ABSTRACT

Soil failure is initiated and preceded by forming and progressing of shear band, defined as the localization of deformation into thin zones of soil mass. To understand the failure mechanism of soil, the spatial distribution and evolution of deformation within the entire specimen need to be evaluated. In cohesive soils, significant heterogeneous deformation behaviors due to the non-uniform distribution of stress may be observed. In this study, vertical compression tests under plane strain condition were performed on reconstituted kaolinite specimens, while capturing digital images of the specimen at regular intervals during consolidation and shearing. Overall stress-strain behavior from initial to post peak has been analyzed together with spatial distributions of deformations from digital images at 4 distinct loading intervals. Failure mechanism and strain softening is strongly related to the shear band forming and evolution.

Keywords: Failure mechanism, Plane strain test, Digital image analysis, Strain distribution

1 INTRODUCTION

Most cases of soil failures in slopes, foundations and retaining structures are initiated and preceded by the forming and progressing of slip surfaces. For relative movements occurring on such surfaces, shear strains are usually localized along the surface. Localization of deformation into thin zones along soil mass of the slip surface is defined as a shear band. Experimental measurement of shear band characteristics is very useful in better understanding the deformation and localization mechanisms of soil materials during shearing (Alshibli and Sture, 1999). For this reason, assessment on the localization of deformation in the entire stressed zone and shear band generation needs to be performed along with stress-strain and pore pressure response.

There are several testing methods to evaluate the shear band characteristics of granular soils. Based on the tri-axial test system in granular soils, X-ray Computed Tomography (CT) was applied to scan the density variation (Wong, 2000). In addition, thin section analysis with epoxy impregnation in soil specimens was applied (Jang and Frost, 2000). However, the CT technique requires an elaborate and costly scanner, and is incapable of measuring the movement and deformation of soils during the loading and the deformation processes. The Epoxy impregnation method evaluates the void ratio and soil fabric after test completion or at limited testing moments. To overcome these limitations, digital image analysis is mainly applied to evaluate the shear band characteristics. Digital image analysis is especially adopted in plane strain tests because of its capability to capture direct and unrefracted physical displacement images of a specimen surface during the whole test process via transparent side walls (Finno et al., 1997; Alshibli and Sture, 2003). In addition, for specimens of small thickness under the plane strain condition, the surface measurements can represent the internal deformation in the plane strain direction. However, plane strain tests which adopted digital image analysis have also been performed only for granular soils.

In this paper, plane strain tests with digital image analysis were performed focusing on the observation of the spatial deformation distribution in cohesive soils. For clear evaluations of spatial deformation distribution in cohesive soils, the optimal condition of digital image analysis was determined and employed for plane strain tests.

2 EXPERIMENTAL PROGRAM

2.1 Plane strain test

The schematic diagram of plane strain testing apparatus is illustrated in Figure 1. Two rigid side walls were applied to restrain the lateral deformation in the direction perpendicular to the side walls; the upper parts of side walls were fixed by bracings, and the lower parts of the walls were connected to the bottom
plate. The bottom plate is composed of two parts: a lower plate, which is fixed to the pedestal, and an upper plate, which carries linear bearings. This mechanical composition allows the bottom plate to control the restrain condition (Jang et al., 2011). One of the rigid walls and the chamber, which was made with a transparent acrylic panel, has a rectangular shape to prevent the refraction and distortion when capturing the digital images.

Fig. 1. Plane strain testing apparatus

Reconstituted kaolinite was used for the test specimen. First, to make the kaolinite slurry, dried EPK kaolinite powder was mixed under the water contents of twice the liquid limit of kaolinite. Then, the prepared slurry was loaded with 10kPa increment loads until the applied vertical pressure reached 150kPa. After reaching the target pressure, the vertical stress was kept constant for two weeks for complete consolidation. The index properties of the reconstituted kaolinite are summarized in Table 1. Dimensions of the specimen as shown in the apparatus of Figure 1 are 128mm in height, 65mm in width, and 45mm in length. After setting up the specimen, oil-based paint was sprayed on the surface to obtain unique intensity image patterns, which is necessary for digital image analysis.

