Distribution changes of grain contacts and menisci in shear band during triaxial compression test for unsaturated sand

Ryunosuke Kido$^{i)}$ and Yosuke Higo$^{ii)}$

$^{i)}$ Ph.D student, Department of Civil and Earth Resources Engineering, Kyoto University, Nishikyo-ku, Kyoto, Japan.
(Research Fellow of Japan Society for the Promotion of Science)
$^{ii)}$ Associate Professor, Department of Urban Management, Kyoto University, Nishikyo-ku, Kyoto, Japan.

ABSTRACT

It is known that unsaturated soil shows more brittle modes of failure with clearer shear band than fully saturated soil. Investigation of three-phase microstructural changes in shear band of unsaturated soil is important to clarify its mechanism. In the present study, x-ray micro computed tomography (CT) focusing on shear band was performed at different stages of deformation during a triaxial compression test for an unsaturated sand. Variations in the local void ratios, degrees of saturation, the number of grain contacts and the number of water menisci with development of shear band were revealed using image analysis techniques. The relationship between their microscopic behaviors and the macroscopic deviator stress of the unsaturated sand under triaxial compression is discussed.

Keywords: shear band, grain contact, water menisci, x-ray micro CT, image analysis, triaxial compression test

1 INTRODUCTION

Unsaturated soil comprises soil particle, pore water and pore air, in which the pore water forms bridge between soil particles, i.e., water meniscus, due to surface tension of water and hydrophilic property of soil particle. Mechanical behaviors of unsaturated soil strongly depend on suction at water menisci. The suction works as inter-particle force resulting in higher stiffness of unsaturated soil than fully saturated soil. On the other hand, unsaturated soil exhibits more brittle modes of failure with clearer shear band than fully saturated soil (e.g., Cunningham et al., 2003; Higo et al., 2011). This is because loss of the suction due to water infiltration or shearing causes a drastic reduction in the stiffness and the strength of unsaturated soil. The suction effect on the stiffness is probably decreased due to the reduction of water menisci at grain contacts during shearing. In addition, the macroscopic response after failure associated with shear band is dominated by the softening inside the shear band. It is important, therefore, to investigate the grain contacts and water menisci with development of shear band and their influence on the macroscopic response to clarify the failure mechanism of unsaturated soil.

In the present study, x-ray micro CT focusing on shear band was performed at different stages of deformation during a triaxial compression test for an unsaturated sand specimen under drained conditions for air and water. The CT images are trinarized and then the local void ratio, degrees of saturation, the numbers of grain contacts and water menisci are quantified using image analysis techniques. The algorithm of detecting the grain contacts is proposed and validated. The progressive changes in the numbers of grain contacts and water menisci with developing shear band under triaxial compression of unsaturated sand are quantified and their influence on the macroscopic deviator stress are discussed.

2 EXPERIMENTAL PROGRAMS

2.1 Material

The material used in the present study was silica sand No.5. Fig. 1 shows grain size distribution curve of the silica sand. The physical properties of the silica sand include a soil density of 2.64 g/cm³, a maximum void ratio of 1.013, a minimum void ratio of 0.694, a $D_{s0}$ of 456 μm, a uniformity coefficient of 1.3 and a fines content of 0.1 %.

2.2 Specimen preparation

Water pluviation technique was applied to prepare the fully saturated sand specimen with a diameter of 35 mm and a height of 70 mm. Air-dried sand was directly poured from a certain height into water that was filled in the mould beforehand. Then, the sand was densely packed by tapping the mould. The target relative density ($D_r$) of the triaxial specimen used in the present study was 90%.

Once the fully saturated sand specimen was prepared with the above procedure, negative water column method (Vnapalli et al., 2008) was applied to
desaturate the specimen: suction was applied to the specimen by water head difference between top of the specimen and the water table in the burette connected to bottom of the specimen as shown in Fig. 2. Suction is then consistent with the water head difference at a hydraulic equilibrium. It took less than two days to be in the equilibrium under a given suction, during which the amount of water drainage was measured using a differential pressure gauge equipped with the double-tube burette. Desaturation for the specimen was done under a confining pressure of 50 kPa. Initial degree of saturation of the specimen was 54.6% and the initial level of suction was 0.98 kPa.

