The Effectiveness of Vacuum Consolidation to Soft Soil Settlement

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Abstract— **The main issue of building constructions on soft soils is not a uniform settlement of soft ground, which has a slow process that effected construction failures and rising maintenance expenses. For many decades, to the improvement of ground soil stability, then applied using prefabricated vertical drain (PVD). Along the development of science and technologies, which followed by improvement of the soil stability method, that is called as Vacuum Consolidation Method (VCM). The objectives of this study are to determine how the effectiveness of vacuum consolidation with various patterns to soft soil settlement of constructions, and to find the right spacing of PVD installation due to un-uniform settlement of soft soils. The analysis of this study compared the numbers and rates of settlements in preloading, PVD, and VCM with various patterns, and to get a uniform settlement by two scenarios analysis, which are various spacing with single suction pressure (scenario 1) and single spacing with various suction pressures. Based on the result of analysis which showed the settlement of VCM in both patterns are 2.247 m in 105 days (square pattern) and 2.252 m in 90 days (triangular pattern). It means with a triangular pattern has 70.2 more effective than others in the rate of the settlement period. It also showed the VCM has larger than others in volume settlements. The results of 2 scenarios analysis showed that the implementation of scenario one was difficult due to various spacing, while scenario two can be implemented because numbers of settlements depend on suction pressure of the vacuum.**

Keywords— **pre-fabricated; vertical drain vacuum; consolidation method; consolidation; soft soil.**

I. INTRODUCTION

The main issue of building constructions on soft soil is not uniform settlement of soft ground, which has a slow process that effected construction failures and rising maintenance expenses. Besides those challenges, construction engineers must deal with time limits to finish the construction project, especially in highway construction projects. To improve soil stability and to accelerate settlement, scientists and engineers had developed many studies developing acceleration of consolidation method for soft soils.

In 1948, Barron has introduced a consolidation method to accelerate soft soil settlements using vertical drain wells, which is known as Barron's solution. The Barron's method is becoming a reference for engineers to estimate time relation of consolidation due to simplification formula that ignored peripheral smear, well resistance, and rigidity of soil [1]. Vertical drain wells can be implicated by sand drains, sand compaction piles, and gravel piles that we can call as traditional vertical drain method. Those applications had been developed with a modern shape, which called as prefabricated vertical drain (PVD). Based on many research studies, majority of the scientist has agreed that PVD can accelerate consolidation [2]-[9], increasing shear strength [10], [11], hydraulic conductivity and increasing surcharge load rate [12].

According to the mechanism of consolidation method that acceleration of soil settlement can be increased by releasing pore air and water pressure with sufficient strength (vertical stress), then in 1948, *Kjellman* has developed vertical drains method that combined with suction pressure to accelerate time relation of consolidation. *Kjellman* method is called as Vacuum Consolidation Method (VCM) due to use vacuum for suction pressure. For many years, this method did not widely apply due to the difficulties of vacuum maintenance during implementation. Along with the development of science and technologies in the last decade, many countries have applied consolidation method by vacuum pressure such as Philadelphia Airport (USA), Tianjin Port (China), Wenzhou Airport [13], North-South Expressway Malaysia, Singapore and Bangkok.

To find the effective result of the implementation of VCM, scientists have developed the new VCM, such as adding some tools on VCM to increase the acceleration suction of pore air and water pressure. Scientist have used a cap installed at the intersection between vertical and horizontal drains [14], [15] and added vacuum specially for suction of pore air pressure [16]-[18]. The scientists also have combined pneumatic fracturing method [19], membranelles vacuum for compressible improvement [20], and compact

vacuum consolidation. Beside the development of VCM tools, many scientists also had developed new methods or model analyses, which are numerical and finite analysis about soft soil settlement related to the implementation of VCM [22]-[28].

