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Numerical simulations of thermal fracturing in nuclear waste disposal

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Regarding high-level nuclear waste (HLW) and spent fuel (SF) disposal, underground geological disposal is likely to be the most feasible and effective solution [1]. The coupled Thermo-Hydro-Mechanical (THM) behaviour of host rocks has been widely studied by laboratory tests, in-situ experiments and numerical analyses. In field experiments performed in underground laboratories, pore pressure generation and damage evolution have been observed. In this context, coupled THM numerical analyses can be an essential tool to better understand the coupled multiphysics behaviour of host rocks, buffer materials and canisters. In addition, large-scale field experiments provide a crucial opportunity to demonstrate understanding and to assess the predictive/modelling capabilities under realistic conditions.

A number of hydromechanical (HM) numerical simulations of underground excavations have been carried out and the mechanisms of pore pressure and damage evolution have been studied [2]. Also, numerical analyses have been used to predict the observations of THM behaviour of in-situ heating tests, and there is some research on the damage evolution due to thermal loading [3], but few studies focus on the analysis of strain localization problems, in part due to specific numerical difficulties. However, thermal fracturing behaviour has indeed been observed in experiments and a better understanding of the phenomenon and of shear band evolution is crucial for a proper assessment of the stability of HLW/SF disposal.

In this study, the coupled THM response of a generic HLW disposal facility under high-temperature has been analysed; in particular, the mechanism of thermal pressurization and the corresponding thermal fracturing behaviour have been examined. For this purpose, an advanced elastoplastic constitutive model with damage has been used to represent the mechanical behaviour of the host rock; it incorporates the following features: (1) a hyperbolic approximation to the Mohr-Coulomb yield surface to represent shear and tensile failure modes, (2) stiffness and strength anisotropy, (3) hardening and softening behaviour, (4) viscous effects and (5) a non-local integral type approach for the plasticity component of the model. The adopted overstress theory and the nonlocal formulation are capable of regularising the spatial distribution of plastic strains, eliminating mesh dependency and improving numerical efficiency. The coupling between accumulated plastic strain and hydraulic permeability has been considered in the analyses. Note that the term damage used in this study, refers to a state of the material, instead of the concept associated with damage mechanics theory; in addition, fracture represents localization phenomena in the damaged area.

Numerical simulations have been performed using the finite element method software CODE_BRIGHT. Two-dimensional generic disposal configurations have been carried out for the two cases of unsupported and supported tunnels. The host rock is assumed to be the Callovo-Oxfordian claystone (COx). Three modelling stages have been considered: the excavation stage, the waiting stage and the heating stage, as shown in Figure 1 (a). In the heating stage, the thermal flow at the borehole wall is set as a constant power (200 W/m) and a no hydraulic flow boundary condition is prescribed. A maximum temperature of around 80 °C has been obtained on the drift wall at heating time t = 10 years.

In addition, Figure 1 (b) shows the contours of plastic shear strains and liquid pressures at heating time t = 10 years. Near-field damage is caused by both the excavation of galleries and the effect of thermal pressurization. In the simulations presented, shear

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bands develop significantly during the heating stage. By comparing two cases in Figure 1 (b), it can be concluded that the installation of liners can efficiently limit the damage evolution and reduce the likelihood of thermal fracturing, significantly improving the stability of HLW disposal. Note that the scales of the two cases in Figure 1 (b) are different. Figure 1(c) shows that a lower pore pressure close to the gallery wall for the unsupported tunnel due to the higher level of damage in this case that results in a larger permeability of the rock in the damaged area.

Apart from the analysis of the mechanism of THM behaviour in a high-temperature environment, numerical simulations have also been carried out of the large-scale PRACLAY Heater test (performed in the HADEs underground laboratory) and of the CRQ heating experiment (performed in the Meuse-Haute Marne underground laboratory). A good agreement has been observed between numerical predictions and experimental data, in terms of both temperature and pore pressure. These numerical validation exercises are, however, outside the scope of this abstract.

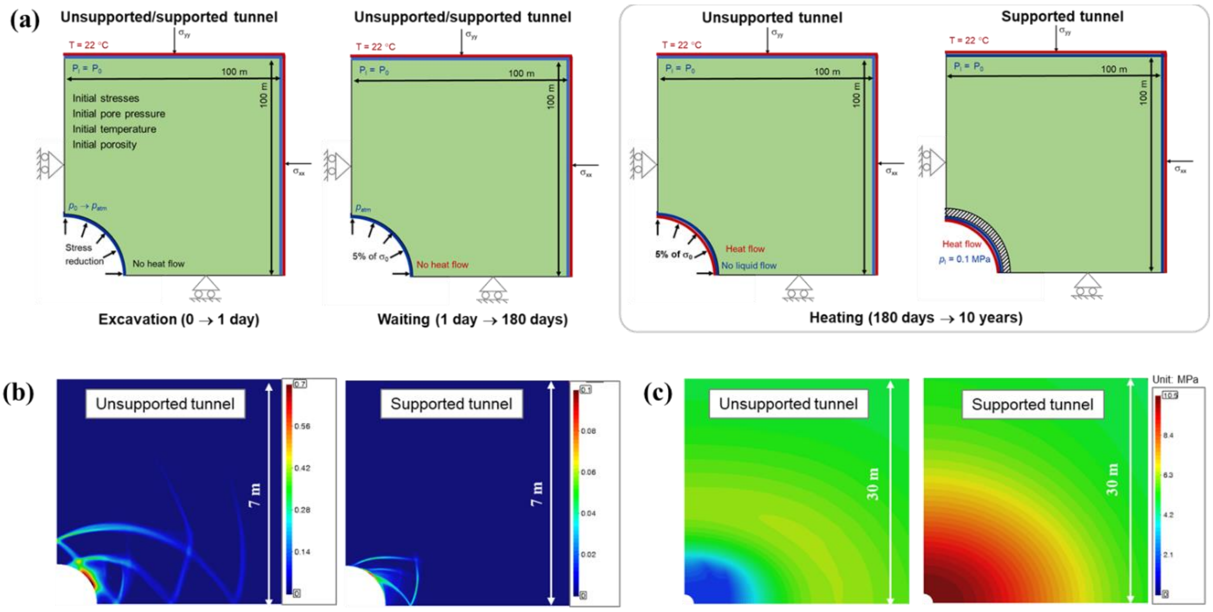

Figure 1: (a) Boundary conditions in three different modelling stages, (b) plastic shear strains, and (c) pore pressure.

Contributor statement

Fei Song: Investigation, Software, Visualization, Writing – Original Draft. **Matías Alonso**: Investigation, Software. **Stefano Collico**: Investigation, Software. **Antonio Gens**: Conceptualization, Funding acquisition, Supervision, Visualization, Writing – Review & Editing.

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