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Slope Stability Analysis with Ground Anchor Reinforcement Alternative Based on Finite Element Method on the Blitar Southern Cross Road

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Abstract

A slope stability analysis was conducted on a road section in Java to evaluate the effectiveness of using ground anchors as an alternative to soil nailing systems, based on the Finite Element Method (FEM). The modeling was performed by considering soil parameters obtained from laboratory tests, slope geometry, and loads consisting of traffic, pavement, and pseudo-static seismic loads. The seismic analysis used a Peak Ground Acceleration (PGA) value of 0.5g for the bedrock with an amplification factor of 1.2, which was then converted into a horizontal seismic coefficient (kh) of 0.3 for the slope stability analysis. The analysis results indicate that the existing condition with soil nailing is unstable, as evidenced by the occurrence of collapse and a maximum deformation of 0.026 m, which exceeds the allowable limit. The use of ground anchors improves the Safety factor (SF) to 1.11 (SF ≥ 1.1) and reduces deformation, thereby stabilizing the slope. Thus, based on the modeling results, ground anchors demonstrate superior performance in enhancing slope stability and reducing deformation caused by seismic loading.

1. INTRODUCTION

Road infrastructure development constitutes a fundamental component in supporting regional economic growth and inter-regional connectivity. An adequate road network facilitates community mobility, the distribution of goods and services, and accelerates the development of strategic areas (Imsar & Zaman, 2024). One of the efforts to improve accessibility in the southern coastal region of Java Island has been realized through the construction of road sections in that area.

Several segments of national road construction traverse areas characterized by hilly topography and steep slopes, presenting various geotechnical challenges, particularly with respect to slope stability (Ramadhan et al., 2025). A slope constitutes a morphological form with specific geometry that resists various types of applied loads. However, when stability conditions are disrupted, slopes are susceptible to landslide failure (Khodijah et al., 2022). Moreover, slope failures may cause infrastructure damage, disruption of transportation activities, and result in economic losses and safety hazards for road users (Mina et al., 2022)(Usman & Saputri, 2025).

On the national road section in the Blitar region, the relatively steep slope geometry and specific soil characteristics constitute factors with the potential to induce slope instability. Parameters such as the physical and mechanical properties of the soil, slope inclination, groundwater level conditions, rainwater infiltration, and additional loading on the slope may influence the slope safety factor (SF) value (Laksono & Prihatiningsih, 2025). Research conducted by Arriola et al. (2025) demonstrates that loading conditions and pseudostatic seismic effects can reduce the slope safety factor, particularly for steeply inclined slopes. Furthermore, the location and magnitude of loading exert a significant influence on slope stability levels. When the SF value

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falls below the minimum threshold stipulated by the Indonesian National Standard (SNI), slope reinforcement measures are required to mitigate landslide risk.

One of the most widely adopted slope reinforcement methods in geotechnical engineering is the soil nailing system (Nabila et al., 2025). This slope stabilization technique involves the installation of steel bar reinforcement elements into the slope at closely spaced intervals to enhance the strength and stability of the soil mass (Adriati et al., 2024). Soil nailing reinforcement is classified as a passive system, as its operational mechanism depends on the interaction between the soil and the nails, which is activated by soil deformation in the absence of prestress forces (Sentosa, 2022). This method is considered effective due to its relatively flexible and economical construction process compared to several alternative reinforcement methods (Hermansyah et al., 2023).

At the research site, the existing slope has been reinforced using a soil nailing system installed in the field as the initial reinforcement measure. Although this system has demonstrated the capacity to improve slope stability, under certain loading conditions, alternative measures remain necessary to achieve superior safety and deformation performance. Consequently, a more effective reinforcement alternative is warranted, with ground anchors being identified as a viable option for improving slope stability performance based on the outcomes of stability analysis evaluation.

A ground anchor is a structural element installed in soil or rock to transfer tensile forces to more stable soil or rock strata (Wyjadłowski et al., 2021)(Kurnia et al., 2024). The tensile force generated by the anchor system functions to maintain equilibrium between the anchor, the reinforced structure, and the surrounding soil mass, thereby enhancing construction stability and reducing the extent of the slip surface (Setiawan et al., 2018; Liu et al., 2023). The application of ground anchors is anticipated to yield a more effective reinforcement system, capable of increasing the safety factor and reducing slope deformation. Although ground anchors theoretically possess greater reinforcement capacity than soil nailing, the present study focuses specifically on evaluating the degree of improvement in slope stability and deformation performance relative to the existing condition, which has employed soil nailing as the initial reinforcement system.

The application of Finite Element Method (FEM)-based analysis in slope stability evaluation is of considerable importance, as it provides a more realistic approach to representing field conditions compared to conventional methods (Sutanto et al., 2026). The Limit Equilibrium Method (LEM) is generally employed solely for determining the slope safety factor value; however, it exhibits inherent limitations in representing deformation behavior and the comprehensive interaction between the soil and the reinforcement system. The FEM is therefore adopted in this study for its capacity to evaluate stress distribution, deformation, and soil–structure interaction in a more realistic and detailed manner (Lin, 2022). Moreover, FEM analysis has been demonstrated to be effective in providing both quantitative and qualitative predictions of deformation and reinforcement system response in slope stability analyses (Lin, 2021). Through FEM analysis, the effects of soil nailing as the initial reinforcement condition and ground anchors as an alternative on changes in the safety factor (SF) and slope deformation can be evaluated in greater detail.

