CHAPTER 7

RESULTS AND DISCUSSION - VISUALIZATION OF LOOSENING IN TRIAXIAL SPECIMEN BY X-RAY CT IMAGES

7.1. Introduction

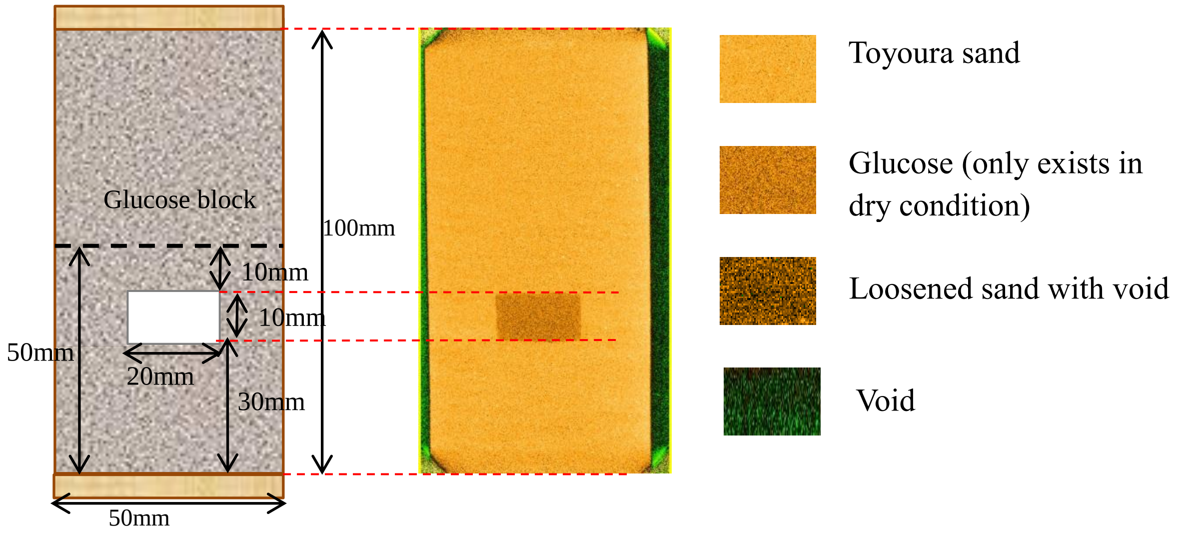
Extend of ground deformation or loosening formed by dissolving glucose in the triaxial tests was not visible though quantitative measurements were done based on assumptions as explained in Chapter 6. Hence, attention was directed to visualize the real situation, extend of loosening in triaxial test by capturing X-ray CT scanning images at important stages of similar triaxial test. The methodology of this test was discussed in Chapter 3.4.5. Control condition of the test is shown in Table 7.1.

Table 7. 1: Conditions of the test

Material	Toyoura sand
Relative Density (Dr %)	41.1%
Void ratio, (e)	0.8
Volume ratio (cavity/specimen)	1.5%
Moisture content at shearing	18%

Small trixial test with Toyoura sand was performed and glucose block was placed inside the specimen as in Figure 7.1(a). X-ray image related to the vertical section of initial stage is shown in Figure 7.1(b) with the referred colour code (Figure 7-c). Two water cycles were applied and X-ray CT scan was done before and after drainage of each cycle. Altogether, images were taken at five stages during wetting and drying cycle as explained in Figure 3.47 and summarized as below.

Stage 1 – **Initial** - Initial (Dry specimen)
Stage 2 – **Cycle -1(In)** - After 1st water infiltration
Stage 3 – **Cycle- 1(out)** - After 1st water drainage
Stage 4 – **Cycle -2(In)** - After 2nd water infiltration
Stage 5 – **Cycle -2(Out)** - After 2nd water drainage



(a) Schematic (b) X-ray CT image (c) Colour code for X-ray image

Figure 7. 1: Vertical sectional view of initial condition of triaxial specimen

7.2. Results and discussion

7.2.1. Influence of water infiltration and drainage on loosening process

2-D images of cross sectional views taken at four locations of the specimen with water infiltration and drainage process is shown in Figure 7.3. Orientations of selected cross sections are also illustrated in Figure 7.2. Arbitrary Z axis was defined for the specimen in order to easy illustration of sectional views. Three sections were selected across the potential cavity as passing through the bottom, center and the top surface of the glucose block which was referred as Z = 0, Z = 5mm and Z=10mm respectively (Figure 7.2). Another section was considered as crossing through 5mm above the potential cavity to observe the effect of soil loosening (z=15mm). Transformation of soil structure with dissolving glucose and cyclic water infiltration and drainage is illustrated by cross sections and vertical sections in Figure 7.3, Figure 7.4 and 7.5.

