THERMO-HYDRO-MECHANICAL SIMULATION OF A FULL-SCALE STEEL-LINED MICRO-TUNNEL EXCAVATED IN THE CALLOVO-OXFORDIAN CLAYSTONE

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Abstract. The paper presents an interpretation of the full-scale ALC1604 in situ heating test carried out in Callovo-Oxfordian claystone (COx) in the Meuse/Haute-Marne underground research laboratory (MHM URL). The MHM URL is a site-specific facility planned to study radioactive waste disposal in the COx. The thermo-hydro-mechanical (THM) behaviour of the host rock is significant for the design of the underground radioactive waste disposal facility and for its long-term safety. When subjected to thermal loading, the Callovo-Oxfordian claystone of low permeability (~10^{-20}-10^{-21} m^2) exhibits a strong pore pressure response that significantly affects the hydraulic and mechanical behaviour of the material. The observations gathered in the in situ test have provided an opportunity to examine the integrated thermo-hydro-mechanical (THM) response of this sedimentary clay. Coupled THM numerical analyses have been carried out to provide a structured framework for interpretation, and to enhance understanding of THM behaviour of COx. Numerical analyses have been based on a coupled theoretical formulation that incorporates a constitutive law specially developed for this type of material. The law includes a number of features that are relevant for a satisfactory description of the hydromechanical behaviour. By performing the numerical analysis, it has been possible to incorporate anisotropy of material parameters and of in situ stresses. The performance and analysis of the in situ tests have significantly enhanced the understanding of a complex THM problem and have proved the capability of the numerical formulation to provide adequate predictive capacity.

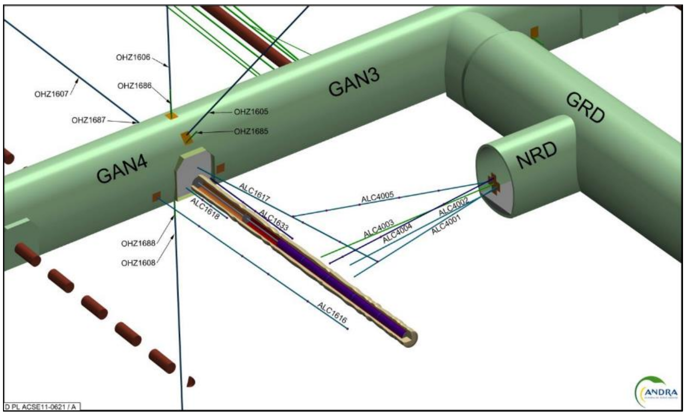
1 INTRODUCTION

Argillaceous rocks provide the geological background to many civil engineering projects. They exhibit favourable characteristics, such as low permeability, a degree of self-healing capacity when fractured, significant retardation properties for solute transport, and no foreseeable economic value (Gens 2003). This paper concentrates on the response of Callovo-Oxfordian claystone (COx) to thermal loading in the context of the ALC1604 in situ heating test performed in the Meuse/Haute-Marne underground research laboratory. Special attention is given to the interplay between the thermal, hydraulic and mechanical aspects of the COx behaviour. Callovo-Oxfordian claystone exhibits a strongly bedded structure that results in a distinct anisotropy of several thermo-hydro-mechanical (THM) properties. The observations are interpreted using a coupled THM analysis that accounts for the main features of the generalised COx behaviour, including its anisotropy.

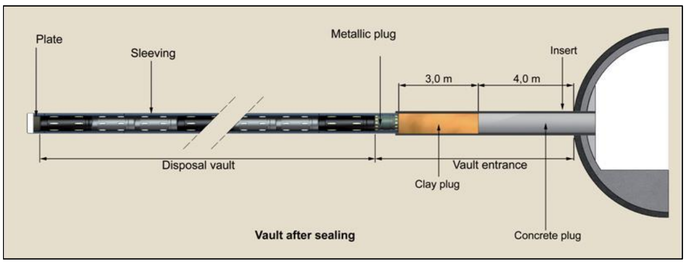
2 APPLICATION TO HA-ALC1604 IN SITU HEATING TEST

The ALC1604 experiment is an in situ heating test performed in the MHM URL where the host rock is Callovo-Oxfordian claystone. It aims to test the 2009 emplacement concept for vitrified HLW in dead-end, horizontal micro-tunnel with an excavated (drilled) diameter of approximately 0.7m and a steel casing (Armand et al. 2017). The micro-tunnel is composed of a body section for package disposal and a head section for cell closure, also called insert. They are favourably aligned with respect to the stress field (Figure 1a).