Based on the foregoing discussion, the present study aims to analyze slope stability using ground anchors as an alternative reinforcement measure relative to the existing slope condition reinforced with soil nailing, employing Finite Element Method (FEM) analysis on a road section. This research is expected to provide insight into the effectiveness of ground anchors in enhancing the slope safety factor and reducing deformation compared to the soil nailing system under existing conditions.

2. METHODS

The present study focuses on slope stability and deformation analysis using a case study approach. The research objective is to evaluate slope stability conditions and identify a more optimal reinforcement alternative to reduce landslide potential. All data utilized in this study were obtained from laboratory test results and relevant soil parameter correlation data.

The analysis was performed using FEM-based software, enabling the behavior of the soil and the reinforcement system to be modeled in a manner more representative of actual field conditions. The research was conducted on a road slope characterized by hilly topographic conditions with potential for slope instability. The analytical procedures carried out in this study are as follows:

a. Initial slope stability analysis was conducted using the soil nailing system to obtain SF and deformation values for each slope section as the existing condition baseline.
b. The slope model was reconstructed by substituting the soil nailing reinforcement system with ground anchors as the alternative reinforcement measure.
c. Slope stability analysis was performed on the ground anchor model to obtain the corresponding SF and deformation values.
d. A comparative analysis between the initial condition (soil nailing) and the alternative condition (ground anchor) was conducted to evaluate the effectiveness of each reinforcement system in improving stability and reducing slope deformation.

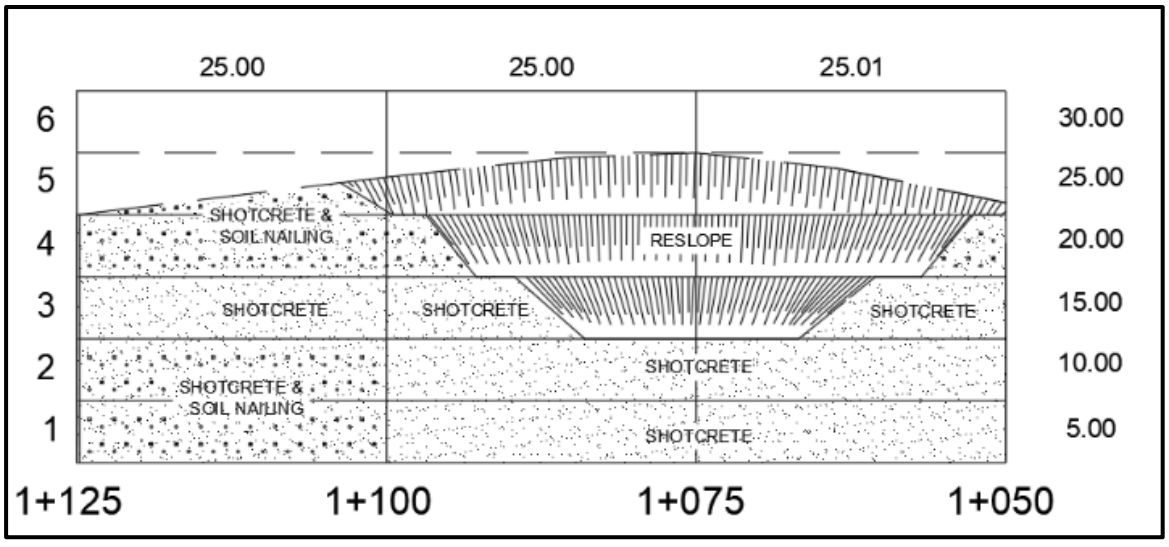
In the FEM-based software modeling, the soil nailing system was treated as the initial slope condition, while the final analysis focused on the performance of the ground anchor system as the alternative reinforcement. Evaluation was conducted based on the SF parameter and total deformation occurring on the slope. This approach was adopted to obtain representative results in determining the more optimal reinforcement system, without dependence on a combined application of both methods.

2.1 CROSS-SECTION GEOMETRY

Longitudinal and transverse cross-sections were utilized to characterize the geometric conditions of the slope along the road section under investigation. These cross-sections serve as the fundamental basis for understanding the topographic characteristics and slope configuration to be analyzed in the stability study.

As presented in Figure 1, the longitudinal cross-section reveals considerable elevation variation along the investigated road section. This elevation variability indicates that the topographic conditions at the research site are non-uniform, which has the potential to influence stress distribution and slope stability. The observed elevation changes also reflect differences in geometric conditions that must be accounted for in slope stability analysis modeling.

Figure 1. Longitudinal Cross-Section STA 1+050 – 1+125 (R)



Source: Project Document (2026)

Elevation differences at each station (STA) induce variations in slope gradient, slope height, and soil geometry configuration, all of which influence the deformation response and safety factor values. As the slope geometry becomes steeper, the driving forces acting on the soil mass tend to increase, thereby elevating the potential for slope instability. In addition, topographic variability may produce non-uniform load distribution and stress concentration on the slope, particularly in areas characterized by abrupt elevation changes.

These geometric conditions constitute critical parameters in FEM-based analysis, given that the shape and dimensions of the slope exert a significant influence on both deformation analysis results and safety factor values. Consequently, longitudinal cross-section data are essential for accurately representing actual field conditions, enabling the model to replicate slope behavior under real-world circumstances.

