The decline of soil due to the pile of highway project Medan-Kualanamu (STA 35 + 901) with the finite element method

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Abstract. Consolidation is the process of discharge of water from the ground through the pore cavity. Consolidation occurs in soft soil or unstable soil that allows an improvement in order to make the soil more stable. The method of using Prefabricated Vertical Drain (PVD) is one way to improve unstable soils. PVD works like a sand column that can drain water vertically. This study aims to determine the decrease, pore water pressure and soil consolidation rate with Prefabricated Vertical Drain (PVD) and without PVD analytically and using finite element method that affect the duration of soil decline to reach 90% consolidation or in other words soil does not decline anymore. Based on the analytical calculation, the decrease obtained is equal to 0.47 m meanwhile the result of calculation using finite element method is 0.45 m. The consolidation rate obtained from analytical calculation is 19 days with PVD and 115 days without PVD. The consolidation rate obtained from finite element method is 63 days with PVD and 110 days without PVD. And the pore water pressure is 0.92 KN/m^2.

1. Introduction
Geotechnical is an area steeped in civil engineering work relating to the ground. In the soil work process, we often find geotechnical problems such as low soil bearing capacity found on soft ground and a decline due to loading. The load above the soil surface causes the ground underneath to consolidate. Consolidation is the process of discharge of water from the ground through the pore cavity. At the time of consolidation, the ground tension at the beginning of the loading is fully borne by the pore water pressure and will slowly be transferred to the effective stresses of soil, so that the strength and bearing capacity of the soil will increase. The construction of buildings that stand on soft ground needs to consider the magnitude of the decline that will happen to get a good bearing capacity. Thus, the construction process should be carried out after the soil is fully consolidated, so a method of soil improvement is needed to overcome the problem. The selection of soil improvement techniques is influenced by the soil layer, soil characteristics, cost, material availability and experience. One of the soil improvement techniques often used in soft soil problems is preloading and with vertical drainage. Preloading is a method of soil improvement by providing additional load at the construction site until the desired consolidation is reached. The implementation of this method is applied with the use of Prefabricated Vertical Drain (PVD). PVD itself is a geosynthetic material whose concept works like a sand column that can drain water vertically. With the vertical drain, the time required to drain water from the ground is faster and soils consolidate faster too.

1.1. Consolidation
Consolidation is a process of reduction in volume or reduction in pore cavity of a low saturated soil permeability due to loading, wherein the process is affected by the speed of pore water press out of the

soil cavity. If a layer of saturated soil which has a low permeability is given a load, the pore water pressure in the soil will increase rapidly. Differences in pore water pressure in the soil layer resulted in water flowing into the soil layer with lower pore pressures, followed by settlement in soil. This process takes time due to low soil permeability. There are three different stages which are obtained from the result of consolidation experiment:

Stage I   : Initial compression, which is generally caused by preloading.

Stage II   : Primary consolidation, the period during which pore pressures are gradually transferred into effective tension, as a result of the discharge of water from the pores of the soil.

Stage III   : Secondary consolidation, which occurs after the pore pressure is completely lost.

    The compression occurring here is due to the plastic adaptability of the soil grains as shown in figure 1.
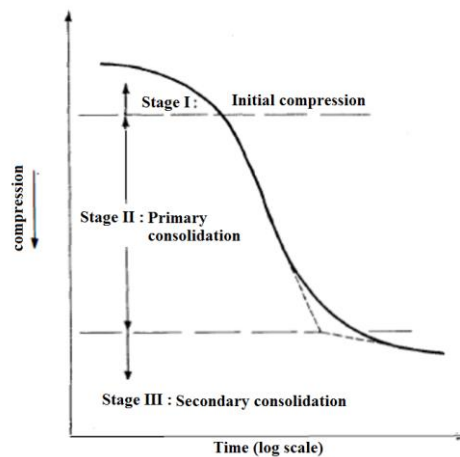

Figure 1. Relation Chart ∆H and log t

The mathematical equation of 1-D consolidated by Terzaghi with parabolic shape:

$$\frac{\partial u}{\partial t} = C_v \frac{\partial^2 u}{\partial y^2} \tag{1}$$