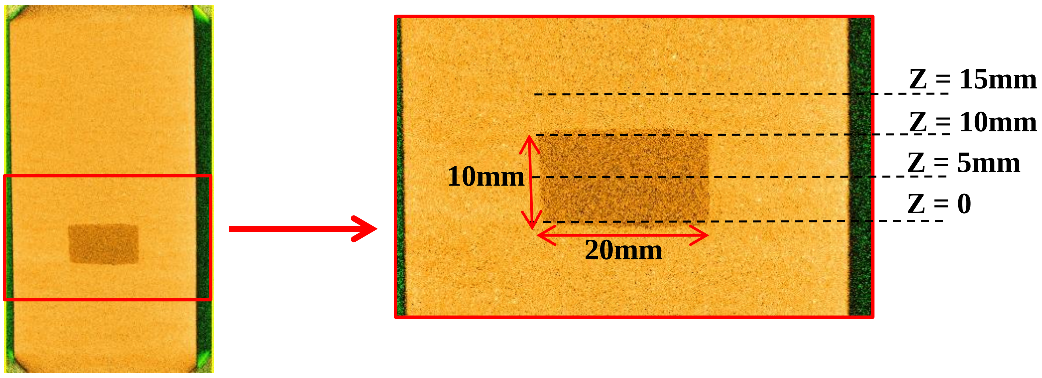


Figure 7. 2: Location of selected cross sections referred to a defined Z axis

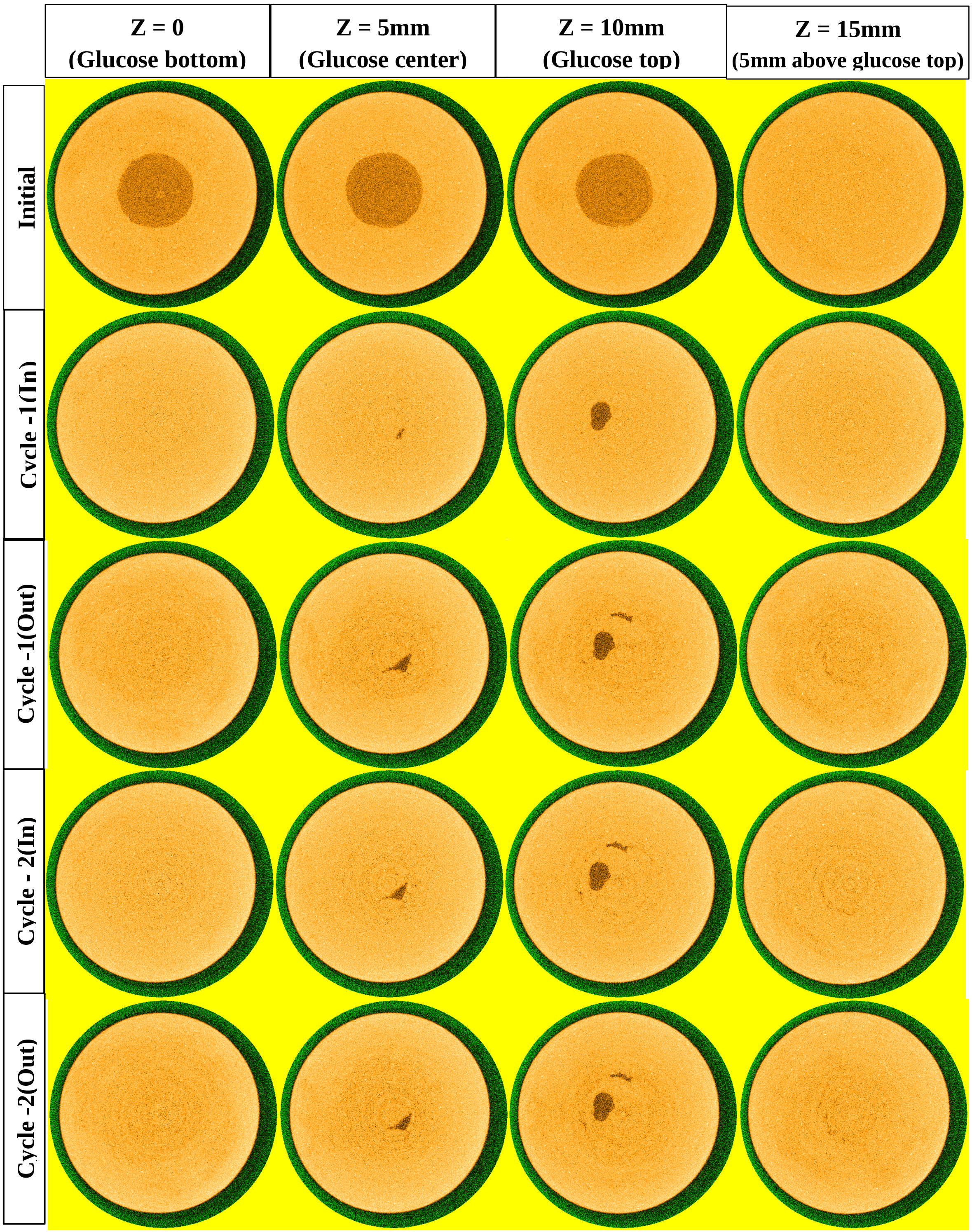


Figure 7. 3: Cross sectional images for visualizing of ground loosening with water cycles

(For high definition images refer Appendix-III)

