

THE ENHANCED SEALING PROJECT (ESP), 7 YEARS MONITORING OF FULL-SCALE SHAFT SEAL AT CANADA'S UNDERGROUND RESEARCH LABORATORY

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Abstract

The Enhanced Sealing Project (ESP) is a research, development and demonstration (RD&D) project monitoring thermal-hydraulic-mechanical (THM) responses of the shaft seal at Canada's Underground Research Laboratory (URL). The project was started in 2009 and is jointly funded by Posiva (Finland), Andra (France), and CNL (Canada) to continue monitoring until the end of 2016. The seal is intended to limit the mixing of saline groundwater below fracture zone (FZ) at ~270 m depth with fresher groundwater above it. The diameter of the shaft seal is approximately 5 m and comprises a clay component (6 m thickness) sandwiched between two concrete components (3 m thickness each). The clay component is a mixture of 40% bentonite and 60% sand and is designed to provide sealing capability. One hundred sensors were installed at strategic locations within the seal and nearby granite rock to monitor evolution of temperature, displacement, strain, hydraulic pressure, total pressure, and saturation. As of December 2015, the monitoring results indicated that the seal is functioning to limit the mixing of the saline and fresh groundwater below and above the fracture zone. Experience gained from the ESP, construction and monitoring methods are valuable to support future development and design of sealing systems to safely close a Deep Geological Repository (DGR). The ESP data combined with experimental and site investigation data at the URL site provide comprehensive data set to calibrate numerical model to simulate the performance of the sealing system in a DGR.

1. Introduction

A final disposal of radioactive wastes is required for safe nuclear waste management, decommissioning and environmental restoration activities. A deep geological repository (DGR) is one of acceptable methods to close the nuclear fuel cycle, especially for final disposal of long-lived and high-activity radioactive wastes [1], [2]. Development of a DGR supports the primary goals of decommissioning and nuclear waste management: to protect current and future generations from potential harm and to avoid imposing undue burdens for future generations [3].

A DGR located at a depth of hundreds metres in a suitable rock formation works in concert with multiple engineered barrier systems. The engineered barrier systems installed in a DGR can include the container, bentonite-based and concrete-based materials to protect the nuclear waste disposal facility from human interference and from natural phenomena such as earthquakes or climate changes. It will require an extremely long design life time hence multidisciplinary Research, Development, and Demonstration (RD&D) projects are needed to provide confidence in the design. The Underground Research Laboratory

(URL) near Lac du Bonnet, Manitoba, Canada was one of the facilities that from 1980 through 2003 provided support to the development of a safe DGR for final disposal of radioactive wastes. The URL was a generic underground research laboratory and was constructed in a granitic pluton on the western edge of the Canadian Precambrian Shield, and was built specifically for research and was never intended for eventual use as a site for disposal of any radioactive wastes. Many of the studies undertaken at the URL were generic in nature and have wider applications, not limited to the characteristics of the site selected to construct a DGR. This generic applicability was demonstrated through conduct of international collaboration projects [4]. Many international collaboration projects at the URL were also done at full-scale, requiring long-duration to complete and represent considerable investment of technical expertise and resources. They are therefore not easily repeated and their results have potential application when further design refinements are done in the future. As there is a considerable time before the first repository shaft will require sealing, successful intergenerational knowledge preservation will be required to ensure that the results of the ESP are accessible for future generations. In response to this need, efforts to preserve the information from the ESP include publication of results in a variety of journal and conferences (e.g. [4]-[15]).

This paper presents the results and experience gained from the final international collaboration project at the URL, the Enhanced Sealing Project (ESP). For 7 years (2009-2015), the ESP has monitored the Thermal-Hydraulic-Mechanical (THM) of a full-scale bentonite-concrete shaft seal installed at the URL. The results of the ESP are applicable for the development of methods to close and seal a DGR, to calibrate THM numerical models, to demonstrate seal construction, and method for post-closure monitoring.

