Excavation Damaged Zone Modelling in Claystone with Coupled Second Gradient Model

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Abstract. Galleries excavation leads to damage and significant properties changes of the host rock. The fracture structure of the excavation damaged zone created around the galleries remains nowadays a major issue especially in the context of underground storage. In order to correctly model the strain localisation, the second gradient local model (regularization method) is used within a hydro-mechanical modelling of a gallery excavation. The numerical results provide information about the strain localisation bands pattern.

Keywords: fracturing, numerical modelling, excavation damaged zone, strain localisation.

1 Introduction

Gallery excavation in clayey rocks induces stress perturbations that trigger damage propagation. The damage can either be diffuse or localised and can lead to significant changes in the material properties. The excavation process creates the so-called excavation damaged zone (EDZ) in which the mechanical and hydraulic properties are modified. The prediction of the extension and especially of the fracturing structure in this zone remains a major issue.

Since strain localisation in shear band mode is frequently observed in experimental works, the excavation damaged zone can be modelled by considering the development of strain localisation bands.

2 Strain Localisation Modelling

Within the framework of classical finite elements, the strain localisation depends on the mesh size and orientation (Collin et al. [1]). An enhanced model, introducing an internal length scale, is thus needed to correctly model the post peak and

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localisation behaviour. Among the different regularization methods, the second gradient local model (Chambon et al. [2-3]) is used. In the latter, the continuum is enriched with microstructure effects: the kinematics includes the classical one (macro) and the microkinematics ([4-6]). For coupled second gradient model, the two balance equations to be solved (Collin et al. [7]), for every kinematically admissible virtual displacement field u_i^* and virtual pore water pressure field p_w^*, read in a weak form:

$$\int_{\Omega}\left(\sigma_{ij}\frac{\partial u_i^*}{\partial x_j}+\Sigma_{ijk}\frac{\partial^2 u_i^*}{\partial x_j \partial x_k}\right)d\Omega=\int_{\Omega} G_i u_i^* d\Omega+\int_{\Gamma_\sigma}\left(\bar{t}_i u_i^*+\bar{T}_i D u_i^*\right)d\Gamma \tag{1}$$

$$\int_{\Omega}\left(\dot{M}p_w^*-m_i\frac{\partial p_w^*}{\partial x_i}\right)d\Omega=\int_{\Omega} Q p_w^* d\Omega+\int_{\Gamma_q}\bar{q}p_w^* d\Gamma \tag{2}$$

where σ_{ij} is the total stress field, Σ_{ijk} is the double stress dual of the (micro) second gradient, which needs an additional constitutive law, and Ω denotes the current solid configuration (volume). G_i is the body force per unit volume, t_i is the external traction (classical) forces per unit area, T_i is an additional external (double) force per unit area, both applied on a part Γ_σ of the boundary of Ω and Du_i is u_i normal derivative. Further, $\dot{M}$ is the time derivative of the water mass inside Ω, m_i is the mass flow, Q is a sink term and Γ_q is the part of the boundary where the input water mass per unit area $\bar{q}$ is prescribed.

The total stress field is defined according to Terzaghi's postulate:

$$\sigma_{ij}=\sigma_{ij}^{'}-S_{r,w}p_w\delta_{ij} \tag{3}$$

where $\sigma_{ij}^{'}$ is the effective stress, $S_{r,w}$ is the water saturation degree and δ_{ij} is the Kronecker symbol. The double stress Σ_{ijk} has no link with the pore water pressure.

The second gradient law gives Σ_{ijk} as a function of the (micro) second gradient. It is a linear elastic law with isotropic linear relationship deduced from (Mindlin [5]) and it depends only on one elastic parameter D. The shear band width is proportional to this elastic parameter ([2; 8]).

3 Numerical Modelling and Results

A hydro-mechanical modelling of a gallery excavation is performed in two-dimensional plane strain state with impervious gallery wall (undrained). It takes into account the hydraulic permeability anisotropy and the initial anisotropic stress state corresponding to a gallery of the Andra underground research laboratory (Meuse/Haute-Marne, France) drilled in Callovo-Oxfordian claystone. The end of excavation corresponds to 5 days of numerical modelling (fig. 1).

