Effect of Installation Pattern of Prefabricated Vertical Drain (PVD) on Degree of Consolidation in Soft Soils

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ABSTRACT

Soft soil has high water content and low permeability, causing a high settlement and long time. Soil improvement with prefabricated Vertical Drain (PVD) can accelerate settlement in soft soils and primary consolidation time. Prefabricated Vertical Drain (PVD) functions to accelerate the release of water from the ground, and the accelerated settlement process, which is indicated by the degree of consolidation (U) reaching 90%, generally this method combines PVD and preloading (additional load). The required time to achieve a 90% degree of consolidation is determined by the PVD installation pattern (triangle pattern and rectangular pattern) and its distance. This study reviewed the effectiveness of PVD installation patterns with distance variations of (1 m, 1.3 m, 1.6 m, 1.9, 2.2 m, 2.5 m, 2.8 m, and 3.1 m). The analysis results show that in the triangular pattern, the time required to achieve a degree of consolidation of 90% (U90) is from 1 to 8.5 months, and in the rectangular pattern is from 1 to 9.5 months. The greater distance between PVDs, the more time is required to achieve a 90% degree of consolidation (U90). The PVD with a triangular pattern could reduce the 6% - 25% time to complete a degree of consolidation (U90) compared to the rectangular pattern. It can be noted that the installation triangle pattern is more effective than the rectangular installation pattern.

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1. INTRODUCTION

Prefabricated Vertical Drain (PVD) is a soil improvement method that functions to drain water from the soil pores, thus accelerating the process of land subsidence. This occurs in soft clay soils with high groundwater levels. With the presence of PVD, the degree of consolidation increases in line with changes in pore water pressure and also increases soil shear strength so that PVD can be used as a soil improvement method for very soft clay soils.[1]. PVD installation is usually combined with preloading to speed up the settlement process. Combining embankment and PVD on the weir can improve embankment performance compared to using only embankment alone[2][10]. Preloading loads can be in the form of temporary and permanent loads and can be carried out in stages. According to Wang et al. [3], the secondary consolidation settlement continues in a gradual embankment after unloading, but the settlement amount is minimal. The main advantage of PVD on soft soils is that it can significantly accelerate soil settlement[4][11][12][13][14][15]. The time needed to achieve a degree of consolidation of 90% is highly dependent on the PVD installation pattern and the distance between the PVD installations.

Padang – Pekanbaru Toll Road Section I Section I Padang - Sicincin passes through several areas with subgrade conditions which are soft soil and are dominated by swampland with high groundwater levels. Based on the soil investigation results using the Standard Penetration Test (SPT) and drilling logs at STA 3+850, soft soil is located at 8.4 m. If the embankment is placed on soft ground, the soil will experience excessive consolidation settlement for a long time. This condition will damage the road pavement structure built on the piledoil[5].

This paper discusses the effect of the PVD installation pattern on changes in the degree of consolidation (U90). PVD installed with a triangular pattern and a rectangular pattern with variations in the distance between the PVD (1 m, 1.3 m, 1.6 m, 1.9, 2.2 m, 2.5 m, 2.8 m, and 3.1 m) with a preload of 5.8 m. The results of this study are expected to determine a more effective installation pattern and spacing to be applied in the field.

PVD is an artificial drainage system installed vertically in a soft soil layer. This vertical drainage system has the form of a belt with a rectangular cross-section, consisting of an outer part in the form of a filter made of synthetic materials such as geotextiles, paper, or jute and an inner part that functions as a water flow medium made of plastic or organic fibers. PVD serves to accelerate the process of settlement in soft soils. The rise/lower time using a PVD depends highly on the distance and installation pattern. The presence of PVD will cause radial/horizontal pore water flow in addition to vertical flow, which causes pore water to be removed more quickly[6].

Guo et al. (2018) examined comparing the consolidation degree with the proposed Asoka methods. The analysis showed that the proposed method's ultimate settlement value was smaller than the Asoka method. The proposed method could predict by considering horizontal and vertical flow directions[7].

According to Aspara et al., achieving a degree of consolidation of 90% on clay at the Riau PLTU Project site takes six months with an installation configuration with a Triangle pattern.[6].

