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Quantitative analysis of deformation in hollow cylinder tests on anisotropic clay formations

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ABSTRACT

A series of triaxial laboratory experiments are performed on thick-walled hollow cylindrical samples of boom clay. The aim of this testing program is to better understand the anisotropic deformation during the excavation. The testing conditions are similar to those to be experienced by host rocks around disposal galleries for radioactive waste. X-ray computed tomography is performed at different steps for each test with the samples remaining inside the loading cell. Initial analysis of the tomography images allows of the observation of the deformation of the central hole. In addition, particles manual tracking and 3D volumetric digital image correlation processing methods are considered being used to analyze the particles displacements and the boundary deformation of the sample quantitatively. An unsymmetrical damaged zone is induced around the hole, with a reverse deformation trend being found at the boundary after unloading, which indicates that the significant anisotropic deformation of boom clay can be induced by mechanical unloading.

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1. Introduction

Medical X-ray computed tomography, as a non-destructive tool suitable for a wide range of geological investigations, has been used to reveal porosity distributions, microstructures and fracture apertures of rocks, and to study the borehole instability in shale intervals and the influence of bedding plane orientation on shale swelling [1–6]. Moreover, X-ray computed tomography (XRCT) is also used to study the internal structure and the mechanical deformation of rocks, monitor local deformations in rock samples during a test, analyze shear bands in triaxial specimens, and track particles movement by means of compared X-ray scans [7–12], so that the degree of deformation in the test samples can be determined correctly, especially for the internal distribution of this deformation.

Hollow cylinder experiments can be carried out for both the characterization of rock properties and the physical modelling at scale of engineering applications [13–15]. In the framework of TIMODAZ WP3.3, a series of triaxial laboratory experiments are performed on thick-walled hollow cylindrical samples. The aim of this testing program is to better understand the mechanical behavior of the host rocks around radioactive waste disposal galleries under conditions, which is similar to those experienced in-situ. In addition to the mechanical testing, medical X-ray computed tomography has been carried out at each step of the test, which allows of a first observation of the change around the central hole and the extent and evolution of damaged zone with the samples remaining inside the loading cell. Then, quantitative analyses of the undergone displacements can be performed. Two different image processing methods are considered: (i) particles manual tracking of the movement of inclusions (pyrite) present in the clayey material; (ii) 3D volumetric digital image correlation which allows mapping and providing full-field measurement of incremental of displacements and strain fields. The deformation distribution around the central hole and along three directions (parallel, perpendicular and at 45° to the bedding planes) by means of above two methods are presented and analyzed, the anisotropic deformation of boom clay is discussed, and some conclusions are derived.

2. Materials and methods

2.1. Materials and tests

Boom clay is being considered as a potential host rock for deep radioactive waste repositories in Belgium. It is one kind of plastic

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clay with many favorable properties, such as very low hydraulic conductivity, good retention capacity of the radionucleides, and fractures self-sealing in short time, which make it ideal as a geological barrier for radioactive waste disposal. This marine sediment of tertiary, the Rupelian age, lies 190–290 m below ground level at the Belgian Mol-Dessel nuclear site. For the test, the thick-walled hollow cylindrical sample is prepared by drilling a coaxial central hole in a drill core with inner and outer diameters of 14 mm and 86 mm respectively. The height of the sample is 172 mm. The samples are drilled both parallel and perpendicular to the bedding plane direction. In this paper, some results of the sample drilled parallel to the bedding plane will be presented (Fig. 1).

The procedures of the test involve the recovery of the in-situ stress conditions followed by reduction of the pressure in the central hole. The aim of this undrained unloading is to model the extension stress path that develops during the construction of disposal galleries and to generate a damaged zone around the central hole. X-ray computed tomography is carried out at different steps of the test to study the changes induced around the central hole by mechanical and thermal loadings without removing the sample from the testing cell, an aluminum body cell instead of the usual stainless steel cell that reduces the X-ray attenuation (Fig. 1), to allow a medical X-ray CT device to scan the sample through the cell walls, and hopefully to observe (density) changes in the sample.