To prevent rock deformation and enable potential retrieval of waste containers during the reversibility period, both cell body and cell head sections have a non-alloy steel casing (Bumbieler et al. 2015). The diameter of the casing in the body is slightly smaller than that in the insert (Figure 1b). shows the concept of the experiment, with the 25m long micro-tunnel and surrounding boreholes for THM measurements. The excavation rate was around 0.3-0.5 mh^{-1} and the excavation was completed in seven days. The power applied in the deepest 15m was constant and equal to 220 W/m, in order to reach around 85 ºC in two years and continues up to the present.



(a)



(b)

Figure 1: a) 3D view of the demonstration test of HLW cells b) 2009 concept of HLW disposal cell (Armand et al. 2017).

3 MAIN FEATURES OF THE NUMERICAL MODEL

The coupled THM formulation employed herein for the solution of the analysed boundary value problem is a particular case of the general formulation presented in Olivella et al. (1996). It is completed by a special mechanical constitutive law adopted for the description of the stress/strain behaviour of the Callovo-Oxfordian claystone (see Mánica et al. 2016 for more details). The model, developed within the framework of elastoplasticity, includes a number of features that are relevant for a satisfactory description of their hydromechanical behaviour: anisotropy of strength and stiffness, behaviour nonlinearity and occurrence of plastic strains prior to peak strength, significant softening after the peak, time-dependent creep deformations and permeability increase due to damage. Both saturated and unsaturated conditions are handled.

The mesh and main boundary conditions (B.C.) are illustrated in Figure 2a. The model includes the geometry of the steel casings, the gap formed between the casings and the COx, and the host rock domain (**Figure 2**b). For computational purposes, the gap will be dealt with as a continuum provided with the bi-linear elasticity model to represent gap opening and closure. According to the experiment arrangement, the casing is supported at the bottom of the excavation and is thus eccentric with respect to the centreline of the micro-tunnel (Figure 2b).

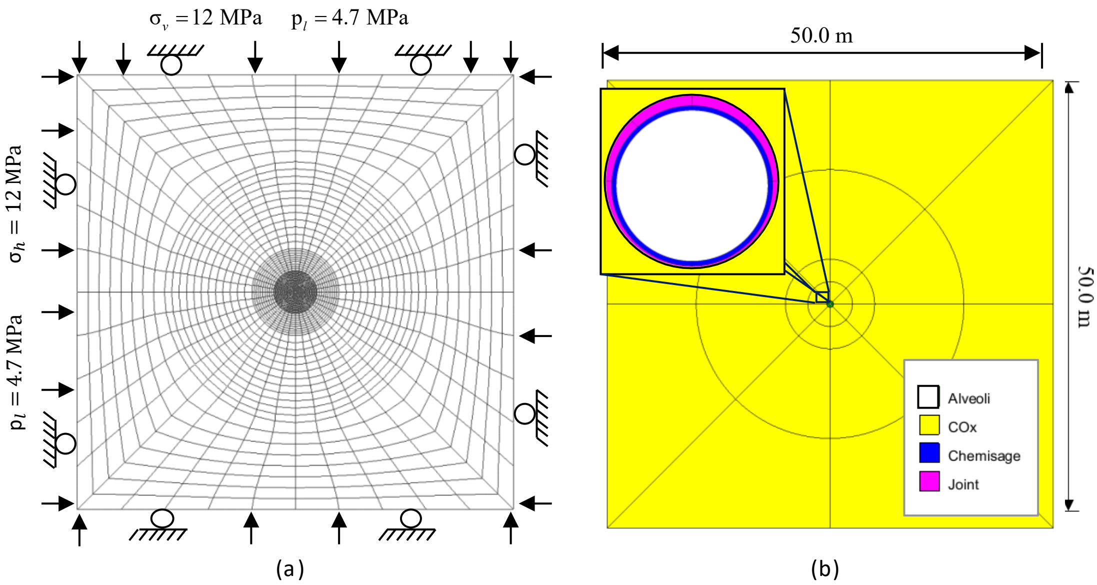


Figure 2: a) Finite element mesh, main boundary conditions b) Geometry and materials.

