Computers and Geotechnics 85 (2017) 351–367

Contents lists available at ScienceDirect

Computers and Geotechnics

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

Research Paper

Modelling the influence of strain localisation and viscosity on the behaviour of underground drifts drilled in claystone

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ARTICLE INFO

Article history:
Available online 1 June 2016

Keywords:
Excavation damaged zone
Strain localisation
Shear banding
Viscosity
Cross-anisotropy
Numerical modelling

ABSTRACT

A benchmark is conducted to characterise the Callovo-Oxfordian claystone behaviour for nuclear waste repository. The objective is to model gallery drilling and Excavation Damaged Zone (EDZ) around galleries. The proposed model is a cross-anisotropic elasto-viscoplastic model whose parameters are calibrated from laboratory tests. Gallery drilling is modelled numerically and shear fractures are reproduced with shear bands. The modelling highlights the contributions of shear banding, viscosity, and anisotropy for the EDZ behaviour. The EDZ and the gallery convergence can be correctly represented only if fractures are reproduced. Modelling shear banding is crucial and leads to a better description of the EDZ.

1. Introduction

The underground repository of nuclear wastes in deep geological formations is nowadays a crucial issues. To assure a safe repository on the long term, the behaviour of the possible host formations and of the underground structures, where the most hazardous type of wastes will be stored, need to be defined and predicted. The underground structures are composed of a network of galleries whose drilling inevitably engenders stress redistribution, damage, and fractures in the surrounding medium. Different low-permeability host materials are envisaged for the deep geological repository and, amongst them, the behaviour and drilling of the Callovo-Oxfordian claystone is studied. This geological medium is studied in France by the national radioactive waste management agency, Andra. Andra conducts various scientific research programs to ensure the feasibility of a safe repository in the Callovo-Oxfordian claystone. The benchmark "Transverse action" consists in developing numerical models to characterise the claystone behaviour, to calibrate them based on experimental results, and finally to use them to numerically model underground structures by the reproduction of the drilling phase.

Many experimental measurements and observations in the considered argillaceous rock have highlighted that damage and fracturing around the galleries play an important role in the hydro-mechanical behaviour of the Excavation Damaged Zone (EDZ) [1,2]. The latter is a zone that develops around underground galleries due to the drilling process and which is dominated by irreversible hydro-mechanical property changes. The shape and extent of the EDZ is also dominated by the material anisotropy either of the *in situ* initial stress state or of the mechanical behaviour. Taking into account the material anisotropy and the representation of the fractures are therefore necessary to correctly predict the behaviour of the EDZ.

The proposed constitutive model is a cross-anisotropic and elasto-viscoplastic model. The anisotropy is considered both for the elastic and plastic behaviours of the material. For the plastic behaviour, the evolution of a strength parameter is considered with a microstructure fabric tensor. Creep deformations are also considered by the introduction of a viscoplastic mechanism in order to reproduce the increase of gallery convergence which is observed in the long term. The different aspects of the model are calibrated based on experimental results obtained in laboratory, on small-scale samples, and provided by Andra.

Amongst various possibilities to represent the fractures, it is chosen to represent them at large scale around galleries with strain localisation in shear bands [3]. This approach is chosen because shear banding is usually observed in geomaterials and develops before localised rupture or fractures [4]. Furthermore, the fracturing process in the Callovo-Oxfordian claystone is dominated by shear fractures around the galleries [2]; thus, shear banding can be an adequate manner to represent these fractures [5].

The proposed approach aims to highlight the contributions of material anisotropy, viscosity, and shear banding in the reproduction of the claystone behaviour as well as in the development of

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http://dx.doi.org/10.1016/j.compgeo.2016.05.017

the EDZ. The numerical modelling are realised with the non-linear finite element code Lagamine developed at the University of Liège [6]. The results indicate that the EDZ behaviour and the gallery convergence cannot be well represented without considering the reproduction of the fractures in the rock.

2. Constitutive models

The Callovo-Oxfordian claystone is assumed to be a biphasic porous medium composed of solid particles and liquid water under unsaturated conditions. The constitutive equations of the hydro-mechanical model are described in this section. Firstly, the balance equations are established, then the mechanical and hydraulic models are detailed for a cross-anisotropic rock exhibiting creep deformation. Moreover, gravity is not taken into account in the problem.

2.1. Balance equations

The balance equations are described hereafter for classical poromechanics defined at macroscale and for microstructure medium. The latter is relevant for the modelling of strain localisation in geomaterials.

2.1.1. Classical medium

The balance equations of the mixture momentum and of the water mass are:

$$\int_{\Omega} \sigma_{ij}\ \epsilon^*_{ij}\ d\Omega = \int_{\Gamma_\sigma} \bar{t}_i\ u^*_i\ d\Gamma \tag{1}$$

$$\int_{\Omega} \left(\dot{M}_w\ p^*_w - f_{w,i}\ \frac{\partial p^*_w}{\partial x_i} \right) d\Omega = \int_{\Omega} Q_w\ p^*_w\ d\Omega - \int_{\Gamma_{q_w}} \bar{q}_w\ p^*_w\ d\Gamma \tag{2}$$

where the general notation a^* represents the kinematically admissible virtual quantity a, Ω is the porous material configuration, u_i is the macroscale displacement field, ϵ_{ij} is the strain field, σ_{ij} is the total stress field ($\sigma_{ij} > 0$ for compression), and $\bar{t}_i$ is the classical external traction force per unit area acting on a part Γ_σ of the total boundary Γ. Further, p_w is the pore water pressure field ($p_w < 0$ if suction), $f_{w,i}$ is the mass flow of water, $\dot{M}_w$ is the variation of the water mass, $\bar{q}_w$ is an input water mass per unit area on a part Γ_{q_w} of Γ, and Q_w is a water sink term.

