

CHAPTER -08

Conclusions and Recommendations

During the last few decades, there is an increased record of cave-in accidents, all over the world. Ground subsidence occurs by forming underground cavities that leads to propagation of loosening towards the ground surface by internal erosion. Modern techniques such as ground penetrating radar are available to detect cavities located in subsurface. However these technologies can only be accurately applied within few meters deep from surface. Furthermore, they only target air filled voids. Since, most cavities are not entirely filled by air, the probability of accurate detection decreases. The suggested method detecting the clear cavity combined with the loosened region and thereby the accuracy could be enhanced. This facilitates detection of cavities even in deeper locations since; loosening is propagated towards the ground surface. Then the accuracy could be enhanced in a cost effective manner. At present, cavity formation and loosening propagation has not properly addressed by geotechnical engineers. This theme is still in preliminary investigation level, therefore, it would be worth to take the first step to find the extent of loosening, the parameters that affect the loosening and mechanical properties of loosened soil. These findings will help to start a new journey towards improving the cavity detection technologies.

In order to achieve above mentioned objectives, two dimensional model tests were conducted to form artificial loosening in laboratory while observing the parameters which affect the degree of loosening. Secondly, same concept was used to form loosening in triaxial specimen and mechanical properties of loosened sand were evaluated. Furthermore, X-ray CT imaging was conducted to observe the extent of loosening in triaxial specimen.

8.1. Conclusions

- Loosening spread vertically up to five times of cavity height in plane strain condition while it was two times in 3-D condition. Loosening expansion in radial direction was very limited in 3-D case, though it was significant in plane strain condition in model tests. Therefore it was confirmed that loosened region is significantly larger, at least twice of the cavity height in subsurface.

- It was found that ground collapse around the potential cavity was higher when the cavity was located above the ground water table rather than beneath the water table. Cavity formed in compacted or dense soil was more stable compared to loose soil and extents of loosening were proportional to cavity size. Furthermore, it can be strongly stated that lower density and cavity located in shallower depth increase the extent of loosening. The point is many cavities originated by pipe defects are located above water table, within 2-4 meters from the surface. Therefore, those cavities are in danger during rainy period.
- When the water was infiltrated and drained out through a cavity, it was witnessed in both two dimensional model tests and triaxial tests that soil sited above original cavity was gradually collapsed into cavity which lead to create a new cavity above the original one. Loosening was mainly expanded vertically upward than radial which can be due to direction of seepage. This fact reveals that, even the cavities originated in deep ground will be gradually moved up, towards the surface during the water table fluctuations repeatedly in droughts and rainy seasons.
- Stability of created cavity ceiling was supported by suction pressure. During water infiltration, cavity collapsing forces were restrained by the suction effect. When the drainage was maintained very smoothly, ground loosening was very limited and abrupt collapse with large loosening was recorded with rapid drainage.
- Young's modulus and small strain modulus evaluated using local deformation measurements have shown reduction for loosened sand, with first and second infiltration process. E , G_s values of loosened sand is nearly 75-85% of the normal sand with similar water infiltration and drainage. Somehow, these values are not representing the real characteristics of loosened sand, which should be rather small since loosened region is inside the specimen and deformation transducers were not directly attached to loosened region.
- In order to evaluate reliable values on stiffness characteristics, parametric analysis was conducted by defining a specific region of loosening based on X-ray CT images (height is twice of cavity height). Computed stiffness values of loosened region in lower density specimen was much lower than which was computed earlier by deformation transducers. Loosening caused by large cavity was having nearly 50% of the non-loosened stiffness and for smaller cavity it was 60%. This means, loosened sand has much lower stiffness than the surrounding soil. This will be a new finding to study more about behaviour of loosened sand since mechanical properties of loosened soil is still unknown.
- When the cavity and loosened region was formed in lower density specimen, progressive loosening expansion was recorded by repetitive infiltration and drainage which was very small in dense specimen. Similarly, expansion of loosening in lower

density specimen at confining pressure of 50 kPa was larger than specimen with confining pressure of 100 kPa. This again states that cavities at shallower depth are much vulnerable for repetitive water fluctuations than cavities at deep ground hence much attention has to be paid on near surface cavities.

- However, it was very difficult to identify a clear tendency of variation of Poisson's ratio when the degree of loosening was changed by soil density, cavity size or cavity location.

So far, there is no record of Poisson's ratio of loosened sand. Therefore, this might be the first time of evaluating the Poisson's ratio of loosened sand. Poisson's ratio of loosened sand has to be theoretically different from uniform sand, because loosening is mostly non uniform in the ground and which can have an unpredictable soil structure re-formation with different scale of voids. Therefore, the relation of transverse and vertical deformations become complex and unpredictable, since the orientation of weaker plane of loosened soil is governed by many local factors around the cavity and loosened area. Hence, this kind of complex behaviour of Poisson's ratio can be accepted.

- When the cavity location was changed as bottom and 45mm from bottom, stress-strain relationship during triaxial shearing was different. Shear band developed at failure was above the cavity and loosened region. Since the loosened region is quite below the shear band, stress-strain relation was not affected by loosening. It was almost similar to the control specimen. On the other hand, when the cavity was originated 45mm from bottom, loosened region was across the shear band which caused reduction in stiffness. Which means cavities in deep ground might sustain for large stresses without causing sudden subsidence.
- In lower density specimen, volumetric strain (ϵ_{vol}) measured after first infiltration for small (0.25% of specimen volume) and large cavity (1.5% of specimen volume) shows ϵ_{vol} is nearly proportional to volume of cavity. ϵ_{vol} initiated by large cavity was nearly six times larger than the small, which is similar to the ratio of volume. Therefore, vulnerability of cavity induced collapse and loosening might be increased when the cavity expands with time.
- Shear strength of loosened sand in lower and dense specimen during triaxial shearing shows two different failure mechanisms. Dense specimen follows the similar stress – strain path as controlled specimen until $1/3^{rd}$ of maximum strength is achieved. Then the stiffness is decreasing and sudden failure due to collapse of cavity is recorded after achieving about $3/4$ of peak strength. Specimen with lower density ($D_r = 36\%$) follows similar path as control specimen up to its $1/4$ of peak strength. Then stiffness is gradually decreasing by achieving lower peak strength at higher strain level than controlled specimen.

- The same argument was confirmed by analyzing X-ray CT images carried out for a lower density specimen. Cavity was gradually filled by loosened soil which was sitting above the cavity and after 7% of axial strain cavity was totally filled without causing sudden collapse in cavity ceiling. Which means loosened soil at lower density can be gradually compressed without causing rapid deformations while loosened sand in dense ground is subjected to sudden collapse during large axial strain levels. That fact is acceptable, since most road subgrades are having higher density and subsidence recorded was sudden.
- During the 1st water infiltration, medium dense Silica sand shows larger axial, radial and volumetric strain than Toyoura sand. During the second infiltration Silica sand shows further contractive deformations while deformation level is negligible in Toyoura sand. This means in Silica sand loosening was further expanded and might be the degree of loosening was reduced when the area of loosening was increased.
- Poisson's ratio of control specimen of Silica sand shows consistent values throughout the test. However, in loosened Silica sand Poisson's ratio has significantly increased by 1st water cycle and it was unchanged by 2nd infiltration. In case of stiffness parameters of Silica sand, stiffness was reduced to almost half of the initial value with 1st water infiltration. However, 2nd infiltration has not affected further reduction in stiffness. It confirms that, as explained previously, deformations were further increased by 2nd infiltration causing degree of loosening to be decreased with self-healing effect.
- Other than main findings stated above, the effect of wall friction on stress distribution of small and thin two dimensional model ground was observed and it develops non-uniform model ground though most of us expected the model will behave in uniform manner.

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Prior to conducting this study, knowledge on cavity formation, parameters which are affecting on extend of loosening and mechanical properties of such loosened soil were not well understood. This research was capable to reveal many facts about ground cavity expansion and propagation of loosening in sandy soil. Some important mechanical properties of such loosened soil were evaluated though it was completely unknown at first. It is obvious that, these findings will be the foundation to improve the cavity detection technologies to higher accuracy with further evaluation of these properties, not only for sandy soils, but for other soil type as well. Therefore following recommendations can be made in order to achieve the ultimate objective of detecting the subsurface loosening, combining the cavity detection technologies with targeting loosened region as well.

8.2. Future Recommendations

- In order to detect both air filled voids with the loosened region, it is essential to find the dielectric constant of loosened soil. Dielectric constant of different soils at different moisture content need to be evaluated. Results and facts obtained in this study will be useful in order to achieve that.
- Density and compaction effort seems to be an important parameter which affects the extent and behaviour of loosening. Therefore, it will be worth to understand the loosening behaviour in different densities and compaction efforts in detail.
- **PIV** (Particle Image Velocimetry) can be used to observe the particle movement during process of loosening in triaxial specimen by X-ray CT images. For small grain soil, small steel particles can be mixed for easy particle detection.
- In similar triaxial test with loosening inside, loosened sand can be further investigated by conducting particle size distribution by taking that loosened soil away after the test. This will support to compare the fine content in loosened region and the rest to analyze the fine particle erosion from soil around the loosened region.
- Evaluated properties can be used to conduct a numerical analysis on ground loosening behavior of granular material associated with cavities, by using Discrete Element Method (DEM).
- Poisson's ratio of loosened soil should be studied more accurately and in detail. Clip gauges used in this analysis was not sensitive enough to measure small strains. Therefore, radial strain measurement has to improve with higher accuracy to observe the variation of Poisson's ratio.
- LDT arrangement used in this analysis, does not allow to directly measuring the stiffness properties for loosened region separately. Small size LDT can be fixed as it is fixed within the loosened region, for better representation on properties of loosened sand

