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Feasibility and behavior of a full scale disposal cell in a deep clay layer

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ABSTRACT: At the Meuse/Haute Marne Underground Research Laboratory, Andra is studying the possibility of disposal for intermediate to high level activity – long life nuclear waste in a 500 m deep clay formation. In particular, a specific technical and scientific program is carried out for several years to test the feasibility of realization and the behavior of disposal cells for high level – long life waste packages. Within the framework of this program, and as part of the European project LUCOEX (Large Underground Concept Experiment), a new phase has started at the end of 2012 with the realization of a full scale disposal cell demonstrator. Heat generated by waste packages is simulated by electrical heaters over a length of 15 m, with the aim to reach 90°C at the cell interface in 2 years. The thermo-mechanical behavior of the cell as well as the THM impact on the surrounding rock is monitored through a very complete instrumentation.

1 INTRODUCTION

1.1 *General context*

Andra, the French national radioactive waste management agency, is in charge of the study on the possibility of disposal for intermediate to high level activity – long life (IL/HL – LL) nuclear waste in deep geological repositories. In this aim, the Meuse/Haute Marne Underground Research Laboratory (URL) has been excavated since 2000 in a 500 m deep claystone layer (Callovo-Oxfordian, COX) to characterize to confining properties of the clay-stone and demonstrate the feasibility of construction and operation of a geological disposal (Delay et al. 2007).

Table 1. COX claystones characteristics.

Rock parameter	Notation	Value
Density	ρ	2.39 g/cm^3
Porosity	N	7.2 ± 1.4%
Intrinsic permeability	k	5×10^{-20} m^2
Water content	W	7.2 ± 1.4%
Young's modulus	E	4 ± 1.47 GPa
Poisson's ratio	ν	0.29 ± 0.05
Uniax. compress. strength	UCS	21 ± 6.8 MPa
Hoek & Brown criterion	S	0.43
	m	2.5
	σ_c	33.5 MPa
Thermal conductivity	λ	1.3–2 W/m*K

1.2 *Callovo-Oxfordian claystones*

The main level of the URL is excavated at a depth of 490 m in the middle of a 135 m thick argillaceous rock layer, overlain and underlain by poorly permeable carbonate formations. Argillaceous rock contains a mixture of clay minerals (40 to 45% on average) and clay-size fraction of other compositions. The clay minerals offer groundwater tightness and radionuclides retention. Silica and carbonate-rich sedimentary components contribute to high strength of the rock and stability of the underground construction.

Table 1 gives Callovo-Oxfordian claystones mechanical characteristics. Sedimentation has led to a slightly anisotropic behavior of claystones. In-situ measurements indicate a strong coupling between mechanical and hydraulic processes (Armand et al. 2011).

In-situ stress field in COX claystones is anisotropic (Wileveau et al. 2007), with $\sigma_v \approx \sigma_h$ and the ratio σ_H/σ_h close to 1.3 at the main level of the URL.

1.3 *Benchmark concept for HL-LL disposal cells*

The benchmark concept of disposal cells for HL-LL waste consists in horizontal micro-tunnels at least 40 m long and about 70 cm in diameter (Fig. 1). It comprises a body part, for packages disposal, and a head part for cell closure. They are favorably aligned with respect to the stress field. To prevent against rock deformation and allow the potential retrieval of waste containers during the reversibility period, both body and head parts have a non-alloy steel sleeve. The sleeve in the body part has a diameter slightly smaller than the one in the head part called "insert". That means it can slide in the insert. Thus, the effects of the thrust produced by its dilation, due to heat generated by the exothermic packages, are absorbed without consequence for the cell head.

The cell base is closed off by a "base plate", also made of non-alloy steel. A metal radiation-protection plug separates the cell head from the body part. For cell

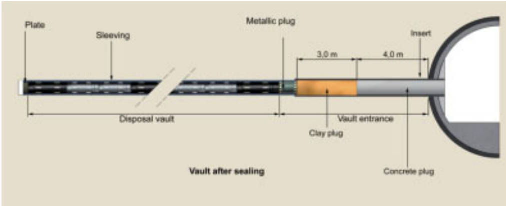

Figure 1. Concept of disposal cell for HL-LL activity waste.

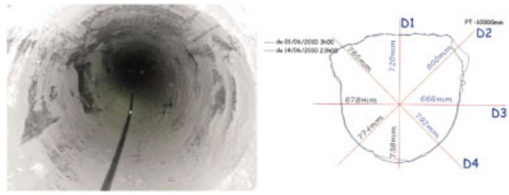

Figure 2. State of the cell wall and typical cell profile (Phase 1b).