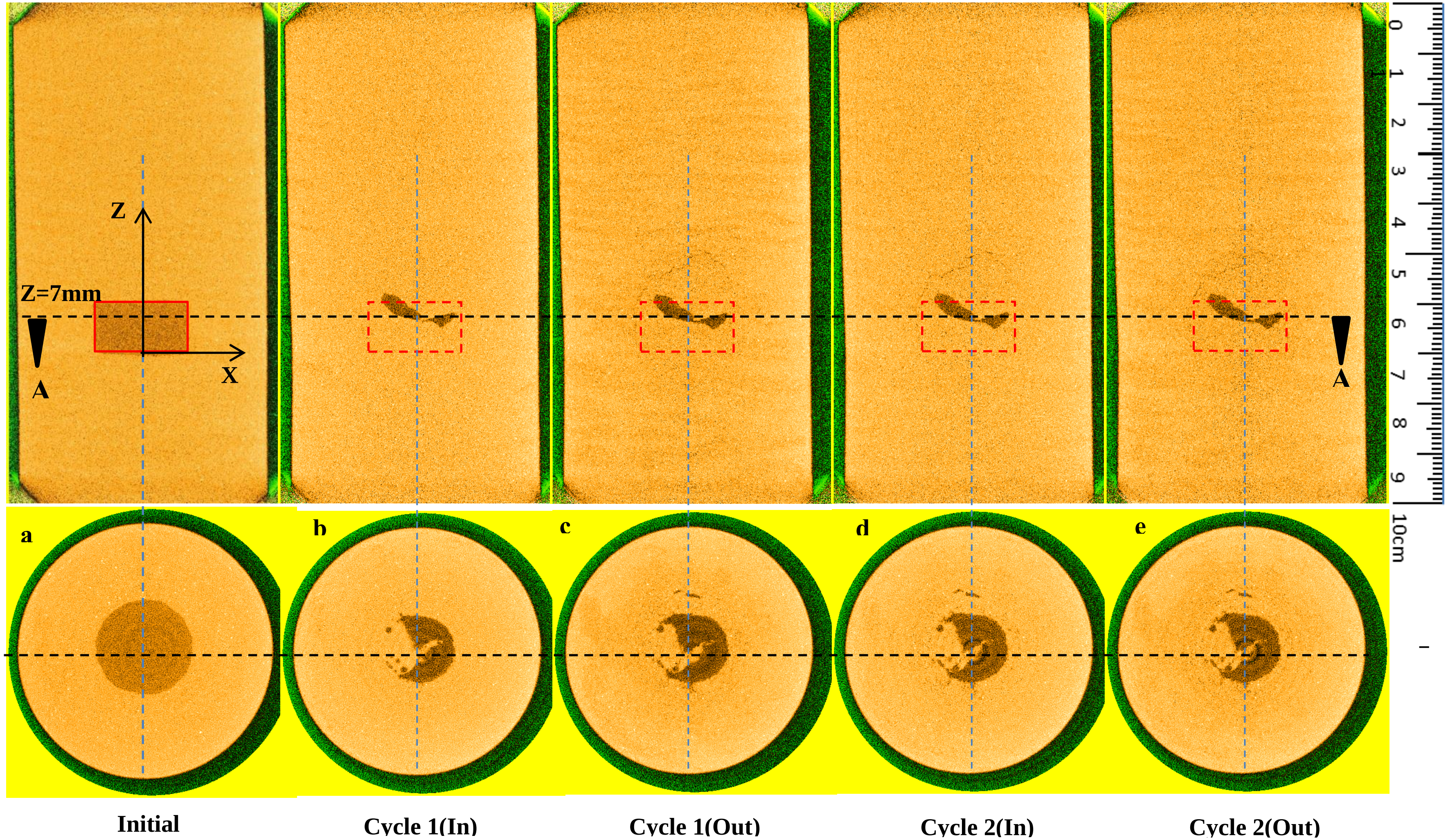


Figure 7. 4: Cross sectional and vertical sectional images for visualizing of ground loosening with water cycles (XZ plane)

