Analysis of Road Embankment Improvement on Soft Soil Using Foamed Mortar Lightweight Embankment

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ABSTRACT

The Calang - Simpang Peut road section, linking Banda Aceh and Meulaboh in Aceh Province, faces severe damage, including longitudinal cracks, pavement settlement, and embankment deformation. Soil testing reveals a soft soil layer beneath the embankment. Alternative treatments that can be used to deal with stability and settlement problems on soft soils are to use foamed mortar lightweight materials. The research evaluates the untreated embankment and the use of foam mortar with varying thickness and slope. Stability, settlement, and uplift pressure are analyzed. The analysis showed that the untreated embankment had a factor of safety of 1.090, close to critical. Improvement of the embankment using foam mortar can increase the factor of safety and reduce settlement as the thickness of the foam mortar increases. The thickness of foam mortar that meets the requirements for the existing slope embankment is 1.50 meters thick or more and for the vertical slope embankment is 2.00 meters thick or more.

Keywords : Infrastructure asset management, soft soil, lightweight material, foamed mortar

INTRODUCTION

The road network is one of the most important infrastructures that have functions to connect nodes, flow traffic, cover the region, support the economy, and make green areas (Suprayitno & Soemitro, 2019; Suprayitno et al., 2020). To keep the road infrastructure functioning properly over time, it is necessary to conduct maintenance called road preservation. Road preservation is a series of long-term road maintenance activities to increase the service life of roads through various processes and forms of treatment effectively and efficiently (Direktorat Jenderal Bina Marga, 2021). Road preservation activities are part of infrastructure asset management, and the main objective is to ensure that infrastructure and facilities can function properly in a sustainable, economical, efficient, and effective manner while maintaining environmentally friendly principles (Soemitro & Suprayitno, 2020). Road preservation consists of various treatments based on the condition and deterioration of the road. Road deterioration that occurs includes pavement cracking, pavement defects, pavement deformation, surface patching, and difficult soil and terrain conditions problems (Soemitro & Suprayitno, 2022).

One of the road preservations works caused by difficult soil problems is located on the Calang - Sp. Peut National Road section. This road section is the West Sumatra Route in Aceh Province which connects the cities of Banda Aceh and Meulaboh and is the main route for transporting goods and services on the west coast of Aceh Province (Error! Reference source not found..**a**). After more than ten years of construction, there are road segments that are damaged in the form of longitudinal cracks, wavy roads and non-uniform settlements on the road (Error! Reference source not found..**b**). The results of the soil investigation showed that there was a soft soil layer with a thickness of 5.00 to 5.50 meters with a value of N-SPT = 2 (Satker P2JN Provinsi Aceh, 2018). The existence of this soft soil layer is thought to be one of the causes of damage to the road body.

(a) (b)

Figure 1. (a) Study locations and **(b)** road damage

Based on these problems, it is necessary to improve the road body with proper treatment by the existing soil conditions. Alternative treatments that can be used to deal with stability and settlement problems on soft soils are to use embankments with lightweight materials (Pt T-10-2002-B). One type of lightweight embankment that has been developed in Indonesia is foam mortar lightweight embankment. Foam mortar lightweight material is a mixture of sand, cement, water, and foam that has self-compacting characteristics. It has a maximum dry density of 0.8 t/m3 for mixtures with a minimum compressive strength (UCS) of 2000 kPa and a maximum dry density of 0.6 t/m3 for mixtures with a minimum compressive strength of 800 kPa (Kementerian PUPR, 2015b). Due to its lighter weight compared to graded embankment and high compressive strength, foam mortar material is suitable for use on soft soil sites to overcome stability and settlement problems. Foam mortar materials can be seen in Error! Reference source not found..

Figure 2. Foamed mortar lightweight mortar.

Foam mortar lightweight embankment has been widely applied as road embankment on soft soil as well as bridge or flyover approaches. Based on the application of foam mortar embankment as a bridge approach road on Kedaton Bridge on the north coast national road in Cirebon City and road embankment on soft soil on the Pangkalan Lima - Kumai road in Pangkalan Bun, Central Kalimantan Province, the mortar embankment can fulfil the stability and settlement requirements (Numan et al., 2012; Iqbal et al., 2012). When compared to granular embankment, the use of foam mortar in soft soil layers has a higher factor of safety and smaller settlement than granular embankment materials (Hidayat et al. 2016; Fadilah & Hamdhan 2017). Lastiasih & Mochtar (2022) compared road embankments using selected embankment materials and foam mortar with variations in the combination of these materials in terms of stability and settlement. Based on the analysis, it was found that the combination of embankment with 75% foam mortar and 25% selected embankment can reduce the settlement by 0.6 times and increase the safety factor value by 1.46 times compared to the embankment with 100% selected material.

