Performance of Prefabricated Vertical Drain Using Triangular Pattern for Soft Soil on Sigli Banda Aceh Toll Road

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Abstract. The Sigli - Banda Aceh Toll Road passes through an area where the subgrade consists of soft soil. Geotechnical issues usually arise that settlement over a relatively extended period, which can damage the structure constructed above it. One of the improvement methods for soft soil problems is a Prefabricated Vertical Drain. The result of consolidation settlement takes a very long time, 21.7 years. Therefore, soil improvement is required beforehand using the Preloading method in combination with Prefabricated Vertical Drain. A prefabricated vertical drain will be paired up to a depth of 8 meters. The installation pattern used is a triangular pattern from 1 meter, 1.25 meters, 1.5 meters, 1.75 meters, and 2 meters. Based on analytical calculations, it can be concluded that the embankment construction process must be carried out step by step, and the construction speed is limited and using installation distance of 1 meter requires 57 days, an installation distance of 1.25 meters requires 80 days, an installation distance of 1.5 meters requires 118 days, an installation distance of 1.75 meters requires 160 days, and an installation distance of 2 meters requires 211 days to achieve a consolidation degree of 90 percent. So, a greater installation distance.

Keywords: consolidation; settlement; preloading; PVD.

1. Introduction

In order to achieve development equity and enhance the community's economy, the Government is constructing several sections of Toll Roads in Sumatra, from Banda Aceh to Bakauheni. [1]. The subgrade will directly support the structure of the Toll Road pavement, so the subgrade must have good load-bearing capacity. There are several areas in the Banda Aceh and Aceh Besar regions where soft clay soil is frequently encountered, especially in marshy areas [2], with the criteria of N SPT value ≤ 10 [3]. The main issue in road construction on soft clay soil is the relatively low bearing capacity of the subgrade and the substantial consolidation of the subgrade, which takes a very long time (years) to occur) [4]. If improvement is not carried out on the subgrade beforehand, the infrastructure built on it could potentially experience damage before reaching its intended lifespan, such as cracked and uneven roads and road surface subsidence. To address these issues, efforts to improve the subgrade are necessary [4]. The Preloading method is one of the approaches to address the issues caused by soft clay soil [5] . However, using only preloading would require considerable time for the

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necessary improvements, making it inefficient in terms of both time and cost [6]. With the advancement of technology, the use of geosynthetic materials has become increasingly common. Geosynthetics are synthetic materials that serve as reinforcement and can function as drainage and filtering elements. One geosynthetic used for drainage is the Prefabricated Vertical Drain [7]. PVD is an elongated strip made of synthetic material consisting of layers capable of allowing pore water to permeate the striped core. This core is a shortcut for pore water drainage, directing it from high-pressure soil layers to lower-pressure ones. Using PVD can expedite the consolidation process in soft soil [8].

When a load is applied on soft soil, excessive settlement will occur. The load due to embankment is initially borne by the pore water in the soil, causing an increase in pore water pressure corresponding to the magnitude of the load. As the pore water pressure increases and gradually decreases, the soil volume changes. The reduction in pore water pressure occurs due to the flow of high-pressure pore water towards zones of lower soil pressure [9]. The gradual reduction in water content is known as consolidation [3].

The Sigli - Banda Aceh Toll Road Section 6, from access road Kuta Baro STA 2+000 to STA 2+100, passes through an area where the subgrade consists of soft soil. Based on the results of soil investigation using Standard Penetration Test (SPT) and borehole logs, soft soil is indicated to be present up to a depth of 8 meters (source: PT. Adhi Karya (Persero) Corporation, Ltd). So, it is necessary to improve the soil to increase its bearing capacity by using preloading and PVD. This research uses a triangular installation pattern, and preloading is used in stages. This research is needed to determine the effective PVD installation distance and safety factors at each preloading stage.

The sketch of soil improvement using preloading plus PVD .

