Effect of heating on clay formations: results of a THM modelling benchmark exercise on two heater tests in indurated and poorly indurated clays

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Abstract

In the framework of the European Joint Programme EURAD, the HITEC work package aimed at investigating the influence of thermal loading on the behaviour of clay-based materials. Three clay formations considered to host potential radioactive waste repositories were studied, the Callovo-Oxfordian (COx) claystone, the Boom Clay and the Opalinus clay as well as different types of bentonite used as engineered barrier. Through HITEC, a series of benchmarking exercises focusing on the clayey host formations were proposed to seven European modelling teams. The benchmark consisted in three consecutive steps, starting with 2D generic models to study the near-field and far-field effects of heating on the behaviour of clay rocks and then considering triaxial compression tests under elevated temperature on COx samples. The last step of the benchmark consisted in modelling two in-situ heating experiments: ALC1605 in the COx claystone and the large scale PRACLAY Heater test in the Boom Clay. In both cases, the teams successfully managed to reproduce the anisotropic response of the clay host rocks to excavation and heating. The evolutions of temperature and pore pressure were well modelled in the far-field with an anisotropic poro-elastic approach but this article highlights particularly how advanced models allowed to capture the processes occurring around the tunnels. In order to match best the measurements, these models required a dependence of the stiffness and permeability with the deformation. One of these advanced models was tested on both in-situ experiments and gave remarkably good results, even though the two clayey host formations have different hydro-mechanical properties. It illustrates a common understanding of THM processes in poorly indurated clay and in claystone and provides some keys for transferring knowledge from one clay formation to another.

Keywords

Claystone, poorly indurated clays, thermo-hydro-mechanical modelling, high-level radioactive waste disposal, in-situ heating experiments, benchmark

Highlights

- A modelling benchmark was organised in the framework of the HITEC work package of the European Joint Programme EURAD.

- Models managed to reproduce the anisotropic response of the clay host rocks to excavation and heating in two in-situ experiments.
- Temperature and pore pressure are well modelled in the far field with an anisotropic poro-elastic approach, but more advanced models are necessary to consider the processes occurring around the galleries.
- Good results were obtained on different formations with a single model, illustrating a common understanding of THM processes in poorly indurated clays and in claystone.

Introduction

The geological disposal of radioactive waste in clayey host formations is envisaged by several countries in Europe. Such disposal will however induce several disturbances in the host formations. In the near-field, the excavation process induces the convergence of the gallery and the formation of a network of fractures called the excavation damaged zone (EDZ) (Tsang et al., 2005, Bernier et al., 2007, Armand et al., 2014). This also induces some changes in pore pressure distribution (Armand et al., 2023a; Vu et al., 2020b, Bumbieler et al., 2021). The heating of a water-saturated claystone generates a pore pressure increase because of the large difference between the thermal expansion coefficient of water and that of the solid skeleton of the clay host rock (Campanella and Mitchell, 1968; Rice, 2006). This effect was studied by many authors as summarized in Villar et al. (2020, 2025) and has been especially highlighted on the COx and Boom Clay by theoretical analysis (Vu et al., 2020a), laboratory tests on samples (Baldi et al., 1991, Cui et al., 2000, Hueckel et al, 2009; Mohajerani et al., 2012), and in-situ experiments (De Bruyn et Labat, 2002; Armand et al., 2017; Conil et al., 2020; Bumbieler et al., 2021, 2024; Dizier et al., 2021). This overpressure may lead to formation damage or even fracturing (Li 2013, Braun et al., 2022; Plúa et al., 2024a, 2024b). The thermo-hydro-mechanical (THM) properties of the rocks may be derived from laboratory experiments on core samples, but numerical models are needed to assess their behaviour over very large periods of time. Modelling field heating experiments highlights that a poro-elastic approach captures well the fluid pressure measurement in the far field (away from the heat source) (Chen et al, 2011, Seyedi et al., 2021; Plúa et al., 2021). However, replicating the measurement in the near field (i.e. in close proximity to the heat source) requires advanced modelling approaches allowing to create an EDZ with its properties consistent with in-situ observations (Yu et al., 2021, Shao et al., 2025; Tourchi et al., 2021, 2023, Chen et al., 2023, Ouraga et al., 2024, Vu et al., 2025, Souley et al., 2026). Today, accurately capturing—and thus reliably predicting—the THM behaviour of clays in the near field of galleries remains a challenge. Although considerable progress has been made in recent years regarding THM coupling in clays, the dependence of key material parameters on temperature or deformation remains an issue that requires further investigation to fully develop advanced models. Only the analysis of full-scale in situ heater tests can help advance this understanding and improve insight into THM processes in the vicinity of gallery walls.

