18 years of monitoring pore pressure evolution during and after excavation in the Callovo-Oxfordian claystone: the main insights

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ABSTRACT: In France, the Callovo-Oxfordian claystone (COx) formation is considered as the host rock for the geological disposal for radioactive waste due to its very low hydraulic conductivity, low molecular diffusion, significant retention capacity and its self-sealing capacity. The hydromechanical behavior around underground openings in such claystone is also of importance for the short- and the long-term. At the short-term, the front advancement in "quasi-undrained" conditions modifies the stress field and create volumetric strains leading to pore pressure disturbance. If the effective stresses reach the failure criterion, the induced damage around these excavations might change the favorable properties of such formation. At the long-term, the geomechanical characteristics of the formation control the evolution of the induced fracture network and the time-dependent behavior around the openings which are key issues to design drift supports. This paper presents a comprehensive field monitoring study at two different scales conducted in the COx since 2004.

Keywords: Callovo-Oxfordian claystone, hydromechanical behavior, mine-by-test, pore pressure.

1 INTRODUCTION

Since 2000, the French National Radioactive Waste Management Agency (Andra) has been developing the Meuse/Haute-Marne underground research laboratory's (MHM URL) network of drifts in the Callovo-Oxfordian claystone (COx) and testing different excavation methods. The mining itself is a scientific experiment to characterize its impact, to understand the hydro-mechanical (HM) behavior of the claystone, and to study the excavation induced fracture network around these openings. Understanding the excavation damaged zone (EDZ) development and hydraulic properties during and after the excavation is a key issue in the context of the deep geological disposal facility for radioactive waste. This understanding will help for the designing optimization of the support systems of the drifts in the short- and long-term (Armand et al., 2013).

Different excavation methods have been tested at the MHM URL in the directions of the in situ principal stresses. These drifts have been excavated at different diameters, and they vary in the range of 3.8 m and approximately 9.6 m. A diameter of about 10 m is planned to be used for the emplacement of intermediate-level long-lived waste.

In a smaller scale, we find the micro-tunnels of less than one meter diameter to test technological and optimization aspects for the emplacement of high-level waste (HLW).

Most of the experimental drifts and micro-tunnels are instrumented to measure the short- and long-term HM behavior of the COx. Among the installed instrumentation, an important piezometric measurement network has been set up to monitor the evolution of pore pressure during and after excavations. The measurements provide an important insight into the anisotropy of the HM behavior of the COx and the relationship between pore pressure and the excavation induced fracture network.

This work presents the pore pressure evolution over a large number of structures during a long period. These observations highlight the large distances of influence where pore pressure changes are observed, the impact of the in situ stress state and the velocity rate of excavation on the pore pressure. Furthermore, we focus on the openings excavated in the direction parallel to the in situ major stress.

2 MINE-BY-TESTS CONDUCTED AT THE MHM URL

Figure 1 shows the different excavation methods used at the MHM URL. At the main level (i.e., -490 m), the orientations of the experimental drifts follow the direction of the in situ stress field: $\sigma_H \approx 16$ MPa and $\sigma_v \approx \sigma_h \approx 12$ MPa. The pore pressure at this level is about 4.7 MPa. In addition, the dip of the bedding at the MHM URL can be considered horizontal.

