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Comparison Between Soil Improvement Design Method of Replacement and PVD Installation for Soft Soil Embankment, Case Study: Probolinggo – Banyuwangi Toll Road Project Section 3 Sta 23+075 – 23+670

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ABSTRACT

The Probolinggo – Banyuwangi Toll Road, part of Trans Java Toll Road, is one of the strategic projects which connects the west to the east of the island of Java. On this toll road, precisely in section 3 STA 23+075 – 23+670, the toll road structure and pavement construction stands on soft ground with varying depths, with the deepest point being around 9 meters. It is concerned that the presence of soft soil which is quite deep will cause damage to the pavement, which will cause discomfort for road users if the soft soil cannot be improved properly. In this study, several alternatives are designed which will later be used as considerations for the project owner to determine the most effective method for improving soft soil at that location. The method used is subgrade replacement which will later be compared with the use of PVD along with estimated costs for each method. Apart from that, an analysis was also carried out regarding compliance with the rate of residual settlement regulations from the Director General of Highways, namely less than 2 cm per year and less than 10 cm per 10 years. From the study results, it was found that the rate of settlement of all variations of soft soil and replacement had met the Bina Marga regulations. In addition, a comparison of PVD cost requirements with replacement showed that PVD requires lower costs than replacement with a maximum time of ±5 weeks so that it can be concluded as the best alternative method.

Keyword : soft soil, PVD, settlement, replacement

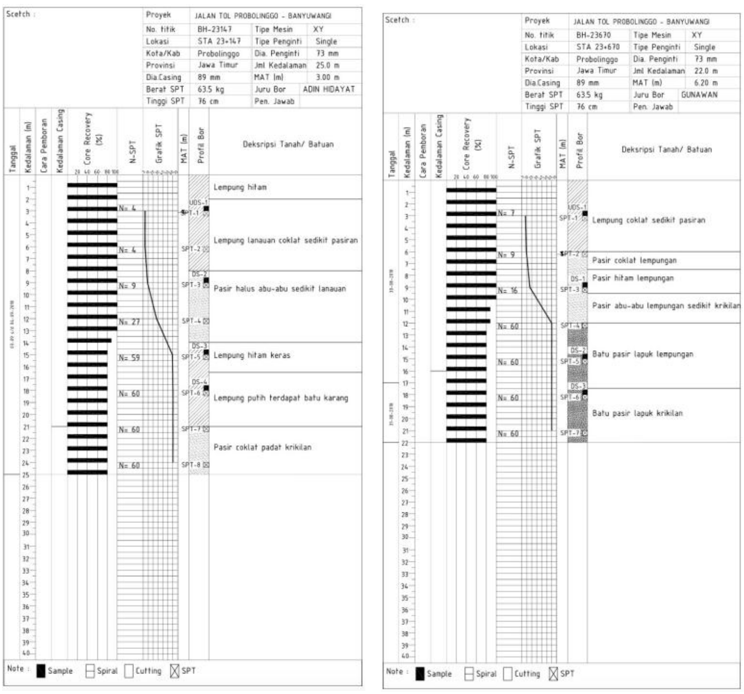
INTRODUCTION

The Probolinggo-Banyuwangi Toll Road is part of the National Strategic Projects (PSN) and an integral segment of the Trans-Java Toll Road network, connecting the western and eastern ends of Java Island. This toll road spans approximately 171.52 kilometers from Probolinggo to Banyuwangi, divided into seven sections. Currently, Phase 1 construction is underway for the Gending–Besuki segment, which covers a distance of 49.68 kilometers. This project, undertaken by PT Jasamarga Probolinggo Banyuwangi, is targeted for completion in the second quarter of 2025.