Within the European Joint programme EURAD on radioactive waste management (2019-2024), the HITEC work package focused on the influence of high temperatures on the behaviour of clay-based materials (de Lesquen et al., 2024; Villar et al., 2025). As part of the task investigating the effect of the thermal loading on clay host rocks, a series of benchmarking exercises were proposed to eight European modelling teams, based mainly on the concepts of radioactive waste disposals developed by Andra (Bumbieler et al., 2024) and ONDRAF/NIRAS (ONDRAF /NIRAS, 2020). In a first phase, the benchmark exercises concerned the modelling of synthetic cases simulating the THM behaviour of clay host formations in both the near and the far fields of heated galleries. The results of these synthetic cases were reported in Simo et al., 2025a and 2025b. The modelling of triaxial compression tests on heated samples performed during the experimental task was then proposed and some of the models were updated to take into account the observed reduction of strength at elevated temperature (Song, 2025; Souley et al., 2026). Finally, the benchmark exercises focused on the modelling of two full-scale in-situ heating experiments: the ALC1605 experiment performed in the Callovo-Oxfordian (COx) claystone (Bumbieler et al., 2024), and the PRACLAY Heater test in the Boom Clay (BC) (Dizier et al., 2021). The analysis of the modelling results for these two heater tests is presented in this article. After a description of these two heater tests in section 1, the results obtained for these two experiments are presented in section 2. Then, a comparison of the approaches followed by each modelling team is proposed in section 3 highlighting similarities and differences in the behaviour of indurated and poorly indurated clays submitted to a thermal load.

1. Full-scale in-situ heating experiments in clay host formations

1.1 ALC1605 experiment in the Callovo-Oxfordian (COx) claystone

1.1.1 Short summary of the experiment

The ALC1605 experiment is a full-scale representation of a single high-level waste disposal cell based on the French concept. It is an on-going heating experiment (at the time of writing) conducted at the Meuse/Haute-Marne underground research laboratory (MHM URL). The experiment consists of a 28.5 m long micro-tunnel, 920 mm in diameter, excavated on 14 November 2018 using a laser-guided micro-tunnel boring machine (TBM). The micro-tunnel is lined with thirteen interlocked steel sleeve elements, each 2 m long. The sleeve is made of API 5L X65 steel, with an outer diameter of 762 mm and a thickness of 25.4 mm. The annular gap between the rock wall and the sleeve was filled with an alkaline cement grout, designed to neutralize the acidic transient caused by COx oxidation during excavation.

Five electrical heaters, each 3 m long and 508 mm in outer diameter, were installed between 10 m and 25 m along the sleeve, referred to as the heated zone (shown in purple on Figure 1, left). The heating system operates through power regulation, with the main heating stage initiated on 8 June 2020 at a power of at 220 W/m (Figure 1, right). Prior to this stage, a short low-power heating test was conducted in March 2020 at 33 W/m. A steel plate was installed at the head of the micro-tunnel on 24 February 2021 in order to reduce convection phenomena in the casing (timepoint shown by the second dotted line of Figure 1, right).

The ALC1605 experiment investigates: (i) the thermomechanical behaviour of the steel sleeve, and (ii) the THM behaviour of the COx. To this end, the sleeve was instrumented on both its inner and outer surfaces, while the COx response was monitored by nine peripheral boreholes equipped to measure temperature and pore pressure in the mid- and far-field (Figure 1, left).

Peripheral observation boreholes were oriented both parallel and perpendicular to the micro-tunnel axis in order to investigate the anisotropic response of the COx claystone during both the micro-tunnel excavation and the subsequent heating stage. Further details on the instrumentation and measurement interpretation are provided by Bumbieler et al. (2024).