A flow model is used to reproduce transfers in porous media. The constitutive mechanical law (first gradient law) used for the clayey rock is an elastoplastic model with a Drucker-Prager yield surface. It includes friction angle hardening and cohesion softening as a function of the Von Mises equivalent plastic strain.

Several calculations were performed to focus on the influence of second gradient elastic modulus D, dilatancy ψ and cohesion softening on the strain localisation. Numerical results emphasize that a cohesion softening is needed to initiate the strain localisation process around the gallery. The second gradient elastic modulus has a significant influence on the width of the shear strain localisation bands appearing around the gallery. Its value has to be chosen carefully regarding the mesh element size. No dilatancy permits the appearance of strain localisation during the excavation whereas, when using dilatancy the strain localisation only appears after the excavation. It emphasizes transient localisation behaviour after the excavation, under constant radial stress at gallery wall (1 atm). It has been observed that excavation process creates rocks fractures during the excavation (Blümling et al. [9]) then a value close to ψ=0 seems preferable.

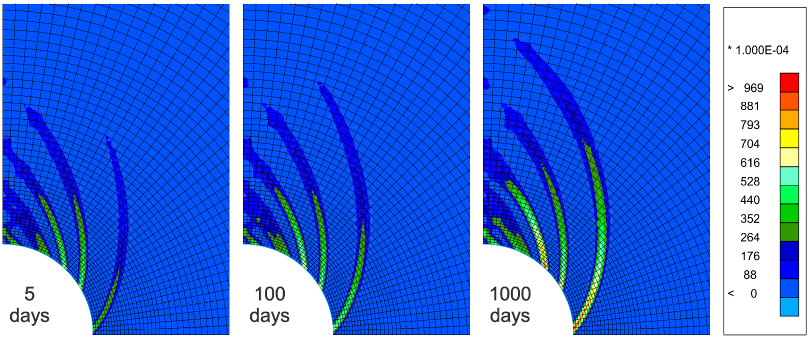

Fig. 1. Evolution of strain localisation bands pattern (total deviatoric strain) after the excavation for an elastoplastic model with cohesion softening

The strain localisation structure (fig. 1) exhibits a chevron fracture pattern around the gallery corresponding to in situ observations (Cruchaudet et al. [10]). The extension of this excavation damaged zone fairly corresponds to the *in situ* experimental measurements of shear fractures. The final dimensions of the zone are about 0.8 m horizontally and 5.5 m vertically. The extension of the damaged zone based on *in situ* shear fracture measurements is 0.8 m horizontally, 3.9 m and 5.1 m respectively vertically upward and downward (Cruchaudet et al. [10]). Because of the material anisotropic stress state, the chevron fractures are concentrated above the gallery and the convergence is anisotropic. The latter is important during the excavation and keeps increasing afterwards. The comparison between numerical results and experimental measurements realized in the considered gallery (fig. 2) indicates a good matching especially for the vertical convergence.

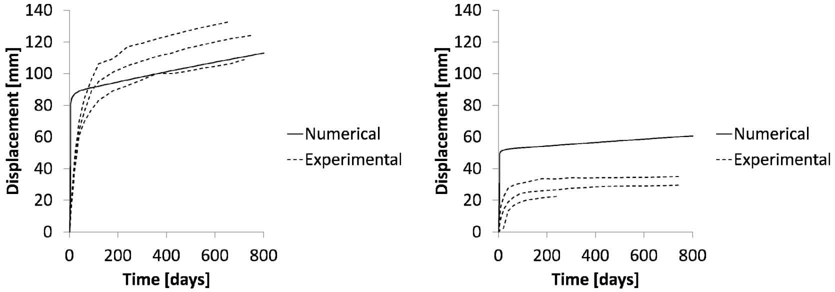

Fig. 2. Matching between numerical results and experimental measurements of the gallery convergence in (left) vertical and (right) horizontal directions

4 Conclusion

The excavation damaged zone in claystone had been fairly well modelled with strain localisation. Within this zone, the modelling provides information about the fracture structure and its evolution corresponding to in situ observations. Nevertheless, the rock state and its properties changes still have to be considered. It would be necessary to validate the results with a more accurate modelling of the rock anisotropy and of the hydro-mechanical coupling occurring in this zone (Levasseur et al. [11]). Permeability is probably not homogeneous in the damaged zone and probably depends on a mechanical parameter such as the plastic deformation (Levasseur et al. [12]).

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