Table 1. Index properties of reconstituted kaolinite.

| Liquid limit (%) | Plastic index (%) | Specific gravity | USCS   | Water content (%) |
|------------------|-------------------|------------------|--------|-------------------|
| 65.3             | 23.1              | 2.62             | MH     | 53.3              |

After the process for the specimen set-up, the specimen was saturated by applying 100kPa of back pressure to obtain a B value of 0.95. The soil specimen was then anisotropically consolidated by an effective vertical stress of 200kPa, and an effective horizontal stress of 100kPa under the assumption that the $K_0$ value equals 0.5, with a restrained bottom plate. After the completion of consolidation, the specimen was vertically compressed with 0.5%/hr of strain rate by raising the chamber with the fixed loading frame under undrained condition. The specimen was sheared with a constant confining stress until the stress-strain response reached the steady-state. During the shearing process, the bottom plate was unrestrained to provide a more efficient condition for the generation of shear band (Alshibli et al., 2004; Finno et al., 1997).

2.2 Digital image analysis

In the geotechnical application of digital image analysis, PIV (Particle Image Velocimetry) techniques have been widely used. PIV basically calculates the correlation of pixel subsets from digital images taken at different times in order to measure the relative displacement of the pixel subsets. In this study, GeoPIV (White et al. 2003), which is the most widely used software for the PIV technique, was employed.

For the optimal PIV technique conditions for investigation of soil behaviors, optimal strain intervals and the pixel subset size should be determined. Kim et al. (2011) recommended that the global axial strain interval should be less than 0.28 % when using the PIV technique for cohesive soils to obtain higher accuracy and precision. Based on the recommendation, the global axial strain interval for digital image analysis was determined as 0.25% in this study. Additionally, the intensity pattern of a pixel subset becomes more obvious with an increase in pixel subset size. Meanwhile, an excessive pixel subset size can make it difficult to express and understand the spatial characteristic of the displacement. The accuracy and precision of GeoPIV with various-sized pixel subsets were verified by comparing two digital images; the original image of the soil specimen and the image artificially shifted by one pixel. Based on the results of the verification tests, the size of a pixel subset which can satisfy high accuracy and precision, along with the assessment of spatial distribution of the displacement was determined as 80 × 80 pixels.

To exclude the effect of friction at the boundaries of the specimen, the central part of the specimen were intensively analyzed. Figure 2 shows 720 (16 × 45) center points in the first image of consecutive images. Digital image analysis provides a displacement vector at each center point of the pixel subsets.

Fig. 2. Selected pixel subsets and center points for digital image analysis

2.3 Computation of strain increment

Deformation characteristics were investigated using a concept of strain, because the strain increment directly expresses the deformation behavior at selected strain intervals. To construct strain fields, the square
unit element with four equally-spaced center points of the pixel subsets was first defined. For each unit element, strains can be obtained as follows:

1) Using four displacement vectors within an element, a linear displacement field is obtained via the least square data fit. The linear fields of the horizontal and vertical displacements for the i-th unit element are defined as:

\[
\Delta u^i = a_i^x x + b_i^y y + c_i^z \Delta v^i = a_i^x x + b_i^y y + c_i^z
\]

where \(x\) and \(y\) are the local coordinate in the plane, \(\Delta u\) (\(\Delta v\)) is the displacement increment in the horizontal (vertical) direction, and \(a, b\) and \(c\) are the coefficients of the displacement fields.

2) Using expressions of \(\Delta u\) and \(\Delta v\), the local strains, \(\Delta \varepsilon_{xx}\) (horizontal strain increment), \(\Delta \varepsilon_{yy}\) (vertical strain increment), and \(\Delta \varepsilon_{xy}\) (shear strain increment) of the i-th unit element can be computed by:

\[
\begin{align*}
\Delta \varepsilon_{xx}^i &= \frac{\partial \Delta u^i}{\partial x} = a_i^x, \\
\Delta \varepsilon_{yy}^i &= \frac{\partial \Delta v^i}{\partial y} = b_i^y, \quad \text{and} \\
\Delta \varepsilon_{xy}^i &= \frac{1}{2} \left( \frac{\partial \Delta u^i}{\partial y} + \frac{\partial \Delta v^i}{\partial x} \right) = \frac{b_i^y + a_i^x}{2}
\end{align*}
\]

