

Comparative Performance of MSE, Cantilever, and Anchored Walls under Rainfall Infiltration and Seismic Loading: A Case Study

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Construction problems often arise due to low slope stability, which has an impact on high costs and potential damage to buildings. This study analyzes the effectiveness of the application of MSE Wall in handling landslides (case study of Junction Kelimutu STA 8+425 and STA 10+475). MSE Wall is considered to have advantages because it is able to withstand large loads, is flexible to follow the contours of the soil and is resistant to earthquakes. MSE Wall can be reinforced using geogrids and anchors. Anchor reinforcement works in improving the stability of the wall against lateral forces. While cantilever walls are designed to withstand loads with high stability on steep slopes. The slope stability was calculated using the finite element method, the rankine method, and the Bishop method (*Limit Equilibrium Method*). The results of the analysis showed that the application of MSE Wall with a geogrid was able to significantly increase slope stability with a safety factor in STA 10+475 of 1.739 and in STA 8+425 of 1.559 (>1.3). The RAB analysis also confirms that the cheapest, most effective and efficient design is the MSE Wall with geogrid reinforcement, with a total cost of Rp. 1,248,080,571.91 at STA 8+425 and Rp. 3,081,214,127.39 at STA 10+475.

Keywords: Slope failure, MSE Wall, Finite Element analysis, Limit Equilibrium analysis

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Introduction

Slope stability is a crucial aspect in construction projects, especially in areas with steep topography and less dense soil (Li et al., 2013). Slope failures typically occur when the shear force on the slope exceeds the shear strength of the soil, leading to collapse. These failures are often triggered by soil movement in steep conditions, high humidity, sparse vegetation, and poorly compacted materials. The stability of slopes is strongly influenced by factors such as slope geometry, material strength, groundwater table position, and local drainage conditions.

Slope collapses are common, as observed in the cases of STA 8+425 and STA 10+475 in Kelimutu, Ende, East Nusa Tenggara. In these locations, steep slopes, high rainfall, and loose soil contributed to significant landslides (Kae et al., 2024).

MSE walls are an effective solution for stabilizing slopes. These retaining walls use a combination of geotextile or geogrid materials with fill soil to create a stable structure (Miyata, 2024). The MSE system is known for its ability to withstand heavy loads and adapt to varying soil contours (Liu et al., 2022). However, cost

remains a major consideration when selecting reinforcement methods (Robson et al., 2024).

Robson et al. (2024) emphasize the importance of considering the risks of slope failure, which can result in significant costs related to rehabilitation, road closures, and loss of time and resources. Therefore, a thorough analysis of the most suitable reinforcement design, including a comparison of the available methods, is essential, factoring in both technical and non-technical considerations such as cost, rehabilitation, and transportation access during repairs.

Method

Research Object and Location

This research is based on case studies of landslides at STA 8+425 and STA 10+475 in Kelimutu, Ende, East Nusa Tenggara. According to Sasarari et al. (2024b) and Sasarari et al. (2024a), these landslides were caused by infiltration, and the soil exhibited behavior similar to sandy soils. The case study location is shown on the map in Figure 1, while the slope failure conditions at STA 8+425 and STA 10+475 are depicted in Figures 2 and 3.

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Figure 1 Research Location (Source: Sasarari *et al.*, 2024a)



Figure 2 Slope Failure Conditions on STA 8+425 (Source: Sasarari *et al.*, 2024a)



Figure 3 Slope Failure Conditions on STA 10+475 (Source: Sasarari *et al.*, 2024a)

Study Procedure

The design of the landslide solution follows the guidelines of SNI 8460:2017. The analysis includes four types of failure, as shown in Figure 4, which illustrates the different types of soil retaining wall failures: (a) overtuning, (b) sliding, (c) bearing capacity, and (d) overall stability (Das, 2011).

This research compares three types of slope reinforcement: MSE wall, cantilever wall, and anchored wall. Geotechnical analysis was conducted in

accordance with the SNI 8460:2017 standard, utilizing both the limit equilibrium method (Bishop and Rankine) and the finite element method (FEM). The MSE wall design follows the procedure outlined in FHWA-NHI-10-024 (2009). The study procedure, including the overall approach, is outlined in Figure 5.

