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THE STABILITY ANALYSIS OF EMBANKMENT SOIL SLOPES IN THE INTERNATIONAL SCHOOL PROJECT

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Abstract

The construction of an international school in Jakarta Garden City faces challenges due to elevation differences requiring additional embankment soil, increasing landslide risks. This study evaluates slope stability using analytical and numerical methods. The Fellenius method yielded a safety factor of 1.239, confirmed by Plaxis at 1.2445—both below the SNI 8460:2017 threshold of ≥1.5, deeming the slope unsafe. Two reinforcement options were analyzed: cantilever retaining walls and geotextile reinforcement. The cantilever retaining wall analysis showed safety factors of 2.233 for overturning, 1.657 for sliding, 3 for bearing capacity, and 1.9753 for global stability. Geotextile reinforcement produced safety factors of 1.556, confirmed by Plaxis at 1.7088. The reassessment was essential due to significant elevation differences, posing risks to the school structure, surrounding communities, and infrastructure. Landslides could lead to costly repairs, delays, and environmental damage such as erosion and sedimentation. The study highlights the economic and environmental implications of slope reinforcement and recommends cantilever retaining walls as the safer alternative. While this research focuses on clayey soil conditions, its findings provide a broader framework that can be adapted for similar geotechnical challenges in other locations with proper adjustments to local soil characteristics.

Keywords: Safety Factor, Slope Stability, Cantilever Retaining Wall, Geotextile

Introduction

The development of educational facilities in Jakarta Garden City involves the use of embankments, as the original soil cannot withstand the load. The embankments are applied from the building area to the sports area, with attention given to the potential for landslides that may occur due to the soil type, slope height, or external factors such as rainfall (Adji, 2021; Imron Maulana Fauzi, 2019). Therefore, slope stability analysis is crucial to ensure the safety of the structure, whether with or without reinforcement (Amri, 2021; Dadan Ali Sadikin, 2018).

Slope stability is highly influenced by various factors, including the higher embankment loads in toll road projects. In slope stability planning, the use of reinforced retaining walls is necessary to ensure safety, with various factors of safety (SF) calculated using software such as Plaxis 8.2 (Nurgia Sari, 2024; Hakam, 2011). Soil reinforcement using geotextiles is a common method used in Indonesia to prevent landslides (B. M. et al Gati, 2018; Septiani, 2024).

Slopes can be formed through natural processes or human intervention, with landslides being one of the main risks. Ground subsidence, which occurs due to an imbalance between driving and resisting forces, is the primary cause of slope failure (M. W. et al Hanif, 2023; Archenita et al., 2016). Therefore, it is important to understand the factors influencing overall slope stability.

The pressure experienced by the soil elements during backfilling is almost similar to the hydrostatic pressure of water, but with differences in horizontal and vertical directions. Retaining walls are designed to stabilize soil or other materials that do not have a natural slope, as explained by Mina et al. (2015) and Sebayang (2022). Factors affecting slope stability can be divided into two main groups: external and internal factors (Terzaghi, 1950; Wagola, 2024).

Soil improvement using geotextiles can enhance soil stability in an economical and effective way. Geotextiles play an important role in soil reinforcement, especially in stabilizing the subgrade (Famungkas, 2015; Rishavilenda, 2018). This method can be used to improve soil quality at a lower cost compared to other techniques.

Geotextiles are made from polymer materials and are used in various construction projects to improve soil strength. Studies by the American Association of State Highway and Transportation Officials (2008) and FHWA HI 95 038 (1998) show that geotextiles can improve soil stability and support the construction of retaining walls. The use of geotextiles also helps reduce the movement of active soil that can cause damage (Legrans, 2016).

Mechanically Stabilized Earth (MSE) walls are an alternative to conventional retaining walls, offering a more economical and flexible option. MSE walls can use geosynthetics or metal materials to provide additional strength to the retaining wall structure (Badan Standardisasi Nasional, 2017; Hulagabali, 2018). A study by Aziza (2022) also highlighted the efficiency of using geotextiles in MSE walls to reduce lateral deformation and improve stability.

Extending the length of geotextiles and increasing tensile strength can reduce lateral deformation in MSE walls. Increasing the vertical spacing of geotextile reinforcement also impacts the stability of the wall (Suryadinullah & Purwanto, 2018; W. H. et al Setiawan, 2019). This research shows that geotextiles can enhance the safety factor (SF) in retaining walls, making them more stable under external loads.

Geotextiles have also been proven effective in improving soil bearing capacity in road projects, such as in the Tuban Highway project. The use of geotextiles can reduce excessive soil deformation after embankment placement and improve the stability of soft soils (Aripindi, 2022; Fitriani, 2024). This reinforcement is crucial for addressing soil subsidence issues that can impact road safety.

