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Analysis of Soil Replacement and Woven Geotextile Reinforcement on Embankment Stability

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Abstract

Toll roads are infrastructure built to improve the regional and national economy. The challenge faced on this toll road is soft soil as deep as 7 m. This research analyzes the stability of the embankment with a slope of 1V:2H and a height of 4.5 m without and with repair using the Limit Equilibrium Method (LEM) because the Safety Factor (SF) value in LEM provides a more critical value than the Finite Element Method (FEM). In addition, the settlement amount was also analyzed. The SF value in short term conditions with an embankment load of 1.31 < 1.4 and earthquake load of 0.83 < 1.1. Then, at pavement installation, 1.33 < 1.4, plus earthquake load 0.84 < 1.1. In long term conditions, during the operational period, 1.48 < 1.5, plus earthquake load 0.84 < 1.1. This indicates that the soil requires improvement. To address the problem, soil improvement utilized 2.5 m deep soil replacement and 75 kN woven geotextile. The SF value with repair under short term conditions, with embankment load 1.53 > 1.4, plus earthquake load 1.18 > 1.1. Then, at the time of pavement installation, 1.56 > 1.5, plus earthquake load 1.19 > 1.1. In the long term condition, it was 1.62 > 1.5 at the time of operation, plus earthquake load 1.22 > 1.1. The total settlement after the operation is 0.21 cm ≤ 10 cm and the settlement rate is 0.68 < 2 cm/year. This shows that improvements can increase the SF value and reduce settlement.

Keywords: Safety Factor, Settlement, Soft Soil, Soil Replacement, Woven Geotextile.

1. Introduction

The road is an access that can connect one area to another. The most crucial goal of toll road infrastructure development is to increase economic growth. The Subang Toll Road is one of the strategic projects that will facilitate access to the port and improve the economy of the people who impact Indonesia. This toll road connects the Cikopo - Palimanan Toll Road and the Port of Subang, which is planned to be 37.7 km long. Therefore, it is necessary to consider aspects of the geotechnical field that support this toll road project.

Planning for road construction often faces obstacles, and one of the problems that usually arises is soft soil. In Indonesia, soft soils are common. Construction built on soft soils will cause several geotechnical problems, one of which is a consolidation settlement that lasts for a long time due to the low permeability of soft soils [1]. Soft soil characteristics of low strength and high compressibility cause bearing capacity and settlement problems [2]. Therefore, with gradual embankment, the consolidation process is expected to optimize the stability of the embankment so that the construction of this toll road can run effectively and efficiently [3].

Soft soil treatment typically uses Prefabricated Vertical Drain (PVD) in combination with preloading using backfill soil. In addition, vertical drainage can be effective on soils with less

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compressible layers. Alternatively, soil improvement using soil replacement has been commonly used for less-thick, soft soil conditions, as it increases the bearing capacity of the soil and reduces the thickness of the compressible soil layer [4].

Previous research on this toll road construction site was conducted by Hamonangan & Syahputra [3]. The stability analysis of the embankment in the study used the Finite Element Method (FEM) with Plaxis software. The Safety Factor (SF) value from the Limit Equilibrium Method (LEM) showed a smaller/more critical value compared to the SF value generated by FEM-MCA [5]. Geotechnical analysis needs to use methods that yield more critical SF values. The analysis is based on the premise that if the critical SF value from the LEM meets the criteria, then the SF value from the FEM, which is greater than that of the LEM, will also meet the criteria.

This research will analyze 7 m deep soft soil with a 602 m long toll road 1V:2H embankment slope and 4.5 m embankment height. The analysis is carried out on embankment stability and subgrade settlement, both without and with soil improvement, namely soil replacement 2.5 m deep and the use of woven geotextiles, under short term conditions with embankment load and pavement load, and long term conditions with traffic load and earthquake load, using the LEM method.

2. Research Methods

The research begins with collecting data, and then analyzing the stability and settlement of the embankment by visualizing the subgrade and embankment using LEM. LEM is based on static force and moment equilibrium [6]. In analyzing the LEM using Geo5 software. Geo5 is designed to solve most common geotechnical tasks, as well as highly sophisticated problems, such as tunnel analysis, damage on buildings due to tunneling, stability of rock slopes, etc. [7]. The Geo5 software program was used to analyze minimum SF and determine the critical slip surface by applying different soil strength and slope geometry parameters [8]. Several soil parameters must be input into the program, such as unit weight (γ), saturated unit weight (γ_{sat}), undrained shear strength, cohesion value, effective shear angle, poisson ratio, E_{ref} value, and permeability value.

2.1 Data Collection

The data collected included borlog data, laboratory data, traffic load, pavement data, and earthquake load data.

2.1.1 Borlog Data

This research is along the toll road around the Purwadadi area, Subang. The borlog data used is located at borlog point DD-03 and selected at that point because the first drilling N-SPT is worth 2, which is critical compared to other borlog points.

2.1.2 Laboratory Data

The laboratory data used in this study are parameters unit weight (γ), saturated unit weight (γ_{sat}), specific gravity (Gs), cohesion, and effective shear angle ($\emptyset$).

2.1.3 Traffic Load and Pavement Data

According to the Regulation of the Minister of PUPR (Public Works and Housing) Number 05/PRT/M/201. The road class is determined by function and intensity [4]. The road class at the research location was determined as class I. The road class at the study site is class I. Therefore, the traffic load acting on the road is 15 kN/m^2. Furthermore, in determining the weight of the contents for the calculation of the pavement load, it refers to [9], and the result of the calculation of the pavement load is equal to 11.82 kN/m^2.

