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Research paper

Analysis of Redesign Right Intake Slope Protection of Karangnongko Dam with Geomat using Simplified Bishop Method and Plaxis 2D

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ABSTRACT

Purpose: This study aims to evaluate slope stability and propose an alternative slope protection method at STA 0+175 of the Karangnongko Dam intake using geomat combined with vetiver grass, following a green construction concept. The research addresses the limitations of the existing geocell design, which, despite meeting SNI 8460:2017, experienced localized slope failures due to high soil shrink-swell potential, intense rainfall, incomplete backfill, and lack of geotechnical data in planning.
Methods: A quantitative approach was employed using primary data from soil investigation at STA 0+175 and secondary data including slope cross-sections, geomat catalogs, vetiver specifications, and existing soil parameters. Slope stability analysis was conducted using the Simplified Bishop Method and PLAXIS 2D software to compare safety factors before and after implementing geomat and vetiver, and to determine the optimal planting spacing of vetiver grass.
Findings: Soil classification indicated high-plasticity inorganic clay (AASHTO A-7, USCS CH). Both analysis methods showed increased slope safety factors meeting SNI 8460:2017 standards. The Simplified Bishop Method yielded a safety factor of 2.134, while PLAXIS 2D gave 2.061. Maximum improvement occurred at a vetiver planting spacing of 40 cm, with safety factors reaching 2.189 (Bishop) and 2.126 (PLAXIS 2D). The difference between the two methods ranged from 2.97% to 4.06%, indicating that both methods can provide a reliable assessment of slope stability.
Practical implication: The results suggest that combining geomat with vetiver grass can effectively enhance slope stability and serve as a practical alternative for slope protection at Karangnongko Dam. Implementing this approach may reduce slope failure risk during construction and provide guidance for future green construction practices in similar environments.

INTRODUCTION

Economic acceleration through sustainable infrastructure development has become a strategic approach to enchancing food security. The Ministry of Publich Works, through the Bengawan Solo River Basin Authority, is undertaking the contruction of the Karangnongko Dam as an infrastructure for irrigation water supply and raw water provision, as welll as a measure for flood control within the Bengawan Solo watershed area. Water is conveyed through supporting structures, namely the left intake, which supplies water demand in Central Java Province, and the right intake, which supplies water demand in East Java Province.

The right intake structure is localised on a slope with gradient of 1:1.5. Based on the geological investivigation conducted by PT Widya Prima Utama (2024) at four investigation points within the planned right intake area, the geological conditions are predominantly characterized by weathered young marl with a gray coloration. The weathered marl material consists of clayey silt and sandy silt. The soil in the right intake area exhibits high shrink-swell potential and low permeability. The shrinkage behavior leads to the deterioration of the marl structure, making it brittle and susceptible to fracturing.

The slope stability analysis conducted by the Supervising Consultant using PLAXIS 2D yielded a safety factor of 2.068. This result satisfies the requirement of SNI 8460:2017, which specifies a minimum of safety factor of 1.5. To preverent slope deterioration due to exposure and the abasence of protective measure, alope protection using geocell was implemented. The selection of geocell wa based on its green contruction concept. Furthemore, the analysis results indicated no significant change in the safety after the implementation of the protection system. However, field observations revealed the accurence of lanslide affecting approximetely 20-30% of the total slope area, including a rotational landslide on the right slope at STA 0+175. The failure occurred progessively in January 2025, primarily triggered by high rainfall intensity, compunded by clogged temporary drainage that led to water ponding on the slope shoulder. This condition incresed the self-weight of slope mass. In addition, according to Istifa & Pramana (2025), backfilling at the toe of the slope and not counterweight support. Moreover, the slope stability analysis was conducted using geological data from areas adjacent to the slope rafther than site-specific geotechnical investigations data from the slope itself.