The application of geotextiles in road improvement also enhances soil bearing capacity and compaction, as well as the performance of heavy vehicles such as HD 785 trucks. Research by Asof (2023) shows that the use of geotextiles increases truck speed and improves field performance. Geotextiles become an effective solution in enhancing soil stability in areas prone to damage due to heavy loads and soil changes (Rachman, 2024; Nalawade), 2024).

This research is positioned as a critical evaluation of slope stability in the context of an international school construction project in Jakarta Garden City, addressing the unique challenges posed by significant elevation differences and the associated risks of landslides. The study not only assesses the stability of the existing slope using both analytical and numerical methods but also explores the effectiveness of two reinforcement options—cantilever retaining walls and geotextile reinforcement. Given the results indicating an unsafe slope without reinforcement, this research contributes valuable insights into slope stabilization strategies. By evaluating the safety factors for both reinforcement methods, the study offers practical recommendations for similar geotechnical challenges in other regions, emphasizing the importance of considering local soil conditions and environmental impacts in the design of slope reinforcement solutions.

Figure 1. 3D Image and Actual Progress of the Project Location Used as a Case Study.

Research Methods

The parameters used in this study are essential elements that determine the accuracy of calculations and the achievement of research objectives. Primary data were obtained through direct field observations, including soil sampling, in-situ testing such as Standard

Penetration Test (SPT), and interviews with relevant parties, including the project contractor. Meanwhile, secondary data were collected from laboratory test reports provided by the contractor, scientific journals, technical industry reports, and relevant geotechnical literature. The selection of these two types of data was designed to complement each other. Primary data provide specific, actual, and contextual site information, such as soil conditions at certain depths. On the other hand, secondary data offer comparative references and empirical parameters to support result validation. This combination ensures a holistic methodological approach with validation based on data triangulation, which is a standard in scientific research.

This study employs soil investigation data using an empirical correlation approach due to resource limitations that hinder the direct testing of fill soils. Although this approach has limitations, such as potential inaccuracies due to the use of empirical assumptions, mitigation measures were taken by relying on correlations documented and widely verified in geotechnical literature. The results of the SPT conducted at elevations between 0.00 and -4.00 meters showed an average N-SPT value of 4, classifying the soil as soft. This data was then used to determine soil parameters such as cohesion, internal friction angle, and modulus of elasticity based on correlations available in the literature.

Fill soils at elevations ranging from 0.00 to +2.80 were classified using an empirical correlation approach, with a California Bearing Ratio (CBR) value of 6%. These soils exhibit characteristics of reddish-yellow color, high dry density, and significant plasticity when wet. According to Table 1, these soils meet the CH classification criteria in the Unified Soil Classification System (USCS). Data from SPT tests, field observations, and in-depth interviews with contractors were combined to provide a comprehensive overview of the soil's geotechnical conditions. Meanwhile, secondary data were collected from reputable journals, technical industry reports, and relevant geotechnical databases to provide comprehensive literature support.

The limitations of not conducting direct testing on the fill soil were addressed through risk mitigation measures based on data validation. Validation was performed by comparing empirical correlation results with similar data from locations with comparable soil and environmental characteristics, as well as through consultations with geotechnical experts. Additionally, a conservative approach was applied in the design, incorporating additional safety factors to anticipate potential inaccuracies.

Table 1. Soil Classification Based on CBR

CBR	**Soil Condition**	**Usage**	**Classification System**	
			USCS	**AASHTO**
0 – 3	*Very Poor*	*Subgrade*	OH, CH, MH, OL	A5, A6, A7
3 – 7	*Poor to Fair*	*Subgrade*	OH, CH, MH, OL	A4, A5, A6, A7
7 – 20	*Fair*	*Subbase*	OL, CL, ML, SC, SM, SP	A2, A4, A6, A7
20 – 50	*Good*	*Base, sub base*	GM, GC, SW, SM, SP, GI	A1b, A2-5, A3, A2-6
> 50	*Excellent*	*Base, sub base*	GW, GM	A1a, A2-4, A3

Source: Bowles, 1922

From the literature review, the soil parameters used for this study are detailed in the tables below.

Table 2. Embankment Soil Parameters (0.00 to +2.80m)

Testing Parameter	Value	Unit
Cohesion (c)	8.8	kN/m^3
Shear Angle (φ)	17.0°	Degrees (°)
Saturated Soil Unit Weight (γ_{sat})	18.0	kN/m^3
Soil Bearing Capacity (q_{all})	304	Kpa
Unit Weight of Water (γ_w)	10.0	kN/m^3
Dry Soil Unit Weight (γ_{dry})	1.63	kN/m^3

Source: Soil Investigation, 2024

For the soil data collected at elevations between 0.00 and -4.00 meters, the contractor's test results, which report an average N-SPT value of 4, classify the soil as soft. Using the N-SPT data and empirical correlations from existing literature, the corresponding soil parameters are summarized in Table 3.