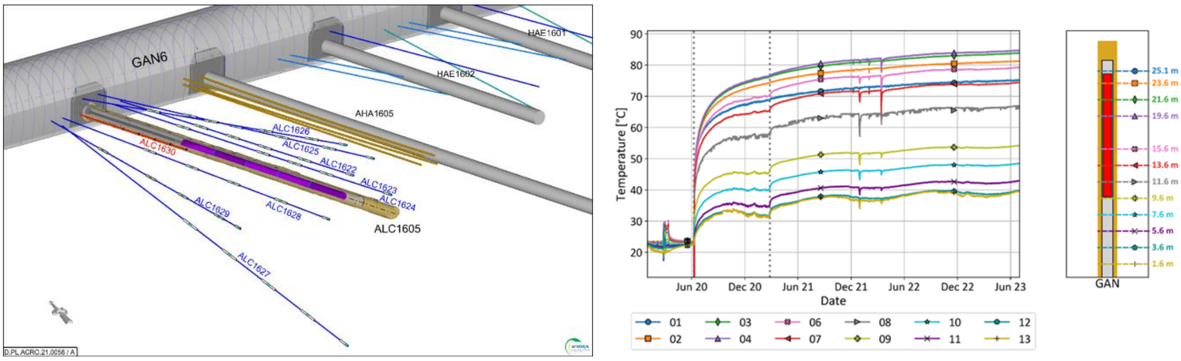

Figure 1 ALC1605 setup and heating history (Bumbieler et al., 2024)

1.1.2 Modelling tasks

The modelling aimed to reproduce the THM response of the COx. It began with a blind prediction of temperature and pore pressure evolutions, considering the material parameters proposed in the previous benchmark steps carried within the HITEC project (Simo et al., 2025a) and previous studies (Seyedi et al., 2021, Tourchi et al., 2021), and continued with interpretative modelling to improve the results. Five teams participated in this modelling exercise: Andra, BGE, EDF, LEI and ULiège.

The geometry included the micro-tunnel, the backfill in the annular gap, the steel sleeve, and the access drift. In some models, two neighbouring non-heated micro-tunnels were also included to assess their hydromechanical influence. The effect of peripheral boreholes was neglected and measuring chambers were represented as observation points.

The simulation considered three stages: (i) access drift excavation, (ii) excavation of the ALC1605 micro-tunnel, and (iii) heating over a period of 3 years.

1.2 The large scale PRACLAY Heater test in the Boom Clay (BC)

1.2.1 Short summary of the experiment

The PRACLAY gallery was excavated in 2007 at the HADES URL (Mol, Belgium), which is managed by EURIDICE. This 45-m-long gallery hosts a large-scale heater test aimed at simulating the effects of heat-emitting radioactive waste on clay.

The heated part of the gallery is 34 m long and is separated from the non-heated part by a hydraulic seal. After the installation of the seal in 2010, the heated section of the gallery was backfilled with sand, saturated, and pressurised with water. The seal is not intended to be representative of a geological disposal facility seal. Instead, its role is to reduce the permeability of the surrounding clay in the seal contact zone, thereby hydraulically isolating the heated section from the non-heated section (Figure 2). To achieve this, bentonite clay was used because of its high swelling capacity upon hydration. This swelling helps to maintain the high pressure inside the PRACLAY gallery and to ensure quasi-undrained conditions in clay. In this way, the test is designed to be representative of a generic disposal gallery for heat-emitting radioactive waste, rather than to exactly simulate the conditions expected for the current repository design.

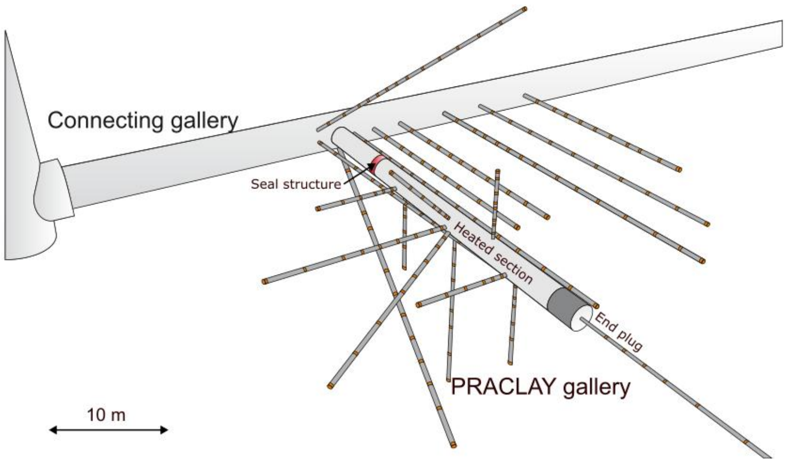

Figure 2 *Overview of the PRACLAY In-Situ Experiment, including the component of heater test. The PRACLAY gallery has an inner radius of 0.95 m and the thickness of the lining is 30 cm (Adapted from Dizier et al., 2021)*

