Assessment of deformation during consolidation using digital image analysis

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ABSTRACT

The measurement systems based on digital image analysis have been widely attempted in geotechnical testings (e.g., physical model tests) for observing the deformation of soils. The accuracy of digital image analysis is influenced by various factors such as image pattern of test materials, performance of digital camera, target area, and analysis conditions. Therefore, optimal analysis conditions should be determined and applied to obtain high quality results on soil deformations. In this study, various influence factors of the accuracy of digital image analysis and the optimizing procedure were described. Finally, the digital image analysis was adopted to evaluate the deformation during lateral drainage consolidation under the given optimal condition.

Keywords: digital image analysis, consolidation, optimization

1 INTRODUCTION

Many researchers have experimentally investigated the deformation behavior during consolidation under horizontal drainage condition. Pyrah et al. (1999) and Atkinson et al. (1985) analysed the lateral deformation by measuring the lateral variations of the water content at the end of the consolidation. Baek and Moriwaki (2004) measured the displacements at three different locations for a clay sample under consolidation with vertical drains by monitoring the movement of the magnets installed in the clay specimens. However, their measurements were available only at a few locations or at a certain time.

There are another techniques such as X-ray computed tomography (CT) (Desrues et al., 1996; Wong, 2000) and thin section analysis with epoxy injection (Kuo and Frost, 1996; Alshibli and Sture, 1999) which is able to evaluate deformation characteristics at multiple locations inside the specimen. The CT technique, however, not only requires a complicated scanner system, but also indirectly measures the void ratio from X-ray attenuation. The sectioning method using epoxy could investigate the void ratio and soil fabric at limited sections and only at the time of epoxy injection.

Recently there has been significant development in digital image technologies and in the field of geotechnical engineering, and consequently, many researches (Arshad et al. 2014; Choo et al. 2013; White and Bolton 2004) have used digital images to analyse the deformation characteristics of soil due to non-invasiveness, cost effectiveness and high measurement accuracy of digital image analysis. Digital image analysis is also able to measure the displacements at any location and time.

It is expected that the continuous measurement of deformation of entire specimen during consolidation is available using digital image analysis. However, the accuracy of digital image analysis is influenced by analysis condition such as a degree of deformation, a size of pixel subsets, and a type of the interpolation method. Therefore, optimal analysis conditions should be determined in advance and applied to obtain high quality results on soil deformations. In this study, various influence factors of the accuracy of digital image analysis and the optimizing procedure were described. Finally, the digital image analysis was adopted to evaluate the deformation during lateral drainage consolidation under the given optimal condition.

2 DIGITAL IMAGE ANALYSIS

2.1 Particle Image Velocimetry (PIV)

In this study, particle image velocimetry (PIV) technique was adopted to evaluate displacement from images taken during the consolidation tests. PIV
A technique was developed and has been used for measuring the displacement and velocity of a moving material in fluid mechanics (Adrian, 1991). Tested pixel subsets are selected in a pre-deformed image called an initial state; then, an estimated moving range of each pixel subset is determined based on an expected displacement in a deformed image. The cross-correlation using initial pixel subset within the estimated range is evaluated at single pixel intervals as schematically shown in Fig. 1; in each evaluation, a correlation coefficient is calculated by

\[
R = \frac{\sum_{m=1}^{M} \sum_{n=1}^{N} f_x(m,n) f_y(m,n)}{\sqrt{\sum_{m=1}^{M} \sum_{n=1}^{N} f_x(m,n)^2 \sum_{m=1}^{M} \sum_{n=1}^{N} f_y(m,n)^2}}
\]  

(1)

where \(M\) and \(N\) are the number of pixels in \(x\) and \(y\) directions inside a pixel subset, respectively; \(f_x\) and \(f_y\) are the pixel contrast values at the pixels of the reference and candidate deformed pixel subsets, respectively. The correlation coefficient field can be obtained over the offset range in the estimated domain; and the correlation field indicates the degree of match between the initial and moved pixel subsets (White et al., 2003). The highest peak in the correlation field denotes the displacement vector of the pre-deformed pixel subset; however, the displacement has only single pixel resolution in this step, because the calculation of cross-correlation was performed by single pixel interval. The displacement vector can be obtained in sub-pixel resolution by utilizing interpolation methods such as bi-square or bi-cubic interpolation. This procedure is repeated for the entire pixel subsets; then, the displacement field developed between the image pair can finally be obtained.

2.2 Performance: accuracy and precision

The performance of a measurement system can be assessed by considering the errors associated with accuracy, precision and resolution (Taylor, 1999). Accuracy is defined as the systematic difference between a measured quantity and the true value. Precision is defined as the random difference between multiple measurements of the same quantity.

The precision of a deformation measurement system based on the tracking of target markers depends on the method used to identify the location of the target within the photograph or digital image. The accuracy of the system depends on the process used to convert from the measured location within the image (image-space coordinates) to the location within the element or model test (object-space coordinates).

This study also evaluated the performance of digital image analysis based on accuracy and precision. The accuracy and precision were statistically evaluated by comparing the true displacements and the resulted displacements from image analysis at a number of locations. For example, the error between the true displacements and the resulted displacements from image analysis at a hundred locations can be represented in a probability density function shown as Fig. 1, where the mean error and the variance stands for accuracy and precision, respectively. In this study, the performance of image analysis was evaluated using the maximum error in 90% of confidence interval which includes the mean error (accuracy) and the variance (precision). The lower the maximum error in 90% of confidence interval means the higher performance of the measurement system.