In Indonesia, the VCM has not used commonly for construction buildings yet. The first construction building has used by VCM in Trans Sumatra Highway Construction. The site of this study is lied on lowland areas with the depth of soft soil on 0 – 30 m and water level at -1 m – 3.5 m from sub-ground surfaces, as showed Figure 1.
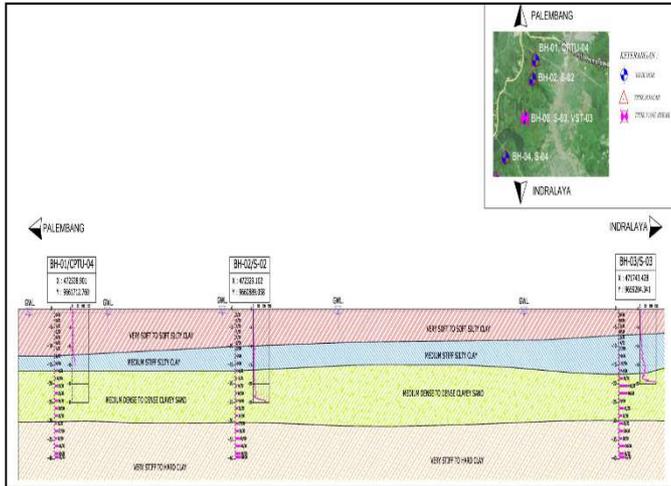
Fig. 1 Soft soil profile on-site study

Based on it, this study will be determined the effectiveness of VCM to PVD and Preloading method for soft soil settlement and found the right spacing of PVD installation due to the un-uniform settlement of soft soil.

II. MATERIAL AND METHODS

This study found out the thick and time consolidation of settlement for each consolidation method. The analysis divided into three methods, as follows:

A. Preloading Method

In the analysis of the preloading method, consolidation of soft soil occurred by following the assumptions that are the applying load at the sub-ground surface with flexible areas and homogenous soil. The settlement analyzed the mechanism of consolidation 1D based on the result of the Oedometer test. The expression estimated the settlement:

$$S_C = \frac{C_c \times H}{1 + e_0} \log\left(\frac{\sigma'_0 + \Delta\sigma'}{\sigma'_0}\right) \qquad (1)$$

Where C_c = compression index, H = soil layer thickness, e_0 = initially of void ratio, σ'_0 = the field sufficient overburden pressure, $\Delta\sigma'$ = the change in adequate pressure, S_c = the settlement thickness. Meanwhile, the estimation of time consolidation, t:

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

Where T_v = time factors which depend on degree of consolidation, H_{dr} = drainage length (for normal consolidation H_{dr} = H, while for consolidation by preloading H_{dr} = 0.5H, C_v = coefficient of consolidation.
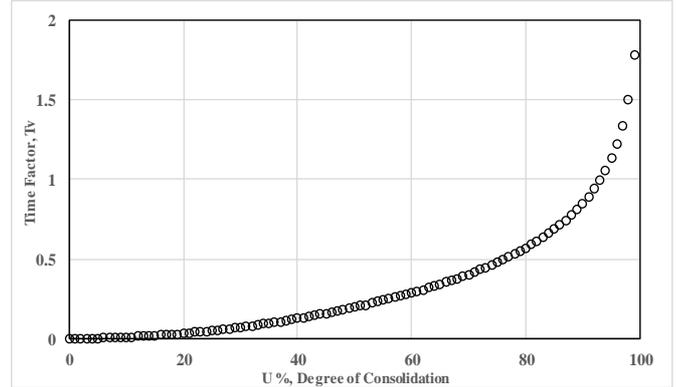
Fig. 2 Time Factor to Degree of Consolidation

The settlement will be stopped if the degree of consolidation (U) at 100%, but according to Terzhagi's theory, which U 100% has un-finite value. The maximum degree of consolidation at 90% is showed in Figure 2.

B. Prefabricated Vertical Drain

The installation of PVD is usually in a square pattern or triangular pattern in which the spacing of vertical drains must be less than the thickness of the soft soil layer. The philosophy of PVD works is reducing the length of pore water drainage, which assumes that the drainage will occur radially at surrounding areas of vertical drains [29]. Therefore, the degree of consolidation and settlement affected by the spacing of vertical drains due to 2D drainage of pore water (vertical and horizontal).