Table 3. Soil Parameters for Elevation 0.00 to -4.00m

Testing Parameter	Value	Unit
Cohesion (c)	24	kN/m^3
Shear Angle (φ)	0	Degrees (°)
Saturated Soil Unit Weight (γ_{sat})	18.0	kN/m^3

Source: Soil Investigation, 2024

There are additional soil parameters for geotechnical software analysis that are incomplete and were obtained from previous tests or literature studies. These parameters are detailed in Table 4 Additional Soil Parameters.

Table 4. Other Soil Parameters

Testing Parameter	Value	Unit
Horizontal Permeability (k_x)	0.04752	m/day
Vertikal Permeability (k_y)	0,04752	m/day
Young Modulus (E)	5 – 25	N/m^2
Poisson's ratio (μ)		
- Saturated Clay	0.40 – 0,50	
- Unsaturated Clay	0.10 – 0,30	
Dilatancy angle (ψ)	0	Degrees (°)

Source: Soil Investigation, 2024

Retaining Wall Parameters

In this study, data or parameters for calculating cantilever retaining walls are used. The parameters employed are described and detailed in Table 5.

Table 5. Retaining Wall Parameters

Design Parameter	Value	Unit
Dead load	10.0	kN
Live load	0	kN
External momen dead load	0	kN – m

Design Parameter	Value	Unit
External momen live load	0	kN – m

Source: SNI 8460 2017

Table 6. Retaining Wall Parameters (Continued)

Design Parameter	Value	Unit
Surcharge	10.0	Kpa
f'c	20.0	Mpa
fy	400.0	Mpa
Height of Wall (H)	3.2	M
Height of Soil (hs)	2.8	m
Height of Water (hw)	0.0	M
Height of Surcharge	3.2	m
Load factor dead load	1.2	
Load factor live load	1.6	
Load factor lateral load	1.6	
Base Width of Footing (L)	2000	mm
Thickness of Footing (D)	400	mm
Thicness of Wall (T)	350	mm
Concrete cover	50	mm
Diameter of Bars	13	m

Source: SNI 8460 2017

Geotextile Data

This study uses geotextile data from PT Tetrasa Geosinindo, specifically woven type Speravi VET 250/50, which has a tensile strength of 95 kN.

Table 7. Geotextile Data from PT Tetrasa Geosinindo

Property	Unit	VT 100/50	VT 200/50	VT 250/50	VT 300/50	VT 400/50	VT 500/50	VT 600/50	VT 700/50
Initial Mechanical Properties									
Polymer	kN/m	PET	PET	PET	PET	PET	PET	PET	PET
Tensile Strength*	%	100/50	200/50	250/50	300/50	400/50	500/50	600/50	700/50
Elongation (MD)	kN/m	10±2	10±2	10±2	10±2	10±2	10±2	10±2	10±2
Strength @5% Strain* (MD)	N	45	95	115	140	180	230	270	320
CBR Puncture Strength*		6.000	8.000	9.000	11.000	14.000	6.000	6.000	6.000
Material Reduction Factor Installation Damage									
in Clay, Silt or Sand		1.150	1.150	1.150	1.150	1.150	1.150	1.150	1.150

Material Reduction									
Property	**Unit**	**VT 100/50**	**VT 200/50**	**VT 250/50**	**VT 300/50**	**VT 400/50**	**VT 500/50**	**VT 600/50**	**VT 700/50**
Factor Creep-Rupture RF									
at 50 years design life		1.430	1.430	1.430	1.430	1.430	1.430	1.430	1.430
at 100 years design life		1.450	1.450	1.450	1.450	1.450	1.450	1.450	1.450
at 120 years design life		1.450	1.450	1.450	1.450	1.450	1.450	1.450	1.450
Material Reduction Factor Environmental Effects (4< pH < 9)		1.100	1.100	1.100	1.100	1.100	1.100	1.100	1.100
Long Term Design Strength in Clay, Silt or Sand	kN/m								
at 50 years design life		55	111	138	166	221	276	332	387
at 100 years design life		55	109	136	164	218	273	327	382
at 120 years design life		55	109	136	164	218	273	327	382
Roll Size	m	5.4 x 100	5.4 x 100	5.4 x 100	5.4 x 100	5.3 x 100	5.3 x 100	5.3 x 100	5.3 x 100

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Research Results and Discussion

1. Analysis Using Manual Methods

This section describes the stability analysis of embankment soil slopes without reinforcement using the Fellenius method (also known as the slip circle method). This method is used to calculate the safety factor (SF) based on the initial geometry of the slope without any modifications such as excavation or reinforcement. This analysis is essential for evaluating slope stability in its natural condition and serves as a basis for assessing the need for reinforcement.