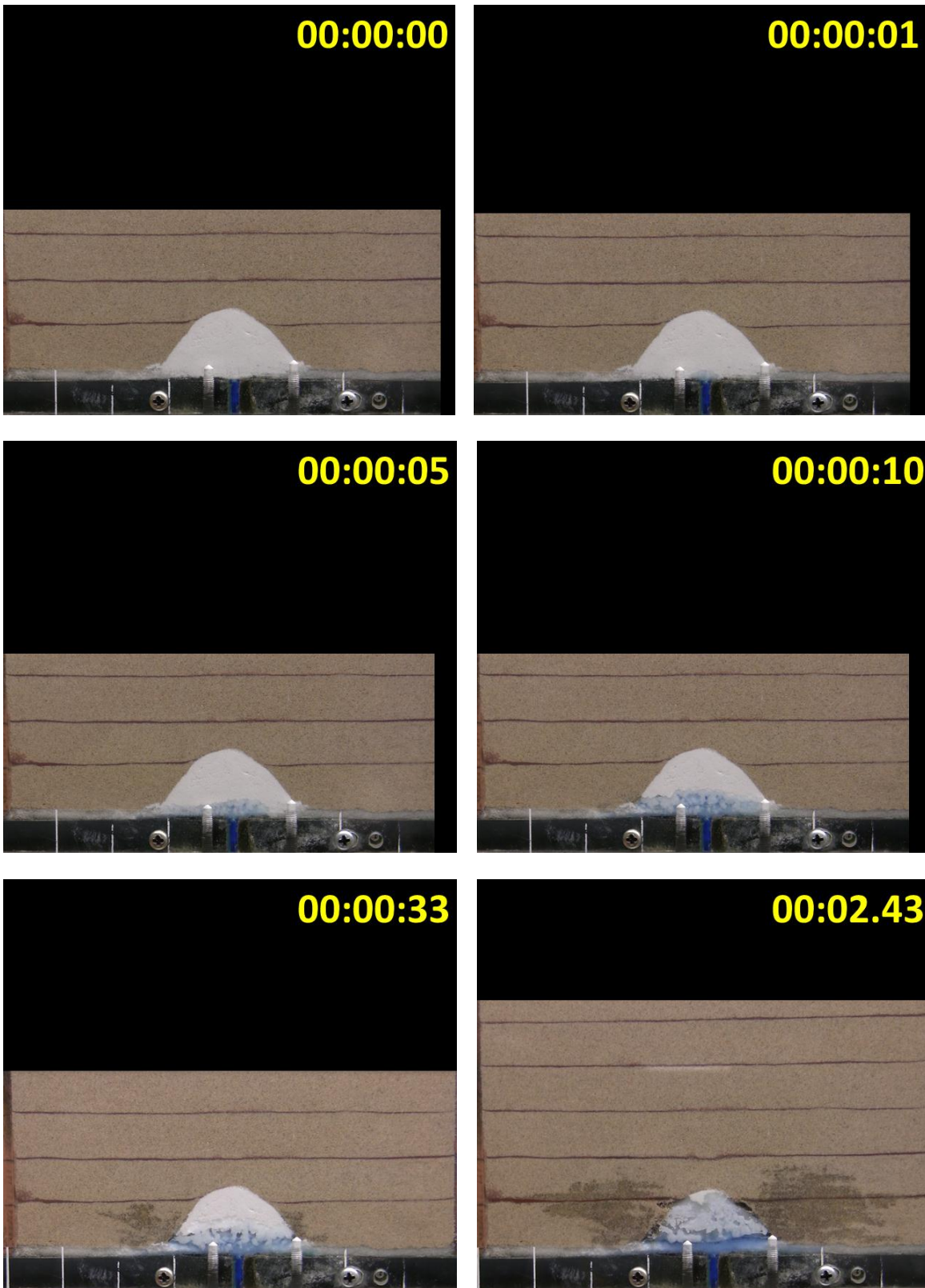
Appendix -I

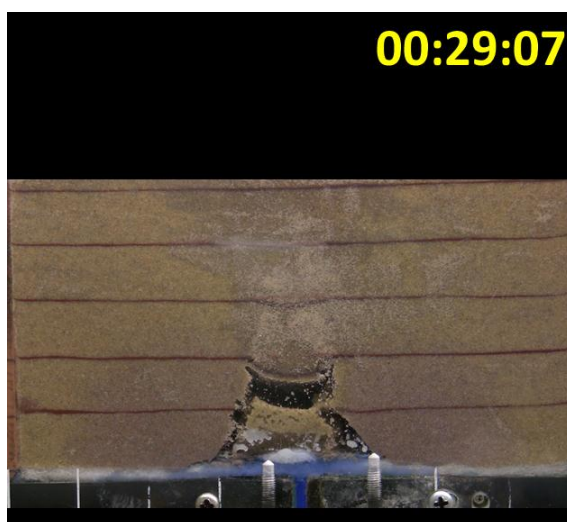
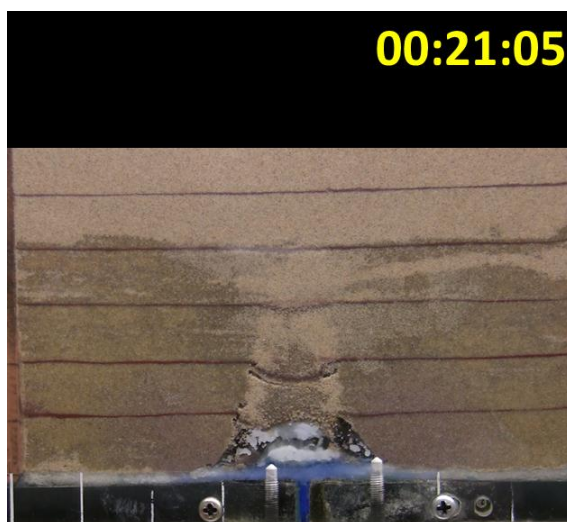
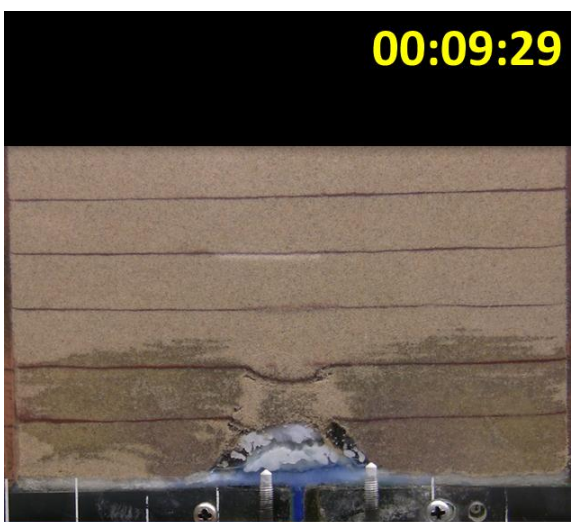
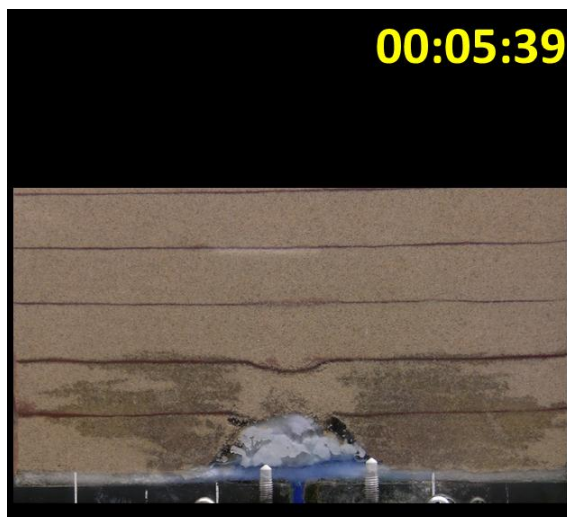
Model tests

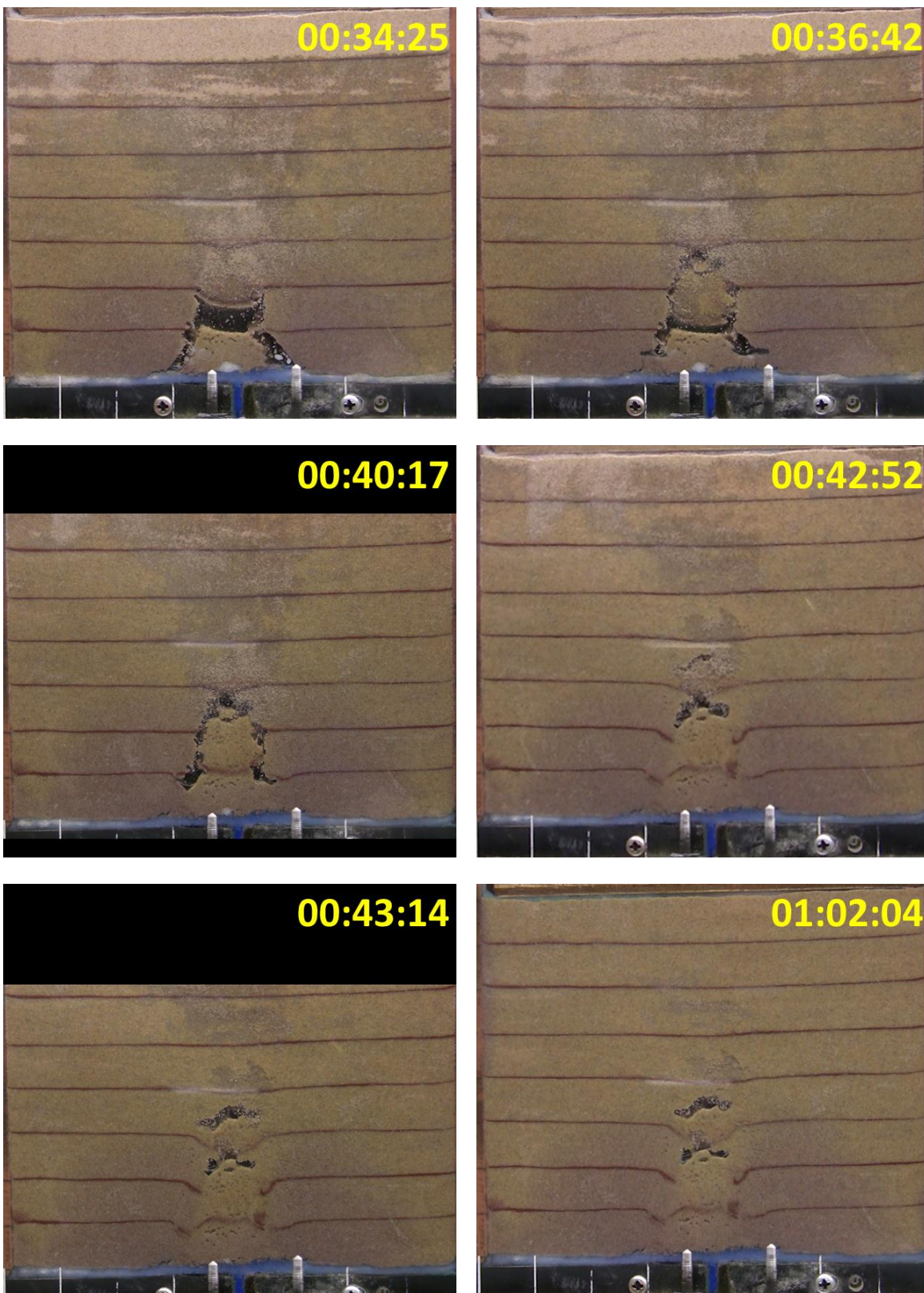
(Process of ground loosening)

Test No-1 (Dr= 70%, Cavity shape- Semi cylindrical, 5.7 ϕ , higher inflow rate)

Time is given in order of hour: minute : second.





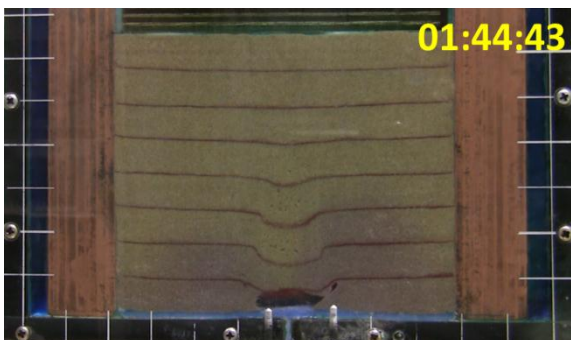
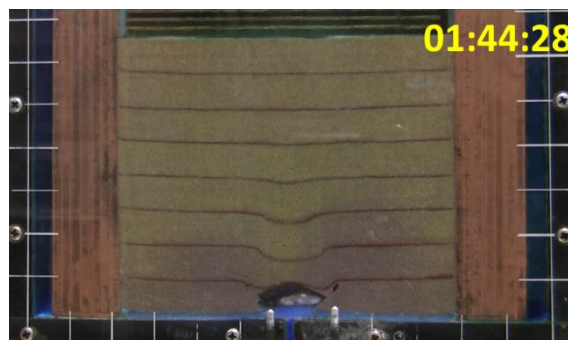
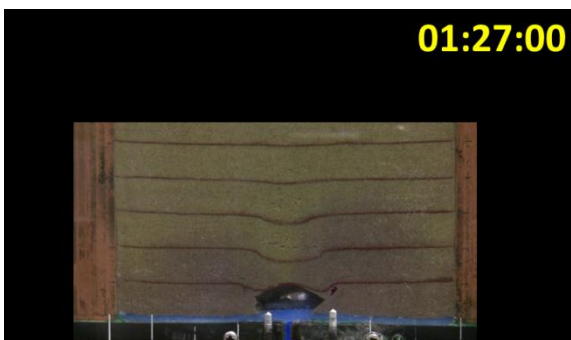


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After drainage

Test No-2 (Dr= 71%, Cavity shape- Semi cylindrical, 5 ϕ , Lower solubility glucose)

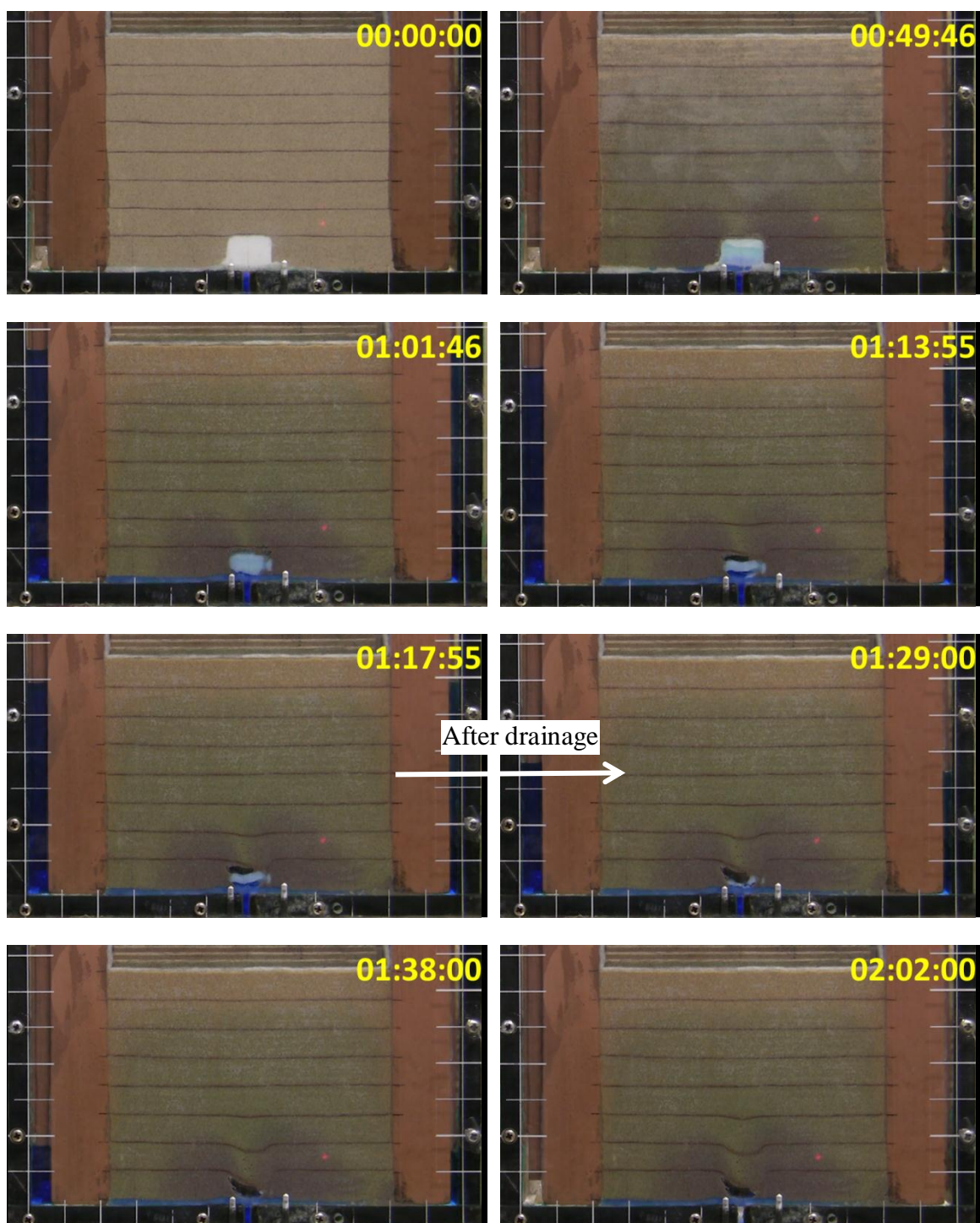
Time is given in order of hour: minute : second.