A study on slope failure in the right intake area has been conducted by Ardha et al. (2025), which proposed slope reinforcement measures, particularly in Block-3 at STA 0+300. The recommended reinforcement methods include geocell, shotcrete, grass block, and hydroseeding. Based on the analysis performed using Slope/W software, shotcrete was identified as the most stable alternatif, with a safety factor of 1.875. However, the study does not provide detailed cross-sectional drawings of the slope or clearly specify the geological parameters used in the analysis. Consequently, the proposed slope protection alternatives are considered insufficient and not fully aligned with the principles of green construction. Considering the factors contributing to slope failure, the geological characteristics of marl, and the applied green construction concept, a more comprehensive geological investigation within the slope area is required. In addition, an alternative slope protection system is needed that can effectively protect the slope during the construction phase and throughout the vegetation establishment period until optimal strength is achieved.

Markiewicz et al. (2024) stated that geomat offers a solution by providing slope protection prior to vegetation establishment until optimal strength is achieved. Zhukova et al. (2023) reported that a geomat system combined with vegetation can function as an effective erosion control measure against rainfall by binding soil particles with plant roots, as well as acting as a filter to prevent soil loss. Direktorat Jenderal Bina Marga (2019) specifies that vegetation applied in geomat systems typically consists of grasses or legume cover crops (LCC). One of the most commonly used grass species is vetiver grass. Vetiver grass has a fibrous root system that can penetrate up to 5.2 meters in depth. It exhibits high tolerance to extreme environmental conditions, including temperatures ranging from −14 °C to +55 °C, as well as resistance to flooding and drought. Furthermore, vetiver grass has the ability to recover after exposure to extreme weather conditions Dorafshan et al. (2023). Nevertheless, further analysis is required to determine the optimal planting spacing of grass in accordance with the existing geological conditions.

The slope stability analysis process is determined by the method employed. The Simplified Bishop Method is an effective approach for analyzing slip surfaces associated with rotational landslides. This method adopts simplifying assumptions by neglecting interslice shear forces (Bishop, 1954). The predicted slip surface obtained from this method is relatively close to field observations. The resulting safety factor is considered more accurate compared to the Fellenius method, which neglects all interslice forces and tends to produce more conservative results. Furthermore, the results are comparable to those obtained from more rigorous methods (Hardiyatmo, 2003). However, limit equilibrium methods are not capable of representing soil deformation behavior due to changes in stress conditions during construction stages (Sulistyo et al., 2024). To obtain a more comprehensive understanding of soil behavior, analysis using a computer-based Finite Element Method, such as PLAXIS 2D, is required, as it is capable of simulating deformation changes (Wahab et al., 2024). In addition, slope protection systems can be modeled under various conditions with a high level of accuracy using this software (Zayadi & Leksono, 2024). Therefore, the combination of these two methods enables a comparison of safety factor values as well as an evaluation of soil deformation behavior. Accordingly, this study aims to determine the safety factor of slope protection using geomat and to identify the optimal spacing for vetiver grass planting in relation to slope stability. This is carried out through geological investigation to obtain parameter data for the slope stability analysis. The analysis process is conducted using manual calculations based on the Simplified Bishop Method and numerical modeling with PLAXIS 2D.

METHODS

This study adopts a quantitative approach by utilizing soil test data as input parameters in the analysis process. The slope stability analysis was carried out using the Simplified Bishop Method and numerical simulation using PLAXIS 2D to evaluate the effect on the safety factor before and after the implementation of geomat slope protection, in accordance with SNI 8460:2017.

Location and Research Period

This study was conducted on the right slope of the right intake structure of the Karangnongko Dam construction project at STA 0+175, Package 2, located in Bojonegoro

Regency, East Java Province. The study area represents a critical slope section associated with the intake structure. Data collection and processing were carried out from September to December 2025.

Data Collection Technique

The data used in this study consist of primary and secondary data. The secondary data include literature review, slope design shop drawings, geomat specifications obtained from PT Pandu Equator Prima (2025) (Table 1), vetiver grass data from previous studies (Table 2), and existing soil data (Table 3). Meanwhile, the primary data were obtained from geological investigations conducted at the study site.