Figure 1. Peta Jalan Tol Probolinggo-Banyuwangi Tahap 1
(Source: PT Jasamarga Probolinggo Banyuwangi)

The existing condition of the planned alignment of the Probolinggo-Banyuwangi toll road, Section 3, STA 23+075 – 23+670, is predominantly characterized by paddy fields, with some residential areas also present, as shown in Figure 3 and Figure 4. Based on the results of subsoil investigations at this location, depicted in Figure 5 and Figure 6, a layer of soft soil was identified up to a depth of 13.5 meters, predominantly consisting of clay with varying N-SPT values. The embankment height is generally uniform throughout the study area, averaging around 5.5 meters. The surface at this location is relatively flat, with no significant depressions or elevations observed.

Figure 2. Location STA 23+075
(Source: PT Jasamarga Probolinggo Banyuwangi)



(a) (b)

Figure 3. N-SPT value from Bore Log STA 23+075 (a) Bore Log STA 23+670 (b)
(Source: PT JasamaSrga Probolinggo Banyuwangi)

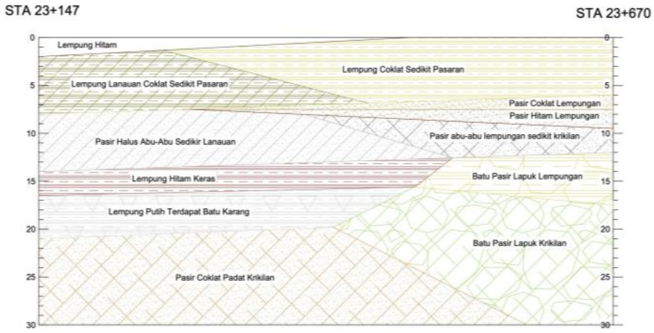


Figure 4. Soil Stratigraphy at Location STA 23+075 – 23+670 Based on Borelog Data (Source: PT Jasamarga Probolinggo Banyuwangi)

The presence of deep soft soil at the site, combined with a limited construction period and a relatively short maintenance phase, necessitates the implementation of soil improvement methods that account for potential soil settlement. This is essential to minimize significant impacts on toll road infrastructure and ensure the comfort of road users. Additionally, it aims to prevent the project owner from incurring substantial costs for repairs after the contractor's maintenance period has concluded.

This study aims to identify alternative methods for effective soft soil improvement that can be implemented in the field. The proposed alternatives in this research include subsoil replacement with varying depths and the use of prefabricated vertical drains (PVD) with lengths corresponding to the depth of the soft soil. The embankment height used in the study is consistent at 5.5 meters, as the planned embankment height at the research location is relatively uniform, averaging approximately ±5.5 meters.

The research location along STA 23+075 – 23+670 is divided into two segments, as follows:

1. The depth of soft soil is less than 6 meters: STA 23+475 to 23+670. In this research location, variations of depth calculations were used, namely 4 meters, 5 meters, and 6 meters. At this location, planning was conducted for the replacement of the subgrade soil with depth variations of 1 meter, 2 meters, and 3 meters, along with the use of PVD up to the depth of the soft soil.
2. The depth of soft soil is more than 6 meters: STA 23+075 to 23+475. In this research location, variations of depth calculations were used, namely 8 meters, 10 meters, and 12 meters. At this location, planning was conducted for the use of PVD up to the depth of the soft soil.

From the methods mentioned above for each segment, an analysis is required regarding the stability of the embankment and the magnitude of the rate of consolidation settlement in relation to the compliance with the requirements set by the Directorate General of Highways for Class I Roads, with a vertical settlement of less than 20 mm per year and less than 100 mm per 10 years for the pavement structure.

Furthermore, it is necessary to calculate the stability of the embankment with a planned safety factor of 1.5. If the calculated safety factor does not meet the minimum value, embankment reinforcement is required using geotextile. Subsequently, a cost estimation calculation for the improvement method mentioned above is carried out as a consideration for selecting the soft soil improvement method.

LITERATUR REVIEW

Soil Compaction

The addition of load on a surface of soil can cause the underlying soil layers to experience compaction (Das, 1985). Consolidation is the process of a decrease in water content in a saturated soil layer without the replacement of water by air (Terzaghi, 1943). Generally, the settlement caused by loading is divided into two main categories:

1. Immediate settlement, which is the elastic deformation of dry, wet, and saturated soils without any change in water content.
2. Consolidation settlement, which results from the change in volume of saturated soil due to the expulsion of water occupying the soil pores, caused by the placement of a fill with a height of H above the soft soil, leading to an increase in stress in the soil.

