

Optimum PVD installation depth for two-way drainage deposit

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Abstract. For a two-way drainage deposit under a surcharge load, it is possible to leave a layer adjacent to the bottom drainage boundary without prefabricated vertical drain (PVD) improvement and achieve approximately the same degree of consolidation as a fully penetrated case. This depth is designated as an optimum PVD installation depth. Further, for a two-way drainage deposit under vacuum pressure, if the PVDs are fully penetrated through the deposit, the vacuum pressure will leak through the bottom drainage boundary. In this case, the PVDs have to be partially penetrated, and there is an optimum installation depth. The equations for calculating these optimum installation depths are presented, and the usefulness of the equations is studied by using finite element analysis as well as laboratory model test results.

Keywords: prefabricated vertical drain (PVD); ground improvement; vacuum consolidation; laboratory test; pre-loading; soft clayey deposit.

1. Introduction

Preloading a soft clayey deposit by a surcharge load and/or vacuum pressure in combination with prefabricated vertical drains (PVDs) is a commonly used and economic ground improvement technique. For a one-way drainage deposit PVDs are normally fully penetrated into the deposit to shorten the preloading period. However, for a two-way drainage deposit (a sand layer underlying a soft clayey layer), full penetration of PVDs into the deposit may not be an economical choice. Due to vertical drainage, a thin clayey layer without PVD improvement can have the same rate of consolidation as a layer with PVDs. Therefore, it is possible to design a PVD improvement with partial penetration to achieve approximately the same rate of consolidation as that of a fully penetrated case. This installation depth will be dubbed the optimum depth. Although several

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consolidation solutions have been proposed for PVD improved subsoils (e.g. Hansbo 1981), there is no rational method proposed for determining this optimum PVD installation depth.

In the case of vacuum consolidation, if PVDs are fully penetrated into a two-way drainage deposit, the vacuum pressure will leak through the bottom drainage boundary and cannot achieve a desired consolidation effect. In this case, PVDs have to be partially penetrated into the deposit and there is an optimum installation depth (H_1) for vacuum pressure at which the maximum consolidation settlement can be obtained (Chai *et al.* 2006). An equation for calculating H_1 has been derived by Chai *et al.* (2006), but there are no test data reported.

In this paper, a method for determining the optimum PVD installation depth for a surcharge load case under two-way drainage condition is presented and the method for vacuum pressure case is briefly reviewed. Then, the effectiveness and limitation of the methods are studied by finite element analysis (FEA) as well as laboratory model tests.

2. PVD installation depth under surcharge load

2.1 Equation for calculating the optimum thickness of PVD unimproved layer (H_c)

The condition for deriving an equation for calculating H_c (Fig. 1) is that the average degree of consolidation of layer H_c under one-way drainage is the same as the average degree of consolidation of the deposit with full penetration of PVDs. Considering both the drainage capacity of the natural deposit and the effect of PVDs, the average degree of consolidation of a PVD improved deposit can be calculated as follows (Carrillo 1942):

$$U_{av} = 1 - (1 - U_{v1})(1 - U_h) \quad (1)$$

where U_{v1} = the average degree of consolidation of the deposit in the vertical direction, and U_h = the average degree of consolidation in horizontal direction caused by a PVD. To obtain an explicit expression for H_c , U_{v1} is calculated by an approximate form of Terzaghi's 1D consolidation theory (Chai *et al.* 2001) assuming the deposit is uniform.

$$U_{v1} = 1 - \exp(-C_d \cdot T_{v1}) \quad (2)$$

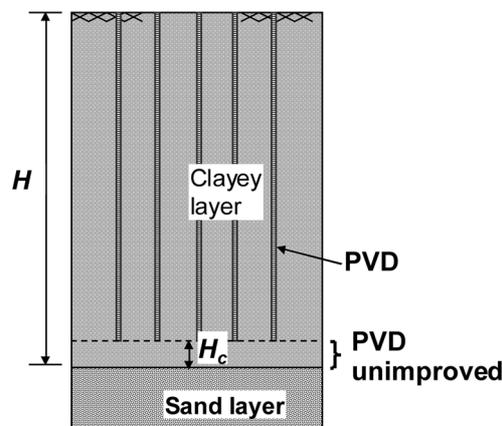


Fig. 1 Illustration of improved and unimproved layer

where $C_d = a$ constant ($=3.2$), and T_{v1} = the time factor for vertical drainage and can be expressed as follows:

$$T_{v1} = \frac{c_v \cdot t}{(H/2)^2} \quad (3)$$

where c_v = the coefficient of consolidation in the vertical direction of the deposit, t = time and H = the thickness of the entire clayey deposit (Fig. 1). Then, U_h can be evaluated by Hansbo's solution (1981) as follows:

$$U_h = 1 - \exp\left(\frac{-8T_h}{\mu}\right) \quad (4)$$

where T_h = time factor for PVD consolidation and μ = a parameter representing the effect of PVD spacing, smear and well resistance and they can be expressed as follows:

$$T_h = \frac{c_h \cdot t}{D_e^2} \quad (5)$$

$$\mu = \ln \frac{D_e}{d_s} + \frac{k_h}{k_s} \cdot \ln \frac{d_s}{d_w} - \frac{3}{4} + \pi \frac{2(H/2)^2 \cdot k_h}{3q_w} \quad (6)$$

where c_h = the coefficient of consolidation in the horizontal direction, D_e = the diameter of a unit cell (a PVD with its improvement area), d_s = the diameter of smear zone, d_w = the equivalent diameter of PVD, k_h , k_s = the horizontal hydraulic conductivities of natural soil and the smear zone, respectively, and q_w = the discharge capacity of a PVD.

