The Study of The Usage of Vacuum Preloading Method in The Construction Project of Palembang – Indralaya Toll Road

L.Y.Ervianty, H.C.Hardiyatmo, S.Hapsoro
Department of Civil and Environtmental Engineering, Faculty of Engineering,
Universitas Gadjah Mada, Yogyakarta, 55281, Indonesia,
e-mail: lilervianty@yahoo.com

***Abstract*— Palembang – Indralaya (Palindra) Toll Road is part of the Trans Sumatera Toll Road built on soft soil. Soil improvement using vacuum preloading method has been conducted to resolve the problem. The method involves replacing a surcharge load with an atmospheric pressure and utilizing vertical and horizontal drains, as well as sand blanket. Factors that influence the effectivity of the performance of the vacuum method comprise the settlement, the time of settlement, the speed of settlement, the degree of consolidation, the distance of the Prefabricated Vertical Drain or PVD, and so forth. The result of the settlement using Terzaghi's equation combined with Indraratna's showed that the addition of the height of the fill would have been effective if it had been equal or larger than the vacuum pressure that was used (80 kPa). It could be observed from attaining faster consolidation time of 56 days. The analysis result was, then compared with the final settlement by using Asaoka method. The design of the PVD distance by using vacuum method showed that the spacing (S) was less restrained, which was 1,23 m, compared to the one using with extra load (surcharge) which was 1,2 m. The settlement of vacuum consolidation was 1,98 m, which was smaller than the surcharge one that reached 2,11 m.**

***Keywords*— Vacuum Preloading, Consolidation, PVD, Terzaghi, Indraratna, Asaoka.**

I. INTRODUCTION

PALEMBANG – Indralaya (Palindra) Toll Road, part of the Trans Sumatera Toll Road connecting Indralaya and Palembang, is 22 km in total length and divided into three sections, namely Palembang – Pamulutan which is 7,10 km long, Pamulutan – KTM Rambutan which is 5,70 km long, and KTM Rambutan – Indralaya which is 9,30 km long. Since the structure of the sections are on soft soil, preloading method usually combined with vertical drains using soil fill as a surcharge loading to accelerate consolidation has been used. Yet, the method is considered ineffective and increases the risks of shear failure on the fill slope. Therefore, improvement has been made by replacing fill as the surcharge loading with vacuum pressure.

A. Objectives of The Research

The objectives of the research are :

1) to determine the coefficient of vertical consolidation (Cv) and for horizontal one (Ch) of the data from the field.
2) to evaluate the result of settlement consolidation, time of consolidation, and degree of consolidation of each method used.
3) to evaluate the distance of vertical drains between vacuum preloading and conventional preloading (common fill) method.

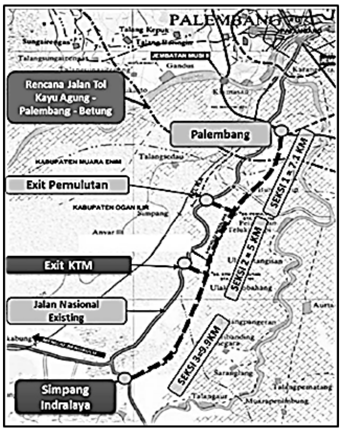

Figure 1. Palindra Toll Road.

B. Soft Soil

The soil where Palembang Indralaya Toll road was constructed is categorized into soft soil. The values of Standard Penetration Test (SPT) varies, most of which is soft soil with the depth of 17 m and the value of SPT is 0 – 4. The consistency ranges from very soft to soft. Generally, the profile of the soil can be seen on Figure 2. Therefore, soil improvement is necessary to resolve the problem by replacing the fill used as a surcharge loading with vacuum pressure to accelerate the consolidation process on the soft soil by using vacuum preloading method.