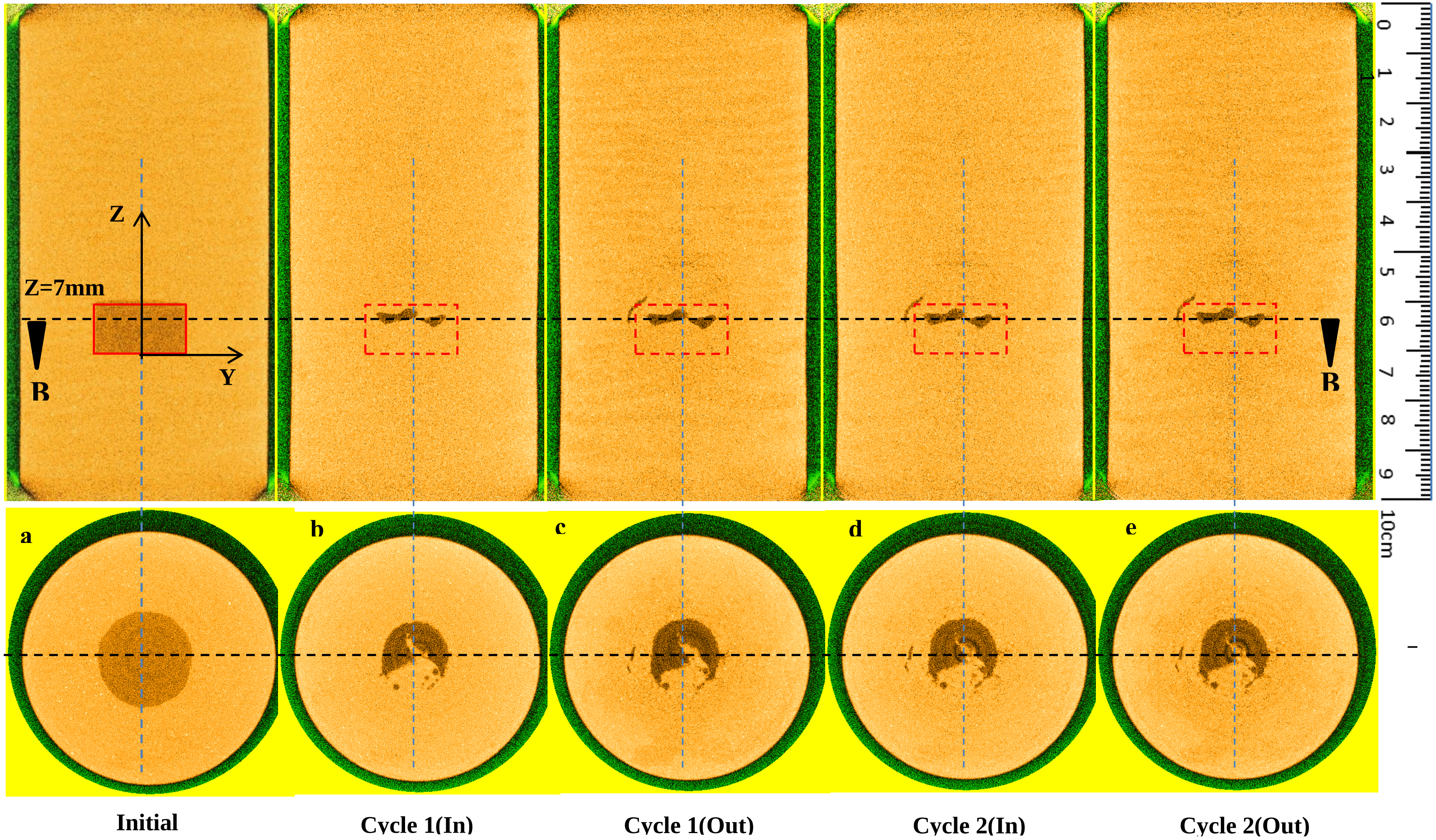


Figure 7. 5: Cross sectional and vertical sectional images for visualizing of ground loosening with water cycles (YZ plane)

Behavior of cavity formation and propagation of loosening during each step can be discussed as below

- **Initial ⟶ Cycle -1(In)**

When water was passed through the specimen from bottom to top, glucose block has completely dissolved. Meanwhile, irregular shape cavity has created closer to the top part of the glucose block. Figure 7.4 and 6.5 clearly illustrate the location and size of newly formed cavity reference to glucose block by vertical and cross sectional views. At this stage, nearly lower half of the potential cavity has filled by loosened and collapsed sand (Figure 7.3, 7.4, 7.5). It is obvious that the soil which moved and replaced the glucose block should have a lower density than the normal surrounding. However, it seems difficult to distinguish such density difference in that region since particle size of Toyoura sand is very finer.

The new cavity is originated from z = 4.8 mm and spread up to z =10.25mm. Therefore the maximum height and width of the cavity is 5.45mm and 14.6mm at this stage. Soil sited on cavity should be affected by loosening effect since the real cavity location is slightly moved up than the potential cavity. However, such weak or loosened region can't be identified clearly by these images.

- **Cycle -1 (In) ⟶ Cycle -1 (Out)**

When the water was drained out from bottom, part of soil around the originated cavity seems to be separated from normal ground. Planner view taken from a 3-D viewer is shown in Figure 7.6 and difference between two stages can be clearly observed by cross sections and vertical sections shown in Figure 7.3, 7.4 and 7.5. Four Cross sections in Figure 7.3 depicts that cavity has propagated, after drainage with spreading loosening even up to z = 15mm level. Maximum height of loosened region is nearly twice of the initial height of glucose block. This ratio observed in two dimensional model tests was nearly 5 which are larger than three dimensional behaviour. This might be due to lower surcharge applied and plain stress condition of model ground. Furthermore, wall friction effect on stress distribution might also be influenced. Extent of loosening is almost similar to the width of the initial cavity, this might be due to gravity effect during infiltration and drainage.

Maximum width of the originated cavity has slightly expanded to 15mm and height is 5.45mm, which is similar to the initial.

- **Cycle -1 (Out) ⟶ Cycle -2 (In)**

After completing one cycle of water, cavity was still remained which will facilitate us to observe the ground deformations with repetitive infiltration and drainage process. Therefore specimen with already loosened ground was subjected to another water cycle. In order to save the time, the amount of water infiltrated in 2nd cycle was smaller than the 1st cycle which was just sufficient to completely penetrate through the specimen height (200ml). The objective was only to observe the influence of water infiltration and drainage on a stabilized cavity with surrounding loosened sand.

2nd infiltration hasn't significantly influenced on propagation of loosening other than smaller reduction in maximum width of cavity. It has reduced from 15mm to 13.6 mm. However, the region of soil which was separately observed in previous stage was affected by 2nd infiltration. Boundary of the loosened region and normal sand has affected and it shows these two regions are slightly blended together with 2nd infiltration. Therefore, the degree of loosening or the overall strength might be higher than the initial.

- **Cycle -2 (In) ⟶ Cycle -II (Out)**

There was no significant influence other than the loosening was further propagated up by nearly 2 mm.