The heating system consists of a primary heater, attached to the gallery lining, and a secondary heater, which is placed in a central tube that rests on a support structure. A control system regulating the heating power as a function of measured and target temperatures is also part of the heating system. During the start-up phase, the power was increased in a controlled manner to limit the thermal gradient over the gallery lining. The heated part of the PRACLAY gallery is divided into three zones and the power input can be controlled independently in each of the three zones. In this way, the end effects can be minimized and a temperature field that is as uniform as possible can be created along the heated section.

The gallery was backfilled with sand (Mol M34) which was put in place by blowing it in a dry state into the gallery before September 2011. Subsequently, a total volume of about 43 m^3 of tap water was injected into this part of the gallery between January and May 2012. Saturation of the backfilled gallery was then naturally completed with the water flowing from the host Boom Clay into the gallery. The pore water pressure in the gallery gradually increased and after ~2.5 years it reached 1 MPa, and the backfilled PRACLAY gallery was estimated to be fully saturated. During the heating phase of the experiment, the pressure in the backfilled gallery evolves naturally without any human intervention (adding or subtracting an amount of water).

The PRACLAY In-Situ Experiment was intensively instrumented with about 1,100 sensors (piezometers, thermocouples, flat-jacks, vibrating wire strain gauges) (Verstricht et al., 2023). Instrumented boreholes were drilled from both the Connecting gallery (CG) and the PRACLAY gallery (PG) (Figure 2).

The heater was switched on on 3 November 2014 and operated at a constant power of 250 W/m in the three zones of the primary heating system. The power was then increased stepwise from 250 W/m to 350 W/m and subsequently to 450 W/m until the target temperature of 80 °C was reached at the Boom Clay–concrete lining interface. This temperature was kept constant by gradually reducing the power in the three zones. The evolution of the temperature and pore water pressure in the vertical and horizontal direction (monitored from a downward and horizontal borehole in the middle section of the heated gallery) is shown in Figure 3. The rate at which the clay temperature increases, depends on their position to the gallery axis. At 2 m, the temperature increased quickly during the start-up phase, but then this increase slowed down. Further away the increase was slower. More details about the large scale in-situ PRACLAY Heater test can be found in Dizier et al. (2021) and in Chen et al. (2023).

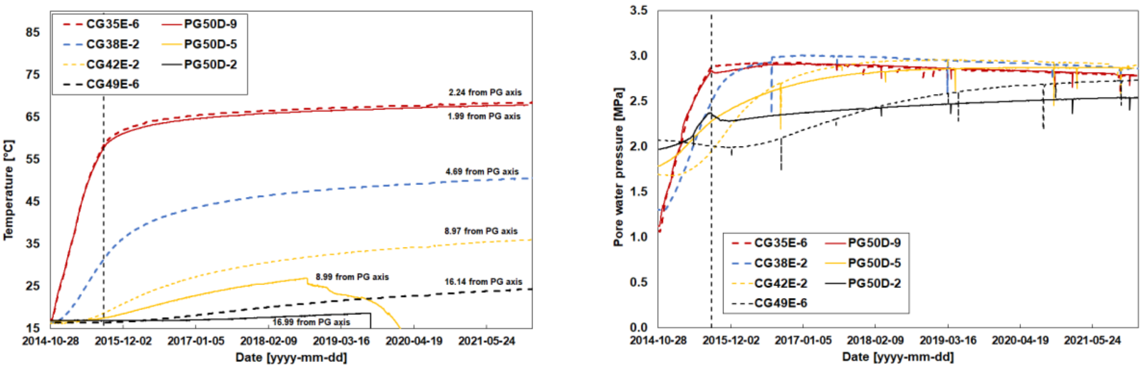

Figure 3 *Evolution of the temperature and pore water pressure around the PRACLAY gallery when the clay is heated at 80°C at the Boom Clay/ lining interface (solid lines for measurements in the vertical direction and dashed lines in the horizontal direction).*

