Eighteen years of feedback on the mechanical behavior of a 500m deep shaft on the Meuse/Haute-Marne (MHM) Andra's URL (France)

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ABSTRACT: Clay formations in their natural state exhibit very favourable conditions for the repository of radioactive waste. In France, the Callovo-Oxfordian claystone has been studied by Andra as a possible host rock for radioactive waste disposal since the 1990's. In 2004, Andra began the construction of an underground research laboratory (called the MHM URL) in Bure, starting with shaft sinking operations (to a depth of 500 m). One of the shaft lining and surrounding rock was instrumented. Its concrete lining is highly monitored to understand its long-term behavior and the evolution of the loading due to the surrounding rock mass. Instrumentations were installed at -455 m, -467 m, -479 m, and -504 m depth. This paper presents the data collected over 18 years of monitoring. The outcome feedback consolidates the robustness of the shafts design forecast for the French Industrial Centre for Geological Disposal (Cigéo project).

Keywords: Shaft sinking, deep excavation, lining monitoring, Callovo-Oxfordian claystone, geological radioactive waste disposal, Underground Research Laboratory.

1 INTRODUCTION

The French National Radioactive Waste Management Agency (Andra) has performed in-situ experiments in the Meuse/Haute-Marne Underground Research Laboratory (MHM URL) in the context of radioactive waste disposal for two decades. The MHM URL is located in the Callovo-Oxfordian claystone (COx) formation of the eastern Paris basin at 490 m deep. The experiments performed within the MHM URL help to demonstrate the feasibility of a reversible deep geological disposal of radioactive waste (Cigéo project).

Starting in 2006, the research program became more dedicated to technological adaptations and improvements and the (multiscale) demonstration of the different issues present in the various underground disposal components (drifts, seals, disposal cells and vaults), in a way to answer the "technological readiness level" (TRL) scale, and to confirm the robustness of the proposed concepts (Armand et al. 2013).

The Cigéo project is divided into several components, in which vertical shafts helps allows the transport of machines and materials for the construction from the surface to the underground. Two shafts were built in the MHM URL, in which a shaft has been instrumented in its lining and surrounding rock to follow its behavior versus time. This information is of importance for the optimization of the shaft component in Cigéo project. This study aims to present the continuous 18 years mechanical loading feedback of the shaft final lining as well as a temperature analysis (for a better understanding of the mechanical behavior).

2 SHAFT CONSTRUCTION KEYDATA

The main access shaft (PPA) of the MHM URL was excavated in 2004 using the drilling/blast method, with volleys of 2 m to 3 m. The final depth of the shaft (-509.8m) was excavated on 27th October 2005. The shaft has an excavated diameter of 6.1 m, and a final diameter of 5.05 m considering the concrete lining. The primary lining was set with an 1m step section, it is composed of 20 radial bolts of 2.2 m length per section, grating, and shotcrete. The final support is composed of a concrete ring of 50 cm thickness. Four sections so-called SGMR1, SGMR2, SGMR3 and SGMR4 were equipped in the shaft with vibrating wires, borehole extensometers, hydrogeological boreholes to measure the pore pressure in the Cox and temperature sensors. These sections are located at -455 m, -467 m, -479 m, and -504 m. Figure 1 presents the position of the sections, as well as the clue dates (excavation, final support).

