



Analysis of Foam Mortar and Prefabricated Vertical Drain (PVD) Application for Soft Soil Improvement on the Aruk–Sp. Take Road Section, Sambas Regency, West Kalimantan

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ABSTRACT

Infrastructure damage on the Aruk – Sp. Take Road Section, Sambas Regency (especially STA 99+000 to STA 99+550), is directly attributed to soft soil conditions characterized by low bearing capacity and high compressibility. Previous conventional repair methods were deemed ineffective, while permanent solutions involving Pile Slabs proved to be financially prohibitive for extensive road segments. This study aims to analyze the effectiveness of combining a lightweight fill material (Foam Mortar) with consolidation acceleration using Prefabricated Vertical Drains (PVD) on key geotechnical parameters: settlement, consolidation time, and slope stability. The methodology comprises soil data analysis, modeling of embankment designs with varying Foam Mortar compositions (0%, 25%, and 50%) at different heights, and consolidation calculations using a triangular PVD pattern. The analysis results demonstrate that installing PVD at an optimal spacing of 1.25 meters achieved a degree of consolidation of 91.2% within 22 weeks. Furthermore, the inclusion of Foam Mortar was proven significant in reducing the overall load and substantially improving stability. In the final height design of 3.30 meters, the 50% Foam Mortar variation reduced the maximum settlement to 1.38 meters (compared to 1.70 meters on 100% conventional earthfill) and drastically increased the Safety Factor (SF) from 1.90 to 3.06.

Keywords:

Soft Soil; Foam Mortar; Prefabricated Vertical Drain (PVD); Consolidation; Slope Stability.

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INTRODUCTION

The development of highway infrastructure in Indonesia, particularly on large islands such as Kalimantan, Sumatra, and Papua, is significantly challenged by local geological conditions. Sambas Regency in West Kalimantan Province presents a case where geotechnical properties are highly distinct and problematic. This region is dominated by Quaternary alluvial deposits and swamps, resulting in soft soil layers of varying thickness. These soils are typically characterized by very low bearing capacity and high compressibility. Such properties render infrastructure vulnerable to structural damage, manifesting as either sudden bearing capacity failure or excessive long-term settlement.

The structural failure of the Aruk – Sp. Take Road Section represents a critical case requiring urgent remediation. This road serves as a strategic corridor connecting economic centers within Sambas Regency to the Aruk Cross Border Post (PLBN), which functions as a vital export-import gateway between Indonesia and Malaysia. However, specific segments of this road, notably from STA 99+000 to STA 99+550, have suffered significant damage, as illustrated in Figure 1.

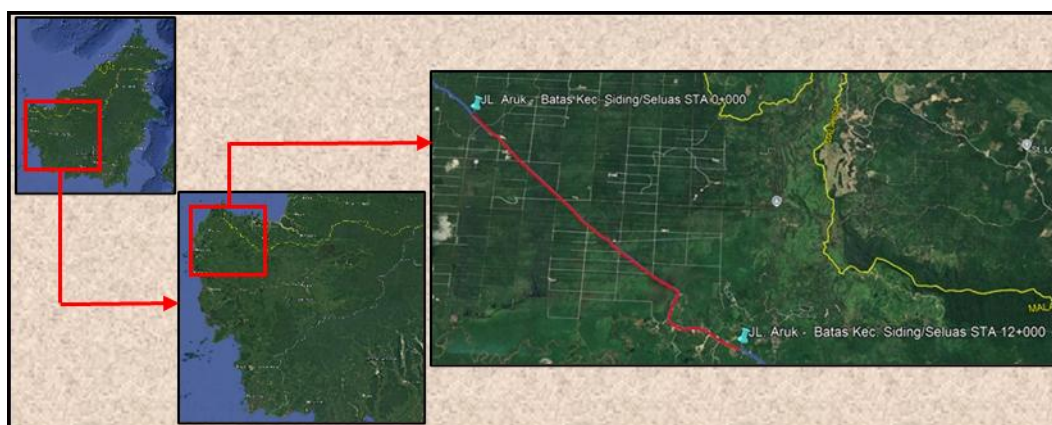


Figure Error! No text of specified style in document.. Location Map of the Aruk – Batas Road Section in Sambas Regency, West Kalimantan

The observed field damage includes vertical deformation (embankment subsidence) and horizontal deformation (lateral spreading at the toe of the embankment). Prior repair efforts, such as overlays and surface drainage improvements, have proven ineffective as they fail to address the core geotechnical problem: the inability of the subsoil to support the combined static and traffic loads.