2.3 Triaxial compression test conditions
Triaxial compression test was conducted under drained conditions for both air and water; namely, the level of suction in the unsaturated sand specimen is kept constant during the test. Axial strain rate was 0.10%/min and a confining pressure of 50 kPa was applied by air pressure.

2.4 X-ray CT scan conditions
The x-ray micro CT facility is KYOTOGEO-μXCT (TOSCANER-32250μhdk, TOSHIBA IT and Control Systems Corporation). The resolution performance is 5 μm. The cone-beam scan provides several slices in the vertical direction during a scanning, namely, the three-dimensional tomographic volume is obtained using an image reconstruction software. Fig. 3 shows the scan area and scan positions for global tomography and local tomography. The global tomography is to observe the deformation of whole specimen. The local tomography is to observe local region of interest focusing on shear band. Voxel size of the global tomography is 72.6×80.0 μm³, whereas that of the local tomography is 12.3×14.0 μm³. Triaxial loading was suspended during the scans for around three hours, after which triaxial loading was resumed with the same strain rate.

3 IMAGE ANALYSIS METHODOLOGIES
3.1 Modification of artifact of CT images
Fig. 4 shows artifact of the local tomography image caused by the difference in x-ray transmission length. When the central axis of scanning is shifted from that of the specimen, the voxels which are far from the center of the specimen show lower CT values (darker in CT image) than those are closer to the center of specimen (whiter in CT image). The x-ray transmission length is then uneven, whereas the x-ray transmission length during image reconstruction using CT value is evenly set in scan area. As a result, longer transmission length causes relatively higher CT value. When several slices of CT images are obtained by cone-beam scan, the artifact is equally observed in each slice.

Fig. 5 describes the procedure of the modification of the artifact. Planer trend of the artifact is extracted by calculating the mean CT value of voxels which exist in the same position in each slice as shown in Fig. 5(b). The difference between the original image and the planer trend provides the modified image of the artifact.
as shown in Fig. 5(c). As indicated by Fig. 5(d), the deviation of the CT value is correctly reduced.

3.2 Trinarization
In the CT images scanning unsaturated sand, a voxel often shares two phases. In this case, the gray value of the voxel is determined using the average density of their phases, which is called the partial volume effect. In particular, voxels sharing the soil particle phase and the pore air phase are often misidentified as the pore water phase due to the partial volume effect (e.g., Higo et al., 2014). In order to separate the soil particle phase, the pore water phase and the pore air phase with sufficient accuracy, the partial volume effect should be considered.

In the present study, the soil particle phase, the pore water phase and the pore air phase in the three-dimensional tomographic volume were separated using region growing method (e.g., Higo et al., 2014). The algorithm and the validity of the trinarization technique considering the partial volume effect are described in Kido and Higo (2017) in detail. Prior to the trinarization, a median filter with 3³ voxels was applied to the local tomography images to reduce noise. The median filter and the region growing were performed using the 3D image analysis software VGStudioMax3.1 (Volume Graphics GmbH). Examples of the original CT image and the trinarized image are shown in Fig. 6 in which the gray, blue and black colors denote the soil particle phase, the pore water phase and the pore air phase, respectively.

3.3 Morphology analysis
Morphology analysis is performed using the 3D image analysis software Avizo9.4.0 (FEI). The pore water phase extracted from the trinarized volumes were divided into a few assemblies with individual continuity which are hereinafter referred to as “clusters”.

Fig. 7 shows the procedure of the morphology analysis. The binary volume for the pore water phase is created from the trinarized volume in which the blue portion is the pore water phase and the black portion is the background phase, as shown in Fig. 7(b). The binary volume contains a few pore water voxels due to the partial volume effect between the soil particle phase and the pore air phase as well as absorbed water surrounding the soil particles. To remove those voxels, erosion and dilation (e.g., Haralick et al., 1987) with 2 voxels are performed in this order. Erosion removes the 2 pore water voxels from the edge of the pore water phase, while dilation adds 2 pore water voxels to the edge of the pore water phase.

The pore water phase is separated and becomes discontinuous in some parts due to erosion-dilation image processing with two voxels, as shown in Fig. 7(c). The separated pore water is labeled by assigning a unique number to all adjacent voxels that constitute a cluster. In Fig. 7(d), each color represents a unique number for each cluster. The number of clusters and cluster volumes are quantified by counting the number of voxels that constitute each cluster.