Installation of PVD with preloading at Juanda Airport in Surabaya at the taxiway location. PVD is installed in a triangular pattern with a distance of 1 m and a depth of 20 m. The degree of consolidation of 90% is achieved within 11.5 weeks; without using PVD, 0% is completed within 87, 78 years[8].

2. METHODS

2.1. Secondary Data

This study's secondary data comprised the boring log and N-SPT obtained from the Padang-Sicincin toll road construction project (PT. Hutama Karya).

2.2. Correlation of N-SPT Values to Soil Parameters.

The soil parameter values were obtained from the results of the correlation of N-SPT values consisting of cohesion values (c) and internal shear angles (φ), and consolidation coefficient (Cv).

Table1. Correlation of SPT values to soil types (Peck et al., 1974)

Sand (Reliable)		Silt and Clays (Unreliable)	
N60	**Relative Density**	**N60**	**Consistency**
0 - 4	Very loose	Below 2	Very Soft
5 – 10	loose	2 – 4	Soft
11-30	Medium	5 – 8	Medium
31- 50	Dense	9 – 15	Stiff
Over 50	Very Dense	16 – 30	Very Stiff
		Over 30	Hard

Source: National Highway Institute (2006)

2.3 Land subsidence (Settlement)

Land subsidence consists of immediate settlement, primary consolidation settlement, and secondary consolidation settlement[9]

2.3.1 Immediate drop *(immediate settlement)*

Settlement occurs immediately after workload, and soil grains are deformed without changing the water content.

$$S_i = \frac{q.B}{E} Ip \tag{1}$$

With,
Si: Immediate Drop
B: the width of each area
I: Steinbrenner coefficient (1934)
E: modulus of elasticity

2.3.2 Primary consolidation decline

Primary consolidation settlement occurs after the load is applied and there is a change in excess pore pressure, resulting in a reduction in volume which causes land subsidence.

For Normally Consolidated, if po' = pc'

$$S_{cp} = \frac{C_c}{1+e_0} H \log \frac{p_o' + \Delta p}{Po'} \tag{2}$$

For Over Consolidated, two conditions must be considered, namely:

- If $p_1' < pc'$

$$S_{cp} = \frac{C_r}{1+e_0} H \log \frac{p_o' + \Delta p}{Po'} \tag{3}$$

With $p_o' + \Delta p = p_1'$

- If $po' < pc' < p_1'$

$$S_{cp} = \frac{C_r}{1+e_o} H \log \frac{p_o'}{Po'} + \frac{C_c}{1+e_o} H \log \frac{p_o' + \Delta p}{Pc'} \tag{4}$$

with
Scp: primary consolidation settlement
pc' : pre-consolidation pressure
Cc/Cr: coefficient of consolidation/ recompression index
e0: pore number.
H: the thick layer of clay
Po: stress due to the soil's weight
ΔP: additional stress due to load
H: the thickness of the consolidated layer

2.3.3 Depreciation Secondary consolidation

Secondary consolidation settlement occurs after the pore water has been completely dissipated, and the settlement occurs only due to the adjustment of the soil grains.

2.4 Vertical Consolidation Coefficient (Cv)

To calculate the magnitude of the consolidation coefficient used, the Taylor method.

$$Cv = \frac{Tv.Hdr^2}{t} \quad (5)$$

Cv: coefficient of consolidation (cm2/s).
Tv : time factor
t: the time required to reach the degree of consolidation U% (sec)
Hdr: length of water path (cm)

Degree of consolidation in the vertical direction (Uv) (Terzaghi, 1942).
Uv between 0 – 60%

$$Uv = \left(2\sqrt{\frac{Tv}{\pi}}\right) x\ 100\% \quad (6)$$

Uv between >60%

$$Uv = (100 - 10^{a}) x\ 100\% \quad (7)$$

2.5 Planning of Prefabricated Vertical Drain (PVD)

PVD serves to shorten the path of the water to the drain (radial and vertical directions) so that the time to reach the 90% degree of consolidation can be shorter (figure 2). The flow will be steep if you don't use PVD (figure 1).

