EXPERIMENTAL INVESTIGATION ON OPTIMUM INSTALLATION DEPTH OF PVD UNDER VACUUM CONSOLIDATION

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ABSTRACT

Laboratory model tests were conducted to investigate the influence of prefabricated vertical drain (PVD) installation depth on the effect of vacuum consolidation under two-way drainage condition. To get detailed information on vacuum pressure distribution in the model ground, the model tests were simulated by finite element analysis (FEA). Both the model test and FEA results show that there is an optimum PVD installation depth at which the vacuum pressure induced settlement is the maximum. Chai et al. (2006) proposed an equation to calculate the optimum PVD installation depth. Comparison between the model test results and the calculated value by Chai et al.'s equation indicates that the equation is useful for design vacuum consolidation involving PVD improvement under two-way drainage condition.

Keywords: Vacuum consolidation, Prefabricated vertical drain, Finite element analysis, Settlement.

1. INTRODUCTION

Vacuum consolidation is an effective preloading method for improving soft clayey deposit, and in recent years, the number of projects using vacuum consolidation is increasing (e.g. Chai et al. 2006). However, the effect of vacuum pressure to a clayey deposit is different from that of surcharge load. In field, generally the vacuum pressure is applied at the ground surface so that the final vacuum pressure distribution in the ground depends on the properties and drainage boundary condition of the deposit. Considering a one-dimensional (1D) problem and a uniform soil deposit, if the bottom boundary is undrained (one-way drainage) the final vacuum pressure in the deposit will be uniform. Conversely, if drainage can occur through the bottom boundary (two-way drainage), a vacuum pressure can not be effectively maintained at this boundary, and at steady state, the vacuum pressure distribution will be linear with the maximum value at the ground surface and zero at the bottom (Chai et al. 2005a). It is obvious therefore that vacuum consolidation involving two-way drainage should result in less settlement than one-way drainage.

Normally a vacuum consolidation is combined with prefabricated vertical drain (PVD) improvement to shorten the vacuum pressure application duration. For a two-way drainage deposit, to avoid vacuum pressure loses at the bottom drainage boundary through PVDs, PVDs are partially penetrated into the clayey deposit. In engineering practice, there is a question on how deep PVDs should be installed? From a settlement point of view, Chai et al. (2006) derived an equation for calculating the optimum installation depth of PVDs considering the state at the end of vacuum consolidation and using the condition of flow continuity. It is desirable to check the applicability of the equation by test results.

Laboratory model tests designed to investigate the influence of PVD installation depth on the effect of vacuum consolidation under two-way drainage condition were conducted. The results are analyzed and the applicability of the equation proposed by Chai et al. (2006) for calculating the optimum installation depth of PVDs is investigated. This paper presents the detail of the model tests as well as the test and analysis results.

2. LABORATORY MODEL TEST

2.1 Test device

A cylindrical model was used and the sketch of the model is shown in Fig. 1(a), and the picture of the actual device is shown in Fig. 1(b). 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 with a hollow shaft with an outside diameter of 100 mm. To prevent the possible tilting of the piston, a guide is 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 silicon grease lubricated “O” rings. Both air pressure and vacuum pressure can be applied as 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 model ground). To further prevent the possible air pressure and/or vacuum pressure leakage through the piston, a rubber membrane with a thickness of 1 mm is installed in the chamber above the piston. Considering the vertical displacement of the piston during consolidation, the rubber membrane is folded in vertical direction initially. A KPD-200kPa type piezometer (manufactured by Tokyo Sokki Kenkyujo Co. Ltd, Japan) is instrumented through the wall of the cylinder. The settlement is measured at the top of the shaft of the piston by a dial gauge.

### 2.2 Materials

The soil used was remolded Ariake clay. The liquid limit of the clay \( W_l = 108.8\% \), and plastic limit \( W_p = 59.2\% \). Initial water content of the clay was adjusted to 120% (more than its liquid limit) and cured in a plastic container for more than 1 day before putting into the model. Mini-PVD was formed by folding non-woven geotextile in 3 layers with a cross-sectional dimension of 30 mm wide and 9 mm in thickness. The geotextile used was made of polypropylene and weighted 131 g/m². The geotextile was used as drainage layers on the bottom and the top of the model ground also.

