Local water-retention behaviour of sand during drying and wetting process observed by micro x-ray tomography with trinarisation

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ABSTRACT

In the present study, water-retention behaviour of sand during drying and wetting process has been observed microscopically using micro x-ray computed tomography (CT). CT images taken at different water-retention states during drying and wetting paths are trinarised to segment the images into the soil, water and air phases. The segmentation technique using region growing method takes into account uniform distribution of the mixels to reduce the inherent partial volume effect. Using the trinarised images, local porosity and degree of saturation are calculated for the cubic subsets centered at reference points, and then frequency maps of the two local values are drawn. Through the comparison of the frequency maps, the relation between the local porosity and the degree of saturation and the changes in the relation during drying and wetting process are discussed.

Keywords: water-retention behaviour, partial saturation, sand, degree of saturation, x-ray tomography, trinarisation

1. INTRODUCTION

Water-retention characteristic is one of the key issues for modeling mechanical and hydraulic behaviour of partially saturated sand because suction level and degree of saturation have a great influence on the strength and permeability of soils. It is well known that the main drying curve and the main wetting curve are not identical, which is referred as hysteresis. The mechanism of the hysteresis has been interpreted by a conceptual manner such as ink-bottle effect. It is however still necessary to study the causes of the hysteresis at grain scale.

In the present study, water-retention behaviour of sand during drying and wetting process has been observed microscopically using micro x-ray computed tomography (CT). Micro x-ray CT provides high resolution three-dimensional images which allow the visualization of pore water volume changes at different suction levels, for drying and wetting curves at the grain scale. Furthermore, the x-ray CT images are trinarised into the soil phase, pore water phase and pore air phase. Trinarisation technique of CT images for partially saturated sand is required to take into account the partial volume effect: in particular, voxels shared by the soil phase and the air phase are wrongly identified as the water phase since the mixture of the soil and the air often gives CT value similar to the water (Hashemi et al. 2014, Higo et al. 2014). Local porosity and degree of saturation for the given size of subset centered at reference points were calculated using the trinarised images. Then frequency maps of local porosity and local degree of saturation were drawn to investigate the relation between these two local values. In addition, the difference between the frequency maps of the drying process and the wetting process is discussed.

2 MATERIAL AND METHODS

2.1 Test sample and testing program

The sand sample used in the present study is Toyoura sand. The physical properties include a particle density of 2.64 g/cm³, a maximum void ratio of 0.975, a minimum void ratio of 0.614, a D₅₀ of 185 μm and a uniformity coefficient of 1.6.

The specimen was prepared by the water pluviation technique with a void ratio of 0.822 (porosity: 45.1%). The size of the specimen was 18.0 mm in diameter and 17.7 mm in height. The specimen was initially almost
water-saturated, and then suction was applied to obtain a main drying curve by the water head difference between the top of the specimen and the burette connected to the bottom of the specimen. Similarly, a main wetting curve was obtained by reducing suction.

During this water-retention test, x-ray CT scanning was performed at several different water-retention states. The x-ray CT facility used in this study is KYOTO-GEOμXCT (Higo et al. 2011) extended by installing a flat panel detector. A small part of the specimen located at the middle of the specimen was partially scanned. Voxel size of the obtained images was $5.5 \times 5.5 \times 7.0 \mu m^3$ by which $D_{50}$ of Toyoura sand particle is drawn by 33 voxels. This spatial resolution is high enough to distinguish individual sand particles from each other.

### 2.2 Trinarisation

The soil, water and air phases are segmented from the original image using the region growing method (Higo et al., 2013, 2014). Since x-ray CT images are an assembly of discrete gray values, they inherently have an artifact referred as the partial volume effect: voxels shared by two phases (mixel) with a gray value equal to the average between grain and air gray values. In particular, mixel of the soil and the air often gives the gray value closely similar to the gray value of the water. In order to reduce the wrong identification caused by the partial volume effect, in particular, between the soil phase and the air phase, mixels were taken into account by the maximum likelihood estimation method (e.g., Kitamoto and Takagi 1999) when determining the tolerance of the region growing method. For the soil-water, soil-air and water-air mixels, uniform distributions of gray value histograms are assumed, while normal distributions are assumed for pure soil, water and air voxels. When the superposition of the weighted distributions is determined by the maximum likelihood estimation method, the gray value at the intersection of the pure soil distribution and the pure water distribution was chosen as the tolerance of region growing of soil phase. Tolerance of the air phase was given by the intersection of the distributions of the pure air and the pure water similarly.