2. The Enhanced Sealing Project (ESP)

The Enhanced Sealing Project (ESP) is the final on going international collaboration research, development, and demonstration (RD&D) project at the Canada's Underground Research Laboratory (URL). Closed in 2003 and subsequently decommissioned and surface facilities removed between 2007 and 2015, part of the activities undertaken was installation of two full-scale seals, at a depth of approximately 270 m, where the main access and ventilation shafts intersecting with the Fracture Zone (FZ2) (Figure 1). These seals are intended to limit the mixing of the saline groundwater below the FZ2 with fresher groundwaters above the FZ2. The construction of these seals was funded by the Natural Resources Canada (NRCan), as part of the Nuclear Legacy Liabilities Program (NLLP). However, the NLLP did not require monitoring the performance of these shaft seals. Recognizing the potential to demonstrate the construction of and to improve understanding of the behaviour of this full size shaft seal, a research, development, and demonstration (RD&D) project, the Enhanced Sealing Project (ESP), was developed by the Atomic Energy of Canada Limited (AECL) in 2008.

Configuration of the seal in the main shaft is illustrated in Figure 1b. The seal has a diameter of approximately 5 m and consists of a 6-m-thick clay component sandwiched between 3-m-thick upper and lower concrete components. The concrete components are keyed into the granitic rock to a maximum depth of approximately 0.5 m (Figure 1b). The clay component spans the fracture zone and extends at least 1 m beyond the maximum identified extent of the fracture zone at either ends, providing the hydraulic sealing capacity to the seal. The clay component is an in situ compacted mixture of bentonite clay (40% dry mass) and quartz/feldspar sand (60% dry mass) compacted in situ to an as-placed dry density of approximately 1810 kg/m³. The concrete components provide mechanical support and confinement to the swelling clay component and are not expected to serve a hydraulic sealing function. The concrete components consist of a heavily-reinforced lower segment and an unreinforced upper segment. The concrete is a low-heat, low pH and high strength concrete mixture [14].

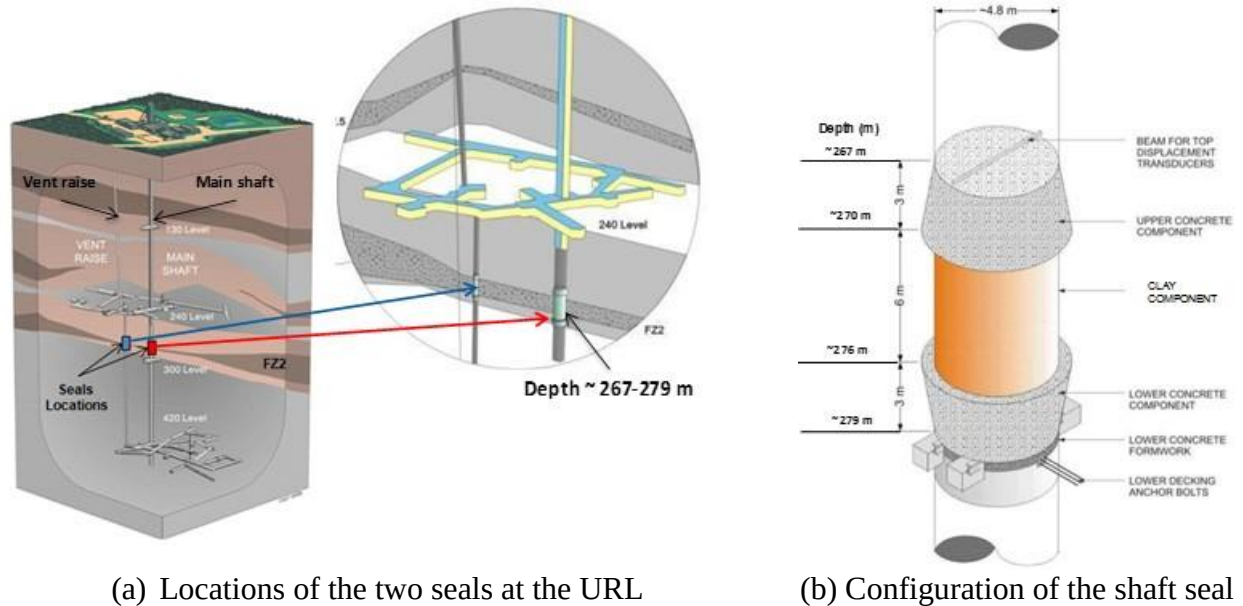


Figure 1 URL site and the Enhanced Sealing Project (ESP)'s main shaft seal dimensions

The 1st phase of the ESP was operated and managed by AECL (Canada) from 2009 to 2013 and was jointly funded by NWMO (Canada), SKB (Sweden), Posiva (Finland) and Andra (France). Its objectives were to document the construction of the shaft seal, to install sensors and monitoring systems, and to monitor initial thermal, hydraulic, mechanical (THM) responses of the shaft seal in the main shaft.

