Displacement in sand under triaxial compression by tracking soil particles on X-ray CT data

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Abstract

The objective of this paper is to obtain displacements in sand in three dimensions under triaxial compression using the results of X-ray CT. A triaxial compression test was conducted on soil called “Yamazuna sand”, which has a wide grain size distribution, and the specimens were subject to CT scanning during the loading process. A large number of CT images, both 2D cross sectional images and also 3D reconstruction images, were obtained from CT scanning. The first objective in this study was to develop a method of tracking soil particles using CT images and then to calculate their movement using this proposed method. The total number of soil particles depended on the relationship between the size of the soil particles and the resolution of the CT apparatus. Finally, the displacement vectors from these movements were calculated in three dimensions under the loading process and the distribution of the localized displacement in the sand was measured. It was confirmed that the combination of the tracking technique with CT images is effective for quantitative discussion on the results of X-ray CT.

Keywords: X-ray CT; Displacement; Triaxial compression test; Image analysis

Introduction

To evaluate the parameters of soils structures and to improve the design of these structures, studies on the mechanical properties of soils have long been considered of great importance. There are two main approaches studying carrying out such studies: one is the experimental approach, which allows for the clarification of the behavior, and the other is the numerical, which allows for the modeling of the behavior. Recently, there has been enormous progress in the latter approach, and the finite element method (FEM), a method based on continuum mechanics, and the distinct element method (DEM), a method based on granular material concept, have been used widely in practice. For the former approach, the behavior of displacement in the soil needs to be better understood in order to characterize the deformation or the failure of soils precisely. In a discussion on the failure of soils, the strain localization in the soil is one of key issues. There have been some investigations on the strain field, including displacement. A number of experimental work focused on element tests, such as triaxial compression or plane strain tests, and scale-model loading tests on soils or artificial materials such as aluminum rods have been published, with detailed data regarding displacement and strain in soils.
However, these have been mostly restricted to a 2D analysis of the visible surface of the test specimens (Yamamoto and Otani, 2001; Nielsen et al., 2003).

In the mean time, the nondestructive testing methods using the X-ray Computed Tomography (CT) scanner have started to be used in the field of engineering. Using this apparatus, the three dimensional behaviors of materials can be investigated without any destruction. The industrial X-ray CT used in this study, with its high power X-rays, has a much higher resolution than that used in the medical field. The authors have already conducted a series of studies on the application of industrial X-ray CT to geotechnical engineering (Otani et al., 2000, 2002a, 2005, 2006). However, the CT image itself has raised some limitations: it is the result of X-ray absorption properties, and since this property depends on the density of materials, it is very difficult to discuss such quantitative values as displacement and strain directly. A quantitative study using the X-ray CT to characterize the displacement field in three dimensions using artificial markers in the soil was done by Takano et al. (2006). However, it may well be that the use of artificial markers interfered with the measurements, and the CT images may not have reliably indicated the actual behavior of the soils during the loading process.

The objective of this paper is to evaluate the displacements in sand under triaxial compression using X-ray CT. First of all, the properties of the X-ray CT images are discussed in detail and then a method of tracking real soil particles in three dimensions is developed using an image analysis technique called Particle Tracking Velocimetry (PTV) (Dracos, 1996; Ohmi and Hang, 2000; Kertzcher et al., 2004) on the CT images obtained from a one dimensional compression test. The material used is a sandy soil called “Yamazuna sand”, which has a wide range of sizes of soil particles. Since there is a wide range of the particle sizes, all the particles cannot be tracked because of the restrictions with the resolution of the X-ray CT apparatus. Thus, here in this study, only some of the particles are tracked, depending on the relationship between the resolution of the CT apparatus and the particle size. Finally, the method proposed for tracking soil particles is applied to the results of the triaxial compression test, and the displacement fields of sand are discussed in three dimensions. This method is a new and effective approach for the investigation of strain localization in soil.

X-ray CT

X-ray CT method

X-ray Computed Tomography (CT) is a non-destructive technique that allows imaging and the quantification of the internal features of an object in three dimensions. The method reveals differences in density and atomic composition. There are two steps involved in the measurement: first, X-ray radiographies of a specimen taken from several different angular positions with a full angle of at least 180° are recorded, and then, the virtual slices from these different projections are reconstructed, using appropriate algorithms, which are either algebraic or based on a back projection principle. The stacking of several sequential slices provides a three-dimensional image of the object: an example of such an image of a soil sample is shown in Fig. 1. CT images are constructed by the spatial distribution of the so called “CT-value”, which is defined as follows:

$$CT-value = \frac{\mu_t - \mu_w}{\mu_w} K$$

(1)