Based on the above description, it is necessary to study the improvement of embankment on soft soil by using foam mortar lightweight embankment material. Since the road condition is still operational by vehicles, the improvement is proposed by replacing part of the existing embankment using foam mortar lightweight embankment. For this reason, this study will review the most effective thickness of foam mortar used in terms of stability, settlement, implementation method, implementation time, and implementation cost.

LITERATURE STUDY

Foam Mortar Lightweight Material

Foam mortar lightweight material is a mortar consisting of a mixture of sand, cement, water, and foam. Foam mortars are self-compacting, so no compaction is needed. Foam mortar applications can be used as a material for pavement base layers and sub-base layers or embankment materials. The application of foam mortar is distinguished by its minimum compressive strength and dry density specifications. Foam mortar specifications based on its application can be seen in **Error! Reference source not found.**.

Table 1. Foam mortar lightweight material specifications

Application	Maximum dry density (gr/cm^3)	Minimum compressive strength (UCS) on 14 days	
		kPa	Kg/cm^2
Base	0,8	2000	20
Subbase or embankment	0,6	800	8

Source: Kementerian PUPR (2015c)

In the application of lightweight foam mortar as backfill material, a layer of lightweight material for the foundation with a minimum compressive strength of 2000 kPa is made with a minimum thickness of 30 cm at the top of the embankment. Steel wire mesh can be added to the foam mortar embankment if required and installed every 1 m thickness. The surface of the foam mortar road embankment is covered with asphalt to function as a jacket using AC/WC asphalt layer with a minimum thickness of 4 cm and AC/BC with a minimum thickness of 5 cm (Kementerian PUPR, 2015a). Typical road construction using foam mortar lightweight material can be seen in Error! Reference source not found..

The modulus of elasticity is calculated based on an empirical formula based on ACI Committee 523 (2014) as shown in equation **Error! Reference source not found.**.

$$E_c = 0{,}043\gamma^{1{,}5}\sqrt{f_c'} \quad \text{.....(1)}$$

Which:

γ = unit weight of foam mortar (kg/m3)

f_c' = compressive strength of foam mortar at 28 days (MPa)

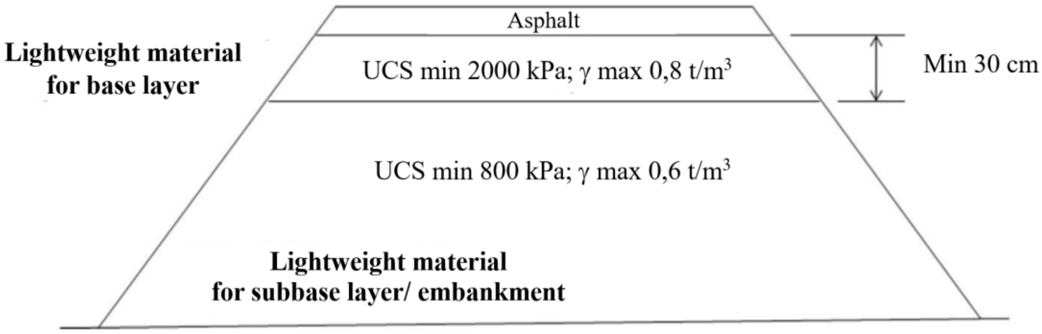


Figure 3. Typical road construction using foam mortar lightweight material.

The lightweight foam mortar material used as road embankment has a smaller unit weight than water, so it has the potential to uplift. For this reason, it is necessary to analyze the road embankment against the risk of uplift due to hydrostatic pressure from water. Analysis of the uplift pressure of the embankment can be calculated by analyzing the uplift of the embankment under the condition that water only presses on one side of the embankment (Arellano, 2010) as in Error! Reference source not found..

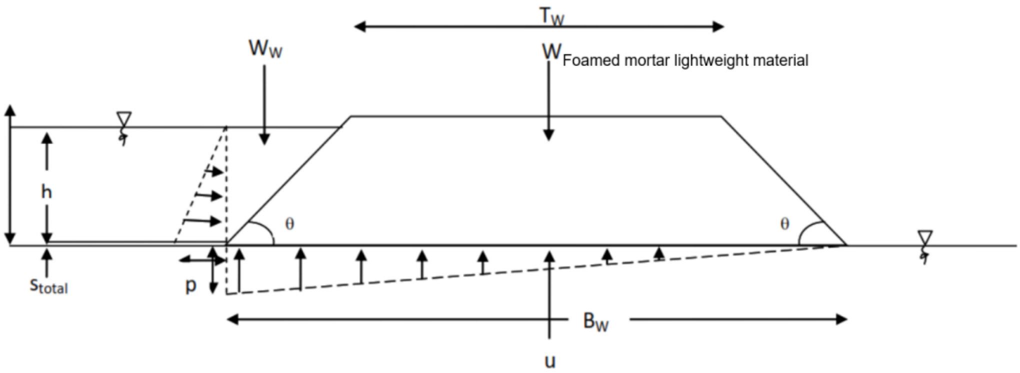


Figure 4. Uplift pressure under the condition of water pressing on one side of the embankment.

