Lateral displacement of unsaturated clay slurry subjected to vacuum consolidation

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ABSTRACT

Vacuum consolidation is a soft ground improvement method. The vacuum consolidation of soil above the groundwater level (unsaturated soil) has not been sufficiently examined in earlier studies. Thus, in this study, vacuum consolidation tests were conducted for unsaturated clay slurry with degree of saturation $S_r \approx 80\%$. During the tests, air bubbles on the sides of the specimens were recorded, and the water content and diameters were measured at the end of the tests. Surcharge consolidation and vacuum consolidation tests of saturated clay slurry were also conducted. The main conclusions are as follows: Surcharge consolidation of unsaturated clay slurry is one-dimensional. Although the settlement curves and water content distribution curves of unsaturated clay slurry under vacuum consolidation and surcharge consolidation are almost identical, lateral shrinkage is observed and the deformation is three-dimensional.

Keywords: unsaturated soil, vacuum consolidation, consolidation test, degree of saturation, lateral displacement

1 INTRODUCTION

Vacuum consolidation—a soft ground improvement method—was originally developed by Kjellman (1952) as a preloading method. As shown in Fig. 1, prefabricated vertical drains (PVDs) are installed in the soft ground and their top end connected to vacuum pumps by horizontal drains instead of a sand mat (Umezaki et al. 1999). The ground surface of the target area is covered by an airtight sheet. Another method, without using an airtight sheet has also been proposed (Takano et al. 1988). By reducing the pore water pressure in the target area, ground settlement is accelerated. Figure 2 shows the variation in pressure in the ground during vacuum consolidation. When vacuum pressure is applied in both cases: with and without using an airtight sheet, the hydraulic pressure in PVD decreases uniformly, while the total stress remains constant. The maximum vacuum pressure achieved at the ground surface is approximately $-78.4$ kPa (Umezaki et al. 1999), and the hydraulic pressure in the PVD is zero at approximately 8 m depth. The hydraulic pressure above this point is negative, whereas that below is positive. Furthermore, the effective stress in the ground increases as the hydraulic pressure decreases. This causes significant inward lateral ground displacement near the ground surface and cracking on the surface around the target area, as shown in Fig. 3.

Umezaki et al. (2002) and Taki et al. (2005) reported about ground deformation and variation of stress conditions during vacuum consolidation. Figure 3

![Fig. 1. Vacuum consolidation method with an airtight sheet.](image1)

![Fig. 2. Pressure variation in the vacuum consolidation method.](image2)
shows deformation of saturated ground due to vacuum consolidation. It can be classified into two as follows.

(A) Laterally deformed condition: The ground deformation near the surface at the edge of the target area is attributed to isotropic consolidation

(B) Laterally confined condition: The deformations at the centre of the target area independent of depth and in the deep regions at the edge of the target area are attributed to one-dimensional consolidation.

Imai (2005) also reported a similar evaluation about ground deformation and stress conditions during vacuum consolidation. Umezaki et al. (2002) performed many vacuum consolidation tests of saturated clay. They showed that similar to surcharge consolidation, vacuum consolidation under laterally confined conditions is one-dimensional. However, the vacuum consolidation of soil above the groundwater level (unsaturated soil) has not been sufficiently examined in earlier studies.

In this study, vacuum consolidation tests were conducted using unsaturated clay slurry with degree of saturation $S_r \approx 80\%$ to simulate the central region right above underground water surface of the target area. During the tests, air bubbles on the sides of the specimens were recorded, and the water content and diameters were measured at the end of the tests. Surcharge consolidation and consolidation tests for saturated clay slurry were also conducted.

2 COLUMN CONSOLIDATION TEST

The soil sample was Ube Port Clay dredged at Ube City in Japan. Its physical properties are listed in Table 1, and the particle size distribution is shown Fig. 4. Unsaturated soil samples with initial water content of $w_0 \approx w_L$ were used. These were prepared by stirring with a rotary beater to facilitate aeration so as to maintain the unsaturated condition of the slurry. Saturated slurry samples were prepared by mixing slurry samples with initial water content of $w_0 \approx 2 \times w_L$ and then decompressed for 12 h at vacuum pressure $p_v = -92$ kPa to remove the air bubbles. At this pressure, no significant change in water content occurs (Umezaki and Kawamura, 2013).

