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

Yoichi Watanabe[a], Nicolas Lenoir[b], Jun Otani[c,*], Teruo Nakai[d]

[a]*Graduate School of Science and Technology, Kumamoto University, Kumamoto, Japan*
[b]*Engineer of Research, Institut Navier, Universite Paris-Est, France*
[c]*X-Earth Center, Graduate School of Science and Technology, Kumamoto University, Kumamoto, Japan*
[d]*Graduate School of Engineering, Nagoya Institute of Technology, Nagoya, Japan*

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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.

*Corresponding author.
E-mail address: junotani@kumamoto-u.ac.jp (J. Otani).

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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 scanner 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:

$$\text{CT}-\text{value} = \frac{\mu_t - \mu_w}{\mu_w} K \quad (1)$$

where μ_t is the coefficient of absorption at the scanning point, μ_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

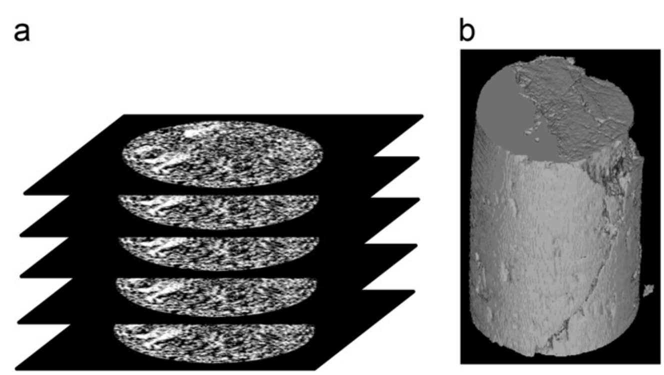

Fig. 1. X-ray CT principle (Otani et al., 2000). (a) A large number of cross sectional images and (b) Reconstructed 3D image.