Comparison of surcharge and vacuum pressure effects on radial consolidation

K. Kianfar
SMEC, Australia

B. Indraratna & C. Rujikiatkamjorn
University of Wollongong, Australia

ABSTRACT: A laboratory study was carried out to investigate the effects of surcharge and vacuum pressure application and removal on soft soil consolidation responses. A modified 150mm Rowe consolidation cell was used for the study. The modified Rowe cell was capable of measuring pore water pressures at four different radii so that capturing the effects of surcharge and vacuum pressure at various distances from the centre of the cell. Kaolin specimens prepared under preconsolidation pressure of 30 kPa were used to perform radial consolidation under combination of vacuum and surcharge pressure. A vertical circular sand drain was installed at the centre of the specimen and vacuum pressure was applied to the soft soil through the drain. Surcharge or vacuum pressure was partially removed at different times during consolidation to investigate the efficient removal time.

1 INTRODUCTION

The idea of application of vacuum preloading was originally proposed by Kjellman (1952). This technique has been then used successfully in various projects worldwide (Holtz 1975; Chen and Bao 1983; Bergado et al. 1998; Indraratna et al. 2005a, 2005b). Combination of vacuum preloading with fill load can reduce the height of the embankment and the consolidation time (Chu et al. 2000).

Vacuum pressure in conjunction of vertical drains accelerates inward radial drainage resulting isotropic consolidation. This results better embankment stability. Therefore, with vacuum pressure application, embankments can be constructed more speedily. (Chu et al. 2000, Chai et al. 2005, Indraratna et al. 2005b, 2013).

A comparison between the traditional fill loading and the combination of fill load and vacuum pressure was carried out by Indraratna et al. (2013). To show the effectiveness of the two methods, they used degree of consolidation based on pore pressure and strain. It was shown that the back-calculated coefficients of radial consolidation obtained from the vacuum-assisted consolidation are higher than those from fill loading application alone. Also, they showed that for a given total applied load, the coefficients of radial consolidation increase with the vacuum–fill surcharge ratio. Kianfar et al (2013) established a nonlinear flow relationship during radial consolidation. The proposed relationship could predict the settlement and excess pore water pressure dissipation quite well.

It should be noted that the operation costs of vacuum pumps can be uneconomical if the consolidation time becomes excessive. Currently there is no criterion to determine the best time to remove the vacuum pressure. It has been demonstrated that the vacuum assisted consolidation can provide much higher rate of excess pore water dissipation, especially during the early stages of consolidation while reducing the lateral displacement of the soil. Therefore, the embankment can be constructed much faster without affecting the embankment stability. This helps in switching off the vacuum pumps earlier than waiting for the primary consolidation to be fully completed.

Although numerous studies have been conducted in relation to application of vacuum pressure for soft soil consolidation, the effects of early removal of vacuum or fill loading on axial strains and excess pore pressure are not yet addressed in detail, which is the main objective of this paper.

2 EXPERIMENTAL PROGRAMME

A modified 150 mm diameter Rowe cell was used to study the effects of the application and removal of fill and vacuum pressures on the radial consolidation (Figure 1). Rigid impermeable discs were used at the base and top of the sample to allow only radial consolidation. The pore-water pressure was measured
at four locations at different radii. The drainage and the application of vacuum pressure was carried out through a central hole at the top plate. Surface settlement was measured at the centre of the top plate.

Figure 1. Modified 150mm Rowe cell

Kaolin was used as soil sample with a moisture content of at least 1.5 times its liquid limit (water content = 88%). Its properties are provided in Table 1. A preconsolidation pressure of 30 kPa was applied to the slurry placed in the cell to simulate typical in situ stress. Skempton’s B parameter of at least 0.99 was obtained to ensure the sample was saturated.

Table 1. Properties of kaolin

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Index Properties:</strong></td>
<td></td>
</tr>
<tr>
<td>Liquid Limit (%)</td>
<td>55</td>
</tr>
<tr>
<td>Plastic Limit (%)</td>
<td>27</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>2.7</td>
</tr>
<tr>
<td>Percent Sand (%)</td>
<td>12</td>
</tr>
<tr>
<td>Percent Silt Size (%)</td>
<td>26</td>
</tr>
<tr>
<td>Percent Clay Size (%)</td>
<td>62</td>
</tr>
<tr>
<td><strong>Engineering Properties:</strong></td>
<td></td>
</tr>
<tr>
<td>Slope of consolidation line, λ</td>
<td>0.17</td>
</tr>
<tr>
<td>Slope of swelling line, κ, in v-lnp’ plot</td>
<td>0.03</td>
</tr>
<tr>
<td>Specific volume at p’ = 1 kPa on the 1D consolidation line (Nₐ)</td>
<td>2.85</td>
</tr>
<tr>
<td>Angle of internal friction (φ’)</td>
<td>27°</td>
</tr>
<tr>
<td>Slope of critical state line in q – p’ plot</td>
<td>1.07</td>
</tr>
</tbody>
</table>