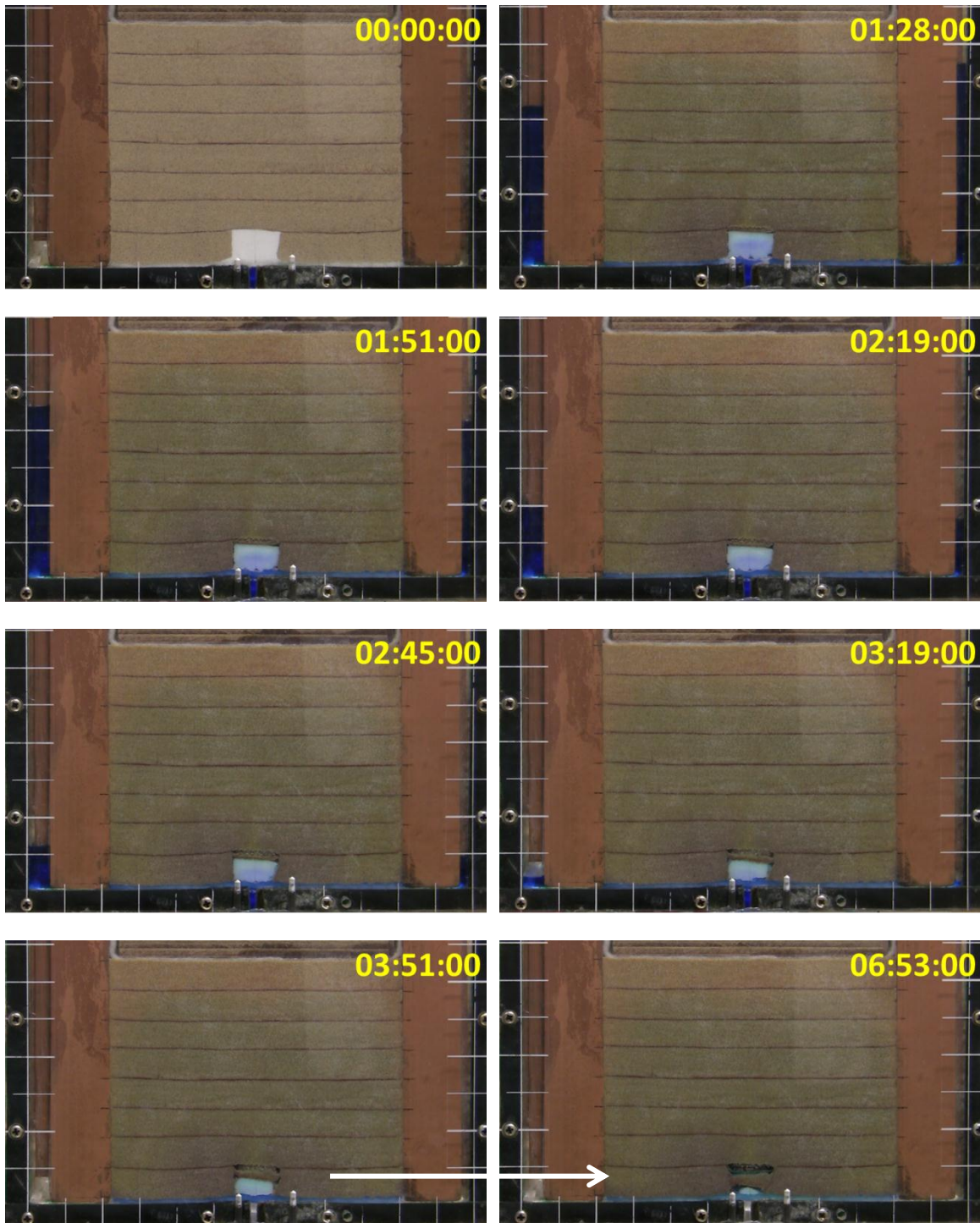


← Collapse caused by sudden drainage

Test No-3 ($D_r = 96\%$, Cavity shape- rectangular, $h=2\text{cm}$, $w=3\text{cm}$, dense ground)

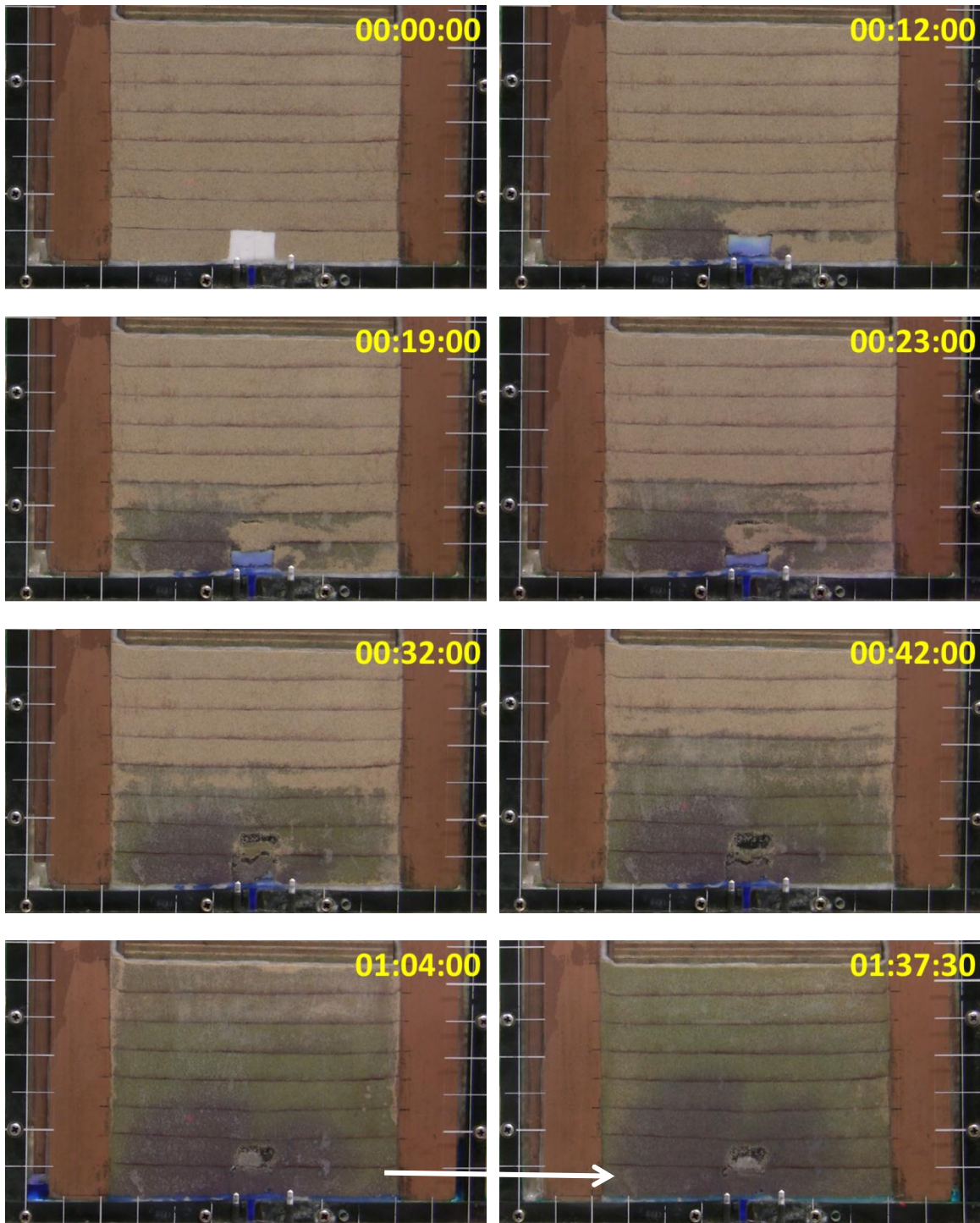


Test No-4 ($D_r = 98\%$, Cavity shape- rectangular, $h=2\text{cm}$, $w=3\text{cm}$, compacted ground)



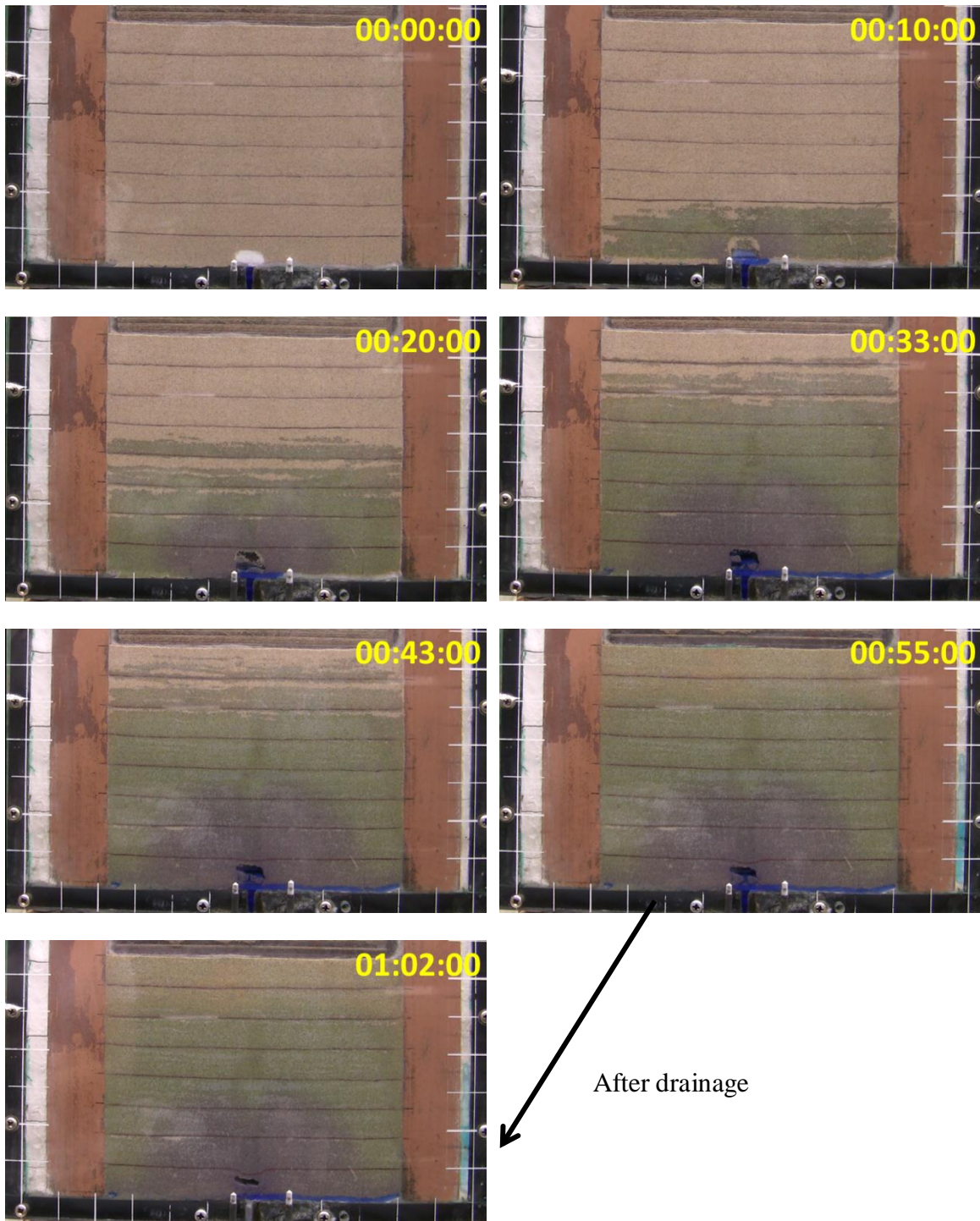
After drainage

Test No-5 ($Dr = 37\%$, Cavity shape- rectangular, $h=2\text{cm}$, $w=3\text{cm}$, loose ground, lower)



After drainage

Test No-6 ($Dr = 84\%$, Cavity shape- rectangular, $h = 1\text{cm}$, $w = 2\text{cm}$, small cavity)

