International Journal of Rock Mechanics and Mining Sciences 111 (2018) 45–53

Contents lists available at ScienceDirect

International Journal of
Rock Mechanics and Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

A new approach to quantify the anisotropy of hydromechanical strains in clay-rock at the gallery scale

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ARTICLE INFO

Keywords:
Anisotropy measurement
Hydromechanical strains
Tournemire clay rock
Digital image correlation

ABSTRACT

We describe a new method to quantify the anisotropy ratio of hydric strains acquired at the gallery scale and over a period of at least one year. This method was applied in the context of an investigation conducted on a gallery front of the Experimental Station of Tournemire (France), which was subjected to a natural seasonal cycle. Our approach was based primarily on a new algorithm for Digital Image Correlation, known as H-DIC, which can accurately locate desiccation cracks and extract fifteen uncracked blocks with quantified sub-vertical and sub-horizontal strains.

The values of the anisotropy ratio of hydric strains (i.e., the ratio of the sub-vertical strains to the sub-horizontal strains, or the ratio of the strains perpendicular to the bedding to those parallel to the bedding) are in the range of [2.84–5.35], with a mean value close to 4.2.

The anisotropy ratio for the hydric strains appears to be independent of the natural cycle (i.e., hygrometry) present in the gallery. This observation is supported by a theoretical estimation of this anisotropy ratio, which suggests that the poroelastic parameters of clay rock are insensitive to climatic changes or that theirs evolutions roughly cancel each other out. With regard to geometrical patterns (area, width, height, aspect ratio and orientation) calculated for the uncracked blocks, the anisotropy ratio of the hydric strains does not depend on the area of these uncracked blocks.

Moreover, a literature review shows that the values of the anisotropy ratio for the hydric strains determined in this study are significantly larger than those obtained at the laboratory scale on undamaged samples or estimated from a theoretical relationship established in a poroelastic framework. These comparisons strongly suggest that damage to clay rock existing on the gallery front contributes to a significant increase in the anisotropy ratio of the hydric strains.

1. Introduction

The disposal of nuclear waste in clay rocks is a topic of interest in many industrialized countries [e.g.,[1]]. Among the critical issues related to the long-term safety assessment of such geological repositories, the study of the excavation-damaged zone (EDZ) is particularly important. The initiation and extension of the EDZ are governed by several parameters,[1–3] including the mechanical properties of the rock, the initial stress field, the existence of natural fracture zones in the rock mass, the geometry of the gallery, and the hydric state existing in the gallery. With regard to the hydric state existing in the gallery, fractures associated with the desaturation of the argillaceous medium have been observed on gallery fronts in several underground research laboratories, such as the experimental platform of Tournemire[4] and the Mont Terri Laboratory.[5] This hydric fracturing process is characterized in situ by sub-horizontal cracks spaced at several decimeters on all of the vertical walls in contact with ambient air. These sub-horizontal cracks induced by desiccation are parallel to the bedding planes, suggesting that they are partially controlled by sedimentological patterns (e.g., vertical differences in sediment grain size and mineral composition or organization). In winter (dry state), the corresponding crack apertures can reach a few millimeters, whereas these cracks close in the summer (wet state).

The DIC technique has been successfully used in geomechanics to observe strain localization in geomaterials,[6] to determine crack positions and to calculate the crack openings in clay rocks at various

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https://doi.org/10.1016/j.ijrmms.2018.07.004
Received 22 November 2017; Received in revised form 2 July 2018; Accepted 27 July 2018

scales.[7–13] Recently, new works performed at the experimental platform of Tournemire and using digital image correlation (DIC) technique have demonstrated (a) the existence of other types of sub-horizontal desiccation cracks at a distance of approximately 64–100 mm and (b) the presence of sub-vertical cracks crossing these sub-horizontal cracks.[11] Moreover, these observations demonstrated the ability of the non-contact DIC method to monitor clay–rock strains for at least four months and to monitor the opening and closing of desiccation cracks for more than one year at the gallery scale with an acquisition every 30 min. However, these kinematic data have been obtained from a classical DIC algorithm, which was not suitable for accurately determining the kinematical fields near desiccation cracks. The limitation of classical DIC algorithms to manage kinematic discontinuities can be overcome by various numerical methods, such as the point-wise[14] and the subset splitting methods,[15] whose presentations are beyond the scope of this paper.

This study focuses on an original use of a new algorithm for DIC known as Heaviside-based digital image correlation (H-DIC), which uses the Heaviside function properties to determine both kinematic fields and crack position when multiple discontinuities are present.[16] This H-DIC algorithm is applied in this study on numerical images recorded from March 2011 to April 2012 (376 days) at the experimental platform of Tournemire.[11] The improvements of H-DIC are the enrichment of kinematical fields by a Heaviside function H to be able to accurately determine displacements in presence of a crack in each subset, and so a better location of desiccation crack when the aperture was superior to 0.1–0.2 pixel. Thus, H-DIC algorithm allows a description more realistic of hydro-mechanical behavior of argillaceous rock at the gallery scale. Contrary to H-DIC, classical DIC is less accurate to detect thin cracks. In the case of classical DIC, the user can consider a presence of a desiccation crack when it is visible (i.e., superior to 1 pixel) [e.g.,[11]]. In other words, the undetected desiccation cracks, when their aperture is inferior to 1 pixel, lead to underestimate the number of fractures.