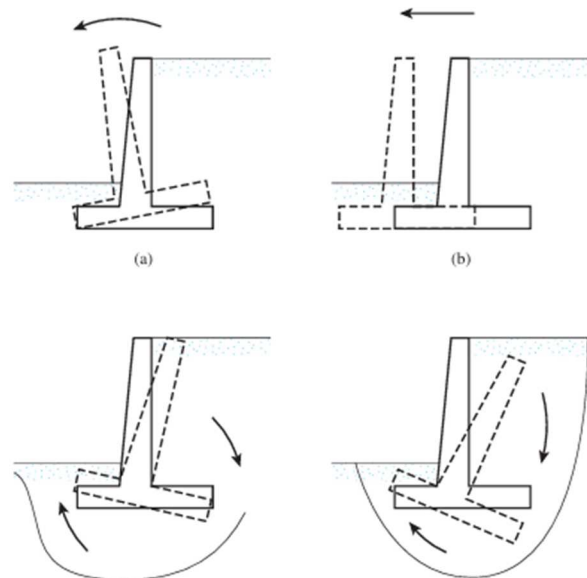


Figure 4 Types - Types of Soil Retaining Wall Failure (a) Overtuning; (b) Sliding; (c) Bearing Capacity; and (d) Overall Stability (Das, 2011)

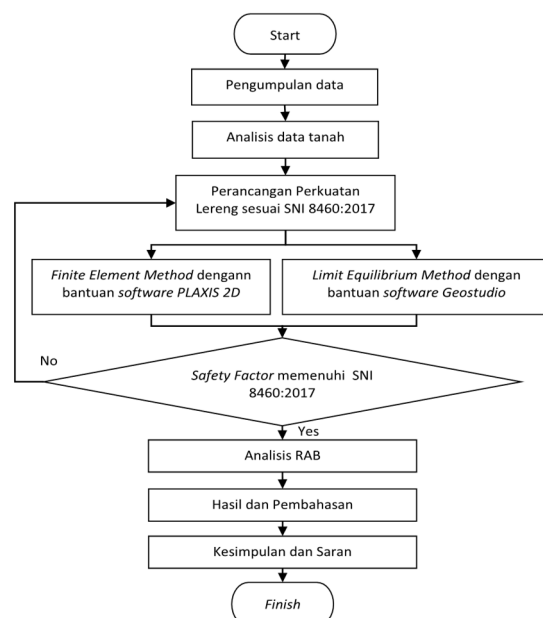


Figure 5 Study Procedure

The finite element method analysis was performed using PLAXIS 2D, which includes plastic analysis for deformation under static load, safety analysis to determine the overall stability safety factor, and fully coupled flow-deformation analysis to simulate changes in water levels due to rainfall. Additionally, Geostudio was used for SLOPE/W analysis (static slope analysis),

SEEP/W for rainwater infiltration analysis, and QUAKE/W for seismic load analysis.

Soil Data Analysis

Soil data analysis refers to the use of models in FEM and LEM so in this analysis the correlation of data is used to meet the soil parameters required in the model. The constructive modeling of the soil in this case uses the Mohr coulumb model approach.

The soil condition at both landslide locations has a clay soil type about 5 m below the ground level and tends to be predominantly sandy, this condition allows showing coherent data in accordance with the research of Sasarari et al., (2024b) and Sasarari et al., (2024a) where landslides occur due to rainwater infiltration.

The results of data analysis showed that in STA 8+425 and 10+475 it was dominant clay soil at a depth interval below 5 so that when *cracked soil* occurred, clay soil would be like sand (*behaving like sand*). This results in the loss of a large part of the shear strength of the clay soil. Incomplete soil parameters are obtained through the geotechnical parameter correlation approach. A recap of the soil parameters used as the calculation inputs is seen in Table 1 and Table 2.

Table 1 Soil Parameters STA 8+425

Layer	γ (kPa)	c (kPa)	ϕ
1	16	5.19	30
2	18	0	35
3	18	0	36
4	18	0	37

Table 2 Soil Parameters STA 10+475

Layer	γ (kPa)	c (kPa)	ϕ
1	16.00	4.44	28.00
2	17.00	0.00	30.00
3	16.00	7.17	30.00
4	16.00	7.17	30.00
5	18.00	0.00	38.00
6	18.00	0.00	30.00
7	18.00	0.00	30.00
8	18.00	0.00	30.00

In addition to soil parameter analysis, it is necessary to carry out rain frequency analysis to obtain the intensity of rainfall. This is based on the statements of Sasarari et al.,(2024b) and Sasarari et al.,(2024a) who stated that this landslide is a direct contribution from the load of rain. So a thorough analysis including the rainfall load is required. Rainfall data was obtained from the East Nusa Tenggara climatology station with data for the last 8 years. Rainfall analysis was carried out using the Peak Over Threshold method and rain frequency analysis was carried out using the Mononobe Rational method. Rain data and the results of rain frequency analysis can be seen in Table 3 and Table 4.