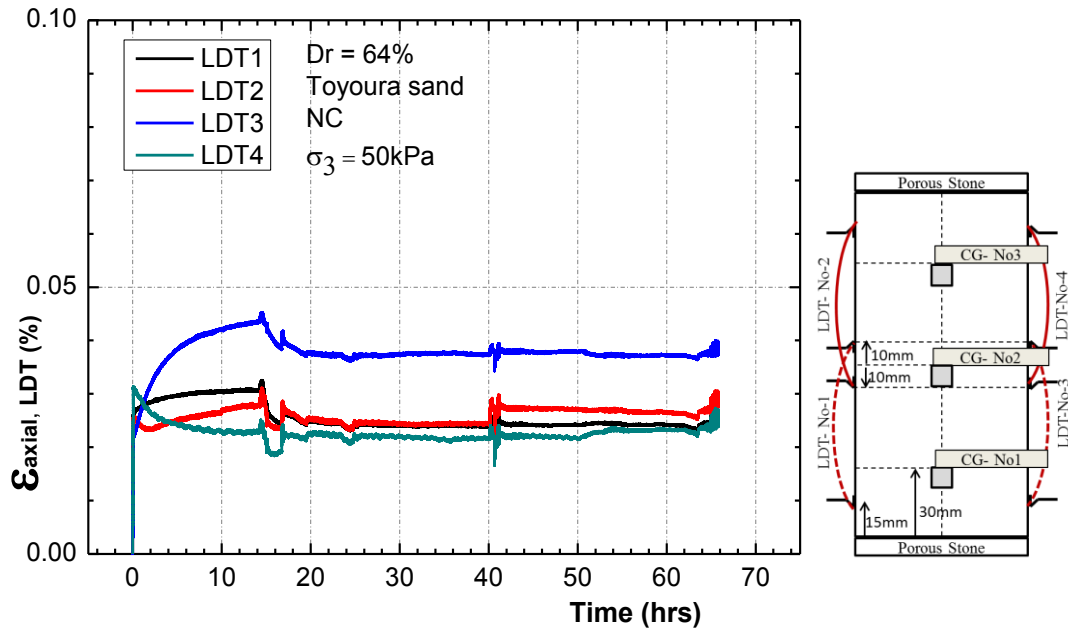


Appendix -II

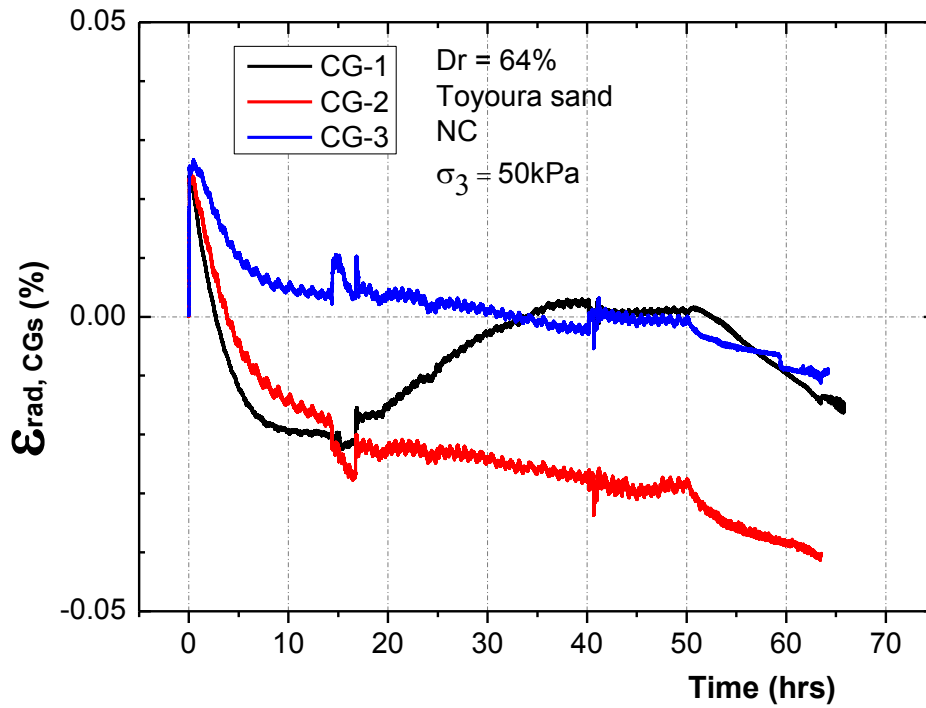
Triaxial tests

(Behaviour of each LDT and Clip gauge)

Test No-1 (NC, Dr=64%, Toyoura sand, $\sigma_3 = 50\text{kPa}$)

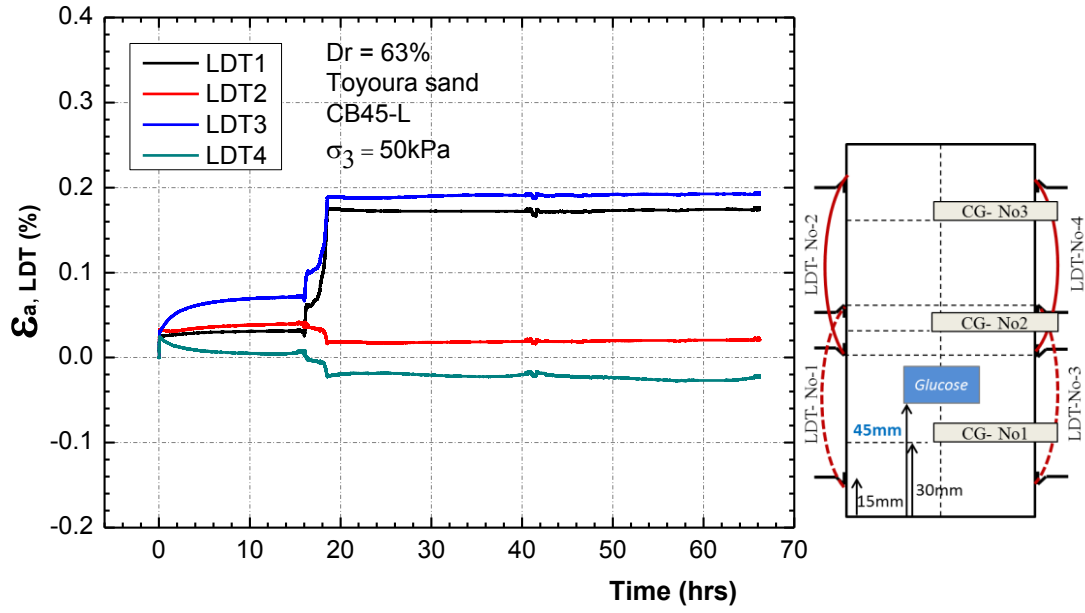


Axial strain variation measured by LDT

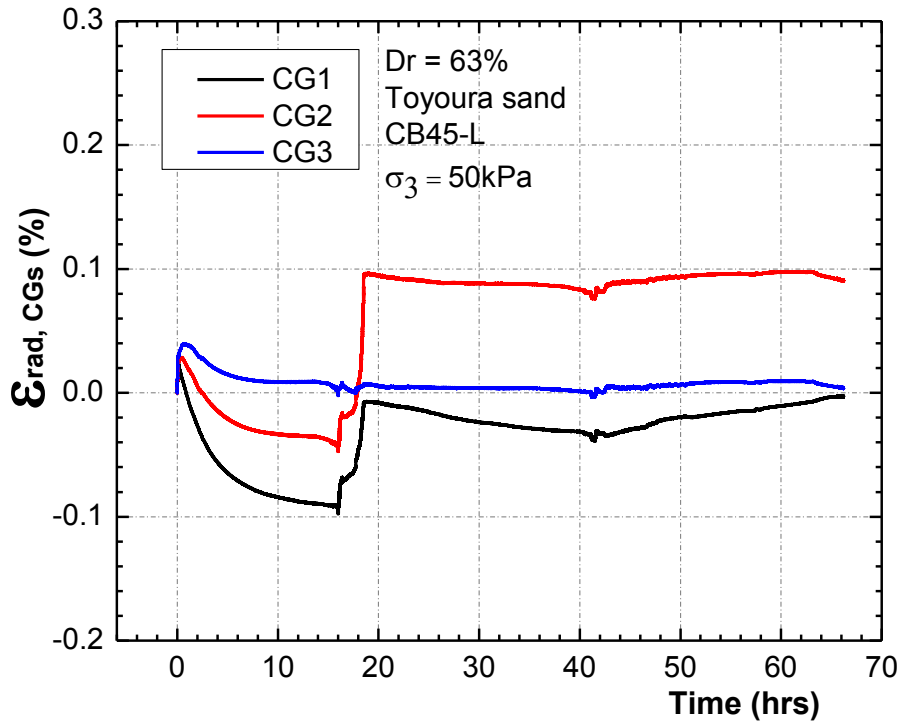


Radial strain variation measured by Clip gauges (CG)

Test No-2 (CB45-L, Dr=63%, Toyoura sand, $\sigma_3 = 50\text{kPa}$)

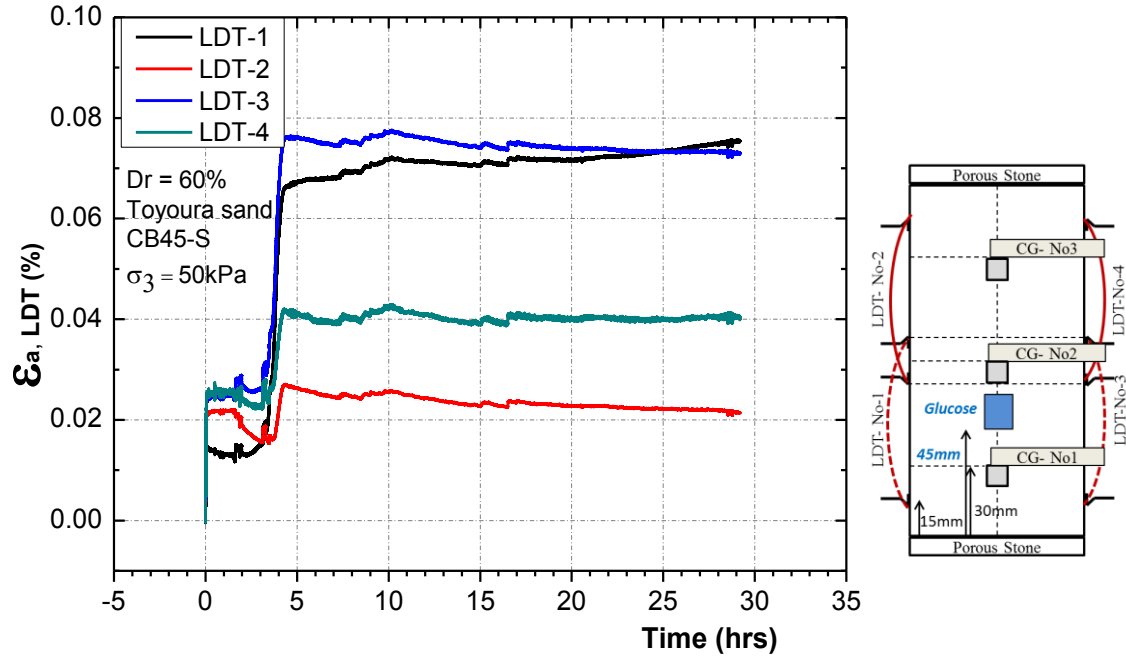


Axial strain variation measured by LDTs

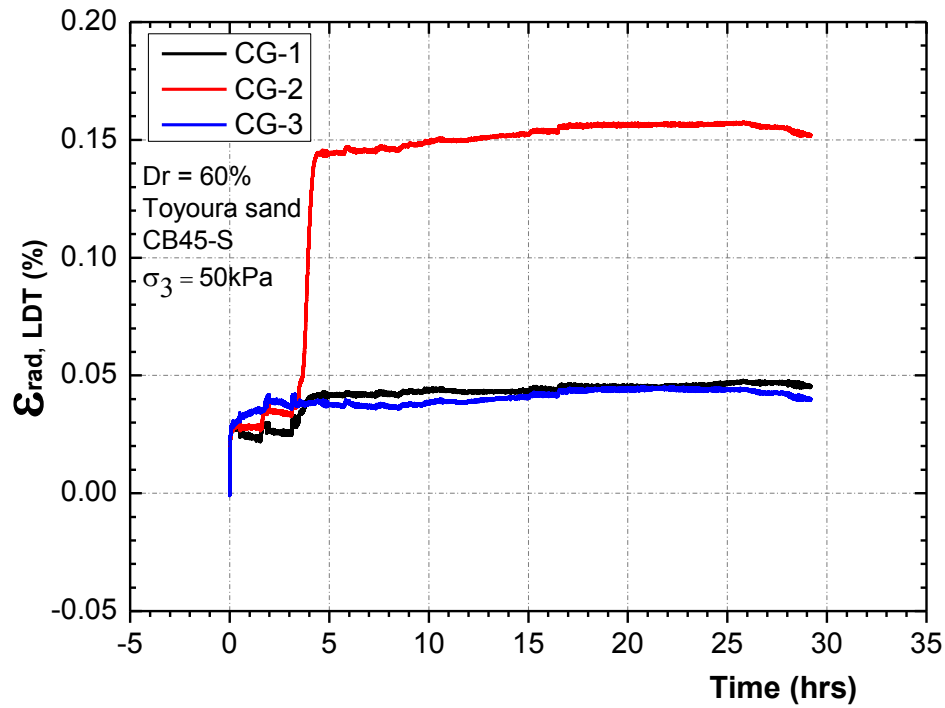


Radial strain variation measured by Clip Gauges (CG)

Test No-3 (CB45-S, Dr=60%, Toyoura sand, $\sigma_3 = 50\text{kPa}$)

