Evaluation of Consolidation Behavior of Soils under Radial Drainage Condition Using Digital Image Analysis

Évaluation du comportement de consolidation des sols sous des conditions de drainage radial à partir de l'analyse d'image numérique

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ABSTRACT: Most of the analytical solutions for consolidation under radial drainage are based on the assumption that only vertical compression occurs. During consolidation, however, soils deform not only vertically but also radially. The radial deformation during consolidation may induce additional excess pore pressure in a soil mass and unexpectedly cause differential settlement and produce stresses in structures founded on consolidating ground. A new consolidation apparatus, which enables the deformation of a specimen to be visually observed, and the total vertical stress as well as the pore water pressure to be measured, was developed. Consolidation tests for reconstituted kaolinite specimens were performed using the new consolidation apparatus under radial drainage, along with test under vertical drainage. Digital image analysis was adopted to analyze the consolidation deformation of the specimen. Radial deformations as well as vertical deformations during consolidation were monitored and compared for the two different drainage condition. Non-uniformities of the specimen induced during horizontal drainage were confirmed by measured total vertical stress.

RÉSUMÉ : La plupart des solutions analytiques pour la consolidation avec écoulement radial sont fondées sur l'hypothèse qu'il n'y a que des compressions verticales. Cependant, pendant la consolidation, les sols se déforment non seulement verticalement mais aussi radialement. La déformation radiale pendant la consolidation peut induire des surpressions interstitielles additionnelles dans le sol, pouvant entraîner des tassements différentiels imprévus ainsi que des contraintes au sein des structures fondées sur le sol en cours de consolidation. Un nouvel appareil de consolidation, qui permet d'observer visuellement la déformation d'une éprouvette et de mesurer la contrainte verticale totale appliquée ainsi que la pression interstitielle, a été développé. Des essais de consolidation ont été réalisés sur des éprouvettes de kaolinite reconstituées en utilisant le nouvel appareil de consolidation avec drainage radial, ainsi que des essais avec drainage vertical. La technique d'analyse d'image numérique a été adoptée pour analyser les déformations de consolidation de l'éprouvette. Les déformations radiales ainsi que les déformations verticales ont été mesurées et comparées pour les deux conditions de drainage. Les hétérogénéités de l'éprouvette induites par le drainage horizontal ont été confirmées par la mesure de la contrainte verticale totale.

KEYWORDS: consolidation, vertical drain, horizontal deformation, digital image analysis
MOTS-CLÉS : consolidation, drainage vertical, déformation horizontale, analyse d'image numérique

1 INTRODUCTION

Soft clayey soil ground under preloading improvement with vertical drains has known to experience mostly vertical deformation with radial drainage. However, even though no radial displacement is expected in the present consolidation theory, progressive consolidation process from vertical drains induces void ratio variation in the radial direction, which is a strong evidence of radial inward displacements of soils toward drains (Yune 2005). These radial displacements during consolidation have already been recognized by many researchers. Pyrah and Tanaka (1999) and Atkinson et al. (1985) investigated possibility of horizontal movements of soils under radial drainage by measuring horizontal variations of water contents of soil specimens at the end of consolidation. Baek and Moriwaki (2004) measured directly the radial displacements during consolidation by monitoring the movements of magnets installed in the soil specimens.

Spatial variations of void ratio and excess pore pressure yield the stiffness variation of soil ground and result in vertical total stress change and excess pore pressure change under constant vertical preloading. Accordingly, monotonic dissipation of excess pore pressure is no longer possible, and consolidation coupled with total stress change and radial displacement will be the precise condition for soft ground under preloading with vertical drains.

To obtain the precise and detailed information on the soil behavior under vertical loading with radial drainage, physical model test equipment under plane strain condition to monitor the soil responses of entire zone under consideration throughout the whole consolidation process was developed. Soil movements during consolidation were determined by digital image analysis using photo images. Detailed strains and void ratios of entire soil specimen can be obtained. Also, variations of total stress and pore pressure were also measured in several locations in the specimen. Using reconstituted kaolinite specimen, a test with horizontal drainage under vertical loading was carried out, together with a test with vertical drainage. Results from both tests are comparatively analyzed.

