Numerical Analysis of Slope Failure Remediation Using Geosynthetic Reinforcement

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Abstract

Slope failures often occur due to inadequate shear resistance within soil layers, posing serious risks to infrastructure and transportation corridors. Geosynthetic reinforcement has been widely adopted as an effective and economical solution for improving slope stability; however, its performance needs to be quantitatively verified through numerical modeling. This study aims to evaluate the effectiveness of geosynthetic reinforcement in slope failure remediation using a numerical approach. Field investigation data, including Standard Penetration Test (SPT) and laboratory parameters, were combined with empirical correlations to define the soil model. Numerical analysis was conducted using the GEO5 Slope Stability software to simulate both the existing and reinforced slope conditions. The back analysis of the failed slope yielded a factor of safety (FoS) of 0.93, validating the observed field failure. Reinforcement was designed with woven PET geotextile based on the graphical method by Jewell (1990), applying reduction factors in accordance with FHWA and SNI 8460:2017. The reinforced model achieved a FoS of 8.96 under static loading and 3.62 under pseudostatic loading (kh = 0.18 g), demonstrating significant improvement in slope stability. The results confirm that numerical modeling effectively captures the behavior of reinforced slopes and provides a reliable design framework for remediation of slope failures. The findings have practical implications for geotechnical engineers in optimizing geosynthetic applications for both static and seismic conditions.

1. Introduction

Slope failure remains one of the most common and damaging geotechnical problems worldwide, often resulting in infrastructure disruption, property loss, and safety risks. Various methods have been developed to remediate failed or unstable slopes, including structural and reinforcement-based techniques. Among them, the use of geosynthetics—such as geogrids, geotextiles, and geocells—has gained significant attention due to their ability to provide tensile strength, improve soil-structure interaction, and enhance overall stability (Shukla, 2011). The increasing use of geosynthetics also aligns with the demand for cost-effective and sustainable slope stabilization solutions.

In practical applications, geosynthetic-reinforced slopes (GRS) have been widely used in retaining structures, embankments, and cut slopes. Recent comparative analyses have demonstrated that mechanically stabilized earth (MSE) walls reinforced with geosynthetics outperform conventional cantilever walls in terms of both safety and constructability (Waskito & Raharja, 2023). Numerical studies further indicate that the strength and spacing of geogrid reinforcement play a significant role in improving slope stability under varying geometric and boundary conditions (Hassan et al., 2022). These findings highlight the potential of geosynthetic systems as reliable remediation measures for failed slopes.

Despite substantial progress, previous research has primarily focused on new slope construction or controlled laboratory settings rather than the remediation of already failed slopes under complex natural conditions (Esmaeili et al., 2018). Moreover, while many studies emphasize material characterization and stability improvement, fewer have addressed how design parameters—such as reinforcement stiffness, layer configuration, and soil type—affect the performance of remediated slopes (Kim et al., 2019).

The purpose of this study is to conduct a numerical analysis of slope failure remediation using geosynthetic reinforcement. This research aims to (i) develop a representative numerical model of a failed slope with geosynthetic reinforcement, (ii) evaluate the effects of critical design parameters on stability improvement, and (iii) provide practical insights for engineers in designing and optimizing slope remediation systems. By integrating existing theoretical concepts and numerical modeling approaches, this study contributes to a more comprehensive understanding of the role of geosynthetics in slope failure remediation.

1.1 Literature Review

In the context of slope failure remediation, prior studies have explored a variety of stabilization methods, including conventional retaining walls, soil nailing, and mechanically stabilized earth (MSE) systems. Among these, MSE structures reinforced with geosynthetics have demonstrated notable efficiency in both cost and performance (Waskito & Raharja, 2023). The inclusion of geosynthetic layers has been shown to improve the factor of safety by providing tensile strength that resists soil movement and redistributes stresses within the slope (Shukla, 2011).

