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THERMO-PORO-MECHANICAL COUPLED PROCESSES DURING THERMAL PRESSURIZATION AROUND NUCLEAR WASTE REPOSITORY

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Abstract. This paper investigates the thermo-hydro-mechanical behavior of Callovo-Oxfordian claystone, a potential host formation for prospective nuclear waste disposal in France. Thermal pore pressure appears in low permeability soils and rocks due to the difference between the thermal expansion coefficients of water and the argillaceous skeleton, as well as the low permeability of the media and the its relative rigidity, which prevent dissipation of the fluid pressure. Coupled thermo-hydro-mechanical numerical analyses have been carried out to enhance the understanding of the Callovo-Oxfordian claystone behavior subjected to heat emitted from radioactive waste that diffuses through the near-field rock to the far-field. In this view, the "thermal pressurization coefficient", defined as the increase of pore pressure due to 1°C increase of temperature, was calculated. This coefficient depends on the nature of the rock, i.e the thermo-poro-mechanical parameters such permeability, Biot's coefficient, rigidity, thermal conductivity as well as their anisotropies. Finally, the effect of parameters' variability on the thermal pressurization coefficient is discussed through a sensibility analysis.

1 INTRODUCTION

Clays and claystones are studied as potential host formation for the disposal of exothermal high activity radioactive waste at great depth in various countries such as the Callovo-Oxfordian claystone (COx) in France, Boom Clay in Belgium, and Opalinus Clay in Switzeland.

During the exploitation stage of deep radioactive geological disposal, exothermic reactions of waste provoke thermal perturbation within the repository environment. Heat emitted from radioactive waste diffuses through the near-field rock to the far-field. Therefore, the host rock is subjected to an increase of temperature (up to about 80°C). The temperature rise in a low permeability porous medium such as COx claystone, generates pore pressure increase essentially due to the difference between the thermal expansion coefficients of water ($\sim 10^{-4}$K^{-}

^{1}) and the one of the argillaceous rock skeleton (~1.28 $10^{-5}K^{-1}$) ([1],[2]). This phenomenon has clearly been observed in undrained laboratory tests conducted on COx ([3]), Boom clay ([4]) and Opalinus clay ([5]). The physical phenomenon is more complicated in reality, where the pore pressure occurs due to following principle factors: difference of thermal dilatation coefficient between water and solid skeleton, fluid dissipation controlled by the permeability, the deformation affected by the rock rigidity and the geological structure, as well as the boundary conditions. Further understanding on the thermal effects in clays has been gained from various in situ heating tests performed in Underground Research Laboratory (URL): CACTUS, ATLAS and CERBERUS tests in the Hades URL (Belgium) ([7],[8]); HE-D test in Mont Terri URL (Switzeland) ([9],[10]) and TER, TED and ALC tests in Meuse/Haute Marne URL (France) ([11],[12],[13]). All these field tests showed that the sedimentary clays react to heat propagation with a raise of pore pressure and related mechanical effects. The measured results and numerical interpretations have led to better characterisation of THM properties of these clay formations ([14],[15],[16],[17]).

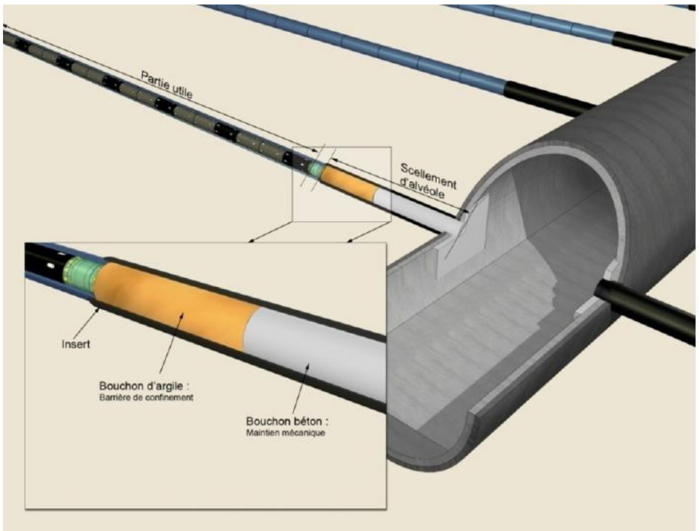

Figure 1: HLW area within nuclear waste storage benchmark concept.