Where in equation one, u is the excess pore pressure (kN/m^2), t is review time (sec), y is review depth (m), $\frac{\partial u}{\partial t}$ is the first derivative of excess pore water pressure against time and $\frac{\partial^2 u}{\partial y^2}$ is the second derivative of excess pore water pressure against depth. The general solution of this equation is:

$$W_{Y,T} = \frac{4}{\pi} \sum_{m=0}^{\infty} \frac{1}{(2m+1)^2} Exp^{-\left[\pi^2 (2m+1)^2 /4\right]T_v} \ \sin \frac{\pi}{2}(2m+1)Y \tag{2}$$

With vertical consolidation degrees (Uv):

$$Uv = \frac{\sqrt{\frac{4\,Tv}{\pi}}}{[1+ (4Tv/\pi)^{2,8}]^{0,179}} \tag{3}$$

With m = integer number; $T_v = \dfrac{c_v t}{H^2}$ (time factor)

The magnitude of primary settlement occurs:

$$S_p = \frac{C_c H}{1+e_0} \log(\frac{\sigma'_0 + \Delta\sigma'}{\sigma'_o})$$

(4)

Where in equation four, σ'_0 is initial effective vertical stress (kN/m^2), $\Delta\sigma'$ is aditional effective vertical stress (kN/m^2), C_c is compression index, H is layer thickness (m) and e_0 is initial void ratio.

Radial consolidation will occur in situations that include drainage of a central source, such as on a vertical drainage used under a pile to accelerate pore water drainage by reducing drainage distance and hence also accelerating consolidation.

The consolidation equation for radial directional drainage is as follows:

$$\frac{\partial u}{\partial t} = C_r \left(\frac{\partial^2 u}{\partial r^2} + \frac{1}{r}\frac{\partial u}{\partial r} \right)$$

(5)

Where in equation five, Cr is radial consolidation coefficient (cm^2/s), R is vertical drainage radius (cm).

Assuming a smear zone effect has solved by equal-strain consolidation (Barron, 1948) the solution of the radial consolidation equation is as follows:

$$F = F(n) + F(s)$$

$$U_r = 1 - e^{(-8T_r/F)}$$

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

Where:

$$S = \frac{r_s}{r_w}$$

$$n = \frac{d_e}{d_w}$$

$$F(s) = \left[\left(\frac{kh}{ks}\right) - 1\right]\ln\left(\frac{ds}{dw}\right)$$

In general, n> 20 so it can be considered to be l/n = 0 so, the formula F (n) will be a simple formula that is:

$$F(n) = \ln(n) -3/4 \quad or$$ (6)

$$F(n) = \ln(de/dw) -3/4$$ (7)

Where, De is equivalent diameter (after cross-section is converted to circle shape) (m), Dw is vertical drainage diameter (m), Rs is smear zone radius (m), Rw is sand drain radius (m), Ks is radial permeability coefficient on smear zone are (1-15) kr (m/sec), Kr is radial permeability coefficient are (1-15) kv (m / sec), and C_r is $C_v(k_r/k_v)$ (cm^2/sec).

$$T_r = \frac{C_r t}{d_e^2}$$

(8)

The smear zone effect is the reduced coefficient value for the clay soil near the vertical drainage or the vertical drainage diameter used is minimized, this is due to the process of remoulding during the installation of vertical drainage by using a pivot.

1.2. Vertical Drain

Table 1. Prefabricated Vertical Drain Installation Method

Type of Drain	Installation Method	Drain Diameter (m)	Distance between Drain (m)	Maximum length (m)
Sand drain	Pushing into the ground with the vibrating system	0,15 – 0,6	1 - 5	≤ 30
Sand drain	Using a long hollow bar with auger	0,3 – 0,5	2 - 5	≤ 35
Sand drain	Jet grouting method	0,2 – 0,3	2 - 5	≤ 30
prefabricated sand drains (sandwicks)	inserting a tool with vibrating systems using the mandrel tip of the tool, using auger	0.06-0.15	1,2 - 4	≤ 30
Prefabricated band-shaped drains	Inserting the tool into the ground using the mandrel at the end.	0,05 – 0,1 (Equivalent diameter)	1,2 -3,5	≤ 60

Source: *(TenCate Polyfelt® Alidrain Prefabricated Vertical Drain)*

1.3. Finite Element Method

One of the most commonly used computer programs for geotechnical field analysis is the 2D finite element method. There are two types of finite element geometry models commonly used in the 2D finite element method, the Plane-Strain and Axysimetry models. The Plane-Strain model can be used to solve problems in cross-sectional areas with relatively uniform stress and deformation conditions in the direction perpendicular to the cross section. While the Axisymetry model is used for field analysis with radial cross section, with uniform stress and deformation conditions in each radial direction.