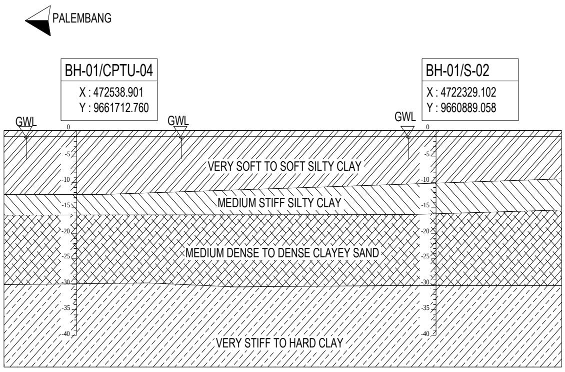

Figure 2. Soil Stratigraphy of STA 1+000 and STA 1+185

C. Vacumm Preloading

Like in conventional PVD, soil improvement with vacuum consolidation combined with vertical drains aims at accelerating the consolidation during the construction. As a result, after the building is completed, the settlement will be very minimum. To achieve the same settlement speed, vacuum pressure could reduce the height of the necessary fill [1]

Vacuum preloading is a system consisting of vertical and horizontal drains that are hydraulically connected through sand drainage and High Density Polyethylene (HDPE) water resistant membranes [2]. Both vertical and horizontal drains are connected to peripheral trenches and sealed by the membrane system. The peripheral trenches are filled with water or bentonite to keep the complete closure of the membrane in the edge of the zone that will be vacuumed. The vacuum pump is connected with the device that disposes of the water to the side trenches. In order to help the effectiveness of the vacuum performance to the soil depth significantly, vertical drains are used simultaneously [3].

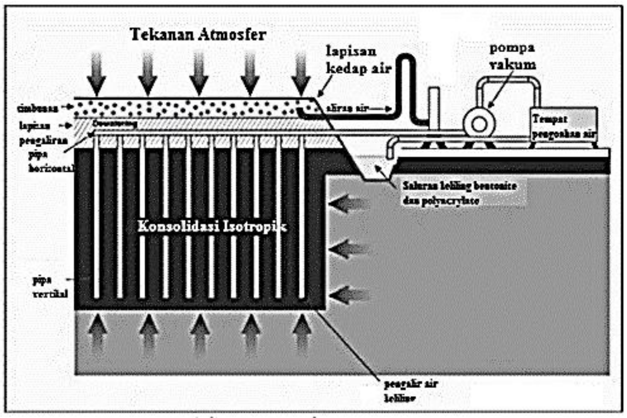

Figure 3. Vacuum consolidation with sealing membrane in the surface [2]

D. Primary Consolidation Settlement

Formula used to calculate the amount of the consolidation (Sc) that is normal (NC-soil) by Terzaghi (1942) is as follows:

$$U = \frac{S_t}{S_c} \times 100\ \% \tag{1}$$

where:
S_c : settlement consolidation (m)
S_c : settlement consolidation in *t* time (m)

1) Coefficient of Vertical Consolidation (C_v).

The value of the coefficient of vertical consolidation (Cv) was obtained by using the following equation:

$$C_v = \frac{Tv.Ht^2}{t} \tag{2}$$

where:
C_v : coefficient of vertical consolidation (m²/year)
T_v : time depending on the degree of consolidation
t : time required to achieve the degree of consolidation U % (year)
H_t : thickness of the consolidated soil (m)

A graphic approach may be used to obtain the value of C_v (correlation between C_v and *LL*) as suggested by [4].

2) Coefficient of Horizontal Consolidation (C_h)

Coefficient of horizontal consolidation (C_h) can be determined by doing back analysis as follows :

1. Determining the amount of settlement at a certain time Sc(t) from the monitoring graphic in the field.
2. Determining the degree of consolidation in the field by using the following equation:

$$U = \frac{S_t}{S_c} \times 100\ \% \tag{3}$$

Determining the value of C_h from Hardiyatmo's Graphic by using the following Figure 4.

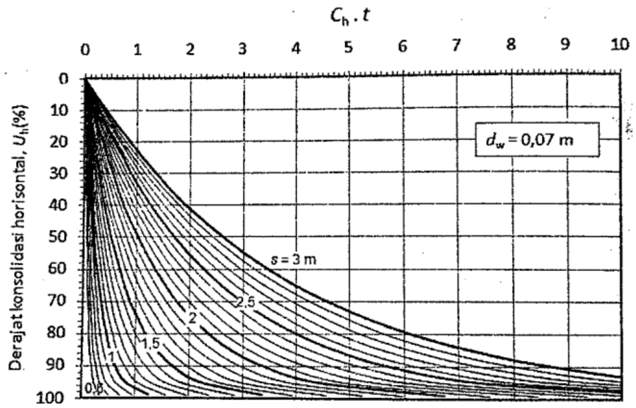

Figure 4. The Correlation between C_{ht} and U_h for d_w = 0,07 m. [5].