Table 3 Maximum Rainfall Data (source: BMKG Online)

Year	Rainfall
2014	156.10
2015	261.30
2016	232.10
2017	195.10
2018	371.10
2019	245.50
2020	265.00
2021	401.70
2022	399.20

Table 4 Results of Rain Frequency Analysis

Repeat Time (tahun)	Rain Plan (R) (mm)	Rain Intensity (I) (mm/jam)
0.22	112.68	110.5
1.44	218.21	214.0
4.48	297.76	292.0
9.49	349.20	342.5
19.5	383.63	376.2
25	383.63	376.2
24.5	426.99	418.7
99.5	459.39	450.5
999.5	560.27	549.5

Seismic analysis in this case used a pseudostatic earthquake approach with earthquake data according to the earthquake map of the "Desain Spektra Indonesia" web site at the landslide site.

Geotechnical Analysis

The results of the geotechnical design show that the MSE wall reinforcement with geogrid reinforcement is designed using the Unggultex U80 product. This is based on an analysis of the spacing, length, and price of geogrid material procurement which is considered to be the most efficient as seen in Table 5 and Table 6. The design image of the MSE wall on STA 8+425 can be seen in Figure 5 and STA 10+475 on Figure 6

Table 5 Calculation of *Spacing* and minimum length of *Geogrid* reinforcement on STA 8+425

T_{ult} (kPa)	<i>Spacing</i> (m)	Panjang (m)	Harga pengadaan
25	0.30	2.5	Rp 1,225,000,000.00
50	0.70	2.5	Rp 731,250,000.00
80	1.10	2.5	Rp 632,386,364.00
100	1.40	2.5	Rp 740,625,000.00
200	2.90	2.5	Rp 552,698,276.00

Table 6 Calculation of *Spacing* and minimum length of *Geogrid* reinforcement on STA 10 +475

T_{ult} (kPa)	Spacing (m)	Minimum length (m)	Cost
25	0.50	3.92	Rp 2,151,296,000.00
50	1.00	3.92	Rp 1,498,224,000.00
80	1.70	3.92	Rp 1,197,675,295.00
100	2.10	3.92	Rp 1,445,173,334.00
200	4.30	4	Rp 1,113,280,000.00

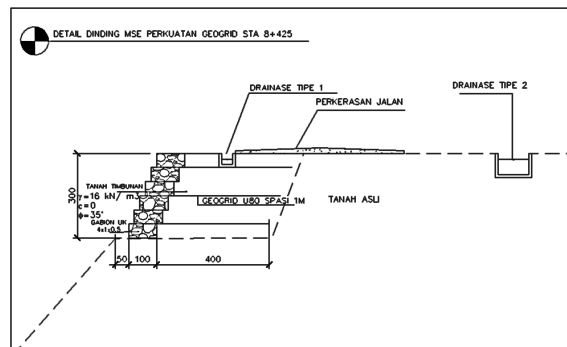


Figure 5 MSE Wall STA 8+425 Design

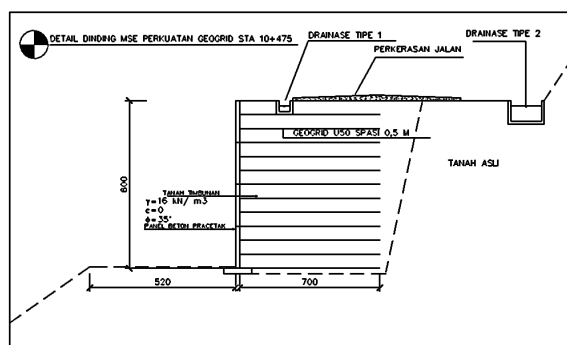


Figure 6 MSE Wall STA 10+475 Design

The design on STA 8+425 uses Gabion according to SNI 03-0090-1999 specifications. Meanwhile, the design on STA 10+475 uses concrete panels according to SNI 8460:2017 specifications. The details of the Gabion and Concrete Panels can be seen in **Error! Reference source not found..** A recap of the results of safety factors can be seen in Table 7.

In addition, it is also proposed that the reinforcement design apart from the reinforcement of the MSE Wall can be planned a conventional ground retaining wall with a cantilever wall type. The initial design of the cantilever wall can be planned according to SNI 8460:2017. The design of the cantilever wall can be seen in Figure 7 and Figure 8.

Anchored wall using anchor freyssi 500. In accordance with SNI 8460-2017, it is known that the free length and bond length are at least 3 m each, so that the free length for the STA 10+475 design can be

taken as 5 m and the bond length is 3 m. As for STA 8+425, a free length of 4 m and a bond length of 3 m can be used (see Figure 9 and Figure 10). The MSE wall design was carried out with PLAXIS 2D (Figure 12 to Figure 14) and Geostudio (Figure 15 to Figure 16).