Generally, the formulas of estimation settlement as the same as preloading, but in PVD method is considering smear effects which affected by during installation PVD and degree.

d_e = 1.128 S d_e = 1.05 S
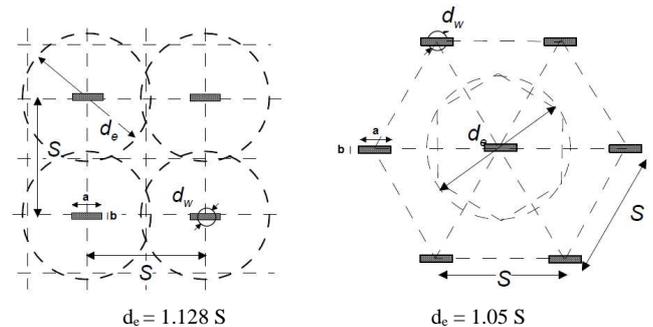
Fig. 3 Vertical drains installation pattern (left: square pattern, Right: triangular pattern).

$$d_w = \frac{2(a+b)}{\pi} \qquad (3)\text{s}$$

$$d_w = \frac{(a+b)}{2} \qquad (4)$$

$$d_w = 0.5a + 0.7b \qquad (5)$$

The settlement of PVD is the average multiplication degree of consolidation, U, and ultimate settlement, S_{ult}, which is the thickness settlement from equation (1).

$$S_C = U \times S_{ult} \qquad (6)$$

$$1 - U = (1 - U_v)(1 - U_r) \qquad (7)$$

Where U_v = average degree of consolidation due to vertical drainage (Figure 2), U_r = average degree of consolidation due to radial (horizontal) drainage.

$$U_v = \frac{\sqrt{\dfrac{4T_v}{\pi}}}{\left[1 + \left(\dfrac{4T_v}{\pi}\right)^{2.8}\right]^{0.179}} \qquad (8)$$

$$U_r = 1 - \exp\left(\frac{-8T_h}{F}\right) \qquad (9)$$

Or U_r from time factor of radial consolidation to the degree of consolidation (Figure 4).

$$T_h = \frac{C_h \times t}{d_e^{\,2}} \qquad (10)$$

$$C_h = 1.2C_v - 3C_v = 2C_v \qquad (11)$$

$$F_{(n)} = \left[\frac{n^2}{(n^2 - 1)}\right]\ln(n) - \frac{(3n^2 - 1)}{4n^2} \qquad (12)$$

$$F_{(s)} = \left[\left(\frac{k_h}{k_s}\right) - 1\right]\ln\left(\frac{d_s}{d_w}\right) \qquad (13)$$

$$n = \frac{d_e}{d_w} \qquad (14)$$

$K_h/K_s = 5$, $d_s/d_w = 2 - 3 = 2.5$ [30], [31].
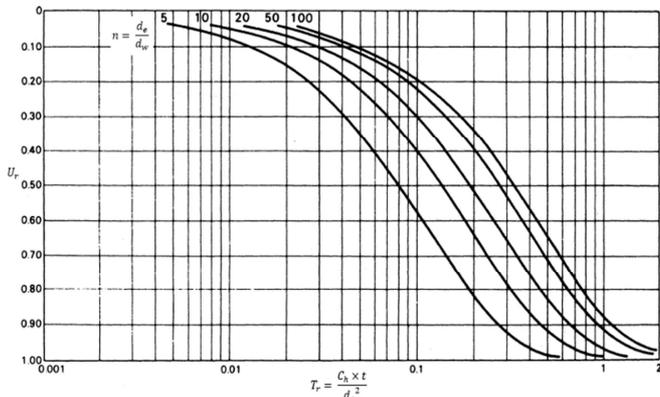
Fig. 4 Graph of radial degree consolidation, U_r, to the time factor, T_r.

