CHAPTER 3

BASIC THEORY

3.1 PVD Installation

The PVD is a thin, geosynthetic material-based drainage, consisting of drainage core, surrounded by geotextile-based filter as shown in Figure 3.1. PVD usually comes in strapped-band shaped, where the drainage is wrapped by the plastic band material. The advantage of PVD installation is its ability to shortened drainage path, normally from tens of meters, to only one to two meters. In construction project, PVD is usually installed in large area with large quantity, until thousands of hectare (Espinoza et al., 2018a; Wardani & Naufan, 2019).

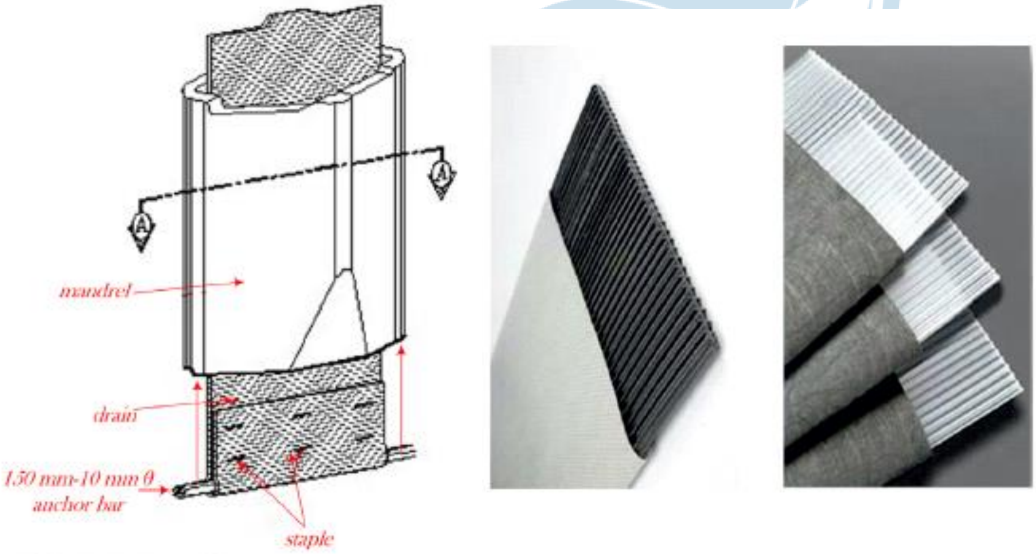

Figure 3.1 PVD Appearance

(Bo et al., 2015)

In installing PVD, heavy equipment that correspond to each of soil conditions are required, as shown in Figure 3.2. Usually, PVD is installed by putting the drain to mandrel, attach it towards the anchor of the heavy equipment, then the heavy equipment will perform the excavation of the mandrel with PVD inside. After reaching certain depth, the PVD will then be released from the mandrel, and the equipment will move to different place. Then, the surcharge load will be applied towards soil with PVD installed, so that the consolidation process will be started immediately

Figure 3.2 Heavy Equipment for PVD Installation

(Bo et al., 2015)

3.2 Consolidation Theory

Consolidation that happened in the soil will cause the soil to move slightly and have a different elevation than the initial, called settlement. This settlement will happen gradually with time, with its maximum value could range to dozens of meters. Projects that have settlements for a very long time are not desirable, as an extreme settlement may occur at one point in time, which causes the structure to fail. To shorten the settlement time greatly, a method called vertical drain is then introduced. (Bo et al., 2015)

For consolidation problem, it is a must to find primary consolidation settlement and degree of consolidation to predict maximum settlement of the soil and how much settlement occurs in certain period of time. The settlement happen for certain amount of time has already formulated by Terzaghi in his One-Dimensional Primary Consolidation Model (Ishibashi & Hazarika, 2010). The model demonstrate that settlement occurs due to water escaping from the soil and stress transfer happen from the total pore water pressure at $t = 0$, to total effective stress during $t = \infty$ (Ishibashi & Hazarika, 2010).

Terzaghi consolidation theory assumes that:

1. The specimen is fully saturated.
2. Water and solid components are inrompressible.
3. Darcy's law is applied.
4. Flow of water is one dimensional.

From the derivation of Darcy's law for water flow and referring to three phase diagrams of the soil shown in Figure 3.3, Terzaghi formulate the final consolidation settlement S_f (at t = ∞) for a clay soil with thickness H as:

$$S_f = M_v \Delta\sigma H \qquad \textit{Equation 3-1}$$

where Mv is the coefficient of volume change, Δσ is the stress increment of soil, and H is the thickness of clay layer (Ishibashi & Hazarika, 2010).