### 2.3 Test procedure

To set-up the model test, firstly, 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. 1(a). The method of installing mini-PVD is: put a stainless steel rod inside the mini-PVD and push it into the model ground vertically, and withdraw the rod and leave the mini-PVD inside the model ground. After that another 3 layers of the geotextile were placed on the top of the model ground as a drainage layer. Finally, the piston, the rubber membrane, and the upper pedestal were installed and the dial gauge was set. The pre-determined air-pressure and vacuum pressure were applied and the test was started.
### Table 1 List of the cases tested

<table>
<thead>
<tr>
<th>Case</th>
<th>Initial thickness of model ground (m)</th>
<th>Mini-PVD installation depth (m)</th>
<th>Air pressure (kPa)</th>
<th>Vacuum pressure (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.78</td>
<td>0.48 (0.30)*</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>0.58 (0.20)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>0.68 (0.10)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>0.73 (0.05)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

### 2.4 Test program

Totally 4 tests were conducted with the conditions as listed in Table 1. 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 was lasted for about 15 days. It is well known that vacuum consolidation not only induces settlement, but also inward lateral displacement of a ground. For the model described above, if only apply vacuum pressure, there is a possibility to form gaps between the soil and the model wall due to possible inward lateral displacement and causing leakage of vacuum pressure. To avoid this kind of situation, both surcharge load (air pressure) and vacuum pressure were applied. Chai et al. (2005b) reported that the condition for no inward lateral displacement to occur can be expressed as follows:

\[
\Delta \sigma_v < \frac{R_v \cdot \sigma_0^0}{1 - k_0}
\]  

where \(k_0\) = at-rest horizontal earth pressure coefficient; \(\sigma_0^0\) = in situ vertical effective stress; and \(\Delta \sigma_v\) = vacuum pressure. Adopting a \(k_0\) value of 0.5, \(\Delta \sigma_v < \sigma_0\) can be obtained. Considering the surcharge load as \(\sigma_0\), a condition of surcharge load equals vacuum pressure (40 kPa) was adopted for all tests.

### 3. FEM SIMULATION OF THE MODEL TEST

To obtain the detailed information about excess pore water pressure (vacuum pressure) distribution in the model ground and provide a cross check, the model tests were simulated by finite element analysis (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 2. \(\lambda\), \(\nu\), and \(k_0\) values are calculated from laboratory incremental load consolidation test results and \(\nu\), \(\kappa\) and \(M\) values were assumed. During consolidation process, hydraulic conductivity \((k)\) was varied with void ratio following Taylor’s equation (Taylor, 1948):

\[
k = k_0 \cdot 10^{(e_0 - e) / \kappa}
\]  

where \(k_0\) = initial hydraulic conductivity; \(e_0\) = initial void ratio; \(e\) = current void ratio; and \(C_k = 0.4e_0\). The effect of mini-PVDs is modeled by equivalent vertical hydraulic conductivity method (Chai et al., 2001). The value of the equivalent vertical hydraulic conductivity of mini-PVD-improved zone, \(k_v\), is calculated as follows:

\[
k_v = \left(1 + \frac{2.5L}{\mu D_v^2} k_e\right) k_l
\]  

where \(D_v\) = the diameter of a unit cell (containing a mini-PVD and its improvement area), \(k_e\) and \(k_l\) = the horizontal and vertical hydraulic conductivities of the model ground, respectively (in this study \(C_k = C_l\)); and \(l\) = the drainage length of the mini-PVDs. The parameter \(\mu\) represents the effects of spacing, smear and the well resistance of the mini-PVDs, that can be expressed as follows (Hansbo, 1981):

\[
\mu = \ln \left(\frac{n}{s}\right) + \frac{k_l}{k_e} \ln(s) - \frac{3}{4} + \frac{2Lk_e}{3q_w}
\]

where \(n = D_v/d_w\) (d_w is the diameter of the mini-PVD); \(s = d/v/d_w\) (d_s is the diameter of the smear zone); \(k_v\) = the hydraulic conductivity of the smear zone; and \(q_w\) = the discharge capacity of the mini-PVDs. For the model tests, \(D_v = 0.225\) m, and all soil was remolded and therefore, there should be no smear zone. The only parameters needed are \(d_v\) and \(q_w\). \(d_v = 10\) mm and \(q_w = 1\) m³/year was back-fitted.

### Table 2 model parameters adopted

<table>
<thead>
<tr>
<th>(\lambda)</th>
<th>(\kappa)</th>
<th>(e_0)</th>
<th>(\nu)</th>
<th>(M)</th>
<th>(k_0) (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.265</td>
<td>3.2</td>
<td>0.3</td>
<td>1.2</td>
<td>2.51 \times 10^{-9}</td>
<td></td>
</tr>
</tbody>
</table>

**Note:** \(\lambda\) = slope of virgin consolidation line in e-lnp’ plot (p’ is effective mean stress and e is void ratio); \( \kappa\) = slope of rebound line in e-lnp’ plot; \(M\) = strength parameter for Cam-clay model, stress ratio at critical state, q_c/p’ (q_c is deviator stress at critical state); \(\nu\) = Poisson’s ratio; \(e_0\) = initial void ratio; and \(k_0\) = initial hydraulic conductivity.