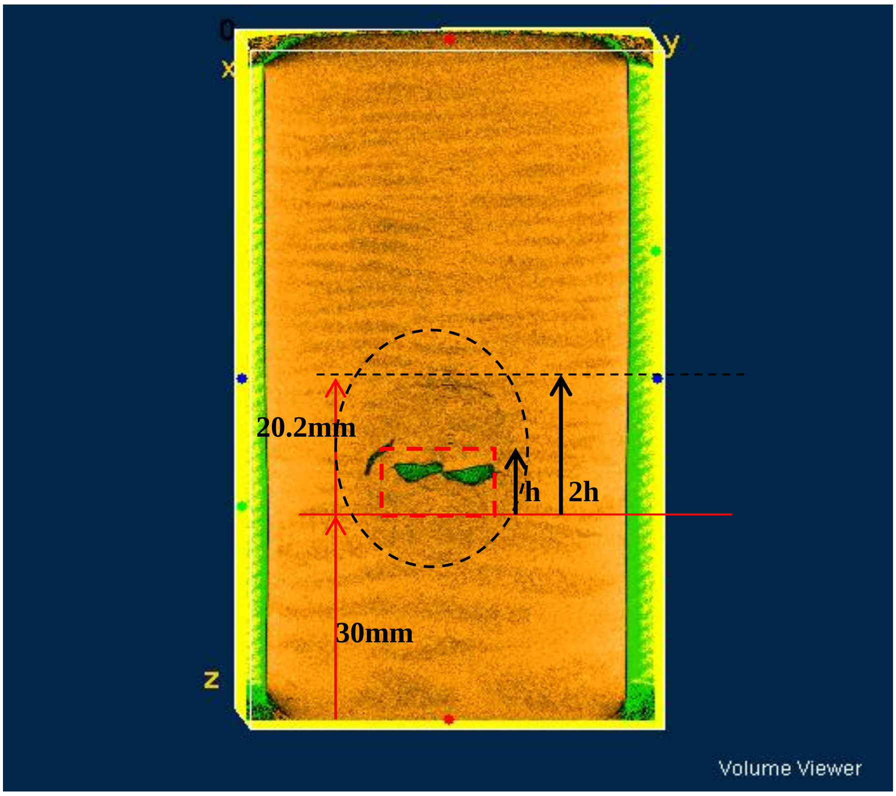


Figure 7. 6: Area affected by loosening – after 1st drainage

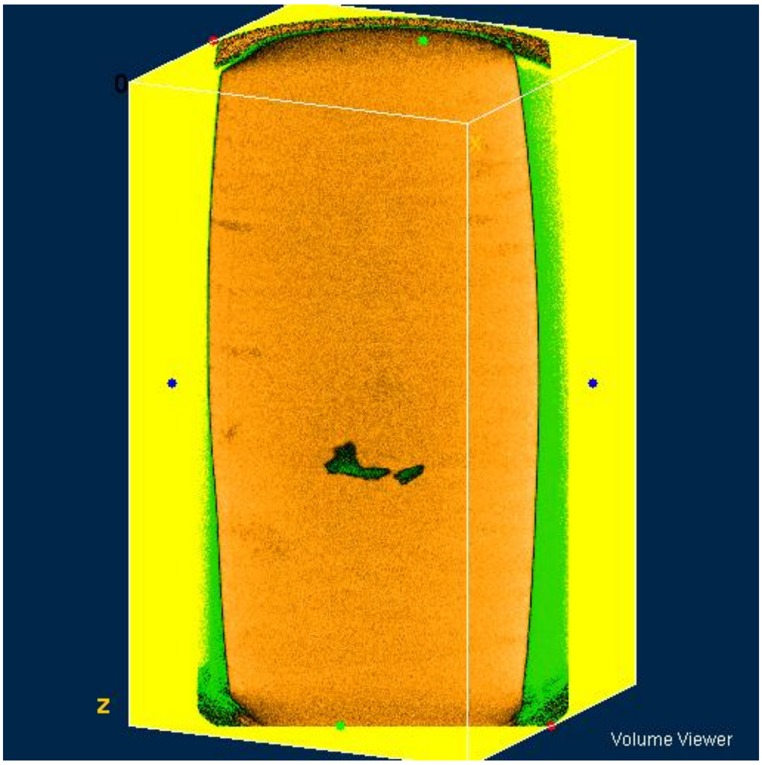


Figure 7. 7: Planer view from volume viewer after 1st water infiltration

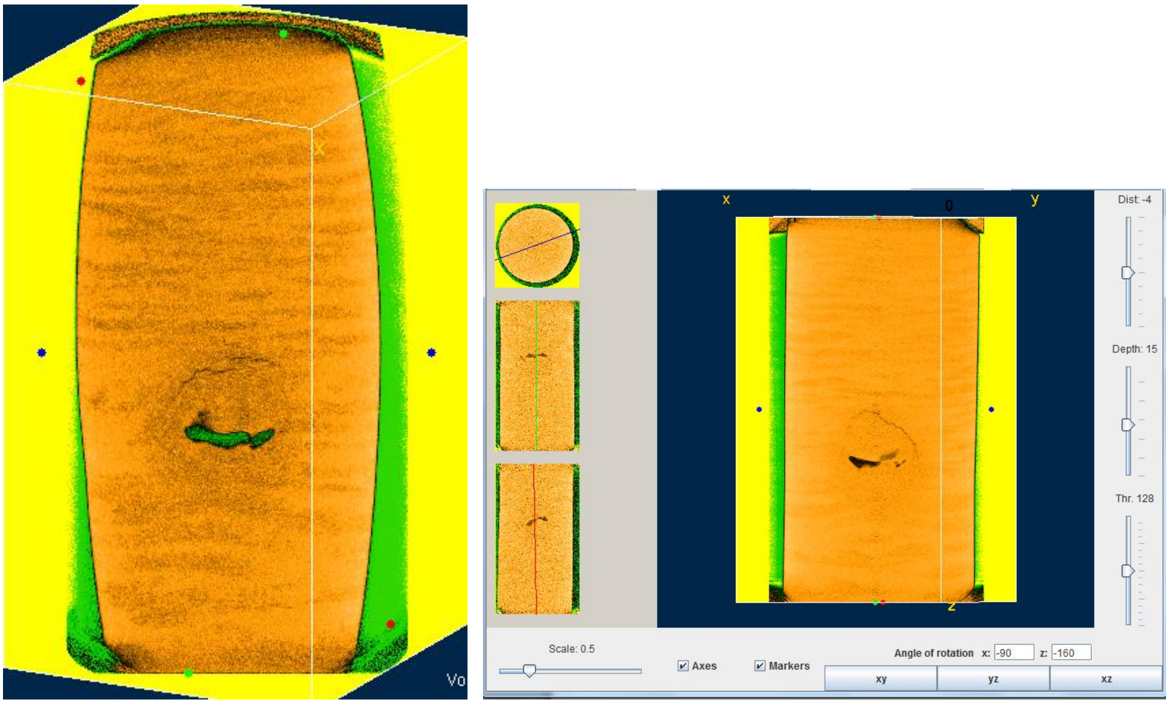


Figure 7. 8: Planer view from volume viewer after 1st drainage

7.2.2. Collapsing behaviour of loosened soil accompanied with a cavity during shearing

Once ground loosening associated with a potential cavity was observed by water infiltration and drainage process, speacimen was subjeted to triaxial shear. Test was done under strain control condition with strain rate of 0.1% per minute under drained condition.