For the unimproved layer (H_c), the average degree of consolidation (U_{v2}) can be calculated by Eq. (2) with corresponding time factor, $T_{v2} = c_v \cdot t/H_c^2$. By equating the average degree of consolidation of the PVD unimproved layer (H_c) and the average degree of consolidation of the deposit which is fully penetrated by PVDs, H_c can be expressed as follows:

$$H_c = \frac{1}{\sqrt{\frac{4}{H^2} + \frac{2.5}{\mu \cdot D_e^2} \frac{c_h}{c_v}}} \quad (7)$$

H_c calculated from Eq. (7) ensures that the average degree of consolidation of the unimproved layer (H_c) under one-way drainage is the same as the average degree of consolidation of the deposit with fully penetration of PVDs. However, with the arrangement as shown in Fig. 1, for the PVD improved layer ($H - H_c$), its vertical drain length is longer than that of the PVD fully penetrated case ($H/2$). Theoretically, this increase of vertical drain length will increase the well resistance for PVD consolidation and reduce the rate of consolidation due to the vertical drainage of a natural deposit. For most practical cases, when the discharge capacity (q_w) of the PVD is larger than 100 m³/year, the effect of well resistance is not significant (Bergado *et al.* 1996). Then this increase of drainage length will mainly reduce the consolidation effect of the natural deposit in the vertical direction. This effect will increase with the increase of PVD spacing, smear effect, and the thickness of a deposit. To compensate for the effect of the longer vertical drain length of the PVD improved layer, the average degree of consolidation of the unimproved layer (H_c) must be higher than that of

the PVD fully penetrated case. One solution to this dilemma is to calculate H_c by assuming that the average degree of consolidation of the unimproved layer is the same as that of the PVD fully penetrated as well as assuming the drainage length of the natural deposit in the vertical direction is $H/8$ (H = the thickness of a two-way drainage deposit). This condition results in a modified form of Eq. (7), which is the final equation for calculating H_c .

$$H_c = \frac{1}{\sqrt{H^2 + \frac{2.5}{\mu \cdot D_e^2} \frac{c_h}{c_v}}} \tag{7a}$$

Eq. (7a) is derived by assuming the deposit is uniform. Although most natural deposits are non-uniform, it is proposed that Eq. (7a) can be used for non-uniform deposits using layer thickness weighted average values of c_h and c_v . The validity of this proposal will be checked in the following sections.

2.2 One-dimensional (1D) finite element analysis (FEA)

The usefulness of Eq. (7a) is checked by 1D FEA. The ground condition at Kubota, Saga, Japan is considered. An approximately 9 m thick soft Ariake clay layer underlain a sand layer forms a two-way drainage deposit. At the site, the groundwater level was about 1.0 m below the ground surface. For most natural clayey deposits, the groundwater level is about 1.0 to 2.0 m below the ground surface, and in consolidation analysis, ground surface is considered as a drainage boundary. The subsoil profiles and the relevant soil properties are given in Fig. 2. In the figure, w_n , w_l and w_p are natural water content, liquid limit and plastic limit respectively, p_c is consolidation yielding stress, σ_v' is initial effective overburden pressure, and OCR is over-consolidation ratio. The selected

