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Effect of mechanical non-linearities on the thermal-hydraulic-mechanical response of a geological repository

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Abstract:

In France, the National Radioactive Waste Management Agency (Andra) oversees the study of a disposal for intermediate-level long-lived (IL-LLW) and high-level activity radioactive waste (HLW) in a deep claystone formation (Callovo-Oxfordian claystone, COx) in the framework of Cigéo project. Several in situ and laboratory THM characterization studies have been undertaken in this formation since 2000. In parallel, theoretical analyses, constitutive models and numerical modelings have been developed to describe different processes during the life of the disposal. This paper presents a regularized anisotropic elastoplastic and damage model including both non-linear short and long terms response. The influence of damage and fracturation on the transport and viscous properties are considered. The proposed model was implemented with a regularization scheme based on the non-local implicit gradient in Comsol Multiphysics[®]. After validating the model on simple stress paths, its operational nature is successfully evidenced on the GCS drift for which the in situ observations are the most challenging to reproduce. It is shown that the model is able of reproducing the measured pore pressure as well as the drift convergences. Importantly, the predicted extent of damaged zones around the drift is consistent with the in situ observations. Secondly, the proposed model is applied to study the THM behavior of a HLW repository. The role of the non-linear behavior of the COx claystone on the THM responses in the near and far fields, is herein highlighted in the framework of a benchmarking exercise within the European program EURAD HITEC.

Introduction

Clay formations are one of the options currently being considered for the storage of radioactive wastes worldwide. In France, the National Radioactive Waste Management Agency (Andra) built the Meuse/Haute-Marne Underground Research Laboratory (MHM-URL) in the Callovo-Oxfordian (COx) claystone formation. The main objective of this URL is to assess the feasibility and safety of an industrial radioactive waste repository (Cigéo) located in a deep geological formation. A comprehensive scientific research program, including specific in situ experiments, laboratory tests and theoretical and numerical modellings, has been undertaken to characterize and understand the thermohydraulic (THM) behavior of the COx claystone (Armand et al. 2017, Manica et al. 2021).

The present paper is a part of ongoing collaborative scientific research on the development of advanced constitutive models for COx claystone behavior and robust numerical tools suitable for the THMC modelling (1D, 2D and 3D) in the Cigéo project. Based on available experimental data, an anisotropic elastoplastic, damage and viscoplastic model is proposed to describe the mechanical behavior of the COx claystone. The model considers state-of-the-art knowledge of the thermohydraulic behavior of COx claystone and focuses on the key mechanisms. Among these mechanisms, we can mention: the nonlinear instantaneous and delayed mechanical responses, the anisotropy of the THM behavior as well as the anisotropy of strengths. As for most semi-brittle geomaterials, the mechanical behavior of COx claystone is marked by a strain softening mechanism, which manifests the initiation, growth and coalescence of microcracks and/or the formation of shear bands after the peak strength. Consequently, appropriate modelling of these geomaterials behavior requires the use of a

regularization technique to overcome the problem of mesh dependence and hence to better represent the development of the EFZ (Excavation-induced Fractured Zones) particularly around the structures of MHM-URL. The proposed model was implemented with a regularization scheme based on the non-local implicit gradient for two internal variables (damage and equivalent shear plastic strain) in the commercial code, Comsol Multiphysics[®], which allows multiple physics to be considered. Simulations of the THM processes around a hypothetical HLW repository based on the French concept have already been undertaken, especially in the framework of Decovalex 2019 with Comsol software (Plua et al., 2021, for example) but restricted to the thermoporoelastic behavior. The specificity herein is the consideration of the observed highly nonlinear response of the instantaneous and delayed behavior of the studied host rock.

2. Key ingredients of the rheological model

Based on numerous experimental results, a new anisotropic elastoplastic, damage and viscoplastic model is proposed to describe the hydromechanical behavior of the COx claystone. This model based on the Hoek and Brown criterion is expressed in terms of stress invariants (p , q , θ) where the Lode angle allows to consider the stresses geometry. The model considers the recent advances in the understanding of the mechanical and hydromechanical behavior of COx, focusing on the key mechanisms. The pre-peak behavior has a plastic hardening with a non-associated flow and no damage occurs (Souley et al. 2022). The post-peak behavior has a softening phase mainly governed by material damage softening, followed by a residual phase represented by a perfect plasticity. The damage occurring in post-peak before the residual stage is assumed to be isotropic and based on the continuum damage mechanics. Brittle behavior under low confining pressure (σ_3) becomes gradually ductile with the increase of σ_3 . Several laboratory tests performed on COx indicate that the minimum compressive strength occurs at about 30-45° to the bedding plane while the maximum strengths are reached in the direction parallel and perpendicular to the bedding. Then, the peak strength and elastic limit are assumed to have the same evolution with respect to the angle between the loading direction and the bedding, α . In the absence of experimental data, the residual strength is assumed to be slightly dependent on α . The other key characteristic of the behavior of COx relates to the creep deformations. Therefore, the long-term behavior based on the isotropic Lemaître's model as suggested by the creep tests, was also considered as well as the damage-induced and shear fractures-induced creep strain and permeability changes (Souley et al. 2017). The proposed model was implemented with a regularization scheme based on the non-local implicit gradient in Comsol for both damage and equivalent shear plastic strain (e.g., non-local average of a local internal variables are computed by considering the non-local value as an additional degree of freedom governed by the solution of the Helmholtz differential equation). To check the numerical implementation, several simulations of triaxial compression tests at $\sigma_3=2$ MPa with different values of α and creep tests at different deviatoric stress were performed and successfully compared to the theoretical curves.