The transverse cross-section presented in Figure 2 illustrates a slope configuration comprising multiple slope faces with relatively steep gradients. Each slope face exhibits distinct geometric characteristics with respect to height and angle of inclination, thereby contributing differently to the overall potential for landslide occurrence.

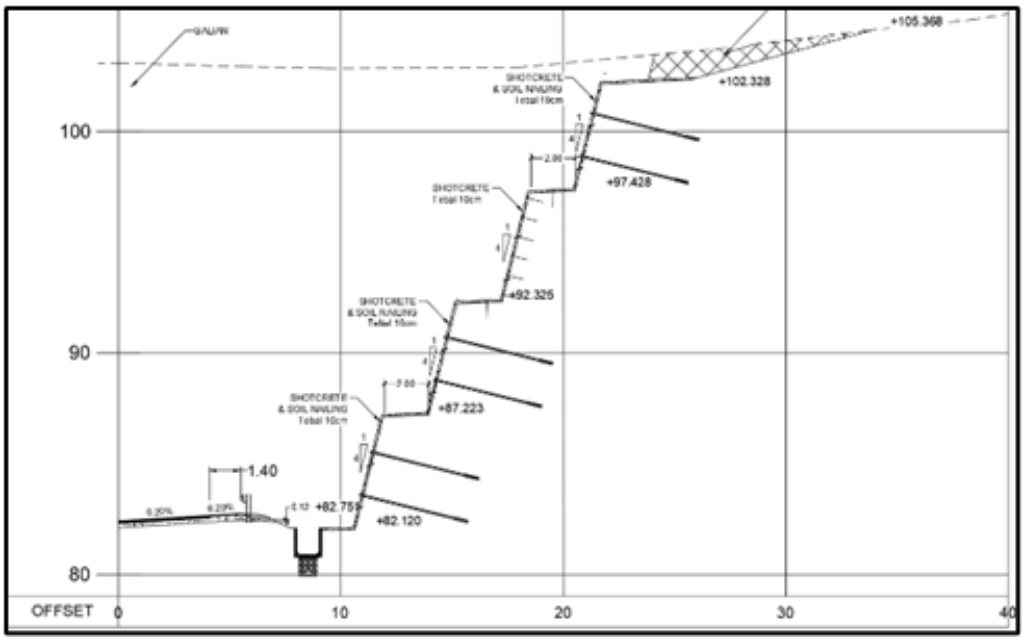


Figure 2. Transverse Cross-Section STA 1+100 (R)
Source: Project Document (2026)

The relatively steep slope gradients observed in several sections indicate a significant potential for slope instability, particularly under the influence of external factors such as surcharge loading, water infiltration, and seismic loads. The slope geometry as represented through the longitudinal and transverse cross-sections therefore constitutes a critical foundation for slope stability analysis and for the determination of appropriate reinforcement methods.

2.2 SOIL PARAMETERS

The soil parameters employed in this study represent the primary data for slope stability analysis. These data were utilized to determine SF and slope deformation values through FEM-based modeling. The modeling was conducted under drained conditions and employed the Mohr-Coulomb constitutive material model to represent soil behavior. The parameters incorporated in the analysis include the soil unit weight (γ), cohesion (c), and internal friction angle (φ), obtained from laboratory soil sample testing. Additional parameters, including Poisson's ratio (ν) and elastic modulus (E), were derived through correlation approaches based on soil type descriptions and interpretation of laboratory test data.

Table 1. Soil Parameter Correlation

Depth (m)	Visual Description	γ kN/m³	γsat kN/m³	E MPa	c' kN/m²	v	φ' °
0-12	Slightly Silty Limestone	14,00	19,00	200	25,00	0,4	43,00
12-13	Sandy Silty Limestone	14,00	19,00	200	25,00	0,4	43,00
13-15	Sandy Silty Limestone	14,00	19,00	200	25,00	0,4	43,00
15-16	Sandy Silty Limestone	19,06	21,09	200	24,00	0,4	43,00
16-28	Slightly Silty Limestone	20,49	22,47	200	22,25	0,4	22,17
28-29	Limestone + Sandy Silty Clay	20,00	26,51	200	17,00	0,4	23,00
29-31	Slightly Silty Limestone	19,01	21,42	200	24,00	0,4	19,00
31-37	Sandy Silty Limestone	20,94	21,97	200	21,00	0,4	21,67

Source: Analysis Results (2026)

2.3 SLOPE REINFORCEMENT PARAMETERS

Two reinforcement systems were employed in this study: soil nailing as the existing condition, and ground anchors as the alternative reinforcement. The parameters of both systems were used as input for analysis using FEM-based software.

The soil nailing parameters comprised a nail length of 6 m, horizontal and vertical spacing of 2 m each, an installation inclination angle of 15°, and a steel bar diameter of 192 mm with an axial stiffness of 21,727,315.77 kN/m². The shear resistance between the grout and soil along the nail was also incorporated as the ultimate tensile capacity of the soil nailing system, generally expressed in terms of the soil–grout shear interaction along the embedment length.

The ground anchor parameters comprised a total anchor length of 21 m, consisting of a free length of 16 m and a bonded length of 5 m, with an installation angle of 30°. A bonded length diameter of 12.7 mm was adopted, with 7 strands and prestress forces of 400, 500, and 600 kN, representing the active reinforcement system through tensile loading.

