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SOIL SUBSTANCE ANALYSIS USING PVD WITH VACUUM CONSOLIDATION METHOD (VCM)

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Abstract— **The construction of toll roads on soft clay has the main problems of the relatively low bearing capacity of the subgrade and the relatively large and long duration of subgrade compression. The infrastructure built on the subgrade could be damaged before it reaches its planned age if the subgrade not repaired first. The selection of the soft clay soil handling method considers the cost and time at the time of construction in the field. For this reason, alternative methods needed that are cost and time efficient and have minimal risk to environmental impacts. The vacuum consolidation method (VCM) is an alternative to improve water saturated soft clay. Soil improvement using the vacuum consolidation method is intended to accelerate the settlement and increase the bearing capacity of the soft native soil by vacuum pumping the soil to reduce the moisture content and air content of the soil grains to accelerate long-term settlement and differential settlement. This study aimed to analyze the soil settlement using PVD with the vacuum consolidation method (VCM). The analysis conducted showed that to achieve 90% consolidation without PVD, it would take 13,922 years and using PVD, it would take 18 months, and using PVD and the vacuum consolidation method (VCM), it would take 4,8 months. The use of PVD with the vacuum consolidation method (VCM) can speed up the consolidation process compared to using PVD or only using PVD. The total decrease that occurred was 2,043 m.**

Keywords— **Soil Settlement, Soft Clay, Vacuum Consolidation Method (VCM).**

I. INTRODUCTION

In general, the construction of toll roads in Indonesia located on land with soft clay soil conditions with low native soil carrying capacity. The problem of large consolidation settlement over a long period of time is a problem found in water-saturated soft clay soils. For this reason, the selection of soil improvement methods is very important. One of the methods used is by using PVD with vacuum consolidation method (VCM). Soil improvement using PVD with a vacuum is intended to accelerate settlement and increase the bearing capacity of soft native soil by vacuum pumping the soil with the aim of reducing the water content and air content of the soil grains so as to accelerate long term settlement and differential settlement.

II. LITERATUR REVIEW

1. Soft Soil

Soft soil is soil that if not recognized and investigated carefully can cause intolerable long term instability and settlement problems. The soil has low shear strength and high compressibility. Soft soil is divided into two, namely soft clay soil and peat soil (Tim Pusat Litbang Prasarana Transportasi Bandung, 2002).

2. Soft Clay Soil

According to the Tim Pusat Litbang Prasarana Transportasi Bandung (2002) soft clay is soil that contains clay minerals and has a high water, which causes low shear strength. In geotechnical engineering, the terms soft and very soft are specifically defined for clays with shear strength as shown in Table -1 below:

Table -1 Definition Of Soft Clay Shear Strength

Consistency	**Sliding Strong (kN/m^2)**
Soft	12,5-25
Very Soft	< 12,5

Source: Tim Pusat Litbang Prasarana Transportasi Bandung, 2002

Soft clay or also known as expansive clay is classified as a type of soil that has large expansion and depreciation value, which can damage structures above it. This is because the magnitude of the activity value (A) of clay, the size of the activity value of clay is influenced by the value of the plasticity index (PI) of the soil, in Table -2 it can be seen the potential development of a type of soil based on the value of its plasticity index (PI), for clay soils that can be categorized into expansive clays, namely soils that have very high development potential, the limit of the plasticity index value or PI > 35%, in addition to the activity value Clay soils can also be influenced by the type of minerals contained in the soil, the more plastic the clay minerals, the more potential to shrink and expand.

Table -2 Development Potential

Development Potential	Expansion (due to pressure 6,9 KPa) (%)	Percent Colloid (<0,001mm) (%)	Plasticity Index PI (%)	Shrinkage Limit SL (%)	Liquid Limit LL (%)
Very High	>30	>28	>35	>11	>65
High	20-30	20-31	25-41	07-12	50-63
Medium	10-20	13-23	15-28	10-16	39-50
Low	<10	<15	<18	<15	39

Source: Tim Pusat Litbang Prasarana Transportasi Bandung, 2002

As a supporter of infrastructure buildings, soft clay has the characteristics of a relatively low bearing capacity and relatively large compression and lasts a relatively long time. So that if there is no repair on the subgrade first, the infrastructure buildings built on it have the potential to be damaged before reaching the planned construction age (Wahyu P. Kuswanda, 2015).
According to Wahyu P. Kuswanda (2015) to overcome the problems of infrastructure development on soft clay soils, there are several methods of soil improvement that can be done, namely as follows:
a. Preloading (with vertical drain);
b. Electro osmosis;
c. Vacuum consolidation;
d. Lightweight fill;
e. Stone column;
f. Jet grouting;
g. Lime columns;
h. Fracture grouting;
i. Ground freezing;
j. Vitrification;
k. Electrokinetic treatment;
l. Electroheating.

3. Prefabricated Vertical Drain (PVD)

According to Putu Tantri Kumala Sari (2015), Prefabricated Vertical Drain (PVD) is a method of improving soft soil which for approximately 20 years has replaced the conventional sand drain method. If a building is built on soft clay soil, settlement will automatically occur on the soil which will disrupt the stability of the structure above it. It may take a long time for the compression or settlement to occur. The use of vertical drains will reduce the time rate of settlement which initially took a long time.