3.4 Grain contact analysis
Water menisci basically exist at grain contacts and their distributions vary due to the rearrangement of the soil skeleton during shearing, which certainly affects the mechanical behaviors of unsaturated sand. It is important, therefore, to investigate the number of grain contacts. This analysis aims at counting the number of grain contacts and the coordination number for each soil particle. Prior to the grain contact analysis, each soil particle is separated using image processing implemented in the 3D imaging software Avizo9.4.0 (FEI). The procedure and techniques applied in this analysis are similar to those in a previous work (Ando et al., 2012). The soil particle phase is binarized using

![Fig. 4. Artifact of local tomography image: (a) difference in x-ray transmission length, (b) Deviation of CT value distribution.](image)

![Fig. 5. Modification of artifact due to difference in x-ray transmission length: (a) original image, (b) planer trend of artifact, (c) difference image, (d) CT value profile of original image, (e) CT value profile of difference image.](image)

![Fig. 6. Original CT image and trinarized image.](image)
the modified local tomography images (see Section 3.1), and the soil particles are individually separated by means of the watershed algorithm implemented in the Avizo9.4.0. The separated soil particles are labeled, giving a unique intensity number to all adjacent voxels which put the soils particles together. There is one voxel for the void phase between two soil particles having different unique labels, which is generated by the watershed algorithm to separate the soil particles. This indicates that a grain contact between two particles exists there; hence, the grain contact is defined as the position where one voxel for the void phase exists as the boundary of two soil particles having different labels.

Fig. 8 shows procedure of detecting grain contacts in the present study. Firstly, the search subset of $3^3$ voxels shifts by one voxel in the labeled image. When the subset contains the void phase voxels (the label is zero) which are adjacent to the center voxel for the soil particle phase whose label is $i$, the size of the search subset is expanded to $5^3$ voxels as the possible contact pattern. As there exist voxels for the soil particle phase whose label is $j$ in part of the extended subset, the center voxel in the search subset is regarded as the grain contact. Labels $i$ and $j$ are different from each other. The total number of grain contacts and the coordination number for each soil particle are calculated.

In order to confirm the validity of the grain contact analysis, the grain contact analysis was applied to the CT image scanning sphere-packed structure whose total number of sphere contacts and coordination number are known. The sphere-packed structure consists of 125 spheres of which 5 spheres are regularly arranged in each of horizontal and vertical directions, as shown in Fig. 9. The diameter of the spheres is 90 voxels (450 $\mu$m) which is equivalent to that of silica sand particles used in the present study. Fig. 10 shows the positions of the sphere contacts and the coordination number of each sphere in two dimensions. Table 1 lists the configurations of the sphere-packed structure. As indicated by Figs. 9 and 10, the positions of the sphere contacts were correctly detected. In addition, the total number of sphere contacts and the coordination number for each sphere calculated by the grain contact analysis were consistent with the known values of the sphere-packed structure. These results confirm the validity of the grain contact analysis proposed in the present study.

4 RESULTS

4.1 Macroscopic responses of unsaturated sand specimen under triaxial compression

Fig. 11 shows deviator stress-axial strain relationship, volumetric strain-axial strain relationship and shear strain distributions calculated by digital image correlation (e.g., Hall et al., 2010; Higo et al., 2013; Takano et al., 2015). The volumetric strain is calculated by counting the number of voxels corresponding to the specimen by means of

![Image](image1)

Fig. 7. Procedure of morphology analysis: (a) trinarized image, (b) binary image of pore water, (c) eroded and dilated image, (d) labeled image of pore water.

![Image](image2)

Fig. 8. Procedure of detecting grain contacts.

![Image](image3)

Fig. 9. Sphere-packed structure used for validation of grain contact analysis and detected sphere contact.

Table 1. Configuration of sphere-packed structure.

| Number of spheres | 125 |
|-------------------|-----|
| Total number of sphere contacts | 300 |
| Frequency of coordination number for each sphere (coordination number, frequency) | (1, 0) (2, 0) (3, 8) (4, 36) (5, 54) (6, 27) |
3D imaging software VGStudioMax3.1 (Volume Graphics GmbH). The shear strain levels shown in Fig. 11 are provided using the B matrix for the eight-nodes isoparametric finite elements and the second invariant of incremental deviatoric strain tensor is defined as the shear strain. Stress relaxation occurs at each step of the scans because axial displacement was fixed for 3 hours during scans. The deviator stress increases until an axial strain of 4% where the peak stress shows about 800 kPa, after which the post-peak softening occurs. The residual
stress is about 550 kPa at an axial strain of 21%. The sand specimen exhibits the volume expansion and the large shear strains develop in upper right and left directions with increase in axial strain.