### 2.3 Local values

Reference points were placed in the images evenly at a certain interval in vertical and horizontal directions. Local porosity and degree of saturation were calculated for the cubic subsets centered at the reference points (Fig. 1). The effect of the size of the subset $n$ on the local porosity and the degree of saturation is shown in Fig. 2. Local porosity converges at $n$ of 100 pixels (0.55 mm, about 3 times $D_{50}$) which possibly corresponds to the size of representative element volume of this material. On the other hand, local degree of saturation does not converge even at $n$ of 160 voxels (0.88 mm, about 4.5 times $D_{50}$). This means that degree of saturation is more heterogeneous than porosity. In the present study, 60 was employed as the size of subsets $n$ to investigate the distribution of the local values. The interval of the reference point was 30 which provides overlapping of 50% between the subsets in each direction.

![Fig. 1 Schematics of reference points and subset volume](image)

![Fig. 2 Effect of the size of subset on the local values.](image)

### 3 RESULTS AND DISCUSSION

Water-retention curve is shown in Fig. 3. The drying path is located above the wetting path, i.e, the hysteresis can be clearly observed. During the drying process, the sand specimen starts to be desaturated when the suction level reaches 1.9 kPa. At higher suction of 10 kPa, the sample is in the pendular state. The degree of saturation starts to increase at suction level of 1.9 kPa during the wetting process and finally slight partial saturation was observed with zero suction, i.e., the specimen reaches insular-air saturation.
The alphabets from “a” to “l” in Fig. 3 indicates the points at which x-ray CT scanning was performed. Fig. 4 and Fig. 5 demonstrate the horizontal slice of the CT images and the trinarised images at the center of the specimen during drying and wetting process, respectively. Yellow, blue and gray portions indicate the soil particles, the pore water and the pore air, respectively. Porosity and degree of saturation of the scanned area were calculated using the trinarised images. The calculated porosities are comparable to the measured global porosity but the degree of saturation values are larger than the global one probably because the portion of the scanned area contains larger amount of water than the other portions of the specimen, i.e., the heterogeneity of the degree of saturation.

Frequency maps of the local porosity and degree of saturation from point ‘c’ to ‘e’ during drying process and from point ‘i’ to ‘k’ during wetting process are shown in Fig. 6. The solid line drawn along the edge of the whitest portion indicates the boundary of the frequency map, i.e., zero frequency outside the line, and the darkest blue portion denotes the peak of the frequency map. The degrees of saturation of these two water-retention states are almost the same. In this two-dimensional histogram, 50 bins are considered for both axes, and the total number of measurement is 18696.

It is clear for both the wetting and drying process that the degree of saturation of the subsets with high porosities tend to be smaller, while those with the lower porosities are larger. This is compatible with the fact that the larger voids have lower water-retention ability, and vice versa.

Through comparison between ‘c’ and ‘k’, it is found that the degree of saturation of ‘k’ is lower than that of point ‘c’ because of trapped pore air as shown in the trinarized image in Fig. 5. In addition, it can be seen in Fig. 6(b) that the larger voids have less degree of saturation. This means that the pore air is likely trapped into relatively larger voids.

The histograms with the similar degree of saturation during drying and wetting process are almost the same,
e.g., histograms at ‘e’ and ‘i’, ‘d’ and ‘j’, ‘c’ and ‘k’, although it is clear that the spatial distribution of pore water of ‘d’ and that of ‘j’ are obviously different from each other. Namely, the distributions of local degree of saturation during drying and wetting process are similar to each other in the case where the global degree of saturation is the same but the suction levels are different. This means that the distribution of pore water with respect to the porosity does not attribute to the hysteresis. Hence, it is possible that the difference of the curvatures of menisci, which provide different suction even when the degrees of saturation are similar, could attribute to hysteresis.

CONCLUSIONS

Micro x-ray tomography with trinarization technique has provided two-dimensional histogram of the porosity and the degree of saturation which makes it possible to discuss the distribution of pore water in partially saturated soil. It is found that larger voids are desaturated faster and re-saturated again slower than small voids. The distribution of the degree of saturation with respect to the porosity, for drying and wetting process of similar degree of saturation, are almost the same. The effect of the difference of curvature on the hysteresis is desired to be investigated in the future. It would also be necessary to use different variables instead of porosity (void ratio), e.g., shape and size of the voids, to discuss more on the mechanism of hysteresis.

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