Several analytical and numerical approaches have been employed to evaluate the performance of geosynthetic-reinforced slopes. Kim et al. (2019) reviewed performance data from field case studies and reported that GRS systems exhibit reliable long-term behavior when proper construction and backfill materials are used. Similarly, Peng et al. (2024) performed numerical analyses demonstrating that geogrid tensile strength and layout significantly influence slope performance under various loading conditions. These studies collectively emphasize the importance of reinforcement design parameters in achieving desired stability outcomes.

However, despite a growing body of research, there remains a lack of focus on slope failure remediation scenarios. Most prior studies have examined newly constructed slopes rather than the complex geometries, residual stresses, and boundary conditions encountered in failed slopes (Patil et al., 2020). Kim et al. (2019) highlighted that many existing numerical models simplify the geosynthetic–soil interface, leading to limited representation of actual behavior. Additionally, research integrating parametric variation in reinforcement stiffness, soil density, and slope geometry remains scarce (Zhang & Zhang, 2024).

In summary, previous studies have established a sound foundation for understanding geosynthetic-reinforced slope behavior. Nevertheless, the literature still lacks comprehensive numerical evaluations specifically targeting remediation applications of geosynthetics in failed slopes. The present study addresses this gap by developing a detailed numerical model that examines the effects of geosynthetic reinforcement parameters on the improvement of slope stability, thereby contributing to the advancement of practical design strategies in geotechnical engineering.

2. Research Methods

This study employs a numerical analysis approach to evaluate slope failure remediation using geosynthetic reinforcement. The analysis integrates field investigation data, laboratory testing, empirical correlations, and computational modeling. Numerical simulations were conducted using the GEO5 software package, specifically combining the Mechanically Stabilized Earth (MSE) Wall and Slope Stability modules to represent the reinforced slope system under both static and pseudostatic (seismic) conditions.

The methodology includes the following stages (Fig):

1. Site investigation and data acquisition.
2. Determination of geotechnical parameters through laboratory testing and empirical correlations.
3. Development of numerical models and load configurations.
4. Stability evaluation under static and seismic loading conditions based on the Allowable Standard Design method following SNI 8460:2017.

2.1. Subsurface Investigation and Geotechnical Data

Soil data were obtained from borehole investigations, which included Standard Penetration Test (SPT) measurements and laboratory analyses on selected samples. Laboratory tests determined basic soil properties such as natural moisture content, unit weight, Atterberg limits, and shear strength parameters.

The engineering parameters required for numerical modeling—namely cohesion (c), internal friction angle (φ), and modulus of elasticity (E)—were derived from a combination of direct laboratory results and empirical correlations with SPT N-values. The correlations used follow established references such as Look (2014) "Handbook of Geotechnical Investigation and Design Tables", ensuring that derived parameters are consistent with international practice.

2.2. Numerical Modeling Using GEO5

Numerical analyses were performed using the GEO5 suite, where the slope geometry and geosynthetic reinforcement were modeled to simulate a typical remediation condition. The MSE Wall module was used to model the reinforced zone incorporating geotextile layers, while the Slope Stability module was used to evaluate overall slope performance and compute the Factor of Safety (FoS).

The analysis was conducted under two principal loading conditions:

1. Static loading, representing the self-weight of the soil mass and external loads.
2. Pseudostatic seismic loading, representing earthquake effects.

The roadway load (traffic surcharge) was applied as a uniform distributed load along the crest of the slope. The seismic load was introduced using the pseudostatic method, with the horizontal seismic coefficient (kh) calculated according to:

$$kh = 0.5 \times PGA \times F_{PGA}$$

where PGA is the peak ground acceleration on rock for a 500-year return period, obtained from the Indonesian Seismic Hazard Map (Peta Gempa Indonesia), and Fpga is the site amplification factor based on the site class determined from SPT data within a 30 m depth.

