TECHNICAL NOTE

Comparison of vacuum consolidation with surcharge load induced consolidation of a two-layer system

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Laboratory consolidation tests for a two-layer soil system under oedometer conditions were conducted under both vacuum pressures and surcharge loads. The effects of the order of soil layers on the behaviour of vacuum consolidation of the two-layer soil system have been investigated by comparing vacuum pressure and surcharge load induced consolidations. Under one-way drainage conditions, for both a surcharge load and a vacuum pressure, the order of soil layers only influences the rate of consolidation but not the final settlement. When a layer with a relative lower value of hydraulic conductivity (k) is located immediately adjacent to the drainage boundary, the consolidation rate is slower. However, for vacuum pressure applied under two-way drainage conditions, the order of the soil layers not only influences the rate of consolidation but also the magnitude of settlement.

KEYWORDS: consolidation; laboratory tests; settlement

INTRODUCTION

Vacuum consolidation as a preloading method has received attention recently (Bergado et al., 1998; Tang & Shang, 2000; Tran et al., 2004). Chai et al. (2005a; 2005b) discussed the characteristics of vacuum consolidation using the results of a laboratory oedometer test with a uniform soil layer under both vacuum pressures and surcharge loads. The response of a layered deposit—natural deposits are often layered—under a vacuum pressure has not yet been the subject of comprehensive experimental and theoretical investigation. Hence, in order effectively to design a vacuum consolidation system, there is a need to clarify the characteristics of vacuum consolidation of a two-layer soil system.

A series of laboratory tests involving vacuum pressure and surcharge load induced consolidation under oedometer conditions were conducted to investigate the fundamental behaviour of vacuum consolidation of a two-layer soil system. The effects of drainage condition (one-way or two-way) and the relative hydraulic conductivity (k) of the soil layer immediately adjacent to the boundary where vacuum pressure is applied were studied with reference to the amount of settlement and the rate of the consolidation.

Des tests de consolidation en laboratoire pour un système de sol à deux couches, avec un oedomètre, sont effectués en présence de pressions sous vide et de surcharges. On examine les effets de l’ordre des couches de sol sur le comportement de la consolidation sous vide du système à deux couches en comparant les consolidations induites par pression sous vide et surcharge. Avec un drainage unidirectionnel, et aussi bien avec pression sous vide et surcharge, l’ordre des couches de sol n’influe que la vitesse de consolidation, et non pas le tassement final. Lorsqu’on relève une couche présentant une conductivité hydraulique (k) à valeur relative inférieure en un point adjacent à la limite de drainage, la consolidation se déroule plus lentement. Toutefois, en cas d’application de la pression sous vide avec un drainage bidirectionnel, l’ordre des couches de sol influe non seulement sur la vitesse de consolidation, mais également sur la magnitude du tassement.

A BRIEF DISCUSSION ON THE CHARACTERISTICS OF VACUUM CONSOLIDATION

Vacuum consolidation for a uniform soil layer

Chai et al. (2005b) reported the laboratory oedometer test results for a uniform soil layer with both surcharge load and vacuum pressure. The conditions adopted can be found from Chai et al. (2005b), and the main findings are as follows.

(a) Settlements induced by vacuum pressure under one-way drainage conditions. For vacuum consolidation, if inward lateral displacement occurs, the settlement induced by a vacuum pressure will be less than that of a surcharge load with the same magnitude. Chai et al. (2005b) defined a stress ratio k_r as follows

\[ k_r = \frac{\Delta \sigma_{\text{vac}}}{\Delta \sigma_{\text{vac}} + \sigma_{\text{at}}} \]  

so that, if \( k_r \leq k_0 \) (k_0 is at-rest horizontal earth pressure coefficient), there will be no lateral displacement and vice versa. Under oedometer conditions, \( S_{\text{vac}}/S_l \) denotes the settlement ratio of the final settlement induced by a vacuum pressure (\( S_{\text{vac}} \)) to that by a surcharge load with the same magnitude (\( S_l \)). Fig. 1 (modified from Chai et al., 2005b) shows the relationship between the stress ratio \( k_r \) and the settlement ratio \( S_{\text{vac}}/S_l \) obtained from the oedometer test results. It can be seen that when \( k_r > k_0 \), \( S_{\text{vac}}/S_l \) increases almost linearly with decreasing \( k_r \) value. When \( k_r \leq k_0 \), \( S_{\text{vac}}/S_l \) is very close to unity.

