



Comparative Analysis of Geotextile-Reinforced Embankment Slope Stability Using the Bishop Method in GeoStudio SLOPE/W and Finite Element Analysis in PLAXIS 2D: A Case Study of the Klaten–Purwomartani Toll Road Project, Section 1, Package 1.2, STA 38+000

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Article Info

Article history:

Received 20 August 2026
Received in revised form 16 September 2026
Accepted 5 October 2026

Keywords:

Slope Stability
Geostudio SLOPE/W
PLAXIS 2D
Geotextile
Bishop Method
Safety Factor (SF)

Abstract

This study aims to analyze the stability of embankment slopes in the Klaten–Purwomartani Toll Road Construction Project Section 1 Package 1.2 STA 38+000 by comparing the analysis results using GeoStudio SLOPE/W and PLAXIS 2D, as well as evaluating the effectiveness of geotextile reinforcement and verification using the Bishop method. The research data were obtained from independent laboratory testing of subgrade soil at depths of 1–3 m. The classification results indicate that the subgrade soil is dominated by clay and silt with different shear strength characteristics at each depth, while the embankment material is classified as loamy sand. The analysis without reinforcement shows that increasing embankment height and variations in loading conditions reduce the Safety Factor (SF) value, with the most critical condition occurring at an 8 m embankment height, which does not meet the requirements of SNI 8460:2017 ($SF \geq 1.5$). The application of Woven Staple Fiber Polypropylene UNW-60P geotextile reinforcement effectively increases the SF value by approximately 80%, allowing all critical conditions to meet the stability requirements. Verification using the Bishop method produces SF values ranging from 1.626–2.884, all of which satisfy the requirements of SNI 8460:2017. The comparative analysis results show that PLAXIS 2D produces more conservative SF values because it considers stress distribution, deformation, and pore water pressure using the Finite Element Method (FEM) with the Strength Reduction Method (SRM), while GeoStudio SLOPE/W based on the Limit Equilibrium Method (LEM) produces relatively higher SF values and is suitable for preliminary slope stability evaluation.

Introduction

The Special Region of Yogyakarta (DIY), a province with special autonomy status, has an economy supported by the service, education, and tourism sectors. With a projected population growth of 0.7%, the population is estimated to reach 4.179 million people in 2025, accompanied by a 15.98% increase in foreign tourist visits reaching 10.25 million trips (BPS, 2025). The rapid urbanization and mobility growth in Yogyakarta, Kulon Progo, and Solo have encouraged the government to develop the Solo–Yogyakarta–NYIA Kulon Progo Toll Road, which is integrated with the Trans-Java Toll Road network. This National Strategic Project, managed by PT Jasamarga Jogja Solo (JMJ), refers to Presidential Regulation No. 109 of 2020 concerning the acceleration of strategic infrastructure development. However,

the project faces geotechnical challenges, particularly in areas with hilly topography and unstable soil conditions (Roshan & Pal, 2023; Sreekantan et al., 2025; Ramli et al., 2025).

Landslides are common natural disasters in Indonesia and are influenced by rainfall, seismic activity, and soil characteristics (Shao et al., 2023; Indratmoko & Koestoer, 2025; Lu et al., 2024; Budianta et al., 2022; Zaenurrohman et al., 2025). One vulnerable area is the Klaten–Purwomartani Toll Road Project Section 1 Package 1.2 STA 38+000 in Sleman Regency, DIY. The area is dominated by regosol soil and volcanic breccia deposits, influenced by the Opak Fault and subduction zones, with relatively high rainfall intensity (Karkasa et al., 2022; Reynaldi Zulkifli & Muhardi, 2024; Putra, 2025; BPS DIY, 2025; Susri Nurhaci et al., 2024). This vulnerability was demonstrated by a landslide event in Tirtomartani Village in January 2025, which damaged road retaining structures and disrupted transportation access.

To overcome slope instability risks, effective reinforcement methods are required. Geotextile is one widely applied alternative due to its high tensile strength, permeability, and ability to reinforce soil (Wu et al., 2020; Kumar & Roy, 2022; Eltarabily et al., 2024; Hasheminezhad et al., 2025). Fadela et al. (2022) stated that increasing geotextile tensile strength improves the Safety Factor (SF), thereby enhancing slope stability. Cahyanto (2020) also showed that geotextile reinforcement performs better than pile reinforcement, achieving an SF value of 7.39 ($SF \geq 1.5$). Additionally, geotextiles provide construction advantages, including fast installation, flexibility, and no requirement for heavy equipment or curing processes, making them an effective and economical reinforcement solution (Elmi et al., 2025; Prasad et al., 2023; Tshifularo & Patnaik, 2025; Mohan & Nandan, 2025; Tanasă et al., 2022; Hasheminezhad et al., 2025; Abedi et al., 2023).

In geotechnical engineering, software development such as PLAXIS 2D and GeoStudio plays an important role in slope stability evaluation (Luc Leroy et al., 2024; Belew et al., 2022; Hakro et al., 2025; Hashim & Yusof, 2025). GeoStudio SLOPE/W applies the Limit Equilibrium Method (LEM), which evaluates force and moment equilibrium without considering deformation. Meanwhile, PLAXIS 2D uses the Finite Element Method (FEM), enabling analysis of nonlinear soil behavior and complex dynamic loading effects (Bagaskoro dan Sophian, 2023 ; Karimov, 2024; Abdullah, 2024; Goshu et al., 2025).

Previous studies on embankment slope stability generally focus on post-failure analysis to determine safety factors, identify failure causes, and evaluate reinforcement effectiveness. For example, Iftikhar (2024) analyzed soil nailing reinforcement using FEM for the Cibereum slope failure, while Rosyadah (2025) investigated post-landslide stability at PT United Tractors Satui branch. These studies showed that many slopes had Factor of Safety (SF) values below 1.0 due to soft soil conditions and high pore water pressure (Jia et al., 2024; Khan et al., 2025).

However, studies focusing on pre-failure analysis of potentially unstable embankment slopes are still limited. This approach is important for early mitigation by identifying potential reductions in slope stability before failure occurs due to internal and external changes. Therefore, this study provides novelty by evaluating embankment slope safety factors under pre-failure conditions through geotextile reinforcement analysis using numerical and analytical approaches. Previous research has also mainly examined specific loading conditions. For instance, (2022) evaluated Safety Factor values under static and seismic loading conditions on the Plono–Kebun Teh Nglinggo Road, Kulon Progo, DIY, while Dorothy et al. (2026) analyzed existing slope conditions at the Pongkor Cement Warehouse area. Comprehensive studies integrating various loading scenarios that represent actual field conditions remain limited.

Therefore, this study addresses this gap by evaluating embankment slope stability under various loading conditions, including self-weight, traffic surcharge, earthquake loads, rainfall

loads, and combined loading conditions. The results are expected to provide comprehensive information regarding safety factors, slope behavior, reinforcement design, and geotechnical risk mitigation for toll road construction.

Furthermore, based on the literature review, no previous studies have specifically examined embankment slope stability at the same research location, considering the project section, package, STA, variations in embankment height, and multiple loading conditions. This research is expected to complement existing studies by providing a more specific analysis based on site characteristics and by integrating manual and numerical approaches for a more comprehensive slope stability evaluation.

Geotextile

Geotextile Nonwoven Staple Fiber Polypropylene is a nonwoven geotextile sheet made from polypropylene (PP) UV stabilizers which has quite high strength and material stability, where short fibers are united by a mechanical process which is united through a pressing process by fine needles and given thermo bonding in the final process so as to create high flexibility and excellent hydraulic value [6].