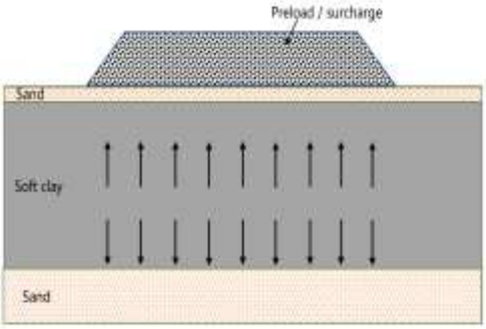


Figure 1. Water flow direction without PVD

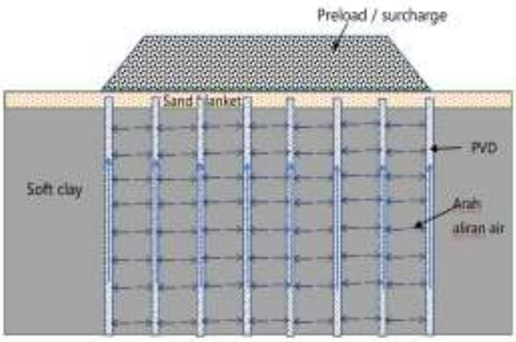
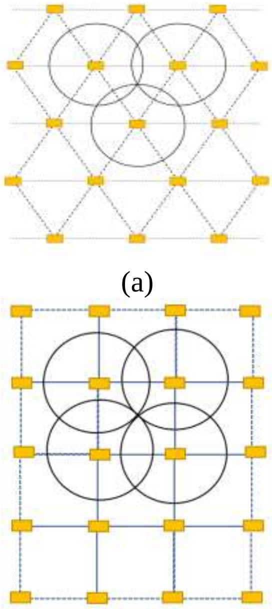


Figure 2. Flow direction with PVD

The PVD installation pattern usually uses a triangular pattern and a rectangular pattern.



(a)

(b)

Figure 3. PVD mounting pattern
Triangle Pattern (a) and Quadrilateral Pattern (b)

To determine the radius of influence of the PVD (equivalent diameter), it is calculated based on the PVD installation pattern

D = 1.13 S (square pattern)
D = 1.05 S (equilateral triangle pattern)

With S: Distance between *PVD*

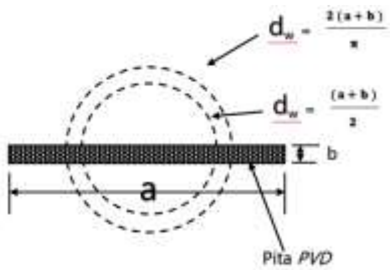


Figure 4. PVD equivalent diameter

$$d_w = \frac{2(a+b)}{\pi} \tag{8}$$

with,

a = cross-sectional width of the PVD
b = thickness of PVD section

$$F(n) = \ln(D/d_w) - 0,75 \tag{9}$$

In this paper, pattern PVD installation uses triangular and rectangular patterns.PVD dimensions used are width (a) = 100 mm and thickness (b) = 5 mm, and variations in installation distance (s) are: 1m, 1.3 m, 1.6 m, 1.9 m, 2.2 m, 2.5 m, 2.8 m, and 3.1m.

2.5.1 Consolidation Time (t) with PVD

The determination of consolidation time (t) when using PVD has been carried out by combining the theories of Kjellman and Baron (1948), as has been done by Hansbo (1970). The equation expresses the result for consolidation time:

$$t = \frac{D^2}{8C_h} F(n) \ln\left(\frac{1}{1-U_h}\right) \quad (10)$$

Where:

t: the time required to reach the degree of consolidation
D: equivalent diameter of the circle of influence
Ch: horizontal consolidation coefficient
Uh: degree of consolidation in the horizontal direction

2.5.2 The average degree of consolidation (U average)

For drainage in the vertical and radial directions, to obtain the combined average degree of consolidation expressed by the equation (Carillo, 1942)

$$U_{av} = 1 - (1 - U_v)(1 - U_h) \quad (11)$$

Uav: average degree of consolidation
Uv: vertical consolidation degree
Uh: degree of horizontal consolidation
The degree of consolidation in the horizontal direction can use the following formula.

$$Uh = \left[1 - \left(\frac{1}{e^{\left(\frac{tx8xCh}{D^2xF(n)}\right)}}\right)\right] \quad (12)$$

3. RESULTS AND DISCUSSION

3.1 Basic Soil data analysis

Field test results include Standard Penetration Test (SPT) data, drill logs, and laboratory tests on soil physical and mechanical properties.Padang-Sicincin toll road.