The shear resistance within the bonded length zone was utilized to determine the ultimate tensile capacity of the ground anchor. An ultimate shear strength (τult) of 1,000 kN/m² was adopted in the analysis, determined based on empirical correlations from the table presented in Sabatini et al. (1999) corresponding to the analyzed soil type. This value was subsequently employed to calculate the ultimate tensile capacity (Tu) using Equation (1):

$$T_u = \pi \, d_b \, L_a \, \tau_{ult} \quad (1)$$

The Tu value was subsequently distributed along the bonded length and used as input in the modeling in the form of maximum tensile forces, Ttop,max and Tbot,max, calculated using Equation (2):

$$T_{top,max} = T_{bot,max} = \frac{T_u}{L_a} \quad (2)$$

This approach was adopted to ensure that the tensile force distribution along the ground anchor element could be modeled uniformly throughout the bonded length zone, thereby enabling the analysis results to more accurately represent the actual working conditions of the reinforcement system.

The detailed soil nailing and ground anchor parameters utilized in this study are presented in Tables 2, 3, and 4. In the numerical model, the soil nailing system was represented using embedded beam elements to characterize the interaction between the soil nail and the surrounding soil mass. The ground anchor system was modeled using a combination of node-to-node anchor elements to represent the tendon and embedded

beam elements for the bonded length portion. The shotcrete layer on the slope surface was modeled using plate elements, which function as surface reinforcement and as a retaining element for the soil at the slope face.

Table 2. Embedded Beam Parameters – Soil Nailing

No.	Parameter	Symbol	Value	Unit
1	Unit Weights	γ	78,5	kN/m^3
2	Spacing	Lspacing	2	m
3	Diameter	Diameter	0,2	m
4	Modulus of Elasticity	E	21727315,7	kN/m^2
5	Skin Resistance	Tskin, start,max	250,05	kN/m
		Tskin, end,max	250,05	kN/m
6	Base Resistance	Fmax	0	kN

Source: Analysis Results (2026)

Table 3. Embedded Beam and Node-to-Node Parameters – Ground Anchor

No.	Parameter	Symbol	Value	Unit
1	Unit Weights	γ	78,5	kN/m^3
2	Spacing	Lspacing	1,5	m
3	Diameter	Diameter	0,2	m
4	Modulus of Elasticity	E	30395000	kN/m^2
5	Skin Resistance	Tskin, start,max	251,428	kN/m
		Tskin, end,max	251,428	kN/m
6	Axial Stiffness	EA	172515	kN
7	Base Resistance	Fmax	0	kN
8	Prestress	Fprestress	400, 500, 600	kN

Source: Analysis Results (2026)

Table 4. Shotcrete Parameters – FEM Software Input

No.	Parameter	Symbol	Value	Unit
1	Unit Weights	w	0,7	kN/m^3
2	Axial Stiffness	EA_1	2487006,232	kN/m^2
3	Flexural Rigidity	EI	16580,042	kNm^2/m^2
4	Poisson's Ratio	v	0,15	

Source: Analysis Results (2026)

2.4 LOADING PARAMETERS

In slope stability analysis, surface loading was incorporated to represent the actual field conditions. The loads considered in this study include uniform surcharge loads, vehicular traffic loads, pavement loads, and seismic loads.

The uniform surcharge load was adopted in accordance with SNI 8460:2017 Clause 11.1.1, with a value of q = 10 kPa, assumed to act from the slope edge to represent construction activity. The vehicular traffic load for Road Class I was taken as 15 kPa in accordance with SNI 8460:2017.

The pavement load was calculated based on the unit weight and thickness of each pavement layer. Based on project data, the AC-WC layer load was determined to be 1.15 kPa and the AC-BC layer 1.39 kPa, yielding a total load acting on the road surface of:

$$q_{total} = 15 + (1{,}15 + 1{,}39) = 17{,}54\ \text{kPa}$$

The seismic effect was computed using the pseudo-static approach. The surface ground acceleration was determined by multiplying the bedrock ground acceleration by the site amplification factor, as expressed in Equation (3):

$$PGA_M = PGA \times F_{PGA} \quad (3)$$

where:
PGA_M = Surface ground acceleration
PGA = Bedrock ground acceleration = 0.5g
F_{PGA} = Site amplification factor for SC soil classification = 1.2

Therefore, the resulting PGA is:

$$PGA_M = 0{,}5 \times 1{,}2 = 0{,}6g$$

The horizontal seismic coefficient was subsequently calculated using Equation (4):