2. EXPERIMENTAL PROGRAM

2.1. Test apparatus

The schematic diagram of the consolidation testing apparatus developed for this study is illustrated in Figure 1. The apparatus takes a rectangular parallelepiped specimen of 150 mm in height, 140 mm in width, and 40 mm in thickness, surrounded by four transparent acrylic walls which enable monitoring the internal movement of soils during consolidation. The photo images on the front wall are used for digital image analysis to find out the soil deformations during the entire consolidation process. On the opposite side, 6 pore pressure transducers at 2 different vertical locations and 3 different horizontal locations are installed to obtain the pore pressure distributions from the drain boundary. And 3 earth pressure gauges are mounted on the top rigid loading platen, which will provide the total vertical stress variations. A plate of porous plastics used for drain materials are placed on the top of the specimen for vertical drainage and at the side for horizontal drainage. The pressure lines were connected to top and side of model box, which allow saturation of the sample by applying back pressure and dissipate pore water.

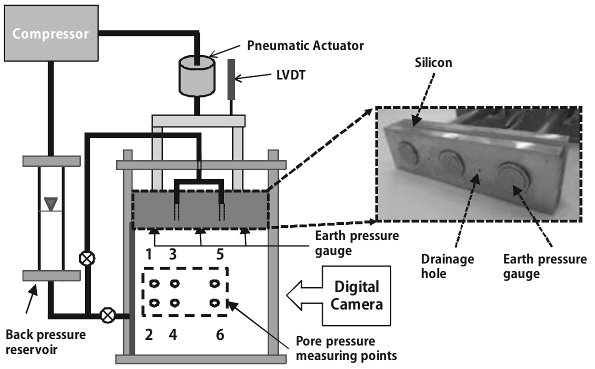


Figure 1. Schematic diagram of developed consolidation test apparatus

Although the axi-symmetric condition with vertical drains is in reality, the developed model box simulates plane strain condition to provide a more favorable environment to perform digital image analysis. So, if necessary, further study for modification of the interpretations of the results will be followed.

2.2. Soils

The reconstituted EPK Kaolinite was used for the test specimen. Its index properties are summarized in Table 1. The clay specimens were created using the slurry consolidation techniques described by Sheeran and Krizek (1971). Dried EPK Kaolinite powder was mixed with de-aired water until the water contents reach twice of the liquid limit of the Kaolinite. The prepared slurry was poured into a large consolidometer of which diameter is 0.3 m. The slurry was loaded with 10 kPa increments until the applied vertical pressure reaches 100 kPa. After reaching the target pressure, the vertical stress was kept constant for 7 to 10 days for the complete consolidation. After removing the vertical pressure, the sample was extruded carefully from the consolidometer, wrapped in plastic films, coated with paraffin wax, and stored in the controlled humidity and temperature storage room until ready for use. The maximum past pressures of the clay samples are determined as about 100 kPa, from the oedometer test results.

Table 1. Index properties of reconstituted kaolinite

Liquid limit (%)	64.4	USCS	MH
Plasticity index (%)	21.8	Initial void ratio	1.56
Percent finer than #200 sieve (%)	98	Initial water contents (%)	61.0
Specific gravity	2.55	Maximum past pressure (kPa)	100

2.3. Test procedure

The test procedure with the developed device for consolidation was summarized as; 1) trimming the reconstituted kaolinite sample, 2) creating image patterns on the surface of trimmed sample and 3) assembling test apparatus. Deformation analysis through image processing is basically done by using two different images taken at two separate times. For this process, a random image pattern was created by spraying oil-based paint on one side of specimen as shown in Figure 2.

After assembling the apparatus with specimen, back pressure was applied for specimen saturation. Pore pressure parameter C value defined as the ratio of excess pore pressure increment to applied vertical total stress, higher than 0.97 was considered as full saturation. For the consolidation test, vertical stress increments by pneumatic pressure were applied on the top of the specimen. Consolidation process was achieved by applying vertical stress increment under undrained condition and then opening drainage line. 3 total stress increments (initial stress to 100 kPa, 100 kPa to 200 kPa, and 200 kPa to 300 kPa) were applied for both tests on horizontal drainage and vertical drainage condition. Initiating consolidation by opening the drainage valve, the values of pore water pressure and total vertical stress are stored via the data logger, and images are taken at regular time intervals, 10 seconds in the early stage of consolidation and increasing time steps as consolidation proceeds. A Nikon D90 digital camera, which has a resolution of 4288 x 2848 pixels, was used to get photo images.