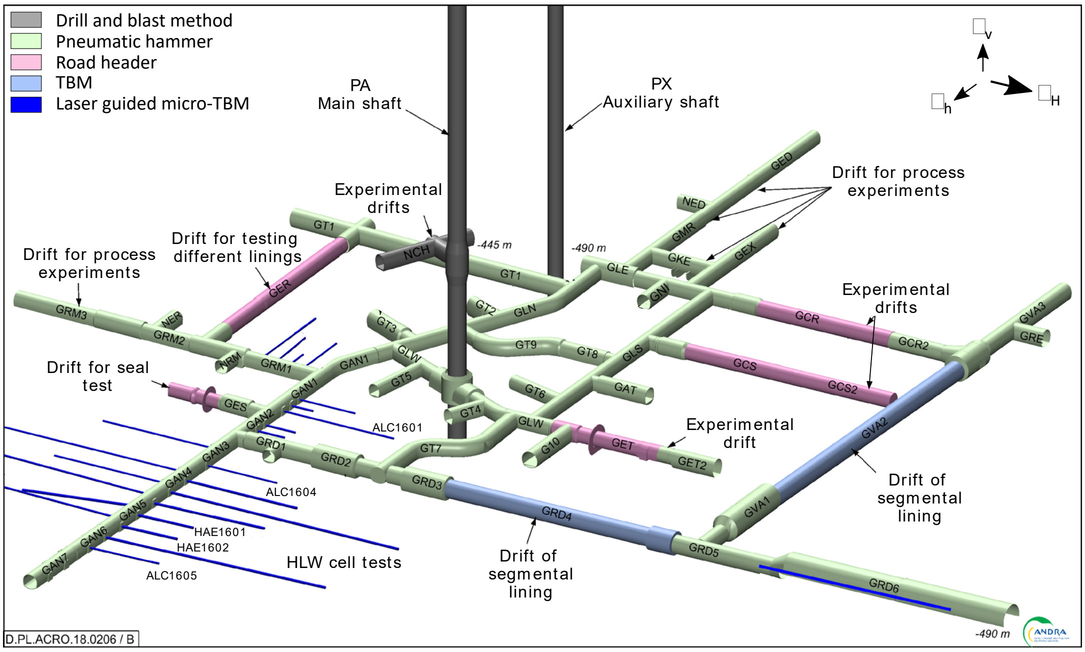

Figure 1. Excavation methods used at the MHM URL.

At the main level, most of the drifts have been excavated with a pneumatic hammer. The spans of the excavation are mainly 1 m long and are immediately covered with shotcrete. Then, the excavated zone is supported by bolts and sliding arches. In addition, a 10 cm thick layer of shotcrete is set in place (Armand et al., 2013) as it is the case of the GT1 drift.

Other excavation technique is the road header with similar supports but also other types. In the case of the GCS drift, the support is ensured by an 18 cm thick shotcrete shell, interrupted by 12 yieldable concrete wedges; completed by 12 radial bolts. The GCR drift has a similar support plus a concrete lining of a 27 cm thick casted in place seven months after the end of its excavation. The last tested method is a TBM associated with segmental lining and backfilling grouting.

In all cases, the sequential procedure results in an average progress of between 2 m/week and 3 m/week. One of the reasons is that the objective is not to reach industrial rates of excavation but demonstrate their feasibility and increase the knowledge of the HM behavior of the COx and the interaction rock-support.

The main characteristics of the drifts used in this study are listed in Table 1.

Table 1. Main characteristics of the drifts considered in this study.

Name	Year of excavation	Excavated diameter [m]	Main support	Average excavation rate [m/week]
GCS	2010	5.20	Yieldable concrete wedges	2.17
GCR	2011	5.40	Yieldable concrete wedges + concrete lining (7 months later)	2.00
GRD4	2013	6.27	Segmental lining	3.28
GT1	2020	5.80	Shotcrete + sliding arches	2.12

The micro-tunnel excavations are also monitored and are referred as HLW cells in Figure 1. The first micro-tunnels helped to improve the excavation methods and to gain knowledge of the mechanical behavior of the steel casing in contact with the rock mass. They also enhanced the knowledge of the rock and the steel casing under thermal loading as it is the case of ALC1604 and ALC1605. Since 2015, the annular space between the steel casing and the rock is backfilling with a cement – based grout material that limits corrosion environmental conditions. The final design of the HLW cells is not fixed yet and technological optimizations are still in progress.

The main characteristics of the selected micro-tunnels used in this study are shown in Table 2. ALC3005 was destroyed as the GRM drift was prolongated two years later.

Table 2. Main characteristics of the micro-tunnels considered in this study.

Name	Year of excavation	Excavated diameter [m]	Backfilling grout	Steel casing	Average excavation rate [m/h]
ALC1601	2010	0.74	No	Yes	1.38
ALC3005	2011	0.74	-	No	1.64
ALC1604	2013	0.75	No	Yes	1.75
ALC1605	2018	0.92	Yes	Yes	2.18
HAE1601	2020	0.92	Yes	Yes	1.93
HAE1602	2020	0.92	Yes	Yes	1.93

Considering the transverse anisotropic behavior of the COx, hydrogeological boreholes are drilled parallel and perpendicular to the bedding plane to monitor the pore pressure evolution during and after the excavation. A hydrogeological borehole consists of a multipacker system with piezometric chambers ranging from 1 to 6 at different depths (Fierz et al., 2007). Each chamber is 0.2 m long. In all cases, the hydrogeological boreholes are intended to be drilled at least 2 months before drift excavation. This allows the pore pressure in the chambers to stabilize to the one of the rock formation.