The safety factor of the embankment against hydrostatic uplift pressure is calculated by equation **Error! Reference source not found.**. The required safety factor for critical conditions is a minimum of SF = 1,1.

$$SF = \frac{w_{foamed\,mortar} + w_w + O_{req}}{\frac{1}{2} \cdot \gamma_w \cdot (h + s_{tot}) B_w} \quad \text{..... (2)}$$

Which:

Ww = weight of water above the embankment

O_{req} = the additional overburden pressure required on top of the embankment to achieve the target safety factor

γw = unit weight of water

h = water level from the bottom of the embankment

s_{tot} = estimated total settlement

Bw = width of embankment base

Primary Consolidation Settlement

The primary consolidation settlement of fibrous peat soil at the end of primary consolidation (EOP) is calculated using the equation **Error! Reference source not found.**

(Mesri & Ajlouni, 2007). The Cc value is obtained based on the relationship curve of e at EOP vs log p'.

$$Sc = \frac{Cc}{1+e_o} Lo \left[\frac{Cr}{Cc} \log\left(\frac{\sigma'_p}{\sigma'_{v0}}\right) + \log\left(\frac{\sigma'_{vf}}{\sigma'_p}\right) \right] \quad \text{..... (3)}$$

Which:
Cc = compression index at EOP
Cr = recompression index
Lo = soil layer thickness
e_o = initial void ratio
σ'_{v0} = effective overburden pressure
σ'_p = pre-consolidation pressure
σ'_{vf} = post construction effective vertical pressure

Secondary Consolidation Settlement

Secondary consolidation settlement has a more significant role than primary consolidation settlement in organic soils and inorganic soils with very high compressibility. Secondary consolidation settlement is calculated using equation **Error! Reference source not found.** (Mesri & Ajlouni, 2007). The secondary compression index (C_α) is calculated by equation **Error! Reference source not found.** based on the e vs log t relationship curve.

$$Ss = \frac{C_\alpha}{1+e_o} Lo \log\left(\frac{t}{t_p}\right) \quad \text{..... (4)}$$

Which:
S_s = secondary consolidation settlement
C_α = secondary compression index
L_o = soil layer thickness
e_o = initial void ratio
t = observation time
t_p = time at the end of primary consolidation

RESEARCH METHOD

This research uses primary data and secondary data. Primary data was obtained by taking undisturbed and disturbed soil samples from the research site, which were then tested for physical and mechanical properties in the laboratory. Meanwhile, secondary data were Detailed Engineering Design (DED) and the result of previous geotechnical testing obtained from the Aceh National Road Implementation Agency. The soil test results were then used to determine the relevant soil parameters in the stability analysis and calculation of soil settlement on the embankment. The analyses were conducted on the existing condition of the road embankment as well as the improved embankment using lightweight foam mortar. The foam mortar lightweight embankment that was the focus of the analysis had a variety of thicknesses and slopes, as listed in **Error! Reference source not found.**.

The various foam mortar embankments were analyzed for stability, settlement, and uplift pressure. Stability and settlement analyses were conducted using a 2D finite element method software. Based on these factors, the thickness of foam mortar that can be used and meets the required requirements is obtained.

Table 2. Variation of thickness and slope of foam mortar lightweight embankment

No	Type	Foam Mortar Thickness UCS 2000 kPa (m)	Foam Mortar Thickness UCS 800 kPa (m)	Existing Backfill Thickness (m)	Slope
1	Existing 1	0,50	-	2,50	Existing (1:1,5)
2	Existing 2	0,30	0,70	2,00	
3	Existing 3	0,30	1,20	1,50	
4	Existing 4	0,30	1,70	1,00	
5	Existing 5	0,30	2,20	0,50	
6	Existing 6	0,30	2,70	-	
7	Vertical 1	0,50	-	2,50	Vertical (90◦)
8	Vertical 2	0,30	0,70	2,00	
9	Vertical 3	0,30	1,20	1,50	
10	Vertical 4	0,30	1,70	1,00	
11	Vertical 5	0,30	2,20	0,50	
12	Vertical 6	0,30	2,70	-	

ANALYSIS

Data Collection

Based on the secondary data of the Standard Penetration Test (SPT) obtained, it is known that the soil layer at the research location is as shown in Error! Reference source not found..