where $\mu_t$ is the coefficient of absorption at the scanning point, $\mu_w$ is the coefficient of absorption for water, and $K$ is the constant (Hounsfield value). Here, it is noted that this constant is fixed at a value of 1000. Thus, the CT-value of air should be $-1000$ because the coefficient of absorption for air is zero. Likewise, from Eq. (1), the CT-value for water is 0. CT images are presented with a shaded gray or dark color for low CT-value and light gray or light color for high CT-value through the black to white range. There are 256 possible variations. It is well known that this CT-value is linearly related to material density. It is also noted that the X-ray CT method has been discussed in detail by Kak and Slaney (1996) and Otani et al. (2000). Fig. 2 shows the relationship between the CT-value and the dry density of the Yamazuna sand used in this study. This relation is under the average sense for whole specimen with the size of the mold (50 mm diameter with 100 mm height). From this figure, although the CT-value is basically affected by both the density of the material and its atomic composition, a linear relationship between the CT-value and the density of the material has been established which depends on the scanning conditions, including the X-ray attenuation, and the size and shape of the scanning materials. Therefore, the size and shape of the scanning materials need to be fixed for all comparative studies. The X-ray attenuation conditions will be discussed in the next section.

CT scanning

The scanning conditions which need to be determined properly totally depends on the material properties to be

![Fig. 1. X-ray CT principle (Otani et al., 2000). (a) A large number of cross sectional images and (b) Reconstructed 3D image.](image)
scanned. Determining the voltage for the X-ray tube alimentation is important: three different voltages were used in this investigation, 150, 200 and 300 kV. In this study, a dry Yamazuna sand with a wide range of grain size distribution, as is shown in Fig. 3, was used. The minimum particle size was 0.001 mm and its maximum was 10 mm with a $D_{50}$ of about 0.54 mm. Note that the grain size distribution was obtained by sieve analysis for particles over 75 μm and a sedimentation analysis was used to determine the size of particles under 75 μm, respectively. The information of the density of Yamazuna sand is shown in Table 1. Each specimen was 50 mm in diameter and 100 mm in height. This sand with dry condition was prepared under the density of 1.579 t/m$^3$ ($Dr = 90\%$) in the plastic mold. Fig. 4 shows the histograms of the obtained CT-values for all three voltages. Each histogram is composed of two peaks; one representing the material of the specimen and the other representing that of the plastic mold. Note that there is a wider range of CT-values at the lower voltage (150 kV) than at higher voltages. This result is normal considering there is more contrast with lower energy. Since the variation of the density in the material is wider is lower at lower voltages, 150 kV was considered the optimum condition. However, low energy X-ray beams are more susceptible to beam hardening, which causes the edges of an object to appear brighter than the center even if the material is uniform throughout. This phenomenon is often called the “cupping effect” in X-ray Physics. This phenomenon occurs since lower energy X-ray photons can be attenuated more easily than higher energy X-ray photons, and polychromatic X-ray beams passing through an object lose the lower energy part of their spectrum. This phenomenon is referred to as the “hardening” of the beam (Kak and Slaney, 1996). There are a number of possible remedies for beam hardening, ranging from scanning preparation (hardware optimization) to data processing (software optimization). In this research, the former technique was chosen to reduce beam hardening. By pacing a piece of absorbing material between the X-ray source and the specimen the lower energy photons were absorbed before the X-rays go through the specimen. In our experiment, copper was used as the filter. Fig. 5 shows the distributions of CT-values along the diameter of specimens with and without the filter using the same voltage, 150 kV. A cupping effect was observed for the distribution of the CT-values, but the cupping effect was reduced considerably by using the copper filter. Considering this, a voltage of 150 kV was decided upon for this investigation, with the use of a copper filter. For a more detailed discussion on this point, please refer to the paper published by Ketcham and Carlson (2001). Finally, the CT scanning conditions were fixed as follows: a voltage of 150 kV, an attenuation width of 0.3 mm, which is the

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Density of Yamazuna sand.</th>
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<tr>
<td>$\rho_s$ (t/m$^3$)</td>
<td>2.695</td>
</tr>
<tr>
<td>$\rho_{dmax}$ (t/m$^3$)</td>
<td>1.615</td>
</tr>
<tr>
<td>$\rho_{dmin}$ (t/m$^3$)</td>
<td>1.256</td>
</tr>
<tr>
<td>$D_{50}$ (mm)</td>
<td>0.54</td>
</tr>
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Fig. 2. Relationship between CT value and dry density of “Yamazuna sand”.

Fig. 3. Grain size distribution in Yamazuna sand.
highest capacity of our industrial X-ray CT, an image thickness of 0.3 mm and a 0.2 mm thick copper filter.

