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One-year monitoring of desiccation cracks in Tournemire argillite using digital image correlation

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ABSTRACT

Digital image correlation (DIC) was used for the first time in an underground gallery to monitor desiccation cracks during an annual climatic cycle. This experimental *in situ* investigation was carried out on a study area of 344 × 275 mm², located on the East96 gallery front at the Tournemire experimental station, during which the relative humidity and temperature were continuously measured for more than one year, from March 2011 to March 2012.

Our results demonstrate the ability of the non-invasive 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. Moreover, our study provides the following phenomenological results. As observed in the laboratory, the hydric strains were anisotropic; the strains perpendicular to the desiccation cracks were almost homogeneous and much larger than those parallel to the same cracks. The changes in crack apertures calculated from the displacement fields (at an accuracy of approximately 26.9 μm) and the strain fields were clearly correlated and concomitant with changes in relative humidity and temperature (with $25\% < RH < 99\%$ and $6\ ^\circ\mathrm{C} < T < 14\ ^\circ\mathrm{C}$). Contrary to direct measurements acquired at the Mont-Terri site, the crack apertures of the desiccation cracks were reversible after one year of data acquisition. Moreover, although the main desiccation cracks were sub-horizontal and associated with the direction of bedding planes, our work demonstrates the existence of sub-vertical cracks. The qualitative interpretation of our entire dataset has emphasized the need for a multi-scale approach to understand the desiccation cracking mechanisms at the scale of an underground facility.

1. Introduction

Clay rocks are considered in several industrial countries as potential repositories for high-level radioactive wastes. Among the critical issues related to the long-term safety assessment of such geological repositories, the study of the so-called excavation damaged zone (EDZ) is of particular importance. The initiation and extension of the EDZ are governed by many parameters [1–3]: the material properties of the rock (*e.g.*, material anisotropy), 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 latter, fractures associated with the desaturation of argillaceous medium have been observed on gallery fronts in several underground research laboratories, *e.g.*, in the experimental platform at Tournemire [4,5] and in the Mont Terri laboratory [6]. This hydric fracturing process is evidenced *in situ* by sub-horizontal cracks spaced at several decimeters on all vertical walls in contact with ambient air. In winter (dry state), the corresponding crack apertures can reach a few millimeters; in summer (wet state), these cracks are closed. These cracks induced by drying are parallel to the bedding planes, suggesting that they are partially controlled by sedimentological patterns (*e.g.*, vertical differences in sediment granulometry and/or mineral composition).

These observations of clay–rock damage induced by drying have been obtained in the field using conventional crackmeters or jointmeters, and one may wonder whether similar observations could have been made using non-invasive optical methods, such as the digital image correlation (DIC) technique. The ability of the DIC technique, a full-field measurement method, to monitor the hydromechanical strains and rock failure of clay–rock samples has been demonstrated in the laboratory under various loadings [7–12]. Moreover, the maps of strain fields obtained using DIC have provided some physical insights into deformation mechanisms at the microscopic scale, typically from a spatial scale of a few centimeters [9–11]. However, despite the growing interest in using

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the DIC method to study rock mechanics, this optical technique has not been used in underground galleries to monitor *in situ* cracking processes.

This paper presents an application of the DIC method in the East1996 underground gallery at the experimental platform of Tournemire; during this study, the Relative Humidity (*RH*) and temperature (*T*) were measured for more than one year. The objectives of this experimental investigation were (a) to assess the ability of the DIC method to measure strain fields and crack apertures induced by climatic changes in an underground gallery, (b) to correlate the measured strain fields and crack apertures with climatic fluctuations (*RH* and *T*) in the gallery, and (c) to discuss our results in the light of current knowledge of hydromechanical behavior of clay materials.

2. Geological, geomechanical, and climatic contexts

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 a main fault (the Cernon fault) and secondary sub-vertical faults of hectometric extension. The studied argillaceous formation is 250 m thick and corresponds to sub-horizontal consolidated argillaceous and marly layers of Toarcian and Domerian age [4,5,13,14]. 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 (kaolinite, illite, and illite/smectite mixed-layer minerals) represent approximately 40 wt% of the bulk-rock composition [15,16]. The clay fraction is mainly composed of illite (5–15 wt%), illite/smectite mixed-layer minerals (5–10 wt%), chlorite (1–5 wt%), and kaolinite (15–20 wt%). The Tournemire argillite also contains 10–20 wt% of quartz grains, 10–40 wt% of carbonates (mainly calcite), and 2–7 wt% of pyrite [4,15,16]. The water content is between 3.5 and 4.0 wt%.