Table 3. SPT Test Result

Depth (m)	Description	N-SPT	Consistency
0,0 – 5,5	Peat	2	Very Soft
5,5 – 8,0	Silty Sand	11	Medium
8,0 – 19,5	Silty Sand	28	Medium
19,5 – 30,0	Silty Sand	50	Dense

Source: Satker P2JN Provinsi Aceh, 2018

Table 4. Primary Data from Laboratory Soil Testing Results

No	Test Type	Unit	Result
1	Depth	m	1,00
2	Water content (wc)	%	947,24
3	Unit weight (γ)	gr/cm^3	0,99
4	Specific gravity (Gs)		1,42
5	Organic content (OC)	%	91,89
6	Ash content (AC)	%	8,11
7	Void ratio (e)		14,16
11	Fiber Content		
	- Unrubbed	%	42,67
	- Rubbed	%	33,33

Based on the primary data of laboratory testing results on soil samples taken from the research site, the results are shown in **Error! Reference source not found.**. Based on these data, it was found that the soft soil layer is a type of peat soil. The physical and mechanical parameters of the soil used in the analysis are shown in **Error! Reference source not found.**. The peat soil parameters used are the results of primary data testing while the layer of soil underneath refers to secondary data soil testing.

Table 5. Physical and Mechanical Soil Parameters

Depth (m)	Description	γ_t (gr/cm^3)	γ_{sat} (gr/cm^3)	e	ϕ (◦)	C (kg/cm^2)	Cc	Cs	Cα
0,0 – 5,5	Peat	0,99	1,027	14,16	26,78	0,0659	9,511	0,30	0,3224
5,5 – 8,0	Silty Sand	1,736	1,78	1,00	8,9	0,045	-	-	-
8,0 – 19,5	Silty Sand	1,822	1,85	0,83	26,5	0,07	-	-	-
19,5 – 30,0	Silty Sand	1,925	1,99	0,58	30,29	0,058	-	-	-

Stability and Settlement Analysis of Existing Road Embankment

<u>Calculation of Existing Road Embankment Settlement During Operational Period</u>

Based on information obtained from PPK 2.2 Aceh Province, the road at the research location has been operating for approximately 13 years since it was constructed. During the operational period, the road experienced a consolidation settlement. Thus, the stability analysis of the existing road embankment will consider the consolidation settlement that has occurred during the operational period. Because the author did not obtain the initial design data of the road construction and the settlement data that occurred, the road settlement will be analyzed based on the laboratory test data. The height of the road embankment based on the DED data is known to be 3.00 m high. Therefore, the embankment settlement that has occurred during the operational period will be calculated in terms of primary consolidation settlement and secondary consolidation settlement.

To obtain the final height of the embankment, the consolidation settlement was calculated with varying loads to obtain the relationship between the final height of the embankment and the settlement that occurred. The primary consolidation settlement in peat soil was calculated using equation **Error! Reference source not found.**. Based on this calculation, the relationship between the final embankment height and the settlement that occurred is shown in **Error! Reference source not found.**.