Slope Geometry Parameters

The parameters used in this analysis include:

R (Radius of slip surface) : The radius of the slip circle used to estimate potential failure paths of the slope. The radius is set at 4 m.

h (Height of embankment soil) : The height of the embankment slope is 2.8 m, representing the vertical distance between the top and toe of the slope.

b (Length of embankment slope) : The length of the slope is 1 m, indicating the horizontal projection width of the slope at its base.

The original slope geometry using the Fellenius method without reinforcement is illustrated in Figure 2.

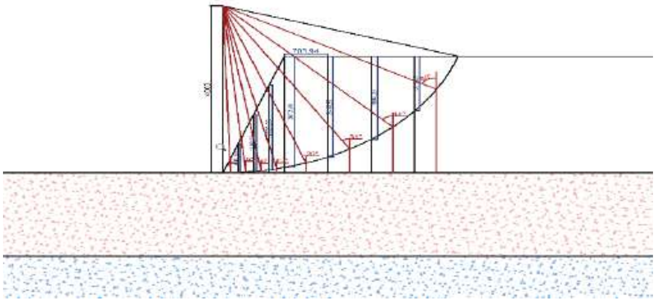

Figure 2. Original Slope Analysis of Embankment Soil Using the Fellenius Method Without Reinforcement

Diagram Interpretation (Figure 3)
In the figure, the slip circle is illustrated to visualize the potential failure path of the slope. The illustration shows:

1. Segmentation of the slip circle, dividing the slope into small elements. Each element is analyzed to determine the forces acting on it, such as soil weight, frictional force, and soil bearing capacity.
2. Force vectors, representing the distribution of forces contributing to the stability or instability of the slope.
3. The boundary of the slip circle, indicating the potential failure path that starts at the toe of the slope.

From the figure, various parameters "used to calculate the safety factor" are identified and are provided in detail in Table 8.

Table 8. Slope Geometry Parameters for Embankment Soil

Slice	**Theta (°)**	**H Front**	**H Back**	**B**	**a (B/Cos θ)**
1	2	0.692	0	0.250	0.250
2	5	1.369	0.692	0.250	0.251
3	9	2.029	1.369	0.250	0.253
4	13	2.673	2.029	0.250	0.257
5	20	2.419	2.673	0.704	0.749
6	31	1.994	2.419	0.704	0.821
7	44	1.313	1.994	0.704	0.979
8	60	0	1.313	0.704	1.408

The equation for calculating the safety factor using the Fellenius method is provided in Equation 1.

$$FK = \frac{\Sigma\,(c_i\,.\;a_i + N \tan\theta)}{\Sigma\, W \sin\theta_i} = \frac{\Sigma D}{\Sigma R} = \frac{\Sigma\, T\,.\,R}{\Sigma\, Tr\,.\,R} \qquad \text{(Equation 1)}$$

a. Calculation of Wi
The calculation of Wi in the Fellenius method aims to determine the vertical load exerted on each soil slice in a slope. Therefore, Wi, is used in the calculation of the factor of safety for slope stability to assess whether the slope is safe or not (Emilda, n.d.2021)
b. Calculation of $c_i \cdot a_i$
Cohesion (c) is a shear strength parameter that reflects the ability of soil particles to bond without the presence of normal stress. In the Fellenius method, the cohesive force is determined by the product of soil cohesion (c) and the area of the slice (a) along the slip surface.
c. Calculation of $N \cdot \tan \theta_i$
The calculation of $N \cdot \tan \theta_i$ aims to determine the shear force that the soil must resist along the slip surface (Mila et al., 2019).
d. Calculation of T
In the Fellenius method for slope stability analysis, the calculation $T = W_1 \times \sin \theta_i$ is used to determine the component of the force that drives the slope to slide along the slip surface (Felicia, 2019).
e. Calculation of Tr
Calbulation of Tr is essential for determining the total shear force that resists sliding along the slip surface. Tr includes the contributions from soil cohesion and internal shear strength. Ensuring that Tr is greater than the driving forces allows us to confirm that the slope has sufficient stability to prevent sliding (Emilda, n.d.2021).

The calculation results obtained through the Fellenius method are presented in Table 9. This table also shows the safety factor calculated for the slope under the original, unreinforced fill soil conditions.