4 THERMAL RESULTS

Purely thermal analysis has been performed to back-analyse the value of thermal conductivity that achieves the closest agreement between computed and measured temperatures. The observed evolution of temperatures at the three sensors located in section *a* (depth of 17.5 m, see Figure 3b) are shown in Figure 3a together with the computed results from the 2D and 3D analysis. Along this section, located at mid-length, that is in the symmetry plane of the heater, results of both 3D and 2D analyses are close to the measurements for all the three sensors, whatever is their orientation (parallel or perpendicular) with respect to bedding plane. Maximum temperatures reach values just above 56°C after 1200 days of the heating stage.

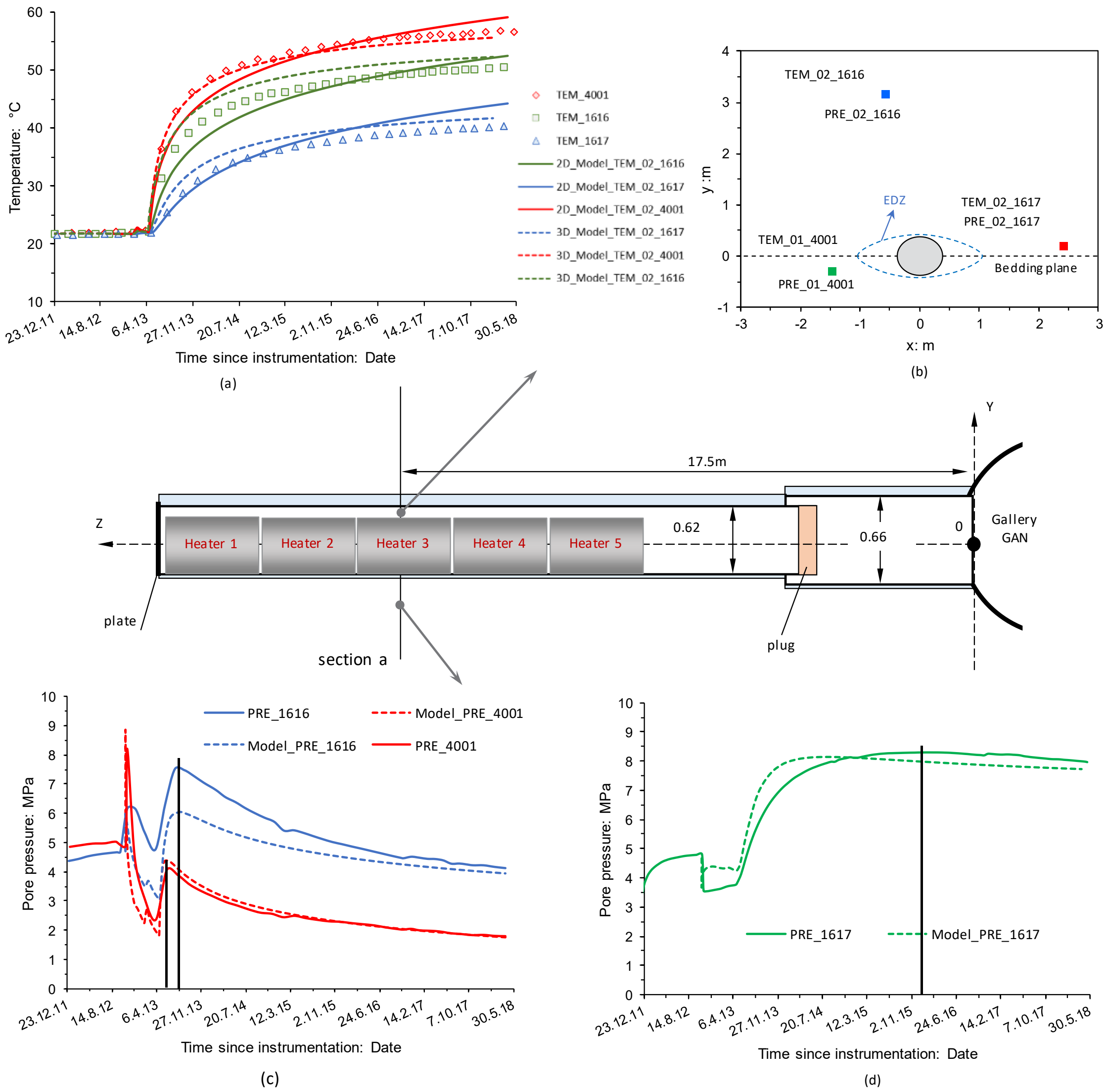


Figure 3: (a) Evolution of temperatures at section *a* (b) Location of observation points at section a (c) Evolution of pore pressure in section *a* at points PRE_1616 and PRE_4001 (c) Evolution of pore pressure in section a, at point PRE_4001

