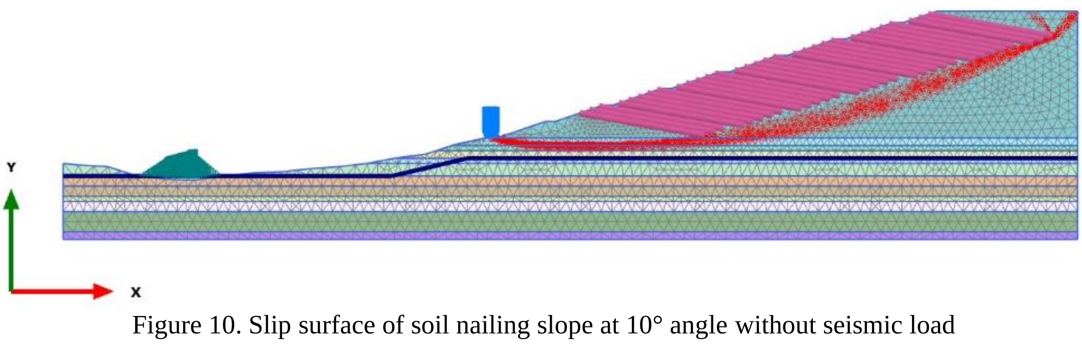

Figure 10. Slip surface of soil nailing slope at 10° angle without seismic load

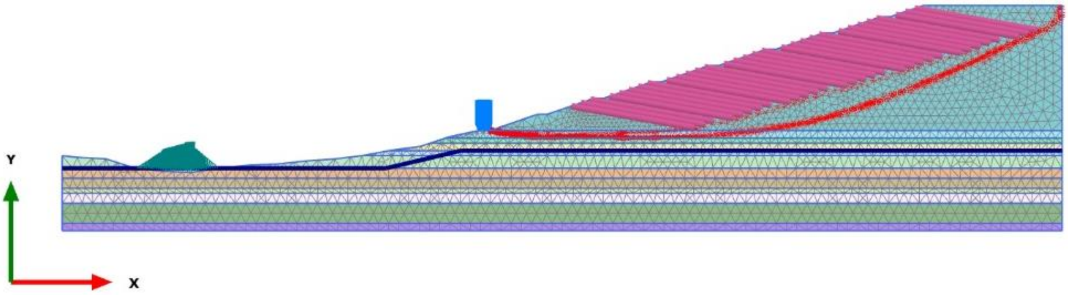

Figure 11. Slip surface of soil nailing slope at 10° angle with seismic load

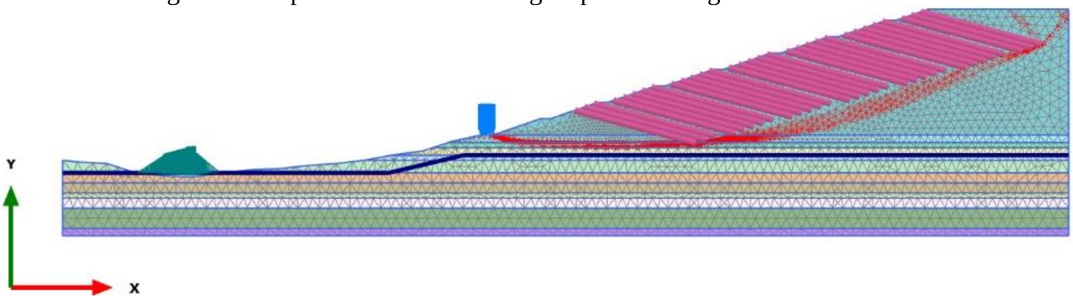

Figure 12. Slip surface of soil nailing slope at 15° angle without seismic load

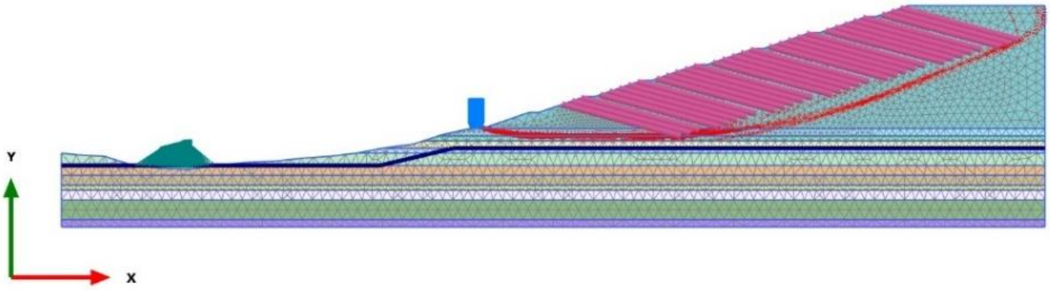

Figure 13. Slip surface of soil nailing slope at 15° angle with seismic load

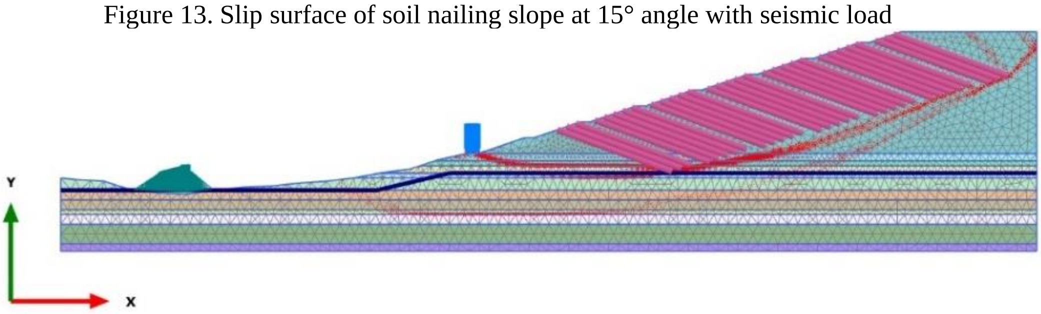

Figure 14. Slip surface of soil nailing slope at 20° angle without seismic load

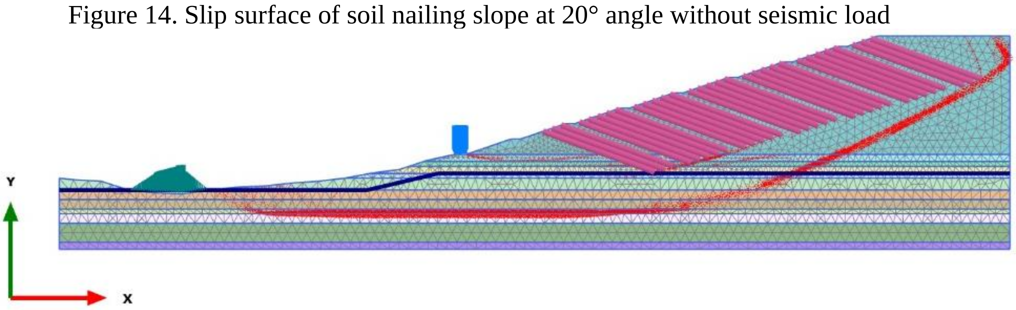

Figure 15. Slip surface of soil nailing slope at 20° angle with seismic load

The modeling results using Plaxis 2D for the existing slope without seismic load, as depicted in Figure (9), show a safety factor of 1.62, which exceeds the threshold of 1.5,

indicating that the slope is considered safe. The analysis was also conducted using the Pseudostatic method with a peak ground acceleration (PGA) of 0.4982, resulting in a horizontal seismic coefficient of 0.2491.
For the slope reinforced with soil nails at different angles, the following observations were made:

- With soil nails at a 10° angle: The safety factor without seismic load, shown in Figure (10), is 2.34, which is above the safe threshold of 1.5. However, when subjected to seismic load, the safety factor decreases to 1.01, as illustrated in Figure (11). This value is below the acceptable safety threshold of 1.1, indicating that the slope is not safe under seismic conditions.
- With soil nails at a 15° angle: The safety factor without seismic load is 2.4, as shown in Figure (12), which is greater than 1.5, suggesting safety. Nevertheless, under seismic load conditions, the safety factor is 1.03 (Figure (13)), still below the required safety threshold of 1.1, implying that the slope remains unsafe.
- With soil nails at a 20° angle: The safety factor without seismic load, illustrated in Figure (14), is 2.55, well above the threshold of 1.5, indicating safety. Importantly, with seismic load, the safety factor improves to 1.102 (Figure (15)), which meets the safety threshold of 1.1, confirming that the slope is now considered safe.

Table 10. Recapitulation of safety factor results for the Cibeureum slope

Detail	Condition	FS
Slope Existing	Without Seismic Activity	1.62
	Seismic Activity	-
Soil nailing with inclination 10º	Without Seismic Activity	2.34
	Seismic Activity	1.01
Soil nailing with inclination 15º	Without Seismic Activity	2.40
	Seismic Activity	1.03
Soil nailing with inclination 20º	Without Seismic Activity	2.55
	Seismic Activity	1.10