In response to these repeated failures, authorities have considered a permanent solution using Pile Slab construction. This structure functions essentially as a structural bridge supported by deep piles, designed to transfer loads directly to the competent hard stratum, thereby bypassing the problematic soft soil. While this method offers high reliability with minimal risk of long-term degradation, it is capital-intensive. Given the limited national budget and the goal of equitable infrastructure development, implementing Pile Slabs for extensive road segments is deemed inefficient and financially burdensome.

Therefore, a comprehensive study of alternatives is urgent. The study must propose an engineering solution that is not only technically reliable but also economically viable. Two technologies with high potential are lightweight fill material (Foam Mortar) and soil consolidation acceleration using Prefabricated Vertical Drains (PVD). Since the integration of these methods has not been widely implemented in West Kalimantan, an in-depth analysis of their combined performance on the soft soil of Sambas Regency is highly relevant.

This study aims to analyze the effectiveness of soil improvement achieved by combining load reduction (via Foam Mortar) and vertical drainage improvement (via PVD). The evaluation includes the prediction of total settlement, consolidation time, and slope stability safety factors for the Aruk – Sp. Take Road Section.

Soft Soil

Soft soil is a term commonly used in geotechnical engineering to describe soil characterized by low bearing capacity and high compressibility. Terzaghi, Peck, and Mesri (1996) proposed a classification system that correlates the SPT N-value with soil consistency and estimated unconfined compressive strength (q_u), as presented in Table 1. Based on the table, soil that is categorized as soft soil and requires soil improvement methods is soil with an N-SPT value below 8 (eight).

Table 1 Classification of Soft Soils Based on NSPT

Consistency	N-SPT Value	Unconfined Compressive Strength (qu) (kPa)
Very Soft	< 2	< 25
Soft	2 - 4	25 - 50
Medium Stiff	4 - 8	50 - 100
Stiff	8 - 15	100 - 200
Very Stiff	15 - 30	200 - 400
Hard	> 30	> 400

Source: Terzaghi, Peck, & Mesri (1996)

Soil Consolidation

Terzaghi's one-dimensional consolidation theory serves as the basis for predicting the magnitude and rate of settlement in saturated clay soils (Terzaghi, 1943). The fundamental assumptions of this theory are that the soil is homogeneous and fully saturated, the soil grains and pore water are incompressible, and water flow occurs exclusively in the vertical direction following Darcy's Law (Das, 2010).

The magnitude of primary consolidation settlement in the field (S_{cp}) for Normally Consolidated (NC) soils is calculated using Equation (1):

$$S_{cp} = \frac{H}{1 + e_0} \left[C_c \log \left(\frac{\sigma'_o + \Delta\sigma}{\sigma'_o} \right) \right] \quad (1)$$

For Over Consolidated (OC) soils, where the preconsolidation stress is greater than the current effective stress, the calculation differs. Determining whether soil is NC or OC is crucial because surface soils are often "pseudo-overconsolidated" due to desiccation processes or historical fluctuations in groundwater levels (Holtz & Kovacs, 1981).

Parameter changes due to compression

The load imposed by the embankment will cause the underlying subsoil to compress or consolidate. This process induces changes in several key soil parameters: the void ratio (e) will decrease, the unit weight (γ) will increase, and the water content (w) will decrease. These property alterations ultimately enhance the bearing capacity of the subsoil. Once the subsoil has stabilized at this increased bearing capacity, the updated parameters serve as the basis for analyzing the stability of the embankment (Ladd, 1991).

The equations used in this study to determine these parameter changes are as follows:

$$e_{new} = e_0 \cdot \Delta e \quad (2)$$

$$\Delta e = (1 + e) \cdot \left(\frac{\Delta H}{H} \right) \quad (3)$$

$$WC_{new} = \frac{e_{new}}{GS} \quad (4)$$

$$\gamma_{new} = \left[\frac{GS \cdot (1 + wc)}{1 + e_{new}} \right] \cdot \gamma_w \quad (5)$$

Consolidation with PVD

Prefabricated Vertical Drains (PVD) consist of a grooved plastic core encased in a geotextile filter jacket, as illustrated in Figure 2. The plastic core functions as a vertical conduit for water discharge, while the geotextile filter prevents fine soil particles from entering and clogging the drainage system. This method is frequently applied in conjunction with preloading techniques, where a surcharge load is applied to the soil surface to generate excess pore water pressure. This pressure gradient drives pore water toward the PVDs, thereby significantly accelerating the consolidation process (Mesri & Khan, 2012).