The values of coefficient of consolidation by [6]. using the following equation :

$$\frac{-\ln \beta_1}{\Delta t} = \frac{8C_h}{d^2 F(n)} + \frac{\pi^2 C_v}{4H^2} \tag{4}$$

E. Degree of Consolidation

Degree consolidation based on settlement is counted by using an equation for vertical drains. For both vertical and radial drains, the average combined degree of consolidation is presented by the following eq. :

$$U = 1 - (1 - U_v) \times (1 - U_h) \tag{5}$$

The average degree of consolidation for the entire depth of soil is determined by comparing the settlement of the soil when *t* ($S_{c(t)}$) and total settlement during the primary consolidation (S_c) based on the Eq. (1)

F. Vacuum Method

According to [3] vacuum suction in PVD depends on the length and type of PVD. [7] also states that efficiency of PVD relies on the amount and distribution of vacuum pressure.

1) Designing PVD with Vacuum Preloading

Rujikiatkamjorn and Indraratna [3] suggested a procedure to determine the distance of *drain* (PVD) as follows:

1. Determine the profile and the characteristics of the soil, as well as the depth of PVD and the intended consolidation time.
2. Assume the degree of consolidation (U_t) required for fill loading.
3. For the vacuum pressure application, determine the average vacuum pressure (p_o), design surcharge, ($\Delta\sigma$) and surcharge fill pressure (Δp), and determine the degree of consolidation by using the following equation:

$$U_{t,vac} = \left(\frac{\Delta\sigma}{p_0 + \Delta p}\right) U_t \tag{6}$$

4. From the data of coefficient of vertical consolidation (C_v), time of consolidation (t) and the length of PVD (L), determine u^* by using Figure 5.

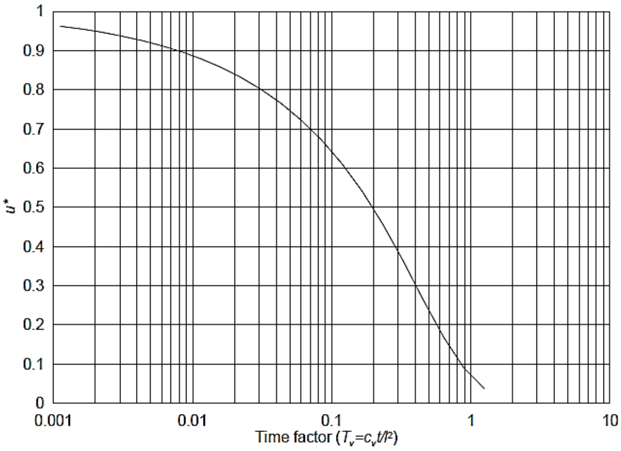

Figure 5. Correlation between *Tv* and *u** [3]

5. Determine the size of PVD and calculate the equivalent diameter.

$$d_w = \frac{2(a+b)}{\pi} \tag{7}$$

6. Determine T$_h$' from equation:

$$T_h' = \frac{C_h t}{d_w^{\ 2}} \tag{8}$$

7. Calculate only the fill surcharge (without vacuum) :

$$\gamma = -\frac{8T_h}{\ln\left(\frac{1-U_t}{u*}\right)} \tag{9}$$

or if including vacuum pressure and fill surcharge:

$$\gamma = -\frac{8T_h}{\ln\left(\frac{1-U_{t,vac}}{u*}\right)} \tag{10}$$

8. Determine the diameter and permeability of the disturbed zone. Calculate λ by using Eq. 11

$$\lambda = \left(\frac{k_h}{k_s} - 1\right)\ln(s) \tag{11}$$

9. Calculate n by using the following equation :

$$n = e\ (\alpha \ln \gamma + \beta\ ) \tag{12}$$

Where,

$$\alpha = 0{,}393 - (\ 9{,}50 \times 10^{-4}\ )\ \lambda^{1{,}5} + 0{,}0371\ \lambda^{0{,}5} \tag{13}$$

$$\beta = 0{,}4203 + (\ 1{,}456 \times 10^{\ -3})\ \lambda^2 - 0{,}5233\ \lambda^{0{,}5} \tag{14}$$