X-ray CT scanning was performed at different strain levels at ε_a = 3%, ε_a = 6.5%, ε_a = 11% and finally at ε_a = 17%. Deviator stress- axial strain relationship is shown in Figure 7.9. During scanning process at above mentioned strain level, applying of axial stress was stopped as a requirement for scanning process. It takes nearly 45 – 60 minutes for scanning whole specimen. Therefore applied stress was not continuous and having unloading and loading condition at three locations as in Figure 7.9. Compassion of this result with previously conducted laboratory experiments (NC, CB45-L with specimen size h=150mm and dia=75mm, Dr=35%) are shown in the Figure 7.10. Shear strength and stiffness of the smaller specimen conducted in PARI shows larger than which was conducted in the University. There can be two reasons for this effect.

- Density of test conducted for X-ray scan is slightly larger than other two tests
- Size of the specimen and glucose block is different and therefore boundary conditions are different.
- Stress and strain measurements were done with different instruments which can affect the computed values.

However behaviour of soil deformations are progressively occurs and abrupt collapse around the cavity was not observed which was similar to the tests conducted previously for similar range of density in University. Progressive behaviour of collapse of cavity and densification of loosened region is illustrated with vertical and cross sections in Figure 7.11. Cross sections were selected at 6mm above the bottom of initial glucose block since that place was the originated cavity observed even at 6 % of axial strain.

Loosened soil sited on cavity ceiling has progressively densified with triaxial compression without causing sudden collapse. That might be due to smaller strain rate (0.1% per min) and the loose sand. (Dr = 41%) In triaxial shearing process, effective soil region will be formed as column shape starting from top of the specimen to resist against the applied vertical stress. Whenever the stress increases the maximum shear strength of soil, specimen will be failed with forming a shear band. In loosened sand, stress transformation from top to bottom of the specimen is much uniform than dense. Loose sand will be densified progressively with application of deviator stress. Therefore, existing cavity will be disappearing gradually after replacement by densified sand which was previously existed in loosened condition. Total volume of the void has disappeared at 6% of axial strain.

However, the collapsing behaviour of real ground is different than this. Most of the road cave-ins are abrupt though few notifications are visible on ground surface before failure. This pattern is different since, cavities in real ground is forming throughout a long period with slower internal erosion. In that case, cavity ceiling is much stable than here. Furthermore scale effect of this small scale specimen can affect for this. Or else, loosening part might not be effectively working in sinkholes in dense ground, where the strength of cavity ceiling is very important.

After achieving the peak shear strength at about ε_a = 10%, shear band was observed in X-ray images captured at ε_a = 11% and 17%. Shear band related to each case is shown in Figure 7.12 and 7.13 respectively. It is clearly observed that the shear band has formed as crossing through the artificially formed loosened part and cavity.