3 PORE PRESSURE RESPONSE DUE TO THE EXCAVATION

3.1 General overview

In the COx formation, the excavation of an opening creates a damage zone. Armand et al., 2014 carried out structural analyses to characterize the extent of the induced fracture network around drifts. These analyses showed that the fracture extension depend on the opening orientation with respect to the in situ stress field.

Regardless the drift orientation, two zones can be identified in the excavation induced fracture network a connected fracture zone (ZFC) with a distribution of extensional and shear fractures connected to some degree with the drift and a discrete fracture zone (ZFD) with only shear fractures that are not well connected with each other. In the case of the openings excavated in the direction of σ_H, a maximum extent of 1.68 R x 1.18 R and 2.93 R x 1.37 R for the ZFC and ZFD, respectively. These values are given in terms of radius and correspond to an ellipse defined by their horizontal and vertical axes. These observations also apply to smaller scales (i.e., micro-tunnels and boreholes) which suggests that scale effects are negligible since the extension is nearly proportional to the radius.

Regarding the HM response during and after the excavation, similar features can be observed at the scales of a drift and of a micro-tunnel, leaving aside time scale. To illustrate the similar response, Figure 2 presents the pore pressure evolution of GCS and ALC1601. Day 0 is the beginning of the excavation. The chambers of these two mine-by-tests are located at one diameter away from the GCS wall and two diameters away from the ALC1601 wall. In these two examples, the chambers are located outside the excavation induced fracture network.

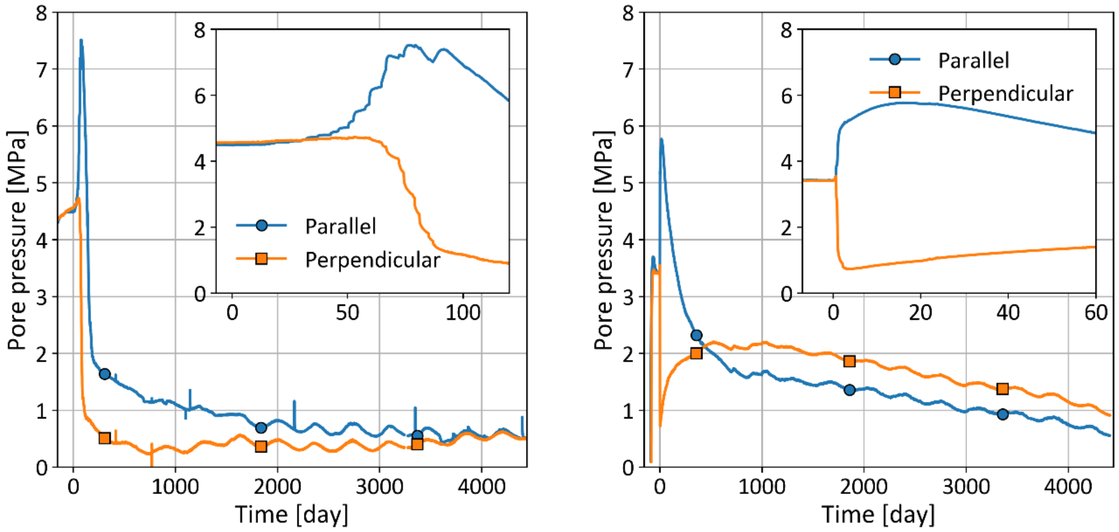

Figure 2. Pore pressure evolution during and after the excavation. (Left) Chambers located at 1 diameter from the GCS wall. (Right) Chambers located at 2 diameters from the ALC1601 wall.

At these two scales, the excavation induces an important excess pore pressure followed by a dissipation process in the direction parallel to the bedding, whereas a moderate overpressure followed by an abrupt drop and a recovery phase is observed in the direction perpendicular to the bedding. The measurements around the micro-tunnel show that the recovery phase reaches a maximum value approximately two years later. In both directions, the temperature seasonality starts to have a relative impact in the long term.

The excavation is performed in a quasi-undrained conditions due to the low permeability of the COx claystone showing an anisotropic response. The pore pressure response is essentially controlled by the volumetric strain with contractant volumetric deformations generated in the direction parallel to the bedding while dilatant volumetric deformations are induced in the direction perpendicular to the bedding. Vu et al., 2020 analyzed these observations and show that there are two main factors controlling this anisotropic response: the inherent anisotropic stiffness of the COx (but insufficient to explain the pore pressure evolution) and the extension of the excavation induced fracture network.

