

Effect of Pore Fluid Chemistry on the Hydro-mechanical Behaviour of Poorly Indurated Boom Clay

Hassan AL MAIS^{1,2,3*}, Yujun CUI², Xiangling LI³, Elie VALCKE³, Suresh SEETHARAM³, Temenuga GEORGIEVA³, Frédéric COLLIN¹

¹Liège University, 1 2 Allée de la Découverte, Liège, Belgium

²Ecole Nationale des Ponts et Chaussées, 6-8 Avenue Blaise-Pascal, Champs-sur-Marne, France

³SCK-CEN, 200 Boertang, Mol, Belgium

*Corresponding author: hassan.almais@uliege.be
hassan.al-mais@enpc.fr

Summary

In the context of deep geological disposal of radioactive waste, particular attention is required for intermediate-level bituminized waste such as Eurobitum, which contains high concentrations of soluble salts, mainly sodium nitrate (NaNO_3). Groundwater infiltration over time is expected to cause Eurobitum swelling and the release of a concentrated saline plume, potentially inducing chemo-hydro-mechanical (CHM) disturbances in the surrounding Boom Clay (BC) formation. This study uses 2D finite element simulations LAGAMINE with the ACC2-Chem model to evaluate the CHM response of Boom Clay at the repository scale across four phases: excavation, drainage, equilibrium, and swelling with saline diffusion. Swelling is modeled by imposed radial displacements on the liner, and chemical effects by diffusion of a saline plume. Despite conservative assumptions, the results—pore pressure, displacement, stress changes, and stress paths—help improve understanding of CHM couplings and the long-term performance of Boom Clay.

1 Introduction

The deep geological disposal of intermediate-level bituminized radioactive waste requires careful assessment of long-term interactions between the waste, engineered barriers, and host clay formations. A key concern is the presence of high sodium nitrate (NaNO_3) concentrations in bituminized waste, which can trigger significant system changes upon groundwater infiltration, leading to waste swelling and release of a concentrated saline plume.

These processes may induce coupled chemo-hydro-mechanical (CHM) perturbations in the surrounding Boom Clay—considered a reference host rock in Belgium—altering its hydro-mechanical properties and causing stress redistribution. To evaluate these interactions, two-dimensional simulations were performed using the THM finite element code LAGAMINE [1] and the ACC-2 constitutive model [2], enhanced in this study to include cohesive behavior and elastic chemo-volumetric effects. Model parameters were calibrated using experimental data [3, 4, 5].

The repository evolution was divided into four phases: excavation, drainage, equilibrium, and long-term swelling with saline diffusion. Swelling was simulated by imposing radial displacements on the intrados of the concrete liner, while saline solution concentrations were imposed in the perturbed zone during the swelling phase and subsequently modeled as diffusing throughout the entire domain. Though the chemical load was intentionally amplified (up to 3 m penetration and saline solutions of 1.0–2.0 M; [3]) to provoke measurable responses, actual affected zones are expected to remain below 0.2 m. Results—including pore pressure, stress, displacement, and stress path evolution—provide insight into Boom Clay's long-term CHM behavior under repository-scale conditions.

2 2D Plane Strain Modelling

2.1 Geometry

Figure 1 shows the two-dimensional plane strain model representing a vertical cross-section of a single gallery within a gallery network spaced 50 m apart. Due to symmetry, the model covers 25 m in width and 50 m in height. At its centre lies a cylindrical excavation zone with a 1.5-meter inner radius, corresponding to the space for five Eurobitum drums [6]. This gallery is lined with a 0.3-meter-thick concrete shell, yielding an outer radius of 1.8 meters. An over-excavation of 0.075 meters is included to simulate clay convergence prior to liner installation. A 3-meter-thick disturbed zone surrounds the liner to represent the region affected by chemical diffusion and waste swelling, bringing the total modelled radius to approximately 4.875 meters. The domain is discretized into 1,800 quadrilateral elements, with mesh refinement near the excavation and perturbed zone to resolve steep chemo-hydro-mechanical gradients.

2.2 Initial & Hydro-Chemo-Mechanical Boundary Conditions

The model assumes homogeneous, isotropic Boom Clay fully saturated at a depth of 225 m. Initial conditions include a vertical stress of 4.5 MPa, pore pressure of 2.2 MPa, and a K_0 of 0.8, giving an initial horizontal effective stress of 1.84 MPa [7]. These stresses and pore pressures are directly prescribed (gravity not modeled), and the concrete liner is assumed dry (0 MPa pore pressure). Mechanical boundaries include fixed horizontal displacements on lateral edges and fixed vertical displacements at the bottom, ensuring plane strain symmetry. The rest are free to deform, except where loads or displacements are applied.