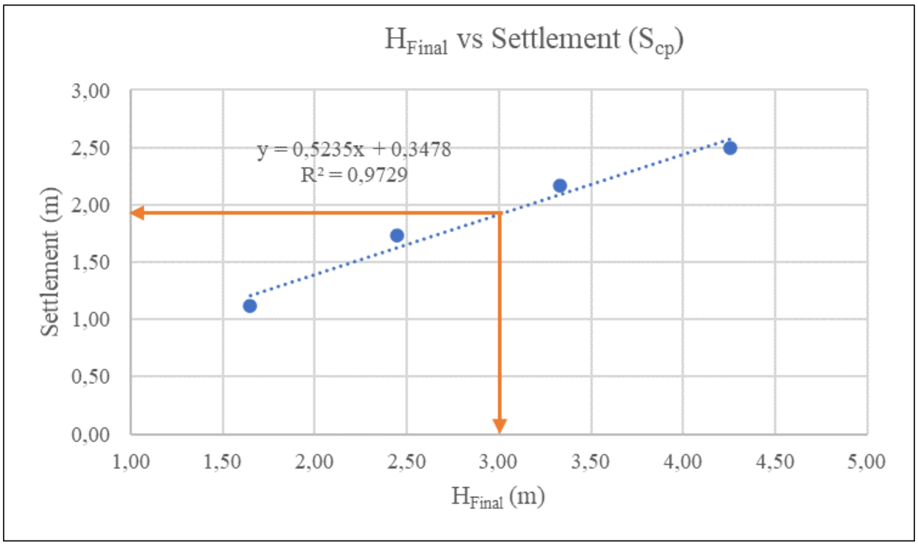


Figure 5. Relationship between embankment final height and settlement

From the above chart, it is obtained that the primary consolidation settlement that has occurred is 1.92m. Then, the secondary consolidation settlement that has occurred during the operational period is calculated. The settlement is calculated using equation **Error! Reference source not found.** and the secondary consolidation settlement that occurs is 0,33 m. Based on the calculation, the total settlement that has occurred is 2,25 m. Thus, the geometry of the embankment after the settlement will be used in the stability analysis of the embankment is shown in **Error! Reference source not found.**. As a result of the settlement consolidation, there is a change in soil parameters under the embankment. The parameters changed include void ratio (e) and unit weight (γ).

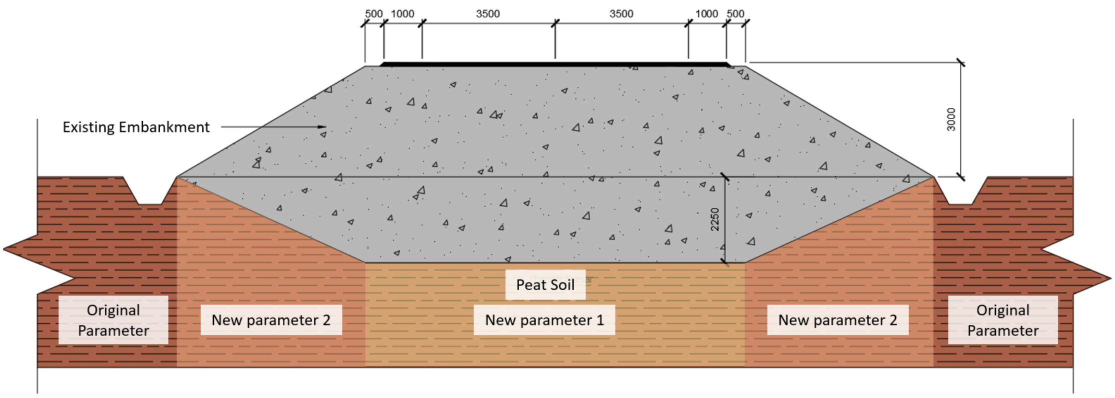


Figure 6. Existing embankment geometry

Stability Analysis of Existing Road Embankment

The stability analysis of the existing road embankment was conducted using 2D finite element method software. The traffic load used was 12 kPa following Pt T-10-2002-B for class II roads. The soil parameters used as input to the finite element method software are shown in **Error! Reference source not found.** and **Error! Reference source not found.**. The embankment geometry, soil parameters, and working loads were then inputted to the finite element method software and analyzed to obtain the safety factor of the embankment due to the working loads.

Table 6. Hardening Soil Model Input Parameters

Parameters	**Unit**	**Embankment**	**Silty Sand 1**	**Silty Sand 2**	**Silty Sand 3**
Soil Model		Hardening Soil	Hardening Soil	Hardening Soil	Hardening Soil
Drainage Type		Drained	Drained	Drained	Drained
γ_{unsat}	kN/m^3	18,5	17,4	17,82	18,67
γ_{sat}	kN/m^3	18,5	17,4	17,82	18,67
E_{50}^{ref}	kN/m^2	50000	17599	39191	48069
E_{oed}^{ref}	kN/m^2	50000	17599	39191	48069
E_{ur}^{ref}	kN/m^2	150000	52797	117573	144207
c'_{ref}	kN/m^2	5	4,5	7	5,8
ϕ	°	30	8,9	25,50	30,29
ψ	°	0	0	0	0
v_{ur}		0,25	0,25	0,25	0,25

Table 7. Soft Soil Creep Soil Model Input Parameters

Parameters	Unit	Peat 1 (Original)	Peat 2 (New 1)	Peat 3 (New 2)
Soil Model		Soft Soil Creep	Soft Soil Creep	Soft Soil Creep
Drainage Type		Undrain A	Undrain A	Undrain A
γ_{unsat}	kN/m^3	9,94	9,94	9,94
γ_{sat}	kN/m^3	10,27	10,38	10,33
e_0		14,165	9,8807	12,023
C_c		6,194	6,194	6,194
C_s		0,300	0,300	0,300
C_a		0,3324	0,3324	0,3324
c'_{ref}	kN/m^2	5,02	5,02	5,02
ϕ'	°	26,14	26,14	26,14
ψ	°	0	0	0
v_{ur}	-	0,15	0,15	0,15
k_x	m/day	3,605 x 10^{-3}	3,605 x 10^{-3}	3,605 x 10^{-3}
k_y	m/day	3,605 x 10^{-3}	3,605 x 10^{-3}	3,605 x 10^{-3}

Based on the analysis, the factor of safety of the embankment due to traffic load is SF = 1,090. This safety factor value is close to the critical condition where it has reached SF = 1,00. It also failed to meet the safety factor required in Pt T-10-2002-B where the minimum safety factor for embankments is SF $\geq$ 1,40. The sliding plane that occurred is shown in Figure. The field condition at the study location has not yet occurred landslide on the road embankment but there has been road damage in the form of corrugated road and cracks on the asphalt surface. The corrugated road surface is caused by ununiform settlement of the embankment.

