An axisymmetric unit cell solution of PVD-improved soft soil considering a varied discharge capacity

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ABSTRACT: Discharge capacity of vertical drain is one of the important factors of prefabricated vertical drain (PVD), which affects consolidation rate of PVD-improved ground. Both previous experimental tests and field behaviors indicated that the discharge capacity of PVD decreases with increase in lateral effective stress. In order to consider varied discharge capacity with depth, an axisymmetric unit cell solution of PVD-improved soil deposit with considering a nonlinear variation of the discharge capacity was developed based on the Hansbo'solution. The results of excess pore water pressure distribution and degree of consolidation with depth were presented and compared to other approaches. The proposed analytical solution of consolidation of PVD-installed soil deposit considering the nonlinear distribution of discharge capacity of PVD was verified via a finite element method (FEM) in plane strain model. The results of the consolidation behaviors in FEM with the nonlinear distribution of discharge capacity of PVD provided a good agreement with the observed data. The proposed solution is recommended as a simple method to estimate the consolidation behavior of PVD-installed soil deposit with considering the discharge capacity variation.

Keywords: varied discharge capacity, axisymmetric unit cell, FEM, PVD, consolidation, soft soil

1 INTRODUCTION

The PVD combined with a preloading method was typically used in ground improvement technique. The role of PVD in subsoil includes shortening pore water travel distance and gaining a shear strength of soft deposit. However, the effective of PVD improvement method is linked with discharge capacity (q_w) of PVD. Theoretical and experimental researches combined with field practices indicated that the discharge capacity of PVD is influenced by a number of factors, including type and shape of the core, cross-sectional area of drain, confining pressure, permeability and durability of filter (Deng et al. 2013). Under embankment loading, although PVD accelerates the consolidation rate, the discharge capacity of PVD decreases with increasing depth (Hansbo 1981; Hansbo 1983; Rixner et al. 1986; Chai et al. 1995). The confining pressure in the surrounding soil increases with depth, which results in decreasing discharge capacity of PVD.

To analyze the consolidation behavior of the PVD-installed soft deposit, the approach of Hansbo (1981) was commonly used because of its simplicity. Although well resistance effects were considered in Hansbo's solution, discharge capacity of PVD was held constant with improved depth. Some previous analytical solutions were proposed to consider variation discharge capacity as follow. To consider effect of well resistance in an axisymmetric to plane strain matching procedure, Chai et al. (1995) developed an analytical model with linear reduction of discharge capacity and obtained a realistic excess pore water pressure distribution with depth. However, the smear effect was ignored in the study, and this is only artificial (or mathematical) treatment to result in more realistic excess pore water pressure variation with depth. In recent years, Deng et al. (2013) suggested a mathematical model to estimate the effect of a discharge capacity variation with depth on consolidation behavior of soft soil deposits in a unit cell, in which discharge capacity was also assumed to be linearly reduced with depth. This solution was followed by

Hansbo's solution. These results indicated that the variation of discharge capacity with depth and time significantly influenced the distribution of the excess pore water pressure. When the discharge capacity decreased with depth, the dissipation rate of excess pore water pressure was further reduced. However, this solution existed many factors (A_1, A_2) which cause inconvenience in consideration of varied discharge capacity with consolidation behavior.

In this study, we further develop an analytical solution in axisymmetric unit cell model to analyze consolidation behavior of PVD-installed soft deposit, in which the nonlinear variation with depth of PVD's discharge capacity was considered. The nonlinear distribution of discharge capacity was assumed in proposed solution based on previous experiment test (Hansbo 1983 and Rixner et al. 1986) as an evidence. The analysis results of consolidation behaviors in proposed solution are compared with Deng et al. (2013) and Hansbo (1981). The proposed mode with the nonlinear distribution of discharge capacity was also validated via finite element method for a case study.

