Analysis on the mechanism of ground settlement induced by vacuum removal

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ABSTRACT

Due to the settlement hazards induced by the soft ground, vacuum preloading has been widely used all over the world. Many studies focus on the process of vacuum application but the process of vacuum removal is generally ignored. Different from observations on surcharge preloading, ground settlement rather than heave occurred during vacuum removal. In this study, a stress-controlled triaxial test was carried out to simulate both processes of vacuum application and removal applied on a soft ground and hence the mechanism of ground settlement induced by vacuum removal is discussed. Compressive axial strain was observed during the decrease of isotropic stress that simulated vacuum removal. To better understand the observed deformation characteristics of the soft ground during vacuum removal, a simple anisotropic elastic model was used in this study. The occurrence of ground settlement of the soft soil during vacuum removal is mainly because that the Young’s modulus in the horizontal direction is lower than that in the vertical direction. Lateral extension is dominant for the ground deformation during vacuum removal.

1. INTRODUCTION

Vacuum preloading is a geotechnical method that has been successfully used for soil improvement or land reclamation in a number of countries such as Australia, China, Korea, Thailand and France (Chai et al., 2005; Wang et al., 2016). Generally, this
method does not necessarily require surcharge fill, whereas the soft ground is sealed from the atmosphere by using a geomembrane. Under the geomembrane the vacuum pressure could reach about 80 kPa by means of vacuum pumps. As discussed by Holtz (1975), when applying the vacuum pressure, the effective stress is increased and thus the improvement of soil is achieved. Different from the conventional improvement method (i.e., surcharge preloading method), the excess positive pore-water pressure will not build up in the vacuum preloading method and thus its failure during the improvement period can be minimized. Due to the quick increase in the vacuum pressure, the duration of vacuum preloading method is relatively short, saving cost as high as 30% (Bergado et al. 2002; Indraratna et al. 2004).

For simplify, an ideal 1-D model was usually employed to understand the deformation mechanism of soft soil subjected to vacuum and surcharge loadings. The increase in vertical effective stress at the end of consolidation should be equal to the surcharge pressure in surcharge preloading method and to the vacuum pressure in vacuum preloading method. If the magnitudes of surcharge and vacuum pressure are the same, the induced vertical effective stresses should be the same and so are the vertical settlements. To verify the effectiveness of these two methods, Chai et al. (2005) compared the vertical deformations by applying the surcharge and vacuum pressures with the same magnitude. However, it was found that the settlement induced by the vacuum application was obviously smaller than that by the surface surcharge loading. Similar findings were also observed by Chu and Yan (2012) and Robinson et al. (2012). A possible reason was due to the different lateral effective stress conditions induced by the surcharge and vacuum preloading. As pointed out by Robinson et al. (2012), the induced effective stress changes were anisotropic for surcharge preloading, but almost isotropic for vacuum preloading. In other words, the lateral compression deformation produced by the vacuum preloading was larger than that by the surcharge preloading. The lateral compression may cause the soft soil mass swell vertically due to Poisson’s effect, which counters the settlement induced by the increase of vertical effective stress. Most of investigations on vacuum preloading focus on the deformation characteristics of ground during the process of vacuum application. However, the deformation characteristics of ground during the process of vacuum removal are generally ignored and ground heave should occur since vertical effective stress is decreased by vacuum removal. For the fill surcharge preloading method, ground heave was observed during the surcharge unloading as expected (Noble 2011; Samson and Rochelle 2011). Similar ground heave was also found during vacuum removal by Wu et al. (2016). However, some measured data presented by Indraratna et al. (2004) and Kianfar et al. (2015) show that ground settlement rather than heave occurred during the vacuum removal. According to the measured results from Indraratna et al. (2004), when the vacuum pressure decreased from 80 to 0 kPa, the settlement increased from 20.1 to 21.5 mm, as shown in Figure 1. This observation indicates that the deformation characteristics of ground during the vacuum removal is not yet clear and further investigation on the underlying mechanism is required.

In this study, a stress-controlled triaxial apparatus was applied to simulate the change of effective stress state during the vacuum removal on a specimen. The corresponding axial and radial strains were measured and analysed to investigate deformation characteristics of soft ground during the vacuum removal and the
underlying mechanism.

