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Numerical modelling of a large-diameter sealing structure in a deep radioactive waste repository

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There is a consensus that deep geological disposal is one of the most appropriated solution to store radioactive waste, and that argillaceous rocks have great potential as possible geological host formation. In this context, The French National Radioactive Waste Management Agency (Andra), is leading the design of a deep geological radioactive waste repository to be located in the Callovo-Oxfordian claystone (COx), at about 500 m depth (Cigéo project).

Radioactive waste disposal aims to protect the environment over a period of several thousands of years. For this purpose, these facilities are designed following the multi-barrier concept, in which engineered and natural barriers are combined, each one providing a degree of safety to the overall system [1]. The long-term safety of Cigéo relies on the COx claystone, the natural barrier that plays the main role, and also on the so-called sealing structures. These structures, installed after the operational phase at some key positions in shafts, ramps and horizontal galleries, are intended to limit the flow of water and the migration of radionuclides to the biosphere, ensuring the post-closure safety over the entire storage life.

Excavation of underground drifts generally causes damage to the rock around the openings [2]. Controlling the preferential pathways of groundwater through the fractures generated by excavation is a key objective related to the long-term safety of a radioactive waste repository. The sealing structures should be designed not only to seal the drifts so that they do not become preferential radionuclide migration pathways, but also to reduce the permeability of the excavation-induced damaged zone (EDZ) to a low value, re-creating conditions similar to those of the intact host rock.

Andra's current sealing concept for large diameter galleries (~ 10 m) is based on the installation of a confined expansive bentonite-based sealing core occupying the entire cross-section area (Figure 1(a)). The expansive core will be confined by two concrete plugs placed at both ends and the remaining section of the gallery will be filled with a backfill consisting of disaggregated and recompacted excavated COx. Swelling under confined conditions leads to the development of a swelling pressure that the core exerts on the surrounding materials. In this way, as the sealing core is saturated, the EDZ will be gradually compressed by the increasing swelling pressure, favoring the self-sealing of existing fractures, and leading to a gradual recovery of the rock low permeability [3]. The sealing core will also exert a pressure on the concrete plugs. As a result, the plugs will slide, compressing the backfill and releasing some of the swelling pressure in the core. The performance of this type of solution therefore relies on the development and long-term stability of the core swelling pressure, which is strongly related to the stability of the entire system.

Numerical simulation is a potentially useful tool for a better understanding of the behaviour of these engineered barriers. This work aims to assess numerically the phenomenology underlying the response and performance of large diameter sealing structures under real disposal conditions. The simulations presented address the complexity of the problem by considering large scale 3D geometries including the main components of the sealing structure (Figure 1(b)), realistic and advanced constitutive models, complex hydro-mechanical (HM) coupled formulation, and key geometric details at decimeter scale such as lining and interfaces between the different components.

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Simulations were carried out with the finite element code CODE_BRIGHT [4]. Particular features of the models include:

a) advanced constitutive laws to capture the non-linear time-dependent anisotropic response of the COx claystone;

b) the development of the fractured zone around excavations;

c) the multi-scale expansive response of the bentonite-based core material.

Physico-chemical processes between bentonite and the nearby materials that could affect the long-term sealing performance, and gas pressurization due to degradation and corrosion of the support elements are not considered at this stage of the work.

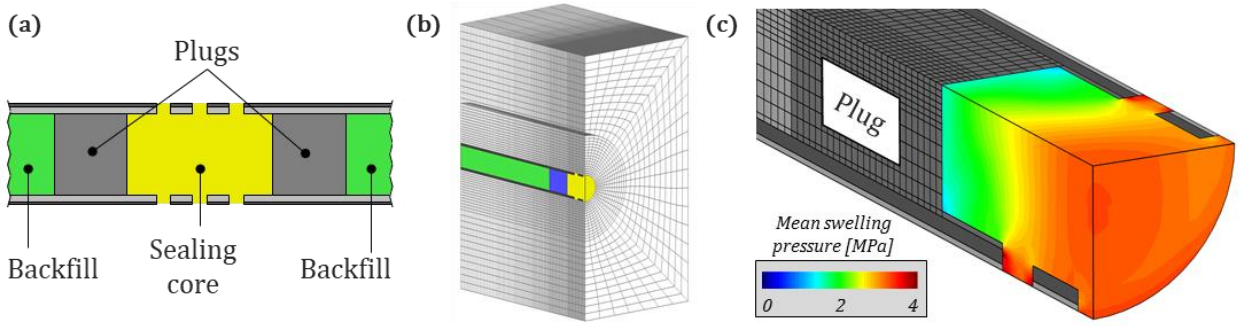

Figure 1: (a) sealing structure overview (b) 3D numerical model (c) mean swelling pressure after seal saturation.

These challenging simulations have provided qualitative and quantitative results on key aspects of the performance and long-term integrity of the current sealing concept in the Cigéo facility. From a practical point of view, the performance was evaluated considering the response associated with the capability of the core to reach full saturation at all points and to develop the target swelling pressure as uniformly as possible, the capacity of the stabilizing components (plugs and backfill) to provide long-term stability, and the capability of the sealing core to recompress the EDZ. The influence of the plug-lining interface shear strength was particularly examined.

Results show that the sealing core reaches a full saturation state around 2000 years after its construction, and that final hydro-mechanical equilibrium with hydrostatic conditions and the supporting elements is reached after an additional 1000 years. During this period, the plugs move around 0.5 m in the longitudinal direction due to the pressure exerted by the expansive core. As a result, the expansive core density and swelling capacity reduce due to deconfinement (Figure 1(c)). Despite this, the central part of the core maintains a swelling pressure within the admissible design range: the value of radial swelling pressure obtained is around 3 MPa (≈ 75% of the target swelling pressure). During the post-closure phase, the EDZ is recompressed by the swelling of the core and part of the initial stresses are recovered.

Contributor statement

Matias Alonso: Investigation, Software, Visualization, Writing. Jean Vaunat: Conceptualization, Funding acquisition, Supervision. Jean Talandier: Conceptualization, Supervision. Minh-Ngoc Vu: Conceptualization, Supervision. Antonio Gens: Conceptualization, Funding acquisition, Supervision. Sebastià Olivella: Software, Supervision.

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