This paper focuses on the analysis of coupled THM processes in COx claystone formation that would result from the development of a high level activity waste (HLW) repository. In the reference concept, the HLW area consists of parallel horizontal cells (i.e., micro-tunnels) excavated from the access gallery (Figure 1). Regarding the periodicity of the micro-tunnels and their lengths, a 2D plane strain model is used for study of the THM behaviour of this area that consists in a plan perpendicular to the cell axis at its middle length. A thermal calculation is performed beforehand in order to simulate the heat emitted from the radioactive waste container as an increase of temperature applied on the cell wall in the THM modeling using the Code_Aster ([6]). Numerical simulations allow also to estimate pore pressure increase and to calculate $\Delta P/\Delta T$, which can be defined as a thermal pressurization coefficient. In fact, this coefficient differs from the classical one determined in undrained conditions. The theoretical analysis shows the dependency of this calculated thermal pressurization on the rate of temperature increase, the stress state and the nature of the rock, i.e., the thermo-poro-mechanical parameters such permeability, Biot's coefficent, rigidity, thermal conductivity, etc ([2]). As for many sedimentary rocks, the THM parameters of the COx present a significant variability. Experiments show also the dependency of the thermal pressurization on the anisotropies of Young's modulus, of permeability and thermal conductivity tensors. A sensibility analysis is carried out to enhance the understanding of the effect of this variability on the thermal pressurization coefficient.

2 THEORETICAL FORMULATIONS

The theoretical equations used in this work are those of fluid saturated porous media with THM coupling, as described in Coussy ([18]). The coupled THM problem requires a solution that verifies simultaneously the following balance equations:

Momentum balance

$$\nabla.\boldsymbol{\sigma} + \rho \boldsymbol{F}^m = 0 \tag{1}$$

Fluid mass balance

$$\frac{\partial m_w}{\partial t} + \nabla.\boldsymbol{M}_w = 0 \tag{2}$$

Energy balance

$$\boldsymbol{M}_w \boldsymbol{F}^m + \Theta = h_w^m \frac{\partial m_w}{\partial t} + \dot{Q} + \nabla.(h_w^m \boldsymbol{M}_w) + \nabla.\boldsymbol{q} \tag{3}$$

where $\boldsymbol{\sigma}$ (Pa) is the total stress tensor; ρ (kg.m^{-3}) the total homogenized specific mass; $\boldsymbol{F}^m$ (N.kg^{-1}) the mass force density; m_w (kg.m^{-3}) the mass content of water; $\boldsymbol{M}_w$ (kg.m^{-2}.s^{-1}) the water mass flow; h_w^m (J.kg^{-1}) the specific enthalpy of water; Q (J.m^{-3}) the non-convective heat; q (J.m^{-2}.s^{-1}) the heat flow and Θ (W.m^{-3}) the heat source.

In porous medium theory, the total stress tensor is decomposed into two contributions: effective stress $\boldsymbol{\sigma}'$ and Biot'stress $\boldsymbol{\sigma}_p = -\boldsymbol{B} p_w$ with $\boldsymbol{B}$ is the Biot's tensor and p_w the pore pressure:

$$\boldsymbol{\sigma} = \boldsymbol{\sigma}' + \boldsymbol{\sigma}_p \tag{4}$$

This preliminary study is focused on the effect of temperature increase in the micro-tunnel on the far field behavior. Therefore, the linear thermo-elastic is assumed for rock skeleton everywhere during the considered time which is consistent far away from micro-tunnel with in situ observations around boreholes. The relation between effective stress $\boldsymbol{\sigma}'$ and total strain $\boldsymbol{\varepsilon}$ is written in the following incremental form:

$$d\boldsymbol{\sigma}' = \boldsymbol{C}:(d\boldsymbol{\varepsilon} - \boldsymbol{\alpha} T) \tag{5}$$

where $\mathbf{C}$ is the drained elasticity tensor that depends on Young modulus and Poisson ratios, T the temperature and $\boldsymbol{\alpha}$ the tensor of thermal dilatation coefficient.