It is worth noting that the two chambers of ALC1601 are below the pore pressure in the formation since they are impacted by the works of the GAN drift's prolongation as they are located in the rock 1.5 diameters away from the drift wall.

3.2 Influence of the excavation rate on the induced excess pore pressure

The amplitude of the induced excess pore pressure is a function of the radial distance from the opening wall but also of the excavation rate as depicted in Figure 3 and Figure 4 for drifts and micro-tunnels, respectively. The distances have been normalized with respect to the opening diameters as well as the pore pressure with respect to the pore pressure measured before the excavation.

The measurements show that the influence range on the laterals of the excavation is approximately 4 times the excavation diameter in the case of the drifts and larger than 6 in the case of the micro-tunnels; the influence is limited in the vertical direction. At both scales, the magnitude of the lateral excess pore pressure follows an exponential curve outside the excavation induced fracture network which is the same as there are no scale effects in terms of diameter. The values are higher for the micro-tunnels since the higher excavation rate reduces the drainage effects and may also reduce the creep effect on the volumetric strains. Inside the excavation induced fracture network, the pore pressures are lower as the fractures allow a rapid dissipation.

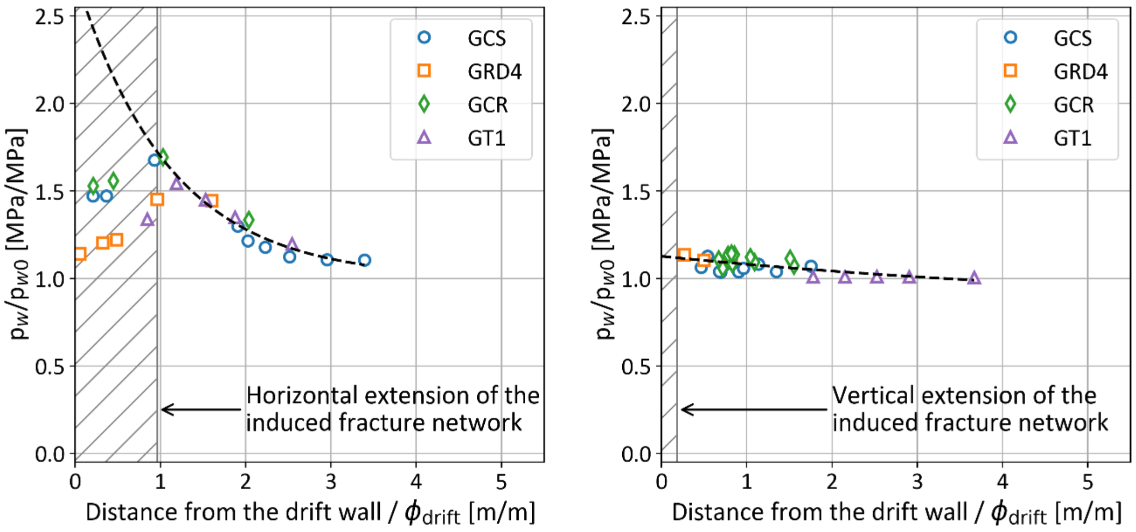

Figure 3. Maximum pore pressure induced by the excavation of a drift. Chambers located in the direction: (Left) parallel to the bedding; and (Right) perpendicular to the bedding.