Fig. 1 Vacuum pressure and surface settlement associated with vacuum loading and removal

2. STRESS-CONTROLLED TRIAXIAL TEST

2.1 Testing equipment

A computer-controlled triaxial stress-path testing system was set up for testing the soft soil as shown in Figure 2. This system is equipped with three digital hydraulic pressure/volume controllers to control the axial effective stress, confining pressure and back pressure.

Volume of water flowing in/out of a specimen is measured using the digital hydraulic pressure/volume controller for back pressure with an accuracy of 1 mm\(^3\). Due to the soft soil sample is saturated and thus the volume change of water is equal to the volume change of the soft soil sample. Another, the axial deformation of the soft soil sample was measured by a linear variable differential transformer (LVDT) with an accuracy of 0.5 mm.

The test in this study is conducted in a room with a temperature of 20 ± 1 °C to decrease the effect of daily temperature fluctuation on test results.

2.2 Material

The samples were analyzed for particle size distribution (ASTM D422-63 2007) and Atterberg limits (ASTM D4318-17 2017). The physical properties of the soft soil used in the test are summarized in Table 1. The dry density (\(\rho_d\)) of the soft soil is 1.24 Mg/m\(^3\), whereas its void ratio is 1.19. The contents of gravel, sand, silt and clay are 0%, 2.1%, 53.4% and 44.5% respectively. According to ASTM D2487-11 (2011), this soil is described as lean clay (CL).
Figure 2 a) Schematic diagram and b) picture of a computer-controlled triaxial system for simulating vacuum removal

2.3 Test program and procedures

A stress-controlled drained triaxial test was carried out to simulate stress path during vacuum application and removal. The changes of axial effective stress (i.e., $\sigma'_a$) and radial effective stress (i.e., $\sigma'_r$) during testing are shown in Figure 3. First, the soft soil specimen was set up in a triaxial apparatus and consolidated under a confining pressure of 50 kPa (i.e., $\sigma'_a = \sigma'_r = 50$ kPa). $\sigma'_a$ was then increased to 100 kPa (i.e. from O to A) by assuming that the coefficient of earth pressure at rest (i.e., $K_0$) equaled 0.5. Subsequently, both $\sigma'_r$ and $\sigma'_a$ were increased simultaneously by 80 kPa (from A to B) to simulate the vacuum pressure by assuming the efficiency of the vacuum transfer is good. In other words, $\sigma'_a$ was increased from 100 kPa to 180 kPa, whereas $\sigma'_r$ was
increased from 50 kPa to 130 kPa. Finally, in order to simulate the vacuum removal, \( \sigma'_r \) and \( \sigma'_a \) were decreased to 100 kPa and 50 kPa (from B to C), respectively. During the test procedure, the water in the digital hydraulic pressure/volume controller can flowed into or out of the soft soil sample and the volume change of the water was recorded. Due to the saturation, the volume change of soil sample was equal to that of water.

**Figure 3** Stress paths in the stress-controlled test for simulating vacuum loading and removal

### 3. RESULTS

The deformation of the soft soil sample was depended on the combination of axial effective stress and confining effective pressure. Under these complex loading conditions, spherical and deviatoric components (Schofield and Wroth 1968) in the changes of effective stress and deformation were chosen to understand the mechanical behaviour of soil.

The spherical pressure is written as

\[
p' = \frac{\sigma'_a + 2\sigma'_r}{3}
\]  

(1)

where \( \sigma'_a \) is axial effective stress and \( \sigma'_r \) is confining pressure. The axial-deviator effective stress is written as

\[
q = \sigma_a - \sigma_r
\]  

(2)

The corresponding strain parameters are volumetric strain for the spherical pressure and axial-distortion strain for the axial-deviator effective stress, respectively. The volumetric strain is written as

\[
\varepsilon_p = -\frac{\Delta v}{v}
\]  

(3)

where \( \varepsilon_p \) is the volumetric strain-increment, \( \Delta v \) is the volume-increment during the test and \( v \) is the volume of soil sample. The axial-distortion strain increment is defined
### Eq. (4) and (6) give

\[ \varepsilon_q = \frac{2}{3} (\varepsilon_a - \varepsilon_r) \]  

\[ \varepsilon_q = \frac{\varepsilon_p - \varepsilon_a}{2} \]  

\[ \varepsilon_q = \frac{3\varepsilon_a - \varepsilon_p}{3} \]  

According to the theory of plasticity (Chakrabarty and Drugan 2006), \( \varepsilon_p \) and \( p' \) are related by bulk modulus, while \( \varepsilon_q \) and \( q \) are related to each other through shear modulus in the elastic region. The bulk and shear modulus are constant. When the soft soil was in the plastic region, they are a function of strain and vary during the process of deformation. In the subsequent chapters, the relationships between \( \varepsilon_p \) and \( p' \), \( \varepsilon_q \) and \( q \) are analysed.