Considering the Eurelian porosity ϕ, its variation is derived as follows:

$$d\phi = \boldsymbol{B}:d\boldsymbol{\varepsilon} - \phi d\varepsilon_v - 3\alpha_\phi dT - \frac{dp_w}{\boldsymbol{M}_\phi} \tag{6}$$

where $\varepsilon_v = \mathrm{tr}(\boldsymbol{\varepsilon})$ is the volumetric strain, $\boldsymbol{\alpha}_\phi$ the differential dilatation coefficient:

$$\alpha_\phi = \frac{1}{3}(\boldsymbol{B} - \phi\delta) \tag{7}$$

and $\boldsymbol{M}_\phi$ the Biot's modulus:

$$\boldsymbol{M}_\phi = (\boldsymbol{B} - \phi\delta) : \boldsymbol{S}^s : \delta \tag{8}$$

with $\boldsymbol{\delta}$ the identical tensor and $\boldsymbol{S}^s$ the compliance tensor of the solid skeleton.

Fluid diffusion and heat conduction are governed by Darcy's and Fourier's laws respectively:

$$\boldsymbol{q} = -\lambda\nabla T \tag{9}$$

$$\boldsymbol{M}_w = \frac{\rho_w \boldsymbol{k}_{int}}{\mu_w}(-\nabla p_w + \rho_w \boldsymbol{F}^m) \tag{10}$$

where $\boldsymbol{\lambda}$ the thermal conductivity tensor, μ_w the fluid dynamic viscosity and $\boldsymbol{k}_{\text{int}}$ (m^2) the intrinsic permeability tensor.

3 THERMO-HYDRO-MECHANICAL MODELING

According to the reference concept of HLW nuclear waste area (**Figure 1**), THM plane strain model is considered. The geometry model consists in a vertical cut, perpendicular to the cell's axis at its middle length, from the surface to 1000m of depth. The left side of the model passes a cell center, while the right side goes over the mean between two cells. The geological strata are presented in the Table 1. The HLW cells are located within the Callovo-Oxfordian UA layer. The temperature evolution due to heat generation from the waste canisters is considered as thermal load in the THM modeling. Thanks to the model symmetry, thermal flow, fluid flow and displacements are imposed to be nil on its left and right sides. These boundary conditions are also applied to the bottom of model. Concerning the initial conditions, the temperature and the pore pressure change linearly from the surface down to the lower side. The vertical stress is equal the ground weight. The horizontal stress in the plan is equal to the vertical stress while the horizontal stress, in the direction perpendicular to considered plan, is 1.3 times more than the vertical stress

Table 1: Geological strata

Layer	Depth (m)
Kimmerdgien	202
Oxfordian Carbonate	485
Callovo-Oxfordian USC	536
Callovo-Oxfordian UA	635
Dogger	1000

In the following, the results of numerical simulations will be analyzed at a small zone located at the middle distance between two parallel cells at the level of the cell center.

3.1 Thermal pressurization coefficient

The THM simulations allow determining the temperature and interstitial pressure evolutions at the considered point. Three different thermal loads applied on the cell wall are considered (**Figure 2**). The first one exhibits a fast increase of temperature during first five year and then a rapid decrease of temperature until 200 years followed finally by a gradual attenuation. The second and third ones present also a fast temperature increase for first twenty years but continued afterwards by a progressive decrease until 10000years. They have the same pattern but different in temperature magnitude. **Figure 3** displays the evolution of the pore pressure as function of temperature at the considered zone.