The objectives of this investigation are (a) to assess the ability of the H-DIC approach to observe new kinematic patterns associated with the hydric fracturing process operating at the gallery scale, (b) to provide new accurate hydric strains measured on a gallery front and (c) to calculate anisotropy ratios of the extracted in-plane components of the mean strains for comparison with the anisotropy ratios from the literature and theory.

2. Geological and geotechnical setting

The Tournemire experimental station of the French Institute for Radioprotection and Nuclear Safety (IRSN) is located in a Mesozoic basin on the southern border of the French Massif Central and at the western limit of the “Causse du Larzac”. The Tournemire massif is a monocline structure and is affected by the Cernon fault and secondary sub-vertical faults of hectometric extension. The argillaceous formation of interest which is 250 m thick corresponds to sub-horizontal consolidated argillaceous and marly layers from the Toarcian and Domerian ages (e.g.,[4,17–19]). This formation is sandwiched between two carbonated and karstified aquifers. The upper Toarcian, corresponding to a 160 m thick layer of argillite, is crossed by a 1885 m long, century-old railway tunnel that was excavated between 1882 and 1886.

The mineralogical composition of the upper Toarcian formation shows that clay minerals composed of kaolinite, illite, and illite/smectite mixed-layer minerals represent approximately 40 wt% of the bulk-rock composition. The clay fraction is composed primarily of kaolinite (15–20 wt%), illite (5–15 wt%), illite/smectite mixed-layer minerals (5–10 wt%) and chlorite (1–5 wt%). This Toarcian formation also contains 10–40 wt% of carbonates (mainly calcite), 10–20 wt% quartz grains and 2–7 wt% pyrite.[4,20,21] The water content is between 3.5 and 4.0 wt%.

Mechanical investigations[22,23] have shown that Tournemire argillite consists of a transverse isotropic geomaterial (i.e. anisotropic behavior). The physico-chemical and mechanical properties of Tournemire argillite can be found in Refs. 4,10,11.

Three different kinds of fractures are observed at the Tournemire experimental station (e.g.,[4,17]): (i) fractures at the gallery walls induced by stress redistributions during excavation (millimeter-scale width and meter-scale extension), (ii) pre-existing tectonic fractures in the rock mass with similar dimensions as the previous fractures i.e., mm-scale widths and m-scale extensions and (iii) networks of regularly spaced (by approximately 20 cm) sub-horizontal cracks parallel to the bedding planes. These sub-horizontal cracks, which are easily observed on the vertical walls of the Tournemire galleries, are each several decimeters deep with a sub-millimeter aperture.

The set of sub-horizontal cracks is directly linked to seasonal variations in atmospheric properties at the Tournemire experimental station that result in variations in the chemical potential of the interstitial solutions during wetting/drying cycles.[11,17,18,24] Hygrometry is characterized by the relative humidity, RH and temperature, T. The RH has been recorded since 1999 and exhibits seasonal variations typically 40% in RH and 8 °C in winter and 99% in RH and 14 °C in summer, with a mean annual RH value of 77% that leads to partial evaporation of the interstitial water. A clear correlation was measured between the aperture of these sub-horizontal cracks and the measured RH with a lag time of approximately 60 h between the fracture aperture and RH variations, as measured using capacitive thermohygrometers.[25]

Our experimental investigation focused on the locations of all the sub-horizontal and sub-vertical desaturation cracks[11] and the deformation of clay rocks to characterize and quantify the anisotropy of hydric strains.

3. Input data: the experimental configuration at the East96 gallery

The numerical images processed in this study were acquired from an experimental investigation performed in the East96 gallery front of the Tournemire experimental station.[11] This gallery was drilled in 1996, fifteen years before the beginning of the experience. Two reasons guided the choice of the East96 gallery: (a) its EDZ is developed, but less than in the old railway tunnel, and (b) the clay rock can be directly observed on the galley wall because no concrete lining exists on the surface of the gallery. With regard to the age of the gallery, no significant evolution of the EDZ extension was expected. The cross-section of the East96 gallery has a horseshoe shape with a height of 3.7 m, a width along the floor of the gallery of 4 m, and a length of 30 m. The mechanical stability of the gallery is ensured by steel supports regularly spaced every 2 m.

The experimental configuration in the East96 gallery (Fig. 1) comprised four parts (see details in[11]):

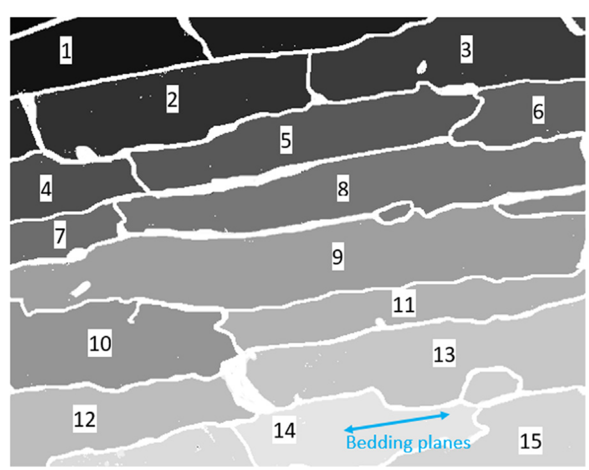

Fig. 1. Location of fifteen blocks (k = 1–15) on the ZOI.