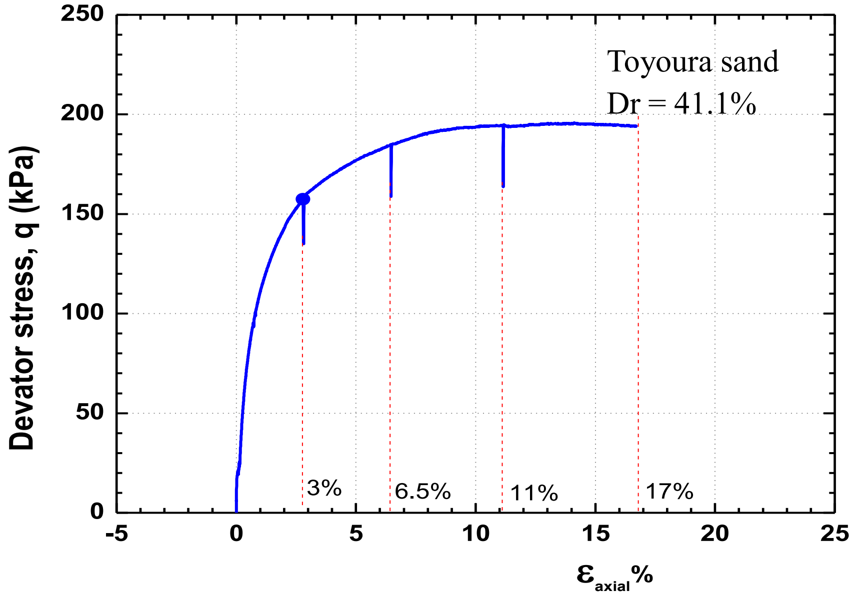


Figure 7. 9: Deviator stress, q vs. axial strain

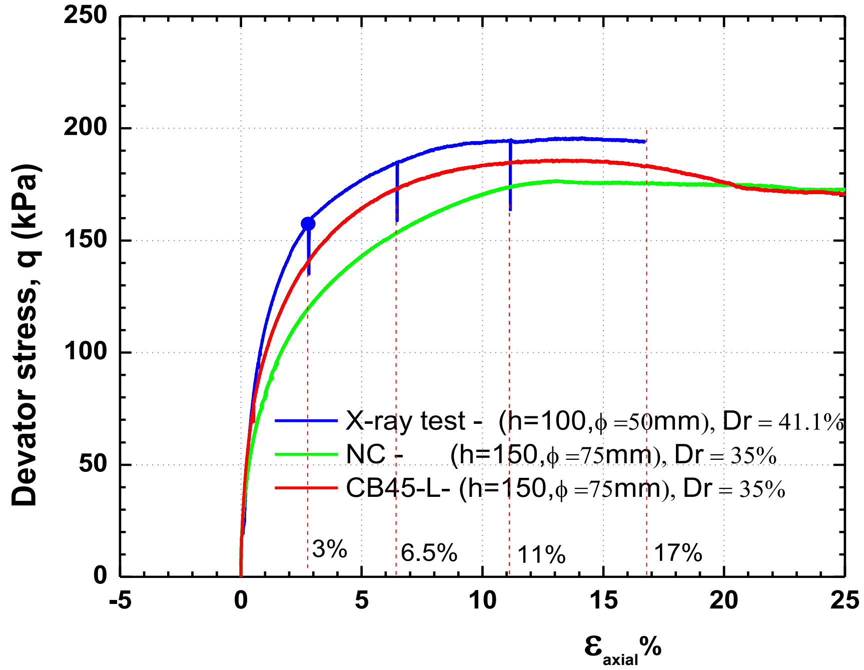


Figure 7. 10: Comparison of q vs. ε_a of X-ray image test with related other test

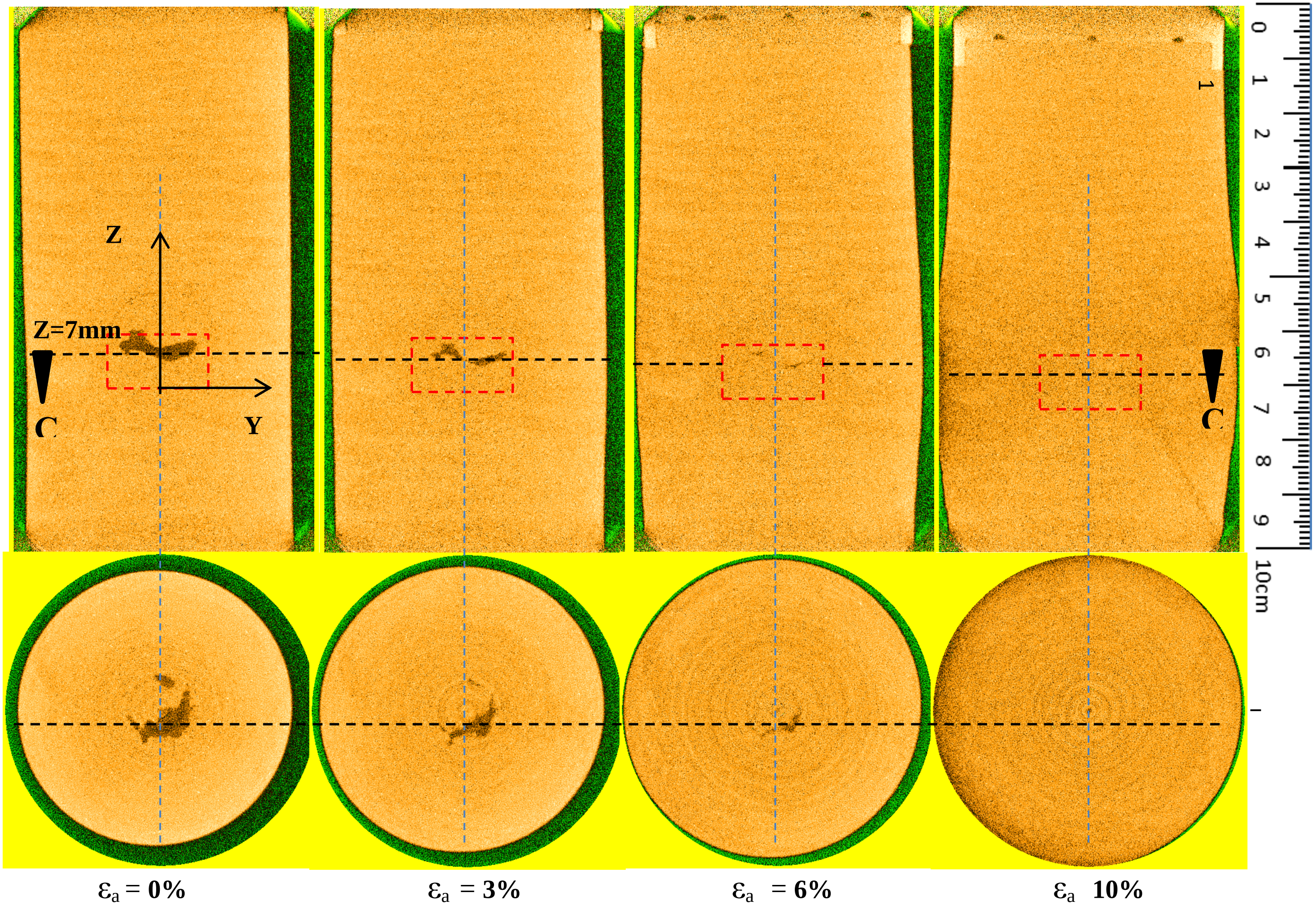


Figure 7. 11: Cross sectional and vertical sectional images for visualizing of ground deformation during triaxial shearing (XZ plane)