1.2.2 Modelling tasks

The first modelling task consisted of performing a code-to-code comparison on an academic experimental case, in which the boundary conditions, constitutive laws, and thermo-hydro-mechanical (THM) parameters are fixed. Four teams participated in this modelling exercise: UPC, SCK CEN / EURIDICE, ULiège, and BGE. The results of this academic case served as a means of validation and verification between the different finite element codes.

In the second phase, a free modelling of the experiment was conducted with the objective of improving the understanding of the THM behaviour of the Boom Clay host formation under thermal loading. Unlike the first phase, where all constitutive laws and parameters were fixed, the teams in this phase were free to use their own modelling approaches and tools.

2. Main results of the benchmark exercise

2.1 ALC1605 experiment

Five teams participated in this modelling exercise. Andra, BGE and EDF developed 3D models including the casing, backfill, and access drift. LEI and ULiège adopted a 2D geometry corresponding to the mid-plane of the heated section, located 17.5 m from the access tunnel. The main features of each numerical approach are summarized in Table 1.

Table 1: Modelling teams, codes and main model characteristics used to simulate the ALC1605 in-situ experiment

Team	**Finite element software**	**Model geometry**	**Mechanical constitutive model**	**Excavation-induced fracture network**	**Power losses applied in the heated zone [%]**	**Hydraulic BCs on the micro-tunnel after excavation**
Andra	COMSOL Multiphysics	3D	Transversely isotropic elasticity	Explicit zone with high permeability	7.5 %	Null flow
BGE	OpenGeoSys / ANSYS OptiSlang	3D	Transversely isotropic elasticity	Strain dependent permeability model	15.5 % and reduced heat power applied in the non-heated zone: 14.5 %	Null flow
EDF	Code_Aster	3D	Transversely isotropic elasticity	Explicit zone with high permeability	10 %	Atmospheric pressure
LEI	COMSOL Multiphysics	2D (Plane strain)	Thermo-elastoplasticity with strength anisotropy	Explicit zone with high perm. + volumetric and plastic deformation dependent permeability model	20 %	Atmospheric pressure
ULiège	Lagamine code	2D (Plane strain)	Transversely isotropic elastoplastic and second gradient	Strain-dependent permeability and stiffness	33.3 %	Atmospheric pressure

Initial conditions were set to measured values at the main level of the MHM URL (Wileveau et al., 2007): major horizontal stress σ_{y0} = 16.0 MPa, minor horizontal stress σ_{x0} = 12.4 MPa, vertical stress σ_{z0} = 12.7 MPa, pore pressure p_{w0} = 4.7 MPa, and initial temperature T0 =

22.0 °C. On the micro-tunnel wall, pore pressure and stress were reduced to account for excavation-induced deconfinement. A heat power of 220 W/m was applied in the heated zone, with heat losses included to account for convective transfer inside the micro-tunnel.

During the blind prediction, most teams adopted a thermo-poro-elastic approach with transverse isotropy. Some variations were observed because the teams used different THM input parameters, from the first step of the benchmark (Simo et al., 2025a) or from published data on the previous ALC1604 experiment (Tourchi et al., 2021 and Seyedi et al., 2021). All the models reproduced the anisotropic trends observed in temperature and pore pressure data but generally overpredicted absolute values. In addition, pore pressure in the vertical direction was poorly captured and the models failed to reproduce the recovery phase during excavation, followed by the gradual dissipation observed during heating (Figure 4).