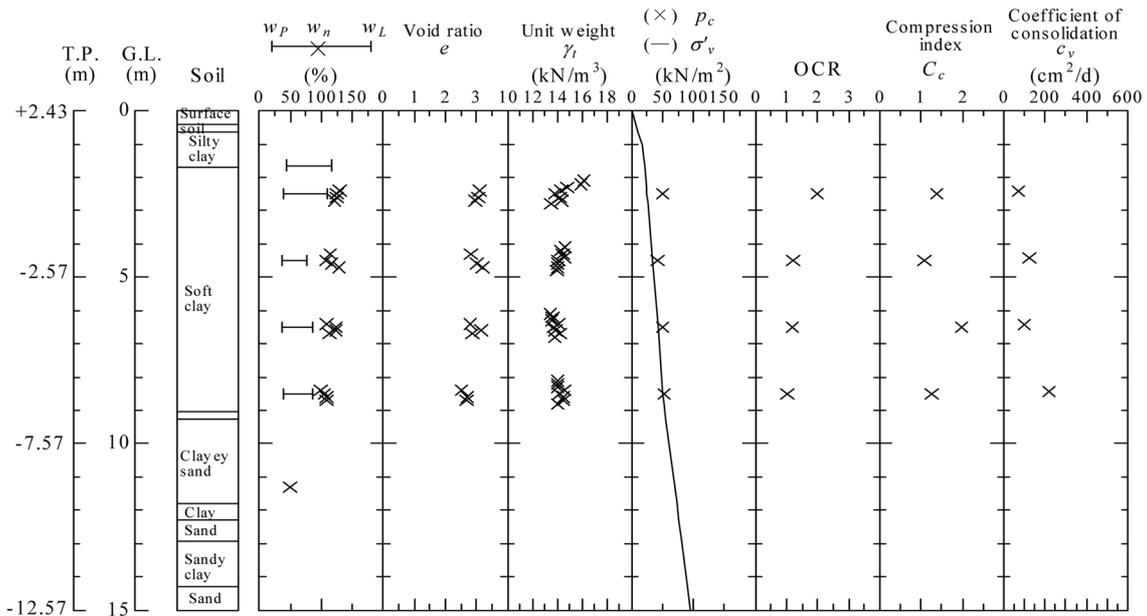


Fig. 2 Subsoil profile and some of soil properties

Table 1 Selected parameters for consolidation analysis

Depth (m)	c_h (m ² /day)	c_v (m ² /day)	γ_i (kN/m ³)	C_c	e_0	OCR
0.0~1.0	0.030	0.020	16.0	1.00	1.54	4.0
1.0~3.0	0.021	0.014	14.6	1.38	2.28	2.0
3.0~6.0	0.036	0.024	14.3	1.07	2.50	1.2
6.0~9.0	0.048	0.032	14.0	1.62	2.75	1.1

Table 2 Parameters related to PVD consolidation

Parameter	Symbol	Unit	Basic value	Variation range
PVD spacing	S	m	1.2	0.8, 1.0, 1.2, 1.5, 2.0
Diameter of unit cell	D_e	m	1.36	0.90, 1.13, 1.36, 1.70, 2.26
Diameter of drain	d_w	mm	50	-
Diameter of smear zone	d_s	m	0.3	-
Discharge capacity	q_w	m ³ /year	100	-
Hydraulic conductivity ratio	k_h/k_s	-	10	1, 5, 10

parameters for consolidation analysis are given in Table 1. All parameters are from test results except the coefficient of consolidation, which are twice of the laboratory test data (Chai and Miura 1999). The parameters related to PVD consolidation are assumed as in Table 2.

Firstly, H_c values are calculated using Eqs. (7) and (7a) and the results are plotted in Fig. 3. In the calculation, a value of $c_h/c_v = 1.5$ is assumed, and k_h value is estimated from the layer thickness weighted average values of c_h , C_c , e_0 and initial effective stress in the ground. It is clearly indicated that the over-prediction of H_c by Eq. (7) increases with the increase of the smear effect and PVD spacing, *i.e.* for the PVD improved layer, the contribution from PVD to the overall average degree of consolidation is reduced as mentioned previously. 1D FEA was conducted to investigate the effect of H_c on settlement rate of the deposit and the analysis results are compared with the H_c values given in Fig. 3.

