Preloading clayey deposit by vacuum pressure with Cap-drain

Jinchun CHAI¹, Norihiko MIURA² and D. T. BERGADO³

A method of improving soft clayey deposit by combining Cap-drain (CPVD) with vacuum pressure is described. The method uses a surface or subsurface soil layer as a sealing layer and no need to place an air-tightening sheet on the ground surface. It is explained that the method has advantages for situations of (a) a higher air/water permeability layer existed on ground surface, and (b) combining vacuum pressure with embankment load. A case history of consolidating a reclaimed clayey deposit by combining CPVD and vacuum pressure is analyzed and discussed. The site was in an under-consolidation state before starting the project. It is shown that the method is effective for this site. The back-calculation shows that for this under-consolidation deposit, vacuum pressure caused almost plane strain type isotropic deformation at near the ground surface.

Keywords: Vacuum consolidation, vertical drain, ground deformation, and reclaimed land

1. Introduction

Vacuum consolidation is one of the methods improving soft clayey deposit¹-². The original technique was developed by Kjellman³, which requires to first place an air-tightening sheet on the ground surface (seal the ends of the sheet by embedding them into the ground), and then suck out air/water below the sheet by a vacuum pump (Fig. 1). As a result, a vacuum consolidation pressure will be applied to the soft clayey deposit. It is obvious that the effect of the vacuum consolidation depends on the air-tightness of the sheet. There are situations under which it is difficult to maintain air-tightness by the technique. Followings are two typical examples.

(a) A high air/water permeability layer at ground surface. To avoid air leakage, the air-tightening sheet must be embedded below this layer, or an air/water cut-off wall penetrating through this layer and into the underlain lower permeability layer must be built around the perimeter of a preloading area. In practice, these options are cost and sometimes their effect is not guaranteed.

(b) Combing vacuum pressure with embankment load. Combining embankment load with vacuum pressure can increase preloading pressure and reduce preloading induced lateral displacement of a ground⁴-⁵. However, after placing embankment fill, any damage to air-tightening sheet cannot be identified and repaired, and consequently the effect of vacuum pressure will be reduced⁶.

Recently a new technique of applying vacuum pressure to soft clayey subsoil has been developed, in which vacuum pressure is combined with a special prefabricated vertical drain, named Cap-drain (CPVD)⁷. The method using a surface or subsurface soil layer as a sealing layer and there is no need to place an air-tightening sheet on the ground surface, and therefore, no worry about the damage to the sheet. The thickness of the surface sealing layer can be determined according to the field condition, and generally the variation of this thickness will not cause additional cost.

In this paper, firstly the structure of CPVD and the mechanism of combing vacuum pressure with CPVD to preload soft clayey subsoil are discussed. Then a field preloading project combining CPVD with vacuum pressure conducted in Yamaguchi, Japan⁸, is briefly described and analyzed to demonstrate the efficiency of the method.

2. Vacuum consolidation with CPVD

(1) Structure of CPVD

A CPVD unit consists of a piece of prefabricated
vertical drain (PVD), a drainage hose and a cap connecting the PVD with the hose as illustrated in Fig. 2(a) and the photo of a real product is shown in Fig. 2(b) (after Chai et al. 2003)\(^9\). For the product shown in Fig. 2(b), the cap has a width the same as the PVD (about 100 mm), a length of about 190 mm and a thickness of about 8 mm. The inside diameter of the hose is about 19 mm. The length of the PVD and the hose will be pre-determined based on the information of site investigation, and the required CPVD will be manufactured in a factory and transported to the field.