4. Vacuum Consolidation Method (VCM)

The vacuum method was introduced in Sweden by Kjellman in 1952 for card board-type vertical drainage, and has been frequently used for soft soil improvement, such as at Philadelphia International Airport and Tianjin Port to speed up consolidation (Yan dan Chu in Putu Tantri Kumala Sari, 2015). Recently, a PVD type drainage system has been applied to distribute vacuum pressure to the depth of the subsoil thus increasing the degree of consolidation (Chu in Putu Tantri Kumala Sari, 2015). According to Yan and Chu in Putu Tantri Kumala Sari (2015), the cost of soil improvement with vacuum loading is reduced by 30% if only in terms of replacing conventional additional loading (preloading).
This loading system aims to achieve a faster consolidation process without increasing the embankment height which can lead to shear failure. As can happen in the case of preloading, especially when in the case of soft soil improvement with very low shear strength, the vacuum loading method is suitable. In addition, the construction time is shorter, does not require heavy equipment, and no chemical mixture is used, so it is an environmentally friendly soil improvement method (Chai in Putu Tantri Kumala Sari, 2015).
The advantages of the vacuum loading method compared to conventional preloading can be described as follows (Qian in Putu Tantri Kumala Sari, 2015):
a. The effective stress increases according to the pressure increases and the lateral displacement of the soil can be resisted. This shear failure can be minimized.
b. The high vacuum pressure can be distributed to great depths beneath the soil layer using a PVD system.
c. The additional volume of the embankment for loading can be reduced and still achieve the same amount of settlement.

A typical vacuum loading is shown in Fig. 1. (Chu in Putu Tantri Kumala Sari, 2015). PVD and horizontal pipes are used to distribute vacuum pressure and pore water loss.

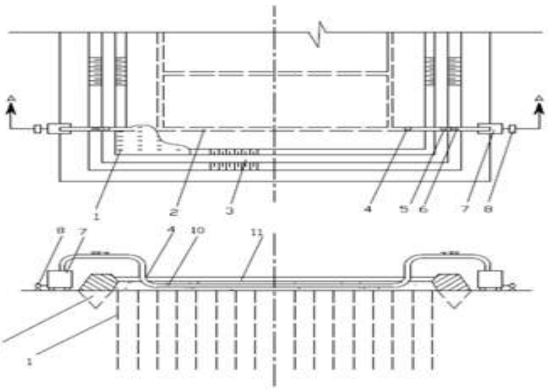

Fig. 1. Schematic illustration of a vacuum loading system (J. Chu, S. Yan in Putu Tantri Kumala Sari, 2015)

Description:
a. PVD (prefabricated vertical drain);
b. Horizontal pipe;
c. Revetment;
d. Water outlet;
e. Valve;
f. Vacuum gauge;

g. Jet pump;
h. Centrifugal pump;
i. Trench channel;
j. Vacuum main pipe;
k. Wrapping membrane.

The stages of the VCM process according to Bagja Nugraha Kurniawan (2016), are as follows:
a. Land Clearing;
b. Tools preparation;
c. Geotextile Installation;
d. Filling Material Stockpiles;
e. Horizontal Sand Drainage Overlay;
f. Prefabricated Vertical Drain (PVD) installation;
g. Perforated Horizontal Drain (PHD) installation;
h. Installation of Stabilizer Geotextiles and Geomembranes;
i. Geomembrane Sealing;
j. Installation of Monitoring Equipment;
k. Pump Installation;
l. Vacuum Gauge;
m. Pump Installation;
n. Vacuum Process.

5. Land Settlement

According to Tigor L. Tobing in Erna Yulianti and Indrayani, (2013) the term settlement indicates the settlement of a building due to compression and deformation of the soil layer under the building. The settlement will occur if a layer of soil is subjected to loading. Settlement is also influenced by the distribution of soft soil or clay below the surface on alluvial plains.
In general, land settlement due to loading can be divided into 3, namely:
a. Immediate settlement is the result of elastic deformation of dry, wet, and water-saturated soils without any change in water content.
b. Primary consolidation settlement is a decrease that is characterized by a large pressure on the soil which can reduce the soil structure, as well as shrinkage in the composition and movement of soil particles into the soil cavity due to compaction and compaction of the soil.
c. Secondary consolidation settlement is a decrease that occurs after all pore water pressures have been completely dissipated.

6. Consolidation

Consolidation is defined as an event of compression due to a constant/continuous load on it caused by a construction or heap of soil so that the process of removing water from the pores occurs. This situation can occur when the soil is saturated or only partially saturated. (Prabandiyani, et al., in Erna Yulianti and Indrayani, 2013).
Consolidation settlement is a settlement caused by the release of water in the soil pores due to the load acting on the foundation whose amount is determined by the loading time and occurs in saturated soil (Sr = 100%) or near saturation (Sr = 90% - 100%) or on soil fine-grained, which has a value of K 10-6 m/s. (Prabandiyani, et al, in Erna Yulianti and Indrayani, 2013).