Table 1. Geomat Specifcation Data

Description	Unit	Specification
Geomat Material	-	4 Layer
Wire Mesh Diameter	mm	2.7
Wire Mesh Size	cm	8 x 10
Thickness	mm	10-15
Geomat Weight	g/m^2	360
Geomat Tensile Strength (MD/TD)	kN/m^2	≥ 3,6/ ≥2.2
Wire Mesh Tensile Strength	kN/m^2	35

Table 2. Vetiver Grass Root Properties

Description	Value	Unit	Source
Average Root Tensile Strength	36.89	MPa	Permana (2022)
Root Area Ratio (RAR)	0.778	%	
Total Root Diameter Width	20	cm	Sya'bania (2025)

Table 3. Existing Soil Properties

Parameters	Description	Value	Unit
Dry Soil Weight	Υ_{dry}	12.2	kN/m^3
Wet Soil Weight	Υ_{wet}	16.75	kN/m^3
Young's Modulus	E_{ref}	13000	kN/m^2
Poisson's Ration	v	0,3	-
Cohhesion	c	32.9	kN/m^2
Friction Angle	ϕ	53.79	o
Dilatacy Angle	Ψ	0	o

Data Analysis Technique

The analysis wa conducted using the Simplified Bishop Method and numerical computation through PLAXIS 2D.

1. Simplified Bishop Method

   The analysis was carried out by defining a rotational slip surface and discretizing the slope into several slices. For each slice, parameters including slice width (b_i), base inclination angle (θ_i), weight (W_i), and pore water pressure were determined. An iterative procedure was then performed until a convergent value of the safety factor was obtained using the Simplified Bishop Method. Subsequently, the contributions of geomat and vetiver grass roots to each slice were incorporated into the analysis, and the iteration process was continued until convergence was achieved again.

2. PLAXIS 2D
   a. Defining material properties in the Soil stage.
   b. Modeling the slope geometry, materials, and applied loads in the Structures stage.
   c. Discretizing the soil and structural model into thousands of elements in the Mesh stage.
   d. Defining the groundwater level in the Flow Conditions stage.
   e. Simulating construction stages, consisting of: the Initial Phase to establish in-situ stress conditions, Phase 1 (plastic analysis of geomat and vegetation) to simulate the soil response due to the addition of geomat and vegetation, Phase 2 (plastic analysis with loading) to represent changes in slope conditions due to applied loads, and Phase 3 (safety analysis) to determine the factor of safety.
   f. Performing the analysis using the Calculate function in PLAXIS 2D.

Research Stage

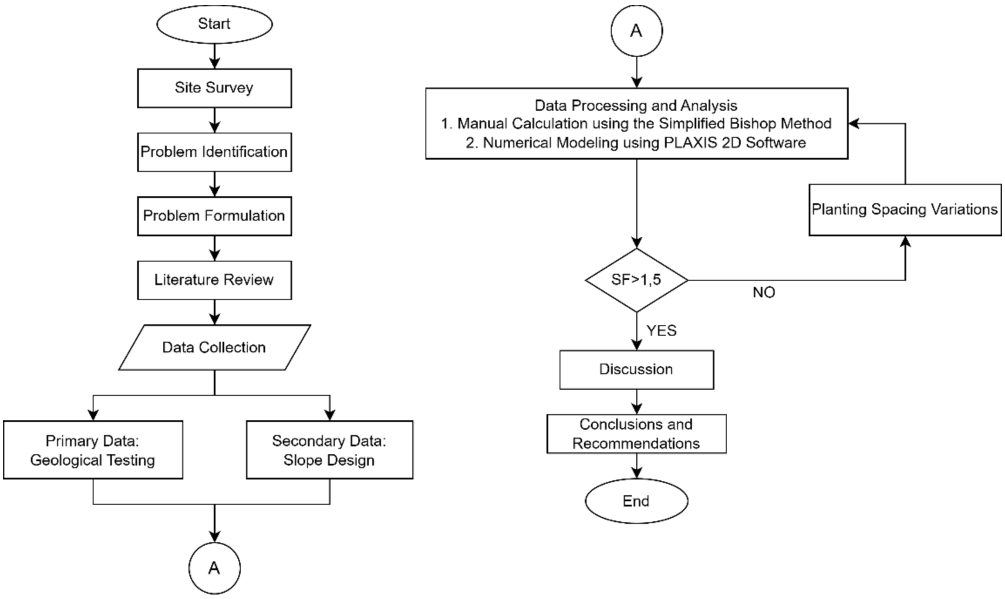


Figure 1. Flowchart of the Research Methodology

FINDINGS

Geological Investivigation Results

The results of the geological investigation in the right slope area of the right intake of Karangnongko Dam at STA 0+175 are presented in Table 4. Based on Table 4, the soil exhibits a considerable capacity for water retention, as indicated by a water content of 36.26%. The soil also demonstrates high shrink–swell potential, as reflected by a liquid limit (LL) of 64.54% and a plasticity index (PI) of 36%. Mechanically, the soil shows good shear strength characteristics, with a cohesion value of 25.144 kPa and an internal friction angle of 30.51°.