10. Calculate drain influence zone

$$D = nd_w \tag{15}$$

11. Select the location pattern of the installation of vertical drains and determine the distance by using the following equation:

$$S = D/1{,}05 \text{ for triangular pattern} \tag{16}$$

$$S = D/1{,}13 \text{ for square pattern} \tag{17}$$

G. Asaoka Method

Asaoka Method [8] is used to predict the final settlement of consolidation of a soil. The final equation to determine the value of settlement at the time interval n is as fallows:

$$S_n = \beta_0 + (\beta_1 \times S_{n-1}) \tag{18}$$

$$S_{ult} = \frac{\beta_0}{1-\beta_1} \tag{19}$$

Where,

S_n : settlement at time n
S_{n-1} : settlement at time n-1
S_{ult} : final settlement
β_0 : coefficient (the amount of the initial settlement)
β_1 : coefficient (the slope between the settlement and the straight line) (in rad)

II. METHOD

The research was conducted by collecting data and design parameters including soil profile, soil properties index, soil parameters of laboratory test result, soil investigation result data (sondir and SPT), result data from monitoring instrument in field such as settlement plate, piezometer, inclinometer, extensometer , vacuum gauge. All the data was collect from secondary data.

The data which was not accordance with soil characteristics, should be conducted back analysis include: value of coefficient of vertical consolidation (C_v) determined by graphic between liquid limit value (*LL*). The coefficient of horizontal consolidation (C_h) of the Hardiyatmo graph of Figure 4 is compared with the Hausmann Eq. (4).

The equation of Terzaghi and Indraratna were used to analysis of the settlement. The analysis of consolidation degree using vertical drain equation combined with Eq. (6) which take into account the influence (smear) and without the influence (non smear). Observation of final consolidation degree based on instrumentation data using Asaoka method.

III. RESULTS AND DISCUSSION

A. Determining the parameter of coefficient of vertical (C_v) and horizontal (C_h) consolidation

According to Figure 4 Value of C_v was obtained for STA 1+00 of 2 m²/year and STA 1+850 1,9 m²/year, resulting in the average value of C_v of 1,95 m²/year. The value of C_h was obtained through *back analysis*. The calculation of the value of coefficient of horizontal consolidation with the value of d_w = 0,066m, U_h = 90%, *t* = 70 days and PVD distance (*S*) = 1m. Therefore, value adjustment, resulting in the value of C_h = 4,17 m²/year and C_h Hausmann = 3,76 m²/year.

B. Consolidation settlement calculation by Asaoka Method

The result of final settlement (S_{ult}) as seen in Figure 6. Coefficient β_1 obtained is approximately 0,63 rad used.

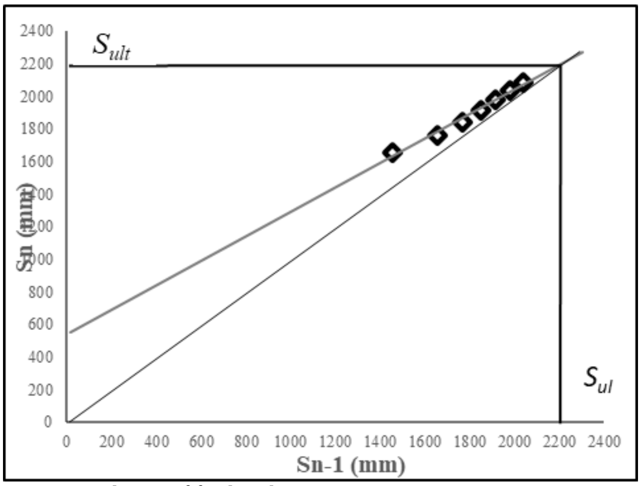

Figure 6. Prediction of final settlement

From the result of settlement using Asaoka method, to calculate the degree of consolidation is in accordance with Table 1.

Table 1.
Degree of Consolidation of Asaoka Method

STA	SP	S_{tot} (m)	S_t (m)	*U* (%)
1+000	SP 06	2.17	2.08	95,58
1+850	SP 01	2.03	1.89	94.49

C. Consolidation Settlement

1) Consolidation Settlement due to vacuum preloading

The fill preloading due to vacuum consists of vacuum preloading of 80 kN/m², levelling platform of 24 kN/m², and sand blanket of 12 kN/m², resulting in vacuum preloading (q) of 114 kN/m². As a result of calculation the amount of additional stress obtained Δp is 114 kN/m³ on each layer. Furthermore, consolidation settlement due to vacuum preloading can be seen in Table 2.