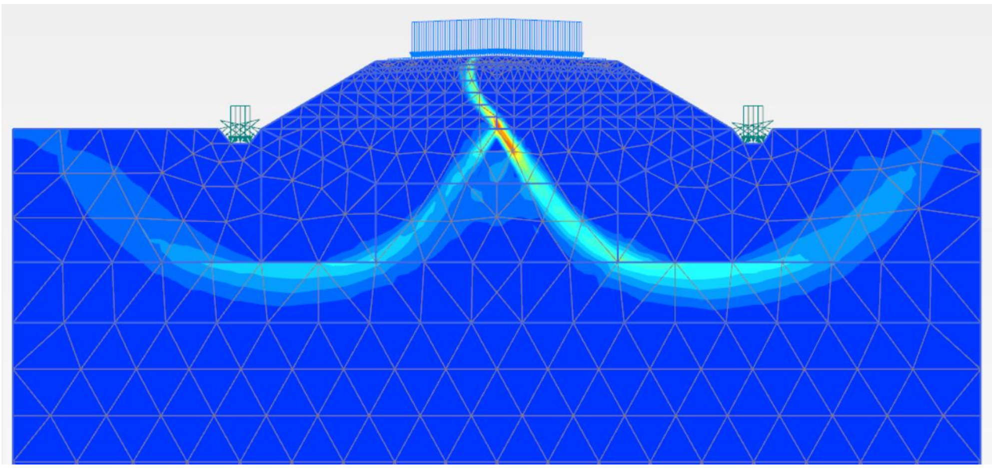


Figure 7. Sliding plane on embankment

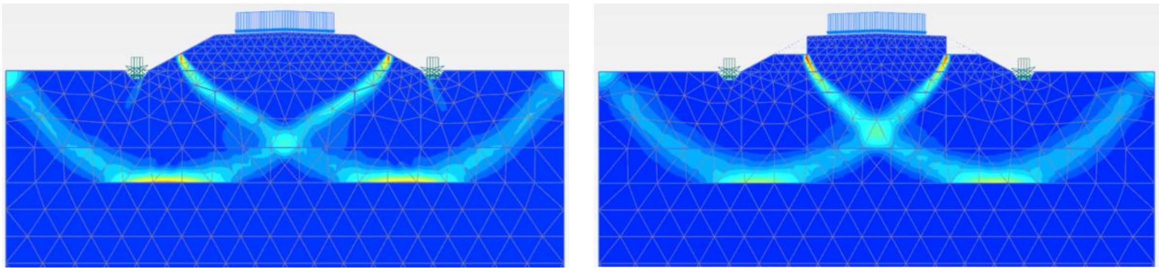
Stability and Settlement Analysis of Foam Mortar Lightweight Fill

Analysis of Embankment Stability

Stability analysis was conducted to obtain the safety factor of the road embankment replaced with foam mortar lightweight material. Stability analysis of the foam mortar lightweight embankment was conducted using a 2D finite element method computer program. The modeling of the road embankment contained variations of the thickness and slope of the foam mortar slope used according to **Error! Reference source not found.**. The design load is the traffic load with a load of 12 kPa applied to all traffic lane surfaces. In addition, there is also a 5 cm thick pavement load on top of the embankment with an asphalt unit weight of 23 kN/m3. The mechanical parameters of the foam mortar lightweight embankment inputted in the finite element method computer program are shown in **Error! Reference source not found.**. The embankment geometry, soil parameters, and working loads are then inputted into the finite element method computer program for analysis to obtain a safety factor for the embankment due to the working load.