The 2nd phase of the ESP (2014-2016) is intended to continue monitoring beyond 2013 and included the period after the demolition of the URL surface facility in 2014. It is currently operated and managed by the Canadian Nuclear Laboratories (CNL) and funded by Andra (France), Posiva (Finland), and CNL (Canada). This extended monitoring period was needed because as of the end of 2013 the extensive excavation volume at the 240 level was not yet flooded, making data extrapolation extremely difficult [12]. These data were required to numerically simulate the shaft seal and to understand long term behaviour of the shaft seal. During this period, sensors have provided information regarding the longer-term behaviour of the shaft seal and groundwater inflow into the open shafts.

Before the 2nd phase of the ESP started, modifications on the methods and project scope of work were made in response to the following challenges.

The first challenge was the complete demolition of the URL infrastructure in 2014 (loss of continuous electrical power, internet, and road to access the site). The original automated monitoring system was modified to an intermittent data monitoring system. Slow on-going evolution of the ESP meant that periodical data collection is sufficient to capture the behaviour of the shaft seal.

The second challenge to ongoing operation of the ESP was the risk of damage to the monitoring systems during and after the demolition. This was overcome by relocation of all the ESP monitoring system into a monitoring enclosure before the demolition. The monitoring enclosure is a non-permanent steel shed with a dimension of 2m x 2m x 2m (Figure 2). It was constructed using 12-mm-thick steel and placed near the main access shaft.

Other challenges were reduced operational budget, organizational changes, gradual failure of certain sensors and staffing attrition. They were overcome by selecting the sensors that are most suitable for long-term monitoring, engaging various stakeholders to support the project, and training new staff and ensuring continued access to key project personnel.



Figure 2 The monitoring enclosure near the main access shaft

3. Monitoring Results and Discussions

3.1 Instrumentations

One hundred (100) sensors were originally installed at strategically selected locations in the clay, concrete components and the host rock to monitor Thermal-Hydraulic-Mechanical (THM) responses of the seal during the 1st phase. Instrumentation consists of vibrating wire (VW), fibre optic (FO) and time domain reflectometer (TDR) sensors. These sensors measure temperature, hydraulic pressure, total pressure, displacements, concrete strains and clay saturation. Sixty four (64) of these sensors were intended to capture the early stages of seal evolution (temperature, concrete strain, and water content near the perimeters of the clay component).

The 2nd phase of the ESP (2014 to 2016) involves monitoring of the long-term behaviour of the shaft seal. Anticipated loss of automated sensor monitoring facilities and a limited operational budget, required that prioritizing of sensors to be monitored was necessary. As temperature and concrete strains were essentially unchanging after 2013, monitoring of the sensors measuring these parameters were terminated, although they were still fully functioning. Similarly, the psychrometers had all served their design function and were no longer providing useful information. Ongoing ESP monitoring was therefore reduced to the vibrating wire (VW) sensors (i.e., piezometers and total pressure cells), fiber-optic sensors (i.e., piezometers and total pressure cells) and TDR (Time Domain Reflectometer) sensors.

3.2 Monitoring Results

3.2.1 Temperature and Concrete Strain Monitoring

Most of temperature changes observed in the concrete and clay components occurred within three months of concrete placement. They were the result of heat of hydration generated during concrete curing and its subsequent dissipation through adjacent materials (rock and clay). The majority of the

strains observed in the concrete were due to these temperature changes. After the concrete curing and cooling was completed in March 2010, the temperature has stabilized at approximately 11-12°C. The concrete components were designed to provide mechanical constraint to prevent the clay component from swelling out of its as-placed location. It was anticipated and observed, that even though the concrete used was low shrinkage, there would be open interfaces between the rock and concrete.