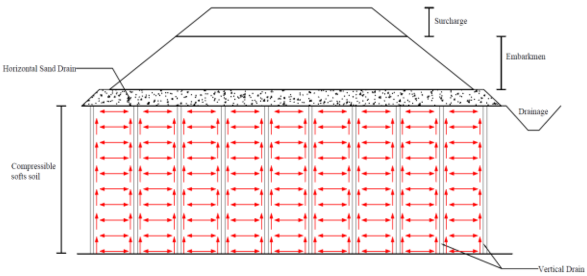

Fig. 1. Cross-section sketch.

2. Method

2.1 Material and Installation Pattern of Prefabricated Vertical Drain

In this improvement planning, the PVD used is Ce Teau - Wick Drain with 100 mm width and 4 mm thickness specifications. In the field installation pattern, PVDs are often installed using a rectangular or triangular pattern, as can be observed in Fig. 2. In this plan, it is determined that a triangular installation pattern will be used with an installation depth of 8 meters. The spacing between wicks will be tested from 1 meter to 2 meters. The choice of a triangular installation pattern is based on the fact that using a triangular pattern is more efficient, ranging from about 6% to 25%, in achieving a 90% consolidation degree compared to a rectangular pattern [11].

2.2. Methode

The main objective of the preloading plus PVD method is to achieve a specific degree of consolidation within a defined timeframe. Here is the sequence of steps in the analysis method.

1) Magnitude of Settlement and Time Without Improvement

Overburden stress is the vertical stress caused by the weight of the underlying soil itself. The value of overburden stress can be calculated using the equation (**1**).

$$P_o' = \gamma_{eff} . h \quad (1)$$

The distribution of additional stress (ΔP) represents the total load acting on the original soil in terms of stress units. The additional load is distributed through the subgrade, where the deeper the soil layer, the less the impact of the additional load. The distribution of additional stress can be calculated using the equation

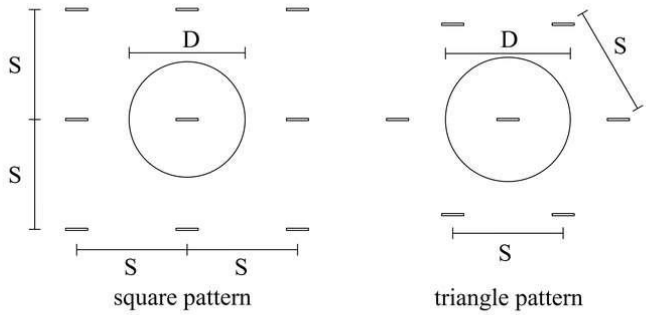

Fig. 2. PVD Installation Pattern.

(**2**).

$$\Delta p = 2.q.I$$

(2)

Based on Terzaghi's theory, the calculation of consolidation settlement in clay soil is given by the equation:

a) Normally Consolidated Soil

This condition occurs when the effective overburden stress at present is the maximum stress that the soil has ever experienced ($p_0=p_c$). The consolidation settlement can be calculated using the equation (**3**).

$$S_{cp}=[Cc.H/(1+e_0).Log\,(p_0'+\Delta_P)/(p_0')] \quad (3)$$

b) Overconsolidated Soil

This condition occurs when the effective overburden stress and the stress due to additional load are either smaller or larger than the stress the soil has experienced. If the stress that occurs is smaller or ($p_0+\Delta_p<p_c$), then to calculate the magnitude of consolidation settlement, you can use the equation (**4**).

$$S_{cp}=[(Cr.H)/(1+e_0).Log(p_0'+\Delta_P)/(p_0')] \quad (4)$$

If the stress that occurs is larger or ($p_0+\Delta_p>p_c$), then to calculate the magnitude of consolidation settlement, you can use the equation (**5**).

$$S_{cp}=[(Cr.H)/(1+e_0).Log\,(p_c')/(p_0')+(Cc.H)/(1+e_0)\,.Log\,(p_0'+\Delta_P)/(p_0')] \quad (5)$$