Figure 2. Prefabricated Vertical Drain (PVD)

The efficiency of PVD is highly dependent on several factors, including the soil permeability coefficient, soft soil layer thickness, and drain spacing. The optimal spacing between PVDs is influenced by soil properties and specific project requirements, with the aim of minimizing consolidation time without significantly increasing costs (Mesri & Khan, 2012). Figure 3 illustrates the working mechanism of PVD.

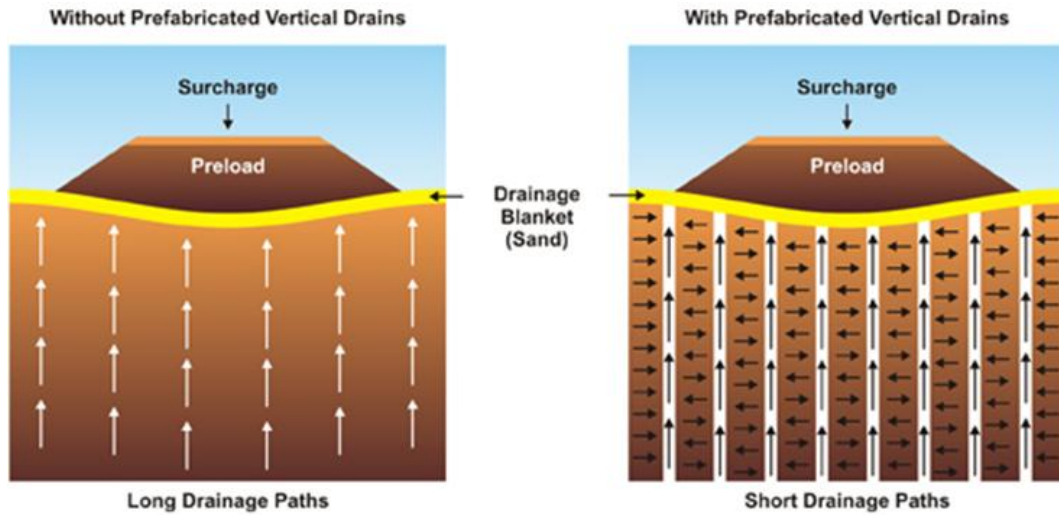


Figure 3. Illustration of How Preloading Works with PVD

Source: Indramas, (2001)

Mochtar (2012) explains that the rate of consolidation tends to decrease due to the smear effect (F_s) and well resistance (F_r). The magnitude of F_s depends on the degree of soil disturbance during PVD installation. For practical design purposes, its value can be approximated as equal to (F_n). Meanwhile, the well resistance factor (F_r) is considered to have a negligible influence; therefore, it can be assumed to be zero in the analysis. Consequently, the equation to calculate consolidation time simplifies to (Hansbo, 1981; Mochtar, 2012):

$$t = \left(\frac{D^2}{8 \cdot Ch} \right) \cdot (2 \cdot F(n)) \cdot \ln \left(\frac{1}{1 - \bar{U}_h} \right) \quad (6)$$

The degree of horizontal consolidation (U_h) in soil layers improved with PVD is determined as a function of time (t). In addition to horizontal flow, vertical consolidation (U_v) occurs simultaneously due to pore water drainage in the vertical direction. According to Das (1988), the value of U_v is calculated using different formulas depending on the magnitude of the time factor (T_v):

1. For U_v up to 60%:

$$U_v = \left(\sqrt{\frac{4T_v}{\pi}} \right) \times 100\% \quad (7)$$

2. For U_v above 60%:

$$U_v = (100 - 10^a)\% \quad (8)$$

With values are: α

$$a = \frac{1.781 - T_v}{0.933} \quad (9)$$

Once U_h and U_v are determined, the total average degree of consolidation (U) can be calculated using the following equation:

$$U = [1 - (1 - U_h) \cdot (1 - U_v)] \times 100\% \quad (10)$$

Foam Mortar

Foam mortar is a construction material produced by mixing cement, sand, and water with a stable, pre-formed foam. The microscopic air bubbles trapped within the cement matrix function as a lightweight aggregate, significantly reducing the material's density while maintaining adequate load-bearing capacity.