C. Vacuum Consolidation Method (VCM)

According to the purposes of the vacuum method to accelerate settlement and time consolidation, which sucking pore air and water in soft soil where is sealed by geo-membrane, as shown in Figure 5. This method had using PVD that connected to the pipe as horizontal drainage to drain off pour air and water to the vacuum pump, as Figure 6. Suction pressure applied in this study at 80 – 100 KPa with average pressure in 90 KPa.

The estimation settlement and time consolidation still using Terzaghi's theory but in the parameter of the change in effective pressure, $\Delta\sigma'$, will be adding extra load from suction pressure.
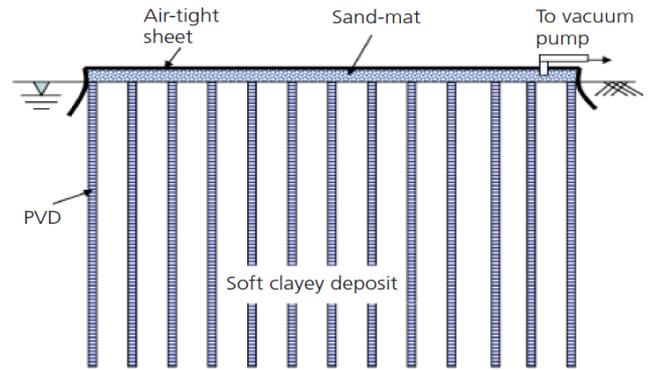
Fig. 5 Illustration of Vacuum Consolidation Technique [32]
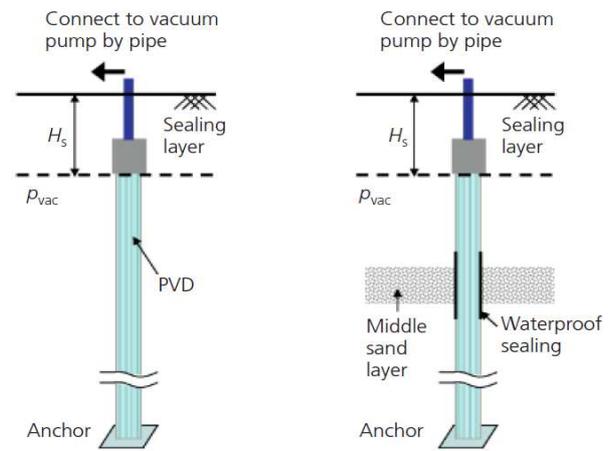
Fig. 6 Vacuum Consolidation with CPVD without (left) and with (right) a sand layer.