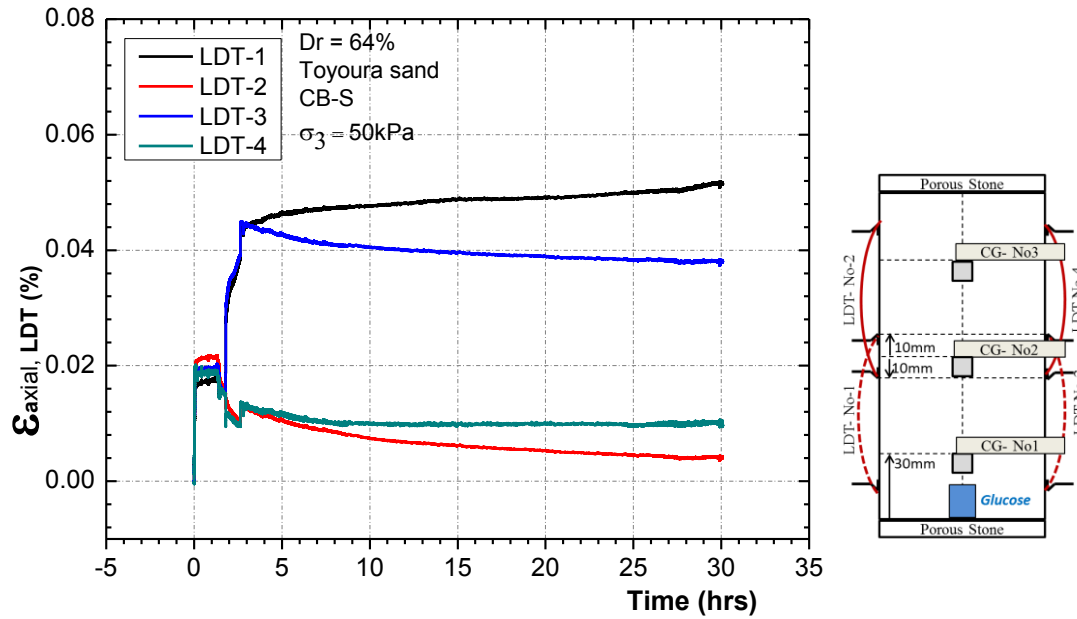


Axial strain variation measured by LDT

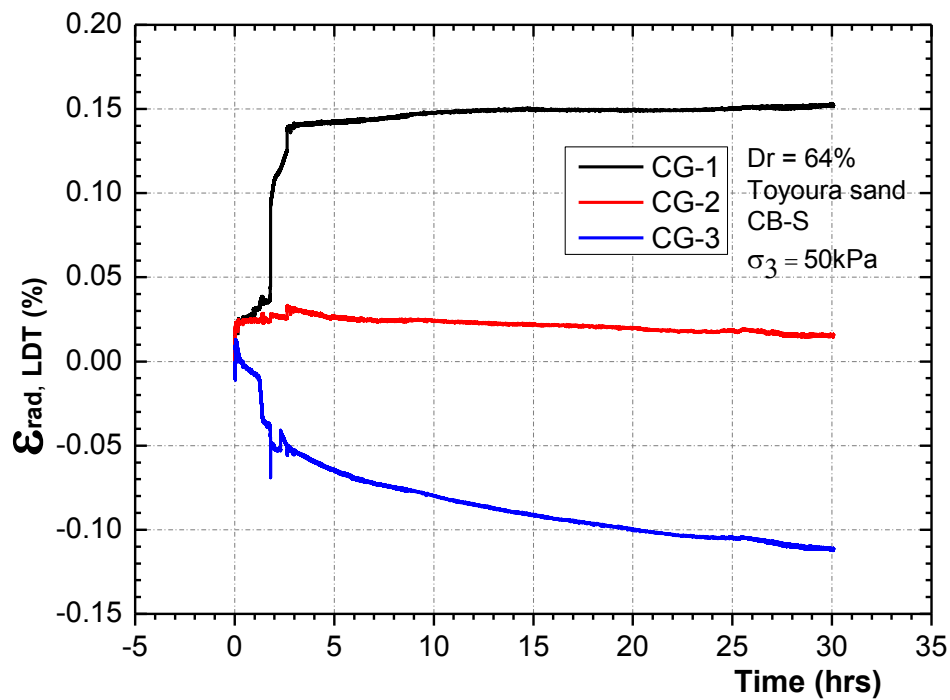


Radial strain variation measured by Clip Gauges (CG)

Test No-5 (CB-S, Dr=64%, Toyoura sand, $\sigma_3 = 50\text{kPa}$)

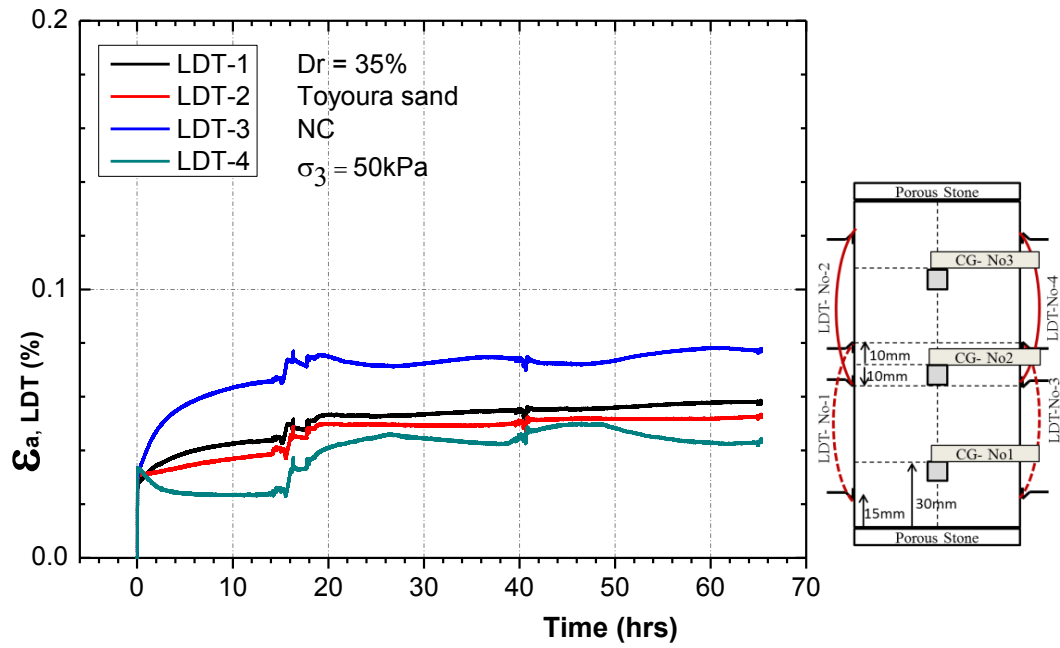


Axial strain variation measured by LDT

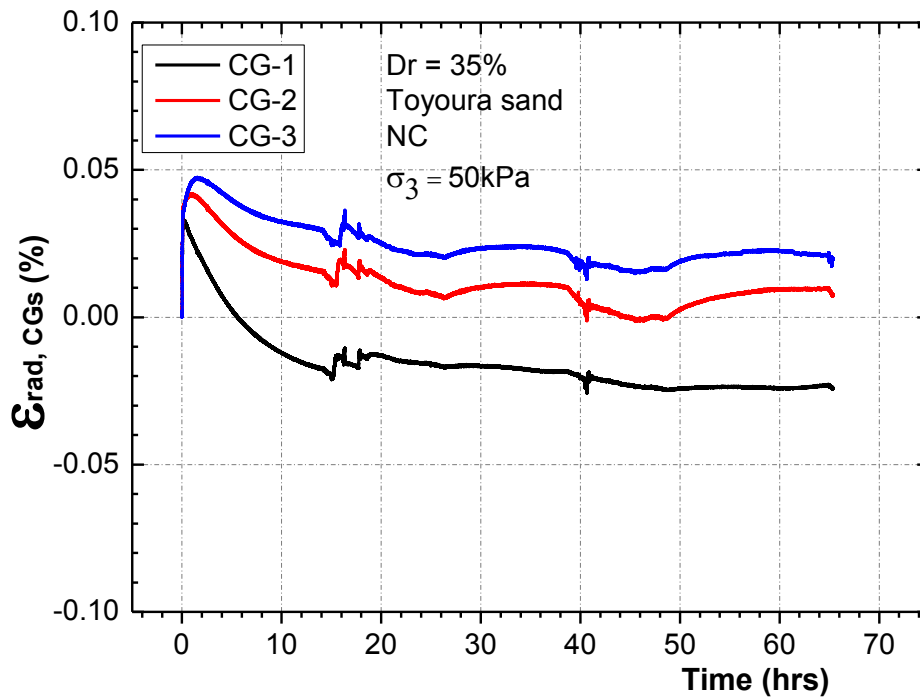


Radial strain variation measured by Clip Gauges (CG)

Test No -6 (NC, Dr=35%, Toyoura sand, $\sigma_3 = 50\text{kPa}$)

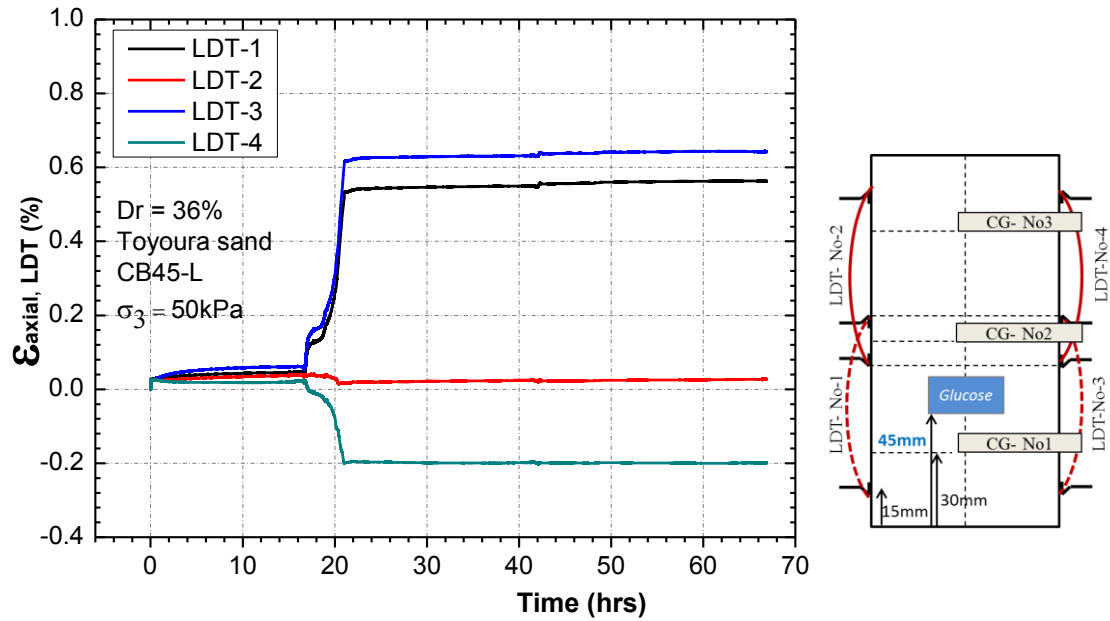


Axial strain variation measured by LDT

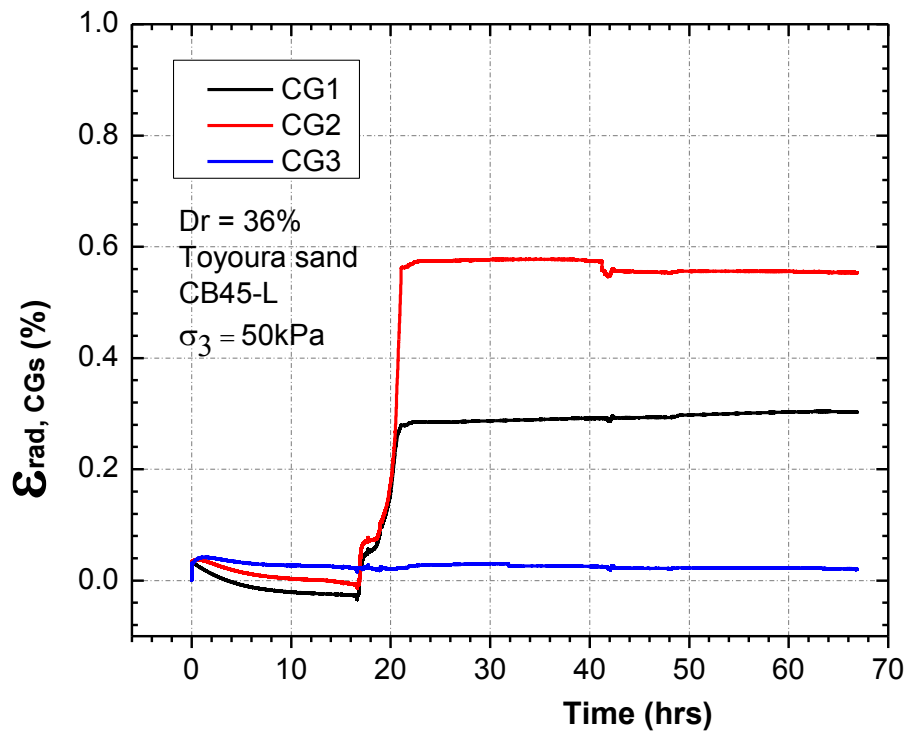


Radial strain variation measured by Clip Gauges (CG)

Test No -7 (CB45-L, Dr=36%, Toyoura sand, $\sigma_3 = 50\text{kPa}$)

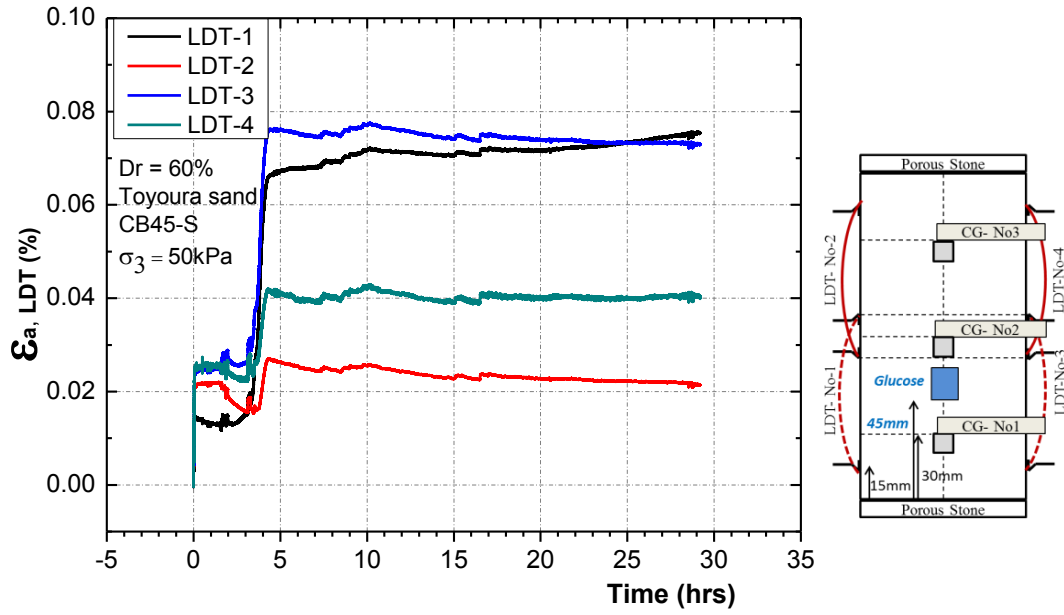


Axial strain variation measured by LDT

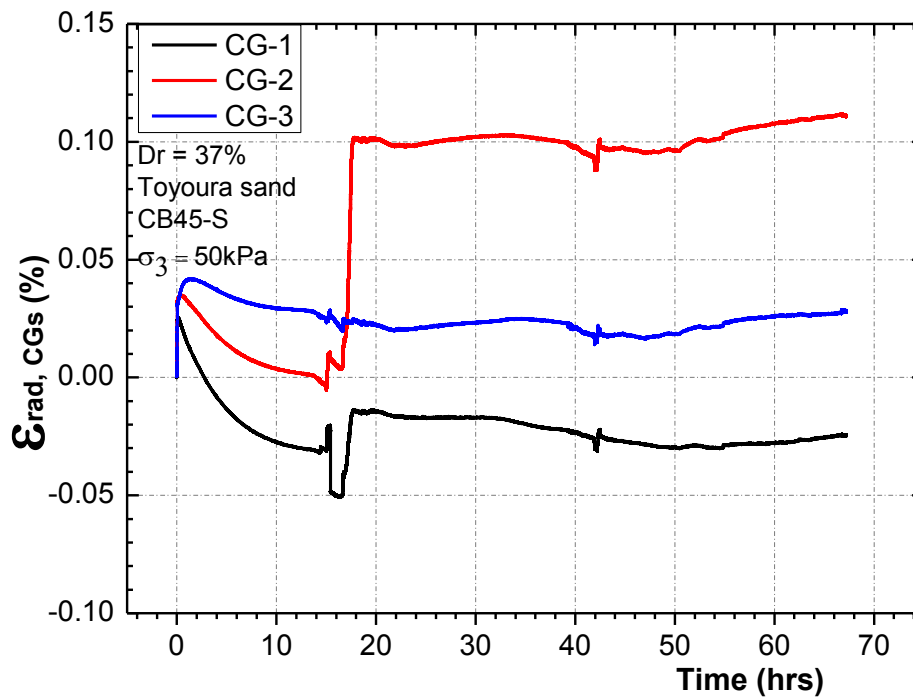


Radial strain variation measured by Clip Gauges (CG)