$$k_h = 0{,}5 \times PGA_M$$

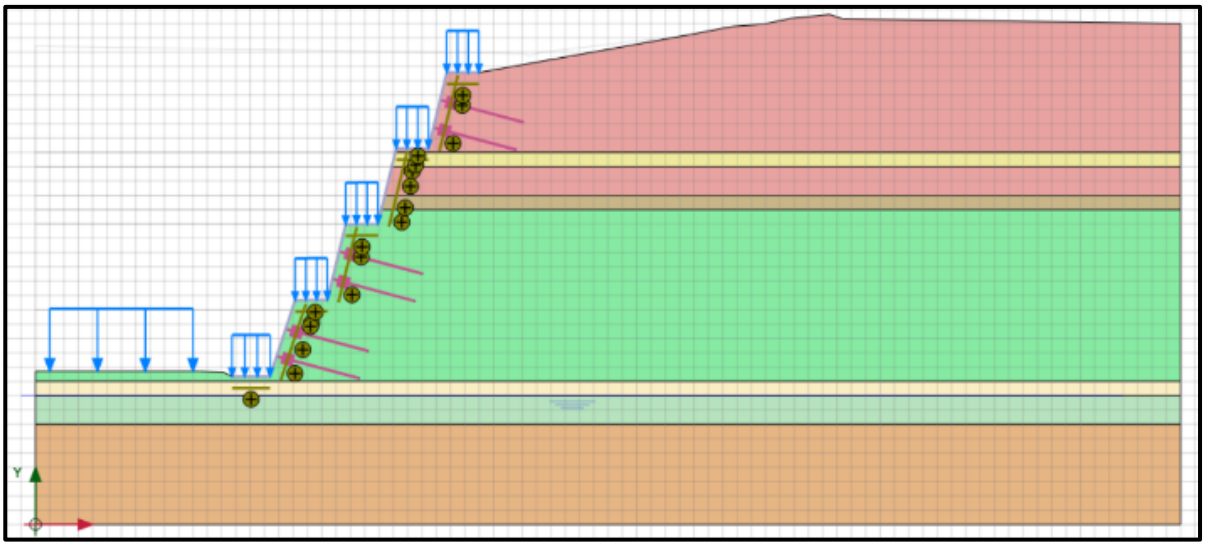
$$k_h = 0{,}5 \times 0{,}6 = 0{,}3$$

A horizontal seismic coefficient of kh = 0.3 was adopted as input in the slope stability analysis to represent the influence of seismic forces on slope conditions.

3. RESULTS AND DISCUSSION

3.1 SLOPE STABILITY ANALYSIS UNDER EXISTING CONDITIONS

Based on the analysis results under seismic loading conditions, the slope exhibited an unstable condition, as indicated by an SF value that failed to satisfy the established safety criteria and a deformation response exceeding the permissible limit. These findings indicate that the existing reinforcement system was unable to provide adequate resistance against the applied forces, particularly under the influence of seismic loading. The



geometric model and existing slope conditions are presented in Figure 3, while the deformation distribution on the slope is illustrated in Figure 4. The deformation pattern reveals a concentration of soil movement in specific slope sections, identifying zones with the highest potential for instability. The relatively large

deformation observed in these areas indicates that the soil is unable to sustain the applied shear stresses, thereby exhibiting susceptibility to more pronounced movement under increased loading.

Figure 3. Numerical Model of Existing Slope Condition
Source: Analysis Results (2026)

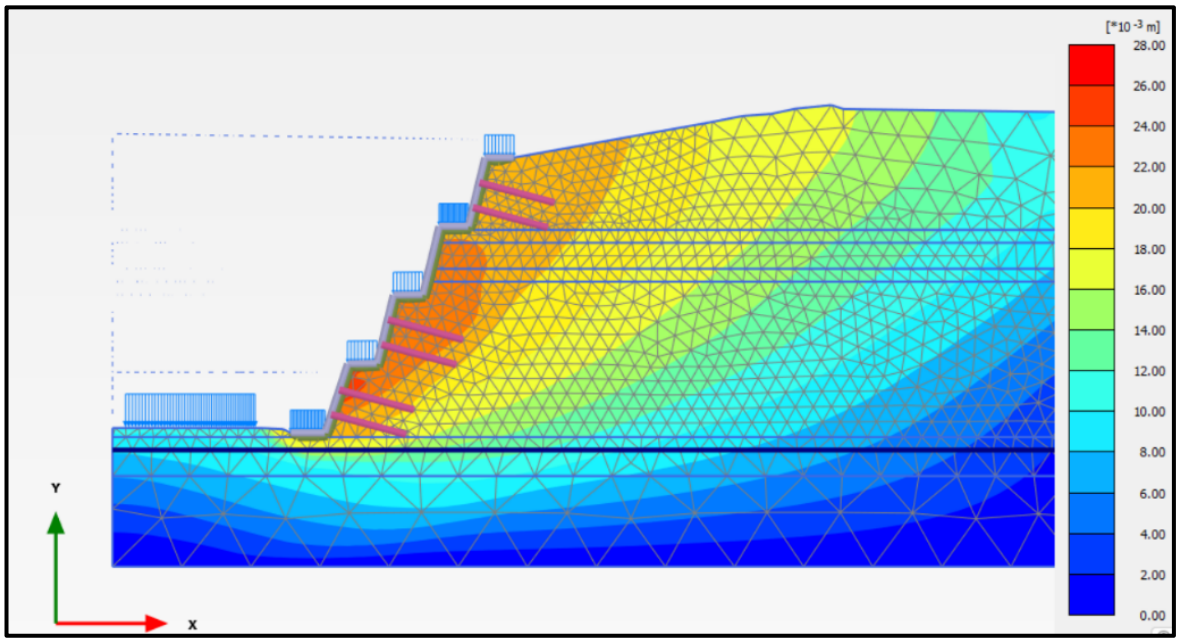


Figure 4. Slip Surface Pattern
Source: Analysis Results (2026)

The magnitude of deformation observed at Slope 4 indicates that this section constitutes the most critical zone, exhibiting the greatest susceptibility to slope failure due to the dominant accumulation of strain and soil displacement relative to other slope sections. The SF value under collapse conditions demonstrates that the soil shear resistance has been entirely overcome by the driving forces acting on the slope, resulting in an extremely high probability of landslide occurrence.