Based on the results shown in Table (10), there is a notable increase in safety factor values with each increment in the soil nailing installation angles of 10°, 15°, and 20°. This observation aligns with the findings of Imbar et al. (2019), who reported the highest safety factor at a 20° installation angle, which was 2.030, compared to a safety factor of 1.866 at a 10° angle. In contrast, studies by Mangnejo et al. (2019) showed different results. Their research, which examined various nail diameters (25 mm and 40 mm) and installation angles (20°, 25°, 30°, 35°, and 40°), revealed that the highest safety factor for a 25 mm diameter nail occurred at a 35° angle, while for a 40 mm diameter nail, it was at a 40° angle. This discrepancy indicates that increasing the soil nailing installation angle does not always correspond directly with higher safety factor values, as the optimal angle is influenced by the specific slip surface of each case study.
The effectiveness of soil nailing is affected by the bond length behind the slip surface, which contributes to the allowable load that the nail can withstand in a state of maximum load (Alsubal et al., 2017). In the Cibeureum slope case, the inclination from 10° to 20° did not result in a significant increase in the safety factor, likely due to the initial installation point being far from the slip line, necessitating a nail length of 50 meters. For large-span topographic conditions, an alternative approach may be to add more soil nails. The installation angle should be determined based

on its position relative to the slip line to optimize effectiveness.

The most effective soil nailing reinforcement design for the Cibeureum slope is at a 20° installation angle, achieving a safety factor of 2.55 without an earthquake and 1.102 with an earthquake. This design provides a robust solution for ensuring slope stability.

Conclusion

Based on the analysis and discussion of the case study, the safety factor of the original slope without an earthquake, as analyzed using the Plaxis 2D V20 program, is 1.62. The analysis shows an increase in the safety factor with each increment in the soil nailing installation angle from 10°, 15°, to 20°. However, the increase from 10° to 20° does not significantly enhance the safety factor due to the initial installation point being distant from the slip line, which necessitates a nail length of 50 meters. The optimal condition for the slope is achieved with a modified slope inclination of 19° and soil nailing at a 20° installation angle with a nail length of 50 meters. This configuration results in a safety factor of 2.55 without an earthquake and 1.102 with an earthquake, as determined by the Plaxis 2D V20 program.

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