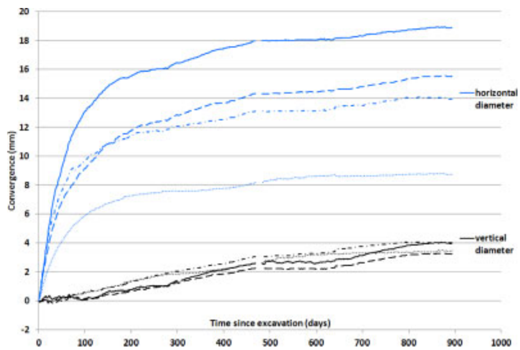

Figure 3. Convergence measured along horizontal and vertical direction in an unsleeved 20 m long cell (Phase 1b) – full line: 16 m depth; dash line: 12 m; dash/dots: 8 m; dots: 4 m.

closure, the insert is partly backfilled with a swelling-clay plug and then sealed with a concrete plug to provide additional safety.

2 EXPERIMENTAL PROGRAM

In order to check the feasibility of such disposal cells construction, and study the behavior of the cell and its impact on the surrounding rock, an experimental program has been defined and carried out through different phases since 2009.

2.1 *Drilling method*

The excavation method uses a guided auger drilling machine. The drilling head can be adapted to excavate in diameter 70 to 75 cm. It also allows the retraction of the drilling machine at the end of the excavation, by rotating in the opposite direction as for the excavation.

The drilling machine is laser-guided, what allows the control of the micro-tunnel trajectory with a precision better than +/−2 cm.

The excavation can be achieved with or without casing. The casing is made of 2 m long, 70 cm in diameter and 2 cm thick metal tubes. The 2 m long elements are welded or socketed to each other as the excavation advances.

The drilling is carried out with air.

2.2 *Experience feedback from former phases*

The first phase, carried out in 2009 (Phase 1) and 2010 (Phase 1b), aimed to check that it was possible to dig cells in several directions with respect to the stress field in the host formation, to test the excavation method (with or without advance casing) and to specify operating procedures for cell excavation in the next phases (Morel et al. 2009). It also provided initial data on the hydro-mechanical behavior of the cells and their environment: the influence distance of the cells, their mechanical behavior and damage around them.

From a technology standpoint, Phase 1 highlighted the necessity to modify the equipment and the excavation operating procedures to be able to produce a cell representative of the benchmark concept, and to make the maximum improvement to the cut quality in order to produce an annular space that is as regular as possible. These modifications were implemented for Phase 1b and showed that a 40 long sleeved cell could be produced. Production of an unsleeved 20 m long cell showed that these modifications also significantly improved the state of the cell wall, much smoother overall, although the formation of breakouts, induced by the natural stress field, is inevitable (Fig. 2).

In terms of impact of micro-tunnel digging, Phases 1 and 1b have shown that overpressures are generated during the excavation. In the horizontal plane, the over pore pressure amplitude and influence distance measured (about 35 bars at 1 m from cell wall) are much higher than the one predicted in the preliminary calculation performed for the experiment. Furthermore, convergence measurements, performed using a specifically designed system on several sections at different depth along 4 different diameters (Gay et al. 2010), show that horizontal convergence is much larger than vertical one (Fig. 3).

This anisotropic behavior, although the cell is oriented along the major stress direction and thus undergoing an isotropic stress field, was also observed for drifts of 5 m diameter with similar orientation. This is related to the shape of the excavation damaged zone (EDZ) around the cell (or drift) and to the anisotropic character of claystones. The convergence velocity decreases with time, and is of the order of 10^{-11} s^{-1} (/cell diameter) 30 months after excavation.

Phase 2, carried out in 2011, aimed to test the production of a cell head with an insert installed with a small annular space (8 mm on radius), and to produce a 40 m long cell with an instrumented sleeve, to study how sleeve/rock clearance reduces over time (resaturation kinetics of the annular space, sleeve loading) and its influence on the mechanical behavior of the sleeve. Lessons learned from this Phase 2 were used to prepare and optimize Phase 3 corresponding to the full scale heating demonstrator.

The test of cell head production was included in the European project LUCOEX (Large Underground Concept Experiment). After 7.5 m of excavation, the insert was jammed in the rock and the thrust forces needed to pursue the excavation reached the maximum capacity of the drilling machine. Consequently, the cell head configuration was modified for Phase 3, with a length of 6 m and an annular space rock/insert of 12 mm.