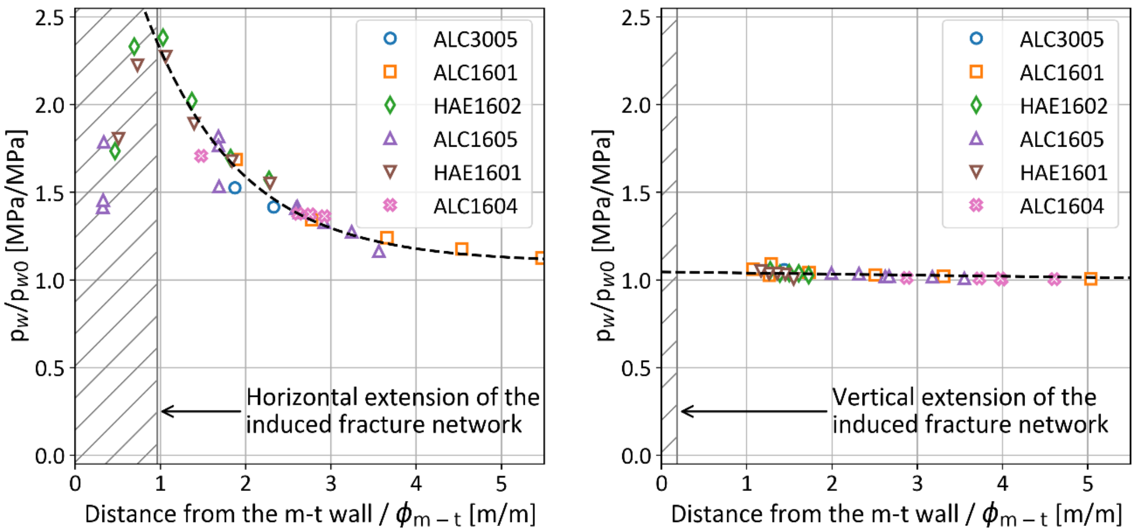

Figure 4. Maximum pore pressure induced by the excavation of a micro-tunnel. Chambers located in the direction: (Left) parallel to the bedding; and (Right) perpendicular to the bedding.

3.3 Long-term evolution of the hydraulic gradients around the drifts

Once the excavation is finished, pore pressure tends to find a hydraulic equilibrium between the opening wall and the pore pressure in the formation. Figure 5 shows the hydraulic gradient around GCS one and eight years after the end of the excavation (after this year, the measurements are disturbed by other works). The lateral excess pore pressure has not been completely dissipated in the horizontal direction as the excess pore pressure is noticeable at 4 diameters from the GCS wall. The measurements in the horizontal direction of the excavation induced fracture network are the atmospheric pressure and starts to read values above and below as they go deep into the rock. This disturbance in the reading is attributed to the impossibility of measuring negative values as they are located in the ZFD or in the sound rock with pressures under suction. This observation is more remarkable in the vertical direction.

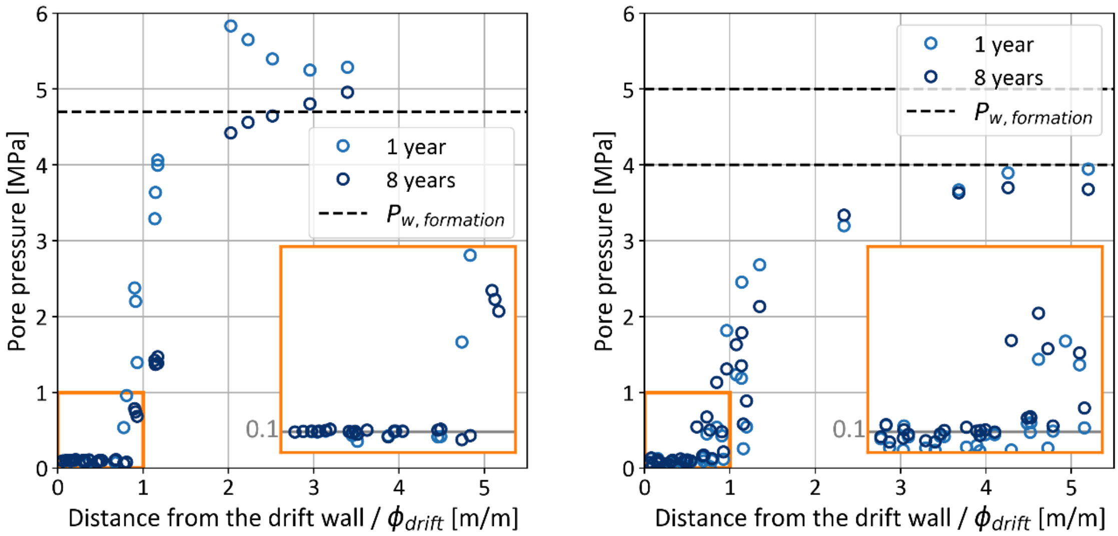

Figure 5. Hydraulic gradient around the GCS one and eight years after the end of its excavation. Chambers located in the direction: (Left) parallel to the bedding; and (Right) perpendicular to the bedding.

4 FINAL REMARKS

Pore pressure measurements during and after opening excavations in the COx formation have been presented at the scales of drifts (~5 m) and micro-tunnels (~1 m). These measurements show similar patterns in terms of HM response with drop and relief of pressure during excavation due to the COx anisotropic behavior and to the excavation induced fracture network development. On the other side, larger pore pressures are observed with higher excavation rates without any significant extend of the excavation induced fracture network. In the long term, the excess pore pressure tends to a hydraulic equilibrium between the opening wall and the pore pressure in the formation (at ~ $4\times Ø_{drift}$).

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