6.1. One Dimensional Consolidation

Terzaghi in Erna Yulianti and Indrayani (2013), introduced the theory of one-way consolidation for saturated clay soils. This theory provides a way of determining the distribution of excess hydrostatic pressure in a layer that is undergoing consolidation at any time after the load is applied.
In calculating the amount of settlement and the duration of settlement of a soil layer, it is necessary to first know one of the soil parameters.
The amount of consolidation settlement can be found using the following equation:

$$S = \sum\left[\frac{C_c.H_i}{1+e_0}\log\left(\frac{Po_i+\Delta p_i}{Po_i}\right)\right] \qquad (1)$$

Where:
S = Settlement (m)
Cc = Compression index
H_i = Soil thickness for sub-layer i (m)
e_0 = Initial void ratio
$Po_{(i)}$ = Overburden pressure for sub-layer i
$\Delta P_{(i)}$ = Addition of Pressure for sub-layer i
To calculate the decline time with the following formula:

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

Where:
Tv = Time factor
Cv = Consolidation coefficient (m^2/second)
H = Depth (m)
t = Time (seconds)

6.2. Three Dimensional Consolidation

Here a vertical drain is used so that horizontal/radial flow can occur so that an overview of the three-dimensional consolidation process can be obtained. Here are some formulas:

$$n = \frac{de}{dw} \qquad (3)$$

Where:
de = PVD hydraulic diameter (cm)
dw = Vertical drain equivalent diameter (cm)

Ch = (kh/kv) Cv (4)

Where:
Ch = Horizontal flow consolidation coefficient (m^2/second)
kh/kv = The comparison between the coefficient of permeability of the soil in the horizontal and vertical directions, for clay soils saturated with water, the value

(kh/kv) ranges from 2 – 5 (chosen 2 because vertical drains will greatly shorten the time of primary consolidation of compressed soils)
Cv = Consolidation coefficient (m^2/second)

$$Tr = \frac{C_h.t}{d_e^{\ 2}} \quad (5)$$

Where:
Tr = Radial time
Ch =Horizontal flow consolidation coefficient (m^2/second)
t = Time (second)
de = Smear zone diameter (cm)

$$Uv = \frac{\sqrt{\frac{4Tv}{\pi}}}{[1+(4\frac{Tv}{\pi})^{2,8}]^{0.179}} \qquad (6)$$

Where:
Tv = Time factor
Uv = Consolidation degree in vertical direction (%)

$$U_r = 1\text{- exp }(\frac{-8\,Tr}{F}) \qquad (7)$$

Where:
Ur = Consolidation degree in the radial direction (%)
Tr = Radial time
F = Resistance factor due to distance between PVD

In general, for Ch values ranging from 1 to 3 times Cv, Cv = Ch was chosen because in order to speed up or shorten the consolidation time of compressed soil.

7. Smear Effect

In the installation of vertical drainage, it is assumed that the properties of the surrounding soil do not change. But in fact, the installation of vertical drainage can disturb the soil, depending on the sensitivity of the soil (Rowe in Togu and Rudi, 2012).
Disturbances in the soil due to vertical drainage such as reducing soil permeability can slow down the consolidation process. This effect is called the smear effect. A possible solution is to reduce the cross-sectional area of the mandrel, but maintain the strength of the mandrel. Baron and Hansbo in Togu and Rudi (2012) analyzed soil disturbances by assuming the annulus of clay soils that had smears around the drainage. With annulus diameter d_s, the soil formed has a lower permeability coefficient k_r than k_h of undisturbed clay.
The smear effect Fs (n) is formulated as follows:

$$F = F(n) + F(s) \quad (8)$$

$$F(n) = [\frac{n^2}{(n^2-1)}]\ln(n) - \frac{(3n-1)}{(4n^2)} \qquad (9)$$

$$F(s) = [(\frac{Kh}{Ks}) - 1]\ln(\frac{ds}{dw}) \quad (10)$$

$$n = \frac{d_s}{d_w} \quad (11)$$

Where:
k_h/k_s = Assumed a value of 2
k_h = Horizontal permeability coefficient (mm/s)
k_s = Radial permeability coefficient (mm/s)
s = Smear zone ratio = ds/dw
d_s = Diameter of smear zone (cm)
d_w = Equivalent diameter of vertical drain (cm)

To determine the total Consolidation Degree value:

$$U = 1\text{- }(1\text{- }Ur)(1\text{- }Uv) \qquad (12)$$

Where:
U = Soil pore pressure (%)
Ur = Consolidation degree in the radial direction (%)
Uv = Consolidation degree in the vertical direction (%)

So, the total decrease (St) that occurs is:

$$St = Si + Scp \qquad (13)$$

Where:
St = Total settlement (m)
Si = Instant settlemrnt (m)
Sc = Consolidation settlement (m)

III. RESULT AND DISCUSSION

1. Calculation of Consolidated Settlement in Subgrade Against Time

The following is the soil depth data for each layer with a depth of z = 0,5 m:

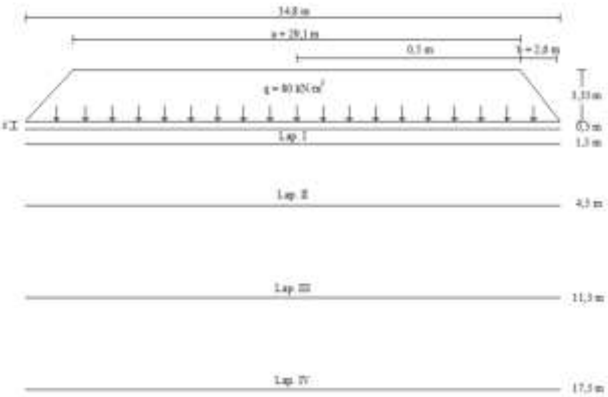

Fig. 1. Soil layer with depth z = 0,5 m

The soil properties index data can be seen in Table -1 the following:

Table -1 Soil properties index data

Soil Data	Soil Layer I	Soil Layer II	Soil Layer III	Soil Layer IV
γ (gr/cm^3)	1,48	1,06	1,61	1,42
Pore Number (e_0)	0,786	1,608	1,608	1,608
Compression Index (Cc)	0,760	0,950	0,950	0,950
Consolidation Coefficient (Cv) (cm^2/second)	6,953x10^{-4}	2,781x10^{-3}	1,514x10^{-2}	1,113x10^{-2}

The vertical effective stress on the soil with a depth of z = 0.5 m in Fig. 1.:

- It is known that the load is evenly distributed over the embankment soil, q = 80 kN/m^2
- Volume weight of soil, γ = 1,48 gr/cm^3 = 1.480 kg/m^3 = 14,519 kN/m^3

So, the vertical effective stress is:
$\sigma o = \gamma . h$ = 14,519 kN/m^3. 0,5 m = 7,259 kN/m^2
For additional vertical embankment stress is:
$\Delta\sigma$ = q (2 x I)

From Fig. 1, it is known that the value of a = 14,55 m, b = 2,6 m, and z = 0,5 m

For half the look of the pile:
a/z = 14,55 m/0,5 m = 29,1 m
b/z = 2,6 m/0,5m = 5,2 m

For the half-section of the embankment, I = 0,5 is obtained in Fig. 2. for the entire embankment, the influence factor I must be multiplied by 2. So the additional embankment stress is:
$\Delta\sigma$ = q (2.I) = 80 kN/m^2 (2 x 0,5) = 80 kN/m^2

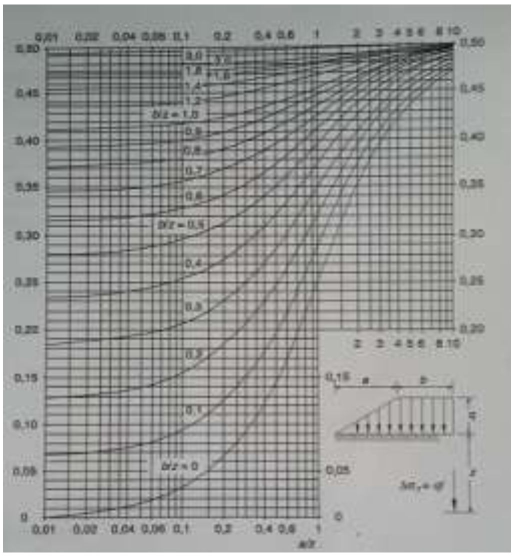

Fig. 2. Graph of factor I (Navfac DM-7 in Indrasurya B. Mochtar, 1998)

The value of factor I in each soil layer can be seen in Table -2 Result of calculation of land settlement per meter. So that the magnitude of the decrease due to the embankment load is:

$$S = \left[\frac{Cc}{1 + e_0} \times H \times \log\left(\frac{\rho'_0 + \Delta\rho}{\rho'_0}\right)\right]$$

$$S = \left[\frac{0,760}{1 + 0,786} \times 0,5 \times \log\left(\frac{7,259\ kN/m^2 + 80\ kN/m^2}{7,259\ kN/m^2}\right)\right]$$

S = 0,520 m
Time analysis 90% consolidation:
– Known the Thickness of Consolidated Soil (H) = 17,5 m
– Consolidation speed coefficient (Cv)
The Cv value was taken from the combined Cv value of all soil layers:
Cv layer soil I = 6,953x10^{-8} m^2/second
Cv layer soil II = 2,781x10^{-7} m^2/second
Cv layer soil III = 1,514x10^{-6} m^2/second
Cv layer soil IV = 1,113x10^{-6} m^2/second
Combined Cv:

$$= \frac{(H_1 + H_2 + H_3 + H_4)^2}{\left(\frac{H_1}{\sqrt{Cv_1}} + \frac{H_2}{\sqrt{Cv_2}} + \frac{H_3}{\sqrt{Cv_3}} + \frac{H_3}{\sqrt{Cv_3}}\right)^2}$$

$$= \frac{(1,5\,m + 3\,m + 7\,m + 6m)^2}{\left(\frac{1,5\,m}{\sqrt{6,953x10^{-8}\,m^2/detik}} + \frac{3\,m}{\sqrt{2,781x10^{-7}\,m^2/detik}} + \frac{7\,m}{\sqrt{1,514x10^{-6}\,m^2/detik}} + \frac{6\,m}{\sqrt{1,113x10^{-7}\,m^2/detik}}\right)^2}$$

= 5,915 x 10^{-7} m^2/second = 18,654 m^2/year
So,

$$t = \frac{Tv \times H^2}{Cv}$$

$$t = \frac{0,848 \times (17,5\ m)^2}{5,915 \times 10^{-7} m^2/detik \times 3600 \times 24 \times 365}$$

t = 13,922 year

From the results of the above calculation, it takes 13,922 years to achieve 90% consolidation without using PVD. For the calculation results of land settlement per meter can be seen in Table -2 below:

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Table -2 Calculation of land settlement per meter:

q (kN/m^2)	a (m)	b (m)	z (m)	a/z	b/z	I	γ (kN/m^3)	σ (kN/m^2)	Δσ (kN/m^2)	Cc	eo	Sc (m)
80	14,55	2,6	0,5	29,1	5,2	0,5	14,519	7,259	80,000	0,760	0,786	0,522
80	14,55	2,6	1,5	9,7	1,733	0,498	14,519	21,778	79,680	0,760	0,786	0,284
80	14,55	2,6	2,5	5,820	1,040	0,489	10,399	25,997	78,240	0,950	1,608	0,220
80	14,55	2,6	3,5	4,157	0,743	0,480	10,399	36,395	76,800	0,950	1,608	0,180
80	14,55	2,6	4,5	3,233	0,578	0,460	10,399	46,794	73,600	0,950	1,608	0,149
80	14,55	2,6	5,5	2,645	0,473	0,440	10,399	57,192	70,400	0,950	1,608	0,127
80	14,55	2,6	6,5	2,238	0,400	0,430	15,794	102,662	68,800	0,950	1,608	0,081
80	14,55	2,6	7,5	1,940	0,347	0,416	15,794	118,456	66,560	0,950	1,608	0,071
80	14,55	2,6	8,5	1,712	0,306	0,392	15,794	134,250	62,720	0,950	1,608	0,061
80	14,55	2,6	9,5	1,532	0,274	0,380	15,794	150,044	60,800	0,950	1,608	0,054
80	14,55	2,6	10,5	1,386	0,248	0,370	15,794	165,838	59,200	0,950	1,608	0,048
80	14,55	2,6	11,5	1,265	0,226	0,350	15,794	181,632	56,000	0,950	1,608	0,043
80	14,55	2,6	12,5	1,164	0,208	0,340	13,930	174,128	54,400	0,950	1,608	0,043
80	14,55	2,6	13,5	1,078	0,193	0,315	13,930	188,058	50,400	0,950	1,608	0,038
80	14,55	2,6	14,5	1,003	0,179	0,310	13,930	201,988	49,600	0,950	1,608	0,035
80	14,55	2,6	15,5	0,939	0,168	0,310	13,930	215,918	49,600	0,950	1,608	0,033
80	14,55	2,6	16,5	0,882	0,158	0,290	13,930	229,848	46,400	0,950	1,608	0,029
80	14,55	2,6	17,5	0,831	0,149	0,285	13,930	243,779	45,600	0,950	1,608	0,027
Penurunan Total =												2,043

2. Calculation of Consolidation Process Time

2.1. Time Analysis 90% Consolidation at time t = 17 months

The following is an analysis of the 90% consolidation time at time t = 17 months.

a. One Dimensional Consolidation Process Time Calculation

- It is known that the load is evenly distributed over the embankment soil, i.e, q = 80 kN/m^2
- Consolidation layer thickness (H) = 17,5 m
- t = 17 month = 0,0466 year
- Consolidation speed coefficient, Cv

The Cv value was taken from the combined Cv value of all soil layers:

Cv layer soil I = 6,953x10^{-8} m^2/second
Cv layer soil II = 2,781x10^{-7} m^2/second
Cv layer soil III = 1,514x10^{-6} m^2/second
Cv layer soil IV = 1,113x10^{-6} m^2/second
Combined Cv:

$$= \frac{(H_1 + H_2 + H_3 + H_4)^2}{\left(\frac{H_1}{\sqrt{Cv_1}} + \frac{H_2}{\sqrt{Cv_2}} + \frac{H_3}{\sqrt{Cv_3}} + \frac{H_3}{\sqrt{Cv_3}}\right)^2}$$

$$= \frac{(1{,}5\,m + 3\,m + 7\,m + 6m)^2}{\left(\frac{1{,}5\,m}{\sqrt{6{,}953x10^{-8}\,m^2/detik}} + \frac{3\,m}{\sqrt{2{,}781x10^{-7}\,m^2/detik}} + \frac{7\,m}{\sqrt{1{,}514x10^{-6}\,m^2/detik}} + \frac{6\,m}{\sqrt{1{,}113x10^{-7}\,m^2/detik}}\right)^2}$$

= 5,915 x 10^{-7} m^2/second = 18,654 m^2/year

1) Consolidation Time Factor

$$Tv = \frac{Cv \times t}{H^2}$$

$$Tv = \frac{18{,}654\ m^2/\text{tahun}\ x\ 0{,}0466\ tahun}{(17{,}5\ m)^2}$$

Tv =0,00284

2) Degree of Consolidation U

$$U = \sqrt{\frac{4 \times Tv}{\pi}}$$

$$U = \sqrt{\frac{4\ x\ 2{,}78\ x\ 10^{-3}}{\pi}}$$

U = 0,0601 =6,01%

b. Three Dimensional Consolidation Process Time Calculation

The following is an analysis of the 90% consolidation time at time t = 17.