The effective stress field σ'_{ij} is defined by Biot's postulate [7] under unsaturated conditions and takes into account the solid phase compressibility:

$$\sigma_{ij} = \sigma'_{ij} + b_{ij}\ S_{r,w}\ p_w \tag{3}$$

where b_{ij} is the Biot's tensor for anisotropic materials, and $S_{r,w}$ is the degree of water saturation.

A residual degree of water saturation S_{res} is generally observed in argilaceous materials. Because the effective stress definition involves $S_{r,w}$, the residual saturation may lead to an unrealistic increase of the effective stress and of the material strength (following the yield criterion of Eq. (6)). This occurs for important desaturation ($p_w \ll 0$), when the residual degree of water saturation is attained. The use of the effective saturation S_e [8]

$$S_e = \frac{S_{r,w} - S_{res}}{S_{sat} - S_{res}} \tag{4}$$

instead of $S_{r,w}$ in the effective stress definition would prevent this unrealistic increase of material strength. In fact, in case of residual saturation $S_e = 0$ engenders $\sigma'_{ij} = \sigma_{ij}$. In Eq. (4), S_{sat} is the saturated degree of water saturation. However, in the considered application of the gallery excavation, the material desaturation is not important (Fig. 12). Consequently, using the degree of saturation $S_{r,w}$ in the effective stress definition is satisfactory in the range of the considered matric suction.

2.1.2. Microstructure enhanced medium

In geomaterials, shear strain localisation is often observed before the localised failure of the material and fracturing. When subjected to external solicitations, homogeneous deformation are firstly visible in geomaterials; then, once the damage threshold is reached, material damage by microcracking develops. Further, if microcracks coalesce, it can lead to strain localisation in shear bands and to the onset of interconnected fractures (macrocracks). It is therefore proposed to represent the shear fractures around the galleries in a continuous manner (weak discontinuities) with strain localisation in shear bands [9,10].

In classical finite element methods, the strain localisation suffers a mesh sensitivity [11] which can be avoided by regularising the numerical method with the introduction of an internal length scale. The latter allows a proper reproduction of the post-localisation material behaviour. Amongst the various regularisation methods that exist, an enrichment with microstructure kinematics is considered [12,13]. The coupled local second gradient model is used and introduces microscale kinematics in addition to the classical macroscale kinematics [3,14,15].

The momentum balance equation of the mixture is:

$$\int_{\Omega} \left(\sigma_{ij}\ \frac{\partial u^*_i}{\partial x_j} + \Sigma_{ijk}\ \frac{\partial v^*_{ij}}{\partial x_k} \right) d\Omega = \int_{\Gamma_\sigma} \left(\bar{t}_i\ u^*_i + \overline{T}_i\ v^*_{ik}\ n_k \right) d\Gamma \tag{5}$$

where Σ_{ijk} is the double stress, $v_{ij} = \frac{\partial u_i}{\partial x_j}$ is the gradient field of the microkinematics, n_k is the normal unit vector to the boundary, and $\overline{T}_i$ is the additional external double force per unit area. The double stress Σ_{ijk} involves an additional constitutive law in which the internal length scale is introduced. It is also assumed that the pore fluid does not have an influence at microscale [16]. Second gradient effects are only assumed for the solid phase and the water mass balance Eq. (2) of classical poromechanics is conserved.

2.2. Mechanical models

The Callovo-Oxfordian claystone is a sedimentary material which exhibits a cross-anisotropy, i.e. transverse isotropy, with quasi-horizontal isotropic planes (bedding planes). Creep deformations have also been observed for this material. Therefore, the rock behaviour is defined with an elasto-viscoplastic hydro-mechanical model including cross-anisotropy.

2.2.1. First gradient

The elasto-plastic behaviour is defined for a transversely isotropic material, which properties depend on the loading orientation relative to the preferential axes of the material structure.

The elastic law is classically defined with the Hooke's linear relation [17,18] and the compressibility of the solid grains is defined through the Biot's tensor [19]. The parameters that describe the elasticity are detailed in Table 2 for the considered rock. The subscripts $\parallel$ and $\perp$ indicate the directions parallel and perpendicular to the isotropic planes, respectively.

A non-associated plasticity is considered with a plastic behaviour defined by an internal friction model and by a Van Eekelen yield surface [20]:

$$F \equiv II_{\hat{\sigma}} - m \left(I_{\sigma'} + \frac{3\ c}{\tan \varphi_c} \right) = 0 \tag{6}$$

where c is the rock cohesion, φ_c is the friction angle in compression, $I_{\sigma'}$ and $II_{\hat{\sigma}}$ are the first and second stress invariants, and m is a model parameter which introduces the dependence to the Lode angle. An isotropic hardening or softening is allowed for the cohesion and