The settlement caused by the embankment load and surcharge load has been obtained. Then, the time of consolidation settlement can be calculated using the equation (**6**).

$$t=(T_v\,(H_{dr})^2)/C_v \quad (6)$$

2) Settlement Time Using the Preloading Plus PVD Method

a) Vertical Drainage

The vertical drainage time factor can be determined using the equation (**7**)

$$T_v=C_v.t/(H_{dr})^2 \quad (7)$$

Where Cv is the coefficient of consolidation in the vertical direction, t is the time under consideration, and H_{dr} is the length of the flow path. The degree of consolidation in the vertical direction can be determined using the equation (**8**).

$$U_v=\sqrt{(T_v/(\pi/4))} \quad (8)$$

b) Horizontal Drainage

The time factor for horizontal drainage can be determined using the equation (**9**)

$$T_h=(C_h.t)/D^2 \quad (9)$$

Ch is the coefficient of consolidation in the horizontal direction, and D is the drainage influence area. The horizontal consolidation degree and the PVD spacing factor are calculated using the solution proposed by Hansbo with the equation (**10**).

$$U_h = 1\text{-}exp^{-((8Th)/F(n)))} \quad (10)$$

Where,

$$F(n) = ln(D/dw) - 0.75 \quad (11)$$

The drainage area and equivalent drainage diameter can be calculated using equations (**12**) and equations (**13**)

$$D = 1.05 \times S \quad (12)$$

$$dw = (a+b)/2 \quad (13)$$

c) Total Consolidation Degree

Without PVD, the consolidation process only occurs in one direction. By employing PVD, the consolidation process will occur bidirectionally, namely horizontally (radially) towards the PVD. It will flow vertically as in . The average consolidation degree due to both vertical and horizontal flow can be calculated using the equation established by Das, as shown in the equation (**14**).

$$U_{total} = 1\text{-}(1\text{-}U_v)(1\text{-}U_h) \quad (14)$$

3) Stage Construction

Soft clay soil with low bearing capacity can only sustain heavy loads indirectly. The initial load magnitude that acts should be calculated first regarding the safety factors stipulated in SNI 8640:2017 [12]. According to this regulation, the safety factor for soil-bearing capacity is 1.5. The critical height of the embankment can be calculated using the equation (**15**).

$$H_{cr} = (N_c\, C_u + P_0'\, N_q + 0{,}5\gamma B\, N_\gamma)/(FS.\gamma_{timb}) \quad (15)$$

In this design, the preloading embankment height is 8.07 meters based on the fact that the road elevation is at a height of 6.5 meters. The traffic load and pavement load are equivalently applied to the additional embankment height of 1.57 meters. Thus, the preloading embankment height during construction is 8.07 meters, with the height of the first stage embankment being 4 meters.

The construction process is planned to be carried out progressively. The process consists of two embankment stages, as shown in Fig. 3.

Fig. 3 Indicates the Relationship of Load Increment (p) of Pile-up Over Time (t). At t_1, it marks the first stage of construction of the embankment. Following the completion of the first stage of embankment construction, there is a waiting time for the consolidation process. As the process unfolds, the soil-bearing capacity will increase, allowing for the application of the load on the second stage embankment. t_2 marks the end of the waiting period for the first stage embankment. At t_3, it is the culmination of the second stage of embankment construction, and t_4 represents the time when the degree of consolidation reaches 90%.

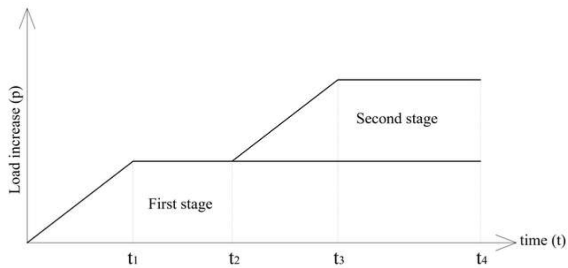

Fig. 3. The Relationship Between the Addition of Load the Embankment to Time.