**Figure 4** Relationship between \( \varepsilon_p \) and \( p' \) during vacuum loading and removal

#### 3.1 Relationship between \( \varepsilon_p \) and \( p' \)

**Figure 4** shows the relationship between \( \varepsilon_p \) and \( p' \) during the test. Before the vacuum loading (Path O-A), the initial state of the soft soil sample was isotropic stress state, whereas it changed to anisotropic stress state with \( K_0 \) of 0.5 at the point A. Correspondingly, \( p' \) increased from 50 to 66.6 kPa, whereas \( \varepsilon_p \) first increased from 0 to 3.2% with a high slope of 19.7 MPa\(^{-1}\) and then increased linearly to 7.1% with a low slope of 2.6 MPa\(^{-1}\). The change of the slope of the curve may be due to the recent
stress history (Atkinson et al. 1990). During the vacuum application, as p increased to 146.6 kPa, \( \varepsilon_p \) increased to 13.0% and its slope was 0.7 MPa\(^{-1}\), only about 25% of that in Path O-A. It indicates that the bulk modulus during vacuum application was larger than that before vacuum application. The increase in bulk modulus during vacuum application may be due to the change of stress state. An opposite process (Path B-C) was carried out after the vacuum application. An excepted decrease in \( \varepsilon_p \) was observed when \( p' \) was decreased to 66.6 kPa again. The slope of the curve in Path B-C was 0.045 MPa\(^{-1}\) only 6% of that in Path A-B, indicating that the swelling (the decrease in \( \varepsilon_p \)) of the soft soil sample caused by the vacuum removal was small. In other words, the elastic volumetric strain among the vacuum application was small compared with the plastic volumetric strain. The large plastic volumetric strain may be due to the large compaction of soft soil.

3.2 Relationship between \( q \) and \( \varepsilon_q \)

The relationship between \( q \) and \( \varepsilon_q \) during vacuum loading and removal was shown in Figure 5. As expected, as \( q \) increased from 0 to 50 kPa, \( \varepsilon_q \) increased nonlinearly from 0 to 3.2%. It indicates that the plastic axial-distortion strain occurred at the beginning. Subsequently, \( q \) maintained 50 kPa during the vacuum application and removal (Path A-B-C). However, \( \varepsilon_q \) increased to 5.9% after the vacuum application, whereas it increased 1.8% during the vacuum removal, about only 60% of that during the vacuum application. The difference of \( \varepsilon_q \) caused by the vacuum application and removal was due to the change of stress condition. It should be noted that almost vertical line was observed in Path A-B-C, indicating that the axial-distortion strains caused by the vacuum application and removal were irrelevant to \( q \). It is difficult to understand the change of the axial-distortion strain just based \( p \) and \( q \) parameters.

Figure 5 Relationship between \( q \) and \( \varepsilon_q \) during vacuum loading and removal
4. CHANGES OF RADIAL AND AXIAL STRAINS

During the process of vacuum application (path A-B), when $\sigma'_a$ was increased from 100 kPa to 180 kPa, the axial strain ($\varepsilon_a$) increased from 5.6% to 10.4%, as shown in Figure 6. Correspondingly, $\sigma'_r$ increased from 50 kPa to 130 kPa, whereas $\varepsilon_r$ increased from 0.7% to 1.3%, as shown in Figure 7. An opposite process (B-C) was carried out after the vacuum application. $\sigma'_a$ was decreased from 180 kPa to 100 kPa, whereas $\varepsilon_a$ increased only from 10.4% to 11.9%. Vertical compression rather than swelling occurred during the vacuum removal. Such observations were consistent with the field monitoring by Indraratna et al. (2004). In addition, the radial strain ($\varepsilon_r$) decreased from 1.3% to 0.4% during the process of vacuum removal. The decrease in $\varepsilon_r$ indicates lateral extension which may cause the vertical compression.