2 ANALTICAL SOLUTION WITH A NONLINEAR DISTRIBUTION OF DISCHARGE CAPACITY

2.1 *A nonlinear distribution with depth of PVD*

According to the experimental results of discharge capacity as shown in Hansbo (1983) and Rixner et al. (1986), the discharge capacity nonlinearly decreased with increasing of confining stress or depth of PVD. Therefore, to consider a nonlinear distribution of discharge capacity with depth, a new equation for discharge capacity with a nonlinear distribution with depth was proposed as:

$$q_{wz} = q_{wo}\left(1 - A\frac{z}{L}\right)^2 \tag{1}$$

where q_{wz} is discharge capacity of PVD at a depth z in subsoil; q_{wo} discharge capacity of PVD at surface ground; L is total length of improved-zone; A is a dimensionless factor with the condition of $0 \le A \le 1$. If A = 0, discharge capacity of PVD is constant regardless of depth, which is the same condition as Hansbo's solution. For the case of A = 1, the discharge capacity of PVD rapidly decreases nonlinearly with depth and becomes zero at a depth of L.

2.2 *Analytical Solution*

This section presents a formulation of analytical solution for average excess pore water pressure of axisymmetric unit cell considering nonlinear distribution of PVD's discharge capacity. Hansbo's solution was followed with modification, in which equal strain condition was assumed. The main assumption in Hansbo's solution was adopted except that discharge capacity of vertical drain decrease nonlinearly.

An analytical solution of an axisymmetric unit cell with a varied discharge capacity of PVD followed the procedure in Hansbo (1981) was implemented. The average excess pore pressure at depth z of soil in unit cell can be described as:

$$\bar{u}_r = u_0 e^{-8T_h/\mu} \tag{2}$$

where μ value considering varied discharge capacity with a nonlinear distribution can be expressed as follows:

$$\mu = \ln\frac{n}{s} + \frac{k_h}{k_s}\ln s - \frac{3}{4} + \frac{2\pi k_h L^2}{q_{wo}A^2}\left[\ln\frac{L}{L - Az} - \frac{Az(1-A)}{L - Az}\right] \tag{3}$$

where $n = D_e/d_w$, in which d_w is equivalent diameter of vertical drain; $s = d_s/d_w$, in which d_s is diameter of smear zone; k_h and k_s are horizontal permeability of natural soil and smear zone, respectively. $T_h = C_h t/(4r_e^2)$, in which $C_h = k_h/(m_v\gamma_w)$, m_v is coefficient of volume compressibility. And, the degree of radial consolidation (U_r) at a depth z of above solutions can be calculated using Hansbo's approach (Hansbo 1981) as follows:

$$U_r = 1 - \frac{\bar{u}_r}{u_o} \tag{4}$$

2.3 *Comparison*

This section examines the consolidation behavior of PVD-installed soil deposit by proposed solution, and then comparing with previous analytical model (Deng et al. 2013 and Hansbo 1981). Note that either the extended solution or the traditional solution was proposed with assumption that surcharge load was imposed instantaneously and simply applied for multilayer ground (Hansbo 1981; Deng et al. 2013). Therefore, the properties of uniform soil and characteristics of PVD used were assumed as follows: r_e = 0.788 m, r_s = 0.355 m, r_w = 0.0263 m, L = 20 m, k_h =2×10^{-8} m/s, k_h/k_s =3, q_{wo} = 3.85×10^{-6} m^3/s. The results shows that the degree of radial consolidation considering nonlinear distribution of discharge capacity was significant delayed, compared with the cases of constant and linear distribution, the delay of consolidation rate is more obvious at a deeper depth, as shown in Figure 1.