(b) Effect of drainage boundary condition. In the case of two-way drainage, at the bottom of the sample the excess pore pressure is fixed at zero and effectively no vacuum pressure can be applied. It is obvious therefore that vacuum consolidation involving two-way drainage should result in less settlement than one-way drainage.

Manuscript received 16 May 2008; revised manuscript accepted 14 November 2008. Published online ahead of print March 2009.

Discussion on this paper is welcomed by the editor.

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General discussion on the characteristics of vacuum consolidation for two-layer soil system

Generally, the effect of initial stress ($\sigma_{v0}'$) in a soil sample on the characteristics of consolidation of a two-layer soil system with a vacuum pressure should be similar to that of a uniform soil layer. However regarding the effect of drainage boundary condition, it is strongly affected by the order of soil layers relating to the boundary where the vacuum pressure is applied.

(a) One-way drainage. The final state will be a uniform vacuum pressure in the soil layers and no flow in the system. The order of soil layers will therefore not influence the final settlement. It will, however, influence the rate of consolidation. Under the condition of no lateral displacement occurring, when a layer with a relative lower k value is located at the drainage boundary, the consolidation rate will be slower; this is the same for a surcharge load case (e.g. Pyrah, 1996).

(b) Two-way drainage. Under a two-way drainage condition with a vacuum pressure, the final state involves a steady water flow towards the boundary where the vacuum pressure is applied. In a two-layer soil system, to satisfy the flow continuity at steady state, the following equation must be hold

$$i_1 k_{v1} = i_2 k_{v2}$$  \hspace{1cm} (2)

where $i_1$ and $i_2$ are the hydraulic gradients of layer-1 and layer-2, and $k_{v1}$ and $k_{v2}$ are the vertical hydraulic conductivities of layer-1 and layer-2, respectively. As can be seen from equation (2), a layer with a lower k value must have a higher i value in order to maintain the continuity of flow. Then, changing the order of the soil layer will not only influence the rate of consolidation, but also the distribution of vacuum pressure in the system as illustrated in Fig. 2. The final settlement will be a function of both the relative k values and the compression indexes of the soil layers ($C_v$).

Laboratory test programme for two-layer soil system

The equipment used was a Maruto multiple oedometer apparatus (manufactured in Tokyo, Japan) (Chai et al., 2005b). The equipment has five consolidation cells, which can be used either as individual consolidation cells or connected to form a 5-layer system. Each sample is 60 mm in diameter and typically 20 mm in thickness. In this study two cells were connected to form a two-layer soil system as illustrated in Fig. 3. For the case of an applied surcharge load, the same amount of load was applied at the tops of both layer-1 and layer-2. For the case of a vacuum pressure loading, however, the desired amount of vacuum pressure was only applied at the top of layer-1. The soil preparation procedure, initial stress and boundary conditions, and the magnitude of the load applied are the same as that of the tests for a uniform soil layer (Chai et al., 2005b). To make a direct comparison between a surcharge load and a vacuum pressure induced consolidation for both one-way and two-way drainages, only cases where $\sigma_{v0}' = 80$ kPa were tested. As shown in Fig. 1, for $\sigma_{v0}' = 80$ kPa ($k_v = 0$), no or very minimal lateral displacement is expected for a vacuum pressure increment of 80 kPa.

Two types of soil were used. One was reconstituted Ariake clay, and another was reconstituted mixed soil consisting of 50% Ariake clay and 50% sand (passing 2 mm sieve) by dry weight. The grain size distribution curves of the Ariake clay and the sand used are given in Fig. 4. Some of the physical and mechanical properties of the soils are listed in Table 1. The values of $k$ and $C_v$ were deduced from the standard oedometer test results. The $k$ values listed represent average values in the normally consolidated region. At an average effective vertical stress of 100 kPa, the coefficient of consolidation ($C_v$) of the mixed soil sample is about 4 times that of the Ariake clay sample. The tests conducted are listed in Table 2.

Test results for two-layer soil system

One-way drainage

The settlement/time curves under one-way drainage are compared in Figs 5 and 6 for the surcharge load and the vacuum pressure cases respectively. It can be seen that with $\sigma_{v0}' = 80$ kPa, the settlements induced by the vacuum pressure are almost the same as those induced by a surcharge load of the same magnitude. Also, the order of the soil layers did not have an influence on the final settlement. Both
figures show, however, that the order of the soil layers did have an obvious effect on the rate of consolidation. The case where the mixed soil sample was located at the drainage boundary (V-2 and S-2 in Table 2) had a faster consolidation rate. For the vacuum consolidation case, the time for 50% of the final settlement reached ($t_{50}$) for C+M case was about 37 min and for M+C case was about 28.5 min, and these times will be compared later with those for the two-way drainage cases.