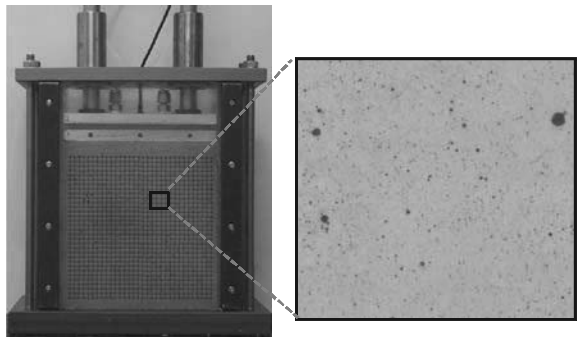


Figure 2. Prepared sample in the assembled test apparatus

The completion of consolidation was confirmed by both measuring pore pressure and interpreting time-settlement curve. After completion of all consolidation tests, water contents at 25 locations for both tests of drained direction were measured. In this study, to exclude the effect of stress history, final loading step (200 kPa to 300 kPa of vertical stress increment) was focused to be analyzed.

2.4. Digital image analysis

In the geotechnical application of the digital image analysis, two major techniques have been widely used; digital image correlation (Rechenmacher and Finno 2004) and particle image velocimetry (White et al. 2003). Herein, the Particle Image Velocimetry (PIV) technique was employed for the deformation measurement because of its better performance in convergence as well as the simplicity of the algorithm. To perform the image analysis, a flat object is supposed to deform 2-dimensionally in the plane of the image which can easily be satisfied in the developed consolidation apparatus which describes plane strain condition.

Kim et al. (2011) suggested a procedure determining optimum image processing condition by statistically analyzing the data of image analysis resulted from the original image of test specimen and manipulated one. Following this procedure, the lowest maximum error, which contains the value of accuracy and precision (Taylor 1999), of approximately 0.002 mm in 90% confidence level was obtained when using PIV with bi-square interpolation, 60 x 60 pixel subset size and 0.28 % of vertical strain interval. As shown in Figure 2, the adopted image in the test specimen is divided into 1024 (32×32) pixel subsets; thus, providing 1024 displacement vectors at the center points of the pixel subsets.

3. RESULTS AND DISCUSSION

3.1. Deformations

Figure 3 shows time-settlement curve for 200 kPa to 300 kPa vertical stress increment of both tests under vertical and horizontal drainages. Time for completion of consolidation in horizontal drainage based on excess pore pressure response is far shorter (3 times) than that for vertical drainage, as expected.

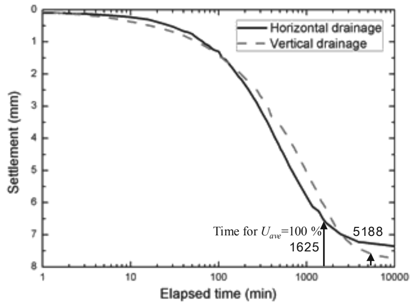


Figure 3. Time-Settlement curve of consolidation tests

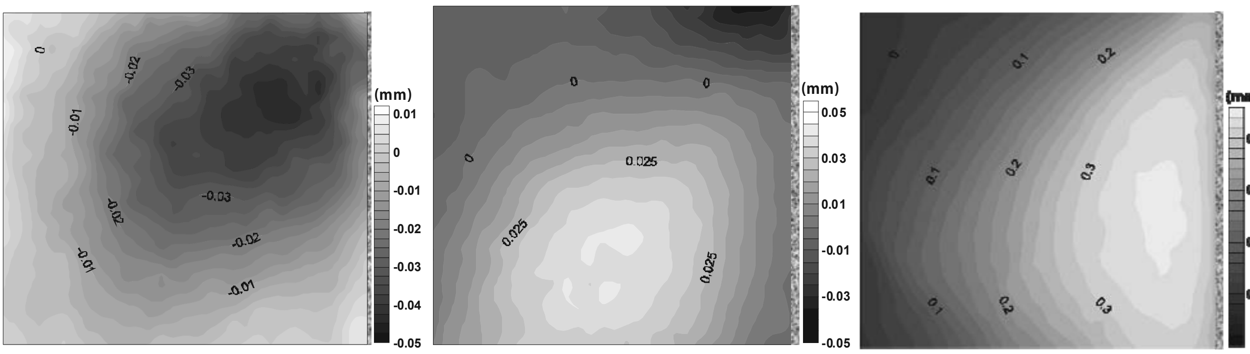
The total consolidation process was divided into 18 and 20 stages for horizontal and vertical drainage condition to achieve the optimum condition of image analysis with a vertical strain interval of 0.28 %. The horizontal and vertical displacement increment contours were drawn for each section using 1024 displacement vectors resulting from image analysis. Interpretation results for horizontal drainage reveals 3 distinct stages based on inner soil displacements. Figure 4 to 6 show representative displacement increment contours under horizontal drainage for "early", "intermediate" and "last" stages of consolidation, corresponding to 0 to 4%, 40 to 46%, and 78 to 82% of average degree of consolidation, U_{ave}, respectively.