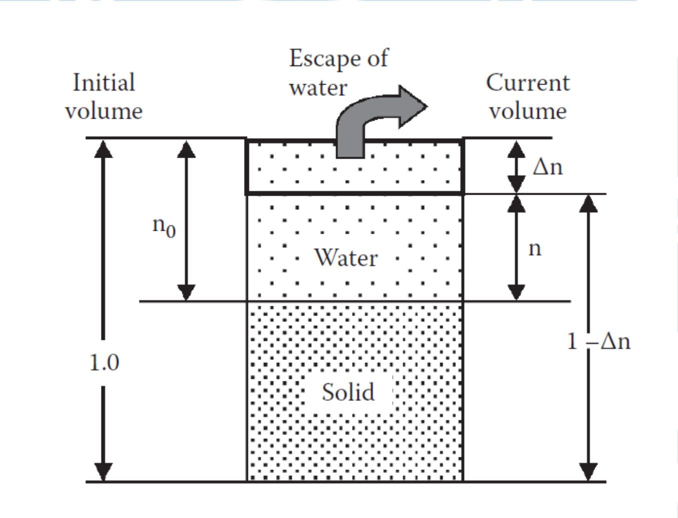

Figure 3.3 Three Phase Diagram of Soil

(Ishibashi & Hazarika, 2010)

Consolidation settlement could also be found by using laboratory test. The specimen tested in lab comes from a certain site; so, it has been subjected to a prior effective overburden stress during the sampling process. This stress subjected to soil is called preconsolidation stress σ_o, which is the stress obtained in turning point on the e-log σ curve, a curve used to determine key relationship of final consolidation settlement in the form of stress (in log scale) and final void ratio e. A linear relation is observed at higher point in the curve and a straight line called as a virgin compression curve could be drawn, shown in Figure 3.4. The slope of the line is read as compression index Cc. σ_o and Cc is then used to obtain final settlement Sf, formulated as,

$$S_f = \frac{H}{1+e_0} C_c log \frac{\sigma_0+\sigma}{\sigma_0} \qquad \textit{Equation 3-2}$$

where H is the total thickness of the clay, e0 is initial void ratio, σ_o is preconsolidation stress, and σ is stress of the soil (Ishibashi & Hazarika, 2010).

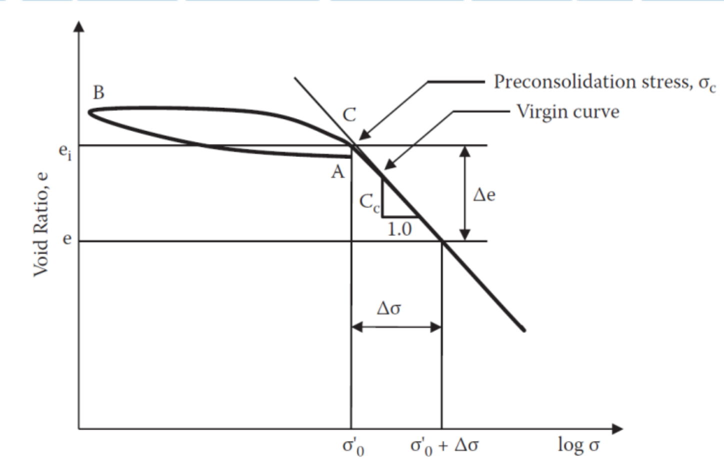

Figure 3.4 e-log σ Curve and Virgin Curve

(Ishibashi & Hazarika, 2010)

To determine essential parameter for consolidation, laboratory test is conducted to obtain Coefficient of consolidation value Cv. Cv is a key parameter for consolidation theory, with a unit of length^2/time (m^2/s)(Ishibashi & Hazarika, 2010). After determining Cv, time factor Tv is introduced to make simpler formula to obtain degree of consolidation. Tv is a nondimensional variable to express Cv in relative to time t and drainage distance H, which can be formulated as

$$T_v = \frac{C_v t}{H^2} \qquad \text{Equation 3-3}$$

3.3 Consolidation in PVD

In general construction project, modern PVDs are always produced in various shape and various sizes. PVD produced in such condition makes it difficult to analyze its effect to radial consolidation caused by it. Therefore, to assess the effect of actual shape of PVD, the shape is then converted into one shape which is circular drain. Its parameter then is labelled as vertical drain, and it is one main component for designing PVD. (Lu et al., 2019).