Table 2. The Plane-Strain and Axysimetry models

No	Model	Parameter	Remarks
1	Mohr-Coulomb (MC)	$E, \nu, \phi, c,$ dan ψ	Perfect elastic - plastic, is the most widely used models in geotechnical analysis
2	Jointed Rock (JR)	E, ν, G, ϕ, c, ψ	Anisotropic elastic - plastic, used to model the behavior of rock layers that have stratification and certain directions
3	Hardening-Soil (HS)	$\phi, c, \psi, \nu, E50, Eur, Eoed, p, Ko, Rf, \sigma$	Isotropic, this model can be used for all types of soil
4	Soft-Soil-Creep (SSC)	$\phi, c, \psi, \kappa, \lambda, \mu, \nu, M, Ko,$	Used for soft soil conditions that have time-dependent behavior
5	Soft Soil (SS)	$\phi, c, \psi, \kappa, \lambda, \nu, M, Ko$	The Cam-Clay model, used for the analysis of primary compression and normal consolidated clay

2. Research Method
The method used in this study is analysis research method:
   a. Collect various types of literature in the form of books and scientific papers related to this thesis.
   b. Collect data from the result of soil investigation such as standart penetration test (SPT) data , consolidation data, direct shear data, and PVD technical data. The data was obtained from PT. BINA KARYA as Planning Consultant and CHEC - CSCEC - HK - JO as the executing contractor.
   c. Analyze the data obtained from the field with reference sources related to the thesis.
   d. Calculate the decline of land with or without prefabricated vertical drains (PVD) with the existing methods.
   e. Finding the magnitude of decline in soil using finite element method, by modeling the behavior of soil on the Finite Element Method. The soil modeling used is Mohr-Coulomb model.
   f. Compare the results between the analytical calculation and the calculation using finite element method, then make conclusions and suggestions.

3. Result and Discussion
3.1 The magnitude of decline
   a. Stage 1

$$\sigma_{0\text{-}1} = \gamma_{unsat} \times h + (\gamma_{sat} - \gamma_w) \cdot (H_{dr} - 1)$$

where, $h = 0.7$ m

$\gamma_{unsat} = 9.8$ kN/m^3

$\gamma_{sat} = 15.2$ kN/m^3

$H_{dr} = 7.3/2 = 3.65$ m

$\sigma_{0\text{-}1} = (6.86 \times 0.7) + (15.2 - 10) \cdot (3.65 - 1)$
$= 20.64$ kN/m^2

The magnitude of decline due to layer 1:

$$S_1 = \frac{0.942 \cdot 0.7}{1+1.883} \log \left[\frac{20.64 + 6.86}{20.64} \right]$$

$S_1 = 0.23 \cdot 0.12$

$S_1 = 0.03$ m

   b. Stage 2

$$\Delta \sigma' = \gamma_{unsatclay} \times H_{clay}$$

$= 9.42 \times 3.3$
$= 31.08$ kN/m^2

$$\sigma_{0\text{-}2} = \gamma_{unsat} \times h + (\gamma_{sat} - \gamma_w) \cdot (H_{dr} - 1)$$

where , $h = 3.3$ m

$\sigma_{0\text{-}2} = (9.42 \times 3.3) + (15.15 - 10) \cdot (3.65 - 1)$
$= 44.73$ kN/m^2

The magnitude of decline due to layer 2:

$$S_2 = \frac{0.942 \cdot 3.3}{1+1.883} \log \left[\frac{44.73 + 31.08}{44.73} \right]$$

$S_2 = 0.25$ m

c. Stage 3

$\Delta \sigma' = \gamma_{unsatclay} \times H_{clay}$

$= 10 \times 3,3$

$= 33 \text{ kN/m}^2$

$\sigma_{0-3} = \gamma_{unsat} \times h + (\gamma_{sat} - \gamma_w) \cdot (H_{dr} - 1)$

where, h = 3,3 m

$\sigma_{0-3} = (10 \times 3,3) + (15,15 - 10) \cdot (3,65 - 1)$

$= 47,02 \text{ kN/m}^2$

The magnitude of decline due to layer 3:

$$S_3 = \frac{0,942. \ 3,3}{1+1,883} \log \left[\frac{47,02 + 33}{47,02} \right]$$