The measured excess pore pressures at the bottoms of layer-1 ($u_1$) and layer-2 ($u_2$) are given in Figs 7 and 8 for the surcharge load and the vacuum pressure cases respectively. It can be seen that $u_1$ dissipated much faster in the M+C case (S-2 and V-2) than in the C+M case (S-1 and V-1). For the surcharge load cases, at the interface of layer-1 and layer-2, the time for $u_1$ to reduce to 40 kPa (half of the applied surcharge load) was 9 min for the M+C case (S-2) and 62 min for the C+M case (S-1). For the case of vacuum pressure, the time for $u_1$ to reach 40 kPa was about 5 min and 35 min for the M+C (V-2) and the C+M (V-2) cases, respectively. Obviously, the vacuum pressure propagated faster than the dissipation of the surcharge load induced excess pore pressure at the early stages of consolidation. The reason considered is the possibility of very small inward lateral displacement occurring in the upper soil sample (layer-1) under the vacuum pressure, which could form micro-gaps between the confining ring and the soil sample causing an apparent increase in the hydraulic conductivity of the sample. In layer-1 and layer-2, the average hydraulic gradients ($i$) can be estimated as $|u_0 - u_1|/h$ and

### Table 1. Physical properties of the soil samples

<table>
<thead>
<tr>
<th>Soil particles: %</th>
<th>Unit weight, $\gamma$: kN/m$^3$</th>
<th>Liquid limit, $W_L$: %</th>
<th>Plasticity limit, $W_P$: %</th>
<th>Void ratio, $e_0$</th>
<th>Compression index, $C_c$</th>
<th>Hydraulic conductivity, $k$: $10^{-5}$ m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay ≤5 μm</td>
<td>18-1</td>
<td>13-9</td>
<td>116-6</td>
<td>3-63</td>
<td>0-88</td>
<td>1-44</td>
</tr>
<tr>
<td>Silt</td>
<td>1-2</td>
<td>1-2</td>
<td>1-2</td>
<td>1-11</td>
<td>0-21</td>
<td>3-13</td>
</tr>
<tr>
<td>Sand</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

### Table 2. Summary of the tests conducted

<table>
<thead>
<tr>
<th>No.</th>
<th>Sample condition</th>
<th>Drainage condition</th>
<th>Consolidation pressure</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Soils</td>
<td>$\sigma_{0e}$: kPa</td>
<td>Type</td>
<td>Magnitude: kPa</td>
</tr>
<tr>
<td>V-1</td>
<td>C+M$^\dagger$</td>
<td>80</td>
<td>One-way</td>
<td>Vacuum pressure</td>
</tr>
<tr>
<td>V-2</td>
<td>M+C</td>
<td>80</td>
<td>Two-way</td>
<td></td>
</tr>
<tr>
<td>V-3</td>
<td>C+M</td>
<td>80</td>
<td>One-way</td>
<td>Surcharge load</td>
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<tr>
<td>V-4</td>
<td>M+C</td>
<td>80</td>
<td>Two-way</td>
<td></td>
</tr>
<tr>
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<td>C+M</td>
<td>80</td>
<td>Two-way</td>
<td></td>
</tr>
<tr>
<td>S-2</td>
<td>M+C</td>
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<td>Two-way</td>
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<tr>
<td>S-3</td>
<td>C+M</td>
<td>80</td>
<td>Two-way</td>
<td></td>
</tr>
</tbody>
</table>

$^\dagger$ $\sigma_{0e}$ is initial vertical effective stress.