In the early stage, significant horizontal displacements were observed, and they were increasing, approaching drained boundary. In the intermediate stage, only minor horizontal displacements were observed. However, in the last stage, even though they were small, displacements to undrained boundary were observed. So, it is found out that significant horizontal displacements occurred in case of horizontal drainage condition under vertical compression and they were highly dependent on consolidation progress. Furthermore, horizontal displacement toward drained boundary is dominant throughout entire process of consolidation and it led into uneven void ratio distribution after completion of consolidation (decreasing void ratio as approaching drained boundary). Figure 7 indicating water content distribution after test provides its strong evidence, with lower values near drained boundary.

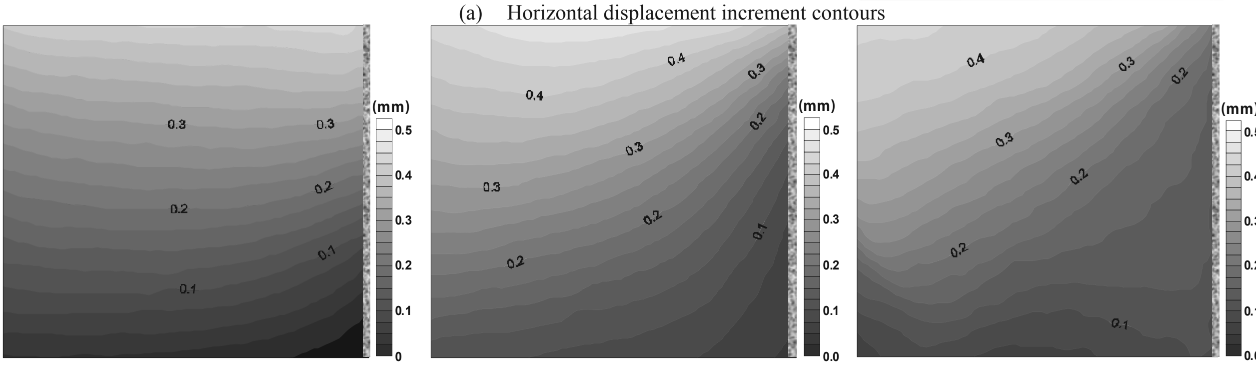
54.8	53	51.4	50.3	49.4
53.4	53.5	53.1	52.4	52.0
54.0	53.3	53.7	53.5	53.4
54.1	53.9	54.1	53.9	53.9
54.6	54.6	53.5	53.6	53.4

Figure 7. Final water content distribution of horizontal drainage

Horizontal displacements for horizontal drainage under vertical loading can be explained by progressive consolidation process from drained boundary. In the early stage, consolidation near drained boundary proceeds quickly with decreasing void ratio, and decrease of void ratio can be induced by horizontal soil displacements (i.e. soils imported from nearby zone) under equal vertical strain condition of test. In the intermediate stage, consolidation rate in the horizontal plane is not much different because of relatively uniform horizontal gradients of flow, and thus minor horizontal displacements are observed. But, in the last stage, dissipation of pore pressure remnant left in zone near undrained boundary invokes infinitesimal horizontal displacements inversely.