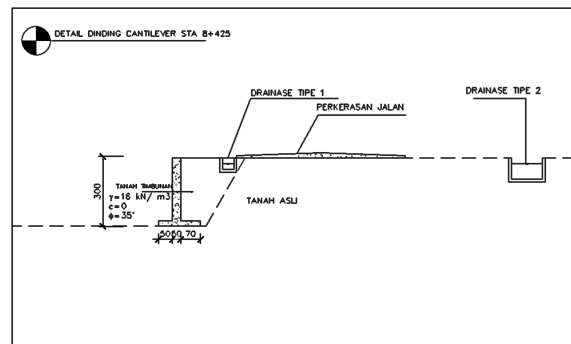


Figure 7 Cantilever Wall Design STA 8+425

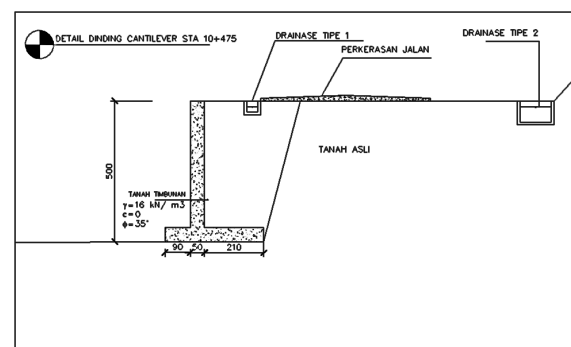


Figure 8 Design of Cantilever Wall STA 10+475

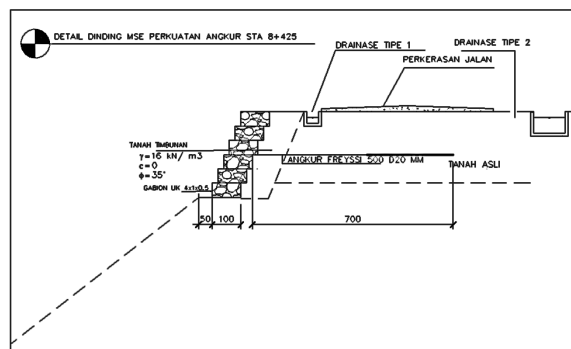


Figure 9 STA 8+425 Anchored Wall Design

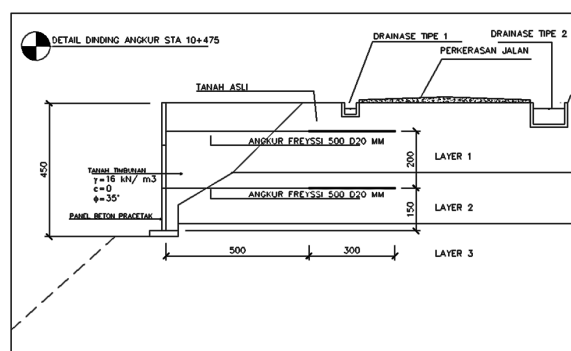


Figure 10 STA 10+475 Anchored Wall Design

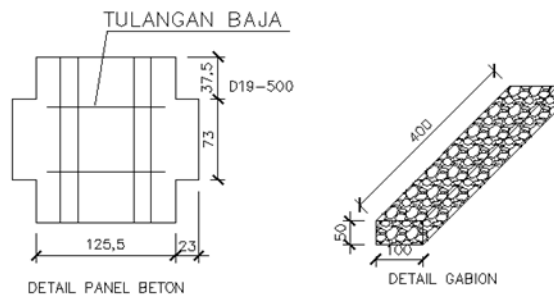


Figure 11 STA 10+475 Anchored Wall Design

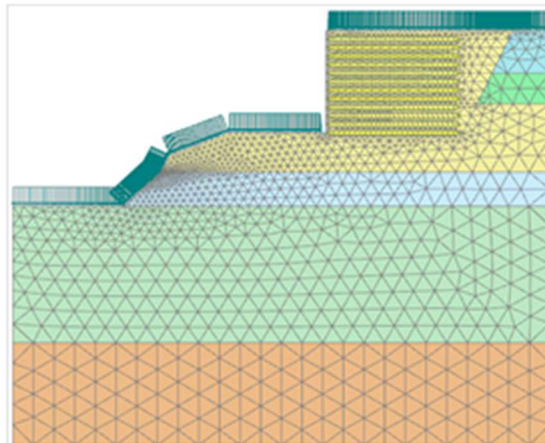


Figure 12 MSE Wall Analysis Results with Finite Element Method (FEM) STA 10+475 (Rainfall Loading)