2.3. Material Properties and Reinforcement Parameters

The geosynthetic reinforcement was modeled using geotextile elements with material properties corresponding to commonly used commercial products in slope reinforcement applications. The allowable tensile strength (T_a) of the geotextile was determined by dividing the ultimate tensile strength (T_u) by the product of relevant reduction factors, including:

$$T_a = \frac{T_U}{RF_{id} \times RF_{cr} \times RF_d}$$

Typical reduction factors were selected in accordance with FHWA ((MSE Walls and Reinforced Soil Slopes — Design & Construction (FHWA-NHI-10-024), 2009)) and related guidance ((Taylor, 2023)) and with reference to SNI 8460:2017 (SNI 8460:2017 Persyaratan Perancangan Geoteknik, 2017). The installation-damage reduction factor RF_{id} was taken in the range 1.1–3.0 depending on backfill gradation (conservative default 1.5 if product-specific data are absent). The creep reduction factor RF_{cr} was chosen as 1.8 for polyester (PET) and 4.5 for polypropylene/HDPE when product long-term data are unavailable (conservative default 4.5). Durability/environmental factor RF_d was applied in the range 1.0–1.25 depending on soil aggressiveness. In absence of full product-specific testing, a conservative combined reduction factor $RF_{TOTAL} \approx 7.0$ (product of the individual factors) was used to calculate allowable tensile strength T_a for GEO5 model inputs (i.e., $T_a = T_u / RF_{TOTAL}$). Where manufacturer test data (ASTM D5262, ASTM D5818, or equivalent confined creep results) were available these superseded default values. These choices follow FHWA/AASHTO practice and are consistent with the requirements of SNI 8460:2017.

2.4. Design Criteria and Factor of Safety

Slope stability evaluations were carried out using the Allowable Standard Design method following SNI 8460:2017. The criteria for acceptable performance were:

1. Static condition: minimum FoS $\geq$ 1.50
2. Seismic (pseudostatic) condition: minimum FoS$\geq$1.10

These thresholds ensure adequate resistance against both gravity-induced and seismic instabilities.

The analysis outcomes include the distribution of slip surfaces, location of critical failure planes, and comparison of safety factors between unreinforced and reinforced conditions. These results form the basis for evaluating the effectiveness of geosynthetic reinforcement in slope failure remediation.

3. Result and Discussion

3.1. Slope Geometri and Soil Parameter

Based on the field investigation, a cross-sectional sketch of the failed slope was developed, as illustrated in Fig. 1. The total height of the slope is approximately 30 meters, with an average inclination of 45 degrees (1V:1H). The failure occurred near the crest of the slope, affecting the shoulder area and approximately one-fifth of the road width. The portion of the slope that experienced failure was about 8 meters high measured from the road elevation.

The failure mechanism was identified as translational, which is consistent with the observed soil stratification and relatively uniform subsurface conditions. The subsurface profile indicates that the slope materials exhibit medium to very stiff consistency, suggesting limited plastic deformation prior to failure. Results from borehole logs and Standard Penetration Tests (SPT) corroborate these observations: the near-surface layer recorded an N-SPT value of 19, while the underlying layer showed a significantly higher N value of 38, indicating a rapid increase in soil strength with depth.