In accordance with Circular Letter No. 42/SE/M/2015 from the Directorate General of Highways, foam mortar used for highway applications must meet specific technical requirements:

- **Unit Weight**

The unit weight is adjustable, ranging from 0.6 to 1.2 tons/m³. For embankments on very soft soil, a unit weight of 0.6–0.8 tons/m³ (6–8 kN/m³) is the optimal choice. This is equivalent to one-third of the unit weight of conventional earth fill (18–20 kN/m³), resulting in a static load reduction of up to 60–70%.

- **Compressive Strength (UCS)**

Despite its lightweight nature, foam mortar possesses significant compressive strength, typically ranging from 800 kPa (for sub-base) to 2000 kPa (for base layers). This strength is sufficient to withstand traffic loads without experiencing significant plastic deformation, unlike natural soil which exhibits elasto-plastic behavior.

The application of foam mortar addresses two critical failure mechanisms in soft soil engineering:

- **Stability:**

The reduction in self-weight decreases the driving moment on the embankment slope, increasing the Safety Factor instantly.

- **Settlement:**

As the overburden load is drastically reduced, consolidation settlement decreases proportionately. In cases where the in-situ soil is near its pre-consolidation pressure, using foam mortar ensures the final stress remains below this threshold. Consequently, the soil stays within the elastic range (recompression curve), avoiding substantial plastic settlement.

METHOD

The methodology of this study combines the collection of secondary data (including Detailed Engineering Design/DED, topographic maps, and field documentation) with primary data obtained through laboratory tests on disturbed and undisturbed soil specimens. This data is utilized to determine the geotechnical parameters of the subgrade and to analyze the feasibility of replacing the existing slab-on-pile structure with an embankment construction.

The alternative embankment design was modeled using conventional earth fill and foam mortar, with variations in foam mortar layer thickness of 0%, 25%, and 50% of the planned

road elevation, with unit weight = 7 kN/m³, applied to a uniform slope geometry. Soil compression analysis was conducted to calculate the total settlement. If significant settlement is predicted, consolidation acceleration is planned to use Prefabricated Vertical Drains (PVD). Additionally, if required, ground reinforcement options include the use of geotextiles.

RESULTS AND DISCUSSION

Soil Data

Borehole data from BH-04 (STA 99+325) reveals distinct soil stratification. The upper layer (0–2.0 m) consists of soft organic soil, underlain by layers of silty clay extending to a depth of 9.0 m with increasing stiffness. Table 2 summarizes the physical and mechanical soil properties.

Table 2. Soil data used for analysis

No.	Soil Type	Depth (m)	Zair	N-SPT	PI (%)	LL (%)	n	Cc	Cv (cm ² /s)	γ _t (t/m ³)
1	Organic Silt	0-1	0	0	10	75	4,236	2,650	0,0005	1,056
2	Organic Silt	1-2	0,5	0	10	75	4,236	2,650	0,0005	1,056
3	Sandy Silt	2-3	1,5	4	37	70	1,125	0,455	0,0007	1,800
4	Silty Clay	3-4	2,5	4	37	70	1,125	0,455	0,0007	1,800
5	Silty Clay	4-5	3,5	7	37	70	1,125	0,455	0,0007	1,800
6	Silty Clay	5-6	4,5	6	37	70	1,125	0,455	0,0007	1,800
7	Silty Clay	6-7	5,5	7	37	70	1,125	0,455	0,0007	1,800
8	Silty Clay	7-8	6,5	6	37	70	1,125	0,455	0,0007	1,800
9	Silty Clay	8-9	7,5	9	30	61	0,889	0,339	0,0010	1,900
10	Sandy Silt	9-10	8,5	8	30	61	0,889	0,339	0,0010	1,900
11	Sandy Silt	10-11	9,5	11	30	61	0,889	0,339	0,0010	1,900
12	Sandy Silt	11-12	10,5	11	30	61	0,889	0,339	0,0010	1,900
13	Fine to medium sand	12-13	11,5	11	0	NP	0,889	0,000	0,0010	1,900
14	Fine to medium sand	13-14	12,5	10	0	NP	0,889	0,000	0,0010	1,900
15	Fine to medium sand	14-15	13,5	31	0	NP	0,700	0,000	0,0040	2,000
16	Fine to medium sand	15-16	14,5	30	0	NP	0,700	0,000	0,0040	2,000
17	Fine to medium sand	16-17	15,5	30	0	NP	0,700	0,000	0,0040	2,000
18	Fine to medium sand	17-18	16,5	30	0	NP	0,700	0,000	0,0040	2,000
19	Fine to medium sand	18-19	17,5	29	0	NP	0,700	0,000	0,0040	2,000