3.2.2 Hydraulic Pressures

The hydraulic head differential across the seal is being measured using VW piezometers located outside of the clay-filled region. Figure 3 shows the hydraulic pressure measured in the region immediately below the clay component (VWPZ02) and the free-standing water above the seal (VWPZ10). The data for the piezometers used in this comparison are elevation-adjusted to the lower concrete-clay contact and the upper concrete-clay contact and the pressure difference between upper and lower concrete-clay contacts is shown in Figure 3. Increase of the groundwater level below the seal (VWPZ02 in Figure 3) did not match the pressures that would be generated as the result of flooding of the upper shaft (VWPZ10). The lower shaft apparently has a higher piezometric head than attributable to the standing head of water in the shaft, the only explanation to date would be a connection of the lower shaft to FZ2, which would have a higher piezometric head than is present in the upper shafts.

As of December 2015, a substantial pressure differential (~156.9 kPa, ~16 m) still exists across the 6-m-thick clay portion of the seal, which indicates the connection between the upper and lower shaft regions is limited as any open connection(s) between the upper and lower shaft would result in loss of this pressure differential. The results are important to repository closure planning and developing confidence in the functionality of shaft seals.

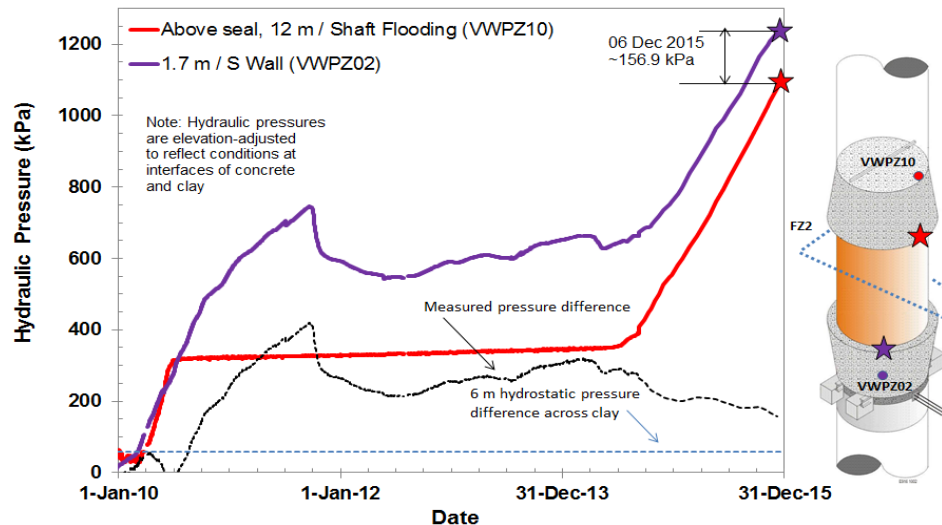


Figure 3 Hydraulic pressure above and below the clay component of the seal

3.2.3 Groundwater Level

The vibrating wire piezometer VWPZ10 at the top of the shaft seal measures the hydraulic pressure at the top of the seal and the groundwater level above the seal (Figure 4). The system developments associated with changes in the slope of the hydraulic pressure-date graph in Figure 4 are as follows: In June 2010, the lower shafts were completely flooded and the flooding of the large volume of 240 Level begun. Above this point, the groundwater level at the main shaft and vent raise were connected

and simultaneously increase. In July 2014, the 240 Level was completely flooded and water began to rise in upper shafts.

As of December 2015, the hydraulic head at the top of the seal was approximately 1571 kPa, corresponding to a groundwater level of approximately 160 m depth, which was some 74 m above the top of 240 level excavations (Figure 4). At this level, the cross-sectional area used to calculate the inflow rate is well defined and equal to the sum of the main shaft rectangular area ($3.1 \times 5.1 \text{ m}^2$) and the vent raise circular area (i.e., a diameter of $\sim 1.8 \text{ m}$). The inflow rate at the end of 2015 was estimated at approximately $3 \text{ m}^3/\text{day}$, lower than the $\sim 4.3 \text{ m}^3/\text{day}$ inflow rate estimated after seal installation but before the 240 level of the URL was closed in 2009 [6]. Ultimately the groundwater level should recover to the pre-URL excavation conditions of 1980 ($\sim 20\text{-}25 \text{ m}$ below the surface). It has been observed that the inflow rate changes over time and is determined by a complex interaction of subsurface water-bearing features as well as seasonally and climatically affected surface and near-surface processes. Assuming a continued, constant inflow rate of $3 \text{ m}^3/\text{day}$, the groundwater level should return to its ambient level by 2019. Measuring the inflow rate will assist in understanding the long term evolution of the shaft seal and regional groundwater evolution.