Consolidation Settlement

Soil consolidation can be divided into two types: primary consolidation and secondary consolidation. Secondary consolidation occurs after primary consolidation is completed. When the soil first receives a load, it is initially absorbed by the water, causing an increase in pore water pressure (excess pore pressure). During primary consolidation, the pore water pressure decreases as water is expelled from the soil pores. Afterward, secondary consolidation occurs, where water moves from the micropores to the macropores under constant water pressure.

Consolidation Time of Natural Soft Clay

A very long time is required for the natural compaction of soft soil, as it is highly impractical to compress the pore water out of the soil, as illustrated in Figure 5.

Figure 5. Consolidation Occurring in Natural Soft Clay
(Source: Wahyu, 2019)

Prefabricated Vertical Drain (PVD)

PVD (Prefabricated Vertical Drain) is a material used to help accelerate the soil consolidation process so that construction work can proceed quickly. PVD is installed vertically in compressible soils such as clay and silty clay, as these soil types are water-saturated and have grain characteristics that do not adhere to one another.

Figure 6. Prefabricated Vertical Drain (PVD) (PT Teknindo Geosistem Unggul, 2015)

The installation pattern for PVDs (Prefabricated Vertical Drains) to date uses two pattern options, namely the triangular pattern and the rectangular (square) pattern, as show in the Figure 7.

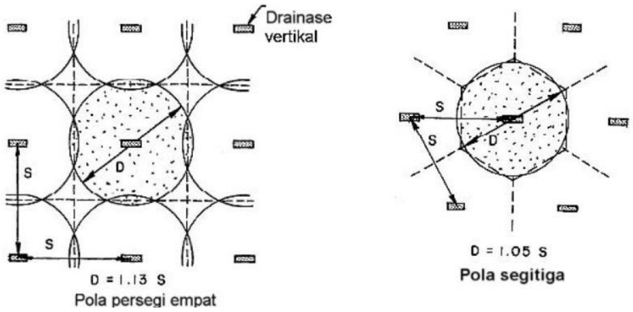


Figure 7. PVD Installation Pattern (Wahyu, 2019)

Calculation of PVD is using formula below:

$$t = \frac{T_v \times S}{C_h} \quad \ldots (1)$$

$$t = \frac{D^2}{8 \times C_h} \times F(n) \times \ln \frac{1}{1 - U_h} \quad \ldots (2)$$

$$U_h = [1 - exp(-x)] \times 100\% \quad \ldots (3)$$

$$x = \frac{8 \times C_h \times t}{D^2 \times F(n)} \quad \ldots (4)$$

$$F(n) = \ln\left(\frac{D}{d_w}\right) - \frac{3}{4} \quad \ldots (5)$$

$$U_v = \left(2\sqrt{\frac{T_v}{\pi}}\right) \times 100\% \quad \ldots (6)$$

$$T_v = \frac{t \times C_v}{(H_{dr})^2} \quad \ldots (7)$$

Where:

Tv = Time factor
S = Distance between PVDs (m)
Ch = Horizontal consolidation coefficient (cm^2/s), where the value of Ch ≈ 2-5 times Cv.
t = Time required to complete primary consolidation (seconds)
D = Equivalent diameter of the soil circle representing the influence area of the vertical drain (m)
Uh = Degree of horizontal consolidation of the soil
Uh = Degree of vertical consolidation of the soil

Geotextile

Geotextile is a type of geosynthetic material that can be used to improve soil stability. There are three common types of geosynthetics used in construction: woven geotextile, non-woven geotextile, and geogrid. In principle, geotextile can enhance soil stability due to the increase in tensile strength ($T_{allowable}$) provided by the geosynthetic material. Geotextile is calculated with formula below:

$$T_{allowable} = T_{ult}\left(\frac{1}{FS_{ID} \times FS_{CR} \times FS_{CD} \times FS_{BD}}\right) \quad \ldots (8)$$