2.3. Results and Discussion

1) Subgrade Soil Condition

The installation location of the PVD is situated along the access road of Kuta Baro, ranging from STA 2+000 to STA 2+100. Based on the Standard Penetration Test (SPT) conducted at a depth of 8 meters, an indicative SPT value of 10 N-SPT was obtained.

2) Soil Settlement

For the magnitude of primary consolidation settlement, it is necessary to determine the coefficient of consolidation index (Cc) and the recompression index (Cr), as well as to establish the type of consolidation that is occurring. Subsequently, equations (3), (4), and (5) can be derived from which the relevant equation can be selected. With consideration of the 20 m subgrade thickness, an immediate settlement of 34.2 cm and a consolidation settlement of 28.1 cm have occurred.

3) Consolidation Time of Subgrade Soil Without Improvement

In calculating the duration of the consolidation process, it is essential to determine the average coefficient of consolidation (C_V) and acknowledge that the flow process occurs unidirectionally along a path of 20 meters. In order to achieve a consolidation degree of 90%, we need to use equation (6) and a time factor value of 0.848. Results in a consolidation process that will take approximately 21.7 years. The duration is considered relatively long, given that the Sigli-Banda Aceh Toll Road project is undergoing acceleration. Therefore, the use of PVD is necessary to expedite the consolidation process.

4) Consolidation Acceleration using Preloading plus PVD Method

Based on the results of the SPT tests, it is evident that the soft soil layer extends to a depth of 8 meters. Therefore, the PVD will be installed to a depth of 8 meters. Based on the laboratory data obtained from the project, the average vertical and horizontal coefficients of consolidation yield relatively small values of 6.85 x 10^{-3} cm^2/s and 2.1 x 10^{-2} cm^2/s, respectively, along with other parameters that can be seen in Table 1. Based on this data, the magnitude of consolidation settlement and the required time for the consolidation process can be calculated, as shown in Fig. 4.

Table 1. Soil properties

Deep (m)	γ_{sat} (kN/m^3)	E_0	Cc	Cr	P_c' (kN/m^2)	C_v (cm^2/sec)	C_h (cm^2/sec)
0 – 2	17.75	1.99	0.63	0.07	135	9.5E-04	2.8E-03
2 – 4	19.25	1.99	0.63	0.07	189.2	9.5E-04	2.8E-03
4 – 6	20	1.87	0.41	0.05	189.2	6.7E-04	2.0E-03
6 – 8	19	1.87	0.41	0.05	343.2	6.7E-04	2.0E-03
8 – 10	19.6	1.87	0.41	0.05	457.6	6.7E-04	2.0E-03

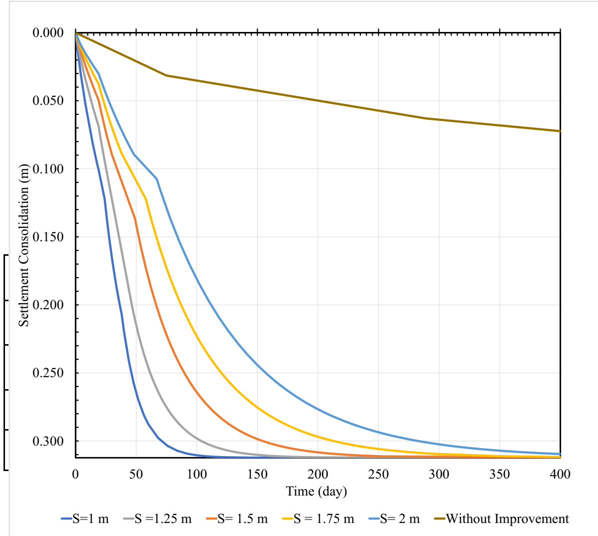

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Fig. 4. The Relationship Between Settlement to Consolidation Tim