Table 2. Recapitulation of Soil Types

Depth(m)	**Thickness(m)**	**Type of soil**	**N-SPT**	**ɣsat (kN/m³)**
0.7	0.7	Sand Piles	0	14
0.7 - 5	4,3	Silt	5	17.75
5-6	1	silt, sand	12	18
6 - 8.4	2,4	Sandy Lana	8	19.5
8.4 - 30	21,6	Sand	34	20,42
30-35	5	Sand	49	21.5
35-50	15	Hard clay silt	>50	22

Table (2) at a depth of 0.7 m to 8.4 m, the soil type is dominated by silt soil mixed with fine sand with an average N-SPT value of <10, indicating that the soil layer is soft soil. A layer of rather hard sand dominates the 8.4 m to 35 m, and a depth of 35 m to 50 m consists of a layer of hard clay with an N-SPT value of > 50.

3.2 Time required to reach 90% degree of consolidation (without PVD)

At the research location of the Padang – Sicincin toll road STA 3+850. The analysis results show that the average consolidation coefficient for each layer is 3.986 m2/year, with 2-way drainage (double drainage). To reach a degree of consolidation of 90%, it takes 3,153 years (Figure 5).

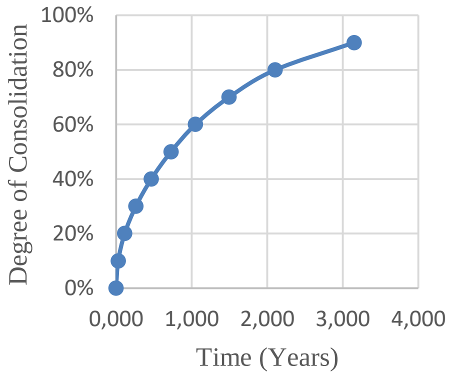


Figure 5.The relationship between time and degree of consolidation without *PVD*

3.3 Prefabricated Vertical Drain (*PVD*)

This paper's PVD dimensions are a = 100 mm and b = 5 mm. Triangular pattern and quadrilateral pattern with variations in the distance between the PVDs, namely 1 m, 1.3 m, 1.6 m, 1.9 m, and 2.2 m, with an embankment height of 5.8 m.

3.4 The average degree of consolidation

The results of the analysis show that the average degree of consolidation (Average) is more significant with increasing time (tables 3 and 4).

Table 3. Degree of consolidation average for the triangular pairing pattern

T (month)	U average (%)							
	1 m	1.3m	1.6m	1.9m	2.2m	2.5m	2.8m	3.1m
1.00	95,707	82,213	67,049	54,719	45,600	38,987	34,160	30,582
2.00	99,799	96,543	88,136	77,597	67,665	59,326	52,635	47,347
3.00	99,990	99,319	95,669	88,762	80,514	72,509	65,455	59,510
4.00	100,000	99,865	98,409	94,325	88,179	81,295	74,635	68,655
5.00	100,000	99,973	99,413	97,123	92,800	87,223	81.303	75,638
6.00	100,000	99,995	99,783	98,538	95,604	91,250	86,182	81,018
7.00	100,000	99,999	99,920	99.256	97,311	93,997	89,771	85,184
8.00	100,000	100,000	99,970	99,621	98,353	95,878	92,419	88,423
9.00	100,000	100,000	99,989	99,806	98,991	97,167	94,378	90,948
10.00	100,000	100,000	99,996	99,901	99,382	98,052	95,829	92,919
11.00	100,000	100,000	99,998	99,950	99,621	98,661	96,905	94,460
12.00	100,000	100,000	99,999	99,974	99,768	99,079	97,704	95,667

Table4. The average degree of consolidation of the rectangular installation pattern

T (month)	**U total (%)**							
	1 m	**1.3m**	**1.6m**	**1.9m**	**2.2m**	**2.5m**	**2.8m**	**3.1m**