Table 2.
Consolidation Due to Vacuum Preloading

Depth (m)	p_o' base (kN/m²)	p_o' middle (kN/m²)	*Δp* (kN/m²)	*Δp+p_o'* (kN/m²)	ΔSc (m)
0	0	0	0.00	0.00	0.00
1.5	5.685	2.8425	114.00	116.84	0.48
4.5	19.755	12.72	114.00	126.72	0.74
9	53.46	36.6075	112.18	148.78	0.45
12.5	79.325	66.3925	109.44	175.83	0.18
15	104.8	92.0625	105.11	197.17	0.13
Σ *Sc*					**1.98**

2) Consolidation Settlement due to fill

Consolidation due to fill loading consisted of fill loading of 60,3 kN/m³, loading due to fill settlement of 41,69 kN/m² where consolidation settlement was counted first by using trial and error to obtain an appropriate result between the calculation of settlement and the height of fill of 2,07 m. As a result, the amount of settlement (S_c + S_i) was 2,32 m. Furthermore, loading due to levelling platform is 24 kN/m² , and, therefore, the total loading working on the fill Δσ = 60,3 + 41,69 + 24 = 125,99 kN/m². Detailed calculation of the consolidation settlement due to fill loading is in Table 3

.

Table 3.
Consolidation Due to Fill Loading

Depth (m)	p_o' base (kN/m²)	p_o' middle (kN/m²)	*Δp* (kN/m²)	*Δp+p_o'* (kN/m²)	ΔSc (m)
0	0	0	0.00	0.00	0.00
1.5	5.685	2.8425	125.99	128.83	0.50
4.5	19.755	12.72	125.99	138.71	0.77
9	53.46	36.6075	123.97	160.58	0.48
12.5	79.325	66.3925	120.95	187.34	0.19
15	104.8	92.0625	116.16	208.22	0.14
Σ *Sc*					**2.07**

3) Consolidation settlement due to temporary loading (surcharge)

The pavement and traffic was calculated equally to the heigh of the surcharge. It was 28,64 kN/m³, fill loading was 60,3 kN/m³, the loading due to fill settlement by using trial and error in order to get the fill *H* (S_c + S_i) was 2,36 m, and loading due to settlement was 19,32 kN/m². Loading due to levelling platform was 24 kN/m², and, thus, the total loading working on the fill was 28,64 + 60,3 + 19,32 + 24 = 132,26 kN/m². Detail calculation is shown in Table 4.

Table 4.
Consolidation Due to Extra Loading

Depth (m)	p_o' base (kN/m²)	p_o' middle (kN/m²)	*Δp* (kN/m²)	*Δp+p_o'* (kN/m²)	ΔSc (m)
0	0	0	0.00	0.00	0.00
1.5	5.685	2.8425	132.26	135.10	0.50
4.5	19.755	12.72	132.26	144.98	0.78
9	53.46	36.6075	130.14	166.75	0.49
12.5	79.325	66.3925	126.97	193.36	0.19
15	104.8	92.0625	121.94	214.01	0.14
Σ Sc					**2.11**

According to the calculation, the total vacuum preloading is smaller than the conventional one (114 kN/m² < 132,26 kN/m²) due to the application of fill loading that exceeds the vacuum's effective pressure (80 kPa ≈ 4,44 m fill). The total settlement due to vacuum preloading in each soil layer is 1,979 m smaller than the one due to conventional loading which is 2,11 m. In other words, the settlement due to vacuum preloading tends to be smaller than the surcharge preloading.

4) The height of vacuum and non-vacuum fill embankment

Figures 7 and 8 show the difference of the fill's height in vacuum and non-vacuum preloading. Vacuum preloading could reduce the embankment height required in the field in order to save the working time because heavy equipment is unnecessary and the work can be started when the degree of consolidation has reached 90%. As a result the project can be completed earlier compared to non-vacuum or using surcharge method.

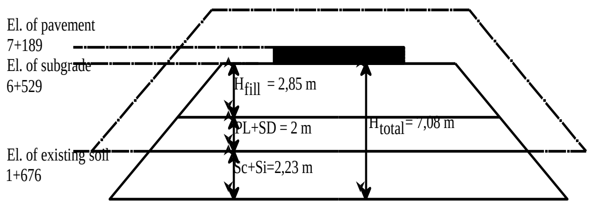

Figure 7. The height of fill in vacuum preloading.