(a) Horizontal displacement increment contours



(b) Vertical displacement increment contours

Figure 4. Early stage of consolidation (U_{ave} = 0 ~ 4%)

Figure 5. Intermediate stage of consolidation (U_{ave} =40 ~ 46%)

Figure 6. Last stage of consolidation (U_{ave} =78 ~ 92%)

Meanwhile, for the vertical drainage, only minor scattering values of horizontal displacement increment less than 0.006 mm were observed, as shown in Figure 8. Furthermore, most of horizontal displacements were less than 0.002 mm, which is the maximum error in a 90% confidence level, and thus, it is estimated that horizontal displacements were hardly detectable under vertical drainage. Vertical displacement increment during consolidation also showed fairly uniform distribution along horizontal plane. Uniform vertical deformation and negligible horizontal deformation is maintained through the whole consolidation period.

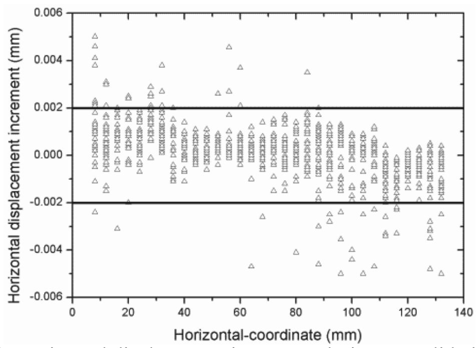


Figure 8. Horizontal displacement increment during consolidation under vertical drainage condition ($U_{ave} = 0 \sim 5\%$)

3.2. Total vertical stress

During the consolidation, the total vertical stresses were measured from 3 earth pressure gauges at different horizontal locations on the top of the specimen as shown in Figure 1. The variation of total vertical stress (measured total vertical stress minus initial total vertical stress, $\Delta\sigma_v$) with consolidation time is shown in Figure 9. In the case of vertical drainage, the vertical total stress maintains constant with minor scattering. On the other hand, in the case of horizontal drainage, total vertical stresses changed with consolidation time in a different manner for each location. At near drainage location, total vertical stress initially decreased and then increased at 35% of U_{ave} . At the end of consolidation, it reached net increase of total stress. Meanwhile, at mid-plane and far drainage locations, total stresses initially increase and then decrease. At the end, net decreases of total stresses were observed.

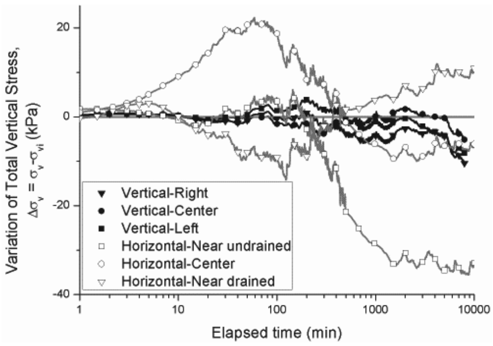


Figure 9. Variation of total vertical stress during consolidation

These total stress variations are strongly related to progressive consolidation process from drained boundary. As mentioned above, initial decrease of void ratio at near drainage induces increase of total stress nearby zone such as mid-plane location. And as consolidation progresses, void ratio of entire horizontal plane decreases and ideally reaches to the same void ratio value at completion of consolidation. In this case, even distribution of total vertical stress is expected. However, uneven void ratio distribution at the end (i.e., decreasing value of void ratio as approaching drained boundary) yields higher total vertical stress at near drainage and lower at far drainage.

4. CONCLUSIONS

In this study, consolidation tests were performed under the condition of horizontal and vertical drainage using the newly developed consolidation apparatus. The developed equipment can monitor inner soil deformations visually and measure the pore water pressure distributions inside the specimen.

Results of digital image analysis and vertical total stress measurement during the experiment are briefly presented as follows. Horizontal displacements for horizontal drainage under vertical loading were predominantly observed. In the early stage of consolidation, significant horizontal displacements to the drainage were observed, and thereafter it is decreasing as consolidation proceeds, and at the last stage of 70 % or more of U_{ave}, relatively small amount of horizontal displacements in opposite direction were monitored. On the other hand, only minor scattering values of horizontal displacement were measured for vertical drainage condition. The induced non-uniformity was confirmed by measuring water content at the end of the consolidation: as approaching to the drainage surface, the measured water contents were decreasing.

The total vertical stress in the horizontal plane measured by three earth pressure gauges showed constant values in vertical drainage conditions. In the horizontal drainage, total vertical stress near drainage boundary initially decreased and then increased, reaching net increase (12 %). Meanwhile, at mid-plane and far drainage locations, total stresses initially increased and then decreased, finally having net decrease. (7, 30% respectively)

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