Hydraulic conditions assume saturation throughout. The top boundary maintains constant pore pressure, while all others are impermeable. The gallery wall is drained (0 MPa) during Phases 1–2, undrained in Phase 3, and fully fixed in Phase 4 to isolate mechanical effects.

Chemical conditions simulate radial diffusion of saline species from the gallery through a 3 m chemically perturbed zone. Though real diffusion is limited (~ 0.19 m, ~ 0.1 M), the model exaggerates this zone (to 3 m and up to 2.0 M) to intensify CHM effects and better evaluate system response.



Figure 1 Geometry of the 2D plane strain model representing the disposal gallery, including the concrete liner, perturbed zone, and surrounding Boom Clay formation: a) Drained and Equilibrium phase b) swelling & saline diffusion phase.

3 Numerical results

This section summarizes simulation results—pore pressure, displacement, and stress—along horizontal (AC) profile, and analyzes stress path at point B' located on the excavated wall in the horizontal direction to assess the separate and combined effects of swelling and chemical diffusion on Boom Clay's hydro-mechanical behavior.

3.1 Excavation phase

Figure 2(a) presents the evolution of pore water pressure, while Figure 2(b) shows the radial displacement along the horizontal profile during the excavation and drainage phases.

In terms of pore water pressure (Fig. 2a), the results indicate a general decreasing trend over time. The pressure drops to zero at the gallery wall due to drainage conditions imposed during excavation, and dissipation gradually propagates into the surrounding clay. As for the radial displacement (Fig. 2b), it remains -0.075 m at $R = 1.8$ m (the excavated wall) and $R = 25$ m (boundary CD), due to the mechanical constraints from the concrete liner and fixed horizontal displacement boundary condition, respectively. Between these boundaries, radial displacement increases with time as pore pressure dissipates. However, during the equilibrium phase, radial displacement starts to decrease over time, reflecting consolidation effects.

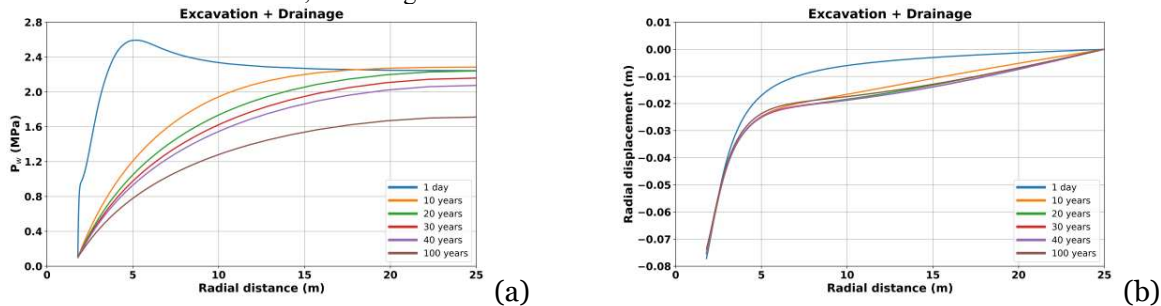


Figure 2 Evolution of (a) pore water pressure and (b) radial displacement along the horizontal profile during the excavation and drainage phases.

3.2 Equilibrium phase

Figure 3(a–d) presents the evolution of pore water pressure, radial displacement, radial stress (σ'_x), and orthoradial stress (σ'_y) along the horizontal profile during the equilibrium phase.

Regarding pore water pressure (Figure 3a), a re-equilibration process occurs, showing a trend opposite to that observed during the excavation and drainage phase: pore water pressure increases over time. The increase is most rapid during the first 10 years, then slows down, although it continues. Due to the low permeability of Boom Clay, full hydraulic equilibrium is only reached after a very long period—approximately 300 years.

The radial displacement (Figure 3b) gradually decreases with time during this phase. The final accumulated displacement at the excavated wall (point B', see Figure 2b) reaches up to 7.5 cm, mainly due to over-excavation effects.

As for the radial and orthoradial effective stresses (Figures 3c and 3d), both decrease over time, which can be attributed to the increase in pore water pressure and the ongoing re-equilibration process.