Concerning the 40 m long instrumented cell, the sleeve was watertight and equipped to study its mechanical behavior (strain gages, convergence measurements, optic fibers); the annular space was instrumented with relative humidity and water pressure sensors, as well as temperature sensors. Most of the sensors (except the strain gages), as well as all cables, had to be installed after excavation by human intervention inside the sleeve, to avoid their damage during drilling. Instrumentation was installed successfully and the procedure used was thus validated for Phase 3.

2.3 *Full scale disposal cell demonstrator*

The purpose of the full scale heating demonstrator (Phase 3 of the program) is to study the behavior of a HL-LL cell under thermal loading by simulating the heat produced by waste packages. The aim is both to demonstrate production and operation of such a disposal cell, and to understand the THM behavior of the neighboring rock.

The experimental concept must thus be representative of a real disposal cell, i.e. with a head and a body part, a base plate, a plug representing the radiation protection plug, and a cover plate on the insert head. The thermo-mechanical behavior of the sleeve and insert will be monitored, as well as the cell head operation (body expansion and sliding in the insert). The impact of thermal gradient along the cell on the access drift, and the analysis of the THM behavior of the rock/sleeve interface and its impact on the mechanical loading of the sleeve will be measured. Finally, peripheral boreholes will allow the study of the THM behavior of claystones beyond the interface, mainly in terms of the overpressure induced by the heating phase.

The demonstration of cell construction and operation is included in the European project LUCOEX.

3 EXPERIMENT SET-UP

3.1 *Cell demonstrator characteristics*

The full scale demonstration cell is 25 m long, and consists in a 6 m long, 791 mm diameter head part and a 19 m long, 750 mm diameter body part. The cell is excavated in the major horizontal stress direction. Heat will be produced in the deepest 15 m. The sleeve consists in 2 m long sections (2 cm thick, 700 mm external diameter) socketed to each other; steel pieces are fixed at the junction between each sleeve section to ensure sleeve rigidity and allow its dilation and sliding in the insert. The insert consists also in 2 m long sections (2.1 cm thick, 767 mm external diameter) welded to each other. Both sleeve and insert are instrumented to monitor their thermo-mechanical behavior. Base plate, body part's head plate and insert cover plate are bolted on crowns themselves bolted on the sleeve or insert.

3.2 *Numerical modeling*

Thermal and thermo-mechanical numerical modeling has been performed to help in the preliminary design of the experiment.

A 15 m heating length has been shown highly representative with respect to the benchmark concept where waste packages are inserted over 30 m, with only 2 to 4°C of difference at the cell wall essentially at both ends of heated zone. Radial temperature profiles from the cell wall in the middle of the heated zone are extremely similar for body part lengths of 15 m and 30 m. The choice of a 25 m long demonstrator cell was thus substantiated.

Position of the heating element, centered in the sleeve or lying on the sleeve's bottom, has been found to produce temperature differences as high as 5°C between invert and crown at the outer side of the sleeve. Final position of the heaters, lying on transfer blocks (cf. next paragraph) is close to centred.

The effect of the base plate and of the body part's head plug on the thermal profile along the cell was found to be negligible.

Thermal impact of the cell on the access drift is not more than 3°C, i.e. well below the annual temperature variations associated with drift ventilation.

Finally, the thermal load to apply was modeled. Obviously, a thermal cycle representative of the repository concept (thermal peak at 10–15 years for the least exothermic packages) cannot be reproduced for the experiment, which needs results in a reasonable timeframe. It was chosen to apply a constant power to reach 90°C at the outer side of the sleeve in 2 years; the power needed was found to be around 220 W/m.

3.3 *Heaters design*

The heater device consists in five identical elements, each 3 m long, 508 mm in diameter and about 500 kg heavy. Each element is composed of 3 concentric tubes (Fig. 4): an inner cylinder providing the necessary space to allow cables path; an intermediate cylinder around which the electrical resistors are coiled; an outer cylinder to protect the resistor and provide, together with 2 lids welded on both sides of the element, water and vapor tightness for the resistors. Each cylinder is made of stainless steel.

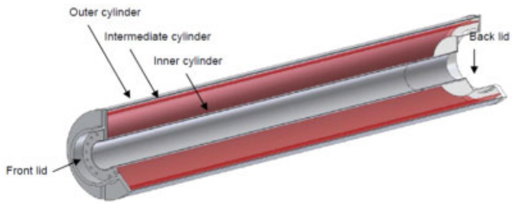

Figure 4. Heater element general design (Aitemin).