Figure 1. Nonwoven Staple Fiber Polypropylene Geotextile

Internal Stability of Geotextiles

The design of reinforcement thickness and length of geotextile layers to meet safety criteria is explained as follows:

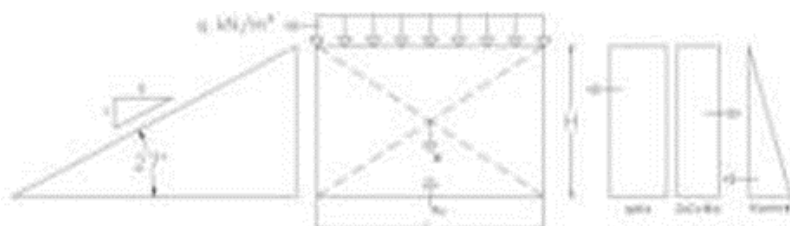


Figure 2. Lateral Earth Pressure

Active soil coefficient

$$\phi K_a = \tan^2 (45^\circ -)$$

Active soil coefficient

$$\phi K_a = \tan^2 (45^\circ -) (1)$$

Average horizontal pressure on the fold

$$\sigma_{hc} = q \times K_a - 2 \times c \times \sqrt{k_a} + k_a \times H \times \gamma_b \quad (2)$$

Distance of vertical reinforcement

$T a$

$$S_v = \sigma_{hc} \times s_f$$

Overlapping Length

$$\sigma_{hc} \times S_v \times SF \times L_o = 2 \times \gamma b \times H \times \tan \phi$$

Panjang Efektif Geotekstil

$$SF \times S_v \times K_a \times \gamma b \times H \times L_e = 2 \times \gamma b \times H \times \tan \phi$$

Panjang Geotekstil pada Zona Aktif

$$L_z = (H - Z_i) \times \tan(45^\circ - \phi) \quad (6)$$

Total Geotextile

$$L_{total} = L_o + S_v + L_e + L_z \quad (7)$$

Shear Stress

$$\tau_1 = c_1 + \sigma_1 + \tan \phi_1 \quad (8)$$

Tensile Stress

$$T = \tau_1 + \tau_2 \quad (9)$$

Information:

Symbol Description

K_a Active earth pressure coefficient

σ_{hc} Average horizontal pressure at the fold

q Uniform surcharge load

SF Safety factor

S_v Vertical spacing of reinforcement

γ Unit weight of soil

c Soil cohesion

T Geotextile tensile strength

H Embankment height

Z_i Depth of the reinforcement folded back into the soil (m)

External Stability of Geotextiles

1. Stability Against Overturning Forces

$$\frac{\sum MR}{\sum MD} = \frac{\text{Momen Penahan}}{\text{Momen Guling}} \geq 1,5 \quad (10)$$

2. Stability Against Shear Forces

$$SF = \frac{(q \times \tan \delta \times L) + (H \times \gamma b \times \tan \delta \times L)}{(q \times K_a \times H) + (0,5 \times K_a \times \gamma b \times H^2) - (2 \times c \times \sqrt{K_a} \times H^2)} \quad (11)$$

3. Stability Against Eccentric Forces

$$\frac{1}{6} \times \dots \geq \dots \quad (12)$$

$$\frac{1}{6} \times \dots \geq \dots \quad (13)$$

4. Stability Against Soil Bearing Force

$$L = \frac{\text{ault}}{(H \times \gamma b) + q} \quad (14)$$

Information:

Symbol Description

L_o Overlap length (m) (14)

Symbol Description

Φ Friction angle between the soil and geotextile ($^\circ$)

L_{ef} Effective geotextile length (m)

Slope Stability Evaluation Using the SLOPE/W Method

GeoStudio SLOPE/W is used to analyze slope stability using the Limit Equilibrium Method (LEM). This program provides various analysis methods, such as Bishop Simplified, Janbu Simplified, Spencer, and Morgenstern-Price. The analysis stages include Define for modeling, Solve for calculating the Safety Factor (SF), and Contour for displaying the analysis results. The accuracy of the results is highly dependent on the completeness and quality of the input data used

Slope Stability Evaluation Using the PLAXIS 2D Method

PLAXIS is used to analyze embankment stability and overall stability using the phi/c reduction method, which reduces the cohesion (c) and internal friction angle ($\tan \phi$) until a landslide occurs. The analysis results include the minimum safety factor and displacement values, as well as visualization of the slope failure plane.

Bishop Simplified Method

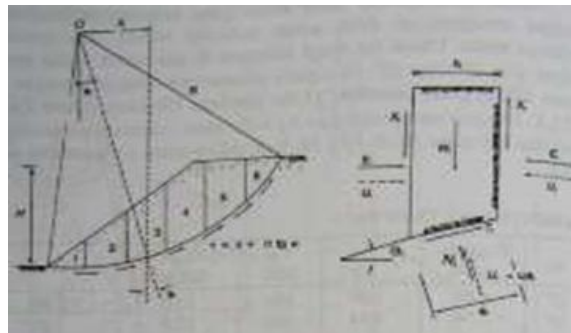


Figure 3. Style and details between Working Slices

The Bishop method, introduced by A.W. Bishop in 1955, analyzed slope stability by dividing the soil mass into several slices. Unlike the Fellenius method, this method considers the balance of moments and normal forces between slices, but ignores the shear forces between slices. Therefore, the resultant forces on the sides of the slices are assumed to be balanced in the vertical direction.

$$SF = (\Sigma[(c b + (\gamma w - u b) \tan \phi)(1/M\alpha)])$$

$$(\Sigma W \sin \alpha)$$

Methods

This study was conducted by analyzing slope stability on the Klaten – Purwomartani STA 38+000 toll road section. Slope reinforcement used geotextiles. Slope stability analysis was analyzed using the Slope/W and PLAXIS 2D programs and the Bishop method. Slope stability is seen from the value of the safety factor (FK) of the slope. Figure 4 shows the research location.



Figure 4. Research Location STA 38+38+000.

Source: Google Earth, 2025

The initial stage of the research was conducted through a literature review. This involved collecting and reviewing various references, such as books, journals, and previous research related to slope stability, safety factors, the use of SLOPE/W and PLAXIS 2D, and slope reinforcement planning using geotextiles.

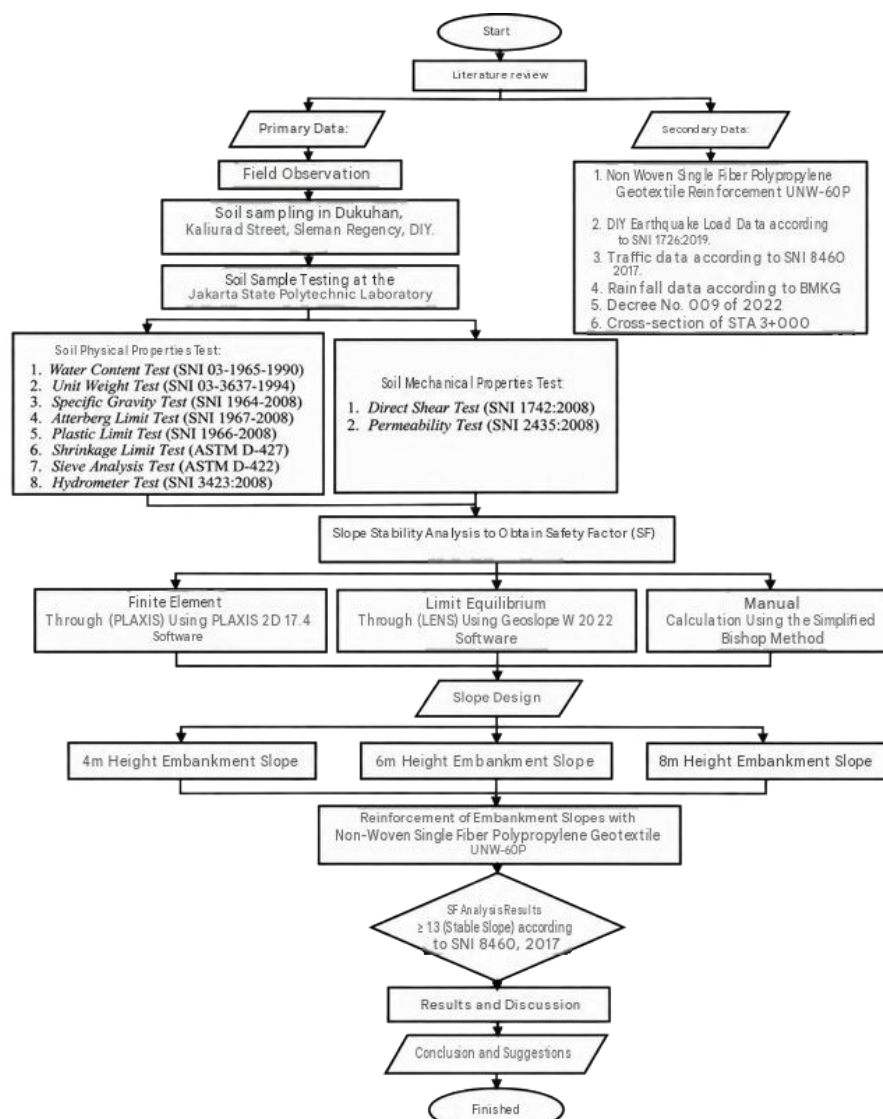


Figure 5. Research Flowchart

The data used in this study consisted of secondary and primary data. Secondary data were obtained from the project's supervisory consultant in 2025, including slope cross-section data