**Test procedure**

**One dimensional compression test**

In order to develop a method of proper image analysis for particle tracking in the soil, a simple one dimensional compression test was firstly conducted using the compression test apparatus originally developed for triaxial compression tests using an X-ray CT (Otani et al., 2002b). Photo 1 and Fig. 6 show the details of the compression test apparatus. The soil specimens were 50 mm in diameter and 100 mm in height, with dry Yamazuna sand with a density of 1.579 t/m³ (Dr = 90%) prepared in a rigid plastic mold. The vertical loading was monotonically applied at the top of the specimen with a loading speed of 0.3%/min until the axial strain of 10% and CT scanning was conducted at the beginning and at the end of the loading test. Only the upper part of the specimen was scanned through a depth of 10 mm from the top of the specimen with a total of 34 scans, each slice 0.3 mm in thickness. In addition, it is noted that it took 5 min for one cross section CT scanning.

**Triaxial compression test**

A triaxial compression test under the drained condition was also performed and at the same time, a series of CT scans were taken during the process of compression. The soil conditions were the same as those used in the one dimensional compression test. In preparing the sample, first a negative pressure was applied to the rubber membrane because of the dry sandy soil and the soil specimen was made by a total of 5 layers, with each layer tamped with 20 times under the drain condition at both ends of the specimen. The final condition of the specimen was ρ_d = 1.58 t/m³ (Dr = 90%). Triaxial compression apparatus was set on the specimen table in the CT room and the test was conducted with a confining pressure of 50 kPa under the drained condition. In the test, the soil specimen was scanned at the initial condition before applying the
compressive force and then, the specimen was compressed under the triaxial condition. When the axial strain level reached a value of 4%, the loading was stopped with closing the drainage connection and the soil specimen was scanned again. This scanning was repeated at the axial strain levels of 7%, 11% and 15%, respectively. A total of 334 slices was taken for the whole specimen at each axial strain level, including the initial condition.

Method of analysis

Image analysis

The fundamental purpose of the method is to track the soil particles in the soil. However, the size of the soil particles varies considerably, and this is especially true for the soil used in this study. Also, it is not possible to track all the particles on the CT images because of the lack of spatial resolution when using the CT apparatus. It is important to select the proper size of soil particles for tracking for optimum image analysis, since the spatial resolution of the X-ray CT is affected by the size of the particles. Fig. 7 illustrates an example of X-ray CT image and histogram of all the CT-values in this image. CT images are 14 bit digital images composed of so the called “CT-value”, which is the preliminary output, presented in monotonic dark shades for low CT-values and light shades for high CT-values, with 256 possible variations. In our X-ray CT apparatus, the CT image is constructed by 2048 x 2048 pixels times the thickness of X-ray attenuation, in which the unit of the image is called a voxel. The voxel is 0.073 mm x 0.073 mm x 0.3 mm for images with a 150 mm diameter sample cross section. A typical histogram is shown in Fig. 7(b), with two peaks on the curve, one representing the soil particles and the other representing the plastic mold.

The first step in the analysis was to transform the image from 14 bit to 8 bit to enhance the contrast of the particle in order to make the image of each particle as clear as possible. An 8 bit CT image is shown in Fig. 8(a). The contrast of the images in this figure is clearer than that in the images shown in Fig. 7(a). The second step was to construct a binary image in which the soil particles can be clearly shown in the image so that the soil particles could be selected. This segmentation process was done by thresholding; i.e., the threshold CT-values were chosen to separate the soil particles from the others in the binary image. This process is crucial since it corresponds to an important loss of information and, therefore, strongly influences the final results. Here in this study, this technique was used to select soil particles large enough to be tracked in the CT images based on the CT image resolution and Otsu’s method (Takagi and Shimoda, 2004). This method involves determining the optimum threshold value using a stochastic approach on the histogram of CT-values. After using Otsu’s method on the CT image shown in Fig. 8(a) of 256 grey levels, the binary image shown in Fig. 8(b) is obtained. However, some of the soil particles were connected to each other, and each soil particle has to be independent to track each particle. This brings us to the third step of the image processing analysis. After completing what is often called an erosion process on the image, the CT image shown in Fig. 8(c) is obtained. Some images in the specimen are also shown in focus in the upper left corners of Fig. 8. The particles were well extracted from the background and separated by using all the data processing described here.
Verification of the method of image analysis

First of all, the proposed image analysis was applied to a one dimensional compression test in order to confirm the effectiveness of this method. Once binary images were obtained, the positions of the larger particles of more than 4000 voxels were measured using Otsu’s method in the CT images at the initial condition. Then, the movements of the same soil particles were measured at a level of 10% axial strain. To do so, the positions of the particles have to be tracked from the initial point to their position after vertical loading and then the displacement vectors based on all the movements of the soil particles were computed. Fig. 9 shows some of the obtained 3-D displacement vectors in the soil specimen at the area of 10 mm depth from the specimen top. All of the particles moved along the loading direction with a vertical strain of nearly 10%, or about 10 mm displacement. The accuracy of the developed image analysis can be considered acceptable since the obtained displacement is almost the same as the applied strain level with the direction of the applied load at an area relatively close to the specimen top.