Where:
Tallow = available geotextile strength
Tult = ultimate geotextile strength
FSID = safety factor due to installation errors
FSCR = safety factor due to creep
FSCD = safety factor due to chemical influences
FSBD = safety factor due to biological influences

Replacement

The soil improvement method using the soil replacement technique is one way to improve the properties of the soil at a construction site by removing the soft underlying soil and replacing it with selected fill material that has a higher bearing capacity. This method is widely applied in infrastructure projects such as road construction, bridges, embankments, and buildings. An illustration of the replacement method can be seen in Figure 8.

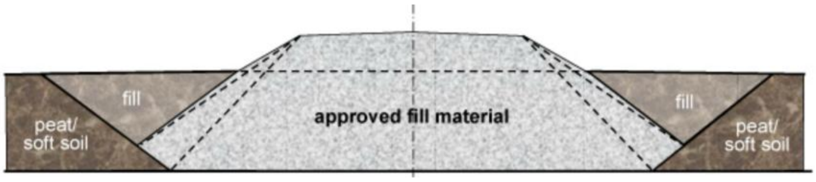


Figure 8. Replacement Illustration

To calculate the settlement of the soil using the replacement method, the value of q is determined using the following equation:

$$q_1 = (H_{initial} \times \gamma_{embankment}) + \left(H_{replacement} \times (\gamma_{soil\ replacement} - \gamma_{soil})\right) \quad \dots (9)$$

$$q_2 = \left((H_{initial} - S_c) \times \gamma_{embankment}\right) + \left((H_{replacement} + S_c) \times (\gamma_{soil\ replacement} - \gamma_{soil})\right) \quad \dots (10)$$

RESEARCH METHOD

1. Secondary Data Collection
   The data collected at this stage consists of secondary data, which includes the Detail Engineering Design (DED), Final Engineering Plan, and the results of the Subgrade Soil Test obtained from PT Jasamarga Probolinggo Banyuwangi.
2. Calculation of Compaction Amount with a Fixed Fill Height of 5.5 meters
   This study investigates methods to eliminate primary and secondary compaction using the preloading method. Therefore, it is necessary to calculate both primary and secondary compaction. Secondary compaction is calculated after primary compaction is completed.
   Primary settlement is calculated using the following assumptions:
   a. The calculation starts after the construction period, without considering the maintenance period, with an assumed construction period of 2 years, i.e., from the 2nd to the 3rd year (for Sc < 2 cm per year) and from the 2nd to the 12th year (for Sc < 10 cm per year).
   b. The calculation starts after the maintenance period, with an assumed construction period of 2 years and a maintenance period of 3 years, i.e., from the 5th to the 6th year (for Sc < 2 cm per year) and from the 5th to the 15th year (for Sc < 10 cm per year).
3. Replacement Design
   The subgrade replacement is carried out by replacing the subgrade with selected fill material. The depth of the replaced subgrade varies, with depths of 1 meter, 2

meters, and 3 meters. Subsequently, primary and secondary compaction calculations are performed.

4. PVD Design

   The use of PVD (Prefabricated Vertical Drain) is applied to the depth of the soft soil to accelerate the soil compaction process.

5. Embankment Stability and Reinforcement Calculation using Geotextile

   At this stage, the new soil parameters after compaction are calculated, followed by a stability analysis using support software. If the soil is unstable, geotextile reinforcement is required, and the soil stability is recalculated using support software.

6. Cost Estimation Calculation

   This cost estimation calculation covers only the material costs to be used in both methods.

7. Determination of Optimal Design

   At this stage, the most effective design from both methods is determined, considering costs and ease of implementation in the field.

DATA ANALYSIS

N-SPT and Laboratory Test Result

The secondary data obtained from PT Jasamarga Probolinggo Banyuwangi that will be used in this research is as follows.