Based on the Unified Soil Classification System (USCS), the soil is classified as CH (inorganic clay with high plasticity). Meanwhile, according to the American Association of State Highway and Transportation Officials (AASHTO) classification, the soil falls into the A-7-6 group with a Group Index (GI) value of 14.74 (clayey soil). In general, the soil is dominated by cohesive properties, exhibits high plasticity, and has low bearing capacity, making it sensitive to changes in water content. According to Song et al. (2024) these characteristics are unfavorable for slope conditions without protection. Therefore, slope protection measures are required to control water infiltration, reduce surface erosion, and maintain slope stability.

Table 4. Geological Investivigation Results

Soil Parameter	Value	Unit
Water Content (W)	36.26	%
Specific Gravity (G_S)	2.61	-
Wet Soil Weight (y_{sat})	17.51	kN/m^3
Dry Soil Weight (y_{dry})	12.84	kN/m^3
Liquid Limit (*LL*)	64.54	%
Plastic Limit (*PL*)	28.5	%
Plascity Index (*P1*)	36	%
Shrinkage Limit (s_L)	64.33	%
% Sand	48.6	%
% Silt	41.55	%
% Clay	9.33	%
Optimum Water Content (OMC)	32,1	%
Cohesion (C)	25.144	kPa
Internal Friction Angle (Φ)	30.51	°
Young's Modulus E)	9143	kN/m^2
Poission's Ratio (V)	0.3	-

Results of Analysis Using the Simplified Bishop Method

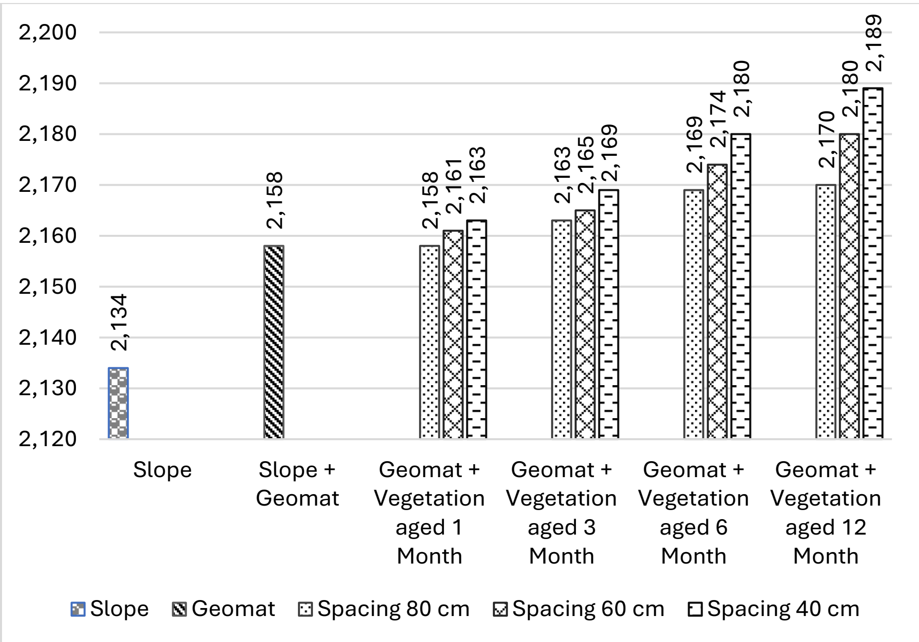


Figure 2. Graph of Recapitulated Safety Factor Value from the Simplified Bishop Method Analysis

Based on the analysis results using the Simplified Bishop Method, as presented in Figure 2, all scenarios satisfy the requirements of SNI 8460:2017, with a safety factor (SF) greater than 1.5. The highest increase in SF was observed at a planting spacing of 40 cm, where the value increased from 2.134 for the unprotected slope to 2.189, representing an increase of 2.59%. The relatively insignificant increase in SF is attributed to the fact that the roots intersect the slip surface only at slice 10. A similar condition is observed for the geomat, where it interacts with the slip surface only at slice 10.