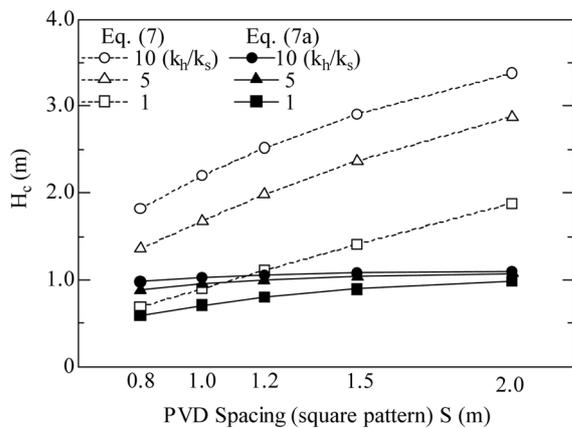


Fig. 3 Comparing the variation of H_c values

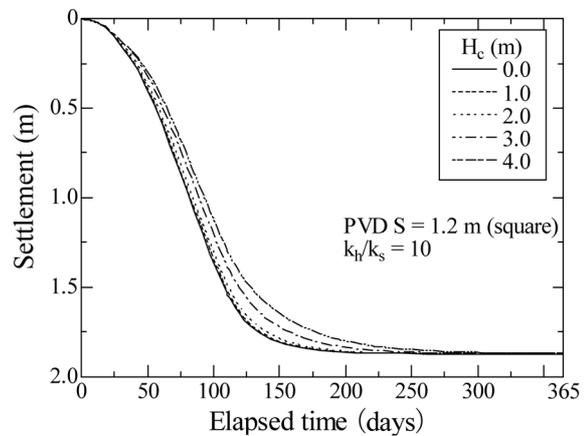


Fig. 4 Effect of H_c on settlement curves

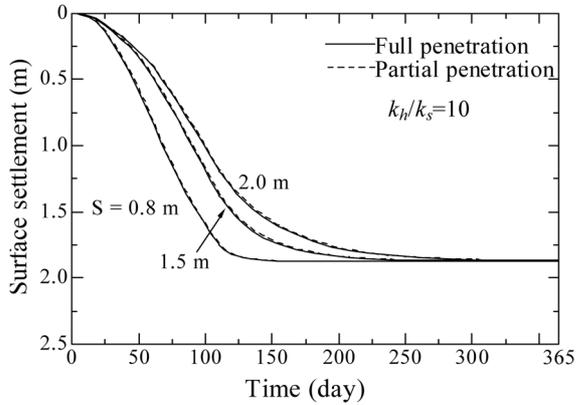


Fig. 5 Comparison of settlement curves with different PVD spacing

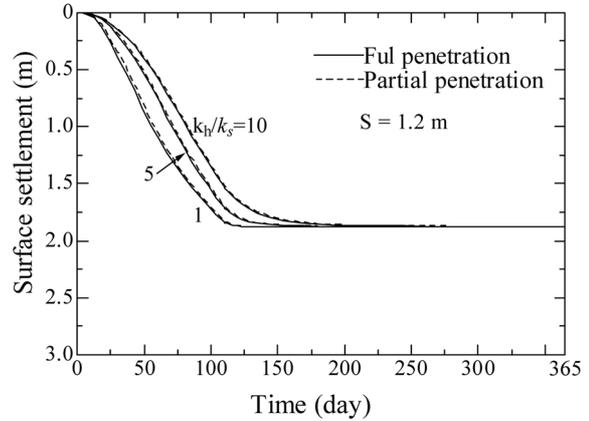


Fig. 6 Comparison of settlement curves with different smear effect

In FEA, the effect of the PVD is modeled by the method of equivalent vertical hydraulic conductivity method (Chai *et al.* 2001). For PVD spacing, $S = 1.2$ m (square pattern) and $k_h/k_s = 10$ case, the effect of H_c on settlement (S)–time (t) curves is compared in Fig. 4. It can be seen that for $H_c = 1.0$ m, the settlement curves are almost identical to that of the fully penetrated case. The H_c value from Eq. (7a) is 1.05 m (Fig. 3), which agrees with the FEA results.

Under the condition of $k_h/k_s = 10$, Fig. 5 compares settlement curves of the PVD fully penetrated cases with that of partially penetrated cases with H_c values from Eq. (7a) for $S = 0.8$ m, 1.5 m and 2.0 m. It can be seen that the settlement curves of partially penetrated cases are very close to those of the fully penetrated cases. Although the difference is small, there is a trend that the difference in settlement increases with the increase of PVD spacing. Fig. 6 shows the comparison of the settlement curves of the PVD fully and partially penetrated cases with $S = 1.2$ m and different k_h/k_s values. Again, the partially penetrated cases yield settlement curves very close to that of the corresponding fully penetrated cases, and the difference increases with the increase of the smear effect.

The comparisons made in Figs. 4 to 6 use the soil profile for the soft clay deposit at Kubota, Saga, Japan by assuming different PVD penetrated depth, spacing and smear effect. To further verify the effectiveness of Eq. (7a), it is assumed that the thickness of the soft layer doubles from 9 m to 18 m (double the thickness of each sub-layer). In this case, for $k_h/k_s = 10$ and $S = 1.2$ m, Eq. (7a) results in an H_c value of 1.81 m. Fig. 7 compares the settlement curves from FEA results with H_c value of 0 and 1.81 m. Although the curve of the partially penetrated case is close to that of the fully penetrated case, in this case, the difference is larger than that in Figs. 5 and 6. This comparison indicates that with an H_c value calculated by Eq. (7a), the delay of consolidation will increase with the increase of the thickness of a soft clayey deposit. All of the calculations made above using $k_h/k_v = 1.5$, but the relative error will reduce with increase of k_h/k_v value and vice versa.

The comparisons made above demonstrate that for a two-way drainage clayey deposit, leaving a layer without PVD improvement with a thickness of H_c as calculated by Eq. (7a), does not drastically alter the consolidation rate. The practical implication of this finding is that for a two-way drainage clayey deposit PVD improvement can be designed more economically. For the subsoil condition at Kubota, Saga, Japan, the PVD partial penetration case can save about 15 to 20% of

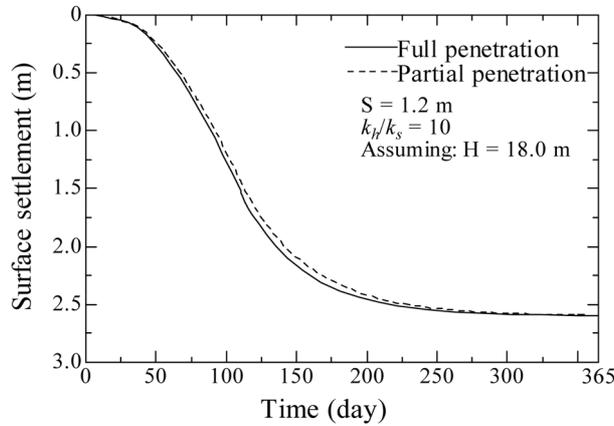


Fig. 7 Comparison of settlement curves assuming the thickness of the deposit $H = 18$ m

PVD improvement cost. Also, leaving a layer without PVDs adjacent to the sand layer has a geoenvironmental benefit, *i.e.* the water squeezed out from the clayey layer collected by PVDs will not directly enter the sand layer (normally an aquifer).