III. RESULTS AND DISCUSSIONS

The result of soil investigation showed that the area study has low SPT value, which means high compressibility and low bearing capacity, as shown in Figure 7. The Graph of N-SPT values showed mostly the first 10 m of depth soils had < 5 N-SPT, which means the soils with very soft to a soft consistency. The consistency of soil itself is strongly influenced by groundwater table (GWT). The GWT of site studies have discovered very shallow, i.e., most of it less than 3 m below ground level, as shown in Figure 8.
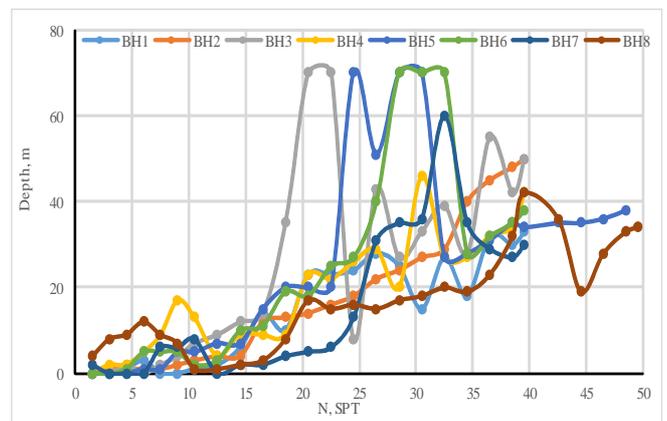
Fig. 7 N SPT Value of Site Study
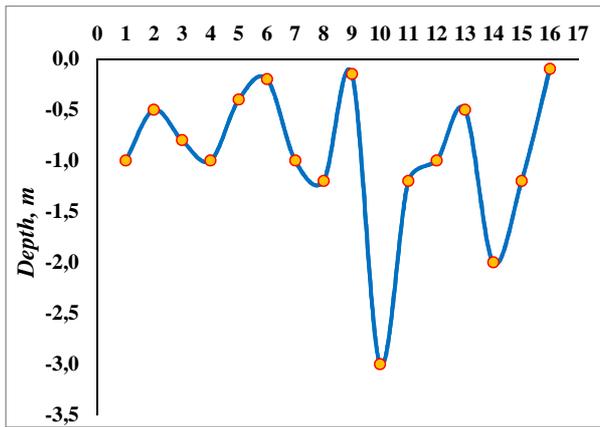
Fig. 8 Ground Water Level at Site Study
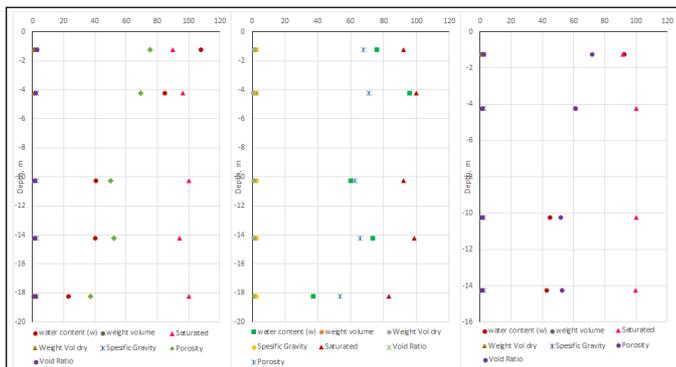
Fig.9 Soil index properties of soft soil in-site study.

At the same time, the soil laboratory test of site studies showed index soil properties, as shown in Figure 9, such as water content maximum has 107.71%, maximum porosity was 75.397, and saturated degree 92 – 100 %. Based on these index properties, it was known that the soil type of site studies are soft clay and silty clay.
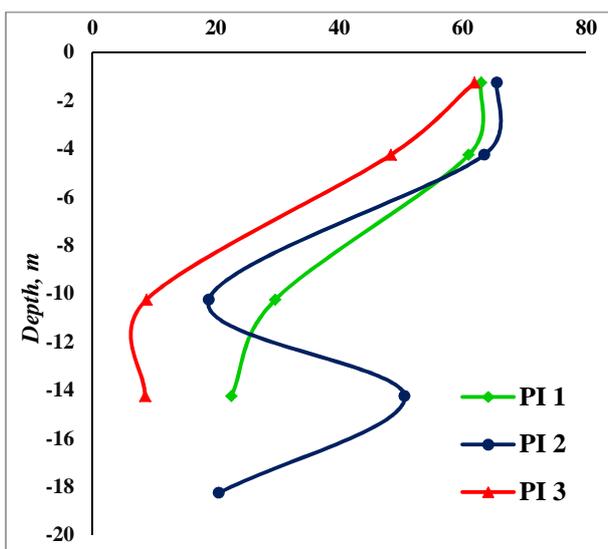
Fig. 10 Plasticity Index of Soft Soil in site Study.

The result of soil test showed that at the sub-ground surface (0 – 5 m) has high Plasticity Index > 50, which means the soil has high clay minerals that will be affected to

the consolidation process, especially in the secondary consolidation process, as shown as Figure 10.