Analysis Results Using PLAXIS 2D Software

Three aspects were evaluated from the slope stability modeling results using PLAXIS 2D, namely deformation, failure pattern, and safety factor. Out of the 14 models, the discussion focuses on those considered most representative, namely:

Table 5. The Failure Pattern Results Were Obstained from the PLAXIS 2D Modeling.

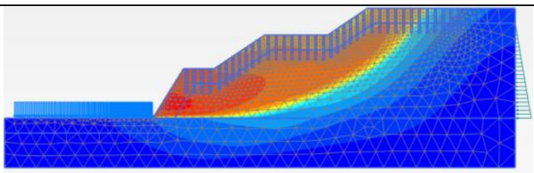
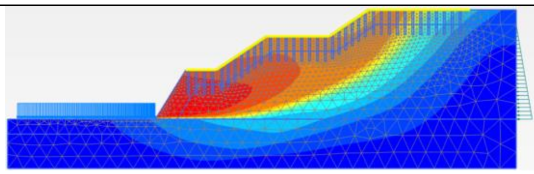
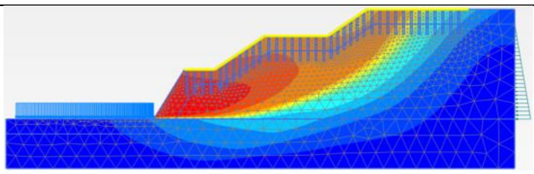
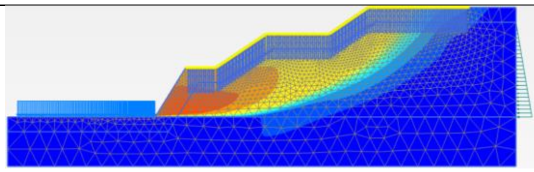
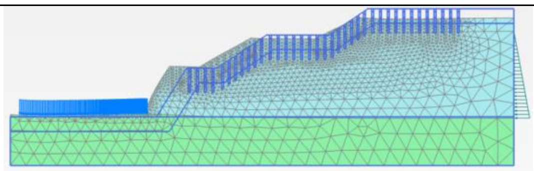
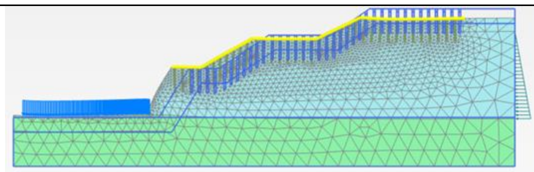
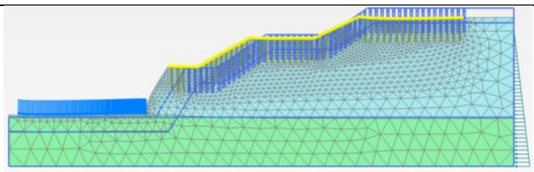
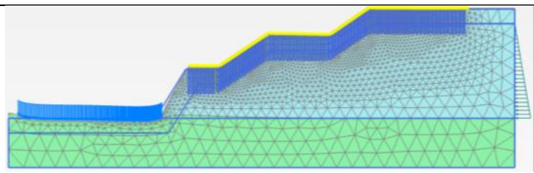
Failure Pattern	
Unproctected Slope	Spacing 80 cm, aged 12 Months
	
Spacing 60 cm, aged 12 Months	Spacing 40 cm, aged 12 Months
	

Table 5 illustrates the soil movement visualized in the total displacement at the Safety Factor (SF) phase. The movement of the soil mass occurs due to the modeled geometry, material parameters, and applied loads. In the presented visualization (magnified by 10 times), soil movement is observed at the toe of the slope, indicated by the red color. The results show that closer planting spacing leads to a smaller critical area, with the smallest area observed at a planting spacing of 40 cm at the age of 12 months.