Following completion of preconsolidation, the preconsolidation pressure was removed and a 14.5 mm in diameter central vertical sand drain was installed in a pre-bored hole. This was followed by reapplication of the 30 kPa preconsolidation pressure. Fill pressure was applied on top of the sample and vacuum pressure was applied through the central drain. This method simulates the membrane-less system where a vacuum pump connects directly to the vertical drains (Indraratna et al. 2013). Application of additional fill pressure was carried out under undrained conditions for about 10 to 15 min to ensure the uniform distribution. Application of vacuum was carried out through the drainage rod to the vertical drain (Fig. 1) simultaneously when the drainage valve was opened. To simulate the groundwater table in field, the drain was connected to a stand-pipe piezometer filled with water. This would also allow a reverse movement of water from the drain to the soil and prevent air entry into the soil during the unloading stage.

Six different tests were conducted and the details are provided in Table 2. The sample diameter (D), vertical drain diameter (dᵥ), and n value for all of the tests were 151 mm, 14.5 mm, and 10.41, respectively. Where, n = D/dᵥ. The testing was carried out to achieve an additional effective stress of 70 kPa (over the 30 kPa preconsolidation pressure) by consolidation completion.

Table 2. Summary of tests

<table>
<thead>
<tr>
<th>Test No.</th>
<th>FP (kPa)</th>
<th>VP (kPa)</th>
<th>FP+VP</th>
<th>VSR</th>
<th>Time of fill or vacuum removal (hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>12</td>
</tr>
<tr>
<td>4</td>
<td>50</td>
<td>50</td>
<td>100</td>
<td>0.5</td>
<td>8</td>
</tr>
<tr>
<td>5</td>
<td>50</td>
<td>50</td>
<td>100</td>
<td>0.5</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>50</td>
<td>50</td>
<td>100</td>
<td>0.5</td>
<td>12</td>
</tr>
</tbody>
</table>

Where, FP = Fill Pressure, VP = Vacuum Pressure, and VSR = VP/(FP+VP)

Loading application was carried out in the following three different stages:

**Stage 1:**
For tests 1–3, a total of 100 kPa fill pressure was applied at the start of the tests.
For tests 4–6, a fill pressure of 50 kPa was applied simultaneously with a vacuum pressure of 50 kPa.

**Stage 2:**
For tests 1–3, half of the fill pressure (50 kPa) was removed after 8, 10, and 12 h, respectively.
For tests 4–6, the vacuum pressure was entirely removed after 8, 10, and 12 h, respectively.

**Stage 3:**
The remaining fill (50 kPa) for all of the tests was removed after 72 h.

3 EXCESS POKE WATER PRESSURE RESPONSES

Equation 1 provides a normalised radial distance (RR) from the centre of the cell:

\[ RR = (r - r_w)/(R - r_w) \]  \hspace{1cm} (1)

where, \( r \) = radius from the centre, \( r_w \) = radius of the vertical drain, and \( R \) = radius of the cell.

The pore-water pressures were measured at \( RR = 0.0, 0.19, 0.48, \) and 0.77. Figure 2 shows the
distributions of excess pore water pressure at different radii for tests 1–3. It shows three distinct excess pore pressure responses during the application and removal of the applied fill (surcharge) simulating the fill placement and removal in the field: (1) when the fill load was initially applied, (2) when half of the fill (surcharge) load was removed, (3) when the second half of the fill load was removed.

![Graph showing excess pore water pressure distribution with time at different radii](image)

Figure 2. Excess pore water pressure distribution with time at different radii:
(a) Test 1 - removal of 50 kPa fill pressure after 8.0 hours
(b) Test 2 - removal of 50 kPa fill pressure after 10.0 hours
(c) Test 3 - removal of 50 kPa fill pressure after 12.0 hours

By application of the fill load, at $RR = 0.77$, the excess pore-water pressure first increased more than the applied load. However, it decreased at the locations closer to the drain. This phenomenon can be attributed to the rigid boundary contributing to the Mandrel-Cryer effect. When the Mandrel-Cryer effect diminishes (after about 0.5 hour), all excess pore-water pressure curves show a similar trend. Upon the removal of the first half of the fill load, an immediate drop in excess pore-water varying with radial distance from the drain could be seen (Fig. 2). The excess pore-water pressures following removal of the first half of the fill load did not decrease to negative values for all three tests. Test 1 showed the highest where the consolidation time was shorter.

After about 72 hours, when the excess pore-water pressures completely dissipated, the remaining 50 kPa fill load was also removed (Fig. 2). This resulted negative (suction) pore-water pressures which took at least 15 hours to return to zero. The negative pore-water pressures were resulted due to the tendency of the soil to expand. As expected, negative excess pore pressures quicker returned to zero at the measuring points closer to the drain.