The outline of the column consolidation test is shown in Fig. 5, and the conditions are listed in Table 2, where $S_o$ is the initial degree of saturation, $h_0$ is the initial height and $m_0$ is the initial mass. A rigid clear acrylic cylinder with an inner diameter of 74.8 mm was used to simulate the laterally confined conditions in Fig. 3. Specimens were prepared by pouring the slurry samples into the column to height $h_0$ and then carefully levelling them. The initial conditions of the specimens
are shown in Table 2. In the case of saturated slurry, in order to remove the air bubbles that formed while pouring, a second decompression stage was performed for 3 h. A filter paper and loading plate were placed on the levelled surface. Pure water was then poured over the loading plate, as shown in Fig. 5, to ensure an airtight environment. To enhance contact between the specimen and the loading plate, air pressure (10 kPa) was applied for 10 min. The specimen was then consolidated by applying a fixed consolidation pressure with drainage at the top of the specimen (single drainage). The consolidation time was determined using the 3-t method. In the case of vacuum consolidation, the top end of the column was open to the atmosphere, and a vacuum pump applying vacuum pressure \( p_v = -78.7 \) kPa was connected to the specimen through a water trap. In the case of surcharge consolidation, the water trap was open to the atmosphere and an air compressor applying air pressure of \( p = 78.4 \) kPa was connected to the column. In both tests, the self-weight of the loading plate and shaft were cancelled out by adding counterweight, as shown in Fig. 5.

During the tests, the vertical displacement of the specimen was measured, and the drainage volume was calculated by the change in mass of the water trap. A clear sheet was wrapped around the column at fixed intervals for recording air bubbles on the sides of the specimens. After the test, the specimens were pushed out of the column and sliced at 2 cm intervals along their height using a wire saw. Photographs of cross-sectional views were taken, and the mass, diameter and water content, measured.

### 3 TEST RESULTS AND DISCUSSIONS

Figure 6 shows the relation between axial strain \( \varepsilon_a \) and elapsed time \( t \). Figure 7 shows the relation between volumetric strain \( \varepsilon_v \) calculated from the drainage volume and axial strain \( \varepsilon_a \). The graph shows the test results for saturated clay (SS and VS tests). Due to the formation of air bubbles in the drainage tube during vacuum consolidation, the volumetric strain cannot be calculated accurately in the case of unsaturated clay slurry. Figure 8 shows the relation between \( h/h_1 \) and \( \varepsilon_a \), \( h/h_1 \) and \( w_1 \) and \( h/h_1 \) and \( S_{r1} \) at the end of the test. Where, \( h \) is the measured height, and \( h_1, \varepsilon_a, w_1 \) and \( S_{r1} \) are the specimen height, lateral strain, water content and degree of saturation, respectively. In Fig. 8, the value of \( \varepsilon_a \) was calculated from the change in the diameter of the specimen measured using a slide gauge. The value of \( S_{r1} \) was also calculated from the mass, volume and water content of the specimen.

In the case of saturated clay slurry, both vacuum consolidation (VS test) and surcharge consolidation (SS test) have almost identical settlement–time curves, as shown in Fig. 6, as well as water content distribution curves, as shown in Fig. 8(b). Moreover, \( \varepsilon_a \) is almost equal to \( \varepsilon_c \), as shown in Fig. 7. Furthermore, the values of \( \varepsilon_c \) in the saturated clay slurry measured at the end of both consolidation tests (SS and VS) are approximately zero, as shown in Fig. 8(a). Thus, the consolidation behaviour in both cases is identical and one-dimensional. These results differ from the laboratory odometer tests performed on saturated clay by Chai et al. (2005) who reported that the behaviour of vacuum and surcharge consolidation is different.

