International Journal of Rock Mechanics & Mining Sciences 85 (2016) 192–208

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

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

Permeability evolution and water transfer in the excavation damaged zone of a ventilated gallery

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ARTICLE INFO

Article history:
Received 20 June 2015
Received in revised form
5 February 2016
Accepted 11 March 2016
Available online 14 April 2016

Keywords:
Permeability modification
Excavation damaged zone
Rock–air interaction
Unsaturated behaviour
Modelling
Shear banding

ABSTRACT

The fluid transfers occurring around underground galleries are of paramount importance when envisaging the long-term sustainability of underground structures for nuclear waste disposal. These transfers are mainly conditioned by the behaviour of the surrounding material and by its interaction with the gallery air. The hydro-mechanical behaviour of the excavation damaged zone, which develops around galleries due to the drilling process, is thenceforward critical because it is composed of fractures having a significant irreversible impact on flow characteristics and transfer kinetics. Besides, the material interaction with the gallery air may engender water drainage and desaturation. Thus, a gallery air ventilation experiment, preceded by its excavation, is numerically modelled in an unsaturated argillaceous rock to study its influence on hydraulic transfers. The fractures are numerically represented with shear strain localisation bands by means of a microstructure enriched model including a regularisation method. The impact of fracturing on the transport properties is addressed by associating the intrinsic permeability increase with mechanical deformation which is amplified in the strain localisation discontinuities. Such dependence permits us to reproduce a significant permeability increase of several orders of magnitude in the excavation damaged zone, in agreement with available experimental measurements. After the excavation, the hydraulic transfers are studied through the reproduction of a gallery air ventilation experiment that implies drainage and desaturation of the surrounding rock. These transfers depend on liquid water and water vapour exchanges at gallery wall that are introduced through a non-classical boundary condition. The model prediction successfully captures the drainage and desaturation kinetics of undisturbed and damaged rock.

1. Introduction

In the context of long-term nuclear waste management, deep underground repository of high-level radioactive waste is envisaged in geological media having good confining characteristics. The behaviour of the surrounding material has to be precisely characterised in order to assess the long-term sustainability of the underground structures. Nowadays, it is commonly assumed that underground drilling process engenders cracks and eventually fractures[1] that deteriorates the hydro-mechanical properties of the surrounding host material. These modifications take place in a zone called Excavation Damaged Zone (EDZ), located around the galleries, which is affected by important modifications of the material flow characteristics such as permeability increase.[2] Since a low hydraulic conductivity is required to ensure a safe long-term disposal, the EDZ behaviour is a major issue because it may constitute a preferential flow path for radionuclide migration. Consequently, the characterisation of the material transport properties and of the transfer kinetics that occurs around galleries still needs to be investigated.

The flow transfers are also conditioned by the interaction with the gallery air. At repository scale, air ventilation is usually realised in galleries during the excavation and the maintenance phases. This ventilation can affect the material behaviour by draining its water and causing desaturation. Therefore, large-scale air ventilation experiments are performed in Underground Research Laboratories (URL). The latter have been developed to investigate the suitability of host formations for nuclear waste disposal and to evaluate the repository feasibility.[3] A numerical reproduction of an air ventilation test performed in a low permeability rock will be realised in order to study the air interaction as well as the effects it engenders on the host formation behaviour. The studied rock is the Callovo-Oxfordian claystone (COx) which is envisaged for deep underground repository of nuclear wastes in France.[4]

Before modelling this ventilation experiment, the material

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http://dx.doi.org/10.1016/j.ijrmms.2016.03.007
1365-1609/

transport properties have to be characterised. They mainly depend on the fracturing process and on the hydraulic permeability increase it engenders. Considering the fracturing process, shear strain localisation can be considered as a precursor to fractures. In fact, material rupture is generally preceded by localised deformation in shear band mode[5] that can lead to material damage, microcracks and fractures. With such macroscopic description, the evolution of permeability within the EDZ can be associated to the strain localisation discontinuities with a dependence on the mechanical deformation.

Numerous modelling of the EDZ behaviour has been realised in the past decades. This modelling often includes separately hydro-mechanical coupling,[6,7] permeability variation,[8] flow transfers,[9] or strain localisation.[10] For strain localisation approaches, there is a lack of numerical modelling which takes into account these different aspects simultaneously, at large scale, and which reproduce *in situ* experimental measurements. The coupled and simultaneous reproduction of these phenomena constitutes the objective and originality of the proposed modelling.

In the present study, a particular attention is given to the characterisation of the EDZ and of the flow transfers during gallery excavation and ventilation. It will be investigated with a non-linear finite element method (code Lagamine) for the Callovo-Oxfordian claystone, a low permeability rock exhibiting a transversely isotropic behaviour. EDZ evidences and the considered large-scale air ventilation experiment are firstly detailed in Section 2. Then, the hydro-mechanical constitutive model is developed in Section 3 for an unsaturated porous media.