and laboratory results of embankment soil property index tests. Meanwhile, primary data were obtained through a series of independent laboratory tests on the subgrade. The data used in this study include: This study analyzed and compared the safety factor values of embankment slopes before and after geotextile reinforcement to assess their effectiveness in improving slope stability. The analysis was conducted using soil data, road and traffic loading data, PGA values for the Yogyakarta location based on rsa.ciptakarya.pu.go.id, and geotextile data. The research flow is presented in the flowchart in Figure 5.

Results and Discussion

Loads Acting on Slopes Embankment Load Soil Parameters

Soil properties were used as input parameters in numerical modeling using PLAXIS 2D V24 and GeoSlope/W 2025. The soil parameter data is presented in Table 1 below.

Table 1. PLAXIS Soil Properties Input Data

Name	Symbol	Loamy Sand	Clay	Silty Clay Loam	Silty Loam	Unit
Depth	–	Embankment Soil	1 m	2 m	3 m	–
Unsaturated Unit Weight	γ_{unsat}	16.031	14.68 7	15.535	15.716	kN/ m ³
Saturated Unit Weight	γ_{sat}	16.617	15.03 5	14.207	15.086	kN/ m ³

Vehicle Traffic Load

As a basis for planning, the traffic load used is 15 kN/m², because the Klaten-Purwomartani Toll Road is classified as a primary arterial road, as shown in Table 2.

Table 2. Effect of Traffic Load on Slope Stability

Road Class	Traffic Load (kPa)
I	15
II	12
III	12

Source: SNI 8460-2017

Pavement Loads

The loads acting on a structure are a critical aspect of design. Uniformly distributed load calculations refer to the SNI table to obtain the necessary parameters, as presented in Table 3.

Table 3. Pavement Load Calculations

No.	Material	Thickness (m)	Unit Weight (kN/m ³)	Load (kN/m ²)
1	FS-45 Concrete Slab	0.30	24	7.2
2	Lean Concrete	0.10	22	2.2
3	Aggregate Base Course Class A	0.15	18	2.7
4	Selected Material (CBR > 15%)	0.15	17	2.5
Total				14.6

Source: (Primary Data, processed by Excel, 2026) This yields the total vertical load (surface loads) or combined load:

$q = \text{Pavement Load} + \text{Traffic Load } q = 14.65 \text{ kN/m}^2 + 15 \text{ kN/m}^2$

$q = 29.65 \text{ kN/m}^2$

Earthquake Load

The earthquake load used refers to data from the Center for Housing and Settlement Research and Development based on the study location. Based on the location of the Klaten–Purwomartani Toll Road, the Peak Ground Acceleration (PGA) value obtained is 0.4905 g, as shown in Figure 6, which is then used to calculate pseudostatic acceleration

PGA = Peak Ground Acceleration

$a = \text{PGA} \times \text{FPGA} \times (1,45 - \text{PGA}) \times \text{PGA}$

$a = 0,4905 \times 1 \times (1,45 - 0,4905) \times 0,4905$

$a = 0,230 \text{ g}$

Information:

PGA = Peak Ground Acceleration

FPGA = Earthquake amplification factor

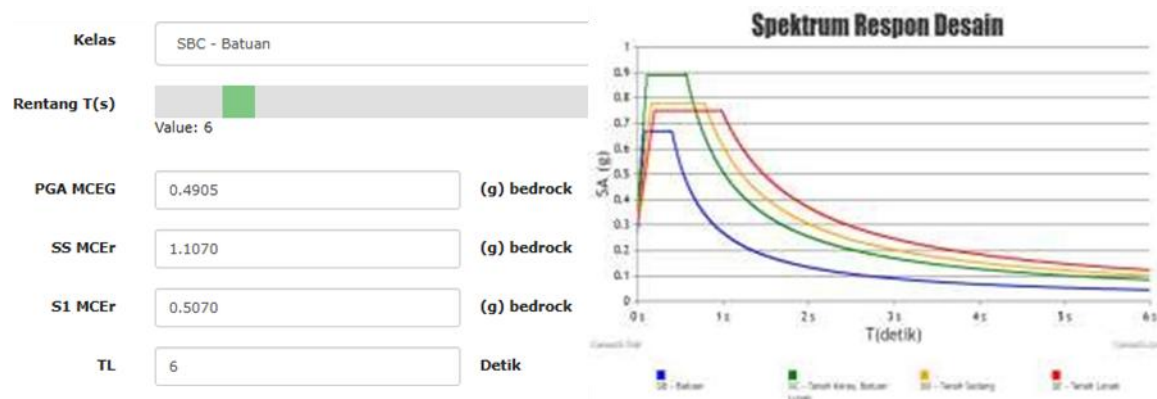


Figure 6. PGA Values for the Yogyakarta Region

Source: rsa.ciptakarya.pu.go.id

Based on the 2023 Projection data from the Sleman Regency Statistics Agency (BPS), updated on May 14, 2024, the average rainfall at the study site is 135 mm/day. Referring to the Head of the BMKG Regulation Number Kep: 009 of 2022, rainfall of ≥ 150 mm/day is categorized as extreme rainfall that has the potential to trigger landslides.

Test Results and Soil Parameters

This study used soil investigation data in the form of laboratory testing on embankment material from the Talun quarry in Kemalang for STA 38+000 of the Klaten–Purwomartani Toll Road Section 1.2. Meanwhile, subgrade parameters were obtained through laboratory testing conducted independently at the PNJ Soil Mechanics Laboratory. The obtained soil parameters were used as modeling input for the Bishop, PLAXIS 2D, and GeoStudio SLOPE/W methods. Soil parameter values for each existing soil layer and embankment material are presented in Table 4.

Table 4. Soil Parameter Data

Description	Loamy Sand (Embankment Soil)	Clay (1 m Depth)	Silty Clay Loam (2 m Depth)	Silty Loam (3 m Depth)	Unit
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γ_{unsat} (Unsaturated Unit Weight)	16.031	14.687	15.535	15.716	kN/m ³
γ_{sat} (Saturated Unit Weight)	16.617	15.035	14.207	15.086	kN/m ³
K (Permeability)	0.006	0.00052	0.00070	0.00077	m/day
C (Cohesion)	17.161	11.552	10.952	26.164	kN/m ²
ϕ (Internal Friction Angle)	30	42	31	36	°
E (Young's Modulus)	25,000	15,000	30,000	7,000	kN/m ²
ν (Poisson's Ratio)	0.3	0.3	0.3	0.3	—

Source: Primary Data, processed in Excel, 2026

Results of Soil Embankment Slope Analysis Using the Bishop Method

Slope stability analysis using the Bishop method was performed iteratively until a convergent Safety Factor (FK) value was obtained. To facilitate the trial-and-error calculation process, Microsoft Excel was used.