Table 6. The Deformation Results Were Obtained from the PLAXIS 2D Modeling

Deformation	
Unproctected Slope	Spacing 80 cm, aged 12 Months
	
Spacing 60 cm, aged 12 Months	Spacing 40 cm, aged 12 Months
	

The maximum deformation presented in Table 6 was obtained from the total displacement phase of the loading, representing the actual deformation caused by the applied load. The maximum total displacement for the unprotected slope was recorded at 0.03668 m. In the visualizations, enlarged 50 times, the deformation distribution shows that the upper layers experienced relatively larger displacements compared to the lower layers. Additionally, deformation occurred from the slope toe to the mid-slope in the direction of the slope inclination, reflecting the soil movement mechanism due to the slope geometry and applied loads. Meanwhile, the lower layers exhibited relatively small deformations, indicating stable conditions. Similar behavior was observed for planting spacings of 60 cm and 80 cm, with visualizations enlarged 10 times, resulting in maximum deformations of 0.03680 m and 0.03677 m, respectively. In contrast, for a spacing of 40 cm with visualization enlarged 200 times, the changes were minimal, with the deformation reduced to 0.004054 m.

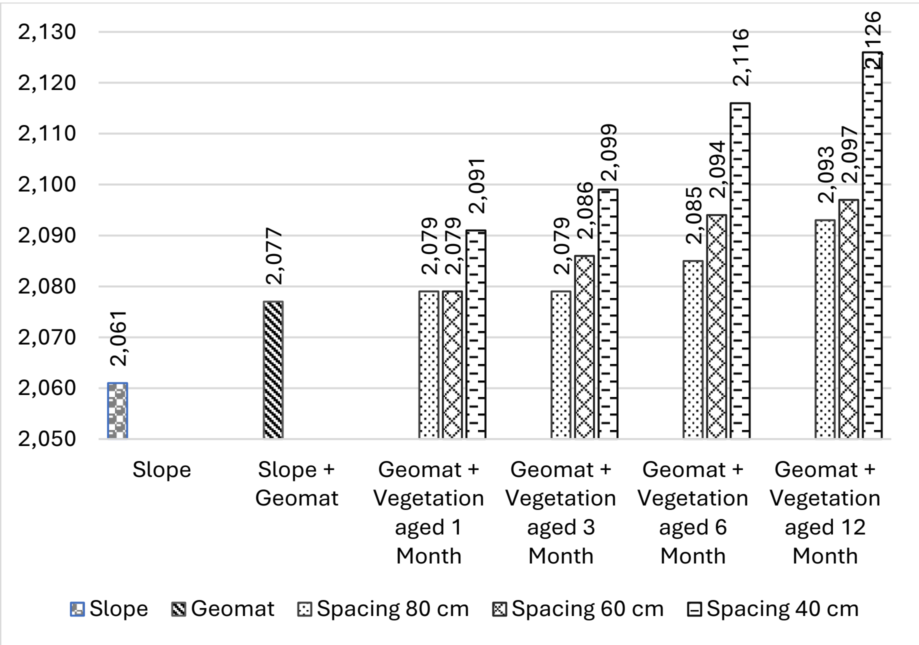


Figure 3. Graph of the Recapitulated Safety Factor Value From the PLAXIS 2D Modeling

The safety factor values from the PLAXIS 2D modeling, as shown in Figure 3, indicate results consistent with the observed failure patterns and deformation magnitudes. Increasing the planting density also led to higher safety factor values. For a planting spacing of 40 cm at an age of 12 months, the highest increase was observed, with the safety factor rising from 2.061 for the unprotected slope to 2.126. The relatively insignificant increase is attributed to the deep-seated slip surface, whereas the contribution of the geomat–vetiver grass combination is limited to shallow surface reinforcement.