Table 8. Foam Mortar Lightweight Fill Parameters

Parameters	Unit	Foam Mortar 800 kPa	Foam Mortar 2000 kPa
Soil Model		Linear Elastic	Linear Elastic
Drainage Type		Non-porous	Non-porous
γ_{unsat}	kN/m^3	6	8
γ_{sat}	kN/m^3	6	8
E_{ref}	kN/m^2	565250	1376000
$\nu_{(nu)}$	-	0,25	0,25



(a) (b)

Figure 8. Type 3 foam mortar lightweight embankment collapse model with existing slope (a) and vertical slope (b)

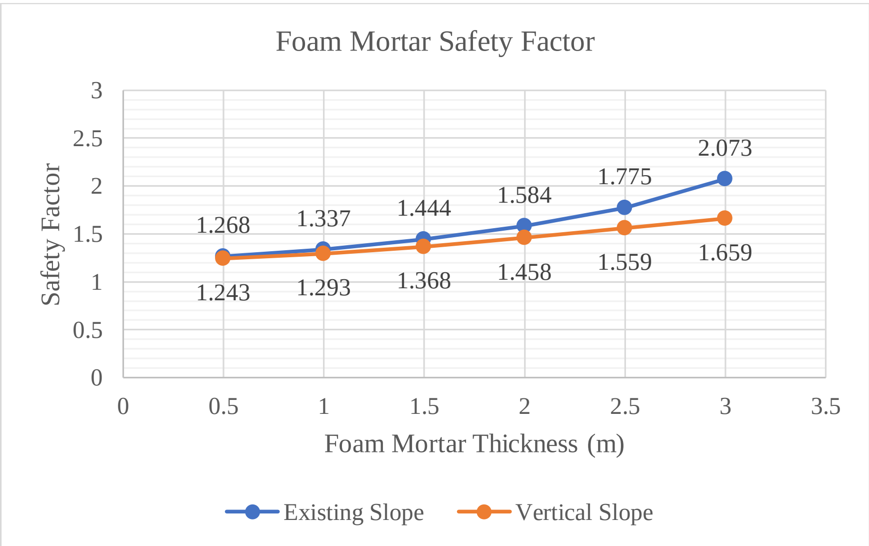


Figure 9. Foam mortar lightweight fill safety factor

Based on the analysis results, the collapse model is shown in **Error! Reference source not found.**. The figure shows an example of a collapse model of type 3 foam mortar with different embankment slopes. From the figure, it is found that the sliding plane that occurs is at the foot of the light embankment both on the light embankment with the existing slope and the vertical slope.

The safety factor analysis results for each model are shown in Figure 9. Based on the analysis, it is found that for the foam mortar lightweight embankment with existing slope and vertical slope, the safety factor value increases as the thickness of the lightweight embankment increases. This is also in line with research conducted by Lastiasih & Mochtar (2022). At the same foam mortar thickness, the factor of safety of the existing sloped foam mortar lightweight embankment has a higher value than the vertical sloped embankment. The factor of safety value for the lightweight foam mortar embankment also increased compared to the existing road embankment with the selected aggregate embankment, which was SF = 1.080. This is also in line with research conducted by Atamini & Moestofa (2018) and Fadilah & Hamdhan (2017). The increase in the safety factor value along with the increase in the thickness of the lightweight backfill layer is due to the increasing thickness of the lightweight backfill, the load on the subgrade is also decreased.

Analysis of Embankment Settlement

The settlement analysis of the road embankment was conducted using a 2D finite element method computer program. The settlement of the embankment was reviewed over a 10-year service life and then compared with the required settlement value. The results of the settlement analysis that occurred in the road embankment are shown in **Error! Reference source not found.**.

Table 9. Settlement of Embankment with Foam Mortar

Type	Thickness (m)			Existing Slope		Vertical Slope	
	Foam Mortar 2000 kPa	Foam Mortar 800 kPa	Embank-ment	10-year settlement (cm)	Rate of Settlement (cm/year)	10-year settlement (cm)	Rate of Settlement (cm/year)
Type 1	0,50	0,00	2,17	1,95	0,20	1,89	0,19
Type 2	0,30	0,70	1,67	0,79	0,08	0,79	0,08
Type 3	0,30	1,20	1,17	0,39	0,04	0,34	0,03
Type 4	0,30	1,70	0,67	0,35	0,04	0,31	0,03
Type 5	0,30	2,20	0,17	0,19	0,02	0,21	0,02
Type 6	0,30	2,70	0,00	0,30	0,03	0,30	0,03

Based on the analysis, it was found that the thicker the foam mortar layer, the smaller the settlement. This is due to the load from the embankment also becoming smaller. The largest settlement that occurred was in Type 1 foam mortar with an existing slope which reached 1.93 cm for 10 years. Meanwhile, the largest rate of settlement also occurred in Type 1 foam mortar with an existing slope of 0.20 cm/year. If compared to the requirements in Pt T-10-2002-B, for the rate of settlement that occurs after construction of road improvements with foam mortar material, it is found that for all types of lightweight embankment, foam mortar has met the requirements of settlement < 25 mm/year and total settlement < 10 cm in 10 years.