- It is known that the load is evenly distributed over the embankment soil, i.e, q = 80 kN/m^2
- Consolidated layer thickness (H) = 17,5 m
- Consolidation speed coefficient, Cv

The Cv value was taken from the combined Cv value of all soil layers:

Cv layer soil I = 6,953x10^{-8} m^2/second
Cv layer soil II = 2,781x10^{-7} m^2/second
Cv layer soil III = 1,514x10^{-6} m^2/second
Cv layer soil IV = 1,113x10^{-6} m^2/second
Combined Cv:

$$= \frac{(H_1 + H_2 + H_3 + H_4)^2}{\left(\frac{H_1}{\sqrt{Cv_1}} + \frac{H_2}{\sqrt{Cv_2}} + \frac{H_3}{\sqrt{Cv_3}} + \frac{H_3}{\sqrt{Cv_3}}\right)^2}$$

$$= \frac{(1{,}5\,m + 3\,m + 7\,m + 6m)^2}{\left(\frac{1{,}5\,m}{\sqrt{6{,}953x10^{-8}\,m^2/detik}} + \frac{3\,m}{\sqrt{2{,}781x10^{-7}\,m^2/detik}} + \frac{7\,m}{\sqrt{1{,}514x10^{-6}\,m^2/detik}} + \frac{6\,m}{\sqrt{1{,}113x10^{-7}\,m^2/detik}}\right)^2}$$

= 5,915 x 10^{-7} m^2/second = 18,654 m^2/year

– Horizontal direction consolidation velocity coefficient (Ch)

Ch = (1-3) x Cv

Then the value of Ch = 2 x Cv

= 2 x 5,915 x 10^{-7} m^2/second

= 1,183 x 10^{-6} m^2/second

= 37,308 m^2/year

– t = 17 month = 0,0466 year

– PVD wide (a) = 10 cm

– PVD thick (b) = 0,4 cm

– PVD diameter (D) = 1,13 x distance between PVD (for square arrangement pattern)

D = 1,13 x 1 m

= 1,13 m

– Equivalent Diameter (dw) = r

dw = $\frac{2\,(a+b)}{\pi}$ = $\frac{2\,(10\text{ cm} + 0{,}4\text{ cm})}{\pi}$ = 6,621 cm

= 0,066 m

– Efective Diameter, R = D = 1,13 m

n = D/dw = R/r = 1,13 m/0,066 m = 17,121

1) Determining the Radial Time Factor

$$Tr = \frac{Ch.t}{(R)^2}$$

$$Tr = \frac{37{,}308\ m^2/tahun\ x\ 0{,}0466\ tahun}{(1{,}13)^2}$$

Tr = 1,361

2) Determine the value of Consolidation degree vertical direction, Uv

$$Uv = \frac{\sqrt{\frac{4Tv}{\pi}}}{[1 + (4\ x\ Tv/\pi)^{2,8}]^{0.179}}$$

$$Uv = \frac{\sqrt{\frac{4}{\pi}\left(\frac{37{,}308\,m^2/\ tahun\ \ x\ 0{,}0466\ tahun}{(17{,}5\ m)^2}\right)}}{[1 + (\frac{4}{3{,}14}(\frac{37{,}308\,m^2/\ tahun\ \ x\ 0{,}0466\ tahun}{(17{,}5\ m)^2})^{2,8}]^{0.179}}$$

Uv = 0,0018

3) Determine the degree of radial consolidation, Ur

Using the smear zone equation, the equation for the degree of consolidation, Ur is:

Ur = 1- exp ($\frac{-8\,Tr}{F}$)

Where:

F = $F_{(n)} + F_{(s)}$

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

$$F_{(n)} = [\frac{(17{,}121\ m)^2}{((17{,}121\ m)^2-1)}] \ln(17{,}121) - \frac{(3(17{,}121\ m)^2-1)}{(4(17{,}121\ m)^2)}$$

$F_{(n)}$ = 2,101

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

$= [3 - 1]\ln(4)$

= 2,773

F = $F_{(n)} + F_{(s)}$

= 2,101 + 2,773

= 4,874

So,

Ur = 1- exp ($\frac{-8\ x\ 1{,}334}{4{,}874}$)

Ur = 0,888

4) Determine the value of the degree of total consolidation, U

U = 1- (1- Uv) (1- Ur)

U = 1- [(1- 0,0018) (1- 0,893)]

U = 0,893 = 89,3%

2.2. Time Analysis 90% Consolidation at time t = 18 month

The following is an analysis of the 90% consolidation time at time t = 18 months.

a. One Dimensional Consolidation Process Time Calculation

– It is known that the load is evenly distributed over the embankment soil, i.e, q = 80 kN/m^2

– Consolidated layer thickness (H) = 17,5 m

– t = 18 month = 0,0493 year

– Consolidation speed coefficient, Cv

The Cv value is taken from the Combined Cv value from all soil layers:

Cv layer soil I = 6,953x10^{-8} m^2/second

Cv layer soil II = 2,781x10^{-7} m^2/second

Cv layer soil III = 1,514x10^{-6} m^2/second

Cv layer soil IV = 1,113x10^{-6} m^2/second

Combined Cv:

$$= \frac{(H_1 + H_2 + H_3 + H_4)^2}{\left(\frac{H_1}{\sqrt{Cv_1}} + \frac{H_2}{\sqrt{Cv_2}} + \frac{H_3}{\sqrt{Cv_3}} + \frac{H_3}{\sqrt{Cv_3}}\right)^2}$$

$$= \frac{(1{,}5\,m + 3\,m + 7\,m + 6m)^2}{\left(\frac{1{,}5\,m}{\sqrt{6{,}953x10^{-8}\,m^2/detik}} + \frac{3\,m}{\sqrt{2{,}781x10^{-7}\,m^2/detik}} + \frac{7\,m}{\sqrt{1{,}514x10^{-6}\,m^2/detik}} + \frac{6\,m}{\sqrt{1{,}113x10^{-7}\,m^2/detik}}\right)^2}$$