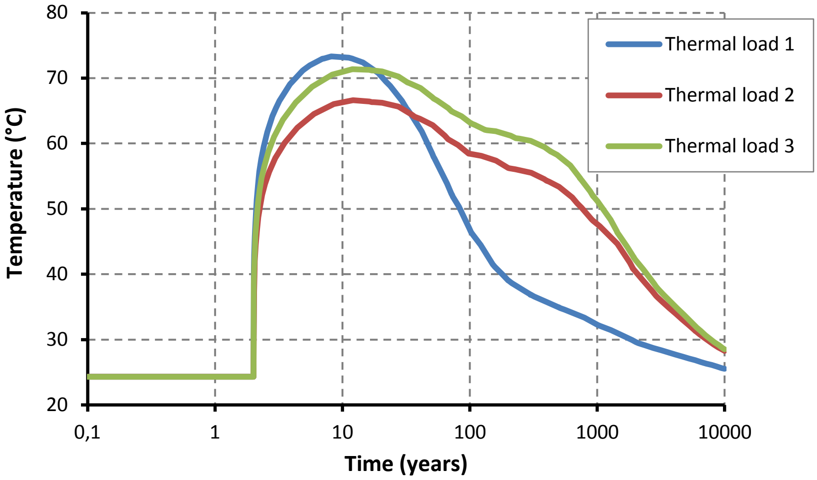

Figure 2: Thermal temperature imposed on the cell wall

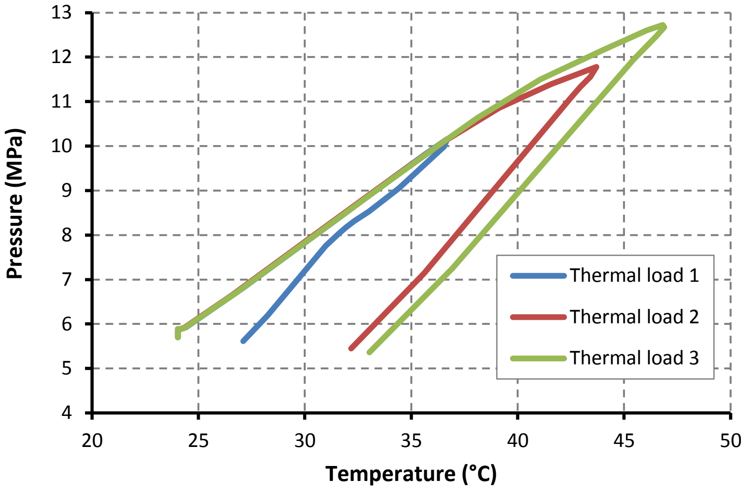

Figure 3: Evolution of pressure versus temperature at considered point.

Two different behaviors can be distinguished during the heating period. Firstly, an almost linear relation between the pore pressure and the temperature is observed when the temperature reaches to about 32°C. Secondly, nonlinearity between these parameters is observed. This observation is translated by a little change of thermal pressurization coefficient before 32° of heating followed by a progressive decrease of this parameter (**Figure 4**). This phenomenon is also remarked in undrained heating test on Rothbach rock ([2]). Over the cooling time, the decrease of pore pressure is linear regarding to the temperature, i.e., the thermal pressurization coefficient is constant. This coefficient is greater for heating phase than cooling one in the considered configuration. As a conclusion, thermal pressurization coefficient depends on the temperature, as well as the thermal load path. The variation of this coefficient calculated in this work is found in the range obtained by in situ heating test carried out on COx at Meuse/Haute Marne URL ([12],[17]).

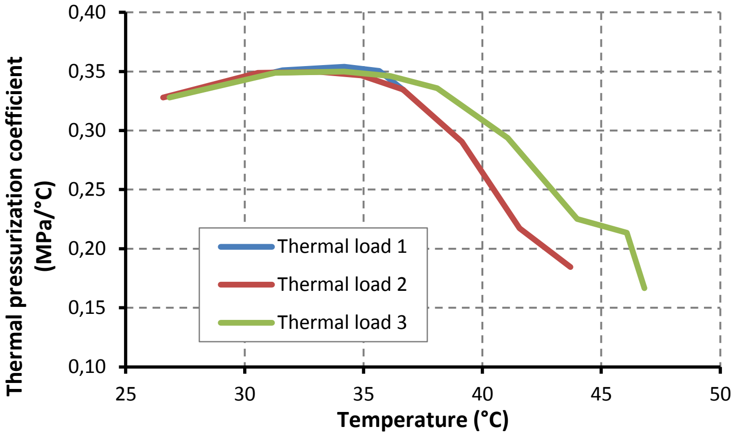

Figure 4: Evolution of thermal pressurization temperature versus temperature during the thermal loading period at considered point.