2.1.4 Earthquake Load Data

Based on SNI standards, the impact of earthquakes on embankments can be analyzed using a limit equilibrium approach, which represents earthquake forces through a pseudo-static model. The seismic coefficient used in this analysis follows the surface acceleration (PSA) by considering the minimum safety against earthquakes. Furthermore, the horizontal seismic vibration coefficient (kh) is set at 0.5

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PSA. Information on earthquake acceleration was obtained from the Indonesian [10], [11] using an earthquake return period of 500 years.

The earthquake load analysis on the embankment was calculated using the equation [11]. The earthquake load analysis on the embankment at this research location with the peak ground acceleration value is based on 0.15 g, where the soil [11] is classified as soft soil (SE).

The following calculation of peak surface acceleration is adjusted to the location classification using equation 1, namely:

$$PSA = 2.15x0.15 = 0.32\ g \quad (1)$$

$$Kh \ = 0.5x0.32 \ = 0.16\ g \quad (2)$$

2.1.5 Geotextile Data

Geotextiles are sheets made from polymer textiles, have water passability, and can be non-woven or woven. These are used to reinforce soil so that the soil has a safe bearing capacity. Geotextiles are used widely for soil reinforcement in different situations slopes and river banks, roads and infrastructure, etc. For such applications, properties such as tensile strength, surface friction, compression strength, pull-out strength, and creep are most relevant as they grant the selected materials a long term service life [12]. However, this research uses 75 kN Woven Geotextile. The value inputted into the Geo5 software is the allowable tensile strength (T_{all}) or long term design strength of reinforcement (R_t). The The following is the calculation of allowable tensile strength referring to [13].

$$T_{ult} = 200\ kN/m^2$$
$$RF_{ID} = 1.10$$
$$RF_{CR} = 2.10$$
$$RF_{CBD} = 1.10$$
$$T_{all} = 200\left(\frac{1}{1.10x2.10x1.10}\right) = 200\left(\frac{1}{2.441}\right) = 75.00\ kN/m^2$$

2.1.6 Research Location

This research was conducted at the DD-03 borlog point at Latitude -6.385670 and Longitude 107.705381 in Pasirbungur Village, Purwadadi District, Subang. The following Figure 1 presents the research location.

Figure 1. Research Location

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2.2 Research Procedure

The following Figure 2 presents the research procedure used to analyze embankment stability and settlement. The procedure involves several steps, beginning with the collection of geotechnical field data, including boring log data, laboratory data, loading data, and geotextile data. These data are then processed and interpreted to calculate soil parameters, followed by the modeling of the embankment and subgrade using the Geo5 program. The analysis includes both short term and long term stability assessments. The procedure continues with an evaluation of the embankment's safety factor (SF). If the stability safety factor without soil improvement is ≥ 1.5 according to SNI 8460:2017 and the settlement meets the criteria outlined in Geotechnical Guide 4 Design and Construction, then soil improvement is not necessary. However, if these criteria are not met, soil improvement is required. Based on SNI 8460:2017 and Geotechnical Guide 4 Design and Construction for embankments, the recommended soil improvements at the research location include soil replacement and geotextile reinforcement. This research analyzes the necessary soil improvements at this location to ensure compliance with the stability and settlement criteria outlined in SNI 8460:2017 and Road Pavement Design Manual.

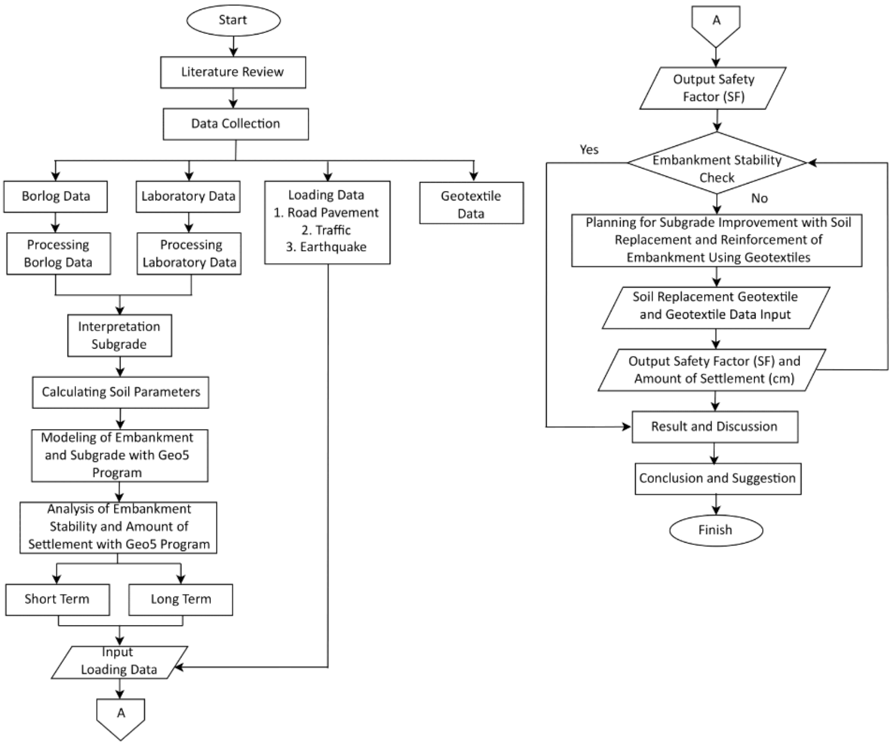

Figure 2. Research Flowchart

2.3 Analysis

The slope stability analysis is performed with the limit equilibrium methods based on assumptions regarding the shape of the sliding surface [14]. This slope stability is the most important stage in the stabilization process for slopes of different scales, and it is determined by the SF [15]. Slope stability depends on two types of forces interacting in the sliding plane. Restraining forces prevent landslides from occurring while driving forces cause landslides to occur [16].