3. Optimum PVD installation depth under vacuum pressure

3.1 Equation for calculating optimum installation depth (H_1)

For a two-way drainage deposit with a vacuum pressure applied at the ground surface, assuming the hydraulic conductivities are uniform in both PVD-improved and unimproved layers respectively, at steady state the vacuum pressure distribution in the ground can be illustrated as in Fig. 8. Due to the total head difference at the bottom and the top of the soft clayey deposit, there will be upward steady flow. Based on the conditions: (1) the flow continuity in this two-layer system is at steady state, and (2) maximizing the area A (the area between the horizontal and the vertical axes and the vacuum pressure distribution line) as indicated in Fig. 8, an equation for calculating the optimum PVD installation depth (H_1), which will results in maximum consolidation settlement, has been derived by Chai *et al.* (2006).

$$H_1 = \left(\frac{k_{v1} - \sqrt{k_{v1}k_{v2}}}{k_{v1} - k_{v2}} \right) H \tag{8}$$

where k_{v1} and k_{v2} = the vertical hydraulic conductivities of PVD-improved and unimproved layers, respectively. The value of k_{v1} can be evaluated by the equivalent vertical hydraulic conductivity method (Chai *et al.* 2001) as follows:

$$k_{v1} = \left(1 + \frac{2.5l^2}{\mu D_e^2} \frac{k_h}{k_v} \right) k_v \tag{9}$$

where l = the drainage length of the PVDs. In the field, a clayey deposit may not be uniform. In

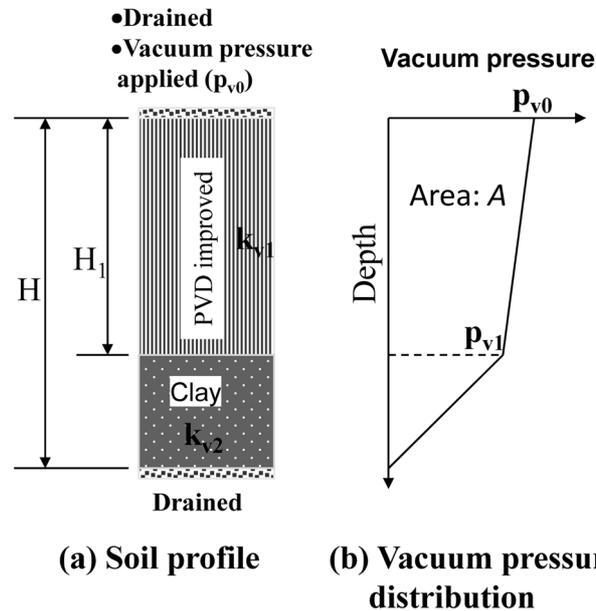


Fig. 8 Illustration of vacuum consolidation with PVD improvement

case the compressibility of the soil layers at the bottom end of PVDs varies significantly, the largest A value may not guarantee the largest final settlement, *i.e.* Eq. (8) may not yield an optimum PVD installation depth.

Note, at a site, if the thickness of the soft clayey layer varies significantly, it may be difficult to determine an optimum PVD installation depth for both surcharge load and vacuum pressure.

3.2 Laboratory model test

(1) *Test device:* A cylindrical model was used and the sketch of the model is shown in Fig. 9. The model mainly consists of a cylinder of 0.45 m in inner diameter and 0.9 m in height made of vinyl chloride with a wall thickness of 15 mm; upper and lower pedestals with a thickness of 40 mm; a piston system; and a burette connected to the drainage layer at the bottom of the model. The upper and the lower pedestals are connected by eight 12 mm in diameter steel rods. The 40 mm thick piston is made of vinyl chloride and a hollow shaft with an outside diameter of 100 mm is fixed to it. To prevent the possible tilting of the piston, a guide was installed on the upper pedestal around the shaft. Sealing between the piston and the cylinder and between the shaft and the upper pedestal is achieved by “O” rings lubricated by silicon grease. Both air pressure and vacuum pressure can be applied as a consolidation load. The air pressure is applied through the upper pedestal to the top of the piston and the vacuum pressure is applied through the hollow shaft of the piston to the bottom of the piston (surface of the model ground). To further prevent possible air pressure and/or vacuum pressure leakage through the piston, a rubber membrane sleeve with a thickness of 1 mm is installed inside the chamber above the piston. Considering the vertical displacement of the piston during consolidation, the rubber membrane sleeve is folded in the vertical direction initially. A KPD-200 kPa type piezometer (manufactured by Tokyo Sokki Kenkyujo Co. Ltd., Japan) is instrumented through the wall of the cylinder around the middle height of the model. The settlement is measured