3.2 Sensitivity analyses

In this section the influence of different parameters on the pore pressure is investigated. A sensitivity analysis has been performed to examine the effect of THM parameters and, in this way, to improve the understanding of the system subject to THM perturbations. To do so, a potential range of variation of parameters is considered. The results of the sensitivity analysis presented here focus on the potentially most important parameters: Young's modulus, Biot's coefficient and intrinsic permeability for the case of thermal load 1 presented in **Figure 2**.

As many bedded formation, Callovo-Oxfordian claystone exhibits transverse isotropic properties. The value of Young's modulus controls the strain in an elastic solid, thus influences also the magnitude of pore pressure since the volumetric strain of the porous media accommodates partially the expansion of water due to the temperature increase. Sensitivity analyses have been performed on this parameter by varying the vertical component of the rigidity tensor, while keeping constant other parameters including the anisotropy ratio between Young's modulus. As showed in **Figure 5**, the Young modulus has a significant effect on the pore pressure increase. The pore pressure variation pattern is unchanged but the increase of Young's modulus leads to an increase of pore pressure magnitude.

The thermally induced increase of pore pressure in porous media is coupled with a decrease in effective stress. Hence, the Biot's coefficient plays its role. Homand et al [19] showed experimentally that this coefficient of COx material depends on the confining stress. The analyses have been realized for three values of Biot's coefficient 0.4, 0.6, 1.0 and the results of which are presented in **Figure 6**. A decrease of Biot's coefficient results in an increase of pore pressure even if the form of the curve remains unchanged. This observation is quite consistent to undrained configuration.

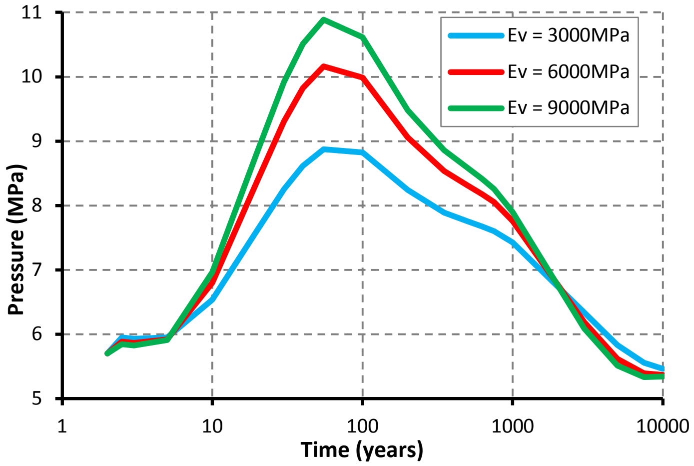

Figure 5: Effect of Young's modulus variation on pore pressure evolution at the considered zone.

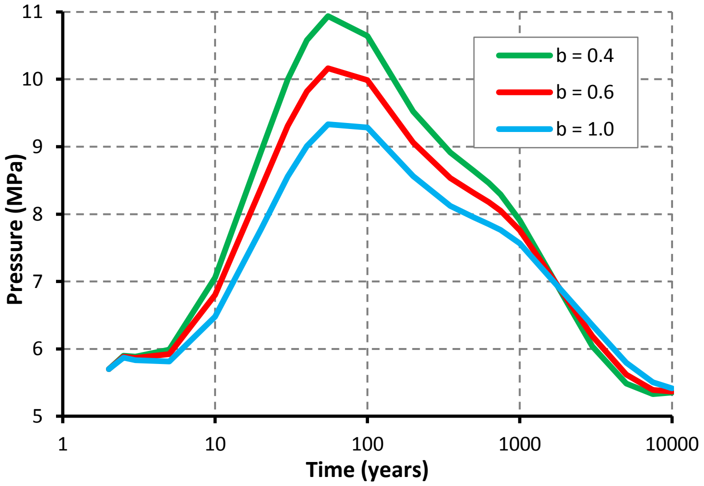

Figure 6: Effect of Biot coefficient variation on pore pressure evolution at the considered zone.