TABLE I
CONSOLIDATION PARAMETERS

Site Study	Depth (m)	e_0	Cc	Cv (E-02)	k (E-06)
PI 1	-1.25	2.5962	0.88	1.57	3.12
	-4.25	2.7775	1.22	2.63	7.08
	-10.25	1.0059	0.33	2.9	3.59
	-14.25	1.0965	0.25	2.71	2.22
PI 2	-1.25	2.1324	0.89	2.4	5.3
	-4.25	2.4399	0.83	1.21	2.5
	-10.25	1.6761	0.48	2.26	3.31
	-14.25	1.9125	0.65	1.86	3.33
	-18.25	1.2384	0.3	0.177	0.413
PI 3	-1.25	2.5726	1	1.66	3.47
	-4.25	1.5804	0.63	1.81	3.3
	-10.25	1.0642	0.14	3.47	1.65
	-14.25	1.1161	0.25	2.07	1.72

The result of this research in the Oedometer test showed soft soil behavior related to the high Plasticity Index, which is occurred swelling at the end of consolidation, as shown in Figure 11. It can be further consideration for scientists to find method improvement of expansive soft soil.
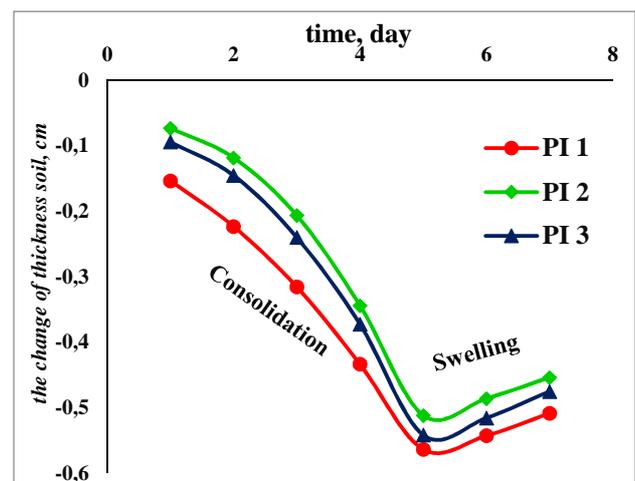
Fig. 11 The change of thickness soil to time consolidation

The analysis of the preloading method has resulted in an average settlement in 0,0235 m/year with average time consolidation for the degree of consolidation 90% in 19.9 years. Meanwhile, for precisely the settlement of each site, studies showed Table II.

TABLE II
THE SETTLEMENT AND TIME CONSOLIDATION ON PRELOADING METHOD ANALYSIS

Site	Cc	Cv	H	σ_0	Δσ	Sc(m)	t
1	0.67	0.025	16.5	1117.49	3.47	0.003	17.34
2	0.63	0.016	17	895.72	3.47	0.002	16.35
3	0.505	0.023	18	1160.85	3.47	0.002	26

In prefabricated method analysis, the settlement and time consolidation is analyzed into two analysis based on pattern installation of PVD, which are a square and triangular pattern that emphasized to accelerate time consolidation. Based on the result analysis, the degree of consolidation of 90 % for the square pattern was achieved in 105 days with the thickness of settlement in 1.314 m, as shown in Table III.

TABLE III
THE RESULT OF SQUARE PATTERN PVD INSTALLATION (PI 1)

t (day)	Uv	1-Uv	Tr	Ur	1-Ur	U (%)	Sc (m)
0	0	1	0	0	1	0	0
5	0.017	0.983	0.047	0.103	0.897	0.118	0.175
10	0.023	0.977	0.094	0.196	0.804	0.214	0.317
15	0.029	0.971	0.141	0.278	0.722	0.299	0.443
20	0.033	0.967	0.188	0.353	0.647	0.374	0.554
25	0.037	0.963	0.235	0.420	0.580	0.441	0.653
30	0.041	0.959	0.282	0.479	0.521	0.501	0.741
35	0.044	0.956	0.329	0.533	0.467	0.554	0.819
40	0.047	0.953	0.376	0.581	0.419	0.601	0.889
45	0.050	0.950	0.423	0.624	0.376	0.643	0.952
50	0.052	0.948	0.470	0.663	0.337	0.681	1.008
55	0.055	0.945	0.517	0.698	0.302	0.714	1.057
60	0.057	0.943	0.564	0.729	0.271	0.745	1.102
65	0.060	0.940	0.611	0.757	0.243	0.771	1.142
70	0.062	0.938	0.658	0.782	0.218	0.796	1.177
75	0.064	0.936	0.705	0.804	0.196	0.817	1.209
80	0.066	0.934	0.752	0.825	0.175	0.836	1.238
85	0.068	0.932	0.799	0.843	0.157	0.853	1.263
90	0.070	0.930	0.846	0.859	0.141	0.869	1.286
95	0.072	0.928	0.893	0.873	0.127	0.883	1.306
100	0.074	0.926	0.940	0.886	0.114	0.895	1.324
105	0.076	0.924	0.987	0.898	0.102	0.906	1.341
110	0.078	0.922	1.034	0.909	0.091	0.916	1.355
115	0.080	0.920	1.081	0.918	0.082	0.925	1.368