= 5,915 x 10^{-7} m^2/second = 18,654 m^2/year

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1) Consolidation Time Factor

$$Tv = \frac{Cv \times t}{H^2}$$

$$Tv = \frac{18{,}654\ m^2/tahun\ x\ 0{,}0493\ tahun}{(17{,}5\ m)^2}$$

Tv =0,003

2) Degree of Consolidation U

$$U = \sqrt{\frac{4 \times Tv}{\pi}}$$

$$U = \sqrt{\frac{4\ x\ 0{,}003\ x 10^{-3}}{\pi}}$$

U = 0,619 =6,19%

b. Three Dimensional Consolidation Process Time Calculation

The following is an analysis of the 90% consolidation time at time t = 18 months.

– It is known that the load is evenly distributed over the embankment soil, i.e, q = 80 kN/m^2

– Consolidated layer thickness (H) = 17,5 m

– Consolidation speed coefficient, Cv

The Cv value was taken from the Combined Cv value from all soil layers:

Cv layer soil I = 6,953x10^{-8} m^2/second

Cv layer soil II = 2,781x10^{-7} m^2/second

Cv layer soil III = 1,514x10^{-6} m^2/second

Cv layer soil IV = 1,113x10^{-6} m^2/second

Combined Cv:

$$= \frac{(H_1 + H_2 + H_3 + H_4)^2}{\left(\frac{H_1}{\sqrt{Cv_1}} + \frac{H_2}{\sqrt{Cv_2}} + \frac{H_3}{\sqrt{Cv_3}} + \frac{H_3}{\sqrt{Cv_3}}\right)^2}$$

$$= \frac{(1{,}5\ m + 3\ m + 7\ m + 6m)^2}{\left(\frac{1{,}5\ m}{\sqrt{6{,}953x10^{-8}\ m^2/detik}} + \frac{3\ m}{\sqrt{2{,}781x10^{-7}\ m^2/detik}} + \frac{7\ m}{\sqrt{1{,}514x10^{-6}\ m^2/detik}} + \frac{6\ m}{\sqrt{1{,}113x10^{-7}\ m^2/detik}}\right)^2}$$

= 5,915 x 10^{-7} m^2/second = 18,654 m^2/year

– Horizontal direction consolidation velocity coefficient (Ch)

Ch = (1-3) x Cv

Then the value of Ch = 2 x Cv

= 2 x 5,915 x 10^{-7} m^2/second

= 1,183 x 10^{-6} m^2/second

= 37,308 m^2/year

– t = 18 month = 0,0493 year

– PVD Wide (a) = 10 cm

– PVD Thick (b) = 0,4 cm

– PVD Diameter (D) = 1,13 x distance between PVD (for square arrangement pattern)

D = 1,13 x 1 m
= 1,13 m

– Equivalent diameter (dw) = r

$$dw = \frac{2\,(a+b)}{\pi} = \frac{2\,(10\ cm + 0{,}4\ cm)}{\pi} = 6{,}621\ cm$$

= 0,066 m

– Efective diameter, R = D = 1,13 m

n = D/dw = R/r = 1,13 m/0,066 m = 17,121

1) Determining the Radial Time Factor

$$Tr = \frac{Ch.t}{(R)^2}$$

$$Tr = \frac{37{,}308\ m^2/tahun\ x\ 0{,}0493\ tahun}{(1{,}13)^2}$$

Tr = 1,441

2) Determine the value of Consolidation degree vertical direction, Uv

$$Uv = \frac{\sqrt{\frac{4Tv}{\pi}}}{[1+(4\ x\ Tv/\pi)^{2,8}]^{0.179}}$$

$$Uv = \frac{\sqrt{\frac{4}{\pi}\left(\frac{37{,}308\ m^2/\ tahun\ \ x\ 0{,}0493\ \ tahun}{(17{,}5\ m)^2}\right)}}{[1+(\frac{4}{3{,}14}(\frac{37{,}308\ m^2/\ tahun\ \ x\ 0{,}0493\ \ tahun}{(17{,}5\ m)^2})^{2,8}]^{0.179}}$$

Uv = 0,0019

3) Determine the degree of radial consolidation, Ur

Using the smear zone equation, the equation for the degree of consolidation, Ur is

$$Ur = 1 - \exp\left(\frac{-8\,Tr}{F}\right)$$

Where:

F = $F_{(n)} + F_{(s)}$

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

$$F_{(n)} = \left[\frac{(17{,}121\ m)^2}{((17{,}121\ m)^2-1)}\right]\ln(17{,}121) - \frac{(3(17{,}121\ m)^2-1)}{(4(17{,}121\ m)^2)}$$