![Diagram of CPVD](image)

(a) Illustration  (b) A actual CPVD (after Chai et al. 2003)

**Fig. 2 Structure of CPVD**

(2) Vacuum consolidation with CPVD

Consolidating a soft clayeey deposit by vacuum pressure with CPVD is illustrated in Figs 3(a) and (b). Figure 3(b) shows the situation that there is a sand layer in the middle of a clayeey deposit. To avoid vacuum pressure losses through this sand layer, a sealing sheet is pasted on the filter of the drain passing through the layer. Vacuum pressure will be applied to the drain through the hose with a maximum value (\(p_{vac}\)) at just below the cap of CPVD. The soil layer above the cap serves as a sealing layer, in which the vacuum pressure varies from the value of \(p_{vac}\) at the bottom to zero at the ground surface. Therefore, the compression of the sealing layer will be less than that applying a vacuum pressure under an air-tightening sheet on the ground surface. For the layers below the sealing layer, the combining vacuum pressure with CPVD method will result in the similar compression as that of applying vacuum pressure under an air-tightening sheet combined with PVD improvement. The method for installing CPVD is the same as installing PVD. An anchor plate is fixed at the end of a CPVD and installed into the ground through a mandrel.

Regarding the thickness of the surface sealing layer (\(H_s\)), it can be estimated using a simple model, i.e. the vacuum pressure at the bottom of the sealing layer is \(p_{vac}\) and zero at the ground surface.

\[
H_s = \frac{p_{vac} - k_{air} \cdot A}{\gamma_w Q_a} \quad (1)
\]

where \(\gamma_w\) is the unit weight of water, \(k_{air}\) is the permeability to air flow of the sealing layer, \(A\) is the area of treatment, and \(Q_a\) is the capacity of a vacuum pump. For example, if \(k_{air}=10^{-7}\) m/s (generally larger than the corresponding permeability for water flow)\(^{10}\), \(p_{vac}=80\) kPa, \(Q_a=0.1\) m\(^3\)/s, and \(A=100\) m\(^2\), then \(H_s=0.8\) m can be calculated from Eq. (1). In case the sealing layer is saturated, Eq. (1) can still be used to estimate \(H_s\) value by using the permeability to water flow \((k)\) and the pump capacity for water \((Q_w)\) in places of \(k_{air}\) and \(Q_a\) respectively. However, if there is no water supply from the ground surface, in long-term, the sealing layer will become partially saturated and air flow will become a dominate factor rather than water flow.

![Diagram of vacuum consolidation](image)

(a) Without middle sand layer  (b) With a middle sand layer

**Fig. 3 Vacuum consolidation with CPVD**

3. A field project of vacuum preloading with CPVD

(1) Description of the project

A project combining CPVD with vacuum pressure conducted at Yamaguchi Prefecture, Japan was reported by Nakaoka et al.\(^8\). The site is a reclaimed land and the
total thickness of the soft deposit was about 28 m (11 m original deposit plus 17 m thick reclaimed layer) as shown in Fig. 4. Some physical and mechanical properties are listed in Table 1. In this site an area of about 250 m long and 44.4 m wide had been improved by vacuum pressure combined with CPVD. CPVDs were installed into 27 m depth with a spacing of 1.2 m and arranged in a square pattern. The thickness of sealing layer was 1.5 m as illustrated in Fig. 4. For the purpose of vacuum consolidation, the area was divided into 7 zones, A to F (Fig. 5, after Nakoka et al. 2005). For each zone, the surface settlement at the center and vacuum pressure inside an instrumented drainage hose, which was connected to PVD, were monitored. To check the ground deformation pattern and vacuum pressure distribution in the ground, inclinometer casings, piezometers (both inside a CPVD and between CPVDs) and a number of surface deformation marks inside as well as outside the improved area were installed for Zone B, and the plan view of the instrumentation points is given in Fig. 5. The depths of the piezometers and subsurface settlement plates are illustrated in Fig. 6.