Table 9. Results of Safety Factor Calculation Using the Fellenius Method

Slice	**c. a**	**N (W Cos θ)**	**N. Tan θ**	**T (W. Sin θ)**	**Tr (c. a + N tan θ)**	**FK**
1	2.201	14.700	0.513	0.513	2.715	1.239
2	2.208	39.195	3.429	3.429	5.638	
3	2.227	62.628	9.919	9.919	12.147	
4	2.258	84.660	19.545	19.545	21.803	
5	6.592	92.080	33.514	33.514	40.107	
6	7.227	73.519	44.175	44.175	51.401	
7	8.612	47.381	45.756	45.756	54.367	
8	12.389	14.987	25.959	25.959	38.348	
Total				182.810	226.525	

From the table, it is found that the safety factor (SF) is 1.239. This value indicates that the slope is unsafe as it does not meet the minimum acceptable threshold (≥1.5) according to SNI 8460:2017 (see Table 9). As the results demonstrate that the slope is unsafe, reinforcement measures are required. The proposed reinforcements include the use of cantilever retaining walls and geotextile reinforcement.

2. Slope Geometry Analysis of Embankment Soil Reinforced with Cantilever Retaining Walls.

This analysis employs a manual calculation approach to evaluate the reinforcement using cantilever retaining walls. This method is applied to embankment soil conditions supported by cantilever retaining walls. The analysis assesses the stability of the retaining wall design against overturning, sliding, and failure, including calculations of the lateral forces acting on the wall.

a. Calculating the Thickness of the Wall Against Shear Force
Based on the calculations, it can be concluded that the shear force occurring on the wall is considered safe, with a value of 89.85 kN < 167.35 kN, because the ultimate shear force does not exceed the permissible shear force limit.

b. Calculation of Wall Reinforcement Against Bending Moments
Based on the findings, the necessary reinforcement is presumed to exceed the actual reinforcement requirements. Table 10 below provides a summary of the safety factor values for the embankment soil slope with cantilever retaining wall reinforcement.

Table 10. Safety Factor Calculation Results for Cantilever Retaining Wall Reinforcemen

Failure Type	**Safety Factor Value**	**Minimum Value**	**Condition**
Sliding	2.233	≥ 2	Safe
Lateral Shear	1.657	≥ 1.5	Safe
Soil Bearing Capacity	3	≥ 3	Safe

These results underscore that reinforcement using cantilever retaining walls not only meets but significantly exceeds the minimum safety factor thresholds for several critical aspects. The guaranteed stability under various loading conditions, including lateral pressure and bearing capacity, demonstrates that this method is highly reliable for application to embankment slopes with similar characteristics. In practical terms, the implementation of cantilever retaining walls provides an economical and efficient technical solution to prevent slope failures. This efficiency not only supports technical aspects but also mitigates environmental, social, and financial risks associated with potential landslides.

3. Analysis of Manual Calculation for Geometric Slope of Embankment Soil with MSE Geosynthetic Reinforcement

This study applies a manual calculation method to analyze the use of MSE (Mechanically Stabilized Earth) geosynthetics for reinforcing embankment slopes. The purpose of this analysis is to assess the effectiveness of MSE geosynthetic reinforcement in improving slope stability. The calculations follow the guidelines outlined in the Curricula & Syllabi (2017) textbook titled "Principle and Practice of Ground Improvement", which provides a comprehensive framework for soil reinforcement techniques.

The analysis incorporates dimensional parameters derived from slope geometry modeled in AutoCAD to ensure accuracy and consistency with field conditions. These parameters are specified as follows:

R = 4 m (radius of the slip surface),
h soil = 2.8 m (height of the embankment soil),
b slope = 1 m (length of the embankment slope),
LG = 3 m (length of the geotextile),
T_{ult} = 95 kN/m² (ultimate tensile strength of the geotextile).

By examining these parameters, the analysis aims to evaluate the influence of geosynthetic reinforcement on the stability of embankment slopes. The approach highlights the practical applicability of MSE techniques in addressing slope stability challenges, particularly in scenarios involving weak subsoil or high embankments. The findings from this analysis provide critical insights into the use of geosynthetics as a cost-effective and reliable solution for slope stabilization, offering potential adaptations for broader geotechnical applications.

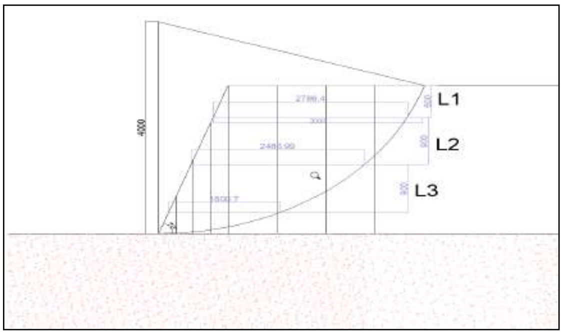

Figure 3. Geometric Layout of Embankment Soil with MSE Geosynthetic Reinforcement.