Test No -8 (CB45-S, Dr=37%, Toyoura sand, $\sigma_3 = 50\text{kPa}$)

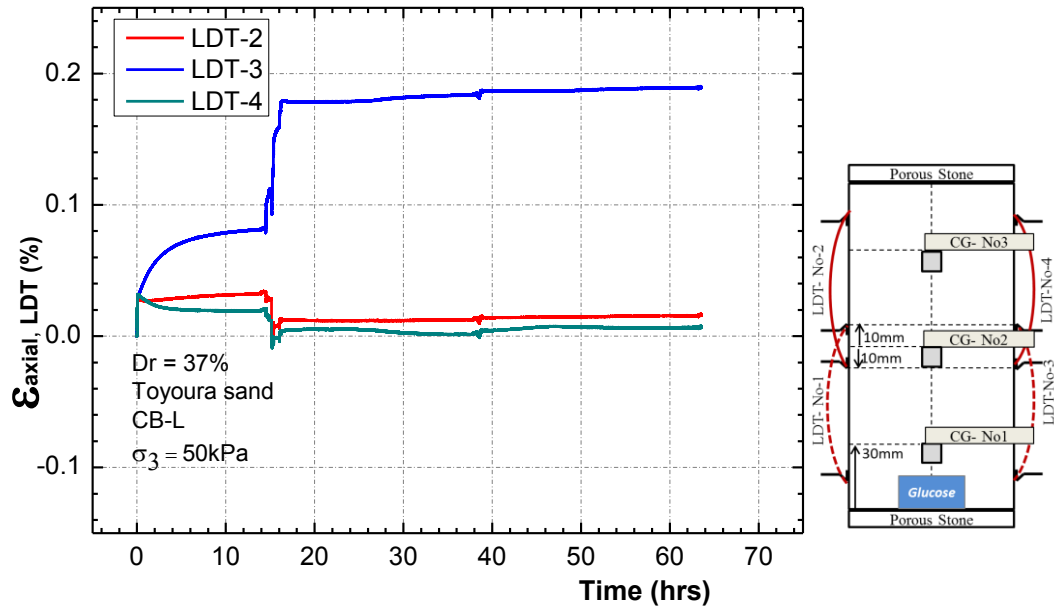


Axial strain variation measured by LDT

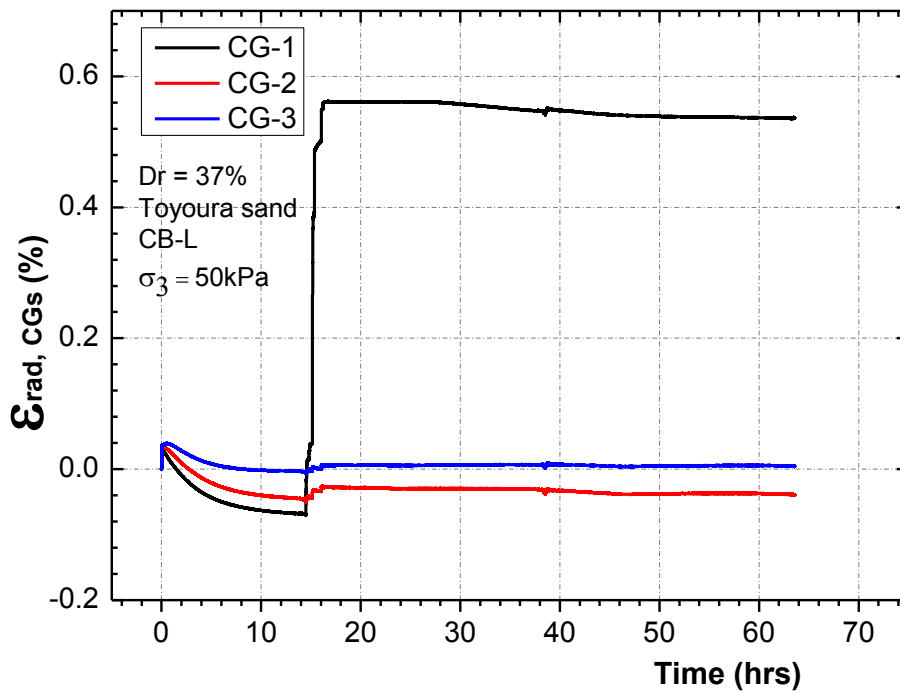


Radial strain variation measured by Clip Gauges (CG)

Test No -9 (CB-L, Dr=37%, Toyoura sand, $\sigma_3 = 50\text{kPa}$)

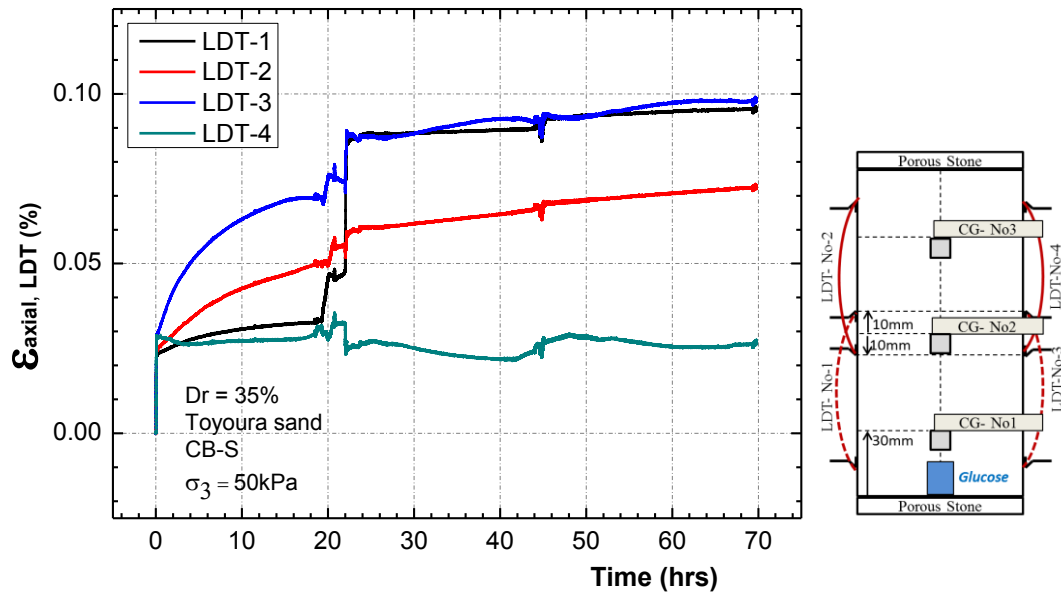


Axial strain variation measured by LDT

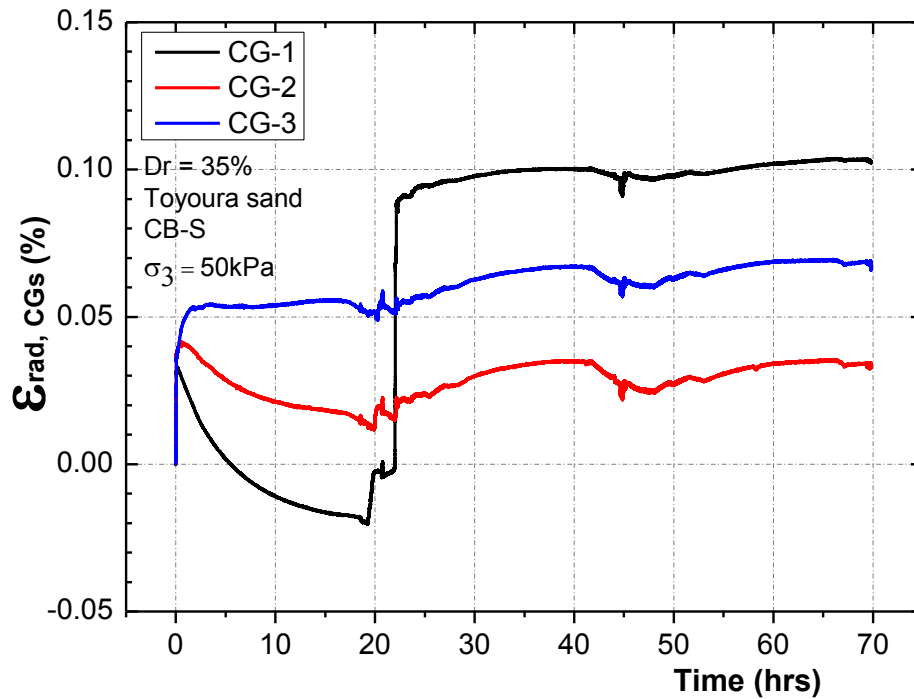


Radial strain variation measured by Clip Gauges (CG)

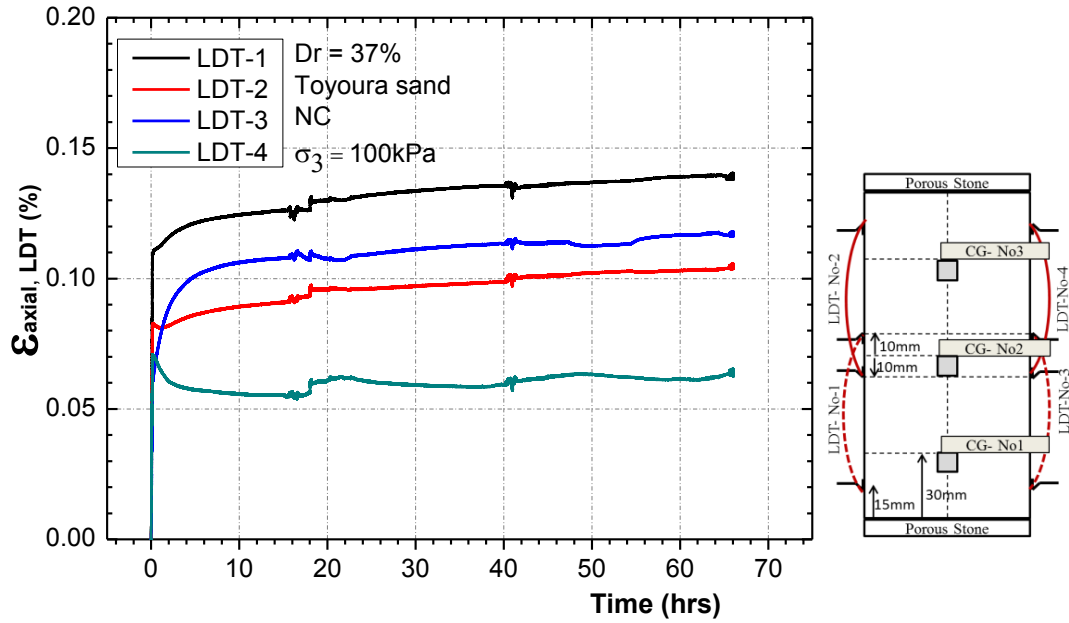
Test No -10 (CB-S, Dr=35%, Toyoura sand, $\sigma_3 = 50\text{kPa}$)