At the work of installing CPVD was carried out from June 15 to September 25, 2003. Vacuum preloading commenced at January 5, 2004 and lasted for 133 days (ended on May 18, 2004). The measured vacuum pressure inside the drainage hose was about -65 kPa and Fig. 7 (after Nakoka et al. 2005) shows the records at Zone B. The field data from the instrumented
CPVD of Zone B confirmed that at the bottom end of the instrumented CPVD, the measured vacuum pressure was almost the same as that measured at the top of the CPVD\(^3\). Although the history of the reclamation of the site has not been reported, it seems that the consolidation induced by the self-weight of reclaimed fill was not finished at the time of installing CPVD. Figure 8 (after Nakaoka et al. 2005) shows measured surface settlement profiles along I-I' line (Fig. 5) of the improved area. It can be seen that before applying vacuum pressure, during and after CPVD installation, the measured self-weight induced surface settlement was about 0.8 – 1.8 m. The settlement versus elapsed time curve for Zone B is given in Figure 9 (data retrieved from Nakaoka et al. 2005). It can be seen that the consolidation due to vacuum pressure was not finished at the time of terminating the vacuum pressure. Since the initial effective stress condition in the ground is not clear, it is a difficult task to calculate the degree of consolidation. Nevertheless, Nakaoka et al.\(^8\) estimated the total degree of consolidation (include the self-weight) was 78.8 to 85.8%.

(2) Analysis of vacuum pressure distribution

As shown in Fig. 4, a gravelly sand layer is underlying the soft clayey deposit and forms a two-way drainage condition. In this case, under an applied surface vacuum pressure the final condition is a steady upward groundwater flow\(^9\). CPVD was partially penetrated into the soft clayey deposit with a penetration depth of 27 m, and in macro-level, the CPVD-improved layer and the unimproved layer form a two-layer system. To satisfy the flow continuity in a two-layer system, the following equation must be held.

\[ i_1 k_{i1} = i_2 k_{i2} \]  

where \(i_1\) and \(i_2\) are the hydraulic gradients, and \(k_{i1}\) and \(k_{i2}\) are the vertical hydraulic conductivities of layer-1 (improved) and layer-2, respectively. Based on Eq. (2), the final value of vacuum pressure at the interface of the two soil layers, \(p_{\text{vac}}\)\(_{\text{int}}\), can be calculated as follows:

\[ (p_{\text{vac}})_{\text{int}} = \frac{h_1 k_{i1}}{h_1 k_{i1} + h_2 k_{i2}} p_{\text{vac}} \]  

where \(h_1\) and \(h_2\) are the thicknesses of layer-1 and layer-2, respectively, and \(p_{\text{vac}}\) is vacuum pressure at the cap location of a CPVD. Chai et al.\(^{11}\) proposed a method to calculate the equivalent vertical hydraulic conductivity of PVD-improved subsoil (here CPVD), which can be used to evaluate the value of \(k_{i1}\) i.e., the mass vertical hydraulic conductivity of the CPVD-improved layer:

\[ k_{i1} = \left( 1 + \frac{2.51^2 k_h}{l \mu k_w} \right) k_i \]  

where \(D_s\) is the diameter of a unit cell (containing a CPVD and its improvement area), \(k_h\) and \(k_i\) are the horizontal and vertical hydraulic conductivities of the natural soil, respectively, \(l\) is the drainage length of the CPVDs, and \(q_w\) is the discharge capacity of the CPVDs. The parameter \(\mu\) represents the effects of spacing, smear and the well resistance of the PVDs, which can be expressed as follows\(^{12}\):

\[ \mu = \ln \frac{n}{s} \frac{k_i}{k_w} \ln (s) - \frac{3}{4} + \frac{2l^2 k_w}{3q_w} \]  

where \(n = D_s/d_w\) (\(d_w\) is the diameter of the drain), \(s = d_s/d_w\) (\(d_s\) is the diameter of the smear zone), and \(k_i\) is the hydraulic conductivity of the smear zone. The adopted parameters related to CPVD performance are listed in Table 2. The values of \(k_0/k_e\) and \(q_w\) are assumed and other parameters are evaluated based on the field conditions. With the parameters in Tables 1 and 2, an average degree of consolidation about 85% at the end of vacuum pressure application can be resulted from PVD consolidation theory\(^{13}\), and the value is within the range of reported field degree of consolidation\(^8\). Using the parameters in Tables 1 and 2 and an effective stress condition under self-weight, the initial hydraulic conductivities (\(k_i\) and \(k_0\)) of the natural soil layers and the equivalent vertical hydraulic conductivities (\(k_{w0}\)) after CPVD improvement are given in Table 3. Although initially the consolidation caused by the self-weight of the reclaimed fill was not finished, the adopted initial

