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Localised deformation in a wide-grained sand under triaxial compression revealed by X-ray tomography and digital image correlation

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Abstract

Understanding the mechanisms of deformation and failure of soils is essential in geotechnical engineering. In particular, strain localisation is a key issue for the failure of soils. In laboratory mechanical testing, localised deformation can be investigated efficiently through full-field measurements of displacement and strain in soil specimens. The objective of this study is to investigate the deformation and the failure of a soil under triaxial compression using in situ X-ray (i.e., X-ray scanning during the loading test) computed tomography (CT) and digital image correlation (DIC). This paper is concerned with the characterisation of internal strains and with strain localisation patterning in wide-grained sand undergoing triaxial compression at different confinement pressures using Three Dimensional (3D) volumetric DIC. Complete 3D images of specimens have been recorded at several stages throughout the triaxial tests and analysed using 3D volumetric DIC in order to obtain 3D incremental displacement and strain fields. Based on the results of the combined X-ray tomography and DIC, the deformation process and especially the strain localisation are quantitatively characterised in space and time under different triaxial compression conditions.

Keywords: Wide-grained sand; Triaxial compression; X-ray tomography; Image analysis; Digital image correlation

1. Introduction

Understanding the mechanisms of deformation and failure of soils is essential in geotechnical engineering. In particular, strain localisation is a phenomenon commonly observed in granular materials in cases of soil failure. A better understanding of the stability of soils or the interaction between soils and structures is key to preventing soil failure. Various experimental, theoretical, and numerical studies concerning strain localisation have been presented in the literature. In experimental approaches, the localised behaviour from the micro- to macro-scale can be quantitatively evaluated through full-field measurements of the displacement and strain fields in soil specimens under load (for an overview see, for example Viggiani and Hall (2008). Digital image correlation (DIC) is a powerful tool in experimental mechanics that has been increasingly used in recent years (see reviews in Withers, 2008; Bay, 2008 for example). This method provides full-field measurements of kinematics and strains at the surface of an object or within an object during its deformation. On the other

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hand, X-ray computed tomography (CT) is a visualisation tool that allows observation of the internal 3D structure of materials and has been applied to study localised deformations of geomaterials during the last two decades (e.g., Desrues et al., 1996; Alshibli et al., 2000; Otani et al., 2002; Lenoir et al., 2007; Hall et al., 2010a; Higo et al., 2011). The combination of X-ray tomography and 3D strain field measurements in granular media, including particle displacements, has also been presented (e.g., Yamamoto and Otani, 2001; Nielsen et al., 2003; Matsushima et al., 2007; Hall et al., 2010a; Higo et al., 2013).

In a previous study (Watanabe et al., 2012), particle tracking was conducted under triaxial compression on wide-graded sand based on X-ray tomography data. The experiment was conducted using a specimen with a standard size of geotechnical engineering. As a result, typical soil particles were extracted from CT images and the movements of these particles were traced using the proposed grain tracking method. Finally, the displacement field in the specimen was visualised for various increments of deformation. However, several queries have arisen from this study. The highlighted behaviour does not seem to truly represent the behaviour of the soil because only a restricted number of particles were traced in the CT images. Moreover, it was difficult to evaluate the strain field because of the discretely distributed displacement vector. The present study addresses these issues by combining X-ray imaging and the DIC full-field displacement measurement method. The objective of this study is to characterise the evolution of the internal displacement and strain fields and the strain localisation patterning in a soil specimen having a standard size of geotechnical engineering. This is achieved using triaxial compression at different confining pressures, with in situ X-ray (i.e., with X-ray scanning during the loading test) computed tomography (CT) and 3D volumetric DIC (3D-VDIC). Complete 3D images of the specimens were recorded at several stages throughout the tests and analysed using 3D-VDIC in order to obtain 3D incremental displacement and strain fields. Based on the results of the combined X-ray tomography and 3D-VDIC, the deformation process and the strain localisation evolution are quantitatively characterised in space and time under different triaxial compression conditions.

2. Materials and methods

2.1. X-ray tomography

X-ray tomography, originally developed for medical investigation, has been increasingly applied to engineering research fields, such as geomechanics, geotechnical, and geoenvironmental. X-ray tomography 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. As the first step of this method, X-ray radiographic projections of a specimen are recorded at several angular points. Virtual slices are then reconstructed from these projections using appropriate algorithms, which are either algebraic or based on the back-

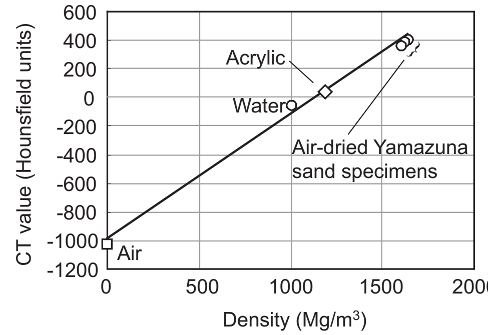

Fig. 1. Relationship between CT value and density of samples.

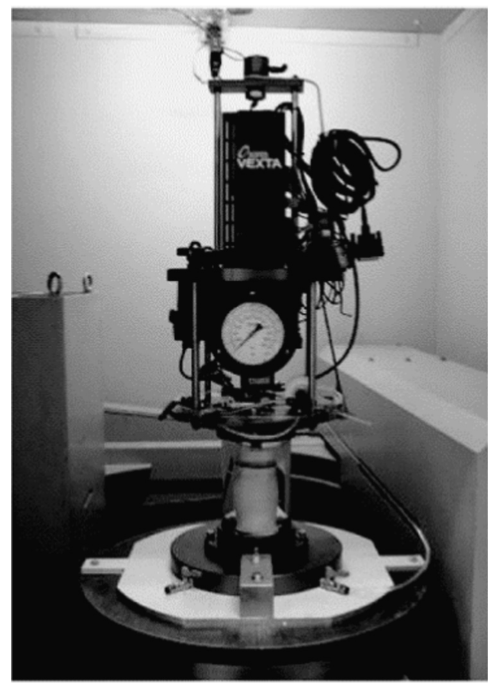

Fig. 2. Triaxial apparatus mounted on the rotation table of the scanner.

projection principle (Kak and Slaney, 1988). The volume image of the specimen can be reconstructed by stacking several sequential virtual slices. A reconstructed slice consists of the spatial distribution of the so-called "CT value", which is calculated from the coefficient of absorption defined in accordance to the following equation:

$$\mathrm{CT-value} = \frac{\mu_t - \mu_w}{\mu_w} K, \tag{1}$$

where μ_t is the coefficient of absorption at the scanning point, μ_w is the coefficient of absorption for water, and K is a constant (Hounsfield value) and fixed at a value of 1000 in the apparatus used. As shown in the literature (e.g., Higo et al., 2011), the CT value is linearly related to material density even if the material has a heterogeneous structure as a geomaterial. Fig. 1 shows the CT values of the specimen as a function of the average density obtained by the X-ray CT system used in this study, under the same scanning conditions (e.g., the voltage was 150 kV, the electric current was 4 mA, the