Analysis of Hydrostatic Uplift Pressure

Based on the flood hazard map of Aceh Jaya District (Badan Penanggulangan Bencana Kabupaten Aceh Jaya, 2013), the study location is included in the medium to high flood hazard index category. For this reason, road embankment with lightweight foam mortar material needs to be analyzed for the uplift pressure. Since there was no data on the flood height that occurred, this analysis will consider a condition with a flood height of 1.00 meters. The analysis was conducted by modeling the lift force of the embankment under the condition that water only presses on one side of the embankment as shown in **Error! Reference source not found.**. The calculation of factor of safety for the uplift pressure is calculated based on equation **Error! Reference source not found.**. The results of the safety factor calculation for the uplift pressure are shown in **Error! Reference source not found.**.

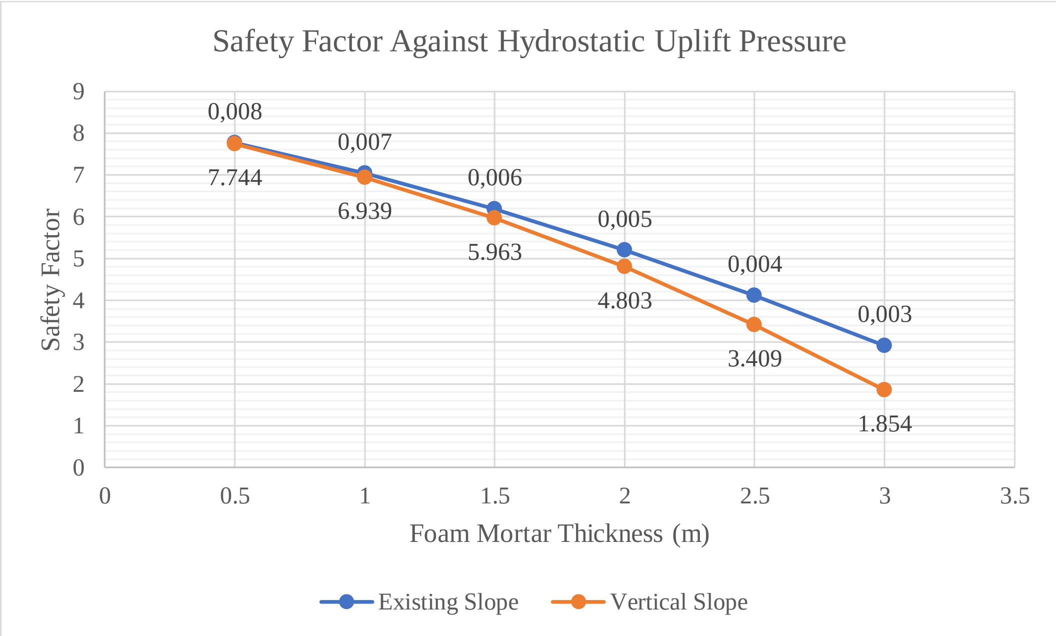


Figure 10. Safety factor against hydrostatic uplift pressure

Based on the results of the analysis, overall, for all types of lightweight foam mortar embankments, the safety factor requirement against lifting forces is at least FK = 1.1. From the figure above, it is also found that the thicker the foam mortar layer used, the lower the safety factor value. This is because the self-weight of the road embankment becomes smaller. At the same foam mortar thickness, the safety factor value of the upright slope foam mortar embankment has a smaller value than the existing slope. This is because the weight of the vertical slope foam mortar road embankment is lighter than the existing slope.

Evaluation of the Use of Foam Mortar Material as Embankment Improvement

Based on the results of the analysis of road embankment improvement using lightweight foam mortar material that has been conducted on the stability, settlement, and lifting force factors, it is found that the thickness of foam mortar that meets the requirements based on Pt T-10-2002-B. Based on these factors, it is found that the thickness of foam mortar that meets the requirements for embankments with existing slopes is 1.50-meter thick or more. Meanwhile, for foam mortar with vertical slope that meets the requirements is foam mortar with thickness of 2.00-meter or more.

CONCLUSIONS

Based on the results of the analysis that has been conducted, it can be concluded as follows :

1. The existing road embankment without any treatment has not met the required stability requirements so it needs reinforcement.

2. Improvement of road embankment using foam mortar lightweight material can increase the stability of the embankment compared to the existing embankment. The thicker the foam mortar layer used, the more the safety factor increases.
3. By improving the embankment using lightweight foam mortar material, the thicker the foam mortar layer used, the smaller the settlement and the rate of settlement that occurs.
4. The thickness of foam mortar that meets the requirements for existing slope embankment is 1.50-meter thick or more and for vertical slope embankment is 2.00-meter thick or more.

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