Fig. 4 Depicting the Relationship between Settlement and Consolidation Time with a Triangular Installation Pattern Configuration. Upon observation, the utilization of PVD significantly impacts the consolidation time. Without employing any improvement measures, the settlement process takes an extended period. This demonstrates the effective horizontal consolidation process due to the implementation of PVD, which indeed works and contributes significantly to the overall consolidation process. The spacing distance of PVD installation affects the overall settlement time. For further details regarding the consolidation time and the extent of settlement, please refer to Table 2 and Table 3.

Table 2 illustrates the duration of improvement in relation to construction stages, and

Table 3 displays the corresponding settlements occurring in each stage. Settlement variations occur during the construction of the first stage embankment with the exact duration of work. This is directly proportional to the

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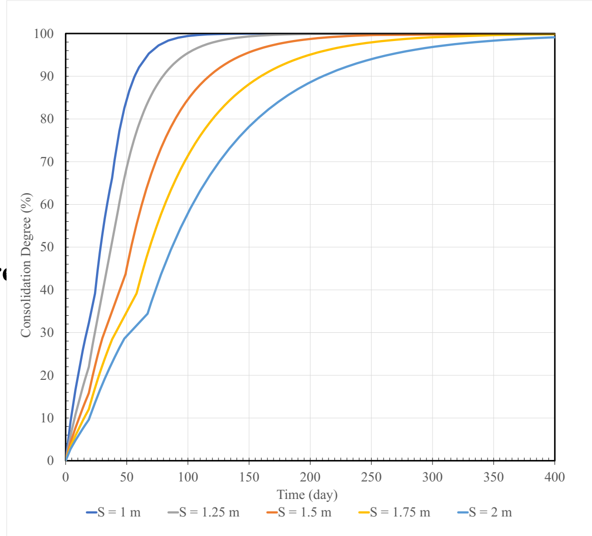


Fig. 5. The Relationship Between Degree of Consolidation to Time.

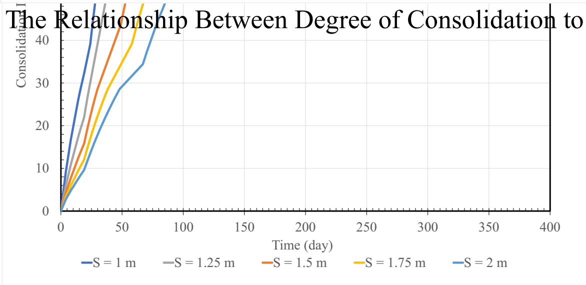


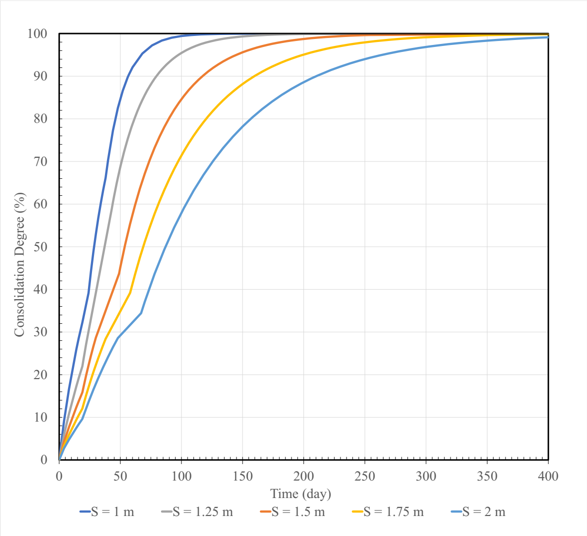
Fig. 5.

Table 2. Consolidation Time in Staged Embankment.