$S_3 = 0,25$ m

So the total primary decline is

$Sp_{total} = S_1 + S_2 + S_3$

$= 0,03 \text{ m} + 0,25 \text{ m} + 0,25 \text{ m}$

$Sp_{total} = 0,53$ m

So the magnitude of the soil decline is equal to Sc, where;

Sc = 0,53. U (90%)

= 0.48 m

3.2 Rate of Consolidation

From the data obtained

$Cv = 0.0114 \text{ cm}^2/\text{sec} = 35.95 \text{ m}^2/\text{year}$

Calculation of declining time rate

Tv 90% = 0.848

Hdr = 7.3 m / 2 = 3.65 m

From equation 2.4 obtained:

$$t = \frac{H^2 dr.T_v}{C_v}$$

$$t = \frac{3,65^2.0,848}{0,0114}$$

$t = 115$ Hari

Table 3. Calculation Sc

Years	Days	Uv	1 - Uv	Tr	Ur	1 - Ur	U	Sc (m)
0,00	0,00	0,00	1,00	0,00	0,00	1,00	0,00	0,00
0,00	1,00	0,10	0,90	0,04	0,09	0,91	0,18	0,09
0,01	2,00	0,14	0,86	0,08	0,17	0,83	0,28	0,15
0,01	3,00	0,17	0,83	0,13	0,25	0,75	0,37	0,20
0,01	4,00	0,19	0,81	0,17	0,31	0,69	0,45	0,24
0,01	5,00	0,22	0,78	0,21	0,37	0,63	0,51	0,27
0,02	6,00	0,24	0,76	0,25	0,43	0,57	0,56	0,30
0,02	7,00	0,25	0,75	0,29	0,48	0,52	0,61	0,33
0,02	8,00	0,27	0,73	0,34	0,53	0,47	0,66	0,35
0,02	9,00	0,29	0,71	0,38	0,57	0,43	0,69	0,37
0,03	10,00	0,30	0,70	0,42	0,61	0,39	0,73	0,39

0,03	11,00	0,32	0,68	0,46	0,64	0,36	0,76	0,40
0,03	12,00	0,33	0,67	0,50	0,68	0,32	0,78	0,42
0,04	13,00	0,35	0,65	0,54	0,70	0,30	0,81	0,43
0,04	14,00	0,36	0,64	0,59	0,73	0,27	0,83	0,44
0,04	15,00	0,37	0,63	0,63	0,76	0,24	0,85	0,45
0,04	16,00	0,38	0,62	0,67	0,78	0,22	0,86	0,46
0,05	17,00	0,40	0,60	0,71	0,80	0,20	0,88	0,47
0,05	18,00	0,41	0,59	0,75	0,82	0,18	0,89	0,47
0,05	19,00	0,42	0,58	0,80	0,83	0,17	0,90	0,48
0,05	20,00	0,43	0,57	0,84	0,85	0,15	0,91	0,48
0,06	21,00	0,44	0,56	0,88	0,86	0,14	0,92	0,49
0,06	22,00	0,45	0,55	0,92	0,87	0,13	0,93	0,49
0,06	23,00	0,46	0,54	0,96	0,88	0,12	0,94	0,50
0,07	24,00	0,47	0,53	1,01	0,89	0,11	0,94	0,50
0,07	25,00	0,48	0,52	1,05	0,90	0,10	0,95	0,50
0,07	26,00	0,49	0,51	1,09	0,91	0,09	0,96	0,51
0,07	27,00	0,50	0,50	1,13	0,92	0,08	0,96	0,51
0,08	28,00	0,51	0,49	1,17	0,93	0,07	0,96	0,51
0,08	29,00	0,52	0,48	1,21	0,93	0,07	0,97	0,51
0,08	30,00	0,52	0,48	1,26	0,94	0,06	0,97	0,51
0,08	31,00	0,53	0,47	1,30	0,95	0,05	0,97	0,52
0,09	32,00	0,54	0,46	1,34	0,95	0,05	0,98	0,52
0,09	33,00	0,55	0,45	1,38	0,95	0,05	0,98	0,52
0,09	34,00	0,56	0,44	1,42	0,96	0,04	0,98	0,52
0,10	35,00	0,57	0,43	1,47	0,96	0,04	0,98	0,52
0,10	36,00	0,57	0,43	1,51	0,97	0,03	0,99	0,52
0,10	37,00	0,58	0,42	1,55	0,97	0,03	0,99	0,52
0,10	38,00	0,59	0,41	1,59	0,97	0,03	0,99	0,52
0,11	39,00	0,60	0,40	1,63	0,97	0,03	0,99	0,52
0,11	40,00	0,60	0,40	1,68	0,98	0,02	0,99	0,53