$F_{(n)}$ = 2,101

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

$= [3 - 1]\ln(4)$

= 2,773

F = $F_{(n)} + F_{(s)}$
= 2,101 + 2,773
= 4,874

So,

$$Ur = 1 - \exp\left(\frac{-8\ x\ 1{,}412}{4{,}874}\right)$$

Ur = 0,902

4) Determine the value of the degree of total consolidation, U

U = 1- (1- Uv) (1- Ur)

U = 1- [(1- 0,0019) (1- 0,906)]

U = 0,906 = 90,6%

For the complete calculation results can be seen in Table -3 and Table -4 below:

Table -3 Calculation of decrease in consolidation time 1 dimension

H (m)	t (bulan)	t (tahun)	Cv (m^2/tahun)	Tv	U %
17,5	1	0,0027	18,654	0,00017	0,0146
17,5	2	0,0055	18,654	0,00033	0,0206
17,5	3	0,0082	18,654	0,00050	0,0253
17,5	4	0,0110	18,654	0,00067	0,0292
17,5	5	0,0137	18,654	0,00083	0,0326
17,5	6	0,0164	18,654	0,00100	0,0357
17,5	7	0,0192	18,654	0,00117	0,0386
17,5	8	0,0219	18,654	0,00134	0,0412
17,5	9	0,0247	18,654	0,00150	0,0437
17,5	10	0,0274	18,654	0,00167	0,0461
17,5	11	0,0301	18,654	0,00184	0,0484
17,5	12	0,0329	18,654	0,00200	0,0505
17,5	13	0,0356	18,654	0,00217	0,0526
17,5	14	0,0384	18,654	0,00234	0,0546
17,5	15	0,0411	18,654	0,00250	0,0565
17,5	16	0,0438	18,654	0,00267	0,0583
17,5	17	0,0466	18,654	0,00284	0,0601
17,5	18	0,0493	18,654	0,00300	0,0619
17,5	19	0,0521	18,654	0,00317	0,0636
17,5	20	0,0548	18,654	0,00334	0,0652

Table -4 Calculation of decrease in consolidation time 3 dimensions

H (m)	t (bulan)	t (tahun)	Ch (m^2/tahun)	Uv	1-Uv	Tr	Ur	1-Ur	U%
17,5	1	0,0027	37,308	0,0001	0,9999	0,080	0,123	0,877	0,123
17,5	2	0,0055	37,308	0,0002	0,9998	0,160	0,231	0,769	0,231
17,5	3	0,0082	37,308	0,0003	0,9997	0,240	0,326	0,674	0,326
17,5	4	0,0110	37,308	0,0004	0,9996	0,320	0,409	0,591	0,409
17,5	5	0,0137	37,308	0,0005	0,9995	0,400	0,482	0,518	0,482
17,5	6	0,0164	37,308	0,0006	0,9994	0,480	0,545	0,455	0,546
17,5	7	0,0192	37,308	0,0007	0,9993	0,560	0,601	0,399	0,602
17,5	8	0,0219	37,308	0,0009	0,9991	0,640	0,650	0,350	0,651
17,5	9	0,0247	37,308	0,0010	0,9990	0,720	0,693	0,307	0,694
17,5	10	0,0274	37,308	0,0011	0,9989	0,800	0,731	0,269	0,732
17,5	11	0,0301	37,308	0,0012	0,9988	0,881	0,764	0,236	0,765
17,5	12	0,0329	37,308	0,0013	0,9987	0,961	0,793	0,207	0,794
17,5	13	0,0356	37,308	0,0014	0,9986	1,041	0,819	0,181	0,819
17,5	14	0,0384	37,308	0,0015	0,9985	1,121	0,841	0,159	0,841
17,5	15	0,0411	37,308	0,0016	0,9984	1,201	0,861	0,139	0,861
17,5	16	0,0438	37,308	0,0017	0,9983	1,281	0,878	0,122	0,878
17,5	17	0,0466	37,308	0,0018	0,9982	1,361	0,893	0,107	0,893
17,5	18	0,0493	37,308	0,0019	0,9981	1,441	0,906	0,094	0,906
17,5	19	0,0521	37,308	0,0020	0,9980	1,521	0,918	0,082	0,918
17,5	20	0,0548	37,308	0,0021	0,9979	1,601	0,928	0,072	0,928

To achieve a consolidation time of 90% without using PVD it took 13,922 years, using PVD it took 18 months, while using PVD and the vacuum consolidation method (VCM) it took 4,8 months.

3. Total Settlement Calculation

The settlement total obtained from each soil layer is as follows:

St = Sc soil layer. I + Sc soil layer. II + Sc soil layer. III + Sc soil layer. IVSt = 0,806 m + 0,676 m + 0,357 m + 0,204 m

St = 2,043 m

IV. CONCLUSION

The conclusions obtained from the analysis of soil subsidence using PVD with the vacuum consolidation method (VCM), are:

a. There is a time difference between the consolidation process without using PVD, using PVD, and using PVD with the vacuum consolidation method (VCM). To achieve a consolidation time of 90% without using PVD it took 13,922 years, using PVD it took 18 months, while using PVD and the vacuum consolidation method (VCM) it took 4,8 months;

b. The use of PVD with the vacuum consolidation method (VCM) can speed up the consolidation process compared to using PVD or only using PVD;
c. The total settlement that occurred was 2,043 m.

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