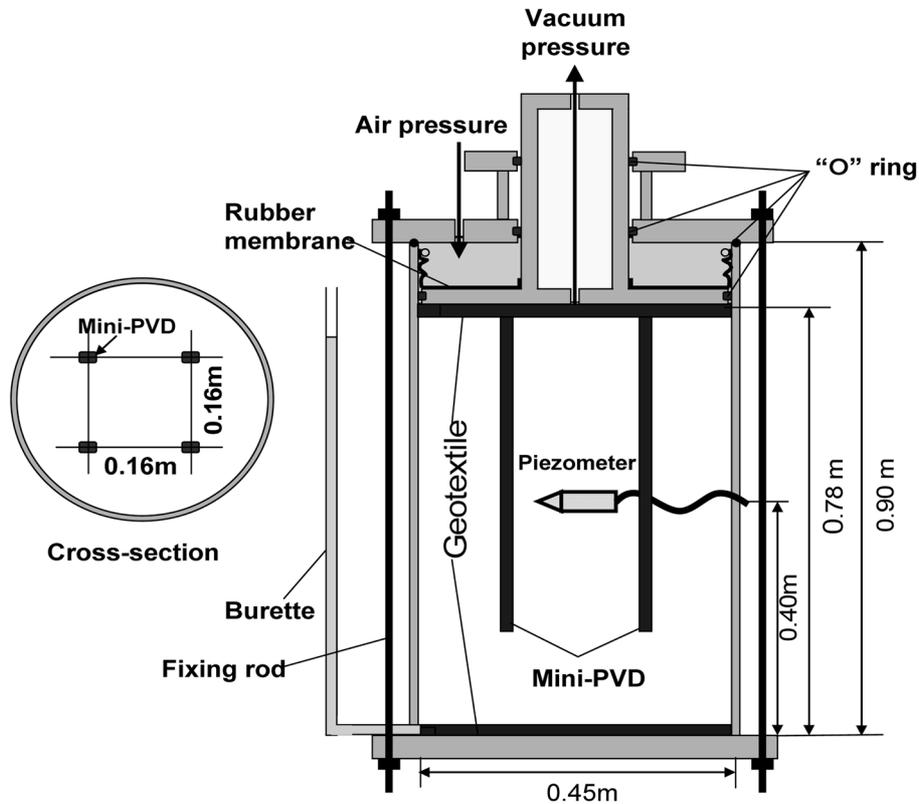


Fig. 9 The sketch of the device

at the top of the shaft by a dial gauge.

(2) *Materials:* The soil used was remolded Ariake clay with a liquid limit $w_l = 108.8\%$, and plastic limit $w_p = 59.2\%$. The initial water content of the clay was adjusted to about 120% (more than its liquid limit) and cured in a plastic container for more than 1 day before putting it into the device. A mini-PVD was formed by folding a non-woven geotextile in three layers with a cross-sectional dimension of 30 mm wide and 9 mm in thickness under no confining pressure condition. The geotextile used was made of polypropylene and weighted 131 g/m^2 .

(3) *Test procedure:* To set-up the model test, the cylinder was installed on the lower pedestal and 3 layers of the geotextile were placed at the bottom of the cylinder as drainage layer. A thin layer of silicon grease was painted on the wall of the cylinder to reduce the friction. Then clay was put inside the cylinder layer by layer and when the thickness of the soil reached 0.4 m from the bottom, the piezometer was installed. The thickness of the model ground was 0.78 m. After the completion of the model ground, 4 mini-PVDs were installed to pre-determined depth with the plan locations as indicated in Fig. 9. The method of installing mini-PVD is: a stainless steel rod was inserted inside the mini-PVD, and it was pushed into the model ground vertically together with the mini-PVD, then the rod was withdrawn leaving the mini-PVD inside the model ground. After that, another three layers of the geotextile were placed on the top of the model ground as a drainage layer. Finally, the piston, the rubber membrane sleeve, and the upper pedestal were installed and the dial gauge for measuring the vertical displacement was set. The pre-determined air-pressure and vacuum pressure

Table 3 List of the cases tested

Case	Initial thickness (m)	Mini-PVD installation depth (m)	Air pressure (kPa)	Vacuum Pressure (kPa)
1		0.48 (0.30)*		
2	0.78	0.58 (0.20)		
3		0.68 (0.10)	40	40
4		0.73 (0.05)		

*The number in parenthesis is the thickness of the mini-PVD unimproved layer.

were applied and the test was started.

(4) *Test program*: Four tests were conducted with the conditions as listed in Table 3. The mini-PVD installation depth varied from 0.48 m to 0.73 m leaving an unimproved layer of 0.30 to 0.05 m in thickness, respectively. Each test lasted about 15 days. It is well known that vacuum consolidation not only induces settlement, but also inward lateral displacement of the ground (e.g. Chai *et al.* 2005). For the model described above, if only vacuum pressure is applied, there is a possibility of forming gaps between the soil and the model wall causing leakage of vacuum pressure. To avoid this kind of situation, both surcharge load (air pressure) and vacuum pressure were applied. Chai *et al.* (2005) reported that the condition for no inward lateral displacement to occur can be expressed as follows:

$$|\Delta\sigma_{vac}| \leq \frac{K_0 \cdot \sigma'_{v0}}{1 - K_0} \quad (10)$$

where K_0 = at-rest horizontal earth pressure coefficient; σ'_{v0} = initial effective vertical stress; and $\Delta\sigma_{vac}$ = vacuum pressure. Adopting a K_0 value of 0.5, $|\Delta\sigma_{vac}| \leq \Delta\sigma'_{v0}$ can be obtained. Considering the surcharge load as σ'_{vo} , a condition of surcharge load equals vacuum pressure (40 kPa) was adopted for all tests.