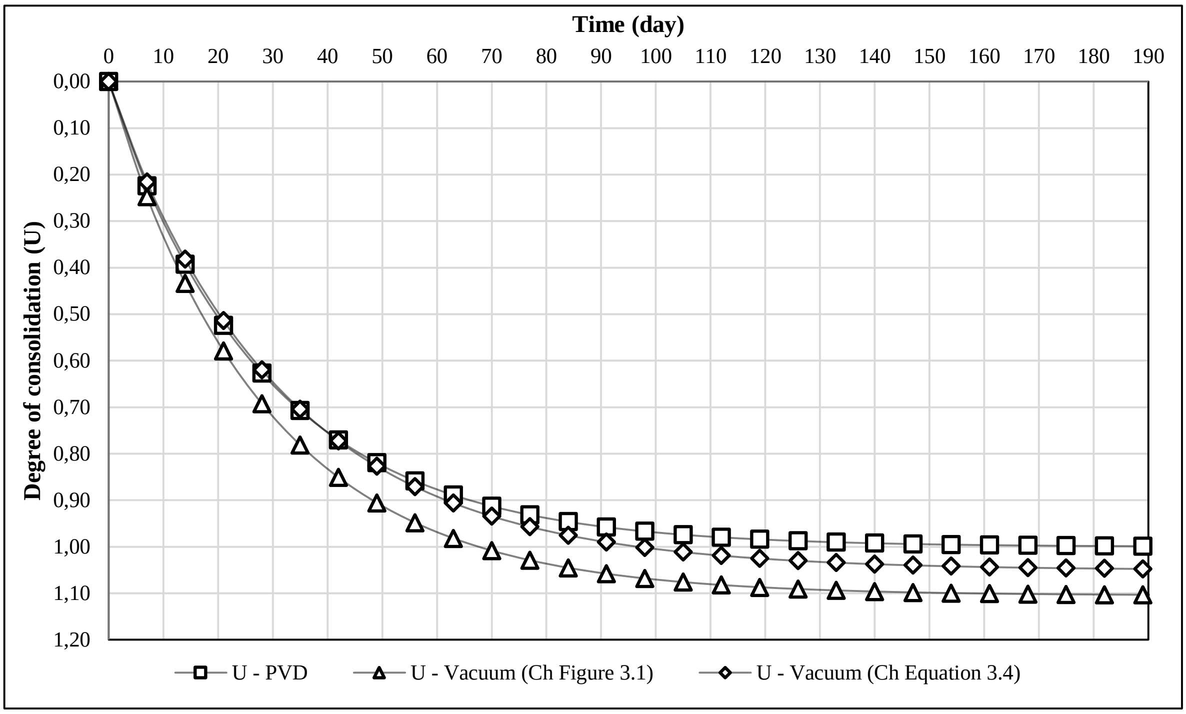

Figure 9. Degree of consolidation towards time

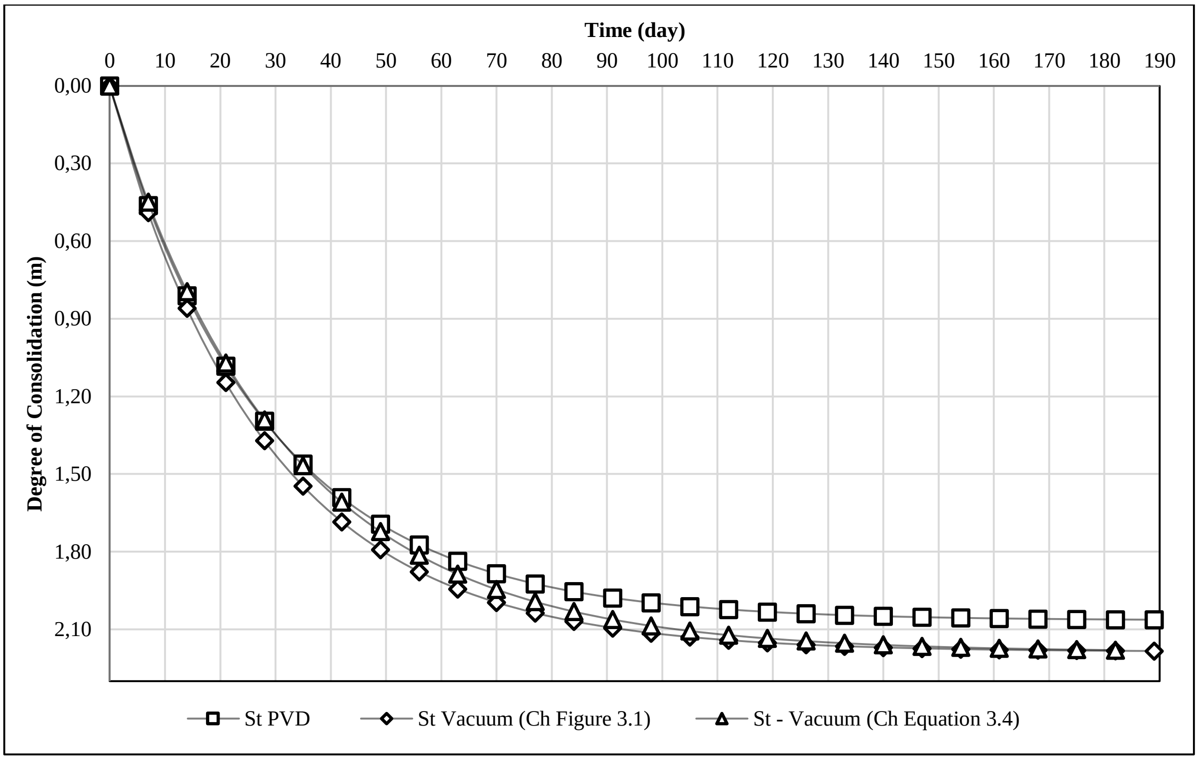

Figure 10. Comparison of settlement between PVD and vacuum

Table 5.
The Prediction of Degree of Consolidation

Stations	Prediction of Final settlement		Degree Consolidation		Time of Consolidation	
	Terzaghi (m)	Asaoka (m)	Terzaghi (%)	Asaoka (%)	Terzaghi - Indraratna (day)	Asaoka (day)
STA 1+000	1,98	2,17	90	95,85	56	70
STA 1+185	2,11	2,00	90	94,49	147	98

Table 6.
Comparison of PVD Spacings

	Spacing of PVD in vacuum method (m)		**Spacing PVD in conventional method (m)**	
	C_h Fig. 4	C_h Eq. (4)	C_h Fig. 4	C_h Eq. (4)
(S) PVD	1,23	1,18	1,12	1,05

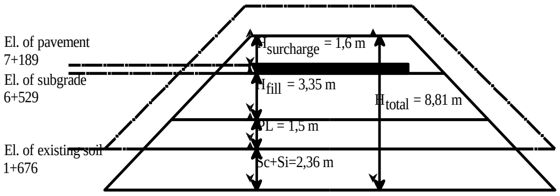

Figure 8. The height of fill in non-vacuum preloading.

D. Determining the degree of consolidation

The degree of consolidation based on settlement is calculated by the combination of equations used in vertical drain, with Eq. (5) and (6). Duration of consolidation in this study, ranging from observations made per 7 days. The result of the calculation for one time observation obtained the value of $F_{(n)}$ = 2.096 F_r = 0.188 F_s = 1.39 F = 3.67 T_v = 1.66 × 10 - 4 T_h = 0.063 U_v = 0.015 U_h = 0.21 U (%) $S_{c\ (t)}$ = 0.46 m and $U_{t,\ vac}$ = 0.25. The degree of consolidation and setllement in time was summarized in Figure 9 and Figure 10.

Figure 9 shows that, in order to reach the planned degree of consolidation U = 90 %, PVD + vacuum is proven to reduce the time. This supports the research conducted by [9] stating that the advantage of accelerating consolidation using vacuum preloading method with PVD is that the consolidation becomes faster due to the influence of the speed of water seepage flow in a radial direction and the possibility of failure during the vacuum preloading is relatively minimum. The variation of the usage of coefficient of consolidation (Ch) shows speed to reach the degree of consolidation (U). The higher the value of Ch is, the faster the value of U can be reached.

Figure 10 illustrates that consolidation settlement using combined vacuum method and fill surcharge results in settlement faster than the one using PVD. This supports research by [10] stating that the usage of vacuum preloading method combined with PVD produces settlement faster than the one using PVD only.

Overall, the recapitulation of the calculation result of settlement, degree of consolidation, and time of consolidation between the calculation combining Terzaghi - Indraratna and Asaoka is presented in Table 5.