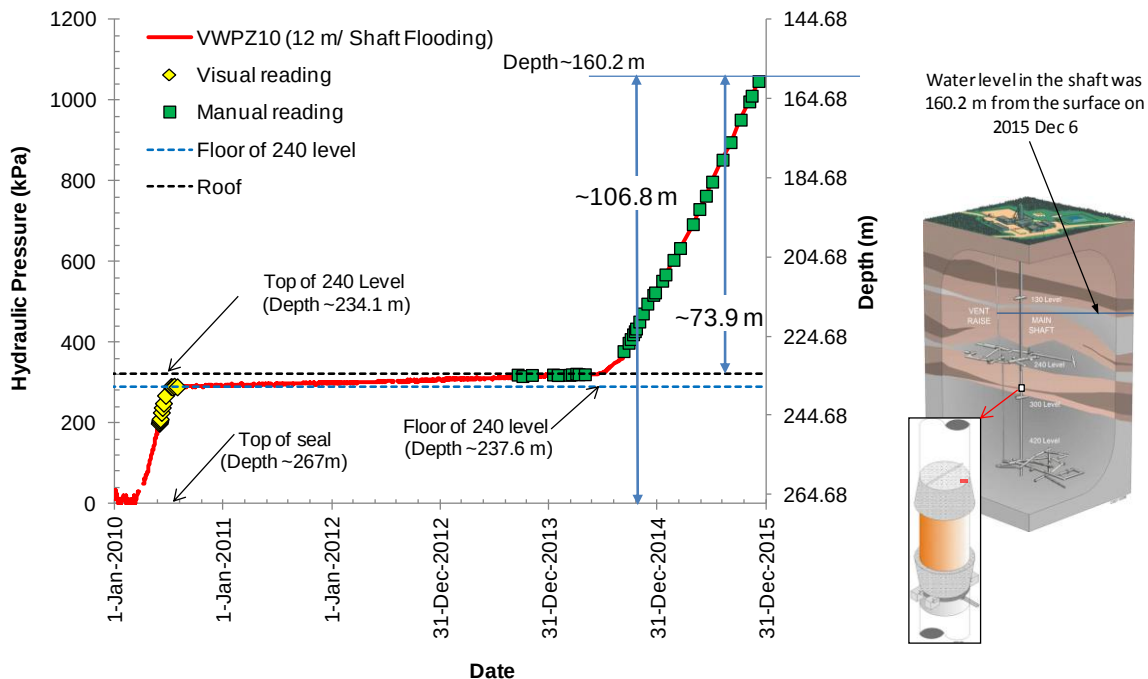


Figure 4 Groundwater level above the shaft seal

3.2.4 Water Uptake of Clay Component

Water uptake in the clay component was measured using two different types of sensors: Vibrating Wire (VW) Psychrometers and Time Domain Reflectometer (TDR) sensors. Figure 5 shows the TDR results. Psychrometers were used to measure the water uptake at several locations near the perimeter of the clay components and intended for short term monitoring. As expected most of the psychrometers indicated saturation had been achieved in 2013, allowing for discontinuing of monitoring in the 2nd phase.

Currently four TDR sensors are measuring water uptake along the central axis of the clay component. Figure 5 shows the data from TDR1 at the core of clay component, showing that the volumetric water

content at the core at the end of 2015 is approximately 30% or 86% degree of saturation. The volumetric water content at saturation is estimated to be 33-34%. Slow groundwater movement into the core regions of the clay component is expected as the result of the very low hydraulic conductivity in the clay component. Continuation of TDR monitoring is therefore very important to understand the saturation of the shaft seal. In 2015, a method to compare the results of TDR and psychrometer in the ESP was developed [5] and indicated that the information provided by both sensors were comparable.