In the surcharge consolidation of the unsaturated clay slurry (SU test), as shown in Fig. 8(a), the values
of \( \varepsilon_r \) are approximately zero, and the consolidation behaviour is one-dimensional, similar to the saturated clay slurry. However, in the vacuum consolidation of the unsaturated clay slurry (VU test), as shown in Fig. 8(a), the values of \( \varepsilon_r \) are 0.5%–1.5%. Thus, lateral shrinkage occurs, the deformation is three-dimensional and the consolidation behaviour is different from the other three cases.

Figure 9 shows scanned images of air bubbles on the sides of the specimens. Due to the flange at the bottom of the apparatus, approximately 2.5 cm of the specimens were hidden, and therefore the air bubbles could not be recorded. Using the scanned images, the ratio of the air bubbles area to the lateral area on the sides of the specimens was calculated by image analysis, as shown in Fig. 10. In the case of the saturated clay slurry, as shown in Figs. 9(a) and 9(b), the air bubbles could not be seen on the side of the specimens in both the SS and VS tests. As shown in Fig. 8(c), although \( S_{r1} \) decreases slightly at the top and bottom of the specimen, the degree of saturation \( S_{r1} \) is virtually constant. However, in the initial conditions of the vacuum and surcharge consolidation of the unsaturated clay slurry (SU and VU tests), as shown in Figs. 9(c), 9(d) and 10, the air bubbles are uniformly
distributed with an air bubble–lateral area ratio of 0.8%–1.3%. As consolidation progressed, although the air bubbles increases more during the VU test, the air bubble–lateral area ratio reaches approximately 20% after about 1 day ($t = 1500$ min) and 35% at the end of the test ($t = 10080$ min). For the SU test, even with the minimal lateral strain as shown in Fig. 8(c), the air bubble–lateral area ratio increased to 4% after about 1 day ($t = 1500$ min) and 15% at the end of test ($t = 8640$ min). The air bubbles were pressed against the specimen side and spread slightly.

Fig. 11 shows the air bubbles on the side and cross-sectional views of the specimens after the test. In the SS and VS test, as shown in Figs. 11(a) and 11(b), air bubbles could not be seen in cross-sectional views of the specimens similar to the sides of the specimens, as shown in Figs. 9(a) and 9(b). In the SU and VU tests, the air bubbles remained inside the specimens. In the SU test shown in Fig. 11(c), although there are large air bubbles locally, the ratio of air bubble-area is lower than that in the VU test in Fig. 11(d). From the $S_{d}$ distribution curve in the SU test shown in Fig. 8(c), the degree of saturation for the entire specimen uniformly increases by about 6% to approximately 92%. The air bubbles in the specimens are assumed to be compressed due to the confining pressure. In the VU test, as shown in Fig. 8(c), the degree of saturation on the upper side increases from 7%–10% to over 95%. The same tendency can be seen in Fig. 11(b) where the air bubbles are fewer at the upper side of the specimen.

At the shallow centre part of the target area, lateral displacement in the case of saturated ground hardly occurs and the consolidation behaviour is almost one-dimensional. However, in the case of unsaturated ground, lateral deformation occurs and the deformation is three-dimensional.

4 CONCLUSIONS

The main conclusions are as follows.

(1) In the case of saturated clay slurry, the settlement–time curves and water content distribution curves of the vacuum and surcharge consolidation tests are almost identical. In addition,
the axial strain is almost equal to the volumetric strain. The consolidation behaviours are almost identical and one-dimensional.

(2) In the case of unsaturated clay slurry, the surcharge consolidation is one-dimensional. Although the settlement curve and water content distribution of vacuum consolidation are almost equal to those of surcharge consolidation, lateral shrinkage occurs and the deformation is three-dimensional.

(3) In the case of vacuum consolidation of unsaturated clay slurry, the air bubbles on the sides of the specimens expand and increase as consolidation progresses. The bubbles gradually increase from the drainage side and spread through the specimens as cavities.

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