Vacuum preloading combined with fill surcharge can be more effective when the height of the fill is equal or higher than the vacuum pressure that is applied, which is 80 kPa or equivalent fill up to 4,44 m. This can be seen from the time of consolidation that is shorter for (STA 1+000) with height fill = 4,85 m compared to (STA 1+185) with height = 3,04 m. Consequently, the time of consolidation is longer and the usage of vacuum method is less effective. Comparison between the heights of the fill is presented in Figure 7

E. PVD Design Using Vacuum Method

Based on PVD design procedure with vacuum loading and use of Eq with input value C_v = 1.95 m² / year C_h = 4.17 m² / year obtained T_v = 0,003 $U_{t,\ \mathrm{vac}}$ = 0.86 u * = 0,92 T_h '= 345,07 γ = 1446,54 λ = 0,81 α = 0,43 β = -0,05 n = 21,20 D = 1,39 to get value of S = 1,23 m . In the same way, the calculation for C_h of Eq. PVD is obtained at a spacing of 1.18 m. The result of conventional PVD design with the various usages of coefficient of consolidation is in accordance with Table 6. The table shows that the time of consolidation is the same, PVD design using vacuum method requires farther spacing compared with the surcharge one. The design PVD with vacuum, it is essential to have additional parameters that are different from regular PVD design.

IV. CONCLUSION

The analysis results leads to the following:

1. The coefficient of vertical consolidation (C_v) was 1,95 m^2/year, and the coefficient of horizontal consolidation (C_h) using Figure 4 was 4,17 m^2/year. The result was similar to C_h of 3,76 m^2/year as a result of Eq. (1.4).
2. The total settlement due to vacuum preloading as a result of Terzaghi and Asaoka methods in STA 1+00 respectively was 1,98 m and 2,17 m. The degree of consolidation from Terzaghi and Asaoka was 90 % and 95,85 %. The time of consolidation was 56 days from the calculation result of Terzaghi Equation (S_c) combined with the degree of consolidation of PVD (U_t) and the degree of consolidation of Indraratna vacuum ($U_{t,vac}$), while the settlement prediction of Asaoka was 70 days.
3. Time of consolidation using vacuum method was faster than the one using non-vacuum method due to multiplying factors in vacuum method caused by total fill loading above the membrane ($\Delta\sigma$) compared with the static fill loading under the membrane (Δp) and vacuum pressure (p_o) itself. If the multiplication result (depending on the height of the fill) is relatively large (h > po) or equal to vacuum pressure (h = po), so the effectivity of this method can be achieved.
4. PVD design using vacuum preloading resulted in PVD spacing of 1,23 m, while the non-vacuum one used 1,12 m and in the field uses a spacing of 1 m with with square pattern. It means that the usage of vacuum preloading more efficient to reduce the usage of PVD.

REFERENCES

[1] H. C. Hardiyatmo, “Metode Vacuum reloading sebagai salah satu alternative solusi pembangunan timbunan di atas tanah lunak,” 2017.

[2] M. F, S. F, W. I.C., and V. S, “Vacuum consolidation - A review of 12 years of successful development,” in *A Geo-Odyssey*, 2001, pp. 1–23.

[3] B. Indraratna and Rujikiatkamjorn, “Analytical solutions and design curves for vacuum assisted consolidation with both vertical and horizontal drainage,” University of Wollongong, 2007.

[4] NAVY U.S., “Soil Mechanics, Foundations and Earth Structures,” in *NAVFAC Design Manual DM-7*, Washington D.C., 1971.

[5] H. C. Hardiyatmo, *Mekanika Tanah 1*, 7th ed. Yogyakarta: Gadjah Mada University Press, 2017.

[6] M. R. Hausmann, *Engineering Principles of Ground Modification*. McGraw-Hill., 1990.

[7] I. B, S. I, B. C, and B. A.S., *Theoretical and Numerical Perspectives and Field Observations for the Design and Performance Evaluation of Embankments Constructed on Soft Marine Clay*, Engineerin. Elsevier Geo, 2005.

[8] A. Asaoka, “Observational Procedure of Settlement Prediction. Soils and Foundations,” *Japanese Soc. Soil Mech. Found. Eng.*, vol. 18, no. 4, pp. 87–101, 1978.

[9] G. Mesri and A. Q. Khan, “Ground Improvement Using Vacuum Loading Together with Vertical Drains,” *J. Geotech. Geoenvironmental Eng.*, vol. 138, no. 6, pp. 680–689, 2012.

[10] S. J., “PVD improvement combined with surcharge and vacuum preloading including simulations,” *Elsevier Geo – Geotext. Geomembranes*, vol. 29, pp. 74–82, 2010.