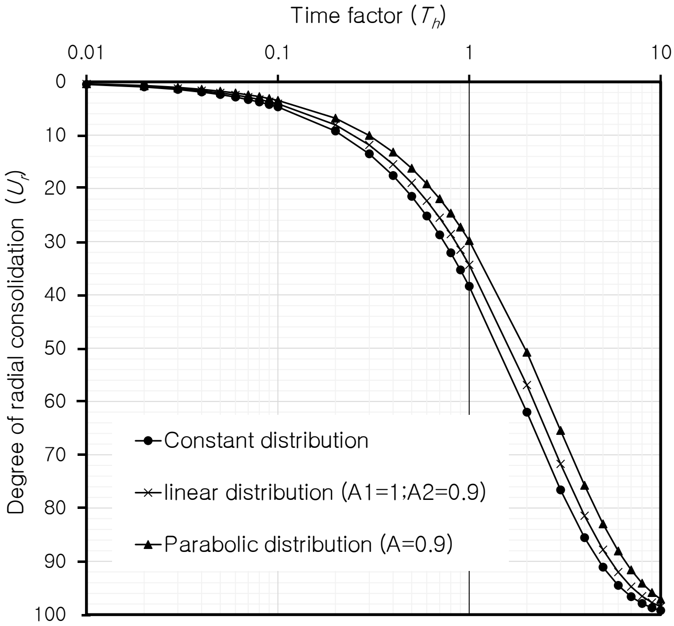

Figure 1. Comparison of degree of radial consolidations for varied distributions of discharge capacity

3 VERYFICATION WITH FINITE ELEMENT ANALYSIS

Chai et al. (2001) proposed the equivalent vertical hydraulic conductivity (k_{ve} method) of PVD-improved subsoil in a plane strain model as follows:

$$k_{ve} = \left(1 + \frac{2.5L^2}{\mu D_e^2}\frac{k_h}{k_v}\right)k_v \tag{5}$$

where D_e is the equivalent diameter of a unit cell (cylinder of soil around a single drain). For a square arrangement of PVD, D_e = 1.13S. For a triangular arrangement of PVD, D_e = 1.05S where S is the space between two adjacent PVDs. Other parameters were mentioned previously. In Eq. (5), note that the one-way drainage condition was assumed; therefore, L is the total drainage length of PVD in an improved zone. The μ value in Eq. (5) can capture the effects of discharge capacity of PVD on consolidation behaviors of soft deposit. Therefore, to evaluate the effects of varied discharge capacity with depth on consolidation behaviors, the following 3 cases were examined:

Case 1: A constant discharge capacity in Hansbo's solution (Hansbo 1981),
Case 2: A linear distribution of discharge capacity of with depth (Deng et al. 2013), and
Case 3: A nonlinear distribution of discharge capacity with depth, as was expressed in Eq. (3).

The plane strain model in FE (Finite element)-Code Plaxis (Brinkgreve and Vermeer 1998) is applied to analyze the consolidation behavior of test embankments on soft mucky clay deposit in eastern China. The test embankment on soft mucky clay deposit in eastern China was presented and detailed by Chai et al. (2001). This test embankment is located at the southern coast of Hangzhou Bay. Figure 2 shows the cross section and soil profiles of this test embankment. The height of the embankment was 5.88 m including the sand mat. PVDs were installed to a depth of 19 m in a triangular pattern with a spacing of 1.5 m. Smear zone was considered with d_s = 0.355 m; d_s/d_w = 6.7; k_h/k_s = 13.8 and discharge capacity q_{wo}=0.28 m3/day (Chai et al. 2001). The properties of subsoil used in numerical analysis are listed in Table 1. The soft soil model (SSM) was used to simulate the behavior of soft clay layers; the embankment fill material and clayey sand were modeled by the Mohr-Coulomb model (MC).