$^\dagger$ C+M: the first layer is the Ariake clay and the second layer is the mixed soil; M+C: reverse the order of the soil layers.
A larger final settlement. The final settlement was 0-80 mm for the C+M case (V-3) and 0-94 mm for the M+C case (V-4), and the values of $t_{50}$ were 43-3 min and 28-5 min respectively. The values of $t_{50}$ are comparable with the corresponding values of a two-layer soil system under one-way drainage conditions as discussed previously (37-0 min and 28-5 min accordingly), and it supports the statement that under vacuum pressure, the rates of consolidation for one-way and two-way drainage should be the same if the coefficient of consolidation of soil sample is a constant during the consolidation. The measured $u_i$ variations are given in Fig. 9. It can be seen that M+C case had a much higher $|u_i|$ values than that of C+M case. At the elapsed time of 48 h (2880 min), the measured $u_i$ values were $-19.0$ for the C+M case (V-3) and $-45.6$ kPa for the M+C case (V-4) ($-52.0$ kPa at time $t = 60$ min and increased to $-45.6$ kPa at $t = 2880$ min). Using equation (2), the ratios of hydraulic conductivity of the mixed soil sample ($k_{mi}$) to that of the clay sample ($k_c$) ($k_{mi}/k_c$) are about 3-2 for the C+M case and 1-9 for the M+C case (using $u_i$ of -52.0 kPa). All these numbers are comparable with the ratio of 2-2 obtained using the $k$ values given in Table 1. Theoretically, if $k_c$ and $k_{mi}$ are constants, the $k_{mi}/k_c$ ratios for both cases should be the same. There are two reasons to explain the difference in $k_{mi}/k_c$ ratios. First, the $k$ value of a soil relates to its void ratio ($e$), and a reduction in void ratio will result in a reduction of $k$ value (e.g. Taylor, 1948). Compressions of the clay samples for both the C+M and the M+C cases are compared in Fig. 10(a). This figure shows that the clay sample had more compression (more void ratio reduction) in the C+M case (V-3) than that in the M+C case (V-4), and therefore a smaller $k_c$ value for the C+M case. Further, the compression of the mixed soil sample in the C+M case was less than that in the M+C case (Fig. 10(b)), and therefore a larger $k_{mi}$ value for the C+M case. Consequently, the C+M case had a larger $k_{mi}/k_c$ value. Second, for the M+C case, there was a possibility of leakage of vacuum pressure for $t > 60$ min owing to the possible vacuum pressure induced inward lateral displacement of the samples, which tends to reduce the $k_{mi}/k_c$ ratio. The mixed soil sample (M) may have a larger internal friction angle ($\phi'$) than the Ariake clay sample (C), which possibly implies a smaller at-rest earth pressure coefficient, $k_c$. The condition for inward lateral displacement to occur can be written as follows (Chai et al., 2005b)

$$\Delta \sigma_{\text{vac}} > \frac{k_o' \sigma'_{vo}}{1 - k_o} \tag{3}$$

Assuming $\phi' = 32^\circ$ for the mixed soil sample, and $k_o = 1 - \sin \phi'$, with $\sigma'_{vo} = 80$ kPa, equation (3) yields a
no lateral displacement $\Delta \sigma_{vac}$ value of less than about 65 kPa. Therefore for an applied vacuum pressure of 80 kPa, it was highly possible that some kind of inward lateral displacement occurred. The direct evidence is the slight reduction of the vacuum pressure at the interface of the soil layers after $t > 60$ min (Fig. 9).

CONCLUSIONS

Laboratory consolidation tests under oedometer conditions were conducted with both vacuum pressures and surcharge loads for a two-layer soil system. The effect of the order of soil layers on the characteristics of vacuum consolidation has been investigated. Based on the results of the laboratory tests and theoretical interpretations, the following conclusions can be drawn.

(a) One-way drainage. For a two-layer soil system with one-way drainage tested with both surcharge load and vacuum pressure, the order of soil layers only influences the rate of consolidation but not the final settlement. When a layer with a relative lower value of hydraulic conductivity ($k$) is located at the drainage boundary, the consolidation rate is slower.

(b) Two-way drainage. It is well known that for two-way drainage with a surcharge load, the order of soil layers has no influence on both the rate of consolidation and the final settlement. However, for two-way drainage with a vacuum pressure (vacuum pressure applied at one face only), the order of the soil layers not only influences the rate but also the magnitude of the consolidation settlement. This is because for two-way drainage with a vacuum pressure, the final state is a steady water flow towards the boundary where the vacuum pressure is applied. To satisfy the flow continuity condition, the vacuum pressure distribution in the soil layers is not only a function of relative values of the hydraulic conductivity, but also a function of the order of the soil layers.

ACKNOWLEDGEMENTS

This research has been partially founded by the programme of Grants-in-Aid for Scientific Research, Japan Society for Promotion of Science (JSPS) under grant No. 18560488. Sincere thanks are extended to Professor J. P. Carter at the University of Newcastle, Australia, for his valuable comments/suggestions during the preparation of this technical note.

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