3 OPTIMAL CONDITION OF DIGITAL IMAGE ANALYSIS FOR CLAYEY SOILS

3.1 Methodology

To determine the optimum analysis condition of PIV technique, the performance verification tests were conducted under various condition as summarized in Table 1. An original image –real picture of reconstituted EPK kaolin clay with an artificial texture as shown in Fig. 2– and six manipulated images –vertically compressed at six different magnitudes using photo editing software– were used. Digital image analysis were performed under total of 48 cases –two types of deformation, six magnitudes of deformation, two types of interpolation method, and six pixel subset sizes. Displacements at a hundred of center point of pixel subset were evaluated by digital image analysis and compared with the true displacements for statistical analysis. The true displacements can simply calculated by displacements from image analysis at a number of

| Strain interval | Interpolation method | Pixel subset size |
|----------------|---------------------|------------------|
| 0.07, 0.14, 0.28 | bi-square, bi-cubic | 15x15, 30x30, 60x60, 120x120 |
| 0.56, 1.1, 2.2  | bi-cubic            | 40x40, 80x80, 160x160 |
3.2 Results and discussions

Each case of verification test produces the probability density function with error as shown in Fig. 3, then the maximum error in 90% confidence interval can easily be obtained. This procedure was repeated for the total of 96 cases, producing the probability density function and maximum error in 90% confidence interval for each case. Fig. 4 shows the variation of the maximum error with interpolation method and size of pixel subsets under each different strain interval.

Fig. 4 shows that the maximum error was reduced up to $1/2 - 1/8$ by choosing appropriate interpolation method and size of pixel subsets at a given strain interval. The maximum error decreased with smaller vertical strain interval and larger size of pixel subset whereas it drastically increased with larger vertical strain interval and smaller size of pixel subset. In short, PIV with large size of pixel subset and small vertical strain interval gives more accurate image analysis results. However, excessively small vertical strain interval results in increasing analysis steps in evaluating deformation of the whole test process and cumulative computational error. On the other hand, it is hard to evaluate spatial variation of deformation when excessively large size of pixel subset is used for the image analysis. Therefore, researcher’s judgement is required in selecting adequate size of pixel subset and vertical strain interval according to the purpose of analysis.

![Fig. 2. Reconstituted EPK kaolin clay with an artificial texture.](image)

![Fig. 3. Error distribution (when using 0.14% compressed image, bi-square interpolation, and 60x60 pixel subset size).](image)

![Fig. 4. Maximum error of PIV at various vertical strain interval.](image)
4 APPLICATION ON CONSOLIDATION TEST

4.1 Consolidation test

PIV was applied to a horizontal drainage consolidation test to confirm its applicability in assessing the deformation during consolidation. Fig. 5 shows a typical image of the test specimen and the center points of the pixel subsets (the lattice points in the figure) where the displacement vectors are obtained together with a consolidation apparatus. Total 1554 displacement vectors (37 by 42 configuration) are obtained from two consecutive images. Since image capturing during the test is necessary for PIV, the test apparatus was made of transparent acrylic plates. To achieve an equal vertical strain condition, a rigid loading plate was placed on top of the specimen. Based on the derived optimal analysis condition, digital images with a vertical strain interval of 0.28% were analyzed with 60-by-60 pixel subsets using bi-square interpolation, and consequently, the maximum error in 90% confidence was estimated approximately 0.002 mm. The actual error can be larger than the estimated error due to the fact that the error was estimated under ideal condition, however, distortion occurs during the consolidation test although the specimen was vertically compressed under one-dimensional condition.

![Fig. 5. Consolidation test apparatus and centers of pixel subsets.](image)

4.2 Test results

First, the consolidation settlement was calculated by averaging the vertical displacements at top row evaluated from PIV and compared with that measured by LVDT. Fig. 6 shows the two settlement curves with respect to time during the vertical consolidation pressure from 100 kPa to 150 kPa with lateral drainage. The two settlement curves were almost identical as shown in Fig. 6. Small discrepancy could exist because it is technically hard to make the pixel subset perfectly cover the top end of the specimen.

![Fig. 6. Time-settlement curves](image)

Fig. 7 plots displacement increment vectors $\Delta u$ for the consolidation processes during average degree of consolidation ($U_{ave}$) from 0 to 10%. The length of each arrow represents the magnitude of the displacement increment vector. It can be seen that significant lateral displacement occurred to the drainage boundary, which is located on the right side of the specimen, during the early stage of consolidation, and that this movement was concentrated in the lower-right part of the sample. Under the horizontal drainage conditions, the pore water near the drainage boundary rapidly moved to the drainage boundary, accompanied by a decrease of the void ratio (or volume); the shrinkage of the clay near the drainage boundary induced lateral displacement under the equal vertical strain condition. This kind of deformation behavior was similar to the previous experimental results (Baek and Moriwaki, 2004). However, digital image analysis provides much more displacement data compared to the previous research, and consequently, further investigation is available by evaluating volumetric strain or void ratio based on the numerous displacement vectors.

![Fig. 7. Distribution of displacement increment vector $\Delta u$ for the consolidation processes of $U_{ave} = 0-10\%$.](image)
5 CONCLUSIONS
This study described a procedure optimizing analysis condition of PIV such as a degree of deformation, a size of pixel subsets, and a type of the interpolation method to more accurately assess the displacement of a clay specimen. Based on the verification test results, the maximum error decreased with smaller vertical strain interval and larger size of pixel subset. It was also seen that the maximum error was reduced up to 12 – 50% by choosing appropriate analysis condition.

The texture of a soil specimen also have influence on the accuracy of digital image analysis. The texture of a clay specimen, however, is artificially and randomly created in general. Therefore, the analysis condition of PIV should be optimized for each test specimen prior to the image analysis and the subsequent maximum error should be specified under the optimal condition.

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