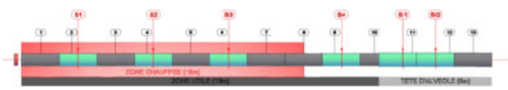

Figure 5. Location of sleeve and insert instrumented sections (Egis Géotechnique).

Each element is equipped with balls transfer blocks to facilitate its insertion in the cell by rolling on rails preliminary screwed on the sleeve and the insert. The balls transfer blocks are made of a low thermal conductivity plastic that can bear high temperature, inlaid in a stainless steel piece welded on the outer surface of the element.

In addition with temperature measurements inside and at the surface of the heaters, each element has an integrated inclinometer to measure its eventual movement induced by sleeve deformation. Moreover, sleeve convergence is measured along horizontal and vertical directions at each junction between heater elements.

Heating is controlled trough a power regulation system.

3.4 *Sleeve and insert instrumentation design*

Figure 5 shows the location of sleeve and insert instrumented sections.

Four sleeve sections (among which 3 are in the heated zone) are fitted, on their internal surface, with strain gages placed evenly around the pipe in 6 measurement areas, to measure circumferential and axial local strain. On each of these sections, the total pressure at the rock/sleeve interface is also measured at 2 locations, as well as rock/sleeve clearance reduction at the sides and vault of the sleeve through specific drillings. Relative humidity and temperature are measured in the annular space.

In addition to these instrumented sections, the sleeve's mean axial strain in the heated zone is measured with an extensometer fixed at the vault.

Two insert sections are, as for the sleeve ones, instrumented with 6 strain gages measurements area. Relative humidity is measured in the insert.

Two temperature profiles are measured along the cell (sleeve and insert), at the vault and at the side, with one measuring point per sleeve or insert section.

Sleeve and insert convergence is measured along horizontal and vertical directions for each instrumented sections outside the heated zone (inside the heated zone this measurement is made with heaters instrumentation, cf. former paragraph).

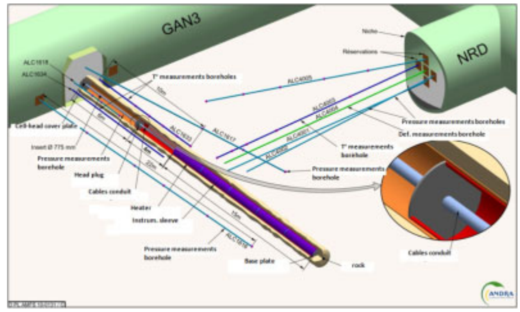

Figure 6. General view of the full scale experiment.

Finally, the sliding of the sleeve in the insert is measured with 3 displacement sensors fixed to the insert inner surface and in contact with the body part's head plate.

3.5 *Peripheral instrumentation*

Peripheral instrumentation consists in 9 peripheral boreholes drilling from the access drift and from a perpendicular one (Fig. 6), and in access drift instrumentation.

Six boreholes are equipped with pore pressure single or multipacker devices with measuring points at different distances from the cell wall in the horizontal and vertical planes. Each pore pressure measuring point is coupled with a temperature measuring point. The devices allow the realization at each measuring point of hydrogeological tests to estimate rock permeability.

Two boreholes, parallel and perpendicular to the cell, are equipped with temperature sensors. The last borehole, oriented perpendicularly to the cell, allows very fine deformation measurements at different distances from the cell wall.

The access drift instrumentation, in the immediate vicinity of the cell head, consists in support instrumentation (strain gages and displacement sensors on sliding steel arches), and displacement and tilt sensors to measure drift wall deformation induced by thermal gradient along the cell.

4 EXCAVATION AND INSTALLATION

Most of the peripheral boreholes (except two ones for temperature and pore pressure measurements parallel to the cell and at 50 cm from it, which could be damaged during excavation operation), as well as drift support instrumentation, were realized before cell excavation, to monitor the hydro-mechanical impact of excavation on surrounding rock mass and drift behavior.

The cell was excavated from 23rd to 31st October 2012, the insert first and then the body part after

Figure 7. Positioning of a heater element at the cell entry before insertion.

Figure 8. View of the convergence instrumentation in the insert.

changing the cutting head diameter. The first 24 m were excavated in about 3 days; a technical problem that occurred on the drilling machine had then to be solved before the last meter could be excavated.