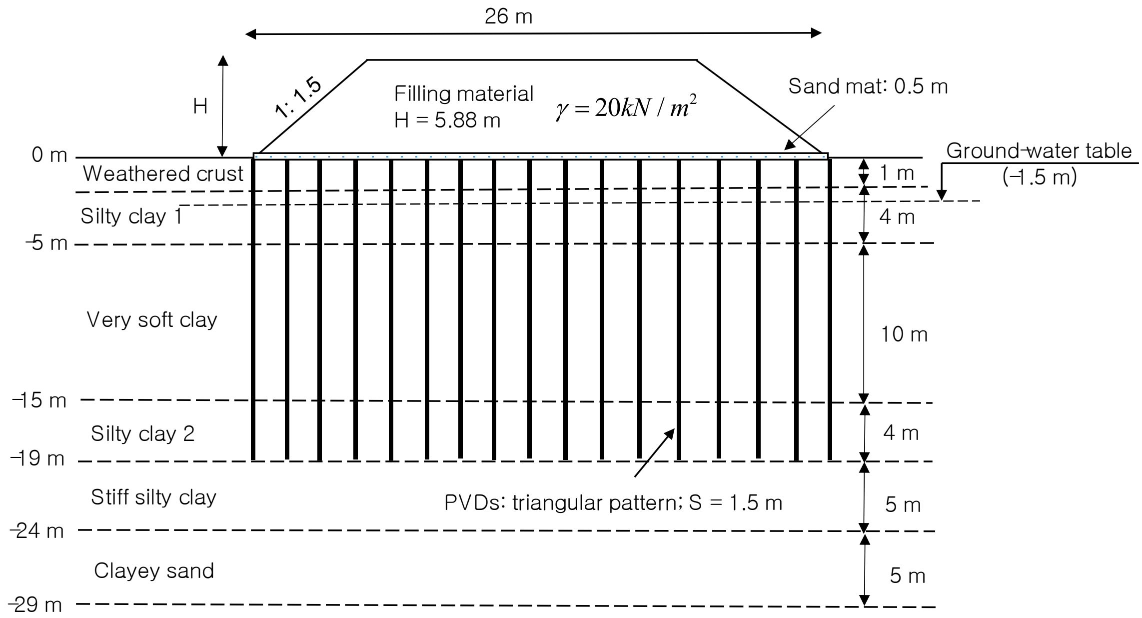

Figure 2. Cross-section and arrangement of PVD under embankment test of Eastern China

Table 1. Geotechnical properties of subsoil in numerical analysis

Layers	Model	γ_{sat} (kN/m^3)	E (kPa)	v	e_0	C_k	κ^*	λ^*	OCR
Weathered crust	SSM	19.3	-	-	0.81	0.405	0.004	0.044	5
Silty clay 1	SSM	18.5	-	-	1.07	0.535	0.007	0.077	1.2
Very soft clay	SSM	17.3	-	-	1.36	0.68	0.012	0.119	1
Silty clay 2	SSM	17.9	-	-	1.1	0.55	0.008	0.086	1
Stiff silty clay	SSM	19.3	-	-	0.81	0.405	0.005	0.055	1
Clayey sand	MC	19.5	25000	0.25	-	-	-	-	-
Fill material	MC	20	30000	0.2	-	-	-	-	-

Figure 3 shows comparison of the settlement between numerical results and observed data. The FEM results indicate that the k_{ve} method considering varied discharge capacity with depth including Case 2 and Case 3 provided a good agreement with the observed results, comparing with Case 1 (constant discharge capacity).