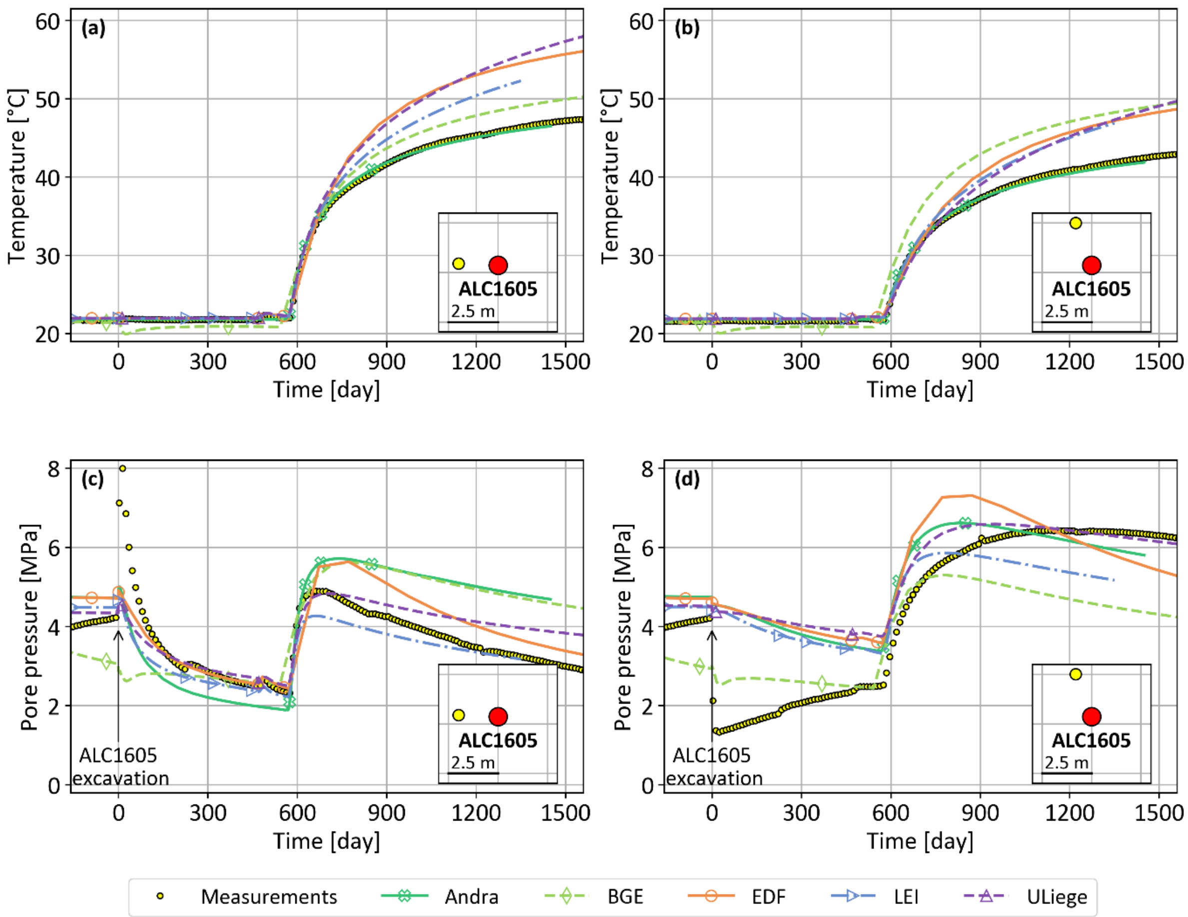

Figure 4 *Blind prediction: actual and modelled temperature and pore pressure at a distance of 2 radii from the heated micro-tunnel, parallel (left) and perpendicular (right) to bedding*

Interpretative modelling allowed the teams to refine their numerical results (Figure 5 to Figure 7). Heat power was reduced to account for convective heat transfer inside the micro-tunnel. In 2D models, higher power losses were applied to represent longitudinal heat flux in the out-of-plane direction. Thermal conductivity was also slightly adjusted in most cases to better match measured temperatures. For pore pressure, improvements were achieved by modifying the permeability within the excavation-induced fracture network. This was represented either by explicitly defining a high-permeability zone or by using permeability as a function of mechanical state; stiffness in this zone was also reduced.

In 2D models, atmospheric pressure was prescribed on the micro-tunnel wall to represent fluid flow in the out-of-plane direction. Both LEI and ULiège used an elastoplastic approach. LEI predefined an EDZ with reduced mechanical and hydraulic properties, using the geometry reported in Armand et al. (2014). During the HITEC project, ULiège also introduced an artificial EDZ with reduced properties, but they implemented afterwards the advanced THM constitutive modelling developed for the PRACLAY Heater test case, considering a dependency of both permeability and stiffness on the shear deformation (Song, 2025). These last results are shown here. Both teams also implemented the strength reduction with elevated temperature that was observed in the triaxial compression tests performed by Université de Lorraine on heated samples (Gbewade et al., 2024) and modelled during this benchmark (de Lesquen et al., 2024, Song, 2025). One should note however that the strength reduction due to heating may not be significant in this case as the maximum recorded temperature in the observation boreholes stayed below 50°C.