Anisotropic effects are noticeable in the temperatures measured in the rock mass (Figure 4a). Take, for instance, points TEM_1616, TEM_400 and TEM_1617: the first two are oriented in a plane parallel to the bedding with respect and passing through the centreline of the micro-tunnel, while the third is perpendicular to the bedding. They reach different temperatures, about 40, 50 and 55 °C respectively. The anisotropic temperature distribution is apparent, with higher temperatures being reached in the direction of the bedding planes. However as stated above, the casings are supported at the bottom of the excavation, higher temperature is concentrated at a lower part of the casing (Figure 4b).

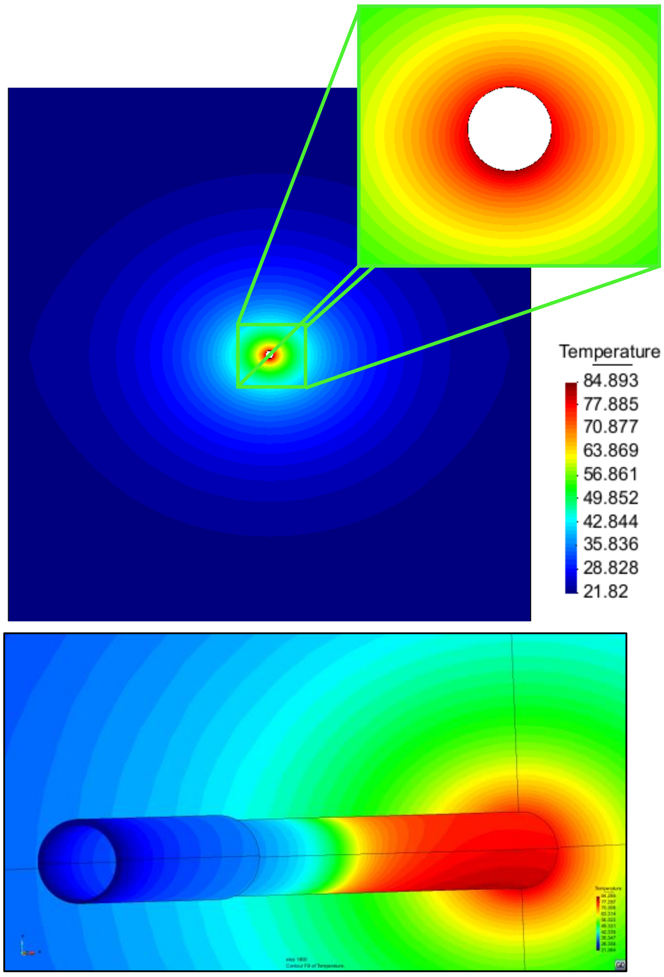


Figure 4: (a) Computed contours of equal temperature (°C) in a cross-section across Heater 3 (b) Three-dimensional view of computed contours of equal temperature (°C) at the end of the computation.