Figure 3 presents the excess pore water pressure plots for the vacuum assisted tests (tests 4–6). For these tests, the initial excess pore-water pressure responses were less than those obtained from tests 1 to 3 due to the effects of the vacuum. Unlike removal of fill pressure, the excess pore-water pressures in the soil specimens increased by the removal of the vacuum pressure (Fig. 3). Prior to the vacuum removal, the excess pore-water pressures were negative at $RR = 0.19$ and positive at other measurement points in tests 4 and 5. While they were negative at all measuring points in test 6.

![Graph showing excess pore water pressure distribution with time at different radii](image)

Figure 3. Excess pore water pressure distribution with time at different radii:
(a) Test 4 - removal of 50 kPa vacuum after 8.0 hours
(b) Test 5 - removal of 50 kPa vacuum after 10.0 hours
(c) Test 6 - removal of 50 kPa vacuum after 12.0 hours
A comparison of the average excess pore-water pressures between the tests conducted with fill load alone and the tests conducted with a fill-vacuum combination is presented in Figure 4. As expected, the initial excess pore pressures obtained from the tests with fill loading alone were higher than those with the combination of vacuum and fill pressure. Excess pore-water pressure dissipation rates for the vacuum assisted tests were higher than others. Noting that due to the scale of the graphs, the differences are less visible for cases b and c.

Figure 4 indicates that if the desired effective stress of soil following improvement is 80 kPa (in situ pressure plus preloading pressure), then the optimum removal time could be at about 12 hours (test 6), where the average excess pore pressures were negative. The delay in the removal of the fill load has less effect on excess pore-water pressure responses, while the extended period of vacuum removal imparts a greater influence on the change in excess pore-water pressure.

4 CONSOLIDATION SETTLEMENT RESPONSES

The axial strains for all of the tests are presented in Figure 5. The vacuum assisted tests (tests 4–6) produce a higher axial strain rate for a given time than the tests conducted with application of fill load alone (tests 1–3). After the removal of the last portion of the applied load, samples swelled with the negative excess pore-water pressure shown in Figure 4. For test No. 6, settlement ceased following removal of vacuum at 12 hours. This also is in accordance with the observation of no excess pore pressure dissipation shown in Figure 4.

![Figure 4](image1.png)

Figure 4. Average excess pore-water pressures:
(a) surcharge/vacuum removal after 8 hours
(b) surcharge/vacuum removal after 10 hours
(c) surcharge/vacuum removal after 12 hours

![Figure 5](image2.png)

Figure 5. Axial strain for:
(a) removal of surcharge/vacuum after 8 hours
(b) removal of surcharge/vacuum after 10 hours
(c) removal of surcharge/vacuum after 12 hours
5 AVERAGE OVERCONSOLIDATION RATIO

The increase in the average effective stresses is a good indication of the effectiveness of the vacuum assisted consolidation compared to application of fill load alone. Figure 6 shows the average increase in effective stresses prior and following removal of fill-vacuum loads. It shows that the gain in average effective stress before removing the vacuum is on average about 23% greater than that for tests conducted using fill pressure alone. This difference increased to an average of about 39% following removal of the external loads. This clearly shows the advantage of using vacuum pressure over conventional fill surcharge alone, especially when embankment stability is crucial.

![Graph showing OCR versus surcharge/vacuum removal time.](image)

Figure 6. Decrease of average effective stress following removal of surcharge/vacuum.

Preconsolidation pressure ($p'_c$) at the end of each test can be estimated by adding the initial effective stress ($p'_0 = 30$ kPa) to the dissipated excess pore-water pressure. Figure 7 shows the associated overconsolidation ratio (OCR) versus the removal time of the fill or vacuum pressure. This figure shows that vacuum assisted consolidation provides OCR than using fill pressure alone. This is consistent with the observed excess pore pressures and strains. The increase in OCR depends on the removal time for both cases. It is shown that OCR can be used as an indicator to compare the performance of both systems.

![Graph showing OCR versus time.](image)

Figure 7. OCR versus surcharge/vacuum removal time.

6 CONCLUSION

Six consolidation tests were conducted using a modified Rowe consolidation cell that could measure pore pressures at four different radii and axial settlement. Kaolin specimens were used to perform consolidation tests under application of fill load alone or combination of vacuum and fill pressure. Fill pressure (partially) or vacuum was removed at different times.

For a given total applied load, the initial excess pore pressures due to the application of fill pressure alone were higher than those with the combination of vacuum and fill pressure. Excess pore pressure dissipation rates were higher for the vacuum assisted tests.

Upon removal of fill surcharge partially, the decrease in excess pore-water pressure was immediate and the excess pore-water pressures continued to dissipate to zero afterwards. While, removal of vacuum pressure resulted a sudden increase in the excess pore-water pressure. Noting that, if the excess pore pressure was negative prior to vacuum removal, it increased to zero (hydrostatic) and remained constant at zero with no further settlement thereafter.

Application of combined vacuum-fill pressure results higher OCR than using fill load alone. The gain in average effective stress before removing the external loads (fill or vacuum) was on average about 23% greater than that for tests conducted using fill pressure alone. This clearly shows the advantage of using vacuum pressure over conventional fill surcharge alone, especially when embankment stability is crucial.
REFERENCES