<table>
<thead>
<tr>
<th>Item</th>
<th>Symbol</th>
<th>Unit</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drain diameter</td>
<td>(d_w)</td>
<td>m</td>
<td>0.05</td>
</tr>
<tr>
<td>Unit cell diameter</td>
<td>(D_s)</td>
<td>m</td>
<td>1.36</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spacing 1.2 m, square pattern</td>
<td></td>
</tr>
<tr>
<td>Smear zone diameter</td>
<td>(d_s)</td>
<td>m</td>
<td>0.3</td>
</tr>
<tr>
<td>Hydraulic conductivity ratio</td>
<td>(k_0/k_i)</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>Discharge capacity</td>
<td>(q_w)</td>
<td>m³/day</td>
<td>0.27</td>
</tr>
</tbody>
</table>
4.78 5) β, vac -80 2.69 8) 0 -60

the final data were read from the figures published by Nakaoka et al. (at the end of the vacuum pressure application) vacuum pressure distributions in the ground are given in Fig. 10. The field data were read from the figures published by Nakaoka et al. 8. Although the measured data (between CPVD) are smaller than the calculated final values, considering the factor that the consolidation was not finished when vacuum pump was stopped, the calculation gives a reasonable estimation of the field data.

(3) Settlement and lateral displacement calculations

Chai et al. 3) proposed a method to calculate the final settlement and lateral displacement of a deposit induced by vacuum consolidation. The method can be summarized as follows.

a) Criterion on vacuum pressure induced lateral deformation

Condition under which vacuum pressure (pvac) will induce lateral deformation of a deposit is as follows:

\[ p_{\text{vac}} > \frac{k_o \cdot \sigma'_{\text{at}} - \sigma_{\text{at}}}{1 - k_c} \]  

(6)

where \(\sigma'_{\text{at}}\) is initial in-situ vertical effective stress, \(k_o\) is at-rest earth pressure coefficient (\(k_o = 1 - \sin \phi'\), \(\phi'\) is effective stress internal friction angle of soil), and \(\sigma_{\text{at}}\) is horizontal earth pressure under the area with vacuum pressure, which can be calculated as follows.

\[ \sigma'_{\text{at}} = \begin{cases} 0 & \text{for } z < z_e \\ k_o \cdot \gamma' \cdot \gamma' & \text{for } z_l > z > z_e \end{cases} \]  

(7)

where \(\gamma'\) is the effective unit weight of soil, which equals to \(\gamma\) above the groundwater level and \((\gamma' - \gamma_w)\) below the groundwater level, \(z_e\) is the depth of tension cracking, \(z_l\) is the depth at which no vacuum pressure induced lateral displacement (can be evaluated by equating Eq. (6)), and \(k_o\) is an earth pressure coefficient with a value between active \((k_a)\) and at-rest \((k_c)\).

Assuming that the groundwater level is \(z_w\) below the ground surface, \(z_e\) can be expressed as follows:

\[ z_e = \frac{2c'}{\gamma' \sqrt{k_a}} \]  

(8a)

\[ z_e = \frac{1}{(\gamma' - \gamma_w)} \left( \frac{2c'}{k_a} - \gamma_w \gamma_w \right) \]  

(8b)

Then, \(k_o\) can be expressed as follows:

\[ k_o = \beta k_a + (1 - \beta) k_c \]  

(9)

where \(\beta = \text{constant} = 0.67 \text{ to } 1.0\).