The mechanism underlying the thermo-hydraulic behavior in the clay is a competition between the generation of pore pressure due to the differential thermal dilatation of fluid and skeleton solid and the dissipation of pore pressure, whose rate is essentially controlled by fluid permeability. The effect of the intrinsic permeability on the pore pressure variation is shown in **Figure 7**. A lower value of permeability prevents the fluid dissipation and thus results in a higher pore pressure regardless a higher permeability. Moreover, a lower permeability delays the pressure peak comparing to a higher permeability. This phenomenon is hidden by logarithm scale.

The sensitivity analyses have also carried out on other parameters namely thermal expansion of solid gains, thermal conductivity, anisotropy ratio of Young's modulus and anisotropy ratio of permeability. The effect of these parameters on the pore pressure is much less significant that three parameters presented above. Moreover, the sensitivity analyses exposed in **Figure 5-Figure 7**show a rather equivalent effect of Young's modulus, Biot's coefficient and intrinsic permeability on the pore pressure variation. This is not the case of in situ heating test observation and interpretation ([14]) where the effect of permeability on generated pore pressure is much more considerable than two others parameters. This difference may be due to the boundary condition. The considered zone is located on the right side of model where the fluid flow and heat flow are nil, i.e. undrained in the horizontal direction. This partially undrained condition may make the effect of permeability less significant. Moreover, the effect of the most influent parameters on the pressure increase depends also to the considered range of the variability. Thus, the obtained results do not represent the intrinsic influence of each parameter, but its influence for the range of its variability.

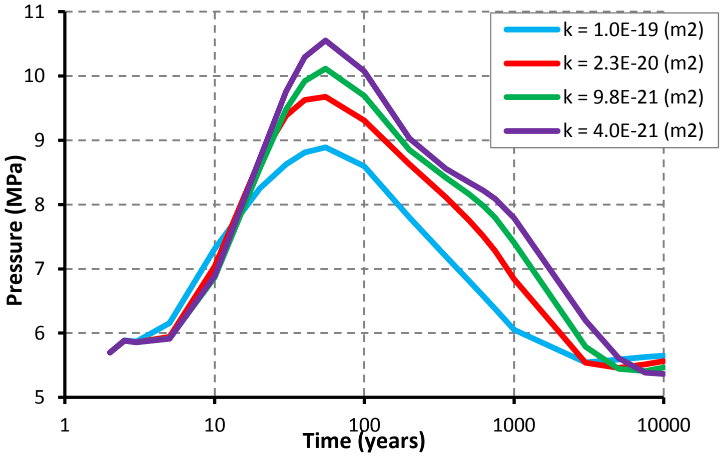

Figure 7: Effect of intrinsic permeability variation on pore pressure evolution at the considered zone.

4 CONCLUSIONS

Thermo-hydro-mechanical coupled process has been investigated in the radioactive high level activity waste repository context. The heat emitted from the waste provokes the pore pressure increase due to the differential expansion of water and solid skeleton. The thermal pressurization coefficient at a particular point, defined as the pore pressure increase induced by 1°C of temperature increase at this point, is calculated for three different thermal load paths. The results show the dependency of this coefficient on the temperature, the thermal load paths, as well as heating-cooling state. A fast increase in temperature yields to an almost constant thermal pressurization coefficient in the low permeability porous medium.

Sensitivity analyses have been also carried out to enhance the understanding of the effect of rock properties on the thermally induced pore pressure in the considered configuration. The significant influences are observed by the variation of Young's modulus, Biot's coefficient and intrinsic permeability. The considerable effect of intrinsic permeability, that controls the fluid dissipation, is not remarked in this study regarding to other works in the literature due to different boundary conditions. This shows that the THM process depends strongly on the boundary conditions. This study emphasize that Young's modulus, Biot's coefficient and intrinsic permeability play a major role on the overpressure due to heating meaning that it is important to well characterize those parameters and to reduce their incertitude in order to perform reasonable THM calculations. Further calculations will be performed with more complex model of the COx behavior to also study the effect of temperature in the near field.

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