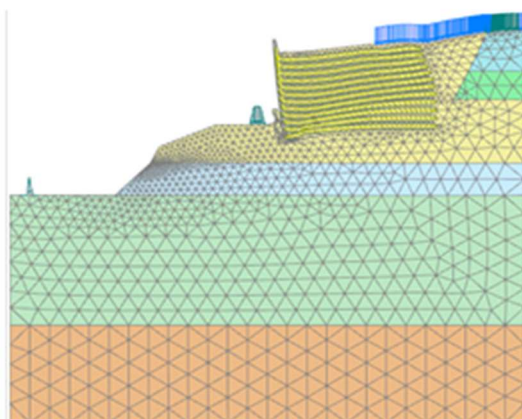


Figure 13 MSE Wall Analysis Results with Finite Element Method (FEM) STA 10+475 (Soil Deformed Mesh)

Table 7 Safety factor MSE Wall Results

Analysis Type	STA 10 +475	STA 8+425
<i>Overtuning</i>	7,04	11,07
<i>Sliding</i>	1,68	2,28
<i>Bearing Capacity</i>	3,05	6,55
<i>Overall Stability (FEM)</i>	1,90	1,68
<i>Overall Stability (LEM)</i>	2,13	1,51

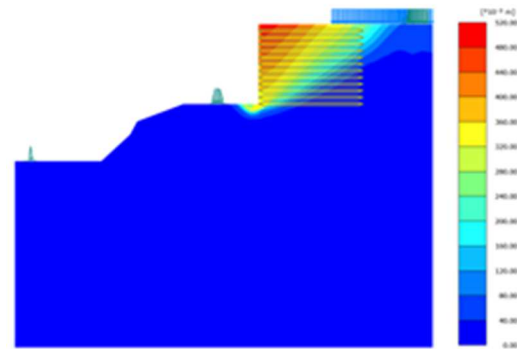


Figure 14 MSE Wall Analysis Results with Finite Element Method (FEM) STA 10+475 (Total Soil Displacement)

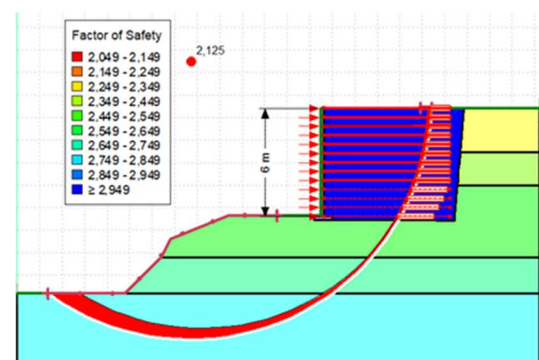


Figure 15 Results of Limit Equilibrium Method Analysis under Static Load

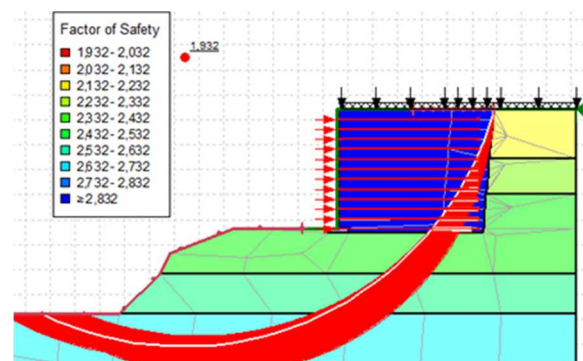


Figure 16 Results of Limit Equilibrium Method Analysis under Seismic Load

MSE wall analysis showed a significant increase in safety factors both in internal stability (Overtuning, sliding and bearing capacity) and external stability (Overall stability). In addition, looking at the results of the analysis, MSE wall is considered suitable for application on high slopes.

Results of the analysis from FEM and LEM show different results due to differences in calculation principles and differences in slip circles (See Figure 19 and Figure 20). A recap of the Safety factor analysis can be seen in Table 8.

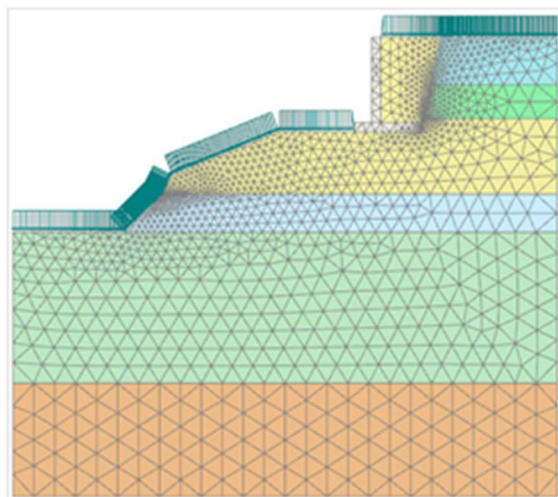


Figure 17 Results of *Cantilever Wall* Analysis with *Finite Element Method (FEM)* STA 10+475 (*Rainfall Loading*)