Table 1. Summary of laboratory test result (secondary data)

		UDS1	DS2	DS3	DS4	UDS1
Depth	m	2,5-3	8,5-9	14,5-15	17,5-18	2,5-3
Soil Consistency		*Soft*	*Stiff*	*Hard*	*Hard*	*Soft*
Specific Gravity, Gs		2,538	2,556	2,541	2,535	2,538
Bulk Density, γn	kN/m^3	18,61	20,68	18,09	19,21	18,61
Dry Bulk Density, γd	kN/m^3	12,5	15,31	11,43	13,21	12,5
Porosity, n		0,51	0,4	0,55	0,48	0,51
Degree of Saturation, Sr	%	100	100	100	100	100
Water Content, Wn	%	48,35	31,78	54,18	45,25	48,35
Liquid Limit, LL		38,75	NP	38,75	80	38,75
Plastic Limit, PL		29,14	NP	26,53	40,27	29,14
Plasticity Index, IP		9,61	NP	12,22	39,73	9,61
Cohesi Undrained, Cu	kN/m^2	12,5	0	9	57	12,5
Shear Angle, ϕ	degree	10,01	29,25	18,78	10,01	10,01
Compression Index, Cc		0,2	0,47		0,3	0,2
Consolidation Coefficient, Cv	cm^2/sec	0,0141	0,005		0,0042	0,0141

The consolidation coefficient used in this calculation is based on the correlation from the Biarez and Favre (1976) table. With a dry density (γd) of 1.25 g/cm^3, the value of Cv obtained from the table correlation is 0.0071875. Meanwhile, the value of Cu is obtained using the formula from Ardana and Mochtar (1999).

RESEARCH ANALYSIS

1. Calculation of Primary and Secondary Compaction Using the Preloading Method

The calculation of primary and secondary compaction is performed based on the thickness of the compressible soil layer. The primary compaction calculation is conducted as a result of the embankment load (q_o) with variations of 4, 7, 10, 13, and 16 t/m^2. Below are the calculation results for soft soil with a thickness of 4 meters, H = 1 meter, and q = 4 t/m² from the surface.

Table 2a. Calculation Results of Primary Compaction for qo = 4 t/m^2

Depth			H	z	e_o	σ'0	σ'c	Δσ	Δσ+σ'0	Sc	ΣSc
m						t/ m²	t/ m²			m	m
0	-	1	1	0,5	1,04	0,377	2,377	6,308	4,377	0,051	0,051

Table 3b. Calculation Results of Primary Compaction for qo = 4 t/m^2

Depth			H	z	e_o	σ'0	σ'c	Δσ	Δσ+σ'0	Sc	ΣSc
m						t/ m²	t/ m²			m	m
1	-	2	1	1,5	1,04	1,130	3,130	2,769	5,130	0,036	0,087
2	-	3	1	2,5	1,04	1,884	3,884	2,062	5,881	0,029	0,116
3	-	4	1	3,5	1,04	2,638	4,638	1,758	6,629	0,024	0,141

After calculating the primary compaction, the next step is to calculate the secondary compaction using the preloading method. This calculation is conducted to eliminate both primary and secondary compaction simultaneously. The calculation of secondary compaction begins after the completion of primary compaction and extends up to the 10th year. The secondary compaction calculation uses the void ratio (e) alue after the primary compaction, with t_2 being 10 years after t_p. After obtaining the initial embankment height ($H_{initial}$) and and final embankment height (H_{final}), the embankment removal height is also calculated to ensure the embankment height aligns with the design specified by the planning consultant. The secondary compaction calculation is performed for all variations of soft soil and embankment loads q_o (4, 7, 10, 13, 16 t/m^2) for each variation of soft soil, with a time frame of 5, 10, and 15 years. A summary of these calculations can be found in Table 4. Summary of Primary (Sc) and Secondary (Ss) Compaction Calculations at a Soft Soil Depth of 4 Meters Table 4.