Settlement occurs in saturated soils and unsaturated soils. The settlement in saturated soil assumes that soil particles and pore water are incompressible, the volume change must be due to the change in void as water flows out of (or into) the soil. Therefore, the volumetric variation is zero at the start of loading. However, in unsaturated soils, immediate settlement is manifested at the initial moment before the consolidation mechanism [17].

The criteria for settlement are fulfilled by the settlement of consolidation (degree of consolidation (U) > 90%) during construction, the settlement of < 10 cm during the operational period, and the settlement rate during the operational < 2 cm/year [18]. Tabel 1 presents the criteria for analyzing embankment stability and soil settlement.

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Table 1. Embankment Stability and Settlement Analysis Criteria

Stability			
Parameter	Load type	Term	Source
Short term	Embankment load	SF > 1.4	Road class I: Geotechnical Guide 4 Design and Construction from [19]
Long term	Pavement load	SF > 1.5	(SNI 8460, 2017)
	Traffic load	SF > 1.5	(SNI 8460, 2017)
	Earthquake load	SF > 1.1	(SNI 8460, 2017)

Settlement		
Parameter	Term	Source
Total settlement after operation	≤10 cm	(Road Pavement Design Manual No.02/M/BM/2017, 2017)
Settlement rate	< 2 cm/year	Road class I: Geotechnical Guide 4 Design and Construction from [19]

3. Result and Discussion

3.1 Subgrade Soil Condition

The following Figure 3 presents the soil stratigraphy in the field. Based on the estimated stratigraphic image of the soil layer, it is known that from the surface of the land to a depth of 5.00 m, there is a layer of clay with a soft consistency. Then, at a depth of 5.00–7.00 m, there is a layer of clay with medium consistency, and at a depth of 7.00–11.00 m, there is a layer of sand with dense density. Then, at a depth of 11.00–14.00 m, there is a silty soil layer with a very stiff consistency, and at a depth of 14.00–17.00 m, there is a sand layer with a dense density. Then, at a depth of 17.00–19.00 m, there is a clay layer with a very stiff consistency, and at a depth of 19.00–21.00 m, there is a sand layer with a very dense density. The final layer is at a depth of 21.00–40.00, which is a layer of clay with a hard consistency.

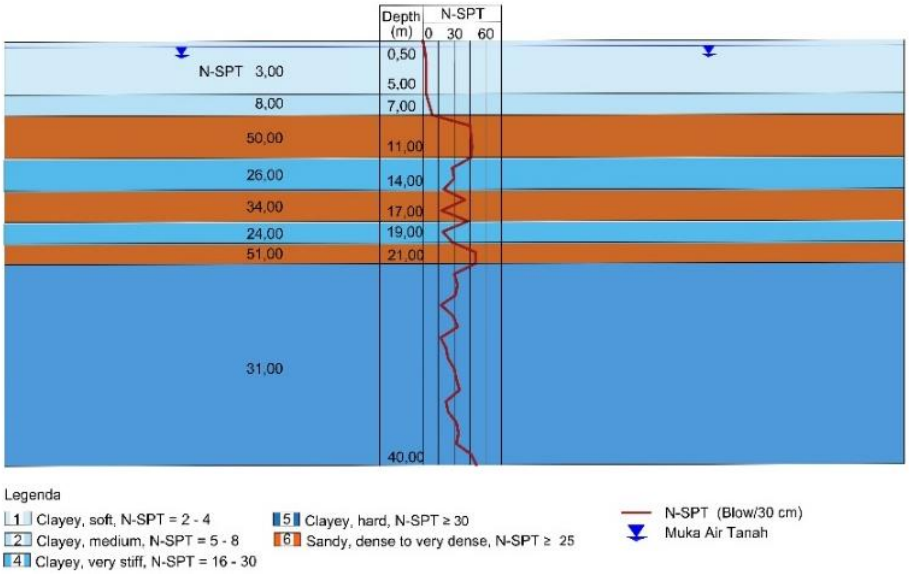

Figure 3. Soil Stratigraphic in the Field of Borlog Point DD-03

3.2 Subgrade Soil Parameters

In all layers in Table 2, the correlation of the N-SPT value is used for the Poisson's ratio parameter and permeability coefficient value. For layers 1 to 4, the soil parameters use laboratory test results. The unit weight (γ) parameter, the results of the laboratory water content, and content weight tests are used.

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The Undrained Unconsolidated (UU) triaxial test results and direct shear test results were used for cohesion and shear angle parameters. The modulus value was obtained from the stress versus strain table from the direct shear test results. The laboratory test results were validated with the range of parameter values from the correlation of the N-SPT values. For other layers, the soil parameters used the parameter correlation of the N-SPT values. For the parameters of unit weight (γ) and cohesion and shear angle based on the parameter correlation of [20].

The parameters inputted in the program have two conditions, namely in the short term and long term. The short term condition occurs after the load application, so when the soil pore has not had time to drain water out or in, the pore water pressure also remains high. The parameter used is Undrained Shear Strength (c_u) because in undrained conditions. The soil also does not have time to remove water from its pores, so the shear strength parameter without drainage is also used. Parameters in the short term condition are obtained by the Unconsolidated Undrained (UU) Triaxial Test.