3. Results

The GCS drift ($\sigma_H = 16.1$ MPa) of MHM-URL remains a challenge for numerical modellings, since to our knowledge, very few authors (except Manica et al. 2021 and Yu et al. 2021) have successfully proposed a constitutive model of COx claystone behavior with an appropriate regularization scheme able to properly reproduce most of the in situ observations. Specifically, they are the anisotropies of the EFZ extension, of the convergences, of the pore pressure distribution, etc., while the initial stress state in the GCS section is quasi-isotropic ($\sigma_v = 12.7$ MPa, $\sigma_h = 12.4$ MPa). It is also a very interesting case that allows to validate the constitutive models, their numerical implementation and possibly to help in the back-calibration of certain model parameters. For all these reasons, we have chosen this gallery for the first operational hydromechanical application of the proposed model with Comsol Multiphysics[®] software.

The observed EFZ around the GCS drift is illustrated in Fig. 1a. The predicted extents of damaged or failed zone (post-peak phase, termed by ZD) and shear plastic zone with strain

hardening (ZSF) at the end of excavation (28 days) and after 2 months are plotted in Fig. 1b-c. Similar to Yu et al. (2021) who used a regularization scheme based on the phase field with their in-house finite element code, the area extent of the damaged zone is quasi-continuous from the GCS sides in opposition to the results published by Pardoen and Collin (2017) and Manica et al. (2021) which reveal rather localized discrete bands of shear plastic strain. Manica et al. (2021) regularized their rheological model by a non-local integral formulation in the finite element code CODE_BRIGHT while Pardoen and Collin (2017) used the local second gradient in the finite element code Lagamine. By drawing an analogy between the numerical damaged zone and the observed connected fracture zone (ZFC), a good agreement between observation and numerical simulation can be noticed. The model allows to reproduce the pressure peak in sensors near the GCS wall (PRE02, PRE03) with 6.2 instead of 6.6 MPa measured in situ as well as the pressure drop after the face passing (Fig. 2a). The convergences are also well reproduced (Fig. 2b) as well as their ratios (horizontal/vertical): the observed ratios are ranged between 1.3 and 2.1 while those predicted are comprised between 1.3 and 1.73.

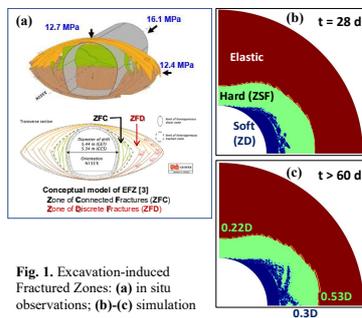


Fig. 1. Excavation-induced Fractured Zones: (a) in situ observations; (b)-(c) simulation

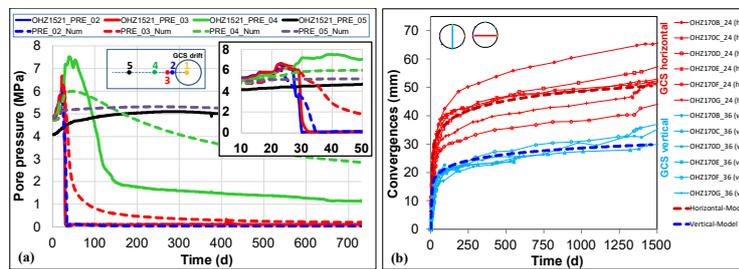


Fig. 2. Comparison with in situ measurements: (a) pore pressure in horizontal borehole; (b) horizontal and vertical convergences

The second application of the developed model is a THM type in two-dimensions. The geometry includes a circular micro-tunnel excavated in 24 h in the COx host rock and dewatered throughout the time of 6 months. Then, a casing is installed with a thermal power over 10 years. Three numerical simulations are performed: thermoporoelasticity (using the proposed model with infinite strengths and creep inactivated) aimed to check the proposed model with several physics, thermoporoelastoplasticity (proposed model with true strengths and without creep) and thermoporoelastoviscoplasticity (full proposed model).