Geomechanical investigations [17,18] have shown that Tournemire argillite consists of a transverse isotropic geomaterial. Some physico-chemical and mechanical properties of Tournemire argillite are listed in Table 1.

Three different types of cracks are observed at the Tournemire experimental station [4,5]: (i) fractures at the gallery walls induced by the stress redistribution during excavation (millimeter-scale width and meter-scale extension), (ii) pre-existing tectonic fractures in the rock mass (same dimensions as the previous fractures *i.e.*, mm-scale width and m-scale extension) and (iii) networks of regularly spaced (of 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 are directly linked to seasonal variations in atmospheric properties (hygrometry and *T*) at the Tournemire experimental station that result in variations in the chemical potential of the interstitial solutions under wetting/drying cycles [4,13]. The *RH* recorded since 1999 shows seasonal variations (typically 40% in *RH* and 8 °C in winter and 99% in *RH* and 14 °C in summer), and the mean annual *y* value of 77% leads to partial evaporation of the interstitial water. A clear correlation was measured between the aperture of these sub-horizontal cracks and the measured y with a lag time of approximately 60 h between the fracture aperture and *y* variations measured using capacitive thermohygrometers [19].

Table 1
Physico-chemical and mechanical properties of Tournemire argillite (from [4,14]).

Density	2.5–2.6 × 10^3 kg m^{-3}
Grain density	2.7–2.8 × 10^3 kg m^{-3}
Pore size	Centered around 2.5 nm
Total porosity	6–9%
Gravimetric water content	3.5–4%
Specific surface area	23–29 m^2/g
Cation exchange capacity	9.5–10.8 meq/100 g
Hydraulic conductivity	10^{-14}–10^{-15} m/s (laboratory) 10^{-11}–10^{-14} m/s (in situ)
In situ stress state	
Minimal vertical stress	3.8 MPa
Minimal horizontal stress	2.1 MPa
Maximal horizontal stress	4.0 MPa
Elastic properties	
Horizontal Young modulus	27,680 MPa
Horizontal Poisson ratio	0.17
Vertical Young modulus	9270 MPa
Vertical Poisson ratio	0.2
Uniaxial compressive strengths	
Horizontal compressive strength	32 MPa
Vertical compressive strength	13 MPa

This experimental investigation was performed in the East96 gallery front of the Tournemire experimental station. The East96 gallery was excavated in 1996. Two reasons guided this choice: (a) the EDZ is less developed in this gallery 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. 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. Its mechanical stability is ensured by steel supports that are regularly spaced every 2 m.

Our experimental investigation focused on the aperture kinetics of desaturation cracks and the deformation of clay rocks.

3. Experimental setup and procedure

3.1. Digital image correlation (DIC)

Full-field optical methods are widely used in experimental mechanics to obtain direct access to the kinematical data issued from mechanical studies [20,21]. Among these optical metrologies, DIC is a non-invasive and non-destructive approach that allows full-field displacement to be obtained [20–25]. The method is very simple to use and can be applied in many experiments on materials and for industrial structures. Nevertheless, because of its large measurement base, this method requires specific developments to analyze kinematical displacement fields when cracks or high gradients are present [21].

In geomechanics, the ability of the DIC method to successfully observe strain localization in geomaterials [26] and to detect cracks in clay rocks [11] has been demonstrated.

To obtain the displacement field of an area undergoing mechanical transformation, the DIC method monitors the positional changes of a speckle pattern located on the sample surface. The speckle pattern is typically the result of a random spatial variation of light intensity. This speckle can be obtained artificially by painting the surface of the sample, but the natural roughness existing on the gallery front was used in this work.

To obtain the full-field displacements (u,v) from DIC, two images are necessary, a first gray-level function $f(x,y)$ acquired at the initial state t_0 and a second gray-level function $g(x,y)$ at an actual state t. The principle of this method is to minimize a