4.2 Visualization using x-ray micro CT

Fig. 12 shows the CT images obtained by the global tomography and local tomography. In the CT images, the whiter color indicates the higher density region while the darker color indicates the lower density region. The middle part of the specimen beyond an axial strain of 4% becomes darker; namely, density is decreased with volume expansion.

In the global tomography images, the development of the lower density region in diagonal direction is apparently observed beyond an axial strain of 9%. This region corresponds to the position where the large shear strains locally develop, as shown in Fig. 12. This indicates that the shear band occurs as shearing progresses in the unsaturated sand specimen. It is clearly seen in the local tomography images that the void spaces locally expand as shearing progresses. Therefore, the shear band was successfully visualized in the local tomography region.

4.3 Variations in local void ratio and degree of saturation

Figs. 13 and 14 show variations in the local void ratio and degree of saturation calculated using the trinarized volumes obtained at each axial strain. Note that trinarization was not applied to the CT images at an axial strain of 21% because the obtained images were of low quality due to mechanical problems.

The local void ratio of 0.728 at an axial strain of 0% is very close to the global void ratio of the entire specimen. Conversely, the local degree of saturation of 40.5% at an axial strain of 0% is lower than the global degree of saturation of the entire specimen of 54.6%. This is because the trinarized volume, located at the upper part of the specimen, contain a smaller amount of pore water than the other portions of the specimen. The local void ratio increases, while the local degree of saturation then decreases with increasing axial strain. These indicate that water retention capability becomes lower with volume expansion.

Fig. 15 shows extraction of subvolumes inside shear band and outside shear band from the trinarized volume. The differences in the local void ratio and degree of saturation between inside shear band and outside shear band are investigated.

Fig. 16 and Fig. 17 show comparisons of the local void ratios and degrees of saturation between inside shear band and outside shear band from axial strains of 9% to 18%. It is apparent that the local void ratios are larger inside shear band than outside shear band and the local degrees of saturation are lower inside shear band than outside shear band. These results indicate that positive dilatancy is more significant and then water retention capability is lower inside shear band than outside shear band.

4.4 Continuity and number of pore water clusters

To investigate the water retention state in the trinarized volumes, continuity of the pore water is evaluated. The continuity is defined as the ratio of the maximum cluster volume to the total cluster volume in the trinarized volumes obtained at each axial strain. The continuity of 100% means that one cluster occupies the total volume of clusters; namely, a large cluster exists. On the contrary, the continuity of almost 0% means that the individual clusters exist independently and spatially.
In other words, a number of clusters with small volume exist. Note that the continuity is defined as an indicator for discussing the water retention states in the present study; it does not directly describe whether or not the pore water is really continuous. In real soil, the pore water existing at grain contacts is continuous entirely though absorbed water at the grain surfaces.

Fig. 16. Comparison of local void ratio inside shear band and outside shear band.

Fig. 17. Comparison of local degree of saturation inside shear band and outside shear band.

Fig. 18. Comparison of local degree of saturation inside shear band and outside shear band.

Fig. 18 shows continuity of pore water-axial strain relationship in trinarized volumes as well as inside shear band and outside shear band. This indicates that the continuity is kept lower than 10% until an axial strain of 18%. Note that the continuity of pore air is almost 100% at each axial strain. These results indicate that pore water in trinarized volumes exist as water menisci.

Number of pore water clusters-axial strain relationship in the trinarized volumes from axial strains of 0% to 18% is shown in Fig. 19. This indicates that the number of pore water clusters is relatively large until an axial strain of 4% and is decreased with increase in axial strain. Considering the result that pore water cluster exists as water meniscus, the number of pore water clusters is equivalent to the number of water menisci. Therefore, water menisci are decreased as shearing progresses.