Finally, the gallery excavation and the air ventilation experiment are numerically modelled in Section 4. The first numerical phase is the gallery excavation modelling during which the development of the fractures that compose the EDZ is reproduced by shear banding.[10] Considering the fractured rock as a continuous medium at the macroscale, the intrinsic hydraulic permeability evolution is reproduced through a strain-dependent relation. Succeeding to the excavation, the air ventilation experiment is reproduced in the underground gallery. In this second numerical phase, the exchanges at gallery wall between the claystone and the cavity air are characterised with a non-classical mixed hydraulic boundary condition.[11,12] Then, the influence of the controlled ventilation on the claystone behaviour is analysed, including a particular focus on the drainage and desaturation kinetics.

2. Underground drilling and air ventilation

The material behaviour around underground structures is significantly influenced by the drilling process and by the air–material interaction. On one hand, the drilling leads to the appearance of cracks or fractures concentrated in an Excavation Damaged Zone (EDZ) that develops around galleries. On the other hand, the interaction with air may engender drainage and desaturation. Both of these aspects modify the transport properties of the underground material.

In the context of research on deep underground nuclear waste repository, Underground Research Laboratories (URL) have been constructed in very low permeability media with the objective of characterising the possible host formations and evaluating the feasibility of a safe repository.[3] Because air ventilation is performed during the construction and operational phases of the galleries that compose the underground structures, air ventilation experiments are performed in URL to investigate the interaction with air and its effects on the host material. In the following, we will particularly focus on the behaviour of the Callovo-Oxfordian claystone. In the Meuse/Haute-Marne URL, the French national radioactive waste management agency (Andra) performs a large-scale ventilation experiment called Saturation Damaged Zone experiment (SDZ) in an experimental gallery (GED).[9,13] This experiment will be studied and numerically reproduced in the following work.

Hereafter, the excavation damaged zone developing around the experimental gallery and the SDZ ventilation experiment are described.

2.1. Excavation damaged zone

It has been widely observed that underground drilling leads to stress redistribution, damage propagation, cracks, and eventually to the development of fractures (macrocracks) around drifts.[1] Thence, an excavation damaged zone expands in the surrounding medium with significant irreversible modifications of hydro-mechanical and geochemical properties due to the fracturing process.[2] These changes inevitably induce major modifications of the material transport and flow characteristics such as the hydraulic permeability.[14–16] When considering the long-term waste repository and the safety function of the host formation, the EDZ behaviour is a crucial issue because it could constitute a preferential flow path.[17] Modelling the damaged zone and its hydraulic property modifications is therefore important when considering hydraulic transfers around underground drifts.

The EDZ has been carefully investigated in URL through, for instance, fracture measurements, permeability analysis, and flow transfers. For the Callovo-Oxfordian claystone, induced extension and shear fractures are detected in the proximity of the galleries composing the Andra's URL, with shearing as the principal failure mechanism because of the high *in situ* stress environment.[1] In the fractured zone, the hydraulic permeability can severely increase up to several orders of magnitude, especially due to the presence of interconnected extensional fractures.[18]

Concerning the SDZ ventilation experiment, it is performed in the GED experimental gallery which is oriented parallel to the minor horizontal principal stress. Around this gallery and the SDZ experimental zone, the permeability increase has been highlighted by measurements performed under saturated conditions in boreholes that are drilled in different orientations (Fig. 1(a)). Moreover, the permeability measurements in the fractured zone are representative of the fracture permeability, not of the permeability of the continuous rock matrix. Three zones can be defined: an undisturbed zone with a permeability lower than 10^{-19} m^2 far from the gallery, a slightly disturbed zone with a permeability ranging from 10^{-19} m^2 to 10^{-17} m^2, and a highly disturbed zone close to the gallery with a permeability higher than 10^{-17} m^2 (increase higher than 2 orders of magnitude). The extents of the zones are detailed in Fig. 1(b) and superposed to the experimental data in Fig. 1(a). A parallelism between hydraulic measurements and fracture measurements can be evidenced and the permeability zones can then be related to shear and tensile fracture zones (Fig. 1(b)). The damaged zone shape also differs depending on the induced fracture network which is related to the orientations of the galleries and to the stress state anisotropy.[18]

2.2. Ventilation experiment

At nuclear waste repository scale, air ventilation is performed in the underground galleries during the excavation and maintenance phases. This ventilation could impact the behaviour of the underground structures by draining the water from the rock. In case of important drainage, it can even lead to rock desaturation, stress modification, as well as modification of the fracturing structure close to the drifts. As a consequence, the damaged zone behaviour could be affected.[19]