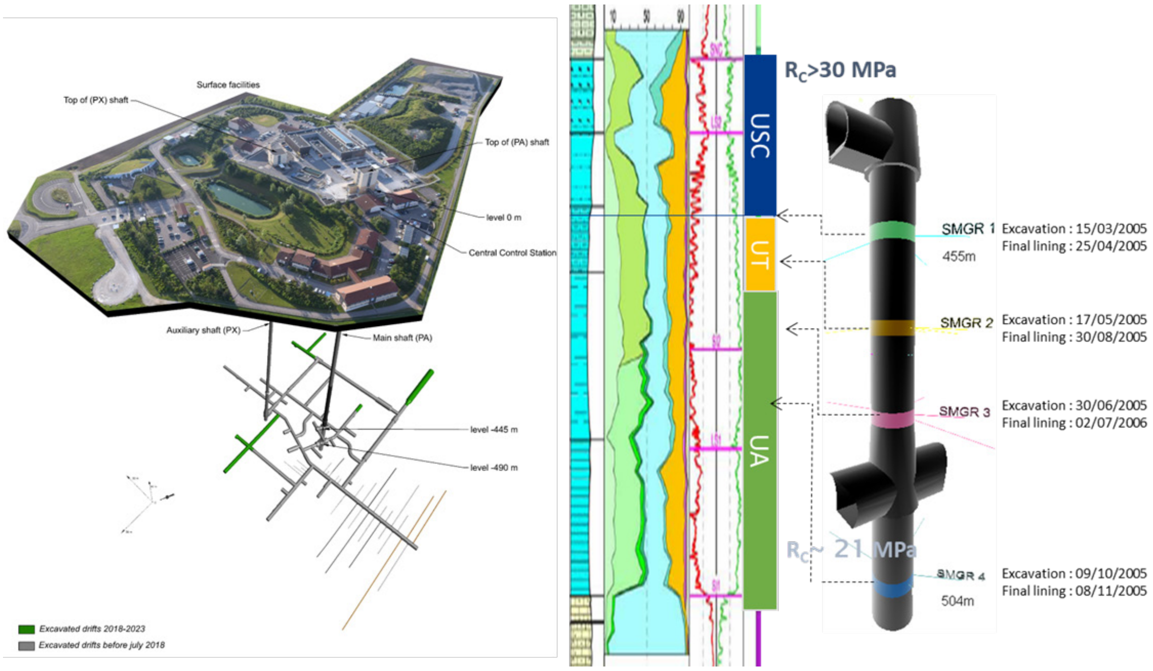

Figure 1. Representation of the MHM URL (left), and the position and clue dates of SMGR sections in homogeneous geological units of the COx claystone (right).

3 CALLOVO-OXFORDIAN CLAYSTONE FORMATION

The four instrumented section SGMR1, SGMR2, SGMR3 and SGMR4 are in the COx stratum, which lies between depths of 420 and 550 m in the MHM URL area. The COx layer can be vertically divided into three lithostratigraphic units listed from the base: the clay unit (UA), approximately two-thirds of total layer thickness with the highest clay mineral content (over 40% on average); the transition unit (UT) and the silty carbonate-rich unit (USC) with the highest carbonate content (40–90%) and a thickness of 20–30 m. The mineralogy of the COx controls its mechanical properties as well as mechanical responses during and after the shaft excavation, in particular the excavation induced fractured zone and the time-dependent behavior. The later one is the main factor controlling the stress and strain evolution within the shaft lining. Main mechanical properties of three lithostratigraphic units of the COx are recapitulated in Table 1.

Table 1. Main mechanical properties of three sub-layers of the Cox formation.

Geological unit	Young Modulus GPa	Compressive strength MPa	Tensile Strength MPa
UCS	13.2 ± 8.5	47.7 ± 21.5	7.6 ± 1.7
UT	10.1 ± 4.3	34.4 ± 10.8	6.4 ± 1.0
UA	5.8 ± 2.3	26.5 ± 6.1	3.5 ± 1.2

4 SEASONAL VARIATIONS

Seasonal temperature variations are reflected at different depths of the PPA and in the lining of the main shaft. The temperature is recorded via sensors embedded in the shaft lining (SGMR1 to 4), meteo station at the surface of the URL, and the temperature sensors in the URL drifts at -490 and -445 m depth. Figure 2 shows the temperature variation over the years, with the seasonal cycles well presented. The peaks recorded at the SMGR levels correspond to the exothermic reaction during the concrete phases.