3.3 FEA simulation of the model tests

To obtain detailed information about excess pore water pressure (vacuum pressure) distribution in the model ground and to provide a cross check, the model tests were simulated by FEA. The mechanical behavior of the model ground was modeled by modified Cam-clay model (Roscoe and Burland 1968). The values of model parameters used are listed in Table 4. The values of λ , e_0 and k_0 were calculated from laboratory incremental load consolidation test results and ν , κ and M values were assumed. During the consolidation process, hydraulic conductivity (k) was varied with void ratio (e) following Taylor's equation (Taylor 1948).

$$k = k_0 \cdot 10^{(e-e_0)/C_k} \quad (11)$$

where k_0 = initial hydraulic conductivity; e_0 = initial void ratio; e = current void ratio; and C_k = a constant (in this study $C_k = 0.4e_0$). For the parameters related to the mini-PVD, because the whole model ground was remolded, there was no smear zone, and $k_h/k_s = 1$. Then considering possible compression of the mini-PVDs under confinement, it was assumed (back-fitted) that the diameter of the mini-PVD, $d_w = 10$ mm, and the discharge capacity, $q_w = 1$ m³/year (Chai *et al.* 2007). For the arrangement as shown in Fig. 9, the diameter of the unit cell, $D_e = 0.225$ m can be evaluated.

Table 4 Model parameters adopted

λ	k	e_0	ν	M	k_0 (m/s)
0.265	0.027	3.2	0.3	1.2	2.51×10^{-9}

Note: λ = slope of virgin consolidation line in e - $\ln p'$ plot (p' is effective mean stress and e is void ratio); κ = slope of rebound line in e - $\ln p'$ plot; M = strength parameter for Cam-clay model, stress ratio at critical state, q_c/p' (q_c is deviator stress at critical state); ν = Poisson's ratio; e_0 = initial void ratio; and k_0 = initial hydraulic conductivity.

3.4 Test and analysis results

(1) *Settlement:* The settlement curves are compared in Fig. 10. Fig. 11 enlarges the final part of the curves. It can be seen that FEA simulated the settlement curves of Case-1 and 2 well. For Case-3 and 4, the simulated settlement rate is faster than the test data for elapsed time less than 10 days. Theoretically, an increase in the mini-PVD installation depth increases the initial settlement rate, and it is not clear yet why the test data did not show this tendency. Nevertheless, both test and analysis results indicate that Case-2 and 3 resulted in larger settlement than Case-1 and 4 (Fig. 11). Fig. 12 plots the final settlement at the corresponding mini-PVD installation depth. It can be observed that from a final settlement point of view, an optimum mini-PVD installation depth exists between Case-2 and 3.

(2) *Excess pore water pressure:* As indicated in Fig. 9, a piezometer was installed around the middle of the model ground (0.4 m from the bottom). The measured and simulated excess pore water pressure and/or vacuum pressure (u) variation with time at the piezometer point is compared in Fig. 13. The simulated maximum u values and dissipation rates are higher than the measured ones. Care was taken to maintain a saturated condition of the piezometer filter during the installation process, but the results in Fig. 13 show that the piezometer might not be 100% saturated. At the time of terminating the tests, the measured and analyzed orders of u values for the four cases are different. But if we extend the time for FEA to 25 days and check the final values, the order of the predicted u values are the same as the measured ones, *i.e.* the largest one is Case-4