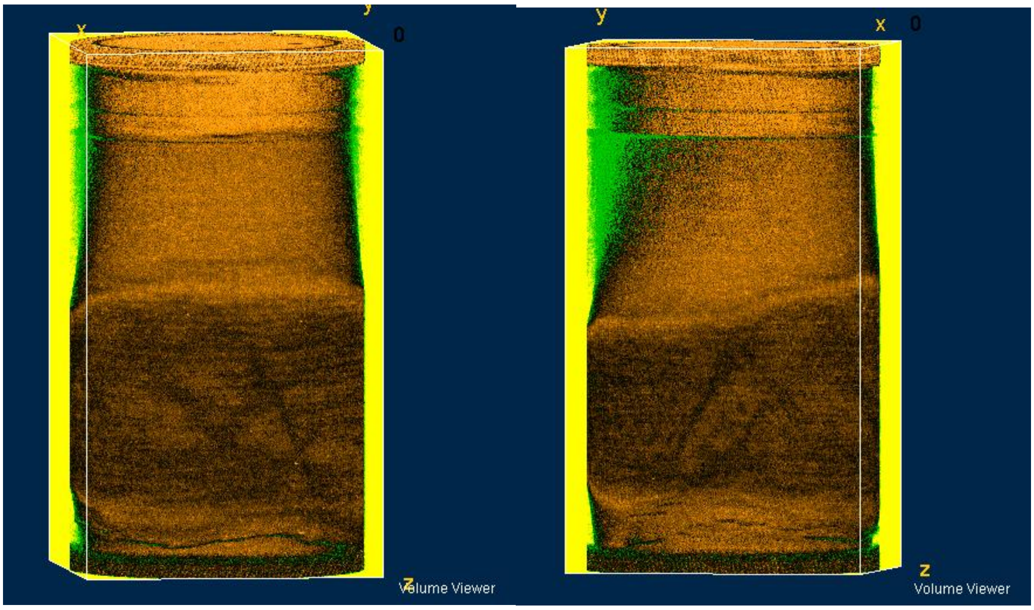
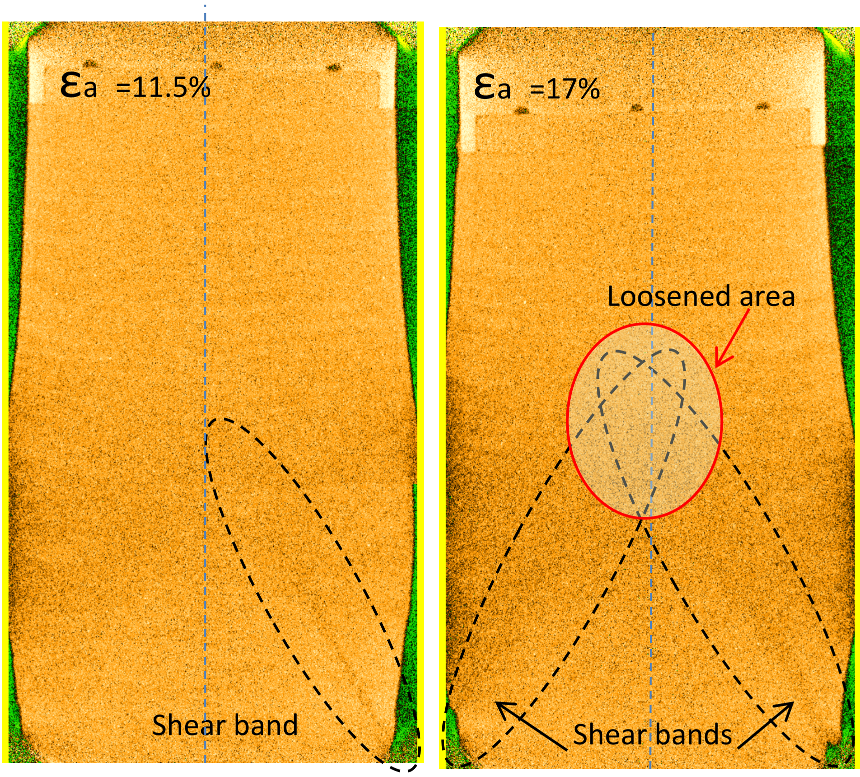


Figure 7. 12: 3-D view of specimen after applying shear up to ε_a = 17%



(a) ε_a = 11.5% (b) ε_a = 17%

Figure 7. 13: Shear band formation at (a) ε_a = 11.5% (b) ε_a = 17%

7.2.3. Summary

In loosening sand, potential cavity is filled by sand which was initially sited on cavity and new cavity is originating above existing cavity. The propagation of loosening is not rapid around the cavity in loose sand, as also observed in two-dimensional model tests. In model tests, loosening had spread vertically up to 5 times of initial cavity, though in triaxial test it is only around two times of the initial cavity. This might be due to lower surcharge (10kPa) applied in model test while 50kPa of confining pressure was used in Triaxial test. In model tests loosening had spread even in lateral direction and in triaxial test width of loosened region is almost equal to the initial width of potential cavity.

However, drainage has influenced on soil collapse above the cavity and also for loosening effect. As previously observed in model test no.2, rapid drainage caused significant effect on loosening and cavity collapse. Such rapid deformations were not observed in triaxial specimen. The reason might be drainage valve of triaxial apparatus is very small and similar rapid drainage can't be obtained in triaxial test as model test. Second infiltration through the cavity has no significant effect on propagation of loosening when the surrounding soil is wet. Similar effect was observed in model test no-2 in chapter 5.

While applying the monotonic loading on already loosened triaxial specimen with a cavity, shows steady and progressive deformation. Sudden collapse with large ground deformation was not observed as in real practice of sinkholes. This can be due to lower density and uniform grain size, used in this example. However, stiffness of the loosened sand has reduced than the normal ground as discussed in Chapter 06. Even in this example, shear band has developed through the weakened part of specimen as crossing the loosened part. It is difficult to make a general conclusion, as this behaviour is only observed under loose density and uniform grain materials.