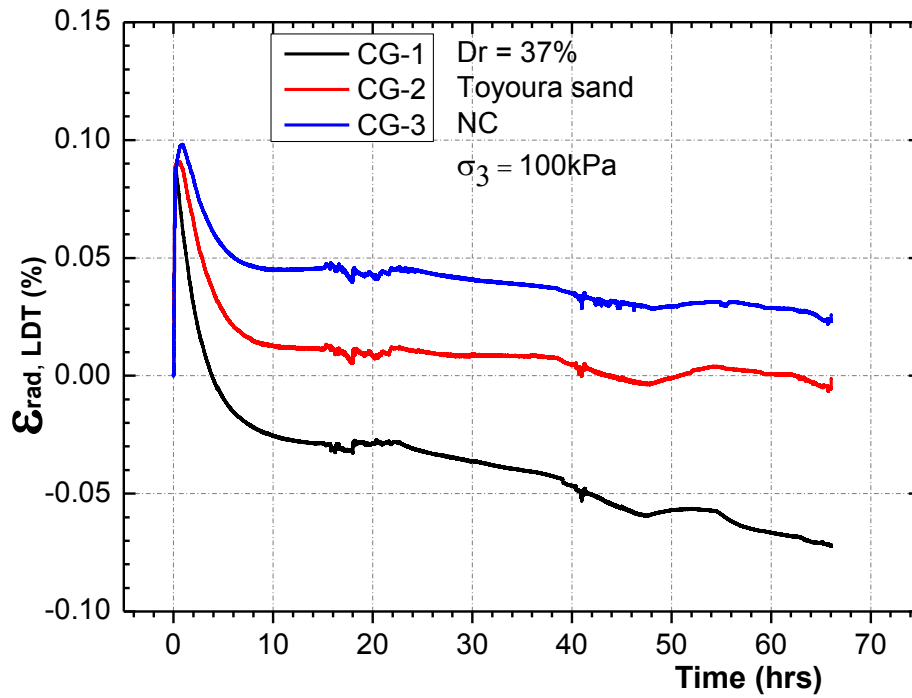
Axial strain variation measured by LDT



Radial strain variation measured by Clip Gauges (CG)

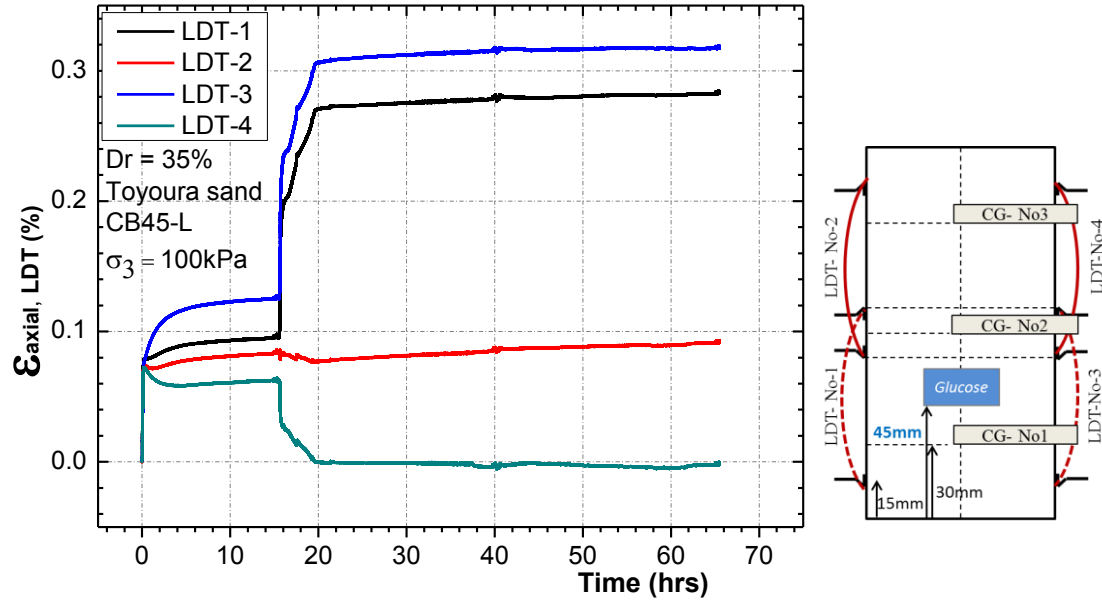
Test No -11 (NC, Dr=37%, Toyoura sand, $\sigma_3 = 100\text{kPa}$)

Axial strain variation measured by LDT

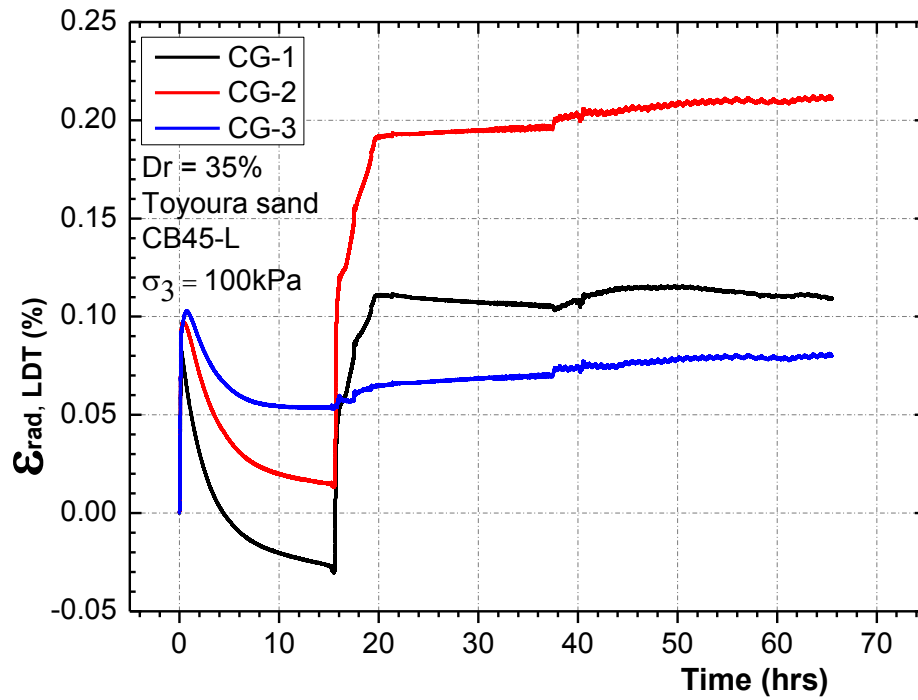


Radial strain variation measured by Clip Gauges (CG)

Test No -12 (CB45-L, Dr=35%, Toyoura sand, $\sigma_3 = 100\text{kPa}$)

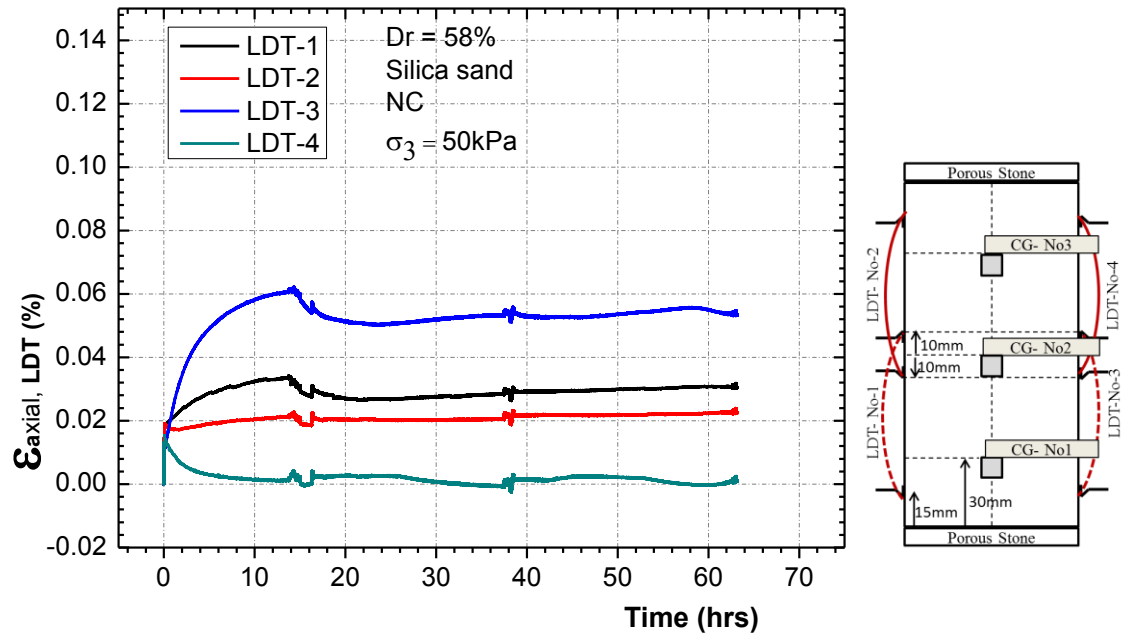


Axial strain variation measured by LDT

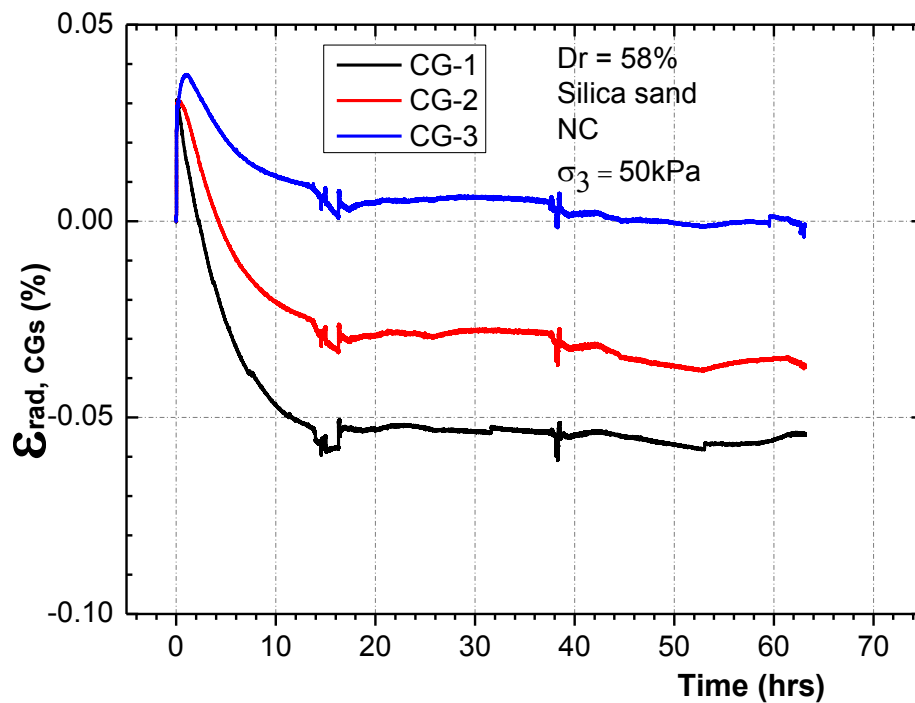


Radial strain variation measured by Clip Gauges (CG)

Test No -13 (NC, Dr=58%, Silica sand, $\sigma_3 = 50\text{kPa}$)

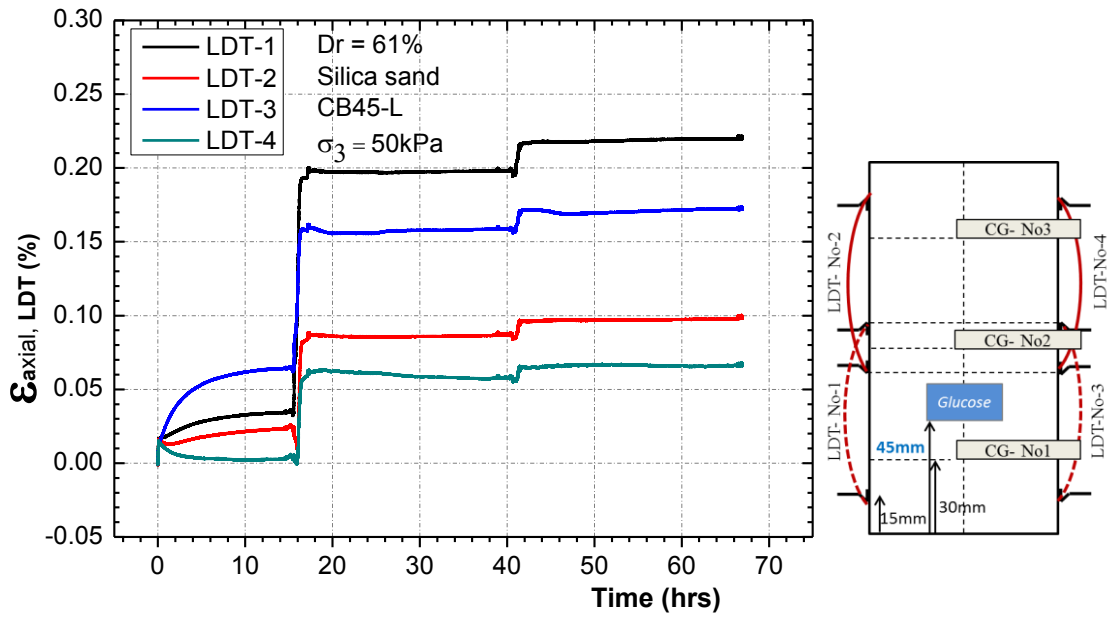


Axial strain variation measured by LDT

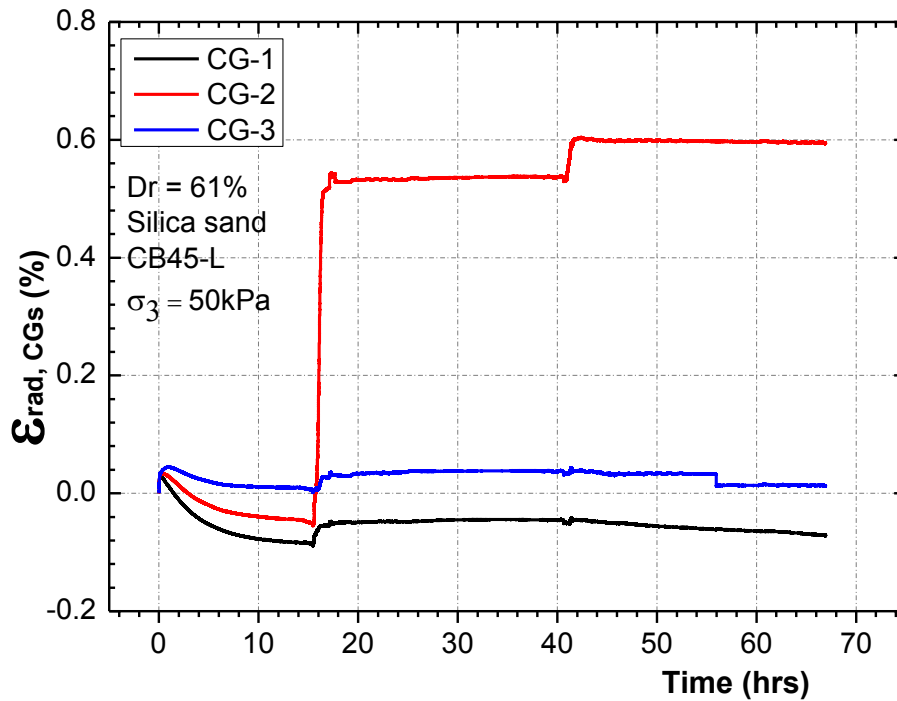


Radial strain variation measured by Clip Gauges (CG)