While in a triangular pattern shows the degree of consolidation, 90 % were achieved in 90 days and the thickness settlement for 1.344 m, as shown in Table IV. In the site field of construction, Vacuum consolidation is implemented by combine with PVD and preloading. So that not only emphasized time consolidation but also to the thickness of settlement.

The result of the analysis is shown that with the same period consolidation in PVD method, Vacuum can be increasing the thickness of soft soil layers significantly. It can be seen the change of thickness from 1.344 m to 2.247 m in the same period 105 days for the square pattern. Meanwhile, for the triangular pattern, the change of thickness, which resulted is 2.252 m.

The variations of index properties and depth of soft soil in each site have affected un-uniform settlement and time of consolidations. The differential result of sites study at U90% shown that PI 2 has larger settlement and time consolidation as 3 m in 188 days, while PI 1 and PI 3 have 2.252 m in 90 days and 2.05 m in 158 days, as shown as Figure 12.

TABLE IV
THE RESULT OF TRIANGULAR PATTERN PVD INSTALLATION (PI1)

t (day)	Uv	1-Uv	Tr	Ur	1-Ur	U (%)	Sc (m)
0	0	1	0	0	1	0	0
5	0.017	0.983	0.054	0.121	0.879	0.135	0.200
10	0.023	0.977	0.109	0.227	0.773	0.245	0.363
15	0.029	0.971	0.163	0.320	0.680	0.340	0.503
20	0.033	0.967	0.218	0.402	0.598	0.422	0.625
25	0.037	0.963	0.272	0.474	0.526	0.494	0.731
30	0.041	0.959	0.327	0.538	0.462	0.557	0.824
35	0.044	0.956	0.381	0.594	0.406	0.611	0.905
40	0.047	0.953	0.435	0.643	0.357	0.659	0.976
45	0.050	0.950	0.490	0.686	0.314	0.701	1.038
50	0.052	0.948	0.544	0.724	0.276	0.738	1.092
55	0.055	0.945	0.599	0.757	0.243	0.770	1.140
60	0.057	0.943	0.653	0.786	0.214	0.799	1.182
65	0.060	0.940	0.708	0.812	0.188	0.823	1.219
70	0.062	0.938	0.762	0.835	0.165	0.845	1.251
75	0.064	0.936	0.817	0.855	0.145	0.864	1.279
80	0.066	0.934	0.871	0.872	0.128	0.881	1.303
85	0.068	0.932	0.925	0.888	0.112	0.895	1.325
90	0.070	0.930	0.980	0.901	0.099	0.908	1.344
95	0.072	0.928	1.034	0.913	0.087	0.919	1.361
100	0.074	0.926	1.089	0.924	0.076	0.929	1.375
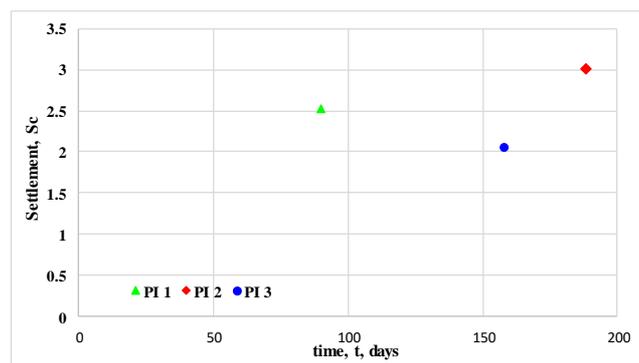
Fig. 12 Various settlement of sites study