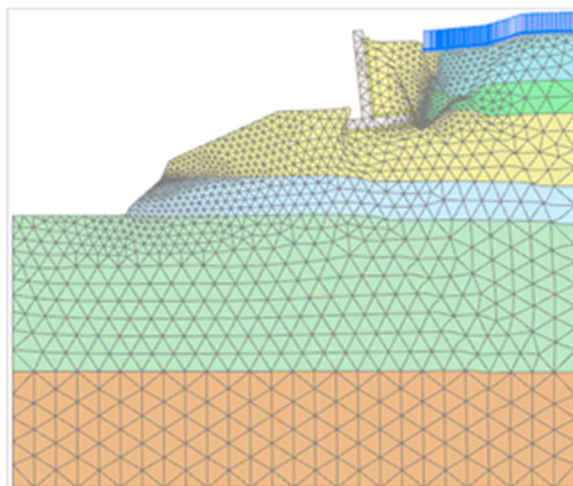


Figure 18 Results of *Cantilever Wall* Analysis with *Finite Element Method (FEM)* STA 10+475 (*Soil Deformed Mesh*)

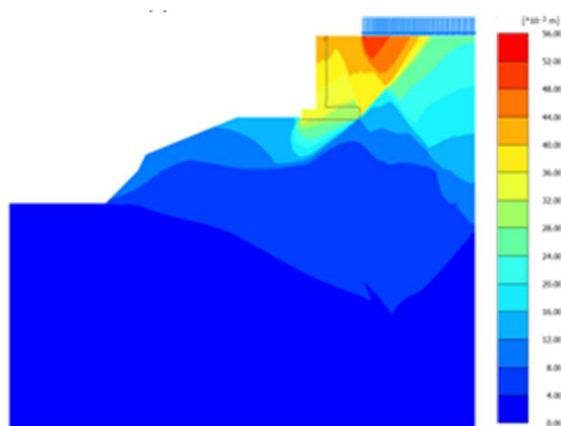


Figure 19 Results of *Cantilever Wall* Analysis with *Finite Element Method (FEM)* STA 10+475 (*Total Soil Displacement*)

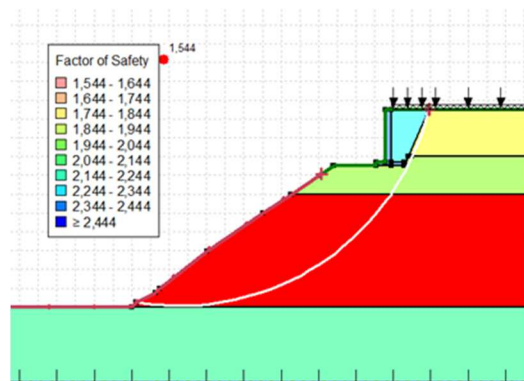


Figure 20 Analysis of *Cantilever Wall* with *LEM*

Table 8 Safety factor *Cantilever Wall* Results

Analisis	STA 10+475	STA 8+425
<i>Overtuning</i>	5,95	1,88
<i>Sliding</i>	7,26	1,45
<i>Bearing Capacity</i>	11,32	6,25
<i>Overall Stability (FEM)</i>	1,50	1,24
<i>Overall Stability (LEM)</i>	1,50	1,54

The repetition is designed in accordance with SNI 2847:2019. *Cantilever walls* are designed like cantilever beams with ground pressure loads. The design results can be seen in Figure 21.

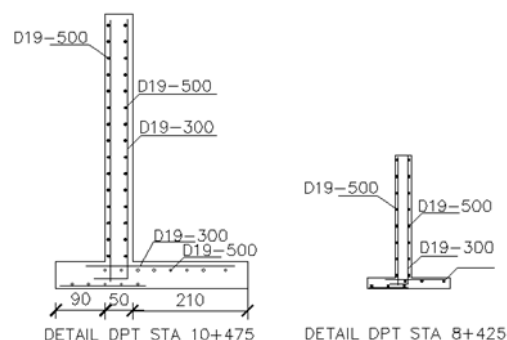


Figure 21 *Cantilever Wall* Rebar Design

Another reinforcement design that is designed is the *anchored wall* reinforcement design. The anchor used is a Freyssi 500 D20 product with a horizontal anchor configuration. The LEM analysis shows the *safety factor* as shown in Figure 22.