### 4. TEST AND ANALYSIS RESULTS

#### 4.1 Settlement

The settlement curves are compared in Fig. 2. Figure 3 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 initial
settlement rate is faster than the test data for elapsed time less than 10 days. Theoretically, increase the mini-PVD installation depth increases the initial settlement rate, and it is not clear yet why the test data do 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. 3). Figure 4 plots the final settlement at corresponding mini-PVD installation depth. It can be observed that from final settlement point of view, an optimum mini-PVD installation depth exists between Case-2 and 3.

Fig. 2 Comparison of settlement time curve

Fig. 3 Enlarged comparison of settlements at close to the end of consolidation

Fig. 4 variation of final settlement with mini-PVD installation depth

4.2 Excess pore water pressure

As indicated in Fig. 1, 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. 5. The simulated maximum $u$ values and dissipation rates are higher than the measured ones. The care was taken to maintain a saturated condition of the piezometer filter during the installation process, the results in Fig. 5 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 4 cases are different. But if we extend the time for FEA to 25 days and check the final values, the order of $u$ value is the same as the measured ones, i.e. the largest one is Case-4 (smaller vacuum pressure) and the smallest one is Case-1. The final vacuum pressure distribution in the model ground is given in Fig. 6. This figure shows that the distribution of vacuum pressure in the model ground varies with mini-PVD installation depth. Designating the area enclosed by $u$ distribution line, left y-axis, and top x-axis as $A$, if the ground is uniform, it can be easily reasoned that the larger the $A$ value, the larger the final

Fig. 5 Excess pore water pressure variation at piezometer point
Fig. 6 Final excess pore water pressure distribution in the model ground

settlement, and the corresponding mini-PVD installation depth will be the optimum installation depth. It can be seen from Fig. 6 that $A$ values for Case-2 and 3 are larger than that of Case-1 and 4.

5. OPTIMUM PVD INSTALLATION DEPTH

Assuming that the static water table is at the ground surface, the hydraulic conductivities are uniform in both PVD-improved zone and unimproved zone respectively, and for this kind of two-layer system, at steady state the vacuum pressure distribution in the ground can be illustrated as in Fig. 7, and due to the total head difference at the bottom and the top of the soft deposit with a vacuum applied at the ground surface, there will be upward steady flow. Based on: (1) the condition of flow continuity in this two-layer system, and (2) maximizing the area $A$ as defined in previous section and indicated in Fig. 7, an equation for calculating the optimum PVD installation depth ($H_1$) has been derived by Chai et al. (2006).

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

where $k_{v1}$ and $k_{v2}$ = the vertical hydraulic conductivities of PVD-improved and unimproved zones, respectively, and $H$ = the thickness of the soft clayey deposit. Using Eqs (3) to (5) and with the values of corresponding parameters explained in the FEA section, an optimum mini-PVD installation depth of about 0.575 m can be obtained, which is close to the installation depth of Case-2 of 0.58 m. At optimum installation depth, parameter $l$ in Eqs (3) and (4) has the same meaning as $H_1$ in Eq. (5), and iterations are needed during the calculation. From Fig. 4, it can be seen that increase the mini-PVD installation depth from 0.58 m to 0.68 m did not increase the final settlement. 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. (5) is useful for determining the optimum installation depth of PVDs under two-way drainage condition.

It is worth to mention that in filed, a clayey deposit may not be uniform. In case the compressibility of the soil layers at around the bottom end of PVD varies significantly, largest $A$ value may not guarantee a largest final settlement, i.e. Eq. (5) may not yield an optimum PVD penetration depth.

6. CONCLUSIONS

Laboratory model tests were conducted to investigate the influence of prefabricated vertical drain (PVD) installation depth on the effect of vacuum consolidation under two-way drainage ground condition. Based the test and finite element analysis (FEA) results, the following conclusions can be drawn.

(1) The test and analysis results confirmed there is an optimum PVD installation depth for vacuum consolidation involving two-way drainage ground condition. The optimum PVD installation depth means at which the settlement induced by a vacuum...
pressure is the maximum.

(2) Equation (5) proposed by Chai et al. (2006) can be used to calculate the optimum PVD installation depth and it is useful for design vacuum consolidation project with PVD improvement and under two-way drainage condition. However, in case the compressibility of the soil layers at around the end of PVD varies significantly, Eq. (5) may not guarantee an optimum PVD installation depth.

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