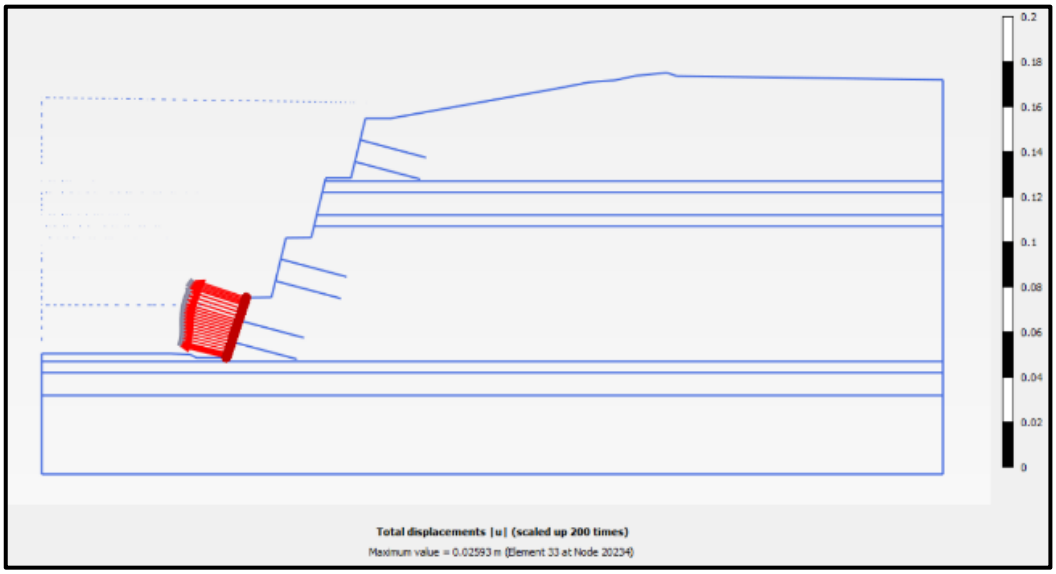


Figure 5. Deformation at Slope 4
Source: Analysis Results (2026)

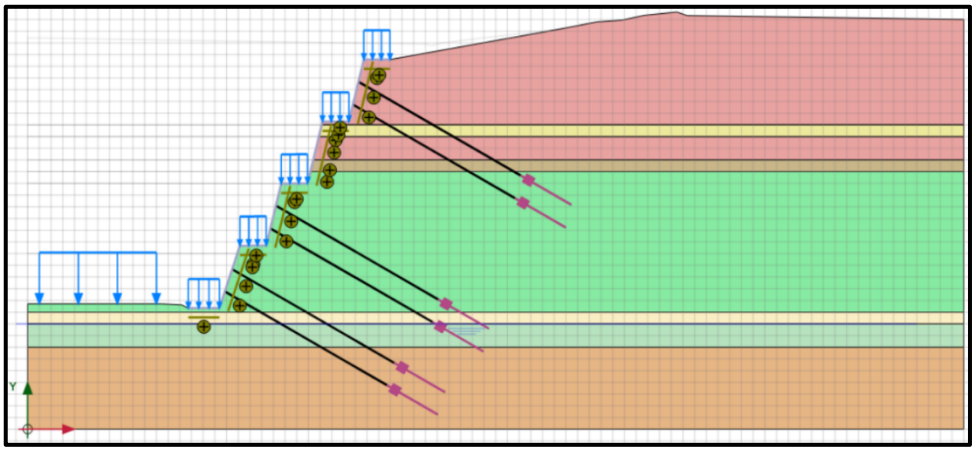
Furthermore, the elevated deformation values indicate a significant reduction in the soil's capacity to withstand shear stresses as a consequence of applied loading, particularly seismic loads that amplify the driving forces acting on the slope. This condition induces a non-uniform stress distribution within the soil and triggers

deformation concentration in localized areas. In the absence of prompt remediation through more effective reinforcement measures, the probability of slope failure will continue to escalate. It is therefore imperative that improvement measures or an alternative reinforcement system be implemented to reduce the occurring deformation and enhance the overall stability of the slope.

3.2 SLOPE STABILITY ANALYSIS USING GROUND ANCHORS

Slope stability analysis employing ground anchor reinforcement was conducted to improve slope stability under seismic loading conditions with a horizontal seismic coefficient (kh) of 0.3g. The numerical modeling was performed using the Finite Element Method (FEM), replacing the soil nailing reinforcement system of the existing condition with ground anchor reinforcement. The parameters incorporated in the modeling include slope geometry, soil parameters, and ground anchor specifications encompassing anchor length, installation angle, anchor spacing, and anchor tensile force.

The results of the FEM-based slope modeling with ground anchor reinforcement demonstrate that the application of ground anchors substantially improves slope stability relative to the existing condition. This improvement is reflected in an increase in the safety factor (SF) value from the previously unstable state to 1.112. This value satisfies the minimum safety factor requirement for seismic loading conditions stipulated by SNI 8460:2017, which prescribes SF ≥ 1.1. The observed increase in SF demonstrates that the application of ground anchors yields superior performance in enhancing slope stability against seismic loading. Moreover,



the use of ground anchors contributes to a reduction in slope deformation, resulting in more controlled soil movement and a safer slope condition compared to the existing state.