Anchor analysis showed that all failures under static load met the requirements of SNI 8460:2017. The design of slope reinforcement to overcome the problem of previous landslides, is designed to meet the problem of rain, so that for all reinforcement designs, analysis under rain load and also seismic load is carried out. The recap of the analysis results under rain and seismic load can be seen in Table 10. In addition, for all designs drainage is added as seen in Figure 5 to Figure 10

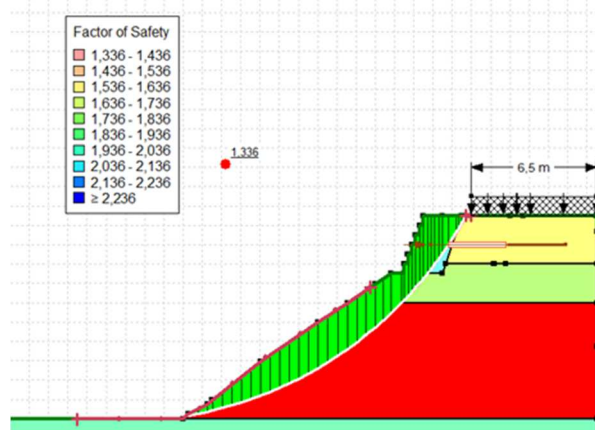


Figure 22 Anchored Wall STA 8+425 Analysis Results

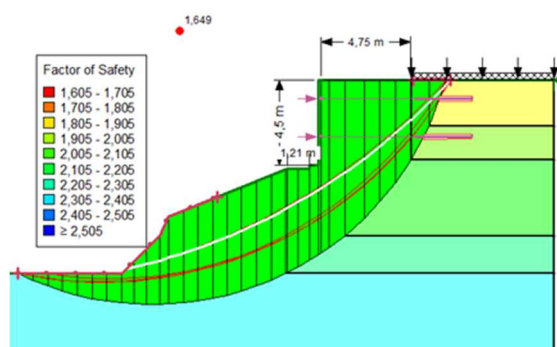


Figure 23 Anchored Wall STA 10+475 Analysis Results

Table 9 Results Safety factor Anchored Wall

Analisis	STA 10 +475	STA 8+425
Overtuning	9,01	37,72
Sliding	1,90	3,77
Bearing Capacity	3,09	6,55
Overall Stability (Normal)	1,50	1,54

Table 10 Results Safety Factors under Rain and Seismic Load

Desain	Beban Hujan	Beban Seismik
MSE Wall STA 8+425	1,56	1,33
MSE Wall STA 10+475	1,739	1,93
Cantilever Wall STA 8+425	1,18	1,34
Cantilever Wall STA 10+475	1,38	1,62
Anchored Wall STA 8+425	1,54	1,31
Anchored Wall STA 10+475	1,42	1,67

The results analysis shown the design of the cantilever wall STA 8 + 425 under rain load, a safety factor of < 1.3 was obtained. This shows the need for a subdrain to improve the safety factor of the design, so that in the design of the subdrain to drain rainwater, the details of the subdrain are seen in Figure 24.

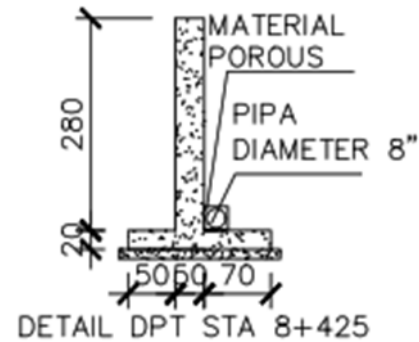


Figure 24 Details of Cantilever Wall STA 8+425 with subdrain

Cost Estimation

The budget planning for the cost of strengthening slope alternatives in this study was prepared based on the Highway Specification and the Minister of Public Works and Public Works Regulation No. 8 of 2023 related to the Analysis of Work Unit Prices (AHSP), especially the Highway AHSP. The price of materials used in this study is based on the NTT Provincial Unit Price Standard 2024 and the E-catalog. Meanwhile, the unit price of wages uses the NTT Provincial Minimum Wage (UMP) approach due to the lack of information about wage standards at the handling location. The total estimated price can be seen in Table 11.

Table 11 Cost of Soil Reinforcement Work by Design

Reinforce	STA 10+475	STA 8+425
MSE wall	3,081,214,127.39	1,248,080,571.91
Cantilever Wall	3,128,565,869.33	1,731,578,004.86
Anchored Wall	4,749,418,665.00	2,414,625,755.59

From the cost analysis, it can be seen for each STA that MSE wall has advantages, where the MSE Wall design gets the lowest cost result. This shows that MSE walls can be a more economical solution in handling landslides.

Non-technical considerations such as road closure on slope reinforcement also need to be considered from the design results can be seen in Figure 5 and Figure 6 that the design of the MSE wall requires total road closure during the construction process, in contrast to the cantilever wall (Figure 7 and Figure 8) which still allows the opening of 1 road lane or anchored wall which does not require any road closures at all (Figure 9 and Figure 10). So that in some cases the MSE wall is less efficient due to non-technical factors.