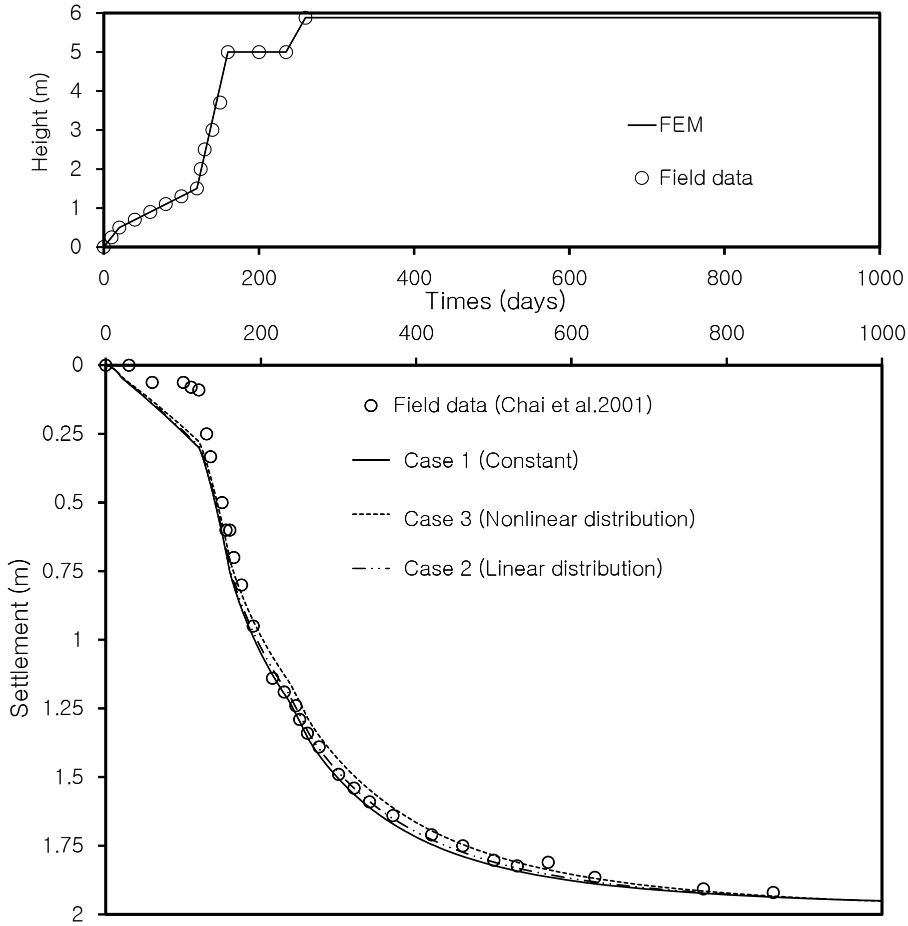

Figure 3. Loading schedule and comparison of the settlement between FEM and measured data

Figure 4 compares the dissipation of excess pore water pressure at depth of 14.05 m under embankment between observed results and FEM results for Case 1, Case 2 and Case 3. It can be observed that dissipation of excess pore water pressure became slower and consistent with observed data when the varied discharge capacity was considered. The results indicated that the excess pore water pressure dissipation at a depth of 14.5 m in Case 3 was good agreement with field behaviors, compared with Case 1 (constant discharge capacity) and Case 2 (a linear distribution of discharge capacity).

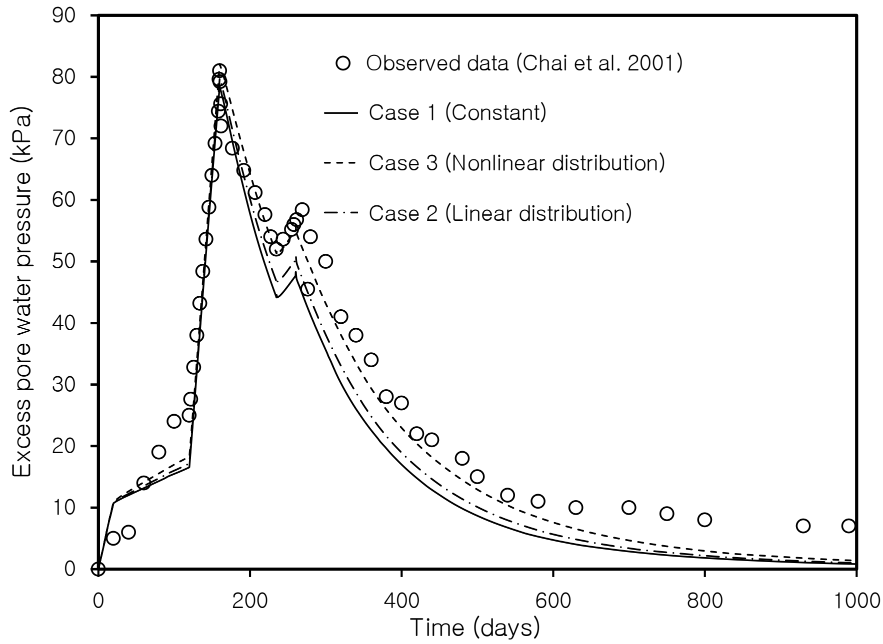

Figure 4. Comparison of the excess pore water pressure between FEM and measured data at depth of 14.05 m

4 CONCLUSION

This study assumed that the discharge capacity decreased with depth in nonlinear distribution. Analytical solution was developed in an axisymmetric unit cell. The proposed model was also verified in the plane strain model with the simple equivalent vertical hydraulic conductivity (Chai et al. 2001) considering a varied distribution of discharge capacity of PVD. The following conclusions were drawn:

- At a given time and depth, the consolidation rate in the case of discharge capacity with a nonlinear distribution is lower than that of a linear distribution. The consolidation rate slowed as A increased, which is similar to the result of the linear distribution case.
- The nonlinear distribution of discharge capacity in FEM provides a good agreement with field behavior when compared with those of constant discharge capacity and linear distribution of discharge capacity.

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