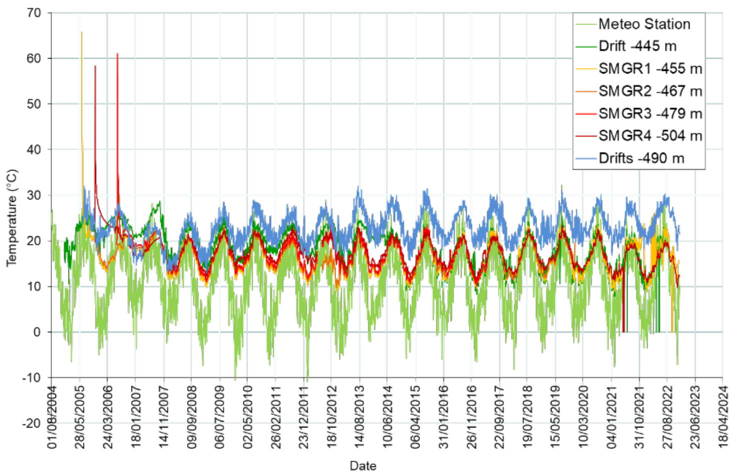

Figure 2. Seasonal variation in temperature in the shaft, in the -445 m drifts, in the -490 m drifts and in the surface weather station.

4.1 Thermal Impact of the Seasonal temperature variation on the rock

The hydrogeological boreholes drilled at the SMGR sections monitored the temperature variation in the rock. The temperature evolution in the near field and the far field are shown respectively in Figure 3 and Figure 4 for the boreholes located at SMG3 (-479 m). In both cases, the measurements show a negative trend probably induced by the shaft ventilation that is directly related to the seasonal temperature variation. On average, the temperature measured by the SMGR sections is decreasing by about 0.12 °C per year since July 2007, one year after the end of the final lining.

To confirm this point, a 3D numerical thermal simulation was performed by applying the temperature recorded by the sensors embedded in the shaft lining (Figure 2) on the shaft wall. The numerical domain consists of a hexahedron of sides 50 m x 50 m x 100 m with the shaft located in the center. Null thermal flux was applied on the external lateral boundaries whereas the top and bottom boundaries remained constant (i.e., 20.7 °C and 21.7 °C, respectively). It was assumed homogeneous thermal properties for the different units of the COx (Table 2).

Table 2. Properties of the COx used for the numerical thermal simulation.

Density	Thermal conductivity parallel to the bedding plane	Thermal conductivity perpendicular to the bedding plane	Heat capacity
kg/m3	W/m/K	W/m/K	J/Kg/K
2450.0	2.0	1.3	1000.0

As shown in Figure 3 and Figure 4, the numerical results show a good agreement with the temperature measurements. It also highlights the impact of the seasonal temperature variation on the rock.

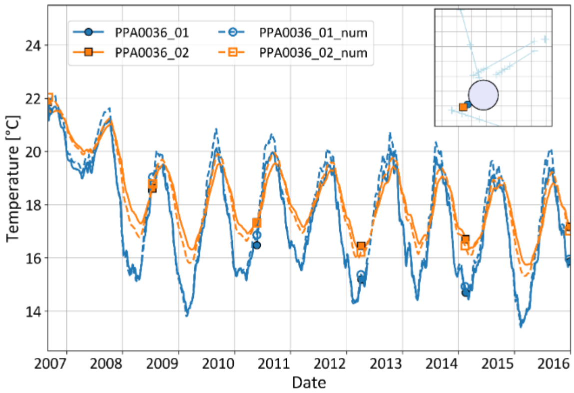

Figure 3. Measurements and numerical results of the temperature evolution in the rock (near field) at SMGR3 section (-479 m).

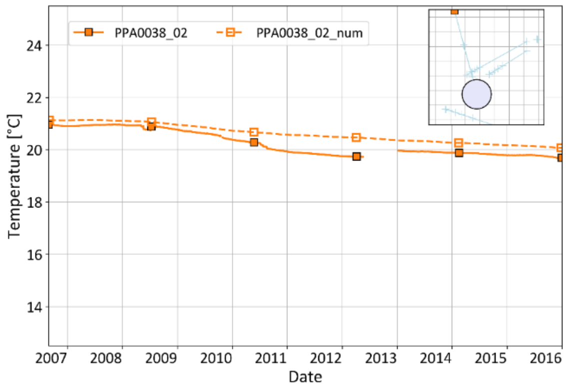

Figure 4. Measurements and numerical results of the temperature evolution in the rock (far field) at SMGR3 section (-479 m).