From the image, several calculation parameters to determine the safety factor are identified, as detailed in Table 11 below.

Table 11. Parameters of Embankment Soil Geometry with MSE Geosynthetic Reinforcement

Layer	Lar	Laf
L1	0.214	2.7864
L2	0.513	2.48699
L3	1.399	1.6007

The formula used in this analysis to obtain the safety factor is explained in Equation

$$FK = \frac{\Sigma\,(c_i\,.\;a_i + N\tan\theta) + \Sigma\,T\,.\,z_i}{\Sigma\,W\sin\theta_i} = \frac{\Sigma R + \Sigma G}{\Sigma D} \quad \text{(Equation 2)}$$

a. Calculation of Geosynthetic Tensile Capacity Reduction

Geosynthetic reduction involves the decrease of properties such as tensile strength, strain, and stiffness of geosynthetic materials, which can affect soil stability and the structure of buildings. It is important to ensure that the geosynthetic can function effectively in the long term without compromising the surrounding environment. For the reduction table, refer to Table 13 on the Geotextile Strength Reduction Factors. The allowed tensile capacity of each geosynthetic layer for the stable section is assumed to have a safety factor (FK) of 1.5.

Table 12. Geosynthetic Strength Reduction Factors

Area	Reduction Factor Value		
	Installation Damage	Long-Term Deformation	Chemical/Biological Degradation
Separation	1.1 – 2.5	1.5 – 2.5	1.0 – 1.5
Cushioning	1.1 – 2.0	1.2 – 1.5	1.0 – 2.0
Unpaved Road	1.1 – 2.0	1.5 – 2.5	1.0 – 1.5
Walls	1.1 – 2.0	2.0 – 4.0	1.0 – 1.5
Embankments	1.1 – 2.0	2.0 – 3.5	1.0 – 1.5
Bearing and foundations	1.1 – 2.0	2.0 – 4.0	1.0 – 1.5
Slope Stabilization	1.1 – 1.5	2.0 – 3.0	1.0 – 1.5
Pavement overlays	1.1 – 1.5	1.0 – 2.0	1.0 – 1.5
Railroad	1.5 – 3.0	1.0 – 1.5	1.5 – 2.0
Flexible forms	1.1 – 1.5	1.5 – 3.0	1.0 – 1.5
Silt fences	1.1 – 1.5	1.5 – 2.5	1.0 – 1.5

(Source : PT. Pandu Equator Prima)

The calculation of the allowable tensile capacity in a stable area is explained using the formula below:

$$Tpo = \frac{2\,\sigma_z'\,L_{ar}\,\alpha_{se}\,C_i \tan\phi\,R_C}{FS_{po}}$$

b. Calculating The Allowable Tensile Capacity Of Each Geosynthetic Layer From The Slip Surface, Assuming A Safety Factor For Tensile Strength Of 1.5.

In this calculation, it is necessary first to determine the weight of the fill above the geosynthetic layer on the active side. The resulting fill weight can then be used as a parameter in calculating the tensile capacity of the geosynthetic layer, using the formulas below (Equations 2 and 3):W-i $= \sigma_z'$ Laf-i

$$Tpo\text{-}i = \frac{2\,W_i\,\alpha_{se}\,C_i \tan\phi\,R_C}{FS_{po}}$$

In calculating the geosynthetic safety factor, it is important to note that the capacity considered is the smallest value among the calculations of Tpo, T'po, and Ta. From the above calculations, these values are obtained and summarized in Table 13, which provides a recap of the Tpo and T'po calculations.

Table 13. Summary of Tpo and T'po Calculations

Layer	Tpo	T'po	Ta
1	0.602	4.526	14.074
2	3.614	23.393	
3	15.771	31.483	

c. Calculation of the total resisting moment provided by the geosynthetic layer is explained using Equation 3.

$$FS = \frac{Mr + Mg}{Md} \qquad \text{(Equation 3)}$$

$$Mg = \Sigma T\ z\text{-}i$$

From the safety factor values, a result of 1.556 ≥ 1.5 is obtained. Thus, it is concluded that the MSE geosynthetic design is safe from failure.