The purposes of VCM installation are to get a larger settlement in the shortest time consolidations. The numbers of settlement and time consolidation are strongly influenced by a spacing of PVD installation (S) and suction pressure of vacuum (σ). Therefore, to get a uniform settlement, then the analysis in 2 scenarios, which are various spacing in the same suction pressure (σ = 8 t/m^2) and same spacing (S = 1 m) in various suction pressure. Those analysis has resulted that the settlement of soft soils will be uniform if the spacing of PVD installation (S) in around 0.75 m with 2 m of settlement, as shown in Figure 13.

Meanwhile, if the consolidation process is using various suction pressure in the same spacing of PVD installation (S = 1 m), then the result of the analysis showed the uniform settlement (Sc = 2.3 m) at sites study (PI 1, PI 2, and PI 3), respectively, will be occurred in 250 KPa, 340 KPa, and 480 KPa, as shown as Figure 14.
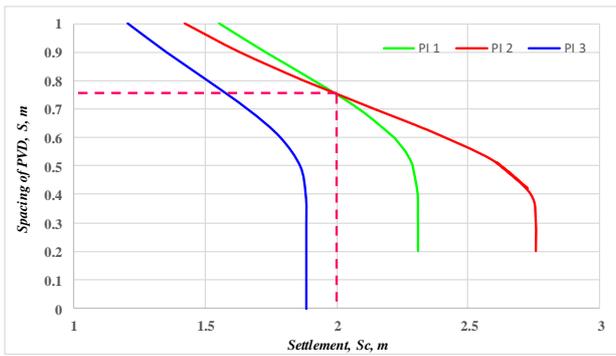
Fig. 13 The effect of Spacing of PVD Installation to numbers of settlement.
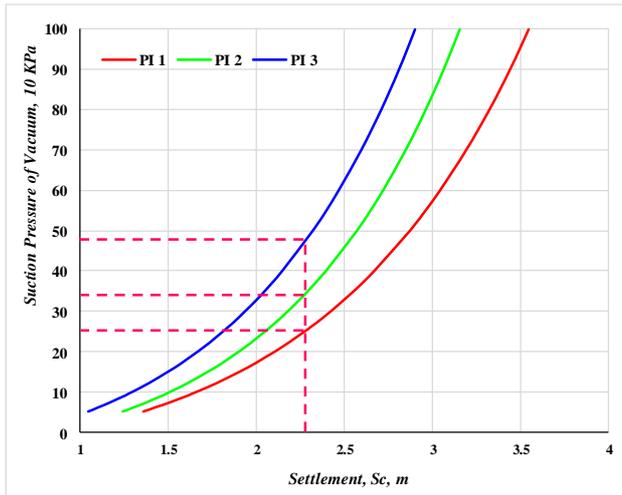
Fig. 14 The effect of Suction Pressure to Settlement of Soft Soils

IV. CONCLUSIONS

Based on all the results of the analysis, the application of the vacuum method for soft soil settlements indeed more effective 67 – 71% than applied only preloading and or combined with PVD. In comparison, the vacuum with triangular pattern installation gives the most effective result of soil settlement. According to the depth and type of soft soil, this study has found that the uniformity of settlement does not follow the effectiveness of VCM. It means additional works for engineers to solve this problem due to the construction project schedule. In the consolidation process by VCM, the numbers of settlement and time consolidation are strongly influenced by the spacing of PVD installation and suction pressure of the vacuum.

Based on the result of 2 scenarios analysis, the first scenario could give uniform settlement, but cannot be applied in some specific sites, especially at sites which have a significant difference of settlement that other sites. Furthermore, the implementation of scenario 1 has difficulties application due to various spacing of PVD installation. Meanwhile, the second scenario can be implemented in various conditions and more simple applications because numbers of settlements depend on suction pressure of the vacuum.

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