S (m)	First Stage Embankment		Second Stage Embankment		Total time (days)
	Construction (days)	Waiting Period (days)	Construction (days)	Waiting Period (days)	
1.00	19	0	19	19	57
1.25	19	4	19	38	80
1.5	19	11	19	69	118
1.75	19	19	19	103	160
2.00	19	29	19	144	211

Table 3. Accumulated Consolidation Settlement in Staged Embankment.

S (m)	First Stage Embankment		Second Stage Embankment	
	Construction (m)	Waiting Period (m)	Construction (m)	Waiting Period (m)
1.00	0.101	0.101	0.207	0.282
1.25	0.069	0.089	0.164	0.282
1.5	0.050	0.900	0.137	0.282
1.75	0.038	0.890	0.137	0.282
2.00	0.038	0.890	0.108	0.282



According to Fig. 5, the spacing of PVD installation influences the increase in consolidation. The closer the spacing of the PVD installation, the faster the rate of consolidation degree enhancement.

a) Duration of Waiting Period for the First Stage Embankment

Based on Table 2, the farther the spacing of the PVD installation, the longer the waiting period duration. This is due to the slower rate of consolidation degree increase. As the consolidation process progresses, there will be an increase in the undrained cohesion value (C_u). The increase in undrained cohesion value (C_u) will be directly proportional to the increase in soil-bearing capacity. Therefore, the second stage embankment will be constructed when the soil-bearing capacity is sufficient to accommodate the load.

b) Duration of Waiting Period for the Second Stage Embankment (Final)

The consolidation process will conclude when the degree of consolidation has reached a minimum of 90%. The duration when the degree of

consolidation reaches 90% can be observed in

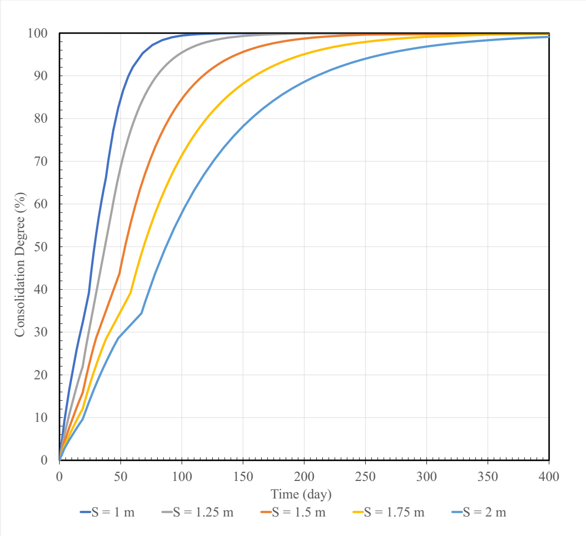


Fig. 5 and Table 2. In order to determine the installation spacing, it is necessary to establish the required time for the soil improvement process.

c) Safety Factor Due to Embankment Construction

The embankment construction process is carried out gradually, performed in 2 construction phases. The safety factor during embankment construction can be observed in Table 4.

Table 4. Consolidation Time in Staged Embankment.

S (m)	First Stage Embankment	Second Stage Embankment	final
1.00	2.13	1.33	1.66
1.25	2.13	1.48	1.66
1.50	2.11	1.49	1.66
1.75	2.11	1.51	1.66
2.00	2.12	1.51	1.66

3. Conclusion

The consolidation settlement that occurs is 28.1 cm. If no improvement is carried out, it would require approximately 21.7 years to achieve a 90% degree of consolidation. The construction process of preloading embankment must be implemented gradually. The triangular installation pattern is used because it is more efficient than other patterns. The installation distance affects the time required for consolidation, where an installation distance of 1 meter requires 57 days, an installation distance of 1.25 meters requires 80 days, an installation distance of 1.5 meters requires 118 days, an installation distance of 1.75 meters requires 160 days, and an installation distance of 2 meters requires 211 days. So, a greater installation distance causes the time required to reach a 90 percent degree of consolidation to become longer.

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