20	Fine to medium sand	19-20	18,5	28	0	NP	0,700	0,000	0,0040	2,000
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Embankment Design

The design of the embankment is planned with a slope of 1:1, height variations ranging from 2 to 3.3 meters and the width of the top subgrade of 15 meters. Analysis was carried out on the variation in the height of the embankment at 2 m, 2.7 m, and 3.3 m with 2 layers of Geotextile $T_{ult} = 200$ kN/m at the bottom as separator. The configuration of materials between the soil common fill and the foam mortar used is 100% common fill 0% foam mortar, 75% common fill 25% foam mortar, 50% common fill 50% foam mortar as illustrated in Figure 4.

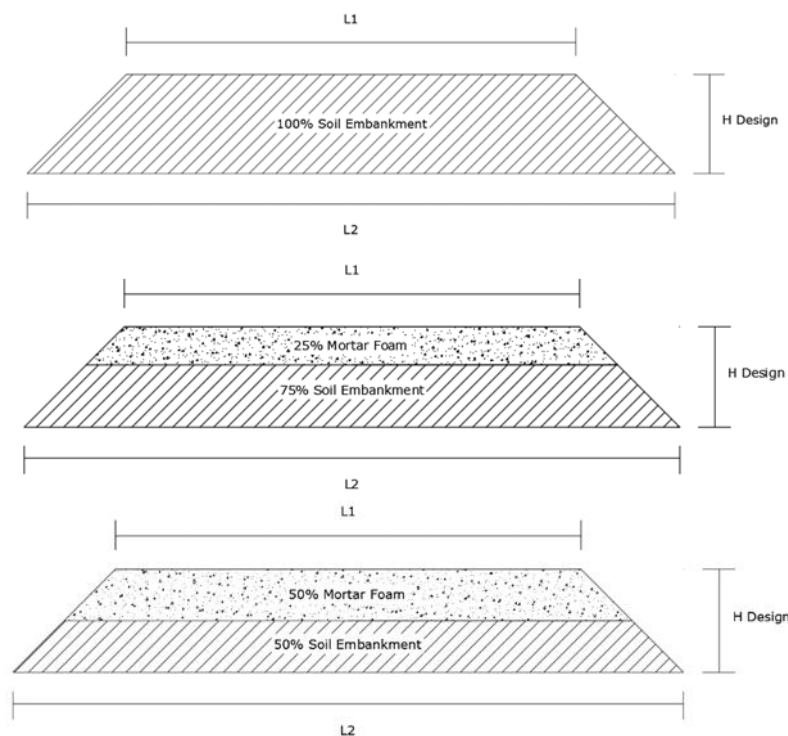


Figure 4. Illustration of the Design of the Embankment

Total Settlement

Furthermore, based on the results of the calculation using Equation (1) for the height variation, the compression value for each combination summarized in Table 3 is obtained. The relationship between the final height (H_{final}) and settlement (Sc) is presented in the form of a curve in Figure 5.

Table 3. Recapitulation of Settlement in Each Variety of Embankment

Common Fill %	Foam Mortar %	Common Fill (m)	Foam Mortar (m)	Pavement (m)	H_{final} (m)	$H_{initial}$ (m)	Sc (m)
100%	0%	2,77	0,00	0,535	3,30	4,46	1,70
100%	0%	2,17	0,00	0,535	2,70	3,72	1,55
100%	0%	1,47	0,00	0,535	2,00	2,82	1,35
75%	25%	2,77	0,69	0,535	3,30	4,31	1,55
75%	25%	2,17	0,54	0,535	2,75	3,58	1,41
75%	25%	1,47	0,37	0,535	2,00	2,70	1,24

50%	50%	2,77	1,38	0,535	3,30	4,15	1,38
50%	50%	2,17	1,08	0,535	2,70	3,42	1,26
50%	50%	1,47	0,73	0,535	2,00	2,56	1,09