Figure 6. Numerical Model of Slope with Ground Anchor Reinforcement
Source: Analysis Results (2026)

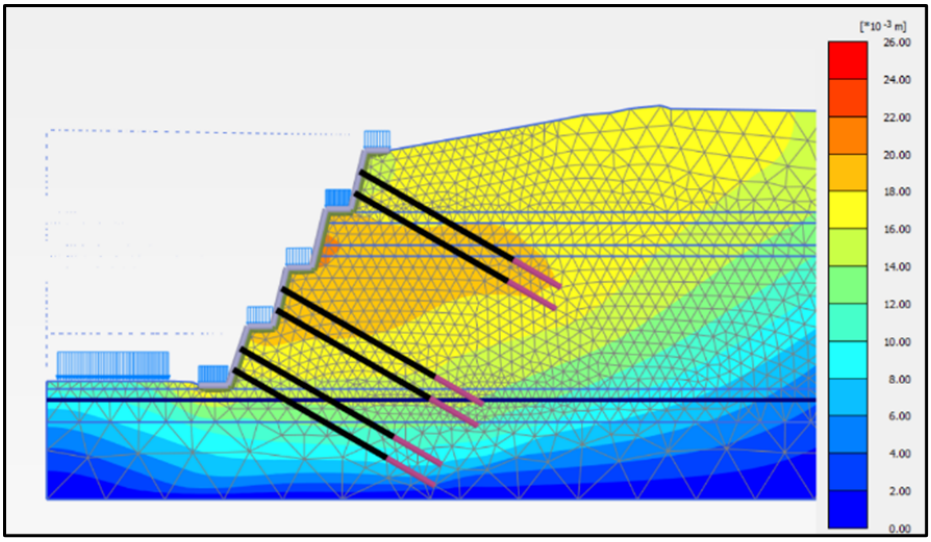


Figure 7. Slip Surface Pattern
Source: Analysis Results (2026)

The increase in safety factor value demonstrates that ground anchor reinforcement is effective in improving slope stability, particularly with respect to resisting seismic loading of 0.5g. In addition to enhancing the safety factor, the implementation of ground anchors contributes to a reduction in slope deformation, resulting in more controlled soil movement. A detailed evaluation of slope deformation following the application of ground anchors is presented in Table 5, which demonstrates that the overall slope performance is improved compared to the existing condition.

Table 5. Safety Factor Values at Each Construction Stage

No	Tahapan Konstruksi	SF	Keterangan
1	Galian 1	4,13	Memenuhi Batas Minimum SNI (SF ≥ 1,5)
2	Galian 2	1,99	Memenuhi Batas Minimum SNI (SF ≥ 1,5)
3	Galian 3	2,21	Memenuhi Batas Minimum SNI (SF ≥ 1,5)
4	Galian 4	1,73	Memenuhi Batas Minimum SNI (SF ≥ 1,5)
5	Pembebanan	1,78	Memenuhi Batas Minimum SNI (SF ≥ 1,5)
6	Gempa	1,11	Memenuhi Batas Minimum SNI (SF ≥ 1,1)

Source: Analysis Results (2026)

Table 6. Deformation Values at Each Slope Section

Slope	Deformasi Eksisting (m)	Keterangan	Deformasi Ground anchor (m)	Keterangan	Batas Izin SNI 8460-2017 (m)
1	0,022	Memenuhi	0,019	Memenuhi	0,025
2	0,023	Memenuhi	0,021	Memenuhi	0,025
3	0,024	Memenuhi	0,020	Memenuhi	0,025
4	0,026	Tidak Memenuhi	0,020	Memenuhi	0,025

Source: Analysis Results (2026)

The improvement in safety factor attributable to the application of ground anchors fundamentally occurs through two technically complementary mechanisms. First, the tensile force generated by the anchor system is decomposed into two components at the slip surface: a tangential component that provides direct shear resistance, and a normal component that induces additional compressive stress on the slip surface. In accordance with the Mohr-Coulomb failure criterion ($\tau = c + \sigma n \cdot \tan \varphi$), the increase in normal stress (σn) at the slip surface directly enhances the soil's shear resistance capacity, thereby increasing the factor of safety (Z. Li et al., 2014). Under seismic loading conditions, the analytical solution developed by Yang et al. (2024) confirms that prestressed anchor cables are capable of significantly improving the slope safety factor by accounting for seismic damping effects in the soil medium. J. Li et al. (2019) affirm that the compressive stress component at the slip surface contributes far more significantly to the improvement of the Factor of Safety (FoS) than the direct shear resistance component of the anchor itself. Second, the prestress applied to the anchor cable generates a compressive zone within the soil mass in the vicinity of the reinforced area, which collectively increases the stiffness and mechanical performance of the soil mass (Z. Li et al., 2014).

From a technical standpoint, the load transfer mechanism of the ground anchor operates through the bonded length (fixed length) zone, which relies upon interface friction between the grout and the soil. Xu & Tian (2020) demonstrated through pull-out tests and numerical simulations that the shear stress distribution within the anchorage zone follows a negative exponential pattern, wherein the maximum shear stress occurs at the proximal end of the bonded length, i.e., the transition point between the free length and bonded length, and decreases monotonically toward the distal end. This finding carries the important implication that the effectiveness of the bonded length in resisting tensile forces is non-uniform along the bonded zone, and that failure invariably initiates at the proximal end. Additionally, Fang et al. (2022) found that the mobilization of soil shear strength in the vicinity of the anchorage zone is progressive, with the internal friction angle and soil cohesion incrementally increasing with increasing relative displacement between the anchor body and the surrounding soil until their limiting values are attained. This implies that the full capacity of the bonded length is only realized following a certain degree of slope deformation, which accounts for the non-linear increasing pattern exhibited by the FoS versus displacement curve.