Furthermore, the long term condition is the period after the soil has reached equilibrium with the applied load, usually after several months or years. This means that the water in the soil pore has had time to flow out or in, and the pore water pressure is stable or zero. The parameters used are Effective Stress Parameters, effective cohesion (c_{ef}), and effective shear angle (ϕ_{ef}). Effective Stress Parameters are obtained from the Consolidated Drained (CD) Triaxial Test.

Table 2. Recapitulation of subgrade soil parameters

Layer (Depth)	N-SPT	Soil Type	Consistency /Density	γ/γ_{sat} (kN/m^3)	ϕ_{ef} (°)	c_{ef} (kPa)	c_u (kPa)	E_{ref} (MPa)	v	k (m/day)
1 (0 – 5)	3	Silty CLAY	Soft	14.96/17.00	21.00	4.10	17.96	4.50	0.40	0.000864
2 (5 – 7)	8	Silty CLAY	Medium	17.07/18.00	25.00	4.70	35.91	12.00	0.40	0.000864
3 (7 – 11)	50	Silty SAND	Dense	19.00/21.50	32.00	10.00	-	75.00	0.40	8.640000
4 (11 – 14)	26	Sandy SILT	Very Stiff	16.86/17.13	30.75	1.61	143.64	39.00	0.40	0.864000
5 (14 – 17)	34	Silty SAND	Dense	19.00/21.50	27.20	2.00	-	51.00	0.32	8.640000
6 (17 – 19)	24	Silty CLAY	Very Stiff	18.20/19.50	40.41	1.18	143.64	36.00	0.40	0.000864
7 (19 – 21)	51	Silty SAND	Very Dense	19.00/21.50	32.00	10.00	-	76.50	0.40	8.640000
8 (21 – 40)	31	Silty CLAY	Hard	20.00/20.00	17.27	4.00	191.52	46.50	0.40	0.000864

3.3 *Embankment Planning*

In embankment design, preloading is one technique used to accelerate the subgrade's compaction. By adding additional load to the soil voids, preloading can improve compaction, resulting in a higher subgrade bearing capacity [21].

It is essential to properly pay attention to the stages of embankment construction in the hope of increasing the shear strength, which will improve the ability of the subgrade to support the embankment load stably. In general, embankment construction should be carried out in stages by adding layer after layer and compacting each layer. This study carried out embankment construction with the detailed construction steps listed in Figure 4.

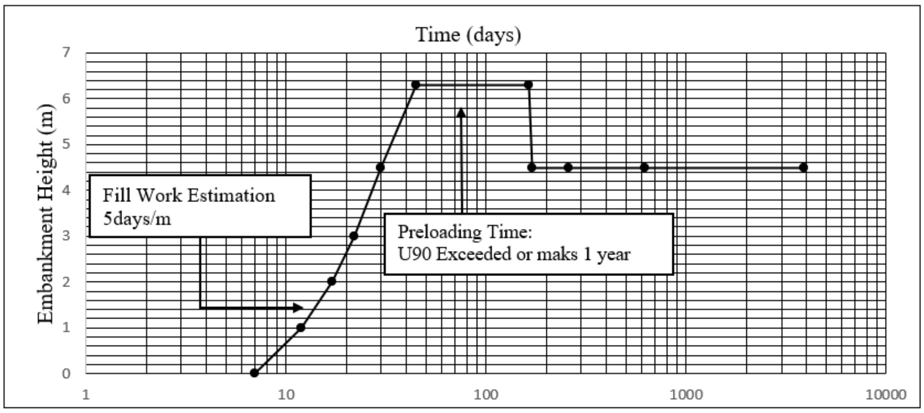

Figure 4. Stages for Embankment Work

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3.4 Embankment Data and Soil Replacement Data

Refer to [19] when determining the selection of embankment materials and soil replacement. Table 3 presents parameter data for embankment design and soil replacement.

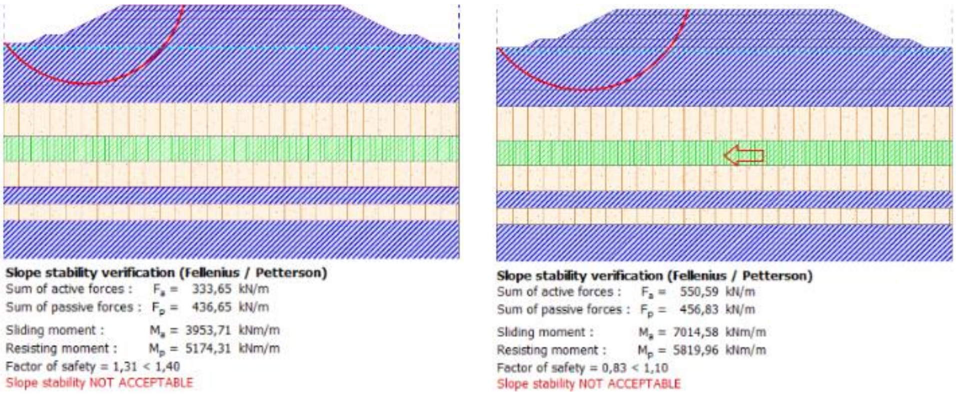
Table 3. Parameters for Embankment Design and Soil Replacement

	γ/γ_{sat} (kN/m^3)	ϕ_{ef} (°)	c_{ef} (kPa)	E_{def} (MPa)	v	k (m/day)
Embankment	17.00/17.00	20.00	5.00	3.00	0.40	0.000864
Soil Replacement	17.00/21.00	36.00	0.50	76.50	0.10	8,640