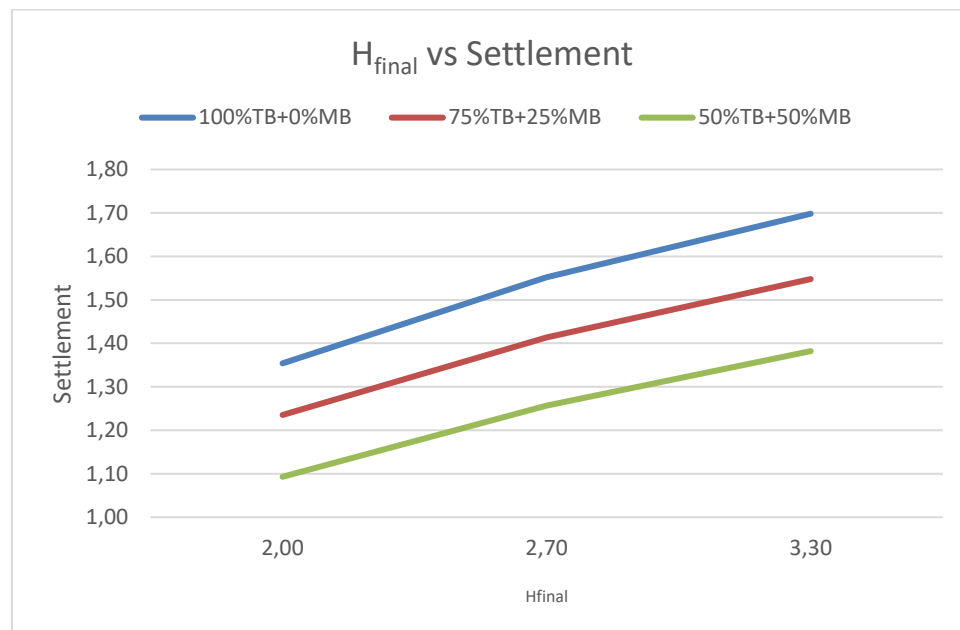


Figure 5. Graph of the Relationship between H_{final} and Settlement

PVD Planning

The acceleration of consolidation due to Prefabricated Vertical Drains (PVD) was analyzed using Equation (6). The analysis assumed a triangular pattern with varying spacing. The calculated degree of consolidation (U) was plotted against time (t) as shown in Figure 6. The results indicate that the target degree of consolidation of 91.2% is achievable within 22 weeks using an optimal spacing of 1.25 meters.

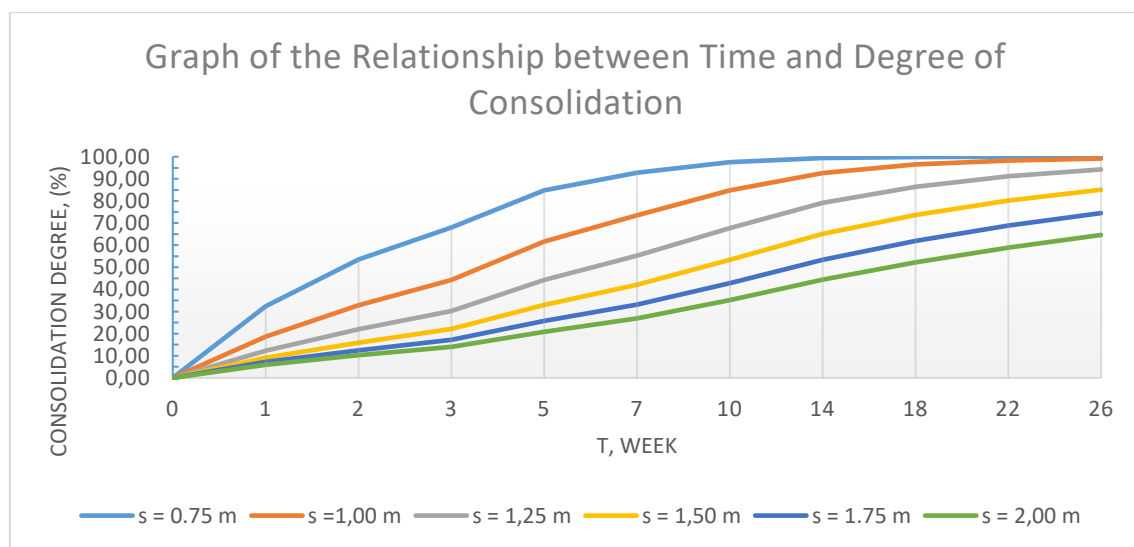


Figure 6. Graph of the Relationship between Time and the Degree of PVD Consolidation

Embankment Stability

By using a LEM-based program, the Safety Factor of each variety of embankment design that has been summarized in Table 4 is obtained and the graph of the relationship between H_{akhir} and SF in each variation of embankment can be seen in Figure 7.