Results and discussion

Test results

Fig. 10 shows the force–displacement relationship from the triaxial compression test. As shown in this figure, scans were taken at the initial strain level and at A, B, C and D. Although there is a stress relaxation due to stopping the loading during CT scanning, the repeatability of the test was checked by conducting one with monotonic loading without CT scanning. Most of the relaxation phase occurs almost immediately after the loading is stopped and is not distributed over the whole scanning period. Fig. 11 shows
the CT images for all the strain levels at a different height \((h=10, 25, 40, 55\) and 70 mm) from the bottom of the specimen to investigate the density change in the soil. The clear soil particles in those images show that the total failure surface resulting from the progression of local failures appears after the peak stress condition, which corresponds to the C strain level. Also, at level D, total failure occurred in the soil. Since a large number of cross sectional images were obtained at all the strain levels, 3-D reconstruction images and cross sectional images, including vertical cross sectional images, can be obtained. Fig. 12 shows 3-D reconstruction images for all the strain levels. The low density area cannot be observed from level B, which is before peak stress. After peak stress, some banded low density areas appear in the middle of the specimen at level C. Finally, these areas extend to the dominant banded shape from the top-right to bottom-left at level D. Fig. 13 shows the vertical images for all the strain levels. The distribution of the density in the soil is clearly evaluated with the existence of soil particles. Low density areas appear in the middle of the specimen from level A and level B before peak stress. Also, some banded low density areas appear in the middle of the specimen which

![Force-displacement relationship](image)

**Fig. 10.** Force-displacement relationship.

![Cross sectional images](image)

**Fig. 11.** Cross sectional images. (a) Initial, (b) Level A, (c) Level B, (d) Level C and (e) Level D.
become a one banded area from the top-right to the bottom-left at the level C. This banded area is larger with increasing volume change of the specimen at level D. The following is a summary of the results shown in Figs. 11–13 for this specimen:

(1) A local band-like low density area starts before the peak stress occurred in the soil, although this behavior could not be observed from the outside of the specimen.

(2) This local area of low density appears from the middle of the specimen.

(3) A three dimensional total banded area can be confirmed after the peak stress in the soil using X-ray CT. These images made it possible to determine the precise behavior in the soil specimen using X-ray CT as a matter of density change. However, these results only reflect the change of density in the soil, and in order to have more quantitative discussion on the failure of soils, displacement also needs to be evaluated.

Calculation of displacements using image processing analysis

The same image analysis method introduced in the discussion of the results of the one dimensional compression test was used in the triaxial compression test. After tracking all the represented soil particles, the displacements of the particles in three dimensions are denoted by vector notations. Fig. 14 shows three dimensional displacement vectors for some of the soil particles at each of the strain levels ((a) initial–A, (b) A–B, (c) B–C, and (d) C–D). The movement of the soil particles around the upper part of the specimen is more obvious than in the lower part. While the displacements before strain level B were not in any specific direction, after level B, all the vectors move to the right below the top left of the specimen. The displacement in the soil was shown to be well evaluated by the movement of the soil particles.

Conclusions

In this paper, the displacements in the soil were measured under triaxial compression by tracking soil particles in the soil based on quantified CT data in three dimensions.

The conclusions drawn from this paper are listed as follows:

(1) A proper method of image processing analysis in which the movement of real soil particles was tracked was developed.
The displacements in sand were visualized using the developed image analysis method.

X-ray CT images depend on the X-ray absorbency of materials and are good indicators of material density. In order to determine the mechanical properties of soil, such as deformation and failure, more quantitative information about the strain field is required. In this study, a new approach to obtain quantitative information from X-ray CT was outlined. It should be noted that it is not possible to track all the soil particles in the soils due to the restrictions of the resolution on the CT apparatus. Further quantitative studies will focus on (1) the use of X-ray CT apparatus at higher resolution, or how to improve the quality of the images, in order to calculate the number of soil particles more precisely; and (2) the use of the image analysis technique known as “pattern matching” for tracking the pattern of the deformation.

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