4. Analysis Using Plaxis Application

a. Plaxis Analysis of Slope Geometry of Fill Soil Without Reinforcement

The analysis using the Plaxis program was conducted to model the existing slope conditions of the fill soil before any landslides occurred. In this analysis, the subgrade soil at the site (natural subgrade soil) as well as the fill soil parameters were used, with the fill soil type being CH. The modeled fill height is 2.8 meters with an elevation from 0.00 to +2.80, while the height of the natural soil taken is 4 meters with an elevation from 0.00 to -4.00. The soil parameters used as input are detailed in Table 4.2, which covers Soil Parameters of Fill Soil from 0.00 to +2.80 meters, and Table 4.3, which addresses Soil Parameters of Fill Soil from 0.00 to -4.00 meters.

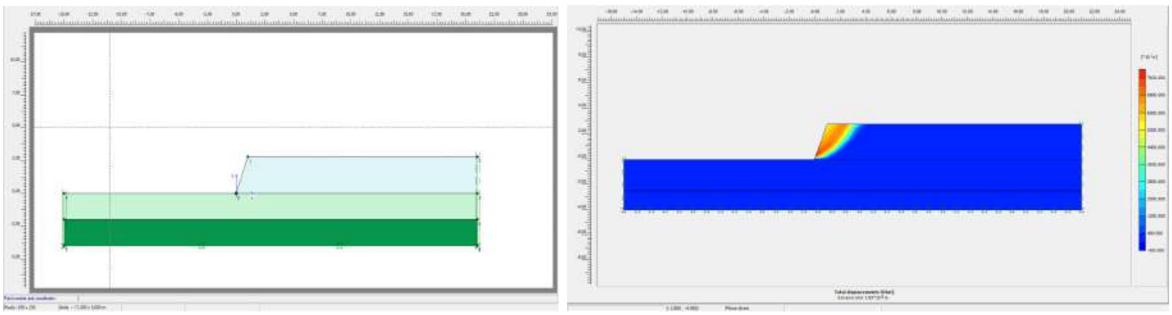

Figure 4. Geometry and Total Displacement of the Fill Soil Slope Without Reinforcement in Plaxis Application.

The output displacement in the Plaxis application is intended to display changes in position or deformation within the analyzed structure or soil. For the unreinforced slope geometry, the displacement results in a toe circle failure with a maximum displacement of 7.95×10^{6} meters. This displacement is depicted in Figure 4. The safety factor (SF) for the slope, as determined by the Plaxis analysis, is 1.2445. This value falls short of the required SF ≥ 1.5, indicating the need for reinforcement to enhance the safety factor to an acceptable level.

b. Analysis Using Plaxis Application: Slope Geometry with Cantilever Retaining Wall Reinforcement

The Plaxis program is used to analyze the slope geometry with cantilever retaining wall reinforcement. The dimensions of the retaining wall for this analysis are based on the parameters outlined in Table 4: Retaining Wall Properties.

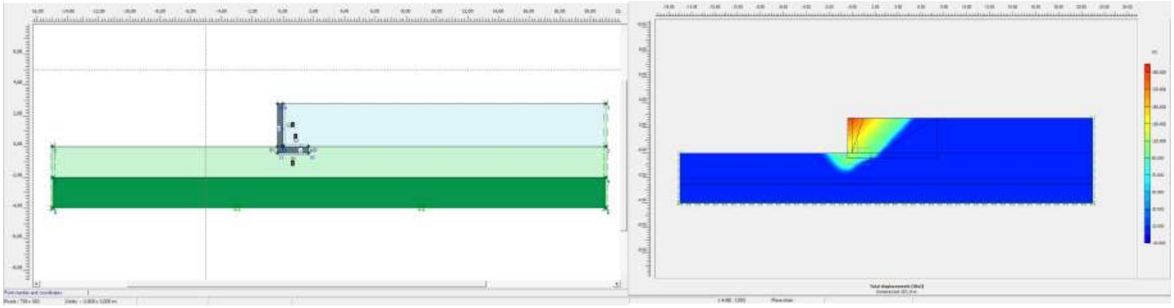

Figure 5. Geometry and Overall Displacement of the Embankment Slope with Cantilever Retaining Wall Reinforcement in the Plaxis Application

In the geometry of the unreinforced slope, the displacement results in a toe circle failure with a maximum displacement of 197.14 meters. This displacement is shown in Figure 5. The global safety factor (SF) for the slope, as determined by the Plaxis analysis, is 1.9753. This safety factor meets the required threshold of SF ≥ 1.5.

c. Analysis of Plaxis Application for Embankment Slope Geometry with MSE Geosynthetic Reinforcement

The analysis using the Plaxis program was conducted to model the geometry of the slope with MSE geosynthetic reinforcement. In this analysis, the dimensions of the embankment slope used are:

h (embankment height) = 2.8 m
b (slope length) = 1 m

For the geotextile parameters, with the reduction results obtained as follows:

$$Ta = \frac{95}{1{,}5 \times 3 \times 1{,}5} = 14.074 \text{ kN/m}$$

The positioning of the MSE geosynthetic reinforcement is applied as shown in Figure 4.4 of the manual MSE geosynthetic calculation analysis.