Table 4. Summary of Primary (Sc) and Secondary (Ss) Compaction Calculations at a Soft Soil Depth of 4 Meters

q	Sc	Ss 5 years	Ss 10 years	Ss 15 years	Sc+Ss 5 years	Sc+Ss 10 years	Sc+Ss 15 years
t/m^2	m	m	m	m	m	m	m
4	0,141	0,021	0,029	0,034	0,161	0,169	0,174
7	0,232	0,022	0,033	0,039	0,255	0,265	0,271
10	0,295	0,025	0,035	0,041	0,320	0,330	0,336
13	0,343	0,026	0,034	0,040	0,369	0,377	0,384
16	0,382	0,026	0,032	0,037	0,408	0,414	0,420

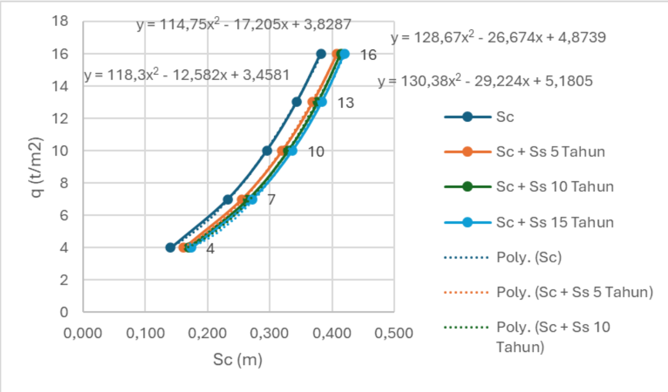


Figure 9. Graph of the Relationship Between Primary Compaction (Sc) and Embankment Load (q)

From Table 4, a graph illustrating the relationship between primary compaction (Sc), combined primary and secondary compaction (Sc+Ss), and embankment load (q) is presented in Figure 9. This graph is utilized to determine q_1 and q_2. The graph shows that as the review period for compaction increases over the years, the value of secondary compaction (Ss) becomes higher, and the required embankment load (q) also increases.

2. **PVD Design**

After obtaining the results of primary and secondary compaction, it was concluded that the installation of PVD is required in this study to accelerate the consolidation process, which is expected to be completed during the project's construction phase. The installation of PVD is one of the methods to expedite the release of pore water from the soil by shortening the pore water flow path toward the horizontal direction within just a few months. Combining PVD with preloading can further accelerate the water flow as the soil becomes compressed. In this calculation, two PVD installation patterns are used: triangular and square, with PVD type CT-D822. Five different spacings (S) are considered: 0.75, 1, 1.25, 1.5, 1.75, and 2 meters. PVD is installed to the depth of compressible soil layers, specifically 4, 5, 6, 8, 10, and 12 meters.

Table 5. Summary of PVD Installation Requirements for the Triangular Pattern Across All Variations in Soft Soil Depth

PVD Installation Spacing	PVD Requirements at Soft Soil Depth (m)					
	4 m	**5 m**	**6 m**	**8 m**	**10 m**	**12 m**
0,75	50.820	63.525	76.230	101.640	127.050	152.460
1	29.000	36.250	43.500	58.000	72.500	87.000
1,25	18.612	23.265	27.918	37.224	46.530	55.836
1,5	12.948	16.185	19.422	25.896	-	-

Table 6. Summary of PVD Installation Cost Requirements for the Triangular Pattern Across All Variations in Soft Soil Depth

Spacing PVD	PVD Installation Cost Requirements at Soft Soil Depth (Rp)					
	4	**5**	**6**	**8**	**10**	**12**
0,75	928.379.760	1.160.474.700	1.392.569.640	1.856.759.520	2.320.949.400	2.785.139.280
1	529.772.000	662.215.000	794.658.000	1.059.544.000	1.324.430.000	1.589.316.000
1,25	340.004.016	425.005.020	510.006.024	680.008.032	850.010.040	1.020.012.048
1,5	236.534.064	295.667.580	354.801.096	473.068.128	-	-

Table 7. Summary of PVD Installation Requirements for the Square Pattern Across All Variations in Soft Soil Depth