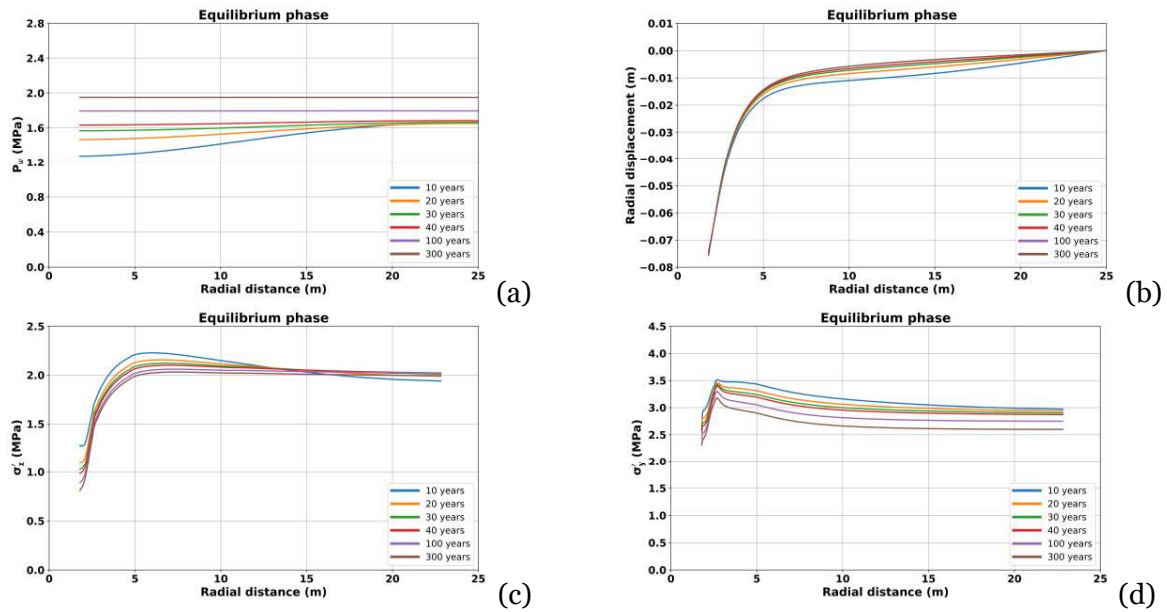


Figure 3 Evolution along the horizontal profile during the equilibrium phase — (a) Pore water pressure, (b) Radial displacement, (c) Radial stress (σ'_x), and (d) Orthoradial stress (σ'_y).

3.3 Swelling + Diffusion phase

Figure 4(a, b, c, d) shows the evolution of pore water pressure, radial displacement, radial stress, and orthoradial stress, respectively, along the horizontal profile during the swelling and diffusion phase.

Regarding the pore water pressure (Figure 4a), the results indicate that swelling causes an increase in pore pressure. However, no significant chemical effect is observed on this increase.

For the radial displacement (Figure 4b), it increases with time due to the imposed boundary condition. After 500 years, the maximum displacement is observed near the clay wall and decreases with radial distance. A slight effect of the saline solution appears after 500 years, as higher sodium concentration and solute occupancy induce a minor contraction of the clay. This effect is visible as a subtle downward trend in the radial displacement curves (shown with dotted lines).

This chemically induced contraction is also observed in the evolution of radial and orthoradial stresses (Figures 4c and 4d), where a decrease in stress values is noted. The stress reduction is attributed to the increase in chemical concentration, which weakens the mechanical response of the clay over time.