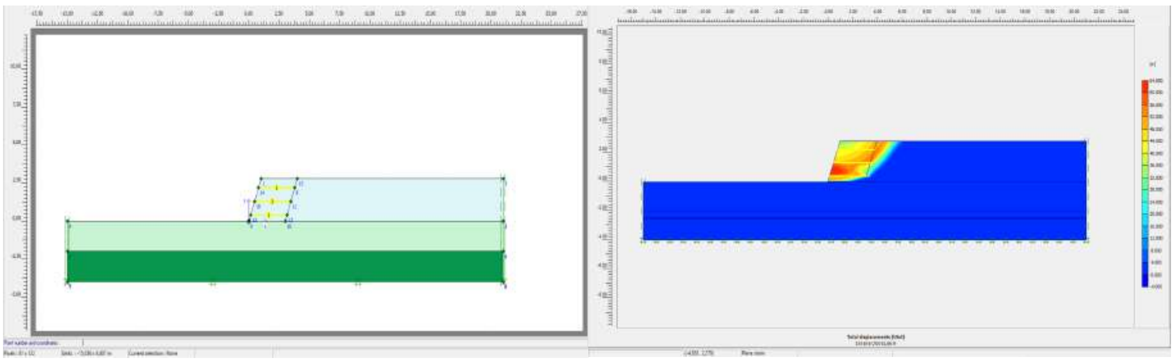

Figure 6. Geometry and Total Displacement of Embankment Slope with MSE Geosynthetic Reinforcement in Plaxis Application.

In this slope geometry without reinforcement, the displacement forms a failure circle with an extreme displacement point of 61.66 m. The displacement output is illustrated in Figure 4.10. The global safety factor (SF) for the slope, obtained from the Plaxis application analysis, is 1.7088. This safety factor meets the required value of SF ≥ 1.5.

Table 14. Summary of Safety Factor Analysis Values

Slope Condition	Failure Type	Manual Analysis		Plaxis Analysis	
		SF Value	Condition	SF Value	Condition
Without Reinforcement	Global	1.239	Unsafe	1.2445	Unsafe
Cantilever Retaining Wall	Sliding	2.233	Safe	-	-
	Lateral Shear	1.657	Safe	-	-
	Bearing Capacity	3	Safe	-	-
	Global	-	-	1.9753	Safe
MSE Geosynthetics	Global	1.556	Safe	1.7088	Safe

Conclusion

Based on the safety factor analysis results obtained through the Fellenius method for slope stability analysis without reinforcement, the safety factor is 1.239, which is further confirmed through the Plaxis analysis with a safety factor of 1.2445. Both methods consistently indicate that the slope without reinforcement is unsafe, as the minimum safety factor required for slope stability is ≥ 1.5, in accordance with SNI 8460:2017. For the slope stability analysis with the addition of cantilever retaining wall reinforcement, the safety factors achieved are 2.233 for overturning failure, 1.657 for sliding failure, 3 for bearing capacity failure, and a global failure safety factor of 1.9753 from the Plaxis analysis. These results demonstrate that the cantilever retaining wall design satisfies all stability criteria and is considered safe. The slope stability analysis with MSE geosynthetic reinforcement yields a safety factor of 1.556, corroborated by the Plaxis analysis with a safety factor of 1.7088. Both analyses indicate that the slope stability with MSE geosynthetic reinforcement is safe, as the safety factors exceed the minimum threshold of ≥ 1.5, as per SNI 8460:2017. The comparison of the two reinforcement techniques reveals critical findings: cantilever retaining walls provide superior stability, especially in scenarios with high-risk slope conditions, while MSE geosynthetic reinforcement is more suitable for applications prioritizing cost-efficiency and environmental considerations.

Novelty and Significance of the Research

The novelty of this research lies in its dual-methodology approach, which integrates numerical modeling using Plaxis and manual stability analysis to evaluate the effectiveness of two different slope reinforcement methods. The study highlights the relative performance of cantilever retaining walls and MSE geosynthetic reinforcements, presenting practical insights for slope stabilization strategies in regions with similar soil and slope conditions. This research provides a significant contribution to geotechnical engineering by offering a detailed analysis of safety factor evaluations under varying reinforcement conditions. The findings emphasize the adaptability of cantilever retaining walls for high-stakes slope stabilization projects while underscoring the environmental and cost advantages of MSE geosynthetic solutions for less critical applications. These insights bridge the gap between theoretical analysis and practical implementation, setting a benchmark for sustainable and effective slope stabilization in construction projects.

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