1.00	92,935	77,039	61,627	49,955	41,646	35,753	31,511	28,396
2.00	99,455	94,240	83,911	72,635	62,794	54,900	48,748	43,979
3.00	99,957	98,535	93,161	84,830	75,949	67,902	61,116	55,564
4.00	99,997	99,625	97,073	91,534	84,349	77,003	70,301	64,516
5.00	100,000	99,904	98,743	95,256	89,775	83,458	77,227	71,553
6.00	100,000	99,975	99,458	97,335	93.303	88,071	82,493	77,137
7.00	100,000	99,994	99,766	98,501	95,606	91,383	86,519	81,593
8.00	100,000	99,998	99,899	99.155	97,114	93,769	89,607	85,165
9.00	100,000	100,000	99,956	99,524	98.103	95,491	91,983	88,035
10.00	100,000	100,000	99,981	99,732	98,753	96,735	93,813	90,346
11.00	100,000	100,000	99,992	99,849	99,180	97,636	95,224	92,209
12.00	100,000	100,000	99,996	99,915	99,461	98,289	96,314	93,714

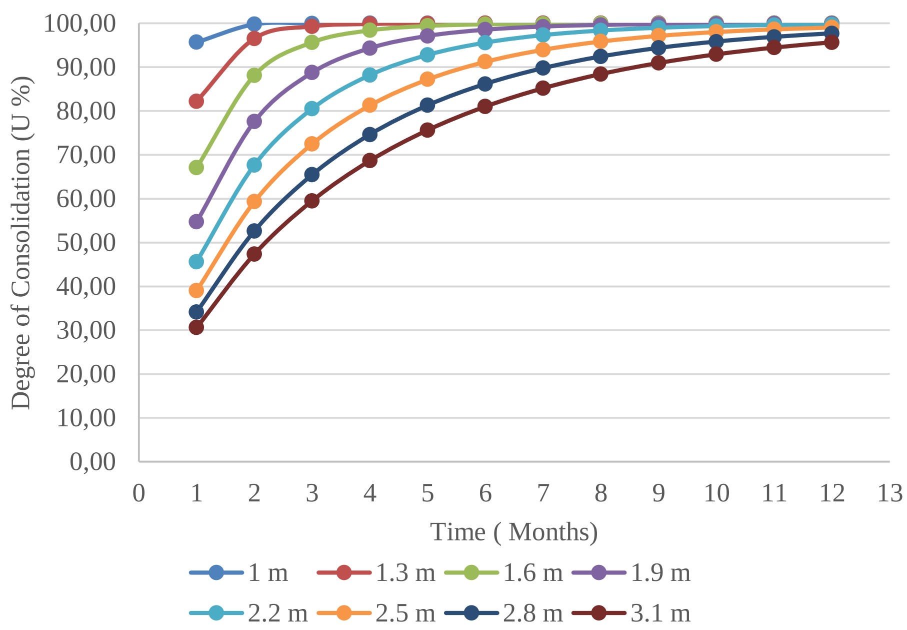


Figure 6. The relationship between the degree of consolidation and the time of the triangle pattern

The triangular installation pattern (Figure 6) shows that with an installation distance between PVDs of 1 m the degree of consolidation (U 90%) is achieved in 1 month, and an installation distance of 3.1 m is achieved in 8.5 months.