The swelling pressure and hydraulic conductivity of the bentonite-based material (i.e., clay component) are dependent on the pore fluid salinity and density of the clay component, which may affect the sealing capability of the clay component. The clay component was designed based on the Effective Montmorillonite Dry Density (EMDD) concept [16]. At the depth between 500-1000 m, the TDS of salinity of the matrix groundwater at the URL was measured less than 50 g/L [17], but the groundwater infiltrating to the shaft seal is practically fresh water, because of artificial flooding done prior the seal installation. To be conservative, the design of the shaft seal assumed the groundwater salinity with TDS of 100 g/L and the clay component with as-placed dry density of 1.81 Mg/m³ will have 550 kPa swelling pressure and a hydraulic conductivity of 10⁻¹¹ to 10⁻¹² m/s, if the clay component is fully saturated and has homogeneous dry density [14]. As of December 2015, the clay component was not fully saturated and as a result the swelling pressure was still relatively low. Different mechanisms associated with system hydration and internal strain may also affect the swelling pressure recorded by the sensors. This process can be investigated through longer monitoring of the saturation of clay component combined with the THM numerical modelling.

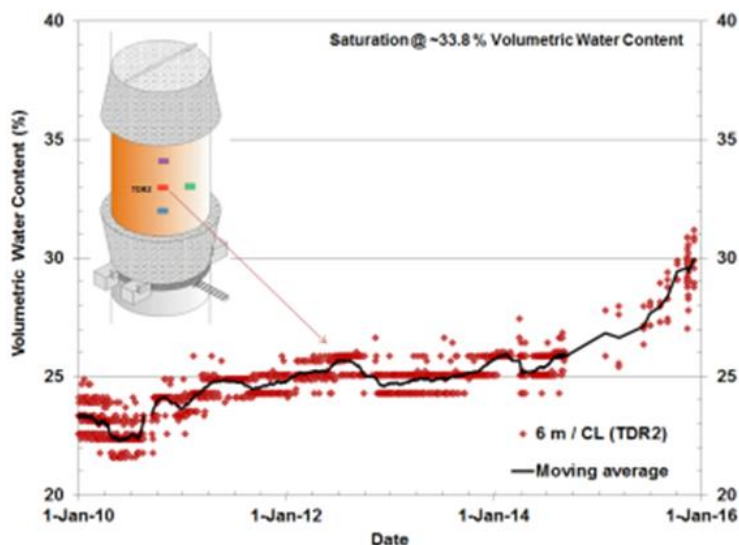


Figure 5 Water uptake measurements using Time Domain Reflectometer (TDR)

4. Preliminary Numerical Modelling

The ESP data combined with other data gained from the URL (e.g., hydrogeological monitoring data, geological features, rock properties) provide data sets suitable for numerical modelling. While not the focus of the ESP, preliminary models were developed with objectives to improve understanding of the mechanisms associated with shaft seal saturation and to develop numerical models that can be used to simulate long term behaviour of the shaft seal [5], [10-13].

Hydraulic-Mechanical (HM) modelling were done using COMSOL Multiphysics with Richard's equations and non-linear elastic deformation models. They use a simplified, 2D-axisymmetric model for the geology, with the boundary conditions and domain shown in Figure 6. The HM model includes 2 stages. Stage 1 simulated the hydraulic pressure of the shaft during the URL operations (~20 years) (Figure 7). During this period the groundwater pressure decreases around the fracture zone (blue colour indicates lower pressure in Figure 7). Stage 2 simulated the evolution of the shaft seal after its installation and up to 1,000 years in the future (Figure 8). The preliminary model indicates that saturation of the shaft seal is expected to be a long process, taking approximately 50 years.

The preliminary models described here are not intended for predictions for long-term behaviour but rather to develop confidence in the ability to capture the processes involved. They are recognized as being limited as they assume that the rock-clay interface was perfectly sealed immediately after seal installation (known to be inaccurate based on field measurements). Additionally, mechanisms such as hydraulic interaction between main shaft and vent raise were not simulated.

The actual hydrogeological features at the URL are available and can also be included for further numerical modelling. As more ESP monitoring data becomes available, the development of more accurate models to simulate the long-term behaviour of the shaft seal can occur. These models may include: 3D-geometry models with more accurately defined geological features, interaction between two seals in the main shaft and vent raise, improvements on constitutive models or hydraulic-mechanical (HM) formulations, and comparison with other computer codes.