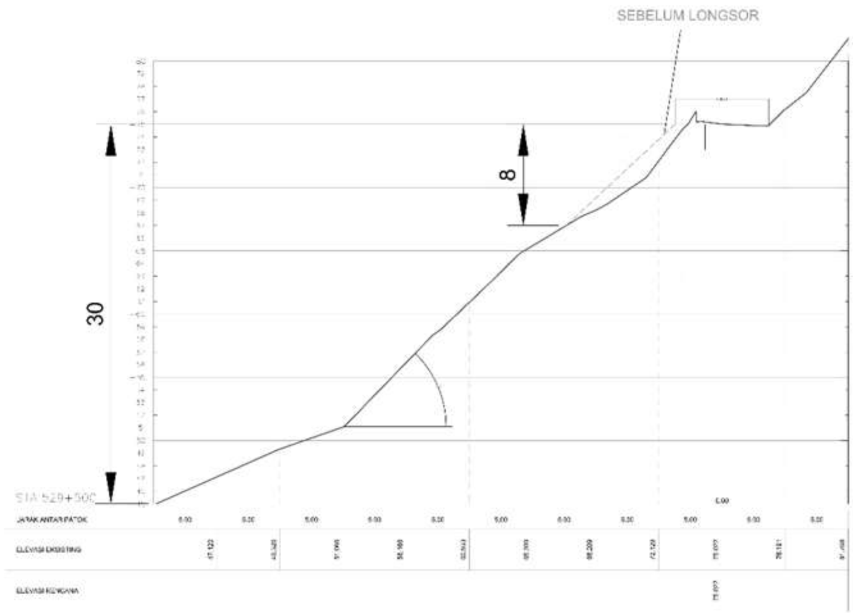

Fig. 1 Slope cross section

The soil parameters used in the numerical analysis were derived from a combination of laboratory test results and empirical correlations based on Standard Penetration Test (SPT) values following the guidelines provided by Look (2014). The laboratory testing provided fundamental soil properties, while the empirical correlations were employed to estimate engineering parameters such as cohesion, internal friction angle, and modulus of elasticity for layers where direct test data were unavailable. A summary of the parameters adopted for the analysis is presented in *Table 1*.

Table 1. Summary of soil parameter

Layer	***Soil Description***	***N-SPT [blw/ft]***	γ ***[kN/m³]***	γ_{sat} ***[kN/m³]***	***c [kN/m²]***	φ ***[°]***	***E [kN/m²]***	υ ***[-]***
1	Brown clayey sand	19	14.62	16.28	1.569	32	26600	0.4
2	Brown clayey sand	38	13.83	16.28	1.863	35	53200	0.4
3	Grayish-brown clayey sand	45	13.73	16.5	1.274	37	63000	0.4
4	Brown clayey sand	57	14.32	17	2.059	40	79800	0.4
	Backfill material	-	17	18	5	30	30000	0.4

3.2. Analysis of Existing Slope

The analysis of the existing slope was performed as a back-analysis to evaluate the soil parameters that could have contributed to the observed slope failure, particularly within the first (uppermost) soil layer. This back-analysis was conducted through a trial-and-error approach by progressively reducing the shear strength parameters of the soil until the computed factor of safety (FoS) dropped below 1.0, indicating a failure condition.

The results of the back-analysis show that the soil parameters presented in *Table 1* are consistent with the field conditions. Specifically, the parameters for Layer 1 reproduced a failure pattern closely matching the actual landslide geometry observed in the field (Fig. 2), yielding a factor of safety of 0.93 (< 1.0), which confirms the occurrence of slope failure under the existing conditions.