6 EXCAVATION DAMAGE ZONE

The experiments have revealed that excavation operations induce damage and fracturing around the galleries (Armand et al. 2014), creating a zone known as the excavation damaged zone (EDZ), where significant changes in flow and transport properties take place (Tsang et al. 2005). The observed configuration of the EDZ depends on the orientation of the excavation with respect to the anisotropic in situ stress state. The EDZ is identified as one of the key issues affecting the long-term behaviour of the tunnel near-field (Blümling et al. 2007). Major efforts have been thus made to simulate these experimental excavations (Seyedi and Gens 2017) and to gain insights into the design of the actual repository.

As stated above, the ALC1604 cell is drilled in the direction of the major horizontal stress σ_H has a nearly isotropic stress state in the plane normal to the tunnel axis. Despite of that, the

EDZ extends further in the horizontal direction (Figure 5), suggesting strong anisotropic characteristics of the rock mass. An estimate of the configuration of the excavation-damaged zone can be obtained by plotting contours of the cumulative plastic multiplier as it is directly related to the magnitude of irreversible strains (Figure 6). Model results suggest that a plastic zone up to 0.7 m away from the micro-tunnel wall is formed, which agrees with the lateral extension of the shear fractures zone observed in smaller openings (close to 1 diameter, Armand et al. 2014). At the point with the higher plastic multiplier, greater mechanical effects will be noticed on the deformability of rock and hydraulic diffusion. It can be seen that the configuration of the damaged zone is similar to that observed in the previous micro-tunnels with the same orientation, extending more in the horizontal direction (Armand et al. 2014, 2017).

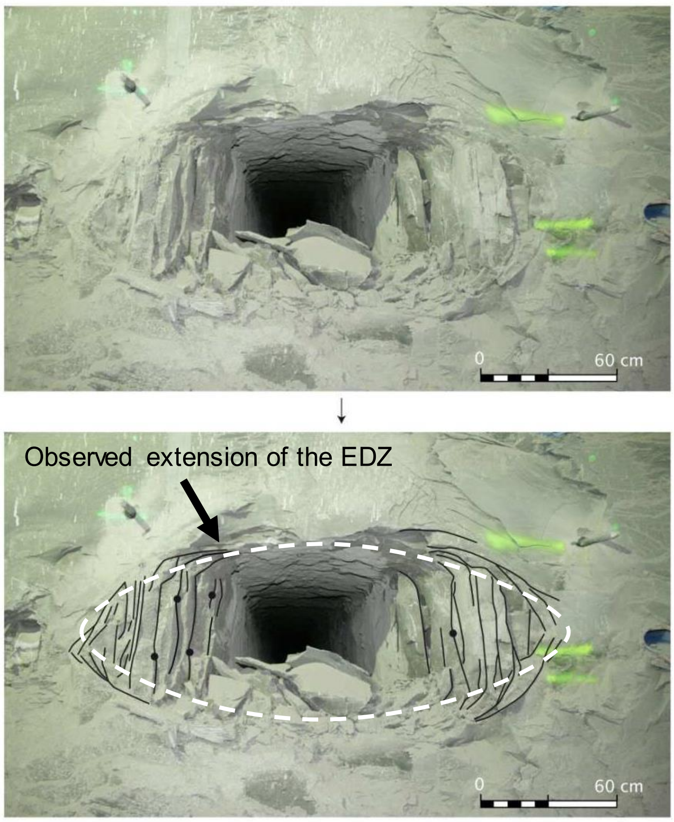


Figure 5: Extension of the damaged zone around a full-scale HLW cell parallel to major horizontal stress.