(b) Vertical strain caused by vacuum pressure

The vertical strain \((\varepsilon_v)\) caused by vacuum consolidation can be expressed as a portion of the vertical strain occurring under one-dimensional (1D) consolidation, i.e.,

\[ \varepsilon_v = \alpha \frac{\lambda}{1 + e} \ln \left( 1 + \frac{p_{\text{vac}}}{\sigma_{\text{at}}} \right) \]  

(10)

where \(e\) is void ratio, \(\lambda\) is virgin compression index in an \(e-\text{ln}p'\) plot (where \(p'\) is effective mean stress), and \(\alpha\) is a factor with a value less than or equal to unity. In case that a vacuum pressure will not induce lateral deformation (Eq. (6) not hold), \(\alpha = 1.0\). Otherwise, \(\alpha\) is less than 1.0, and can be calculated as follows:
\[
\alpha = \alpha_{\min} + \frac{1 - \alpha_{\min}}{p_{\text{vac}}} \left( \frac{k_{\sigma'} - k_{\sigma^0}}{1 - k_{\sigma}} \right)
\]  

(11)

where \(\alpha_{\min}\) is a constant. For a normally consolidated ground, Chai et al.\(^5\) proposed that for triaxial stress conditions, \(\alpha_{\min} = 0.80\) and for plane strain conditions (vacuum pressure applied on a long strip area), \(\alpha_{\min} = 0.85\).

(c) Horizontal displacement

Under plane strain condition horizontal strain (\(\varepsilon_h\)) in the area under vacuum pressure can be calculated as follows:

\[
\varepsilon_h = (\varepsilon_{\text{vol}} - \varepsilon_v)
\]  

(12)

\(\varepsilon_{\text{vol}}\) is volumetric strain assumed to be equal to the vertical strain under 1D condition. Once \(\varepsilon_h\) is known, the lateral displacement (\(\delta_h\)) can be approximated quite simply as follows:

\[
\delta_h = B \cdot \varepsilon_h
\]  

(13)

where \(B\) is the half width of the area treated by vacuum consolidation.

At the site, the reclaimed fill load (self-weight) induced consolidation was not finished before starting the project. Since the history of reclamation is not clear, it is difficult to make a direct deformation calculation. The following calculation was conducted by assuming (1) an initial effective vertical stress distribution in the ground, and (2) a fraction (\(\alpha\)) of unconsolidated self-weight was consolidated after installing CPVD and before applying vacuum pressure. Under the condition of obtaining a reasonable simulation of surface settlement, and referring to the excess pore pressure distribution pattern from 1D consolidation theory, by few tries, the adopted distribution of initial vertical effective stress is given in Fig. 11, which corresponds to a degree of self-weight induced consolidation (\(U\)) of about 38\%. Using a \(C_v\) value of 0.018 m\(^2\)/day (Table 1) and a drainage length of 14 m, \(U = 38\%\) implies that the reclamation was made about 3.3 years before installing CPVD in the field. The back fitted \(\alpha\) value (fraction of consolidation induced by CPVD installation alone) is 0.5. In other words, before applying vacuum pressure, about 69\% (38\% + 62×0.5\%) of the self-weight induced consolidation was finished.

The other parameters used for calculating vacuum pressure induced ground deformation are effective stress internal friction angle, \(\phi' = 30^\circ\), cohesion, \(C' = 5\) kPa, and \(B = 22.2\) m (half width of the improved area). Groundwater level was at the ground surface. Then a depth of tension crack, \(z_c = 4.33\) m is evaluated. For this under-consolidation deposit, the following two points were considered for calculating the vacuum pressure induced settlement.

(i) About \(\sigma'_{\text{av}}\), \(\sigma'_{\text{av}}\) was not calculated by Eq. (7), instead it was calculated using the vertical effective stress distribution before starting vacuum consolidation in Fig. 10, \(z_c = 4.33\) m (Eq. 8b with \(z_w = 0\)) and \(k_{\sigma'} = k_{\sigma} (\beta = 1.0\) in Eq. (9)).

(ii) About incremental consolidation pressure. Calculated vacuum pressure distribution in Fig. 9 was used, and the uncompensated self-weight induced stress was added into vacuum pressure at corresponding depth.