Fig. 20 shows number of pore water clusters-axial strain relationships inside shear band and outside shear band. With increase in axial strain, the number of pore water clusters is decreased. A smaller number of pore water clusters exists inside shear band than outside shear band.
4.5 Variation in grain contacts

Table 2. lists number of soil particles given by the watershed and the cluster labeling. Fig. 21 shows number of grain contacts-axial strain relationships inside shear band and outside shear band, which indicates that the number of grain contacts is increased outside shear band, while that is decreased inside shear band.

Figs. 22 and 23 shows coordination numbers of grain contacts inside shear band and outside shear band. The coordination number means the number of grain contacts per a grain. The number of grains with the coordination number of 3 or 4 is kept larger outside shear band. On the contrary, inside shear band, the number of grains with the coordination number of 2 or 3 is larger and the coordination numbers of 3 and 4 are decreased at an axial strain of 18%.

Table 2. Number of soil particles.

| Axial strain (%) | 9   | 12  | 15  | 18  |
|------------------|-----|-----|-----|-----|
| Inside shear band| 2664| 2556| 2534| 2385|
| Outside shear band| 3097| 3168| 3330| 3329|

Fig. 21. Number of grain contacts-axial strain relationship inside shear band and outside shear band.

Fig. 22. Coordination numbers of grain contacts inside shear band.

Fig. 23. Coordination numbers of grain contacts outside shear band.

Fig. 24. Example of position of pore water cluster.

5 DISCUSSIONS

Fig. 24 show example of presence of pore water cluster, which indicates that the pore water cluster separated by the morphology analysis apparently forms water meniscus between grains.

It is clearly seen in Figs. 11 and 19 that a large number of water menisci exist until the peak deviator stress, after which the water menisci tend to decrease as shearing progresses. Namely, the strain hardening occurs under a large number of water menisci, whereas the strain softening corresponds to the decrease in the number of water menisci. This is because a large number of water menisci, at which suction works as inter-particle force, effectively contributes to the stiffness of the unsaturated sand until the peak deviator stress, whereas the suction effect tends to be decreased due to the loss of water menisci. In the meantime, the level of suction in the unsaturated sand is certainly kept constant during triaxial compression test because the test condition is drained conditions for air and water. Therefore, the strain softening of unsaturated sand is attributed to not only decreasing density caused by positive dilatancy but also decreasing water menisci with a certain level of suction during shearing.

As indicated by Figs. 21 to 23, the grain contacts are decreased as shearing progresses and a smaller number of grain contacts exists inside shear band. This is certainly because of more significant volume expansion...
as shown in Fig. 16, and this tendency corresponds to the post-peak softening of unsaturated sand specimen as displayed in Fig. 11. The previous study, e.g., Marte and Abdalsalam (2014), have confirmed that the force chains that comprise a set of particles which transmit compressive load through their particle contacts are collapsed due to the loss of particle contacts during shearing, which causes the softening of the particulate structure. The post-peak softening accompanied by decreasing the grain contacts inside shear band observed in the present study corresponds to the previous findings. Therefore, the decrease in the grain contacts, in particular, inside shear band, causes the collapse of force chains, leading to the softening of unsaturated sand specimen.

Comparison of Figs. 20 and 21 confirms that the tendency for decreasing grain contacts corresponds to the tendency for decreasing water menisci as shearing progresses inside shear band. In other words, decreasing water menisci is accompanied by decreasing grain contacts. This indicates that the suction effect on the stiffness of unsaturated sand is smaller inside shear band than outside shear band because of decreasing water menisci and a smaller number of water menisci. Therefore, the influence of decreasing the water menisci on the strain softening is more significant inside shear band than outside shear band.

6 CONCLUSIONS

Progressive deformation of unsaturated sand specimen under triaxial compression under drained conditions for air and water, i.e., under constant suction, was visualized using x-ray micro CT. The numbers of grain contacts and water menisci inside shear band and outside shear band were investigated using image analysis techniques.

Local void ratio is increased and then local degree of saturation is decreased with development of shear band. The decrease in water menisci is accompanied by decreasing grain contacts as shearing progresses. These trends are more significant inside shear band due to more significant volume expansion.

The decreases in the numbers of water menisci and grain contacts correspond to the strain softening of unsaturated sand. Therefore, the causes of the strain softening of unsaturated sand is not only decreasing density caused by positive dilatancy but also decreasing water menisci inside shear band.

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