Table 4. Safety Factor Recapitulation for Each Variation of Embankment

Common Fill %	Foamed Mortar %	H_{final} (m)	SF
100%	0%	3,30	1,90
100%	0%	2,70	2,07
100%	0%	2,00	2,20
75%	25%	3,30	2,35
75%	25%	2,70	2,68
75%	25%	2,00	2,91
50%	50%	3,30	3,06
50%	50%	2,70	3,28
50%	50%	2,00	3,62

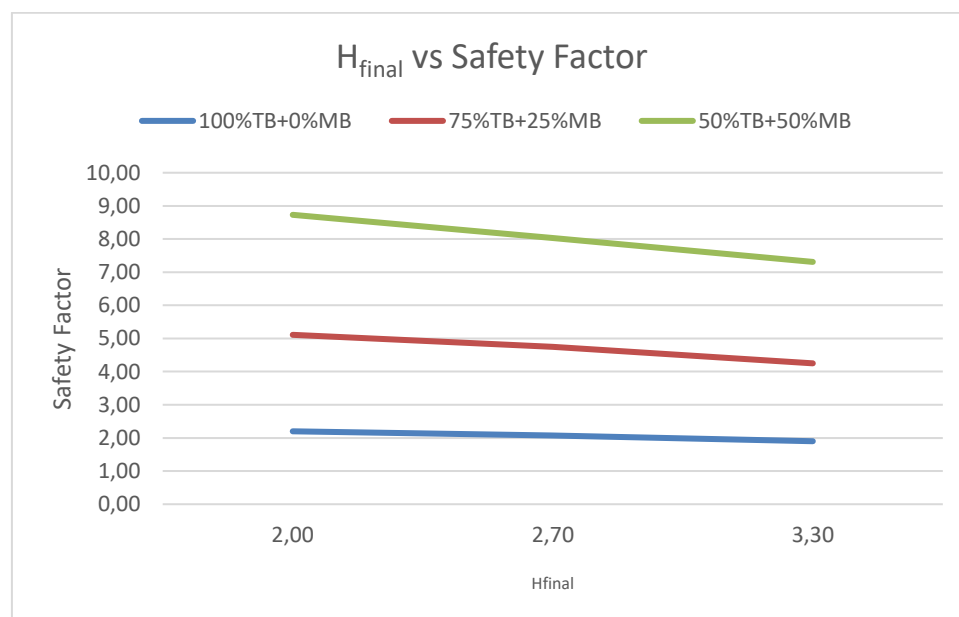


Figure 7. Graph of the Relationship between H_{final} and Safety Factor

Based on the summary analysis in Table 4 and Figure 7, it can be concluded that the embankment material composition and final height significantly influence the Safety Factor (SF). There is a positive correlation between the percentage of foam mortar and slope stability. Notably, substituting conventional fill with 50% foam mortar substantially increased the SF compared to 100% conventional fill. This is evidenced by the SF increase from 1.90 to 3.06 at a height of 3.30 m.

CONCLUSION

Based on the analysis of Foam Mortar and Prefabricated Vertical Drains (PVD) as soil improvement methods for the Aruk – Sp. Take Road Section, Sambas Regency, it is concluded

that applying PVD in a triangular pattern is essential for accelerating consolidation. An optimal spacing of 1.25 meters achieves a 90% degree of consolidation within 22 weeks. Additionally, Foam Mortar serves as an effective lightweight filling material to mitigate settlement caused by embankment loads. At a final height of 3.30 meters, substituting conventional fill with 50% Foam Mortar reduced settlement to 1.38 meters, compared to 1.70 meters with 100% conventional soil fill. This indicates that reducing the overburden load significantly minimizes subsoil settlement. Furthermore, substituting conventional fill with Foam Mortar substantially improves slope stability, as evidenced by a significant increase in the Safety Factor (SF). At an embankment height of 3.30 meters, 100% conventional soil fill yields an SF of 1.90, whereas a 50% Foam Mortar configuration increases the SF to 3.06, indicating a significantly reduced risk of slope failure.

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