3.5 Results

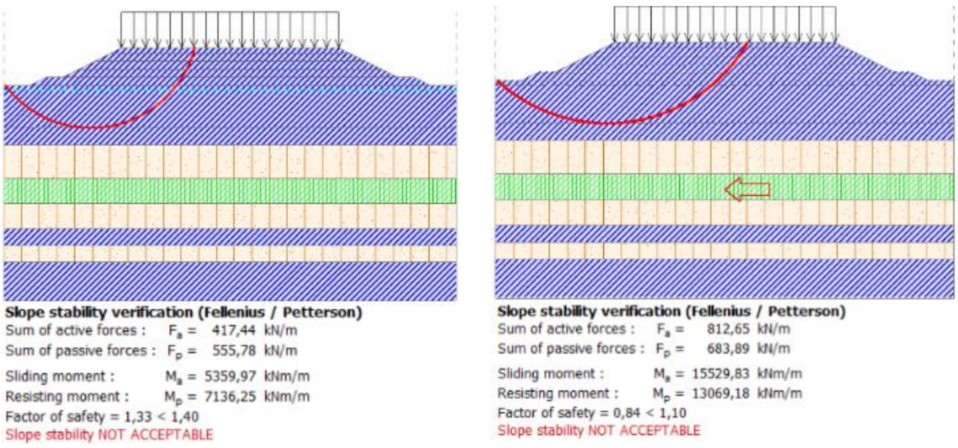
3.5.1 Embankment Stability Analysis without Improvement

The following Figure 5 and Figure 6 present the results of the embankment stability analysis in the short term without improvement. The results of the stability analysis of the embankment in the short term without improvement with embankment load obtained an SF value of 1.31 < 1.4 and an earthquake load of 0.83 < 1.1. Furthermore, the pavement installation obtained a value of 1.33 < 1.4 and an earthquake load of 0.84 < 1.1, indicating that the stability of the embankment collapse.



(a) (b)

Figure 5. a. Embankment Load without Improvement, b. Embankment Load Plus Earthquake Load without Improvement



(a) (b)

Figure 6. a. Pavement Installation without Improvement, b. Pavement Installation Plus Earthquake Load without Improvement

The following Figure 7 presents the results of the embankment stability analysis in the long term without improvement. The results of the stability analysis of the embankment in the long term without

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improvement during the operational period obtained an SF value of 1.48 < 1.5 and an earthquake load of 1.04 < 1.1. This indicates that the stability of the embankment collapse.

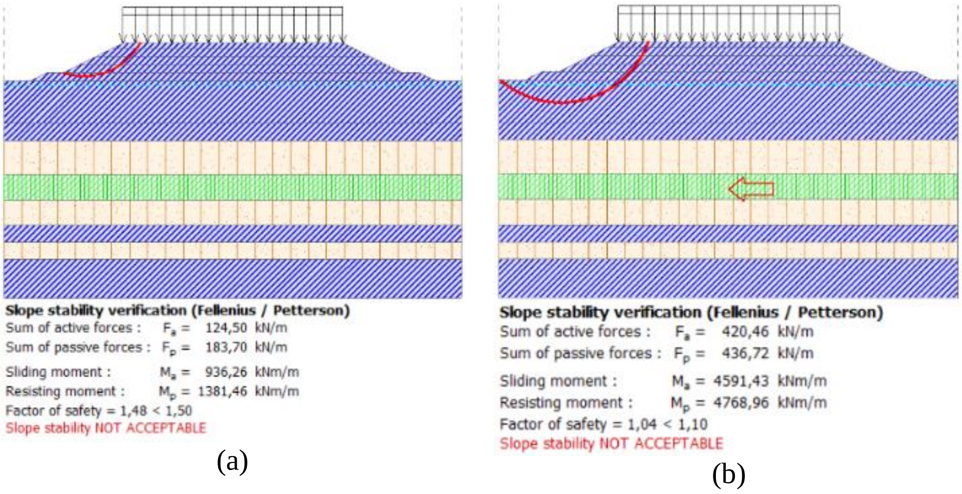

Figure 7. a. Operational Period without Improvement, b. Operational Period Plus Earthquake Load without Improvement

3.5.2 Soil Improvement Method

In an effort to determine the type and planning of effective soil improvement based on the problems that exist in the existing soil, it refers to [19], [22], namely using embankment reinforcement with Geosynthetic Woven Geotextile type, because it has a good function to overcome embankment collapse. In addition, the soil conditions in this borlog have deep soft soil, so determining an efficient method for soil improvement refers to [4] which states as an alternative to soil improvement using soil replacement for thick soft soil conditions. In handling embankment stability by considering costs, the selection of soil improvement is to use partial replacement. So, soil improvement and embankment reinforcement are planned with 2.5 m deep soil replacement and woven geotextile.

3.5.3 Embankment Stability Analysis with Improvement

The following Figure 8 and Figure 9 present the results of the embankment stability analysis in the short term with improvement. The results of the stability analysis of the embankment in the short term with improvement with embankment load obtained an SF value of 1.53 > 1.4 and an earthquake load of 1.18 > 1.1. Furthermore, the pavement installation obtained a value of 1.56 > 1.4 and an earthquake load of 1.19 > 1.1, indicating that the stability of the embankment safe.