Discussion

In the study of Mechanically Stabilized Earth (MSE) walls, a comparison between three types of slope reinforcement systems—MSE walls, cantilever walls, and anchored walls—reveals that MSE walls offer distinct advantages in terms of both performance and

economic feasibility under varying conditions. The performance of MSE walls is significantly influenced by factors such as reinforcement type, soil type, and geotechnical properties.

MSE Wall Performance in Rainfall Infiltration Conditions

Rainfall infiltration plays a crucial role in slope instability, particularly when dealing with soft or loose soils that are prone to failure under wet conditions. The primary mechanism by which rainfall infiltration destabilizes slopes is through the reduction of matric suction, which decreases the shear strength of the soil (Rahardjo & Satyanaga, 2019). This behavior is consistent with the findings in MSE wall systems, where the flexibility of the geosynthetic reinforcement allows for effective adaptation to changing water levels, reducing deformation under moist conditions (Gofar & Hanafiah, 2018).

Research has shown that MSE walls exhibit enhanced performance in maintaining internal stability despite rainwater infiltration, compared to more rigid systems such as cantilever or anchored walls, which are more susceptible to displacement and slippage under similar conditions (Damians et al., 2023; Yünkül & Gürbüz, 2023). The geosynthetic reinforcements used in MSE walls contribute significantly to their ability to resist shear failure and provide sufficient resistance even in wet conditions (Bathurst et al., 2023).

The drainage properties of MSE walls, particularly when designed with proper geogrid reinforcements, further reduce the risk of excessive water buildup in the soil behind the wall. This allows for the prevention of increased pore water pressure that can destabilize slopes (Ambriz et al., 2020). The inclusion of such reinforcements helps mitigate the impacts of rainfall infiltration, maintaining wall stability and preventing failure due to soil erosion or saturation.

Seismic Response of MSE Walls

Under seismic loading, MSE walls outperform traditional retaining systems, including cantilever and anchored walls, primarily due to their flexibility and energy dissipation capacity. The geosynthetic reinforcement in MSE walls allows for better distribution of seismic forces, enabling the wall to absorb and redistribute the energy exerted by seismic motion without catastrophic failure (Yünkül & Gürbüz, 2023). In contrast, more rigid systems like cantilever walls tend to exhibit higher displacement under seismic loads, which can lead to significant damage or failure in high seismic zones (Srivastava & Chauhan, 2020).

Finite element modelling (FEM) has highlighted that MSE walls show considerable resistance to both horizontal and vertical displacements during seismic events, especially when using high-stiffness geogrids (Targhi et al., 2025). Plate anchors integrated into these systems can further enhance the seismic resistance, reducing the likelihood of structural failure (Targhi et al., 2025).

Economic Considerations and Design Optimization

From an economic standpoint, MSE walls are particularly beneficial because they require less material than traditional retaining walls, such as cantilever and anchored walls. The simplified stiffness method used in MSE wall design optimizes reinforcement usage, reducing costs without compromising safety (Bathurst et al., 2019). Additionally, MSE walls' low maintenance requirements and adaptability to different soil conditions make them an attractive option for long-term infrastructure solutions, particularly in regions susceptible to both rainfall infiltration and seismic activity.

Conclusion

Based on the research conducted, the comparative performance of MSE walls, cantilever walls, and anchored walls under conditions of rainfall infiltration and seismic loading shows significant results. The MSE wall, utilizing geotextile or geogrid materials, proves to be an effective solution in maintaining slope stability, especially when subjected to excessive water infiltration. The advantage of MSE walls lies in their ability to withstand large loads and adapt to irregular soil contours, making them a more efficient choice for slopes with varying soil conditions.

On the other hand, cantilever walls perform well under static conditions but face limitations when dealing with changes in groundwater levels due to rainfall infiltration. In slopes with steep gradients and weaker soil conditions, cantilever walls require additional attention to drainage design to prevent structural failure. Anchored walls demonstrate high stability, particularly under seismic conditions, with significant resistance to soil displacement. However, cost and the need for access during construction are important considerations in their selection.

Overall, the analysis results indicate that the choice of reinforcement method should consider a combination of technical factors, such as structural stability, and non-technical factors, such as cost and accessibility during construction. The MSE wall proves to be a more economical and effective solution for slopes exposed to rainfall infiltration, while the anchored wall is more suitable for conditions requiring higher resistance to seismic loads. Cantilever walls may be considered for simpler applications or when cost is the primary concern.

The recommendation for the application of slope reinforcement is to conduct a thorough analysis of local conditions, including soil characteristics, slope profiles, and seismic risk, to select the most appropriate and efficient design to prevent future slope failures.

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