3.3 Consolidation time with and without PVD using finite element method
The consolidation time obtained by finite element method until the degree of consolidation reaches 90 is 63 days as shown in figure 2.
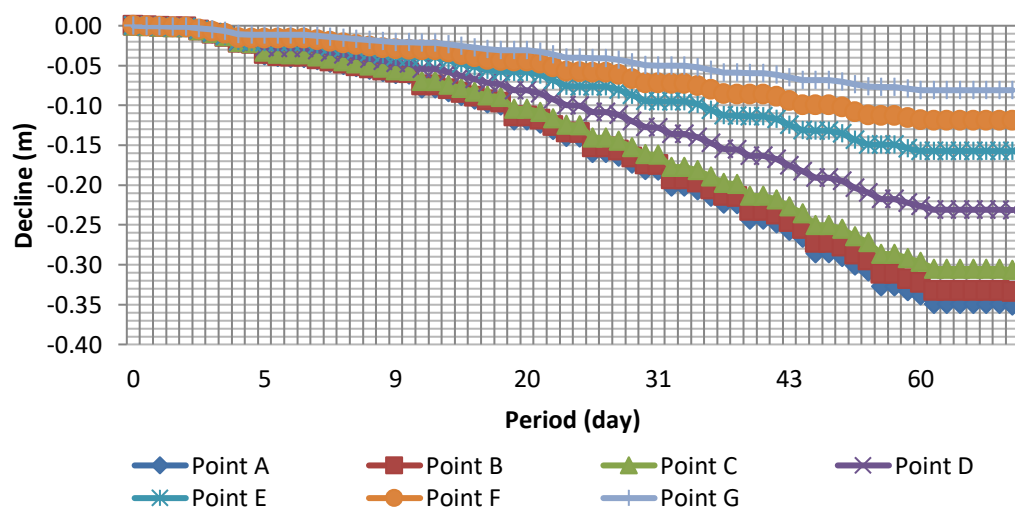

Figure 2. The consolidation time

1. At point A the decline that occurs until the 90% consolidation is 0.35 m
2. At point B the decline that occurs until the 90% consolidation is 0.33 m
3. At point C the decline that occurs until the 90% consolidation is 0.31 m
4. At point D the decline that occurs until the 90% consolidation is 0.23 m
5. At point E the decline that occurs until the 90% consolidation is 0.16 m
6. At point F the decline that occurs until the 90% consolidation is 0.12 m
7. At point G the decline that occurs until the 90% consolidation is 0.01 m

- The result of soil declining occurred due to embankment without the vertical drainage with finite element method. The length of time required to achieve 90% consolidation is 110 days with the magnitude of decline 0.36 m
- The magitude of pore water pressure at 90% of consolidation
  10% x 9,2 (The highest peak of the pore water pressure) = 0,92 KN/m^2

4. Conclusions

1. From the analytical calculation of the soil decline at STA 35 + 901 using prefabricated vertical drain (PVD) to reach 90% consolidation degree obtained a decline of 0.47 m. While the total decline result obtained from Finite Element Method at STA 35 + 901 using prefabricated vertical drain (PVD) to reach 90% consolidation degree is 0.45 m

2. The result of consolidation time calculation with PVD and without PVD:
    - Consolidation time obtained with analytical calculation
      With PVD   : 19 days
      Without PVD   : 115days
    - Consolidation time obtained with finite element method
      With PVD   : 63 days
      Without PVD   : 110 days

3. Pore water pressure when it reaches 90% consolidation with PVD occurred on day 9 is 0,92KN/m^2.

Acknowledgements

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