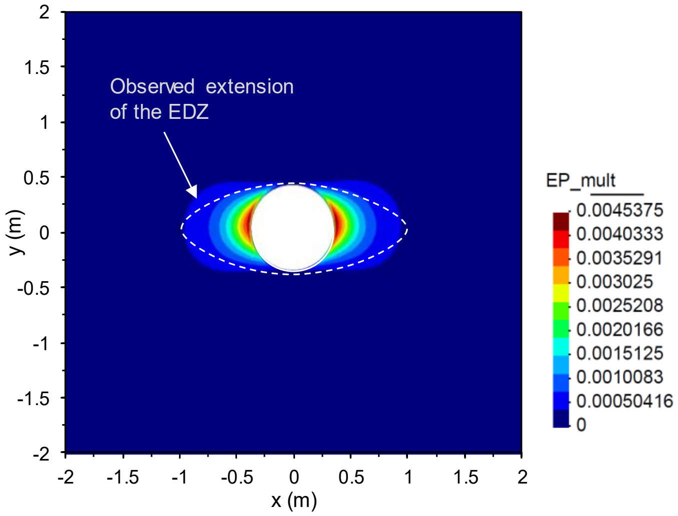


Figure 6: Obtained configuration of the EDZ in terms of plastic multiplier in the section *a* at the end of excavation.

5 PORE PRESSURES

As expected, temperature increases triggered a large upsurge of pore pressures. A typical set of observations is presented in Figure 3c and Figure 3d where the pore pressure recorded in sensors PRE_1616, PRE_1617 and PRE_4001 are plotted. The hydromechanical impact of the cell excavation monitored on the peripheral boreholes is consistent with the measurements taken during the excavation of the previous cells parallel to the major horizontal stress. Indeed, the excavation leads to pore pressure increase in the horizontal plane (Figure 3c) of the cell and to pore pressure drops in the vertical plane (Figure 3d). As was observed in the TED experiment (Garitte et al. 2014), the influence of heating upon the pore pressure firstly results in thermal pressurisation (controlled by the difference between the thermal expansion coefficients of the pore water and of the rock), followed by the dissipation of the overpressure when the speed of the temperature rise decreases. Anisotropic effects are also here noticeable: although the overpressure peak was observed in the cell's horizontal plane (Figure 3c) in the 140 days after the start of heating, peak had not yet been reached in the vertical plane (Figure 3d) after more than 800 days. The difference between the times taken to reach the overpressure peak in the vertical and horizontal planes can be explained by the anisotropic thermal and hydraulic properties of the rock.

A comparison between the results of the 2D analysis and observations, in terms of pore pressure increases, for various points in section "*a*" is presented in Figure 3c and Figure 3d. It is apparent that the maximum pore pressure value at peak is reasonably well captured by the formulation and parameters used. The evolution of pore pressure is also reproduced well, with the noticeable exception of borehole PRE_1616, located in a horizontal plane. This is due to the fact that pore pressure after excavation is not well-captured by the model, which shifts of the further evolution during heating. In Figure 3c and Figure 3d, the time at which the maximum pore pressure increase is calculated is indicated for each measurement point. Time is longer as the distance to the main borehole increases. This comes from the combined effect of the lower temperature rise and lower pore pressure dissipation as the distance from the drainage/heating condition prevailing at micro-tunnel wall increases.

7 CONCLUSIONS

A full-scale in situ heating test has been performed to simulate the conditions of high-level radioactive waste disposal in a deep geological repository excavated in Callovo-Oxfordian claystone (COx). The test has provided, for a period of up to five years, a large amount of information concerning the thermo-hydro-mechanical behaviour of the COx, sleeve and the air gap. When COx claystones are subjected to thermal loading, they may develop a strong pore pressure response. In turn, the generated pore pressures will affect subsequent thermo-hydro-mechanical behaviour. The performance of a heating test in the Meuse/Haute-Marne underground research laboratory (MHM URL) has provided the opportunity to observe in situ the development of the coupled THM behaviour in this type of material. A priori, the strongly bedded nature of the COx suggested that anisotropy effects could be significant. Performance of three-dimensional thermal analysis has proved very useful in providing a structured framework for interpretation. A 3D simulation has allowed the interpretation of the temperature field obtained during the heating experiment and the determination of the optimum thermal parameters. By comparing the results of the 3D thermal computations with those of 2D analyses, it is possible to conclude that the anisotropic effects are certainly noticeable although not large. The mechanical behaviour of the material has been described by a constitutive model that explicitly developed for this type of material. It is of interest to note that the predicted damaged zone appears to be quite consistent with the test observations. Overall, the theoretical formulation adopted and the analysis performed have been able to provide a satisfactory reproduction of in situ test observations, even from a quantitative point of view.

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