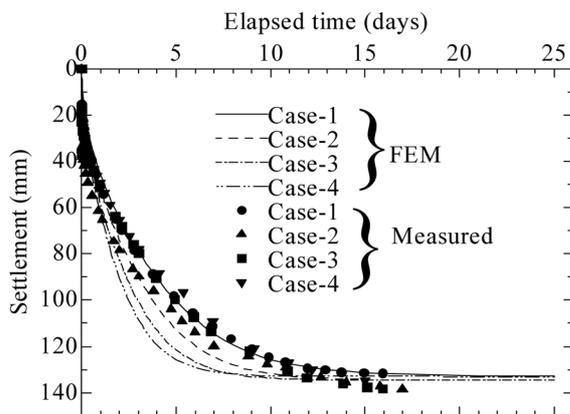


Fig. 10 Comparison of settlement time curve

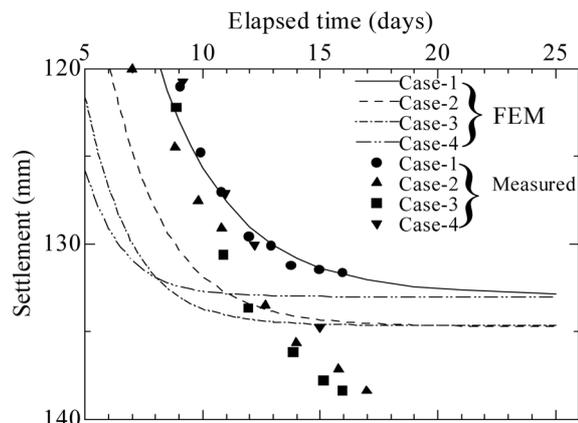


Fig. 11 Enlarged comparison of settlements at close to the end of consolidation

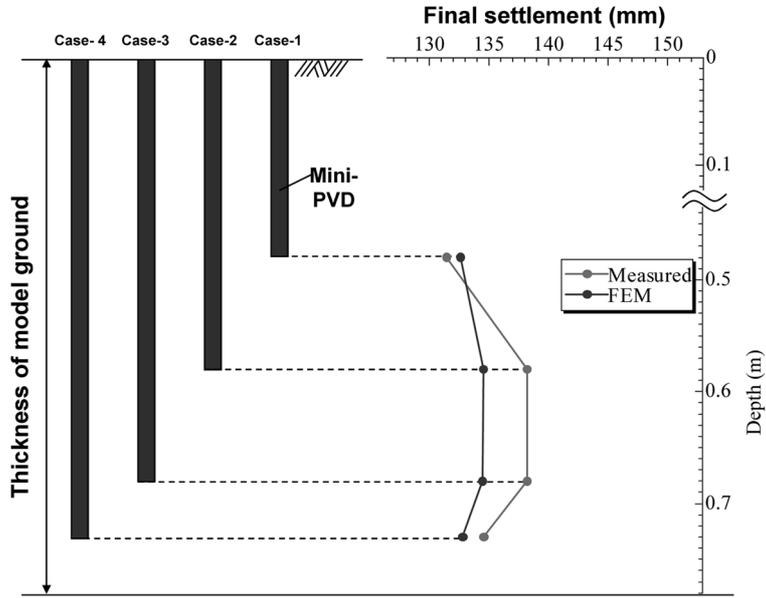


Fig. 12 variation of final settlement with mini-PVD installation depth

(smaller vacuum pressure) and the smallest one is Case-1. The final vacuum pressure distribution in the model ground is given in Fig. 14. This figure shows that the area *A* enclosed by the *u* distribution line, the left y-axis, and the top x-axis is larger for Case-2 and 3 than that of Case-1 and 4.

Using parameters adopted, Eq. (8) gives an optimum mini-PVD installation depth of about 0.575 m, which is close to the installation depth of Case-2 of 0.58 m. From Fig. 12, it can be seen that an

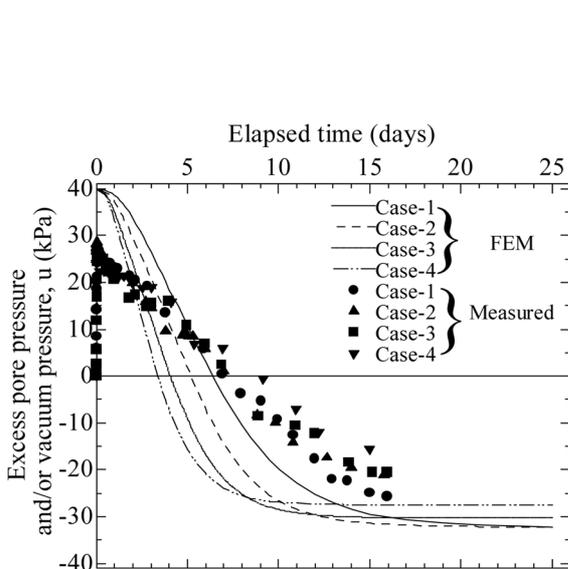


Fig. 13 Excess pore water pressure variation at piezometer point

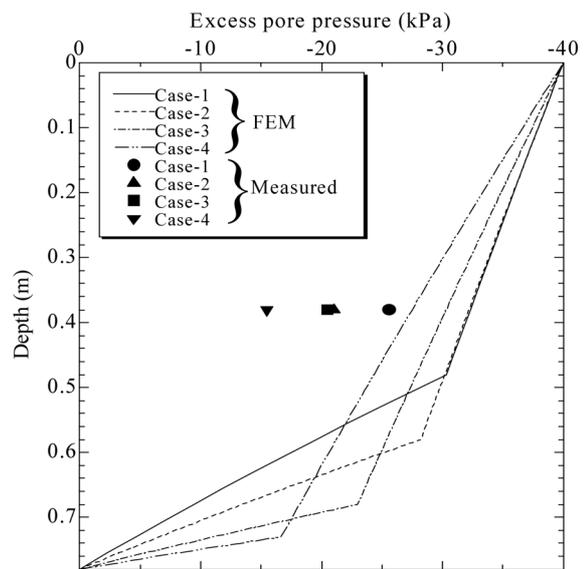


Fig. 14 Final vacuum pressure distribution in the model ground

increase in the mini-PVD installation depth from 0.58 m to 0.68 m did not increase the final settlement greatly. From an economic point of view, the optimum installation depth should be close to 0.58 m. The above comparison and discussion indicate that Eq. (8) is useful for determining the optimum installation depth of PVDs with two-way drainage condition under vacuum pressures.

4. Conclusions

Prefabricated vertical drain (PVD) improvement is commonly employed when preloading a soft clayey deposit by a surcharge load and/or vacuum pressure. In the case of a two-way drainage deposit, there are optimum PVD installation depths to result in a more economic design and/or a better improvement effect.

(1) Under a surcharge load: A semi-theoretical equation is derived for calculating the optimum PVD installation depth for a two-way drainage condition. A partially penetrated case with the optimum PVD installation depth can result in approximately the same average degree of consolidation as a fully penetrated case. The effectiveness of the proposed equation has been investigated by one-dimensional finite element analysis (FEA).

(2) Under a vacuum pressure: PVDs have to be partially penetrated into the soft clayey deposit to prevent the vacuum pressure leaking from the bottom drainage boundary. The results of both laboratory model test and FEA simulation indicate that there is an optimum PVD installation depth at which the maximum vacuum consolidation settlement can be obtained and Eq. (8) is effective for calculating this depth.

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