Once the base plate and the rails for heaters insertion put in place, and the last 2 peripheral boreholes drilled and equipped, instrumentation of the sleeve and insert was installed (except the strain gages that were already preinstalled) and all sensors connected to the URL data acquisition system.

Heaters were then inserted in the cell in January 2013 (Fig. 7). For this operation, sleeve and insert convergence instrumentation (Fig. 8) had to be removed, to be reinstalled just after heaters installation together with the fixation of the body part's head plate, the sleeve/insert relative displacement sensors and insert cover plate (Fig. 9).

At last, instrumentation of the access drift wall around the cell head was finalized.

5 FIRST RESULTS

A 3D scan performed before instrumentation showed that the cell trajectory was close to the theoretical one,

Figure 9. View of body part's head plate (left) and insert cover plate (right).

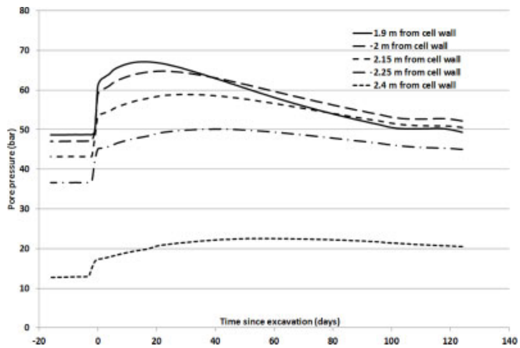

Figure 10. HM impact of cell excavation in the horizontal plane.

with a maximum deviation of 1.5 cm in the horizontal plane and 8 cm in the vertical one.

Hydro-mechanical impact of cell excavation on surrounding rock mass was found very consistent with what was measured during the former phases of the program. Induced overpressures in the horizontal plane ranged between 9 and 35 bars at distances respectively between 2.4 and 1 m from the cell wall (Fig. 10, initial pore pressure depends on the depth of the measuring point from the access drift). The time to reach the pressure peak increases with distance to cell wall.

Sleeve convergence measurements show compression in the horizontal direction and extension in the vertical one (Fig. 11). This indicates a contact with the cell wall and subsequent mechanical load of the sleeve first in the horizontal direction while no contact occurs with the sleeve vault. This behavior has been observed also in Phase 2 on the 40 m long instrumented cell as well as on smaller scale experiments of similar orientation with respect to the stress field. This observation is also consistent with convergence measurements performed in unsleeved cell (Fig. 3).

A preliminary heating test has been carried out between 30th January and 15th February 2013, to validate the operation of the heaters regulation system and the measurements acquisition. Heating power was set to 100 W/m.

Temperature on the sleeve reached 30°C (for an initial temperature of about 22°C). The test was successful, although the increase in temperature was not strong enough to measure any significant influence on sleeve behavior.

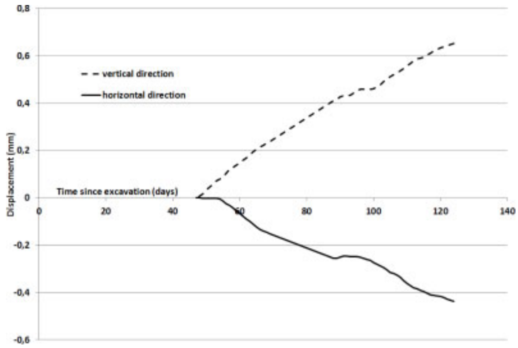

Figure 11. Sleeve diameter evolution at 8 m depth – positive displacement corresponds to extension, negative to compression.

After a slow decrease of temperature to ambient conditions, the main heating phase, at a constant power of about 220 W/m to reach 90°C on the sleeve in 2 years, will start at the end of March 2013.

6 CONCLUSIONS

Using the experience feedback from the former phases of the dedicated experimental program carried out since 2009, a full scale HL-LL waste demonstration cell has been designed and successfully realized and instrumented at the Meuse/Haute Marne URL.

First results from excavation and sleeve behavior are consistent with similar measurements performed on former demonstration cells, on drifts and on smaller scale experiments of same orientation with respect to the stress field.

Heat generated by the exothermic waste packages will be simulated with electrical heaters over a length of 15 m. The main heating phase will start at the end of March 2013 with the goal to reach 90°C on the sleeve surface in about 2 years. Numerical modeling, taking into account the back experience of smaller scale heating experiments simulation, will be performed to be compared with experimental data.

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