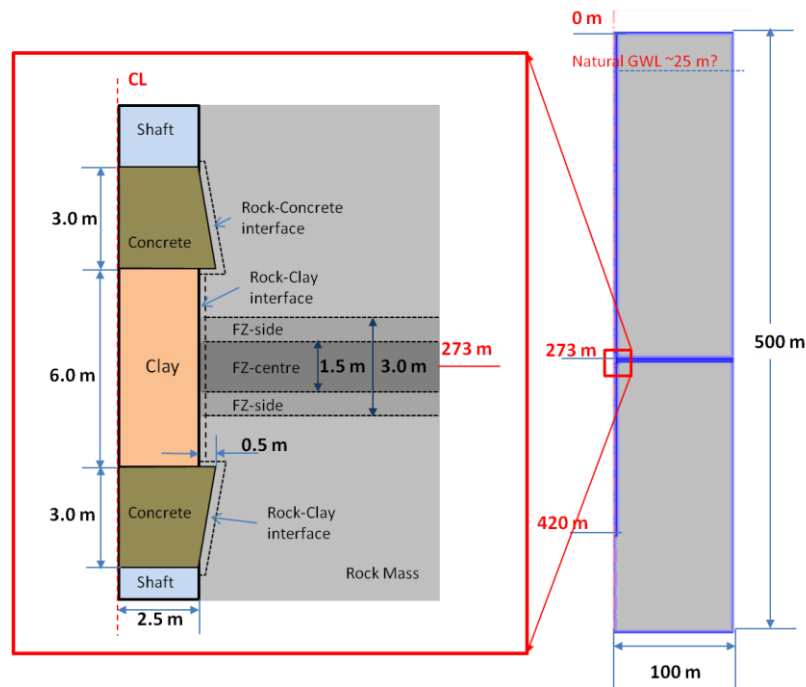


Figure 6 Model geometry and boundary conditions

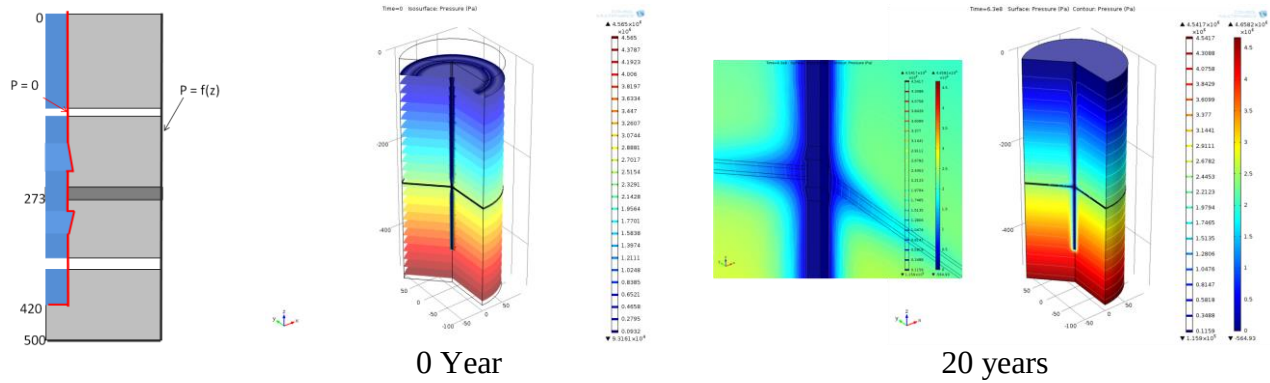
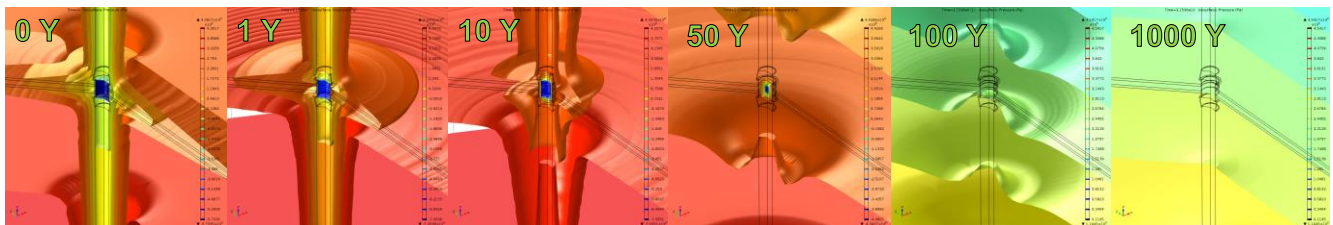
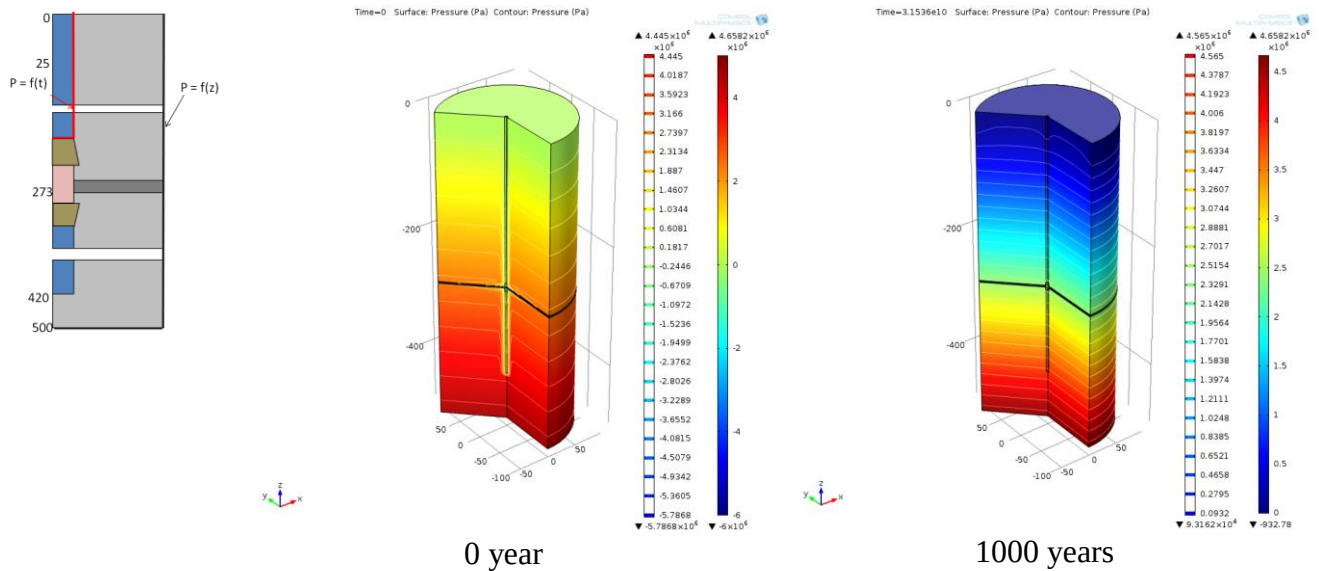


Figure 7. Results of Stage 1 Modelling



Evolution around the shaft seal

Figure 8 Results of stage 2 modelling, after seal installation

5. Concluding Remarks

- After 7 years of operation (2009-2016), the Enhanced Sealing Project (ESP) is continuing to supply valuable information on the in situ evolution and performance of a full-scale shaft seal of the type

that could be used in a nuclear waste repository. As the project focusses on the behaviour of the engineered barrier system, the applicability of the study is less dependent on the host rock. Information gained from the project can also be used to aid in the development of non-vertical (room and tunnel) seals in granitic or alternative geological media and to assess their performance.

- As of December 2015, the shaft seal at the URL is functioning as intended to limit the mixing of the groundwaters below and above Fracture Zone 2 (FZ2). Sufficient sensors were still available to provide monitoring coverage to the shaft seal.
- Ability to adapt to operational and organizational challenges were key to the success of the project after the demolition of the URL surface facility in 2014.
- Preliminary numerical simulations have improved understanding of the mechanisms dominating in the shaft seal, but still require further development in order to accomplish long-term prediction. This will be facilitated with extension of monitoring and incorporation of more detailed numerical descriptions of the geometry and boundary conditions.
- The large time gap between research-focussed installations such as the ESP, intended to support technological and safety assessment activities and implementation of them for a DGR project highlights the need to plan for successful intergenerational knowledge preservation. The ESP with its international partnerships and ongoing publication of results provides a way to accomplish this knowledge preservation.

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