Comparasion of Safety Factor Value Between the Simplified Bishop Method and PLAXIS 2D Software

The comparison of safety factor values for each scenaro between the two methods ranged from 2.97% to 4.06%. The average difference in safety factor increments, as shown in Table 7, was 0.34%. This discrepancy is influenced by the determination of the slip surface in the Simplified Bishop Method, which is performed through trial and error by assuming several circle centers, making it prone to subjective limitations. The obtained slip surface does not necessarily represent the minimum value. In contrast, PLAXIS 2D automatically and systematically identifies the weakest slip surface within the slope body. The soil parameters used in manual calculations are relatively simpler compared to the more complex and realistic modeling in PLAXIS 2D, such as elastoplastic modeling (Mohr-Coulomb), initial stress conditions (K_0), detailed variation of soil parameters in each layer, and a more realistic method for reducing shear strength values. The interaction between the soil and geomat is also numerically modeled in PLAXIS 2D, whereas in manual calculations it is treated only as an additional force. Furthermore, the PLAXIS 2D analysis subdivides the slope into thousands of small elements and computes force equilibrium, while the Simplified Bishop Method simplifies the slope into several slices and neglects inter-slice forces.

Table 7. Comparison of Safety Factor Increases

No	Description	Safety Factor Results			% Increase in Safety Factor		
		SBM	PLAXIS 2D	Difference	SBM	PLAXIS 2D	Difference
1	Slope	2.134	2.061	3.42%	-	-	-
2	+ Geomat	2.158	2.077	3.90%	1.12%	0.78%	0,35%
3	J80-U1	2.158	2.079	3.80%	1.13%	0.87%	0.26%
4	J80-U3	2.163	2.079	4.06%	1.38%	0.87%	0.50%
5	J80-U6	2.169	2.085	4.02%	1.63%	1.16%	0.47%
6	J80-U12	2.170	2.093	3.69%	1,70%	1.55%	0.14%
7	J60-U1	2.161	2.079	3.95%	1.27%	0.87%	0.40%
8	J60-U3	2.165	2.086	3.77%	1.44%	1.21%	0.23%
9	J60-U6	2.174	2.094	3.83%	1.88%	1.60%	0.28%
10	J60-U12	2.180	2.097	3.94%	2.14%	1.75%	0.39%
11	J40-U1	2.163	2.091	3.46%	1.38%	1.46%	0.08%
12	J40-U3	2.169	2.099	3.33%	1.63%	1.84%	0.21%
13	J40-U6	2.180	2.116	3.01%	2.14%	2.67%	0.53%
14	J40-U12	2.189	2.126	2.97%	2.59%	3.15%	0.57%

PRACTICAL IMPLICATION

The results indicate that the soil, classified as high-plasticity inorganic clay, exhibits pronounced shrink–swell behavior, making it susceptible to volumetric changes and reduced slope stability. This highlights the necessity of appropriate protection techniques for such soil conditions.

The combined application of wire mesh geomat and vetiver grass effectively improves slope performance. The geomat provides surface confinement and erosion protection, while vetiver grass contributes to moisture regulation through evapotranspiration, reducing pore water pressure and controlling shrink–swell behavior. Consequently, the shear strength of the soil can be better maintained.

Stability analyses using the Simplified Bishop Method and PLAXIS 2D indicate that the slope remains within a stable condition. Increased planting density of vetiver grass tends to enhance the safety factor, although the improvement is relatively limited due to the deep-seated nature of the slip surface, where reinforcement primarily acts at shallow depths.

The minor discrepancy between the two analytical methods suggests that they can be applied complementarily to obtain a more robust stability assessment, depending on the required level of accuracy and field complexity.

In practice, this method can be implemented based on the guidelines of The Vetiver Network International and relevant slope erosion control specifications. It offers both technical and environmental advantages by integrating mechanical and biological reinforcement. However, its performance is influenced by environmental conditions, vegetation growth, and soil variability. Therefore, further research is required to evaluate long-term performance and applicability under diverse field conditions.

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DISCLOSURE STATEMENT

The authors state that this research was conducted without any conflict of interest

NOTES ON CONTRIBUTOR

Fajar Tri Prasetya is an undergraduate student in the Department of Applied Civil Engineering Faculty of Vocational, Yogyakarta State University. His research interests include geotechnical engineering, particularly slope stability and slope protection. Pradtya Galuh Oktafiani is a lecturer in the Department of Applied Civil Engineering Faculty of Vocational, Yogyakarta State University. Her research interests include geotechnical engineering.

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