5 MECHANICAL BEHAVIOR OF THE SHAFT

5.1 Characteristics and position of vibrating wires

Vibrating wires were embedded in the concrete of the shaft lining at the SMGR1 to SMGR4. The vibrating-wire are installed in 8 fixed positions in the final lining (Figure 5). Four of these positions are equipped with 3 orthoradial extensometers (strain at the outer, neutral/center and inner of the final lining), and four positions with 5 extensometers (3 in the same way + one radial and another vertical deformations). In total, on each SMGR, 32 vibrating-wire extensometers were set up, as well as 4 temperature sensors. 81% of the vibrating-wire are functional to date.

Figure 5. Position of the vibrating-wires and temperature sensors in the instrumented sections of the shaft's lining.

5.2 *Strain results*

The first step to analyze the measured strain in the shaft consists of correcting the obtained values from the dilation and temperature effect. The correction method used is described by the following equation:

$$\varepsilon_{cor-therm} = \varepsilon_{measured} + (T - T_0) \times (\alpha_{steel} - \alpha_{concrete}) \tag{1}$$

The value of the dilation coefficient used in our work is $(\alpha_{steel} - \alpha_{concrete})$ = 4.4 x 10-6/°C, it is based on a step by step verification process taking into account laboratory surface tests, continuous or temporary sensor measurement (different directions and loading level) analysis due to temperature evolution, and it is applied to all the presented measurements. The Figure 6 shows the evolution of the annual average strain measured with the vibrating-wires in the 4 sections SMGR1 to 4. The results show three global phases in all the results. The strain increases rapidly between 2005 and 2008. The slope of the strain evolution decreases between 2008 and 2012 compared to the first phase. After 2012, the strain continues to evolve especially for the SMGR4, but slowly. However, the deformation of the final lining in SMGR1 tend to be more stabilized than the other sections. This must be set against the mineralogical variation in the Cox with SMGR1 being in the UCS unit with higher carbonate content and lower shaft initial convergences.

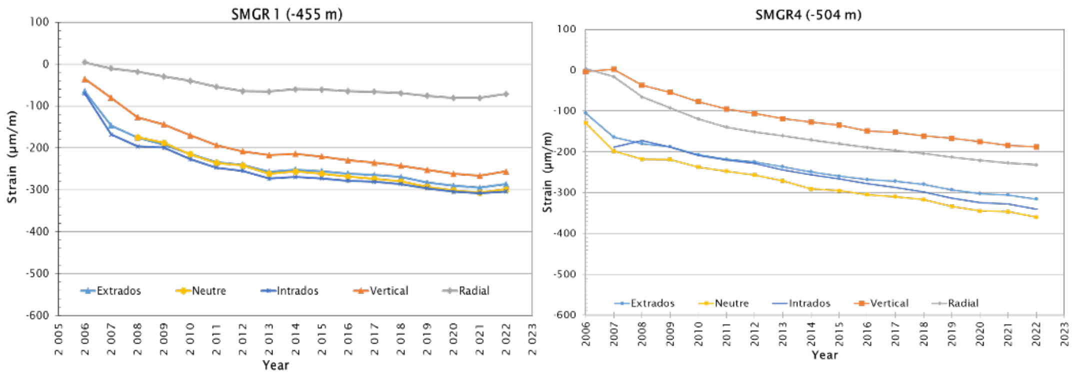

Figure 6. Evolution of the annual average strain measured with the vibrating-wires in SMGR1 and SMGR4.