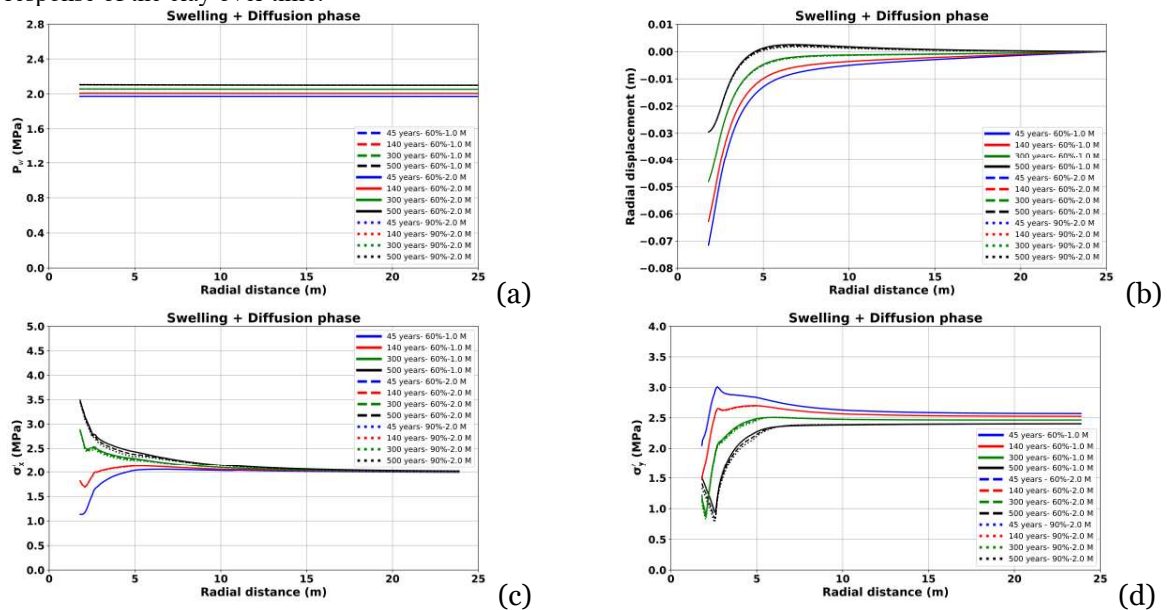


Figure 4 Evolution along the horizontal profile during the swelling and diffusion – (a) phase water pressure, (b) radial displacement, (c) radial stress (σ'_x), and (d) orthoradial stress (σ'_y).

3.4 Stress Path

Figure 4(a) presents the complete effective stress paths of the element located on the excavated wall in the horizontal direction (point B' in Fig. 1) for the different simulation phases under a diffusing 60%–1.0 M saline plume. The stress paths are shown in a p' - q plot, where p' represents the mean effective stress and q the deviatoric stress. During the drained phase, the mean effective stress p' increases gradually due to the dissipation of pore water pressure. In contrast, during the equilibrium phase, p' decreases progressively, indicating a reversal in the stress evolution trend. In the swelling phase, the stress path reflects the influence of swelling pressure: the deviatoric stress initially decreases, then increases within the yield surface. Once the yield surface is reached near the critical state line (CSL), the stress path evolves further due to hardening associated with the expansion of the inner yield surface.

Figure 4(b) focuses on the stress paths during the swelling and diffusion phase for three different saline concentrations. A slight variation between the stress paths is observed, which is attributed to the chemical effect induced by the higher salinity. This chemical influence leads to local shrinkage or compression of the clay matrix, slightly altering the stress state. However, the overall impact remains moderate, showing that chemical concentration has a small but noticeable effect on the mechanical response.

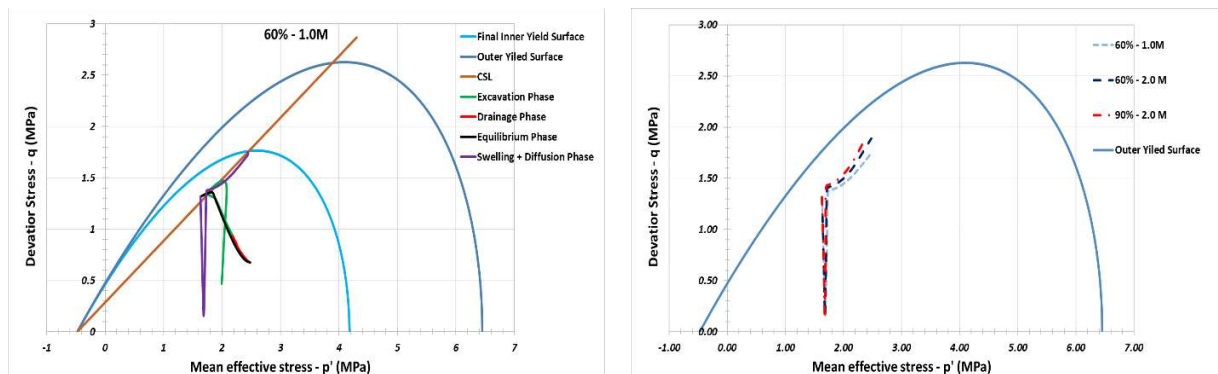


Figure 5 Effective stress paths at point B' in the horizontal direction: (a) Stress path evolution over all simulation phases for the 60%–1.0 M saline case; (b) Comparison of stress paths during the swelling and diffusion phase for different saline concentrations.

4 Conclusion

This study evaluates the long-term chemo-hydro-mechanical (CHM) behavior of Boom Clay surrounding bituminized radioactive waste using 2D finite element simulations with the ACC2-Chem model. The simulations cover excavation, drainage, equilibrium, and swelling with saline diffusion phases. Results show that excavation and drainage cause pore pressure dissipation and stress redistribution. In the equilibrium phase, slow re-saturation leads to stress reduction. During swelling and diffusion, mechanical effects dominate, while chemical effects from saline intrusion are minor but detectable. Overall, Boom Clay maintains its mechanical integrity under conservative chemical conditions, supporting its suitability as a host rock for deep geological disposal.

References

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