Test No -14 (CB45-L, Dr=62%, Silica sand, $\sigma_3 = 50\text{kPa}$)



Axial strain variation measured by LDT



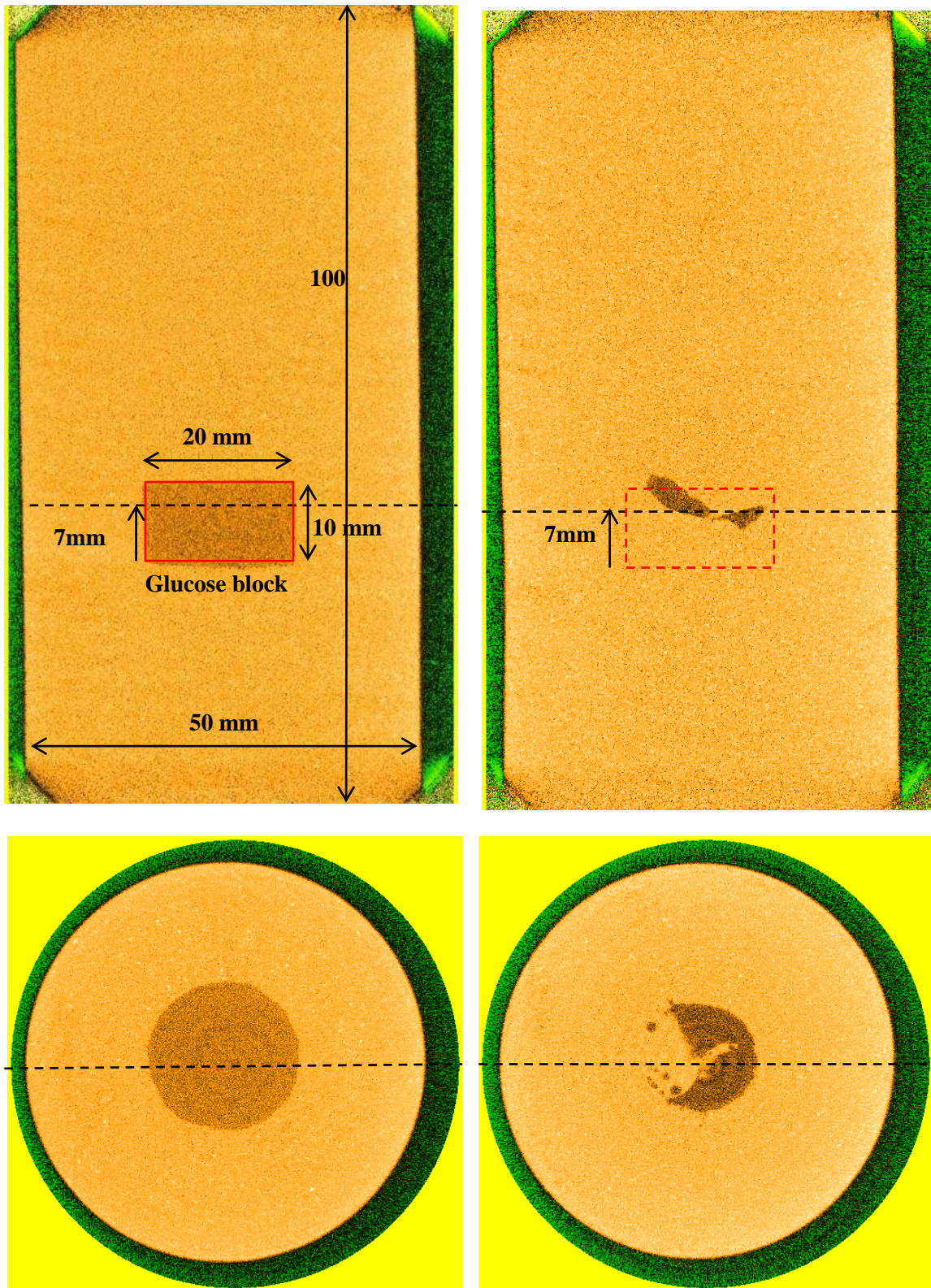
Radial strain variation measured by Clip Gauges (CG)

Appendix -III

X-ray CT images

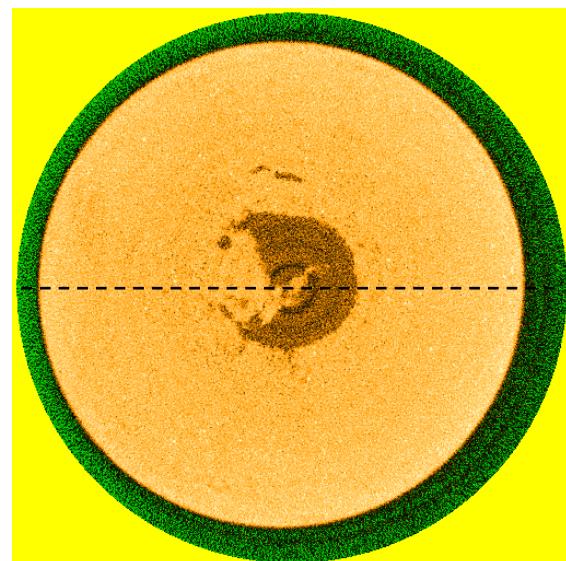
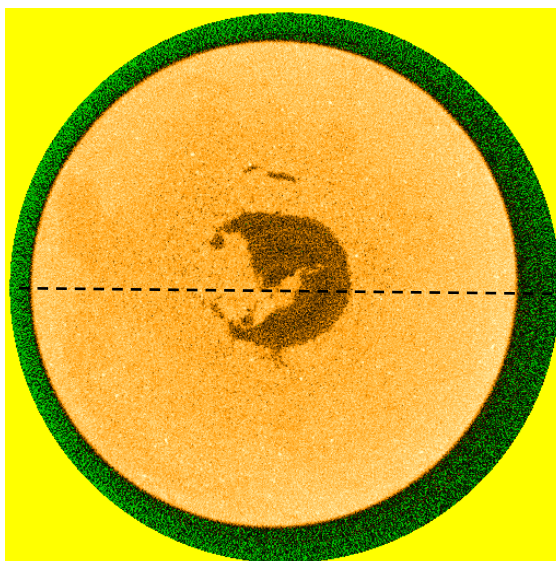
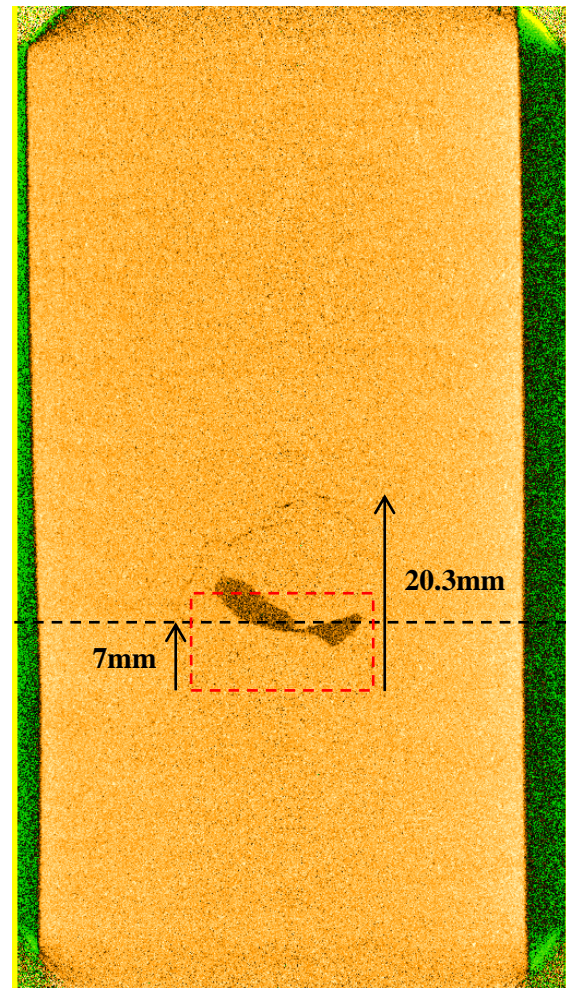
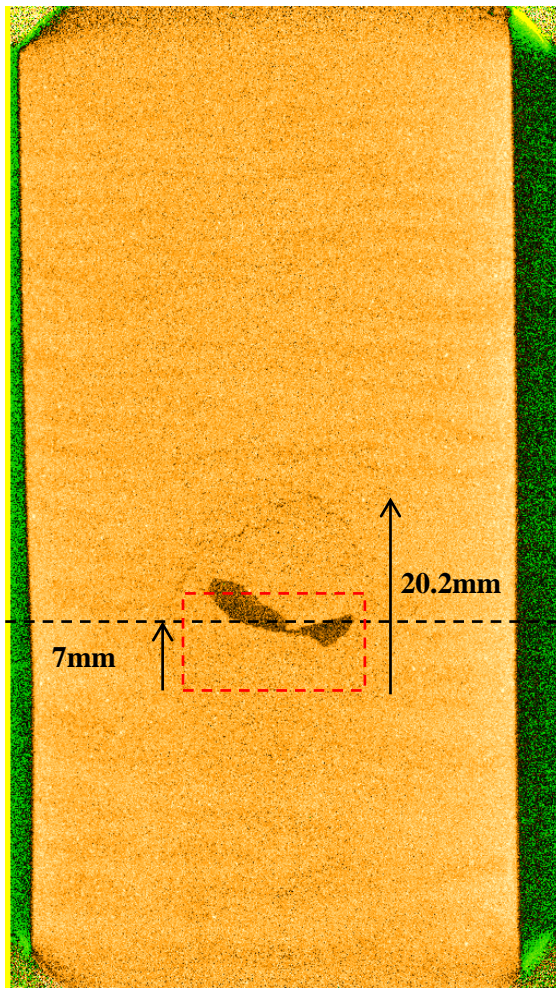
(Extent of loosening)

High-definition X-ray images – Visualization of loosening process by water infiltration and drainage



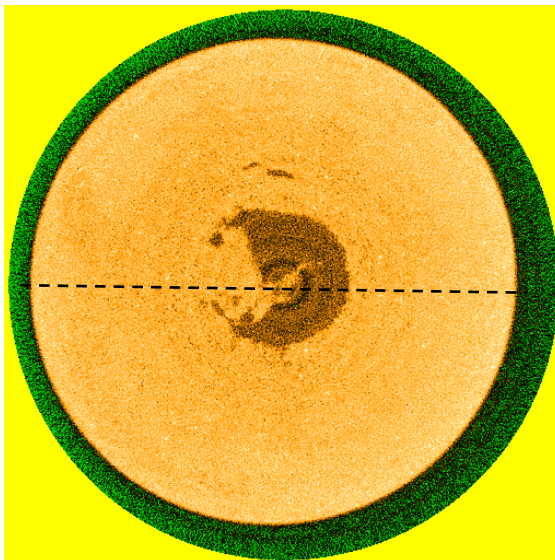
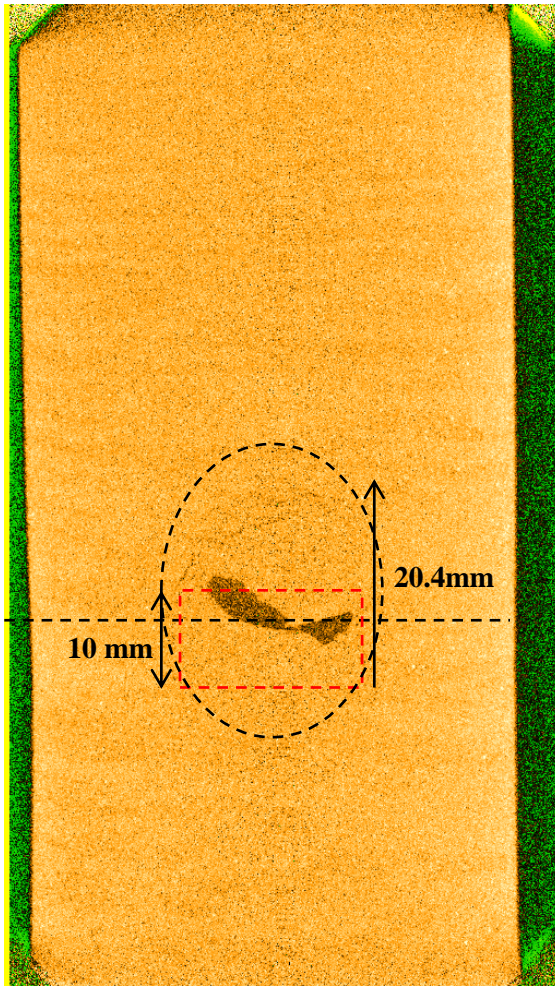
(a) Initial

(b) After 1st water infiltration



(c) After 1st drainage

(d) After 2nd infiltration



(e) After 2nd drainage

References

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