In the thermoporoelastoplastic case, the evolutions between the ends of excavation (1 d) and heating (10 y) of the EFZ extension, the damage rate and the equivalent shear plastic strain are shown in Fig. 3. The extensions of the damaged and residual plastic zones (ZD) after the peak strength or plastic zones in pre-peak (hardening) do not progress after ten days of drainage ($t = 11$ d) in the entire drainage and heating phases. On the other hand, the magnitudes of damage and plastic strains are still increasing in these two phases. As an indication, the plastic strain is 65% higher between the ends of excavation and drainage and 10% higher after 10 days of heating.

4. Conclusions

Based on numerous experimental results, a new anisotropic elastoplastic, damage and viscoplastic model is proposed to describe the hydromechanical behavior of the COx claystone and implemented in the commercial finite element code, Comsol Multiphysics®, well suited for problems involving multiple physics. After checking the numerical implementation, the paper focusses on the mechanisms of the THM processes occurring in the COx claystone by emphasizing the role of mechanical nonlinearities on the thermal pressurisation and the impact on pressure and stress changes in the near and far fields. Two applications were discussed: the hydromechanical mine-by-test around the well-known experimental GCS gallery of the Meuse/Haute-Marne Underground Research Laboratory (MHM-URL), and a THM benchmarking exercise in the framework of a European program HITEC with a 10-year heating period. For this latter application, the extension of EFZ in the near field resulting from the end

of drainage phase does not change with the increase in temperature during the thermal loading. Conversely, the damage rate and plastic strain increase during the heating. Plasticity reduces the magnitude of the mean effective stress in the near field (then increasing the risk of further failure) while creep mechanism relaxes the deviatoric stress and increases the mean effective stress (reducing the risk of failure).

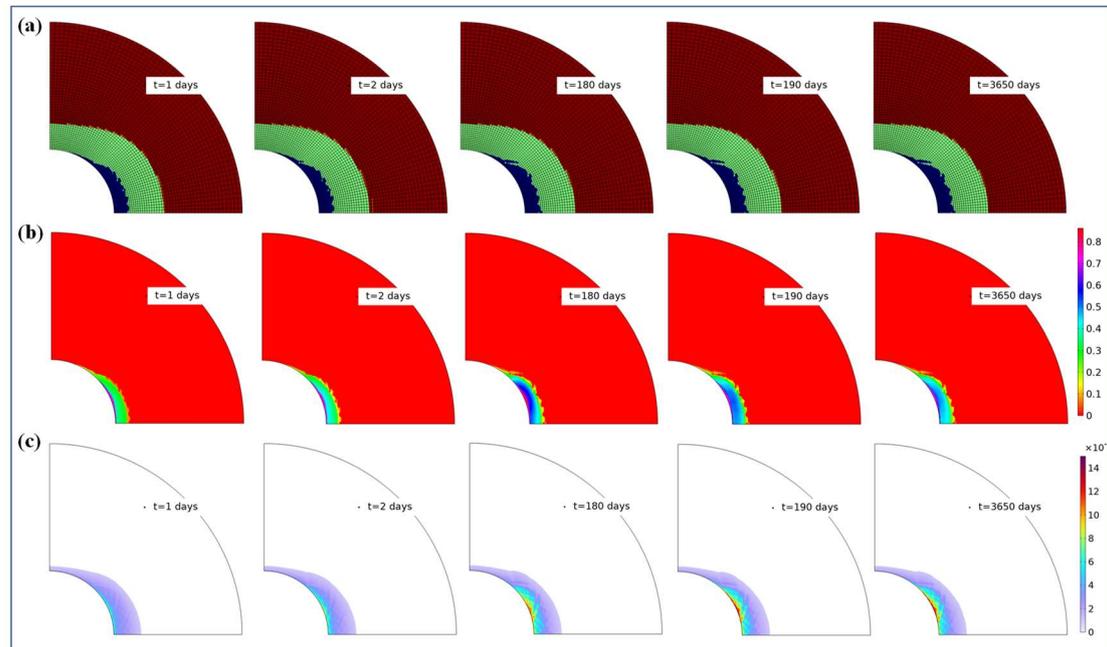


Fig. 3. Extent of numerical EFZ (a), damage rate (b) and shear plastic strain (c) at the end of excavation (1 d); 2 d; end of drainage (180 d); 10 days of heating (190 d) and 10 y (thermoporoelastoplastic case).

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