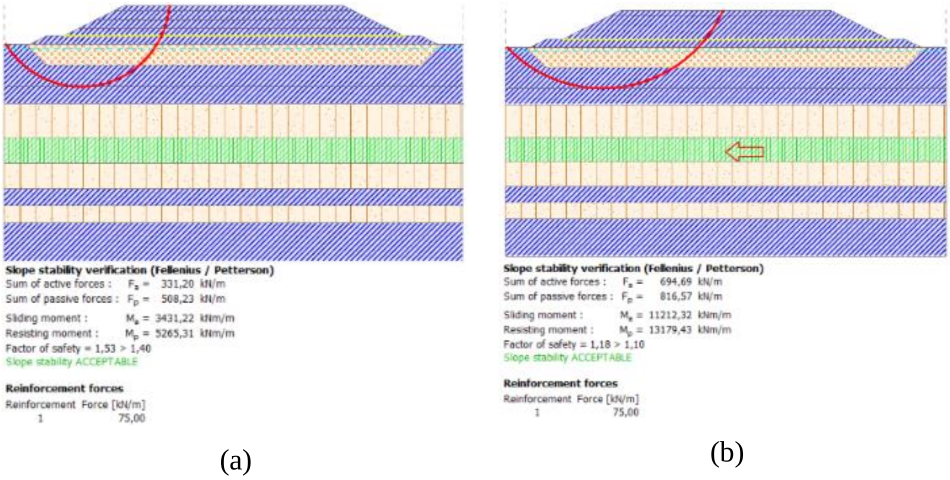

Figure 8. a. Embankment Load with Improvement, b. Embankment Load Plus Earthquake load with Improvement

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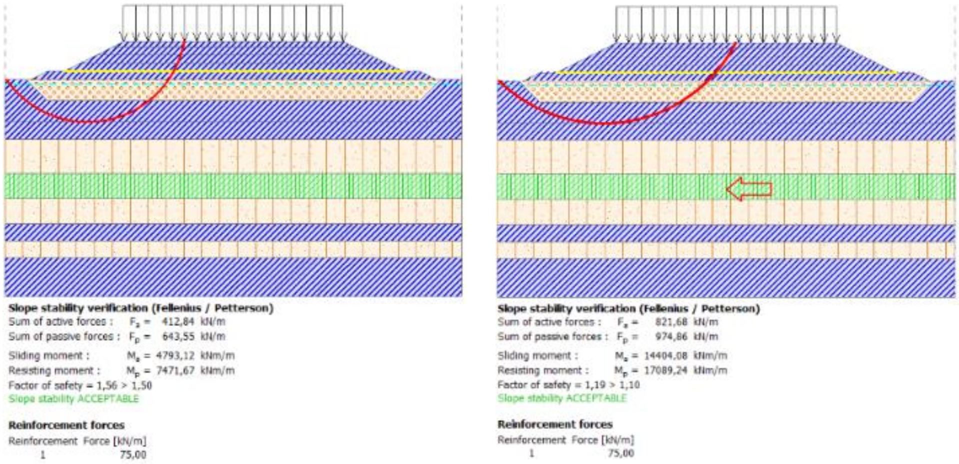
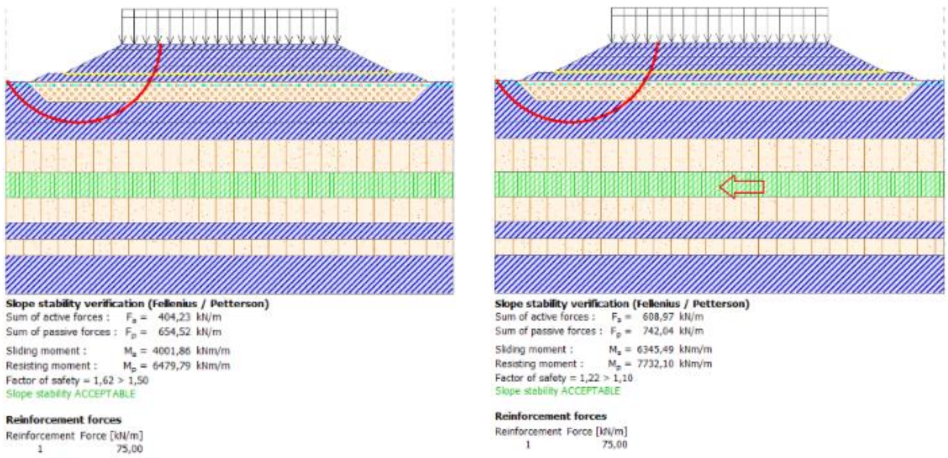


(a) (b)

Figure 9. a. Pavement Installation with Improvement, b. Pavement Installation Plus Earthquake Load with Improvement

The following Figure 10 presents the results of the embankment stability analysis in the long term with improvement. The results of the stability analysis of the embankment in the long term without repair during the operational period obtained an SF value of 1.62 > 1.5 and an earthquake load of 1.22 > 1.1. This shows that the stability of the embankment with repairs can increase the value of the safety factor, so the embankment is declared safe.



(a) (b)

Figure 10. a. Operational Period with Improvement, b. Operational Period Plus Earthquake Load with Improvement

According to research Laurits Bjerrum in [23], embankments built on soft soil under long-term conditions will show greater safety factor values than those under short term conditions. This is because, in the short term, pore water pressure is high, and consolidation needs to be completed. Meanwhile, in the long term, the soil is well consolidated, pore water pressure is reduced, and soil strength is increased, resulting in better safety factor.

3.5.4 Settlement Analysis

Table 4 presents the stages and cumulative construction time to be input in the settlement analysis modeling process.