3 EXPERIMENTAL RESULTS

The measured deviatoric stress and excess pore pressure with axial strain during the test are plotted in Figure 3. Based on the stress-strain response, the shearing process was divided into four stages bounded by dotted lines: 1) initial stage (axial strain, \(\varepsilon_a=0-1.75\%\)), 2) peak stage (\(\varepsilon_a=1.75-2.25\%\)), 3) softening stage (\(\varepsilon_a=2.25-4.5\%\)), and 4) steady state stage (\(\varepsilon_a>4.5\%\)). To investigate the deformation characteristics for each stage, digital image analysis was performed by 0.25% global axial strain intervals as previously stated.

From the results of digital image analysis, intervals which indicated the most representative characteristics for each stage were selected as the vertical bars in Figure 3. The contours of vertical displacement, horizontal displacement, and shear strain increments at the selected representative strain intervals are shown in Figures 4 to 7. The positive values and blue color represent horizontal displacements in the right direction, and vertical displacements in the downward direction. On the other hand, the negative values and red color represent horizontal displacements in the left direction, and vertical displacements in the upward direction. The location of the shear band evaluated at the steady state stage is marked at each contour as a black line.

Figure 4 shows deformation characteristics of the initial stage. Distinct indications of deformation characteristics are rarely identified in the initial stage. Only a potential failure tendency can be observed from the horizontal displacement contours inclined to shear band line. At the peak stage shown in Figure 5, a potential failure surface was relatively clearly observed, but still did not show a distinct failure surface. The horizontal and vertical displacement contours showed spatial heterogeneous distribution. The upper left-hand side of the soil specimen shows a left side movement, whereas the lower right-hand side shows a right side movement. In addition, strain increments were intensified in the vicinity of potential shear band which is located at the boundary between the upper left side and lower right side of the soil specimen. However, the intensified zones of strain increments did not completely coincide with the shear band evaluated at the steady state stage.
localization was observed. The specimen was clearly divided into three zones: a shear band zone and two sliding wedge zones as shown in Figure 6. Deformation was mostly concentrated around the shear band and the shear strain increments in the shear band reached up to 5%. The sliding wedges, however, showed relatively large displacements with little shear strain, depicted as a rigid body motion. The upper sliding wedge showed only a left-side movement of nearly 0.09 mm, whereas the lower sliding wedge showed only an upward movement of 0.22 mm, which is almost identical to the global strain of 0.25% used for the image analysis. Excess pore pressure in the soil specimen increased from the initial stage until the softening stage. At the steady state stage, a complete shear band was generated with more intensified strain localization and steeper angle of failure plane of shear band. Defining shear band as the area above 1.0% shear strain increment, the angle and thickness of the complete shear band were estimated to be 54.5° and 8.6 mm, respectively.

Under the plane strain condition were performed on reconstituted kaolinite, and PIV analyses were carried out using digital images in the 4 selected stages during the tests. The spatial deformation characteristics were evaluated by the contours of the horizontal and vertical displacement, and shear strain increment. Based on the experimental results presented in this paper, the following conclusions were drawn:

1) Distinct indications of strain localization are not identified during the initial stage ($\varepsilon_a=0$-1.75%). At the peak stage ($\varepsilon_a=1.75$-2.25%), shear strain increment was clearly intensified, but still did not show a distinct failure surface.

2) After the softening stage ($\varepsilon_a=2.25$-4.5%), evident strain localization was observed along the complete shear band. The specimen was clearly divided into three zones: a shear band zone and two sliding wedge zones.

3) Deformation was mostly concentrated around the shear band. However, upper sliding wedge only showed a left-side movement, whereas the lower sliding wedge only showed an upward movement without strain localization.

4) At the steady state stage ($\varepsilon_a>4.5$%), a complete shear band was generated with more intensified strain localization and steeper angle of failure plane.

4 CONCLUSIONS

This experimental study attempted to evaluate the failure mechanism of cohesive soils with spatial deformation distribution during the shearing process. To investigate the deformation of the specimen, the plane strain testing apparatus was used to obtain digital images of the specimen. Vertical compression tests

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