2.2. X-ray computed tomography

The X-ray technique allows of the visualization of the internal structure of opaque objects from different directions. For this purpose, the object is illuminated with X-ray radiation and the change in transmitted X-ray intensity is measured. The details on physical principles of X-ray computed tomography have been reviewed by Jacobs [16]. In the simulation test, X-ray CT scans are carried out at different steps (i.e. before and after the mechanical unloading as well as after the heating and cooling cycle when this stage is successful) to observe changes around the central hole and hopefully the extent and the evolution of the damaged zone. Medical X-ray CT scans are performed with a 64-MSCT (light speed VCT, GE Healthcare, USA) scanner at the department of Diagnostic and Interventional Radiology, CHUV, Lausanne. The tube voltage as well as the tube charge is fixed to 120 keV and 650 mAs. A voxel size of 0.6 mm × 0.215 mm × 0.215 mm is obtained. Data from CT scanners are collected as image sequences in the DICOM format [17]. The CT images of the hollow cylinder samples (86 mm in diameter and 172 mm in length) provide about 600 slices reconstructed density maps of 512 × 512 pixels each with a dynamic range of 16 bit.

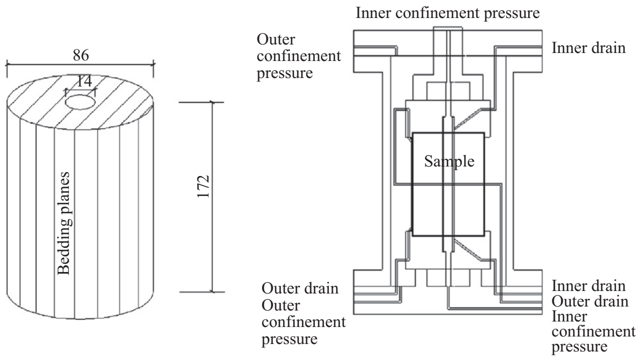

Fig. 1. Schematic of the sample drilled parallel to the bedding plane (left) and the skeleton of testing device (right).

A corresponding X-ray CT slice of the clay sample is obtained before and after the mechanical unloading (Fig. 2). Although the medical X-ray CT has a medium resolution, some important observations can be made: (i) a very clear ovalisation of the central hole is noticed, with principal axes approximately parallel and orthogonal to the bedding planes (dashed lines); (ii) a small ovalisation of the outer boundary is observed in the opposite sense, i.e., a decrease in diameter perpendicularly to the bedding planes. Depending on the section, a damaged zone seems to develop around the central hole.

2.3. Particles manual tracking

From initial analysis of the X-ray tomography scans, little information can be gained about the deformation away from the central hole and the outer perimeter of the sample (Fig. 2). Therefore, particles manual tracking is carried out to gain quantitative information from the X-ray images by comparing the position of well-discernible particles (i.e. pyrite inclusions) in the CT images performed before and after the mechanical unloading, possible to determine their displacement. The procedure consists of several steps: (i) A stack of the before and after mechanical unloading images which are corrected for rotation due to the different orientation of the sample during the two scans; (ii) In the CT scans located in the central part of the specimen (to avoid the boundary effects of the upper and lower caps), identification of pyrite inclusions and determination of their boundary and centre using the MATLAB© image toolbox; (iii) Computation of the displacement of these inclusions by a combination of image plugins; (iv) Projection of all the tracked particles along the axis of the sample to represent their displacement in a single plane (assuming that the considered slices move evenly); (v) Consideration of the points located into three azimuthal sectors defined by two lines at ±15° to the diameters respectively parallel, perpendicular and at 45° to the bedding planes direction. Total displacement profiles along these 3 directions are provided (Fig. 3). In addition to this tracking of pyrite inclusions located inside the clay, the radial component of displacement of the central hole wall is determined along 12 directions and averaged along the sample axis.

2.4. 3D volumetric digital image correlation

X-ray tomography monitoring during tests allows of the observation of the development of deformation only when there are significant changes in material density. Therefore, 3D volumetric digital image correlation (3D volumetric DIC) of the X-ray CT images is used to provide full-field measurement of incremental of displacements and strains throughout the imaged volume [18]. The basic procedures of the program can be summarized as: (i) definition of nodes distributed over the first image and that of a region centered on each node (the correlation window);

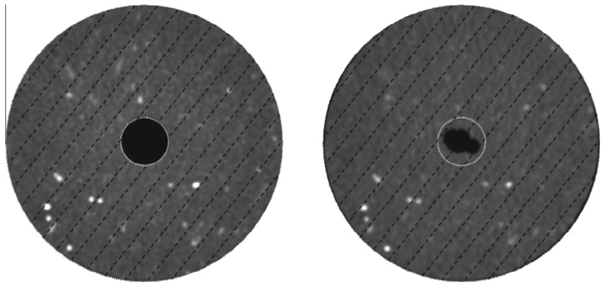

Fig. 2. X-ray CT scans of the boom clay sample before (left) and after (right) the mechanical unloading.

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