The back-fitted \(\alpha_{\min}\) (Eq. (11)) under plane strain condition is 0.55, which indicates that the deposit almost deformed in a plane strain type isotropic way. \(\alpha_{\min} = 0.5\) means a true plane strain type isotropic deformation. The comparison of calculated and measured settlements is given in Table 4. Although there are discrepancies,
considering the unknown initial effective stress distribution in the field, the calculation gives a fair simulation of the field behavior in term of settlement. There are two reasons to explain the larger calculated vacuum pressure induced surface settlement than the measured value. First one is at the end of vacuum pressure application, the consolidation was not finished, but the calculation only gives a final value. Second one is that at the zone near ground surface, adopted vacuum pressure is larger than the field value. Vacuum pressure of -65 kPa was only measured at the cap location of the CPVD (1.5 m below the ground surface), but the calculation assumed at 1.5 m depth vacuum pressure was -65 kPa everywhere.

Table 4 Comparison of settlement

<table>
<thead>
<tr>
<th>Surface settlement after PVD installation and before applying vacuum pressure</th>
<th>Measured (m)</th>
<th>Calculated (m)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>1.84</td>
<td>1.71</td>
</tr>
<tr>
<td>Vacuum pressure and partial self-weight induced surface settlement</td>
<td>1.97</td>
<td>2.28</td>
</tr>
</tbody>
</table>

Comparison of lateral displacement is depicted in Fig. 12. The measured data is from Nakaoaka et al.5) for at the end of vacuum pressure application. The calculated lateral displacement almost matches the field data. As the method proposed by Chai et al.5) does not consider the interaction between soil strata, at near ground surface and the bottom of the soft layer, there are some differences. In the field, the stiff gravelly sand layer at the bottom restricted the lateral deformation of the above clay layer, but the calculation can not consider this effect and yielded a larger lateral deformation. Further, in the field, the surface layer was dragged by the layer below it and had a largest lateral deformation, but again the calculation can not consider the phenomenon and gave a smaller lateral deformation due to the smaller vacuum pressure. The calculated jump at 17 m depth is caused by the change of soil parameters (especially void ratio) at this interface of soil layers.

4. Conclusion

A method of improving soft clayey deposit by combining CPVD and vacuum pressure is analyzed and discussed. It is shown that CPVD with vacuum pressure is an effective method for consolidating soft clayey deposit. Further the back-calculation revealed the following points.

(a) The method proposed by Chai et al.5) for calculating vacuum pressure induced ground deformation gives a fair simulation of the field behavior of the case investigated.

(b) The site was in an under-consolidation condition before starting the vacuum consolidation. The estimated reclaimed fill load induced degrees of consolidations are: about 38% and 69% at the times of installing CPVD and applying vacuum pressure, respectively.

(c) For this under-consolidation deposit, vacuum pressure caused almost a plane strain type isotropic deformation at near the ground surface with a back-calculated $\alpha_{min}$ value (in Eq. (11)) of 0.55 ($\alpha_{min} = 0.5$ means a true plane strain type isotropic deformation). For normally consolidated ground and under plane strain condition, the reported $\alpha_{min}$ value is 0.85).

References
キャップドレーンと真空圧の組み合わせによる軟弱地盤改良の解析

柴 銀春・三浦哲彦・D. T. BERGADO

キャップドレーン（ médec）と真空圧を併用して軟弱地盤を改良する方法を説明した。この方法は表層土をシート層として利用するため、通常の真空圧密のように地表面にシートを敷く必要がない。また地表に厚い高透水・透気性層が存在する場合でもキャップを深く挿入することで対応できるという利点がある。さらに、真空圧と盛土荷重と組み合わせた場合、シートが壊れると恐れないので、通常の方法により有効である。本報告では、 médecと真空圧と併用して軟弱な埋立地を改良した事例を解析検討し、この方法の有効性を示した。この現場は真空圧密を開始した時点で自重圧密はまだ終了していなかったが、このような地盤においては真空圧による地盤の変形状態は平面ひずみ条件での等方変形に近くることを示した。