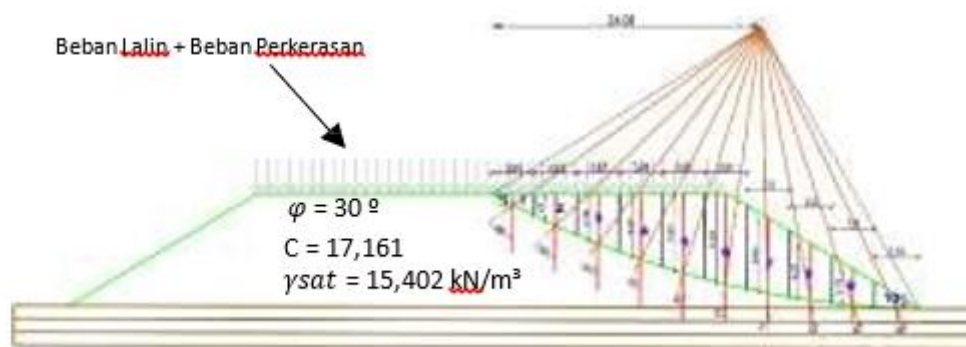


Figure 7. Slope Modeling Scheme Using the Bishop Method

1. Calculation of SF Due to Immediate Load

$$SF = \Sigma[(c b + W_n \tan \phi) \times (1/M\alpha)] / \Sigma(W \sin \alpha)$$

$$SF = 1556.008 / 810.592$$

$$SF = 1.920 \text{ (Stable Slope Condition)}$$

2. Calculation of SF Due to Self-Load

$$SF = 1179.297 / 408.943$$

$$SF = 2.884 \text{ (Stable Slope Condition)}$$

3. Calculation of SF Due to Earthquake Loads

$$SF = 1054.775 / 604.223$$

$$SF = 1.746 \text{ (Stable Slope Condition)}$$

4. Calculation of SF Due to Combined Loads

$$SF = 1239.364 / 604.223$$

$$SF = 1.626 \text{ (Stable Slope Condition)}$$

Table 5. Summary of Slope Stability Analysis Using the Bishop Method

Loading Condition	Resisting Force	Driving Force	SF	Condition
Immediate load	1556.008	810.592	1.920	Stable
Self-load	1179.297	408.943	2.884	Stable

Earthquake loads	1054.775	604.223	1.746	Stable
Combined loads	1239.364	604.223	1.626	Stable

Based on the PLAXIS V.24 analysis, the safety factor (SF) values obtained for various loads on unreinforced embankment slopes are as follows, are presented in Figure 8 until Figure 17:

Stability Analysis of Embankment Slopes Without Geotextile Reinforcement Using PLAXIS V.24

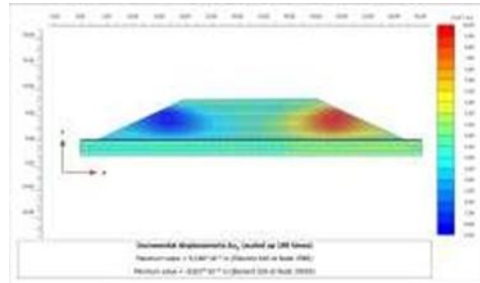


Figure 8. Slope Stability Using Plaxis Slope Without Geotextile Due to Self-Load (Maximum 0.00918 m)

Reached values	
Reached total time	0,000 day
CSP - Relative stiffness	2,974E-3
ForceX - Reached total forc	0,000 kN/m
ForceY - Reached total forc	0,000 kN/m
Pmax - Reached max pp	0,000 kN/m ²
ΣM_{stage} - Reached phase p	0,000
ΣM_{weight} - Reached weight	1,000
ΣM_{sf} - Reached safety fact	1,333

Figure 9. Safety Factor for 8 m Embankment Slope Due to Self-Load Without Geotextile

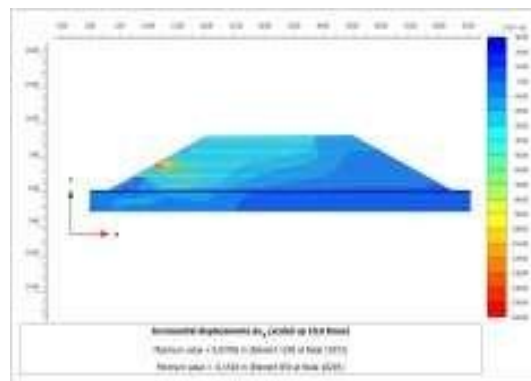


Figure 10. Slope Stability Using Plaxis Slopes Without Geotextiles Due to Earthquake Loads (Maximum 0.0270 m)

Reached values	
Reached total time	0,000 day
CSP - Relative stiffness	0,999E-3
ForceX - Reached total forc	0,000 kN/m
ForceY - Reached total forc	0,000 kN/m
Pmax - Reached max pp	0,000 kN/m ²
ΣM_{stage} - Reached phase p	0,000
ΣM_{weight} - Reached weight	1,000
ΣM_{sf} - Reached safety fact	1,107

Figure 11. Safety Factor of 8 m Embankment Slope Due to Earthquake Loads Without Geotextiles

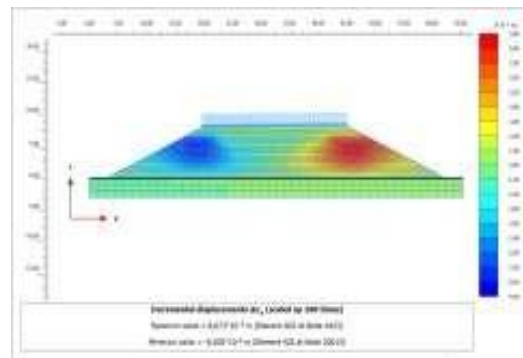


Figure 12. Slope Stability Using Plaxis Slopes Without Geotextiles Due to Evenly Distributed Loads (Maximum 0.00867 m)

Reached values	
Reached total time	0,000 day
CSP - Relative stiffness	0,01884
ForceX - Reached total force	0,000 kN/m
ForceY - Reached total force	0,000 kN/m
Pmax - Reached max pp	0,000 kN/m ²
ΣM _{stage} - Reached phase p	0,000
ΣM _{weight} - Reached weight	1,000
ΣM _{sf} - Reached safety fact	1,252

Figure 13. Safety Factor for 8 m Embankment Slope Due to Evenly Distributed Load Without Geotextile

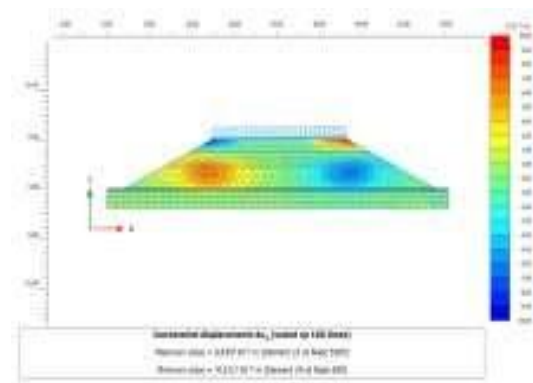


Figure 14. Slope Stability Using Plaxis Slope Without Geotextile Due to Combined Loads (Maximum 0.00943 m)

Reached values	
Reached total time	0,000 day
CSP - Relative stiffness	0,7964
ForceX - Reached total force	0,000 kN/m
ForceY - Reached total force	0,000 kN/m
Pmax - Reached max pp	0,000 kN/m ²
ΣM _{stage} - Reached phase p	1,000
ΣM _{weight} - Reached weight	1,000
ΣM _{sf} - Reached safety fact	1,000

Figure 15. Safety Factor for an 8-m Embankment Slope Due to Combined Loads Without Geotextiles

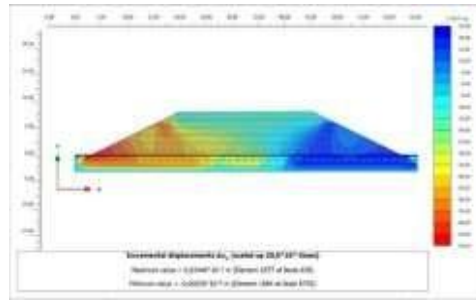


Figure 16. Safety Factor for an 8-m Embankment Slope Due to Rainfall Loads Without Geotextiles

Reached values	
Reached total time	0,000 day
CSP - Relative stiffness	3,542E-3
ForceX - Reached total force	0,000 kN/m
ForceY - Reached total force	0,000 kN/m
Pmax - Reached max pp	0,000 kN/m ²
ΣM _{stage} - Reached phase p	0,000
ΣM _{weight} - Reached weight	1,000
ΣM _{sf} - Reached safety fact	1,375