Figure 6 Relationship between $\sigma'_a$ and $\varepsilon_a$ during vacuum loading and removal

Figure 7 Relationship between $\sigma'_r$ and $\varepsilon_r$ during vacuum loading and removal
5. SIMPLIFIED MODEL ON GROUND SETTLEMENT INDUCED BY VACUUM REMOVAL

Based on the measured results, the vacuum removal can be generally regarded as an elastic unloading process and hence the following cross-anisotropic elastic model (Muir 2004) is used to further analyse deformation characteristics of soils under vacuum removal:

\[
\frac{\delta \varepsilon_a}{\delta \varepsilon_r} = \left[ \frac{1/E_v}{-\nu_{vh}/E_v (1-\nu_{hh})/E_h} \right] \frac{\delta \sigma'_a}{\delta \sigma'_r}
\]

where \( E_v \) and \( E_v \) are Young’s modulus for unconfined compression in the vertical and horizontal directions respectively; Poisson’s ratios \( \nu_{hh} \) and \( \nu_{vh} \) relate to the lateral strains that occur in the horizontal direction orthogonal to a horizontal direction of compression and a vertical direction of compression respectively. In the following analysis, the anisotropy of Poisson’s ratio is not considered for simplification. Thus, \( \nu_{hh} \) and \( \nu_{vh} \) are assumed be the same and Eq (8) can be simplified as follows:

\[
\frac{\delta \varepsilon_a}{\delta \varepsilon_r} = \left( \frac{1/E_v}{-\nu/E_v (1-\nu)}/E_h \right) \frac{\delta \sigma'_a}{\delta \sigma'_r}
\]

where \( \nu \) is Poisson’s ratio. According to the first Equation in Eq (9), \( \delta \varepsilon_a \) can be decomposed into two components. The first component, \( \frac{\delta \sigma'_a}{E_v} \), corresponds to vertical unloading, which causes vertical heave (\( \delta \sigma'_a \) is negative value during the vacuum removal). The second one, \( -2\nu \frac{\delta \sigma'_r}{E_h} \), is related to lateral extension, which causes vertical settlement due to Poisson’s effect (\( \delta \sigma'_r \) is also negative value during the vacuum removal). For the process of vacuum removal, the decreases in \( \sigma'_r \) equals to that in \( \sigma'_a \). Therefore, \( \delta \varepsilon_a \) can be calculated by

\[
\delta \varepsilon_a = \frac{\delta \sigma}{E_v} (1 - \frac{2\nu}{E_h/E_v})
\]

where \( \delta \sigma' \) is the increase in effective stress (\( \sigma'_r \) or \( \sigma'_a \)). During the process of vacuum removal, \( \delta \sigma' \) is smaller than 0. Based on Eq (10), when \( E_h/E_v \) is smaller than 2\( \nu \), the effect of lateral extension on ground deformation will be dominant and hence ground settlement occurs.

The Poisson’s ratio of soil is typically equal to about 0.3 (Su et al. 2013; Noorzad and Manavirad 2014). Based on the stress-strain curve from O to A, \( E_v \) is determined as 1.79 MPa. The calculated axial strain using different values of \( E_h/E_v \) (i.e., 0.2, 0.45, 0.5, 0.8 and 1.1) during the vacuum removal is ill illustrated in Figure 8. For comparison, the measurement data from the stress-controlled triaxial test is also added in the figure. When \( E_h/E_v = 0.45 \), the measurement data are well captured by the anisotropic elastic model. The lower horizontal Young’s modulus is perhaps caused by the stress-induced anisotropy (Pennington et al. 1997; Lings et al. 2000). In other words, the higher vertical effective stress in the soft soil during K_0 consolidation results in a higher vertical Young’s modulus. From the above analysis, it indicates that the ground settlement induced by vacuum removal can be well explained by considering the anisotropy in Young’s modulus (Jing et al. 2017).
Figure 8 Comparison of $\varepsilon_a$ between measured and calculated results during vacuum removal

6. CONCLUSIONS

In this study, a stress-controlled triaxial test was carried out to simulate the process of vacuum application and removal applied on a soft ground and hence the mechanism of ground settlement induced by vacuum removal is discussed. The following conclusions may be drawn:

1. Ground settlement during vacuum removal can be captured by the triaxial test, in which compressive axial strain was measured during the decrease of isotropic stress.

2. Ground settlement during vacuum removal is mainly due to the anisotropy in Young’s modulus and hence the role of lateral extension is dominant for the ground deformation during vacuum removal.

3. A simplified cross-anisotropic elastic model could be used to assess the deformation behavior of soil during vacuum removal.

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References