Another key aspect for designing PVD lies in its spacing and discharge speed. While discharge speed is also affected by its vertical diameter of the pipe, spacing of the PVD is also considered as key design for obtaining faster consolidation ratio. More number of PVD means accelerating the consolidation rate better, while fewer number of PVD slow down the consolidation process. (Ahlfeldt, 1996)

Degree of consolidation U is defined as percentage of settlement at a certain point of time to its final settlement at $t = \infty$. In the case of PVD, drainage effect happens in vertical drainage of natural soil and radial drainage due to PVD. The drainage effect cause consolidation to happen in two condition, vertical consolidation and horizontal consolidation. Both consolidations should be computed separately, and later combined as one degree of consolidation. (Chai, J; Shen, 2001; Ishibashi & Hazarika, 2010).

Radial consolidation, Ur, could be obtained using Hansbo's solution (Chai, J; Shen, 2001). The equiation is derived from equal vertical strain assumption and the vertical drain of natural soil is ignored. It is formulated as

$$U_{h=} 1 - exp\left(-\frac{8}{\mu} T_h\right) \qquad \textit{Equation 3-4}$$

where Th is the time factor for radial consolidation obtained from

$$T_h = \frac{C_h}{D^2} t \qquad \textit{Equation 3-5}$$

Ch is the radial coefficient of consolidation, which can be obtained by performing laboratory test or estimated based on existing soil properties (Hong & Shang, 1998). It can be estimated as

$$C_h = \frac{k_h}{k_v} C_v \qquad \textit{Equation 3-6}$$

Notation t is time for PVD to perform desired degree of consolidation, and D is the diameter of area effected by PVD. μ is a very complex function, but it could be simplified as function of

$$\mu = ln\left(\frac{n}{s}\right) + \frac{k_h}{k_s} ln(s) - \pi \frac{2l^2 k_h}{3q_w} \qquad \textit{Equation 3-7}$$

where n is the ratio between diameter of area effected by PVD and diameter of PVD,

$$n = \frac{D}{d_w} \qquad \textit{Equation 3-8}$$

s is the ratio between diameter of smear zone and diameter of PVD,

$$s = \frac{d_s}{d_w} \qquad \textit{Equation 3-9}$$

Kh is horizontal hydraulic conductivities of the natural soil, ks is horizontal hydraulic conductivities of the smear zone, l is PVD length, and qw is the discharge capacity of PVD. For simplification of this study, the square grid spacing PVD will be used; thus, D = 1.184S, where S is the spacing for the PVD(Chai, J; Shen, 2001).

Vertical consolidation in soil happens naturally if structure load, usually foundation or embankment, is installed in soil site (Chai, J; Shen, 2001; Ishibashi & Hazarika, 2010). Terzaghi's formula for consolidation could be used to obtain vertical degree of consolidation for soil. Alternatively, to obtain vertical degree of consolidation U_v, its relationship with time factor T_v could be found using the following table

Table 3-1 Relationship between Vertical Time Factor and Vertical Degree of Consolidation

(Ishibashi & Hazarika, 2010)

U (%)	T_v	U (%)	T_v
0	0	3.751	0.001
5	0.00196	5.665	0.0025
10	0.00785	7.980	0.005
15	0.0177	9.772	0.0075
20	0.0314	11.28	0.01
25	0.0491	17.84	0.025
30	0.0707	25.23	0.05
35	0.0962	30.90	0.075
40	0.126	35.68	0.1
45	0.159	56.22	0.25
50	**0.197**	76.40	0.5
55	0.239	87.26	0.75
60	0.286	93.13	1
65	0.340	99.83	2.5
70	0.403	100	5
75	0.477	100	7.5
80	0.567	100	9.5
85	0.684		
90	**0.848**		
95	1.129		
100	∞		

Vertical consolidation in soil happens naturally if structure load, usually foundation or embankment, is installed in soil site (Chai, J; Shen, 2001; Ishibashi & Hazarika, 2010). Consolidation happening to soil occurs in a very long time that cause time-delayed settlement. The ratio between settlement in certain period of time and its maximum consolidation is defined as degree of consolidation (Ishibashi & Hazarika, 2010). Settlement happening in period amount of time could be formulated as:

$$S_t = (M_v \Delta\sigma H)\ 1 - \frac{4}{\pi^2} \sum_0^\infty \left[\frac{1}{2N+1} . e^{-\frac{(2N+1)^2\pi^2}{4}T_v}\right] \quad \textit{Equation 3-10}$$

Thus, vertical degree of consolidation is formulated as:

$$U_v = \frac{S_t}{S_f} = 1 - \frac{4}{\pi^2} \sum_0^\infty \left[\frac{1}{2N+1} . e^{-\frac{(2N+1)^2\pi^2}{4}T_v}\right] \quad \textit{Equation 3-11}$$

where N is the number of nodes in the soil layer and Tv is time factor.