Figure 17. Safety Factor for an 8-m Embankment Slope Due to Rainfall Loads Without Geotextiles

Table 6. Safety Factor Without Reinforcement for STA 38+000 Using PLAXIS 2D V.24

Embankment Height	Loading Condition	Safety Factor (SF)	SNI 8460:2017 Criterion	Status
4 m	Self-weight	2.090	$SF \geq 1.5$	Safe
4 m	Uniform surcharge	2.055	$SF \geq 1.5$	Safe
4 m	Seismic	1.699	$SF \geq 1.5$	Safe
4 m	Seismic (Additional Condition)	1.447	$SF \leq 1.5$	Unsafe
4 m	Rainfall	1.375	$SF \leq 1.5$	Unsafe
6 m	Self-weight	1.562	$SF \geq 1.5$	Safe
6 m	Uniform surcharge	1.668	$SF \geq 1.5$	Safe
6 m	Seismic	1.380	$SF \leq 1.5$	Unsafe
6 m	Seismic (Additional Condition)	1.234	$SF \leq 1.5$	Unsafe
6 m	Rainfall	1.415	$SF \leq 1.5$	Unsafe
8 m	Self-weight	1.333	$SF \leq 1.5$	Unsafe
8 m	Uniform surcharge	1.252	$SF \leq 1.5$	Unsafe
8 m	Seismic	1.107	$SF \leq 1.5$	Unsafe
8 m	Seismic (Additional Condition)	1.000	$SF \leq 1.5$	Unsafe
8 m	Rainfall	1.375	$SF \leq 1.5$	Unsafe

Based on the Safety Factor are presented in Table 5, values for embankments of 4 m, 6 m, and 8 m height with PLAXIS 2D, do not meet the requirements of SNI 8460:2017 ($SF \geq 1.5$), so geotextile reinforcement is required to improve slope stability.

Slope Stability Analysis of Embankments Without Geotextile Reinforcement Using SLOPE/W V.25

Based on the SLOPE/W V.25 analysis, the safety factor (SF) and landslide potential values for unreinforced embankment slopes are as follows:

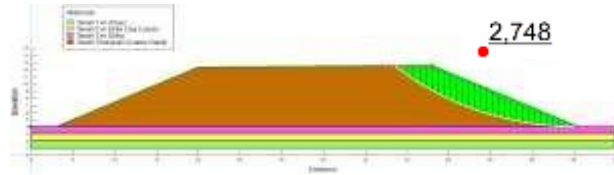


Figure 18. Slope Stability Using SLOPE/W Slope Without Geotextile Due to Self-Load

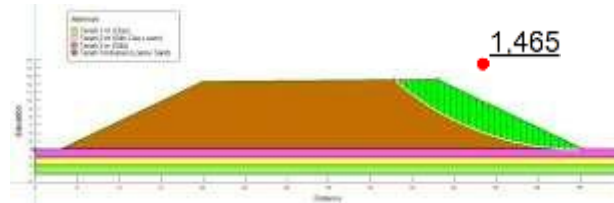


Figure 19. Slope Stability Using SLOPE/W Slopes Without Geotextiles Due to Earthquake Loads

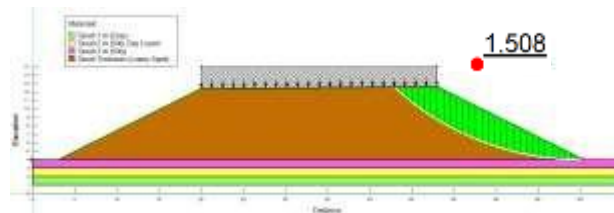


Figure 20. Slope Stability Using SLOPE/W Slope Without Geotextile Due to Uniform Load

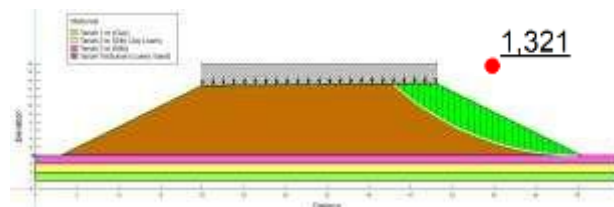


Figure 21. Slope Stability Using SLOPE/W for Slopes Without Geotextiles Under Earthquake Loads

Table 7. Recapitulation of Safety Factors Without Reinforcement for STA 38+000 Using SLOPE/W 2D V.24

Embankment Height	Loading Condition	Safety Factor (SF)	SNI 8460:2017 Criterion	Status
4 m	Self-weight	4.298	$SF \geq 1.5$	Safe
4 m	Uniform surcharge	1.919	$SF \geq 1.5$	Safe
4 m	Seismic	2.132	$SF \geq 1.5$	Safe
4 m	Seismic (Additional Condition)	1.749	$SF \geq 1.5$	Safe
6 m	Self-weight	3.183	$SF \geq 1.5$	Safe
6 m	Uniform surcharge	1.679	$SF \geq 1.5$	Safe
6 m	Seismic	1.672	$SF \geq 1.5$	Safe
6 m	Seismic (Additional Condition)	1.447	$SF \geq 1.5$	Unsafe
8 m	Self-weight	2.748	$SF \geq 1.5$	Safe
8 m	Uniform surcharge	1.508	$SF \geq 1.5$	Safe
8 m	Seismic	1.465	$SF \geq 1.5$	Unsafe
8 m	Seismic (Additional Condition)	1.321	$SF \geq 1.5$	Unsafe

Based on the Safety Factor values presented in Table 6, the embankments with heights of 4 m, 6 m, and 8 m analyzed using SLOPE/W V.24 require reinforcement to improve slope stability under critical loading conditions. The analysis is evaluated against the SNI

8460:2017 criterion of $SF \geq 1.5$. Therefore, geotextile reinforcement is introduced to increase the stability of the embankment slopes.

Non-Woven Geotextile Data

The slope reinforcement used in this study was Woven Staple Fiber Polypropylene UNW-60P geotextile, produced by PT Teknindo Geosistem Unggul. The geotextile has an ultimate tensile strength of 52 kN/m and a strain of 20%. The geotextile parameters used in the PLAXIS 2D and GeoStudio SLOPE/W models include normal stiffness (EA), which was calculated based on the material specifications.

Normal Stiffness (EA)

The normal stiffness of the geotextile was calculated using the following equation:

$$EA = F_g / \varepsilon$$

$$EA = 52 / 0.20$$

$$EA = 260 \text{ kN/m}$$

where:

F_g = Geotextile tensile strength (kN/m)

ε = Geotextile strain

Allowable Tensile Strength

The allowable tensile strength was determined using a safety factor (SF) of 2 against the ultimate tensile strength:

$$T_{all} = T_{ult} / SF_{geo}$$

$$T_{all} = 52 / 2$$

$$T_{all} = 26 \text{ kN/m}$$

The safety factor of 2 used in determining the allowable tensile strength is higher than the minimum safety factor requirement of 1.5 specified in SNI 8460:2017.

Table 8. Non-Woven Staple Fiber Polypropylene Geotextile Data (UNW-60P)

Parameter	Notation	Value	Unit
Ultimate Tensile Strength	T_{ult}	52	kN/m
Allowable Tensile Strength	T_{all}	26	kN/m
Normal Stiffness	EA	260	kN/m
Strain	ε	20	%

Source: PT Teknindo Geosistem Unggul.

Soil Bearing Capacity Coefficients

Based on an internal friction angle (ϕ) of 30° for the embankment soil, the soil bearing capacity coefficients are:

$$N_c = 30.14$$

$$N_q = 18.4$$

$$N_\gamma = 22.4$$

External Stability

Determination of the Vertical Distance Between Geotextile Layers (S_v)

The active earth pressure coefficient (K_a) is calculated as:

$$K_a = \tan^2(45^\circ - \phi/2)$$

$$K_a = \tan^2(45^\circ - 30^\circ/2)$$

$$K_a = 0.333$$

Minimum Vertical Distance Between Geotextile Layers

The minimum vertical distance between geotextile layers is exemplified for a 4 m high embankment.