With respect to the slip surface position, the FEM analysis results in this study indicate that the slip surface pattern tends to migrate to greater depths compared to the existing condition. This phenomenon can be attributed to two interrelated mechanisms. First, the bonded length of the anchor may directly intersect or traverse the critical slip surface, effectively locking it and preventing further development. Second, the anchor system may induce migration of the potential slip surface to deeper zones characterized by higher soil shear resistance, a phenomenon known as slip surface migration. Pham et al. (2026) confirmed through FEM-SSR simulation that the anchor system effectively locks the initial slip circle on the slope and compels the potential slip surface to migrate to considerably greater depths beyond the zone in which anchors are installed, thereby passing through soil volumes with higher shear resistance. Concurrently, Liu et al. (2023) through large-scale physical model tests on clay slopes, demonstrated that the maximum stress concentration in the anchor rod occurs near the transition zone between the free length and bonded length, i.e., in proximity to the slip surface, confirming that the intersection between the anchor and the slip surface constitutes the critical force transfer zone that governs the overall effectiveness of slope reinforcement.

Table 7. Effect of Ground Anchor Tensile Capacity Variation on Slope Deformation

Slope	Ground Anchor 400 kN Deformation (m)	Ground Anchor 500 kN Deformation (m)	Ground Anchor 600 kN Deformation (m)
1	0,020	0,019	0,018
2	0,022	0,021	0,020
3	0,021	0,020	0,019
4	0,021	0,020	0,019

Source: Analysis Results (2026)

As presented in Table 7, slope deformation values demonstrate a consistent decreasing trend with increasing ground anchor tensile capacity. At a tensile capacity of 400 kN, slope deformation ranged from 0.020 m to 0.022 m. Upon increasing the tensile capacity to 500 kN, deformation was reduced to values between 0.019 m and 0.021 m. At a tensile capacity of 600 kN, deformation values were further reduced, ranging from 0.018 m to 0.020 m.

These results demonstrate that increasing the ground anchor tensile capacity effectively reduces slope deformation, as the resisting force applied to the soil mass is augmented, thereby producing more controlled slope movement. This finding is consistent with the research of Chengzhong & Shuangjian (2023), who report

that an increase in anchoring force results in reduced slope deformation and enhanced slope stability. Fan et al. (2024) similarly conclude that increasing prestress in anchor cables improves the effectiveness of slope reinforcement and significantly reduces slope displacement. This is further corroborated by Liu et al. (2024), who demonstrated through field monitoring that a combination of anchor rods and anchor cables effectively controls excavation slope deformation, with frame anchor cables recommended for application at the base of the slope where deformation is more pronounced. Furthermore, Wang et al. (2021) identify prestressing force as the primary factor governing stress and deformation in slope reinforcement systems.

Based on the FEM analysis results, the application of ground anchors induces stress redistribution on the slope, enabling a reduction in shear strain concentration in critical areas. This mechanism results in an increase in the safety factor value and a decrease in slope deformation relative to the existing condition. These findings are consistent with the research of Zeng et al. (2024), who report that the safety factor value is significantly influenced by soil strength parameters and slope geometry, and that the application of ground anchors, which induce additional compressive stress at the slip surface, is effective in enhancing slope stability.

Furthermore, the results of the present study are consistent with Pham et al. (2026), who explain that ground anchors function by establishing a structural bond between the unstable soil mass and the more stable underlying soil layer, thereby inducing migration of the slip surface toward zones with higher shear resistance. Liu (2025) similarly reports that ground anchors are capable of controlling slope deformation through the mechanisms of tensile force transfer and increased confinement of the soil mass, resulting in more controlled slope movement.

3.3 RESEARCH LIMITATIONS

The present study was conducted using FEM-based numerical modeling incorporating several simplifying assumptions. Furthermore, under seismic loading conditions with a horizontal seismic coefficient (kh) of 0.3, Error Code 113 was encountered, indicating convergence difficulties attributable to the high loading intensity applied to the slope. Based on the modeling results, this error was not observed when the seismic coefficient value was reduced, indicating that the high seismic loading condition renders the model in a near-unstable state. Additionally, the present study did not perform sensitivity analysis with respect to variations in soil parameters or ground anchor parameters; consequently, the influence of individual parameter changes on safety factor values and slope deformation could not be evaluated in greater depth. Sensitivity analysis is therefore recommended as a direction for future research to enhance the reliability of the modeling results.

4. CONCLUSIONS

Based on the slope stability analysis results employing the Finite Element Method (FEM), the existing slope condition reinforced with soil nailing was found to exhibit instability under seismic loading conditions with a horizontal seismic coefficient (kh) of 0.3g. This instability is manifested by an SF value that fails to satisfy the established safety criteria, and a maximum deformation of 0.026 m at Slope 4, which exceeds the permissible deformation limit of 0.025 m stipulated by SNI 8460:2017.

The application of ground anchor reinforcement demonstrated superior slope stability performance. Analysis results indicate that ground anchors increase the safety factor (SF) to 1.11, satisfying the minimum requirement for seismic loading conditions ($SF \geq 1.1$). Moreover, the implementation of ground anchors effectively reduces slope deformation, resulting in a more stable slope condition under seismic loading. These findings confirm that ground anchors constitute a viable and effective reinforcement alternative for slopes susceptible to seismic-induced instability.

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