Vertical drains increase the mass hydraulic conductivity in vertical axis. The vertical hydraulic conductivity is represented by the effect of vertical consolidation due to natural soil and the effect of radial consolidation due to the existence of PVD. This consolidation due to both effects could be combined by using Carillo's theoretical solution of vertical drainage effects (Chai, J; Shen, 2001). The formula is

$$U_{avg} = 1 - (1 - U_v)(1 - U_h) \quad \textit{Equation 3-12}$$

3.4 Cost Estimation

Cost estimation is the most important aspect in optimization problem. It consists two basic task which are determining material quantities and worker required, and estimating the cost required for them. Although cost estimations are divided into four level of complexness by Means, the usually used cost estimation method is unit price estimate (Wang & Kulhawy, 2008).

In unit cost estimate, the work is divided into smallest unit called work items, and the unit price is the price for each one of those unit. The unit price will then be multiplied by the volume or quantity of work needed, resulting in the price of each work, while the total cost is the sum of price in all works. All volume of the work needed is already calculated and decided before the unit price estimates, because all drawing details, specification, equipment, and worker data are needed to make the estimation. In general, unit cost estimation is considered as cost estimation with highest accuracy compared with other method. Therefore, it is selected as the method for this study, with simplification to it to make the computation much faster but still accurate (Sun et al., 2020; Wang & Kulhawy, 2008).

Cost estimation in this study is the cost of labour cost, preloading material cost, and PVD material cost in PVD installation. In Sun's simplified cost estimation formula, labour cost and preloading material cost are considered as function of PVD numbers. Then, the overall cost of PVD is considered as ratio length and spacing of the PVD (Sun et al., 2020).

$$Cost = \frac{L}{S^2} \qquad \textit{Equation 3-13}$$

3.5 Optimization

Optimization is a method used to find optimal or near optimal solution of problem, indicated by lowest effort in process and quantity of material possible used to solve the problem. Generally, optimization method could be distinguished with two different types, exact and heuristic optimization method. Exact optimization guarantees the exact solution for problem exist, while heuristic optimization does not guarantee the exact solution of certain problem. However, exact optimization generally used in low data size, as bigger data size requires high amount of effort and time to solve using exact method. In this case, the problem could then be solved using heuristic optimization, when the solution of the problem is case specific solution with approximation solution (Rothlauf, 2011). In this study, the problem will be solved using exact optimization method.

In any structure design, including geotechnical structure design, optimization is needed to make the structure fulfil the design parameter with smallest cost possible (Santos et al., 2018; Wang & Kulhawy, 2008). In optimization method, design parameter is called optimization constraint and cost of the structure is considered as optimization goal. The design constraint is parameter that should be fulfilled in optimization method and optimization goal is the target that will be achieved by the optimization.

There are many optimization methods that have already been developed before (Chan et al., 2009; Debnath & Ghosh, 2020; Liu, 2013; Rabiei & Janalizadeh Choobbasti, 2018; Zhang et al., 2011). In this study, optimization used is to calculate all variation of data within selected data range for optimization constraint. The data used in this optimization include soil properties, embankment load for surcharge pressure, and PVD properties. They are taken from previous literature that is already validated and used for designing PVD models (Carter & Bentley, 2016; Chai, J; Shen, 2001; Sun et al., 2020; Terzaghi et al., 1996).

3.6 Sensitivity Study

Soil properties are the main factors that control geotechnical engineering designs. Thus, it is very important to conduct proper soil investigation in the site to determine the soil conditions and to investigate any possible unusual behaviour of soil that may affects the design parameter. However, site investigation produced additional fund of the project, represented by cost increment of the project. Therefore, in economic model, it is expected that the cost for investigation is also minimalised. To minimalize the cost of soil investigation, it is necessary to find which of the soil parameter that needs to be addressed the most (Wang & Kulhawy, 2008).

Different soil properties interact differently with the construction material in the field. Each of soil properties will need different investigation and treatment to make the soil fulfil the design code of the construction. Therefore, for economic model, soil properties that affect construction cost the most is investigated to determine minimum treatment and investigation possible for those parameters. Soil treatment also become the factor controlling the overall cost of the project, hence it needs to be minimalised (Wang & Kulhawy, 2008).