The horizontal stress is calculated as:

$$\sigma_{hc1} = (q \times K_a) + (K_a \times H_1 \times \gamma_b) - (2 \times c \times \sqrt{K_a})$$

$$\sigma_{hc1} = (29.65 \times 0.333) + (0.333 \times 4 \times 15.401) - (2 \times 17.161 \times \sqrt{0.333})$$

$$\sigma_{hc1} = 10.604 \text{ kN/m}^2$$

The minimum vertical spacing between geotextile layers is:

$$S_{v1} = T_{all} / (\sigma_{hc} \times SF)$$

$$S_{v1} = 26 / (15.401 \times 1.5)$$

$$S_{v1} = 1.634 \text{ m}$$

Geotextile Length Requirements

Stability Against Shear Forces

The stability against shear forces is determined using:

$$SF = [(q \times \tan \delta \times L) + (H \times \gamma_b \times \tan \delta \times L)] / [(q \times K_a \times H) + (0.5 \times K_a \times \gamma_b \times H^2) - (2 \times c \times \sqrt{K_a \times H^2})]$$

Using the given parameters:

$$SF = 8.253 \text{ m} > 1.5$$

Therefore, the requirement for stability against shear forces is satisfied.

Stability Against Rolling Forces

The stability against rolling forces is calculated using:

$$SF = [(2 \times q \times L^2) + (2 \times \gamma_b \times H \times L^2)] / [(q \times K_a \times 2 \times H^2) + (2 \times K_a \times \gamma_b \times H \times 1/3 \times H) - (2 \times c \times \sqrt{K_a \times H^2})]$$

Using the given parameters, the required geotextile length is:

$$L = 3.175 \text{ m}$$

Stability Against Eccentric Forces

The stability against eccentric forces is determined from:

$$L > 6 \times [(q \times K_a \times 1/2 \times H^2) + (2 \times K_a \times \gamma_b \times H \times 1/3 \times H) - (2 \times c \times \sqrt{K_a \times 2 \times H^2})] / [(H \times \gamma_b \times L) + (q \times L)]$$

Based on the calculation:

$$L = 2.812 \text{ m}$$

Stability of Soil Bearing Capacity

The ultimate bearing capacity is calculated as:

$$Q_{ult} = [(c \times N_c) + (0.5 \times L \times \gamma_b \times N_\gamma)]$$

$$Q_{ult} = [(17.161 \times 30.14) + (0.5 \times L \times 15.401 \times 22.4)]$$

$$Q_{ult} = 517.202 + 172.499L$$

The allowable bearing capacity is then determined using the safety factor:

$$\sigma_{ult} = Q_{ult} \times SF$$

$$\sigma_{ult} = (517.202 + 172.499L) \times 1.5$$

Based on the calculation:

$$L = 7.327 \text{ m}$$

Therefore:

$$SF = 7.327 \text{ m} > 1.5 \text{ (Qualified)}$$

Table 9. Summary of Geotextile Stability Requirements

Stability Criterion	Required Geotextile Length/Spacing	Result
Vertical spacing between geotextile layers (Sv)	1.634 m	Required
Stability against shear forces	8.253 m	Satisfied
Stability against rolling forces	3.175 m	Satisfied
Stability against eccentric forces	2.812 m	Satisfied
Stability of soil bearing capacity	7.327 m	Qualified

Source: Calculation based on embankment soil parameters and geotextile specifications.

Table 10. Summary of the Results of the Calculation of Geotextile Overlapping Length

Embankment Height	Stability Check	Safety Factor (SF)	SNI 8460:2017 Criterion	Status
4 m	Overturning Stability	2.454	$SF \geq 2.0$	Safe
6 m	Overturning Stability	2.936	$SF \geq 2.0$	Safe
8 m	Overturning Stability	3.175	$SF \geq 2.0$	Safe
4 m	Sliding Stability	3.268	$SF \geq 1.5$	Safe
6 m	Sliding Stability	4.355	$SF \geq 1.5$	Safe
8 m	Sliding Stability	8.253	$SF \geq 1.5$	Safe
4 m	Eccentricity Stability	1.274	$SF \geq 0.5$	Safe
6 m	Eccentricity Stability	0.631	$SF \geq 0.5$	Safe
8 m	Eccentricity Stability	2.812	$SF \geq 0.5$	Safe
4 m	Bearing Capacity Stability	4.632	$SF \geq 3.0$	Safe

6 m	Bearing Capacity Stability	5.676	$SF \geq 3.0$	Safe
8 m	Bearing Capacity Stability	7.327	$SF \geq 3.0$	Safe

Source: Calculation based on SNI 8460:2017 and geotextile stability analysis.

Internal Stability

Overlapping Length (L_o) for an 8 m High Embankment

The overlapping length is calculated as:

$$L_o = (\sigma_{hc} \times S_{v1} \times SF) / (2 \times \gamma_b \times H \times \tan \phi)$$

$$L_o = (10.604 \times 1.634 \times 1.5) / (2 \times 15.401 \times 8 \times \tan 30^\circ)$$

$$L_o = 0.183 \text{ m}$$

The overlapping length used in the design is 1 m.

Effective Length of Geotextile (L_{ef}) for an 8 m High Embankment

The effective geotextile length is calculated as:

$$L_{ef} = (SF \times S_{v1} \times K_a \times \gamma_b \times H) / (2 \times \gamma_b \times H \times \tan \phi)$$

$$L_{ef} = (1.5 \times 1.634 \times 0.333 \times 15.401 \times 4) / (2 \times 15.401 \times 8 \times \tan 30^\circ)$$

$$L_{ef} = 9.204 \text{ m}$$

The effective length used is 1 m.

Length of Geotextile in the Active Zone (L_z)

The length of geotextile in the active zone is calculated as:

$$L_z = (H - z_i) \times \tan(45^\circ - \phi/2)$$

$$L_z = (8 - 8.5) \times \tan(45^\circ - 30^\circ/2)$$

$$L_z = 0.289 \text{ m}$$

Total Geotextile Length (L_{total})

The total geotextile length is calculated as:

$$L_{total} = L_o + S_v + L_{ef} + L_z$$

$$L_{total} = 0.183 + 0.5 + 9.204 + 0.289$$

$$L_{total} = 10.232 \text{ m}$$

e. Shear Stress (τ)

The shear stress is calculated as:

$$\tau_1 = C_1 + \sigma_1 \times \tan \phi_1$$

$$\tau_1 = 17.161 + (1 \times 1 \times 8) \times \tan 30^\circ$$

$$\tau_1 = 12.217 \text{ kN/m}$$

Tensile Stress (T)

The tensile stress is calculated as:

$$T = \tau_1 + \tau_2$$

$$T = 12.217 + 14.526$$

$$T = 26.743 \text{ kN/m}$$

Since:

$$26.743 \text{ kN/m} < 56 \text{ kN/m}$$

the calculated tensile stress is below the allowable tensile capacity. Therefore, the geotextile reinforcement is considered safe

Stability Analysis of Embankment Slopes with Geotextile Reinforcement Using PLAXIS V.24

Based on the PLAXIS V.24 analysis, the safety factor (SF) and landslide potential values for reinforced embankment slopes are as follows:

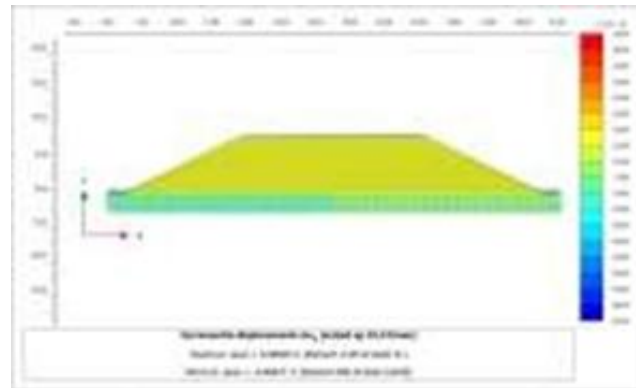


Figure 22. Slope Stability Using Plaxis Slope with Geotextile Due to Self-Load (Maximum $0.0866 \times 10^{-3} \text{ m}$)