PVD Installation Spacing	PVD Requirements at Soft Soil Depth					
	4 m	5 m	6 m	8 m	10 m	12 m
0,75	37.867	47.333	76.230	75.733	94.667	113.600
1	21.200	26.500	43.500	42.400	53.000	63.600
1,25	13.760	17.200	27.918	27.520	34.400	41.280

Table 8a. Summary of PVD Installation Cost Requirements for the Square Pattern Across All Variations in Soft Soil Depth

Spacing PVD	PVD Installation Cost Requirements (Rp)					
	4	5	6	8	10	12
0,75	691.748.267	864.685.333	1.392.569.640	1.383.496.533	1.729.370.667	2.075.244.800
1	387.281.600	484.102.000	794.658.000	774.563.200	968.204.000	1.161.844.800

Table 9b. Summary of PVD Installation Cost Requirements for the Square Pattern Across All Variations in Soft Soil Depth

Spacing PVD	PVD Installation Cost Requirements (Rp)					
	4	5	6	8	10	12
1,25	251.367.680	314.209.600	510.006.024	502.735.360	628.419.200	754.103.040

3. Replacement Calculation

The replacement calculation is performed using the primary compaction calculation as previously described.

Table 10a. Summary of Primary and Secondary Compaction Calculations for All Soft Soil Depths with Various Replacement Variations

	Depth (m)	q (t/m2)	Δq (m)	Preloading Requirements (m)	Sc (m)	Ss (m)	Sc+Ss (m)	t (years)
Without Replacement	4	12,829	2,398	1,076	0,339	0,034	0,373	1,50
	5	11,130	4,046	1,815	0,401	0,040	0,441	2,34
	6	12,943	2,174	0,975	0,459	0,044	0,503	3,37
	8	13,043	1,927	0,864	0,563	0,049	0,612	5,99
	10	13,075	1,697	0,761	0,651	0,052	0,703	9,35
	12	13,231	1,516	0,680	0,734	0,053	0,787	13,47
Replacement 1 m	4	13,349	0,488	0,219	0,278	0,027	0,305	0,84
	5	13,445	0,613	0,275	0,349	0,034	0,383	1,50
	6	13,645	0,730	0,327	0,416	0,040	0,456	2,34
	8	13,893	0,937	0,420	0,534	0,050	0,584	4,58
	10	14,105	1,119	0,502	0,638	0,051	0,689	7,58
	12	14,297	1,281	0,575	0,731	0,053	0,784	11,32
Replacement 2 m	4	13,654	0,354	0,159	0,202	0,018	0,220	0,37
	5	13,825	0,496	0,223	0,283	0,026	0,309	0,84
	6	13,976	0,625	0,280	0,356	0,034	0,390	1,50
	8	14,247	0,852	0,382	0,486	0,044	0,529	3,37
	10	14,472	1,048	0,470	0,598	0,050	0,647	5,99
	12	14,674	1,223	0,549	0,697	0,053	0,750	9,35

Table 11b. Summary of Primary and Secondary Compaction Calculations for All Soft Soil Depths with Various Replacement Variations

	Depth (m)	q (t/m2)	Δq (m)	Preloading Requirements (m)	Sc (m)	Ss (m)	Sc+Ss (m)	t (years)
Replacement 3 m	4	13,932	0,197	0,088	0,112	0,007	0,120	0,09
	5	14,108	0,360	0,161	0,205	0,013	0,218	0,84
	6	14,299	0,504	0,226	0,288	0,026	0,314	0,84
	8	14,593	0,755	0,338	0,430	0,039	0,469	2,34
	10	14,838	0,968	0,434	0,552	0,050	0,602	4,58
	12	15,050	1,156	0,519	0,659	0,051	0,711	7,58

4. Cost Calculation

Cost calculation for this section counts the replacement and unloading required in the field.