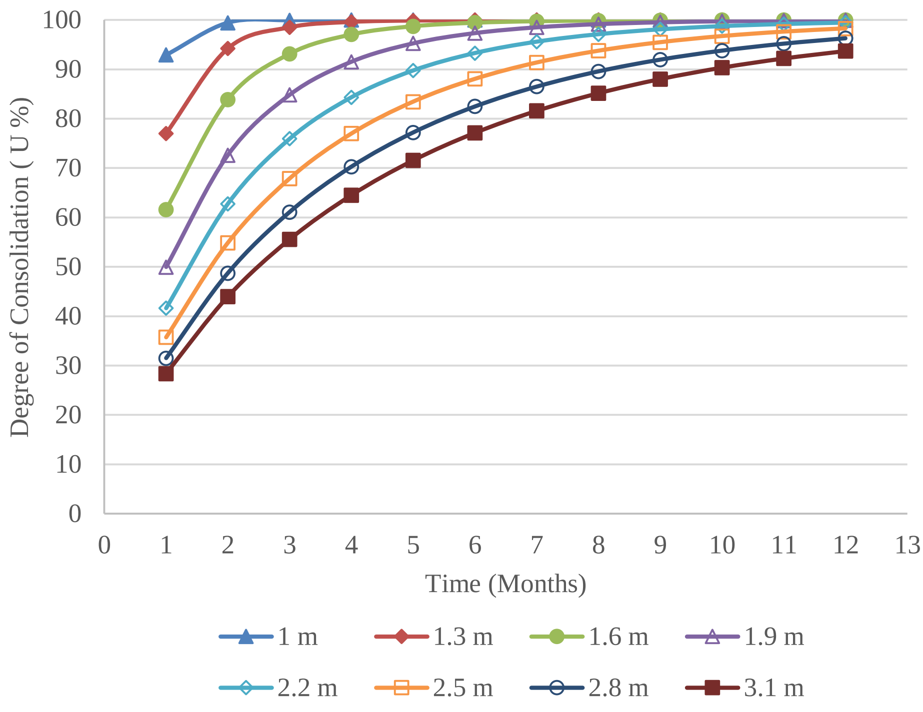


Figure 7. Chart of consolidation time and degree of consolidation of the quadrilateral pattern

In the rectangular installation pattern (Figure 7) with an installation distance between PVDs of 1 m, a degree of consolidation of 90% was achieved in 1 month, and a PVD installation distance of 3.1 m was completed in 9.5 months

Table 5. Consolidation time recapitulation with average U (U 90%) for the Triangle pattern

No	PVD distance S(m)	Consolidation Degree uav %	Time t (month)
1	1	90	1
2	1.3	90	1.5
3	1.6	90	2.1
4	1.9	90	3
5	2.2	90	4.25
6	2.5	90	5.75
7	2.8	90	7
8	3.1	90	8.5

Table 6. Consolidation time recapitulation with U90% for the Quadrilateral pattern

No	PVD distance S(m)	Consolidation Degree uav %	Time t (month)
1	1	90	1
2	1.3	90	1.6
3	1.6	90	2.5
4	1.9	90	3.75
5	2.2	90	5

6	2.5	90	6.4
7	2.8	90	8
8	3.1	90	9.5

Tables 5 and 6 show that the triangular pairing pattern is faster to reach a degree of consolidation of 90% compared to the quadrilateral pattern.

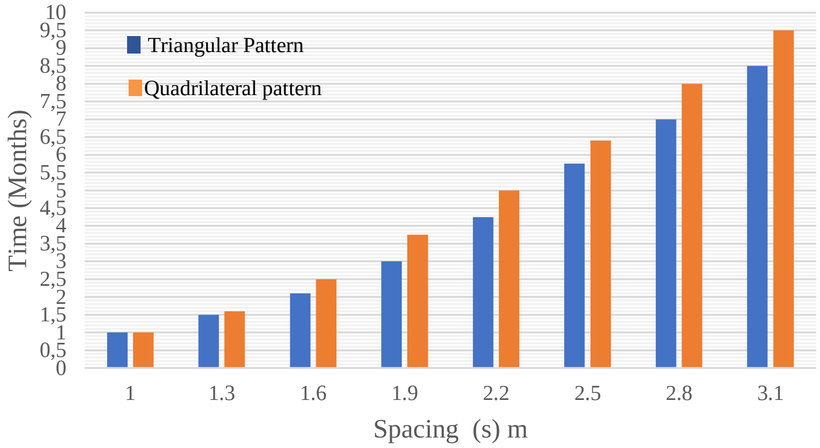


Figure 8. Distribution of PVD installation distance to time with a degree of consolidation U90%

Figure 8 shows that with increasing installation distance between PVDs (s) and significantly increasing time (t) to reach a 90% degree of consolidation, overall installation with a triangular pattern requires a shorter time when compared with a rectangular installation pattern.

4. CONCLUSION

If the soil receives preloading loads, consolidation increases with time. The average degree of consolidation is inversely proportional to the distance between the PVDs. The greater the distance between the PVDs, the smaller the moderate degree of consolidation and vice versa. To achieve a degree of consolidation of 90%, the PVD installation pattern with a triangular pattern is more effective when compared to a rectangular installation pattern. From the results of this study, several suggestions need to be considered. Further research on various soil types and reflections on the PVD material is required.

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