Reached values	
Reached total time	0,000 day
CSP - Relative stiffness	0,07545
ForceX - Reached total force	0,000 kN/m
ForceY - Reached total force	0,000 kN/m
Pmax - Reached max pp	0,000 kPa/m ²
ΣM_{stage} - Reached phase p	0,000
ΣM_{weight} - Reached weight	1,000
ΣM_{sf} - Reached safety fact	1,642

Figure 23. Safety Factor of 8 m Embankment Slope Due to Self-Weight with Geotextile

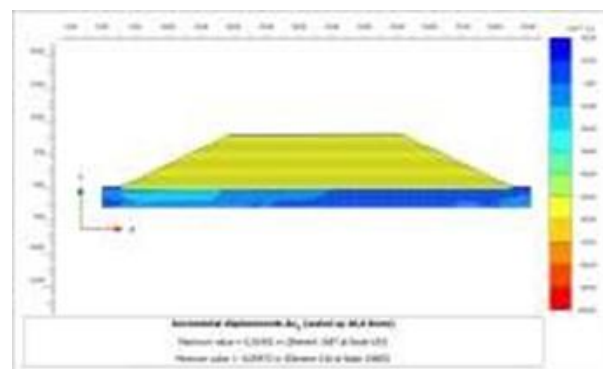


Figure 24. Slope Stability Using Plaxis Slope with Geotextile Due to Earthquake Loads (Maximum 0.01401 m)

Reached values	
Reached total time	0,000 day
CSP - Relative stiffness	6,809E-3
ForceX - Reached total for	0,000 kN/m
ForceY - Reached total for	0,000 kN/m
Pmax - Reached max pp	0,000 kN/m ²
EM _{stage} - Reached phase p	0,000
EM _{weight} - Reached weight	1,000
EM _{sf} - Reached safety fact	1,900

Figure 25. Safety Factor of 8 m Embankment Slope Due to Earthquake Loads with Geotextiles

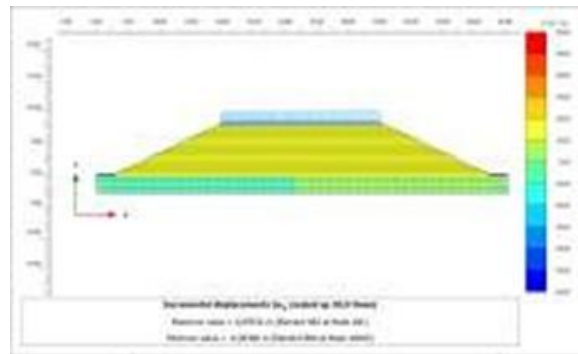


Figure 26. Slope Stability Using Plaxis Slope with Geotextile Due to Evenly Distributed Load (Maximum 0.0536×10^{-3} m)

Reached values	
Reached total time	0,000 day
CSP - Relative stiffness	0,04535
ForceX - Reached total for	0,000 kN/m
ForceY - Reached total for	0,000 kN/m
Pmax - Reached max pp	0,000 kN/m ²
EM _{stage} - Reached phase p	0,000
EM _{weight} - Reached weight	1,000
EM _{sf} - Reached safety fact	1,723

Figure 27. Safety Factor of 8 m Embankment Slope Due to Evenly Distributed Load with Geotextile

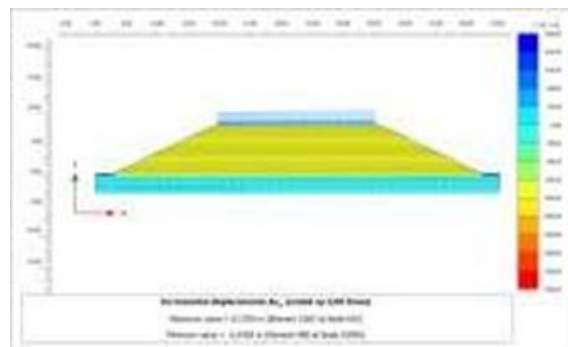


Figure 28. Slope Stability Using Plaxis Slope with Geotextile Due to Combined Loads (Maximum 0.178×10^{-3} m)

Reached values	
Reached total time	0,000 day
CSP - Relative stiffness	0,3103E-3
ForceX - Reached total for	0,000 kN/m
ForceY - Reached total for	0,000 kN/m
Pmax - Reached max pp	0,000 kN/m ²
ZM _{stage} - Reached phase p	0,000
ZM _{weight} - Reached weight	1,000
ZM _{sf} - Reached safety fact	1,541

Figure 29. Safety Factor of 8 m Embankment Slope Due to Combined Loads with Geotextile

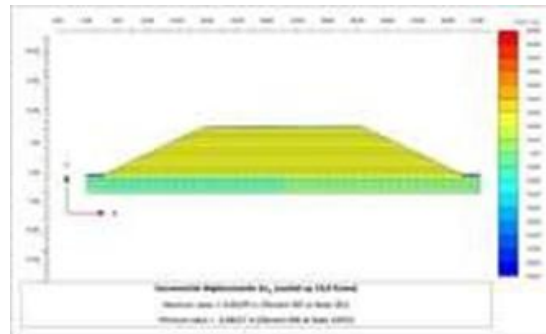


Figure 30. Slope Stability Using Plaxis Slope with Geotextile Due to Rainfall Loads (Maximum 0.819 m)

Reached values	
Reached total time	0,000 day
CSP - Relative stiffness	0,08367
ForceX - Reached total for	0,000 kN/m
ForceY - Reached total for	0,000 kN/m
Pmax - Reached max pp	0,000 kN/m ²
ZM _{stage} - Reached phase p	0,000
ZM _{weight} - Reached weight	1,000
ZM _{sf} - Reached safety fact	1,675

Figure 31. Safety Factor of 8 m Embankment Slope Due to Rainfall Loads with Geotextile

Table 9. Recapitulation of Safety Factors With Geotextile for STA 38+000 Using PLAXIS V.24

Table. Safety Factor Analysis of Embankment Stability

Table 11. Safety Factor Analysis of Embankment Stability

Embankment Height	Loading Condition	Safety Factor (SF)	SNI 8460:2017 Criterion	Status
4 m	Self-weight	2.296	SF $\geq$ 1.5	Safe
4 m	Uniform surcharge	2.170	SF $\geq$ 1.5	Safe
4 m	Seismic	1.741	SF $\geq$ 1.5	Safe
4 m	Combined loading	1.541	SF $\geq$ 1.5	Safe
4 m	Rainfall	2.041	SF $\geq$ 1.5	Safe
6 m	Self-weight	1.668	SF $\geq$ 1.5	Safe

6 m	Uniform surcharge	2.306	$SF \geq 1.5$	Safe
6 m	Seismic	1.876	$SF \geq 1.5$	Safe
6 m	Combined loading	1.706	$SF \geq 1.5$	Safe
6 m	Rainfall	1.562	$SF \geq 1.5$	Safe
8 m	Self-weight	1.642	$SF \geq 1.5$	Safe
8 m	Uniform surcharge	1.723	$SF \geq 1.5$	Safe
8 m	Seismic	1.900	$SF \geq 1.5$	Safe
8 m	Combined loading	1.803	$SF \geq 1.5$	Safe
8 m	Rainfall	1.675	$SF \geq 1.5$	Safe

Based on the table 9, the Safety Factor values for embankments with heights of 4 m, 6 m, and 8 m have met the requirements of SNI 8460:2017 ($SF \geq 1.5$), so that geotextile reinforcement effectively increases slope stability.