For a better understanding of the mechanical behavior of the shaft, vibrating wires results are analyzed according to the angular position of the sensors and their position in the thickness of the Lining (inner, neutral, outer position). Figure 7 shows the orthoradial strain evolution over time and in an angular position of the shaft section with 0 the North direction. The measured orthoradial strain appear not to be constant in the inner or outer position all over the section, behavior that reflect an anisotropic loading on the final lining that can be due to the initial stress state on the Callovo-Oxfordian Claystone (Wileveau et al. 2007). We note as well that the inner sensors appear to be less compressed in the area of application of the major horizontal stresses (green arrows).

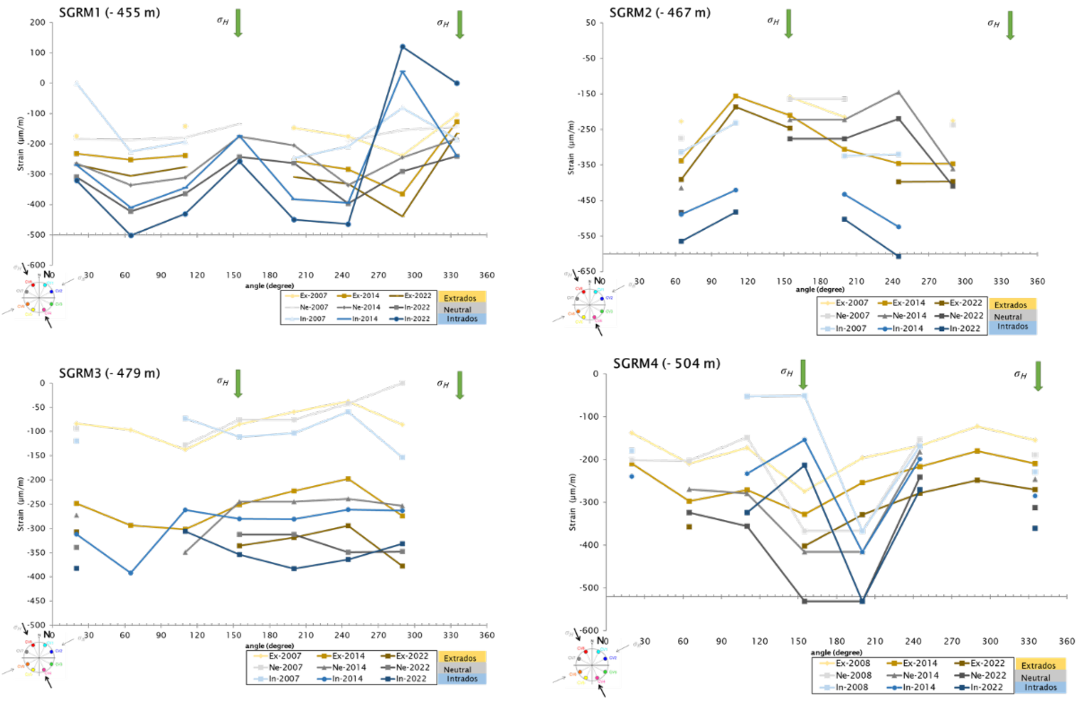

Figure 7. Orthoradial strain evolution over the years, as a function of angular position of the vibrating wires in the lining.

6 CONCLUSION

This paper presented the results of almost two decades of monitoring in the main access shaft PPA of the MHM URL. Both temperature and strain results are presented in this paper. The obtained measurements show the mechanical interaction between the PPA lining and the Callovo-Oxfordian claystone, thermal (seasonal temperature variation) and hydric (ventilation, seasonal variation of relative humidity) conditions. Vibrating-wires measurements, corrected with a thermal coefficient, showed that the strain in the shaft support continues to evolve, but slowly and tend to be stabilized in the UCS unit. The orthoradial measured strain shows an anisotropic loading that is in agreement with the principal directions of the in-situ stress state. The effect of the seasonal temperature and ventilation on the measurements is relatively high on the inner of the lining thickness and decreases gradually in the rock as shown by the borehole measurements and numerical simulations. An overall cooling of about 0.12 °C per year is also measured since 2007. This amplitude is verified by numerical calculations.

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