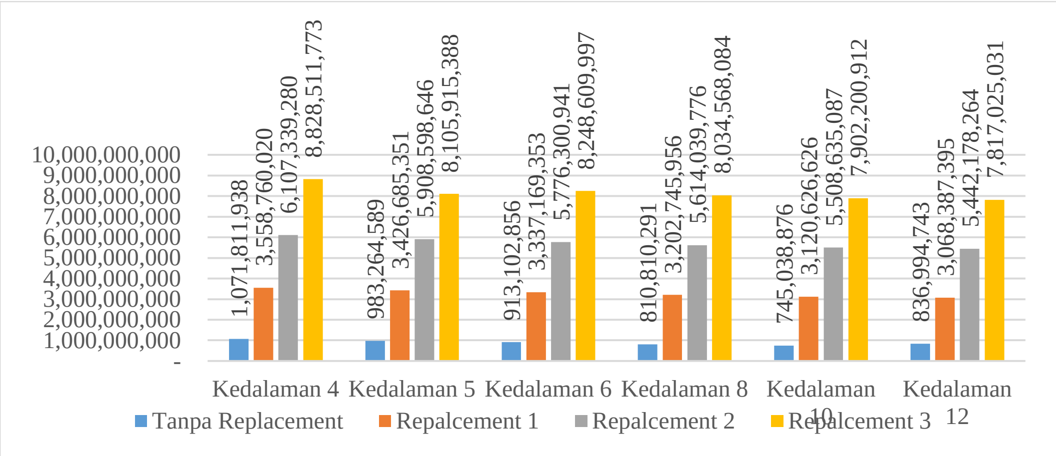


Figure 10. Summary of the Calculation of Replacement and Unloading Costs

Based on the graph in Figure 10, it can be observed that as the depth of replacement increases, the required cost also increases. However, as the soft soil depth increases, the cost decreases. This is due to the higher preloading requirements for lower soft soil layers.

CONCLUSION

Based on the results and discussions presented, the following conclusions can be drawn: Based on the results and discussions presented previously, the following conclusions can be drawn:

1. The thickness of the foundation soil replacement that meets the settlement requirement of < 2 cm per year from year 2 to year 3, and the settlement requirement of < 10 cm between year 2 to year 12, is 1 meter, 2 meters, and 3 meters.
2. The thickness of the foundation soil replacement that meets the settlement requirement of < 2 cm per year from year 5 to year 6, and the settlement requirement of < 10 cm between year 5 to year 15, is 1 meter, 2 meters, and 3 meters.
3. No reinforcement with geotextile is required for embankments with foundation soil replacement of 1 meter, 2 meters, and 3 meters because the embankment stability results using the auxiliary program show that the Safety Factor (SF) for embankments at the planned height in all variations of soil improvement is above 1.5.

4. The need for PVD (Prefabricated Vertical Drain) length in the compressible layers of 10 meters and 12 meters without using soil replacement is as follows:
   a. 10-meter depth
      The need for PVD at a depth of 10 meters with a triangular installation pattern with a spacing of 1.25 meters is 39,445 meters, with a duration of 3.97 months. Using a square installation pattern with a spacing of 1.25 meters, the required length is 34,400 meters, with a duration of 4.73 months.
   b. 12-meter depth
      The need for PVD at a depth of 12 meters with a triangular installation pattern with a spacing of 1.25 meters is 47,334 meters, with a duration of 3.97 months. Using a square installation pattern with a spacing of 1.25 meters, the required length is 41,280 meters, with a duration of 4.73 months.
5. For the foundation soil conditions described in point 4, calculations using the auxiliary program show that the Safety Factor (SF) at the depth of the compressible layer of 10 meters is < 1.5, so geotextile reinforcement is required, amounting to 54.9 m². However, for the compressible layer at a depth of 12 meters, no geotextile installation is needed as the SF is > 1.5.
6. When comparing the cost requirements between PVD and soil replacement, it can be concluded that the cost of PVD is cheaper than that of soil replacement.
7. The most effective method to implement is PVD because, in addition to being cheaper, the time required to achieve 90% consolidation (t90%) is only 6 months. However, if the project execution time is limited, soil replacement may be considered, as it can be completed faster depending on the method employed by the contractor, even though the costs may be higher.

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