Stability analysis of embankment slopes with geotextile reinforcement with SLOPE/W V.25

Based on the SLOPE/W V.25 analysis, the safety factor (SF) value and potential for landslides were obtained in embankment slope conditions with the following reinforcement:

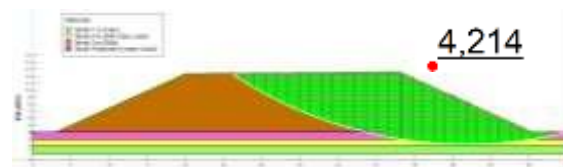


Figure 32. Slope Stability Using SLOPE/W Geotextile Slope Due to Self-Load

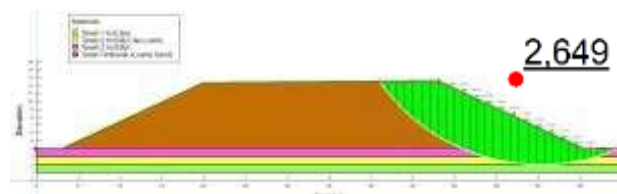


Figure 33. Slope Stability Using SLOPE/W Slopes With Geotextiles Due to Earthquake Loads

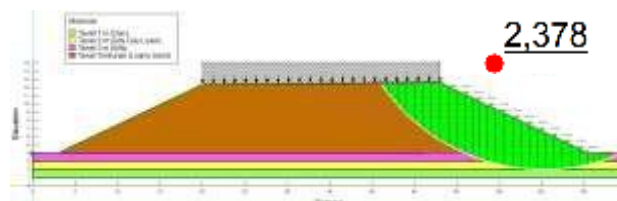


Figure 34. Slope Stability Using SLOPE/W Slopes With Geotextiles Due to Uniform Self-Load

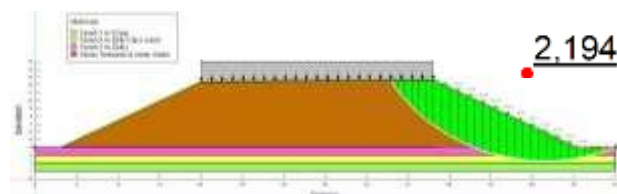


Figure 35. Slope Stability Using SLOPE/W Slope With Geotextile Due to Self-Load Combination

Table 12. Recapitulation of Safety Factors with Geotextile for STA 38+000 Using SLOPE/W V.24

Embankment Height	Loading Condition	Safety Factor (SF)	SNI 8460:2017 Criterion	Status
4 m	Self-weight	6.354	$SF \geq 1.5$	Safe
4 m	Uniform surcharge	4.058	$SF \geq 1.5$	Safe
4 m	Seismic	5.593	$SF \geq 1.5$	Safe
4 m	Combined loading	3.514	$SF \geq 1.5$	Safe
6 m	Self-weight	4.808	$SF \geq 1.5$	Safe
6 m	Uniform surcharge	3.433	$SF \geq 1.5$	Safe
6 m	Seismic	3.900	$SF \geq 1.5$	Safe
6 m	Combined loading	2.990	$SF \geq 1.5$	Safe
8 m	Self-weight	4.214	$SF \geq 1.5$	Safe
8 m	Uniform surcharge	2.378	$SF \geq 1.5$	Safe
8 m	Seismic	2.649	$SF \geq 1.5$	Safe
8 m	Combined loading	2.194	$SF \geq 1.5$	Safe

Based on the table 10, the Safety Factor values for embankments with heights of 4 m, 6 m, and 8 m have met the requirements of SNI 8460:2017 ($SF \geq 1.5$), so that geotextile reinforcement effectively increases slope stability.

Conclusion

This study includes the stability analysis of an embankment slope at the Klaten–Purwomartani Toll Road Development Project Section 1 Package 1.2 STA 38+000, as well as independent laboratory testing of subgrade soil samples taken from depths of 1–3 m from Babadan, Jl. Raya Kalimati, Sleman Regency, Special Region of Yogyakarta. Based on all analysis and testing stages, the following conclusions can be drawn:

Subgrade soil characterization

The subgrade soil data were obtained from independent laboratory testing at depths of 1–3 m. Based on the Unified Soil Classification System (USCS), soil at a depth of 1 m was classified as CL (inorganic clay with low plasticity), soil at 2 m depth as ML (inorganic silt with very fine sand), and soil at 3 m depth as CL-ML (clayey silt with low plasticity). Based on the USDA classification, the soil at 1 m depth was classified as clay, the soil at 2 m depth as silty clay, and the soil at 3 m depth as sandy clay. The shear strength parameters showed that the internal friction angle (ϕ) and cohesion (c) were 41.909° and 11.552 kPa at 1 m depth, 30.550° and 10.952 kPa at 2 m depth, and 36.448° and 26.164 kPa at 3 m depth. Meanwhile, the embankment fill material was classified as clayey sand based on USDA classification, with an internal friction angle of 29.680° and cohesion of 17.651 kPa.

Slope stability analysis without reinforcement

The unreinforced slope stability analysis showed that increasing embankment height and variations in loading conditions reduced the Safety Factor (SF). PLAXIS 2D identified critical conditions starting at a 4 m embankment height, while SLOPE/W indicated critical conditions beginning at 6 m. For the 8 m embankment, combined loading represented the most critical condition, producing the lowest SF values of 1.000 (PLAXIS 2D) and 1.321 (SLOPE/W).

These results indicate that several loading conditions did not satisfy the slope stability requirements according to SNI 8460:2017 ($SF \geq 1.5$).

Effectiveness of geotextile reinforcement

To improve the Safety Factor (SF), geotextile reinforcement was applied to the embankment slope. The geotextile used was Woven Staple Fiber Polypropylene UNW-60P, with a tensile strength of 52 kN/m and elongation of 20%. The reinforcement design used a vertical spacing between geotextile layers (S_v) of 0.5 m across three zones. The installed reinforcement consisted of 8 layers in Zone 1 and 4 layers each in Zones 2 and 3. Based on SLOPE/W and PLAXIS 2D analyses, unreinforced embankments with heights of 6 m and 8 m showed high vulnerability to failure, particularly under earthquake loading, vehicle loading, and combined loading conditions. The application of geotextiles effectively improved slope stability, increasing the Safety Factor by approximately 80%, particularly under critical conditions where SF values were previously below 1.5. After reinforcement, all critical conditions achieved SF values exceeding the minimum requirement of SNI 8460:2017 ($SF \geq 1.5$), indicating improved slope stability and reduced failure potential.

Manual verification using the Bishop Method

Slope stability was also evaluated manually using the Simplified Bishop Method as verification of the numerical analysis results. The calculations produced Safety Factor values of 2.884 for self-weight loading, 1.920 for uniform loading, 1.746 for earthquake loading, and 1.626 for combined loading conditions. Although the SF values decreased under several loading scenarios, all results remained above the minimum stability requirement according to SNI 8460:2017 ($SF \geq 1.5$), indicating that the slope remained stable against potential failure.

Comparison of FEM and LEM analysis approaches

The PLAXIS 2D analysis based on the Finite Element Method (FEM) combined with the Strength Reduction Method (SRM) produced Safety Factor values that tended to be more conservative because it considers stress distribution, deformation, and pore water pressure comprehensively. Meanwhile, the GeoStudio SLOPE/W analysis based on the Limit Equilibrium Method (LEM) generated relatively higher SF values because it is based on force and moment equilibrium along potential slip surfaces. Therefore, SLOPE/W is suitable for preliminary slope stability evaluation, whereas PLAXIS 2D provides a more representative assessment of actual slope behavior and deformation mechanisms.

Recommendations

Research is needed using various other soil stabilization techniques to improve the specifications of the geotextiles used and to compare them with other reinforcement methods, such as the use of chemical stabilizers (e.g., lime, cement, or cement injection) and combining them with mechanical methods such as bamboo piles, vetiver grass, sheet piles, soil nailing, reinforcing walls, PVD, and so on, to determine the synergistic effects of different reinforcement methods.

In addition to technical aspects, an analysis of the implementation time and volume of excavation and embankment work is necessary to evaluate the effectiveness and efficiency of each soil improvement and reinforcement method.

In future research, analysis of soil consolidation and groundwater level conditions over a specific time period should be taken into account to obtain more comprehensive results.

Acknowledgment

We would like to express our deepest gratitude to all parties who contributed to this research. We would like to thank our colleagues who provided advice, support, and inspiration throughout the research process. We would also like to thank all participants and respondents who took the time to participate in this research. We would also like to thank the institutions that provided support and facilities for conducting this research. All contributions and assistance were invaluable to the smooth running and success of this research. Thank you for all your hard work and collaboration..

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