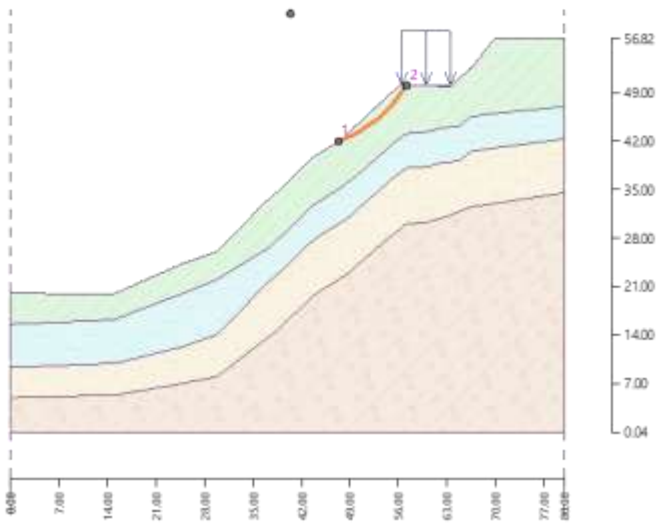

Fig. 2 Stability analysis result of existing slope

3.3. Analysis of Reinforced Slope

The slope remediation in this study was carried out using layered geotextile reinforcement, commonly referred to as a Reinforced Soil Slope (RSS) system. Several design parameters must be determined during the design process, including the anchorage length, ultimate tensile strength of the geotextile, and vertical spacing between reinforcement layers. One of the approaches to estimate these parameters is the graphical method proposed by Jewell (1990), as adopted in Waskito & Raharja (2023). This graphical method requires input data in the form of the soil internal friction angle and the slope inclination.

In this study, the soil's internal friction angle was taken as 30°, and the designed slope inclination was 60°. By plotting these parameters on the Jewell (1990) design chart, the ratio of anchorage length to slope height (L/H) was obtained as 0.5. Given the designed slope height of 8 m, the required anchorage length was calculated as: L = 0.5 x 8 m = 4 m.

The next design parameter, the required tensile force (R_{req}), was derived from the earth pressure coefficient (K_{ne}q) obtained from the same graphical method. Using the same input parameters, the value of K_{req} = 0.14 was obtained. The required reinforcement tensile load can then be calculated using the following expression:

$$R_{req} = K_{req} \times \gamma \times \left(z + \frac{q}{\gamma} \right)$$

where: γ is unit weight of the soil, z is depth of reinforcement, and q is urcharge load (road traffic load). For a design depth of 8 m and a road surcharge (q) of 10 kN/m^2, the required tensile force was R_{req} = 20.44 kN. Similarly, for a depth of 4 m, the calculated value was R_{req} = 10.92 kN. Based on these results, the allowable tensile strength of the geotextile must exceed these required tensile forces.

The allowable tensile strength (T_a) of the geotextile is obtained by dividing the ultimate tensile strength (T_u) by the product of reduction factors that account for creep, installation damage, and environmental effects, as discussed in the previous section. For woven PET geotextile, which is commonly used for reinforcement applications, the following reduction factors were adopted:

1. Creep reduction factor, $RF_{creep} = 1.6$
2. Installation damage factor, $RF_{installation} = 1.1$
3. Environmental reduction factor, $RF_{environment} = 1.6$

Hence, the required ultimate tensile strengths were determined as 30.75 kN/m at a depth of 4 m and 57.55 kN/m at 8 m. Considering both design depths, a woven geotextile with an ultimate tensile strength of 50 kN/m was selected to provide adequate safety across the entire slope.

The vertical spacing between reinforcement layers was determined based on the required tensile resistance and the thickness of compacted soil lifts. Following standard practice, a vertical spacing of 0.5 m was adopted in this study.

Using these design parameters, the reinforced slope model was constructed and analyzed in GEO5, as illustrated in Fig. 3. The results of the static stability analysis indicate a significant improvement in slope stability, with the factor of safety (FoS) increasing to 8.96 along the critical slip surface that corresponds to the observed field failure.

For the pseudostatic (seismic) analysis, the horizontal seismic coefficient (kh) was determined first. Based on the Indonesian Seismic Hazard Map for a 500-year return period, the study area has a peak ground acceleration (PGA) of 0.3 g. According to the SPT-based classification, the site corresponds to Site Class D (medium soil), with an amplification factor F_{PGA} = 1.2. Therefore, the horizontal seismic coefficient was computed as:

$$kh = 0.5 \times PGA \times F_{PGA} = 0.5 \times 0.3 \times 1.2 = 0.18g$$

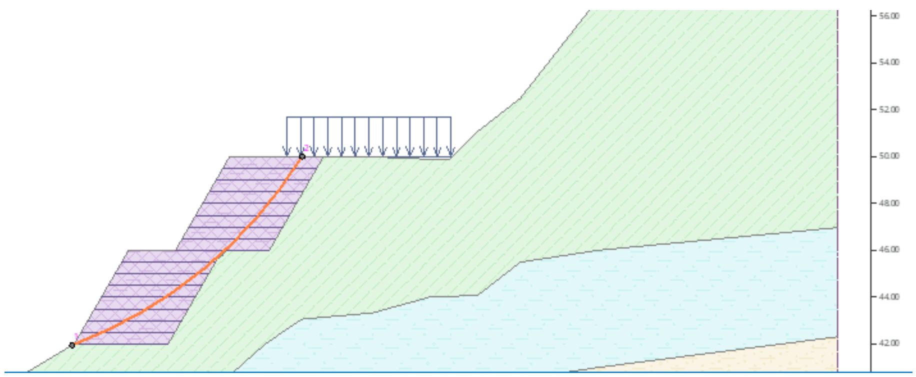

Fig. 3 Stability analysis result of reinforced slope

This value was applied in the GEO5 pseudostatic analysis, resulting in a factor of safety of 3.62 (> 1.10), which satisfies the minimum requirement for seismic stability as per SNI 8460:2017.

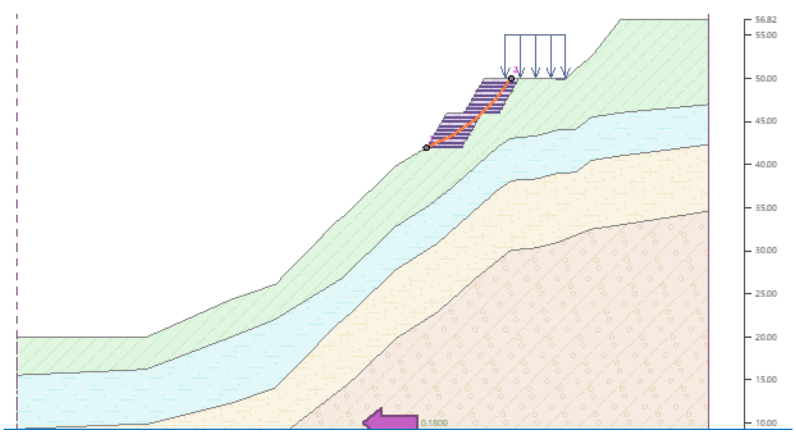

Fig. 4 Stability analysis result of reinforced slope under pseudo Statik loading

4. Conclusions

This study conducted a detailed numerical analysis to evaluate the effectiveness of geosynthetic reinforcement in remediating slope failure. Using the GEO5 Slope Stability module, the analysis was performed to simulate both the existing failed condition and the improved reinforced slope. The back analysis of the existing slope reproduced the observed translational failure pattern with a factor of safety (FoS) of 0.93, confirming the validity of the soil parameters obtained from field and laboratory investigations. This step provided a realistic baseline for subsequent reinforced slope modeling. The reinforcement design employed a woven PET geotextile, with parameters determined using the graphical approach proposed by Jewell (1990) and reduction factors consistent with FHWA and SNI 8460:2017 guidelines. The adopted configuration included a 4 m anchorage length, 0.5 m vertical spacing, and 60° slope inclination, which were incorporated into the numerical model.

The numerical results demonstrated a significant enhancement in slope stability after reinforcement. The factor of safety increased from 0.93 to 8.96 under static loading, indicating that the geosynthetic layers effectively mobilized tensile resistance and reduced potential sliding. Under pseudostatic seismic loading with a horizontal acceleration coefficient (kh = 0.18 g), the slope maintained stability with a FoS of 3.62, exceeding the minimum requirement of 1.10 as specified in SNI 8460:2017. The study confirms that numerical modeling provides a powerful and reliable tool for evaluating slope failure remediation. The incorporation of geosynthetic reinforcement—particularly woven PET geotextiles—significantly improves slope performance under both static and seismic conditions.

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