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Table 4. Construction Stages for Settlement Analysis in the Program

Number	Construction Stages	Cumulative Road Construction Time (Days)
1	Excavation and soil replacement	7
2	Embankment 1 m	12
3	Embankment 2 m	17
4	Embankment 3 m	22
5	Embankment 4.5 m	30
6	Installation surcharge load (1.8 m)	45
7	Preloading (4 month)	165
8	Unloading surcharge	170
9	Installation pavement	260
10	1-year consolidation	625
11	10-year consolidation	3910

Based on the analysis results obtained from the modelling program, Figure 11a presents a graph settlement against time and Figure 11b presents a graph of the degree of consolidation against time.

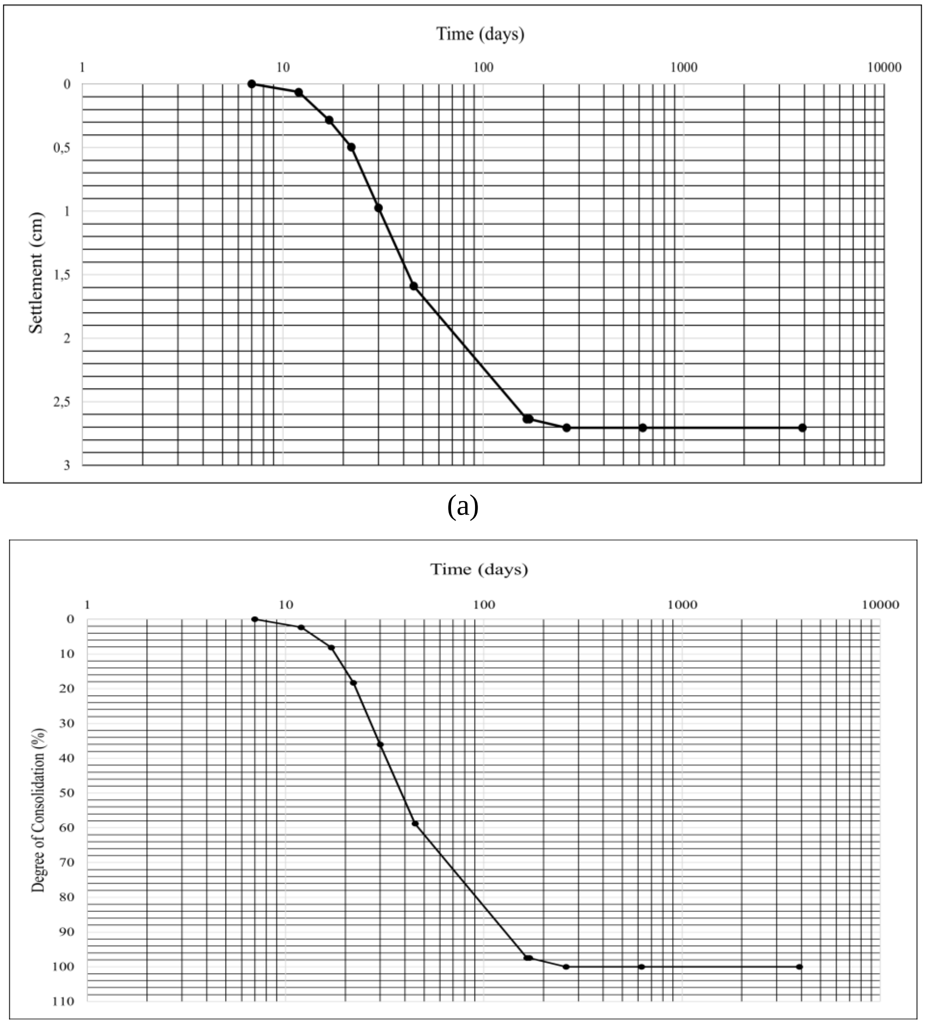

Figure 11. a. Graph Settlement Against Time, b. Graph of the Degree of Consolidation Against Time

Figure 11 shows that at the end of preloading, the settlement has reached a degree of consolidation > 90%. The settlement after the construction period or operational period is 0.21 cm ≤ 10 cm, which

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meets the requirements of the Geotechnical Guidelines 4 Design and Construction by [19] and the settlement rate is 0.68 cm < 2 cm/year, which meets the requirements of [24].

3.5.5 Recapitulation of Analysis Results

The following Table 5 presents a recapitulation of the results of the embankment stability and settlement analysis.

Table 5. Recapitulation of the Results of the Embankment Stability and Settlement Analysis

Embankment Stability				
Condition		Construction Stages and SF Term	SF Value	Description
Without improvement	Short term	Embankment, SF > 1.4	1.31	Collapse
		Embankment plus earthquake load, SF > 1.1	0.83	Collapse
		Pavement installation, SF > 1.4	1.33	Collapse
		Pavement installation plus earthquake load, SF > 1.1	0.84	Collapse
	Long term	Operational period, SF > 1.5	1.48	Collapse
		Operational period plus earthquake load, SF > 1.1	1.04	Collapse
With improvement	Short term	Embankment, SF > 1.4	1.53	Safe
		Embankment plus earthquake load, SF > 1.1	1.18	Safe
		Pavement installation, SF > 1.4	1.56	Safe
		Pavement installation plus earthquake load, SF > 1.1	1.19	Safe
	Long term	Operational period, SF > 1.5	1.62	Safe
		Operational period plus earthquake load, SF > 1.1	1.22	Safe
Settlement				
Total settlement after operational period			0.21 cm < 10 cm	
Settlement rate			0.68 cm < 2 cm/year	

From Table 5, a comparison graph of SF values without improvement and with improvement can be seen in Figure 12 and Figure 13 presents a comparison graph of SF values of earthquake load without improvement and with improvement.

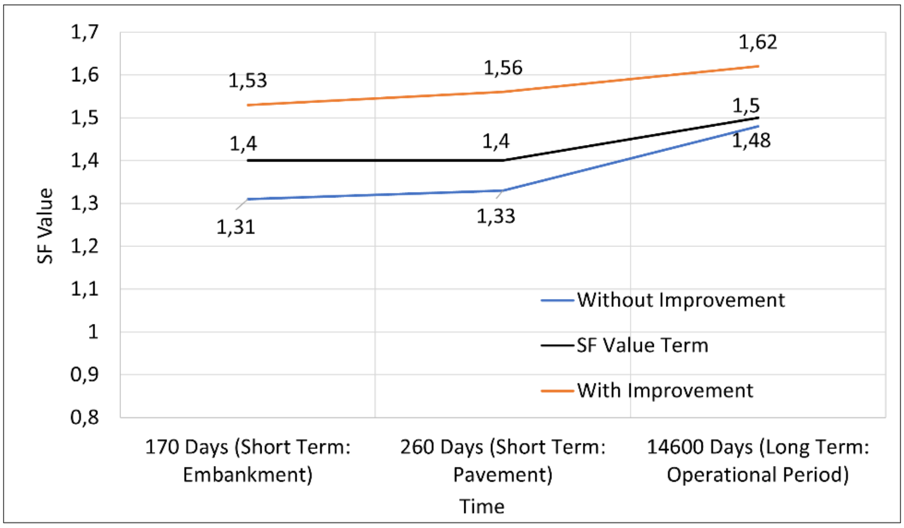

Figure 12. Comparison Graph of SF Value without Improvement and with Improvement

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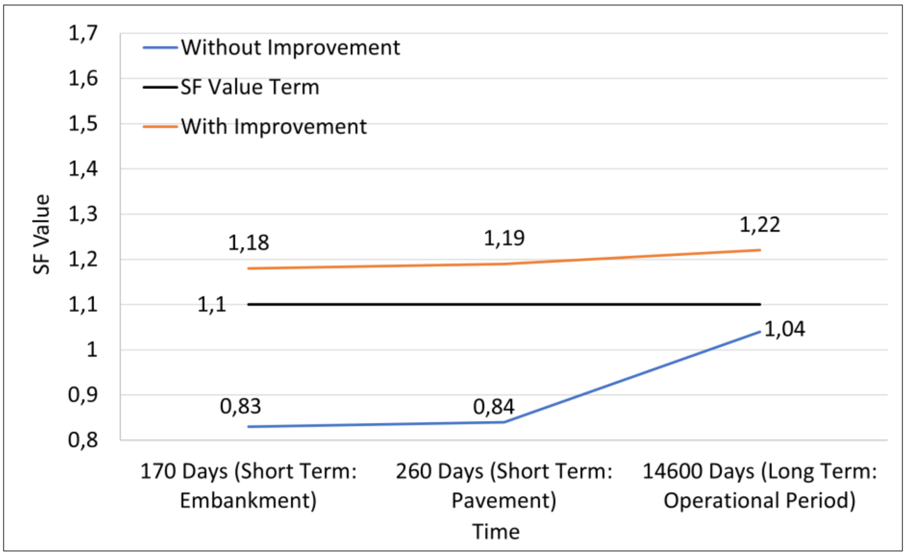

Figure 13. Comparison Graph of SF Values of Earthquake Load without Improvement and with Improvement

4. Conclusion

This study can be concluded that the results of the stability analysis of the embankment without soil improvement are declared unsafe. The SF value indicates this in short term conditions with an embankment load of 1.31 < 1.4, embankment load plus earthquake load of 0.83 < 1.1, and SF value in pavement installation of 1.33 < 1.4 if added with earthquake load of 0.84 < 1.1. Under long term conditions, the SF value during the operational period was 1.48 < 1.5, and the earthquake load was 0.84 < 1.1. This indicates that the embankment requires soil improvement.

The soil improvement was 2.5 m deep soil replacement plus 75 kN woven geotextile reinforcement. The way soil replacement works is by replacing unstable or less supportive soil layers with more stable and robust materials. Then, the new material is spread in place of the excavated soil, and the new layer that has been spread is then compacted so as to increase the bearing capacity and reduce settlement. Then, woven geotextile reinforcement with a tensile strength of 75 kN was used for additional reinforcement. Geotextile is a synthetic material that functions to strengthen soil and prevent erosion. The way this geotextile reinforcement works is to bind soil particles that can increase shear strength and soil stability. To reduce deformation and increase the bearing capacity of the soil. The results of this analysis show that the stability of the embankment after repair is safe. The SF value indicates this in short term conditions with an embankment load of 1.53 > 1.4, then the SF value of embankment load plus earthquake load of 1.18 > 1.1 and SF value at pavement installation of 1.56 > 1.5 and earthquake load of 1.19 > 1.1. Under long term conditions, the SF value during the operational period was 1.62 > 1.5, and the SF value plus the earthquake load was 1.22 > 1.1. The total settlement after operation of 0.21 cm ≤ 10 cm is by the criteria of the Geotechnical Manual 4 Design and Construction, and the settlement rate of 0.68 < 2 cm/year meets the MDP 2017 Rev 2020 requirements. This shows that minimizing the thickness of easily compressible soil plus woven geotextile reinforcement can increase the bearing capacity of the soil and reduce settlement.

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