These refinements improved the reproduction of pore pressure parallel to bedding. However, pore pressure perpendicular to bedding remained difficult to capture as the models underestimated the recovery after excavation and the slow dissipation observed during heating, particularly in sensors closest to the tunnel.

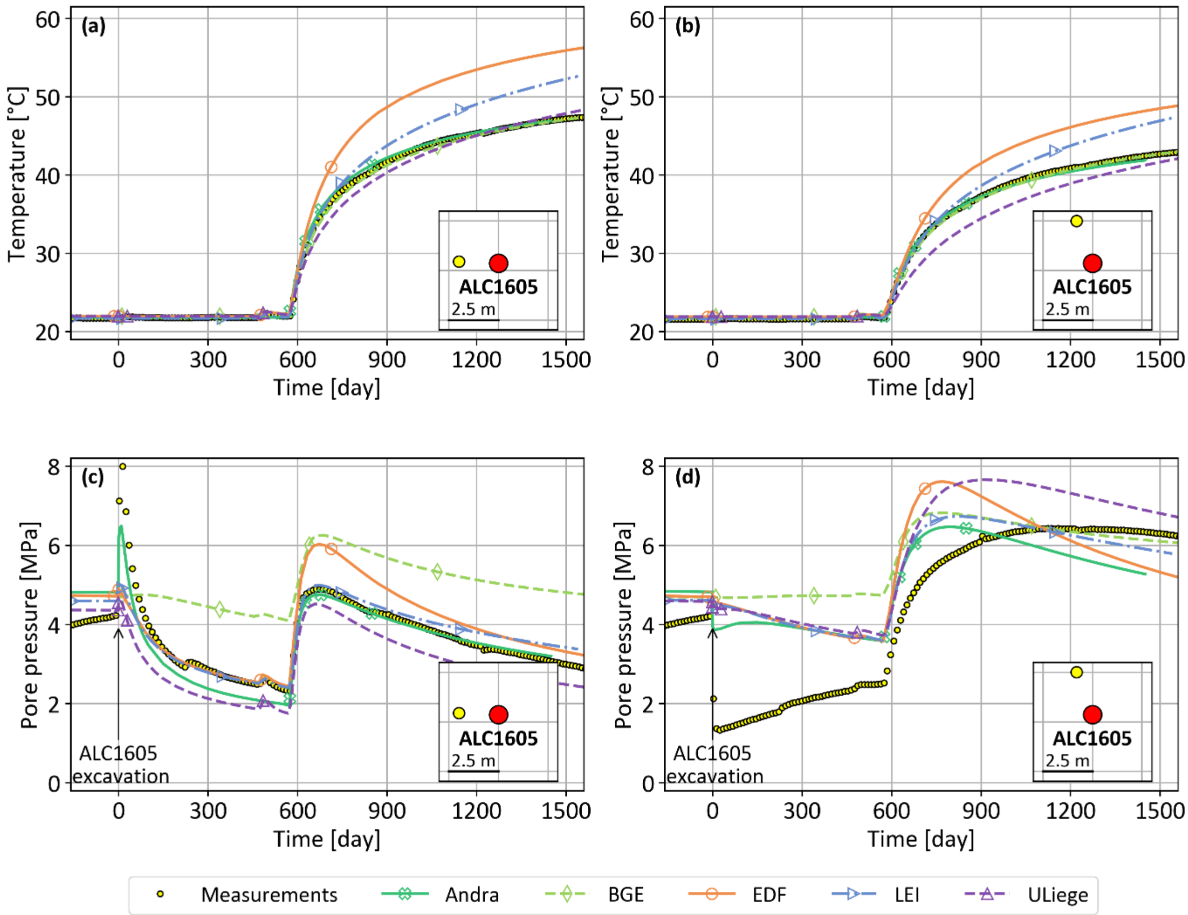

Figure 5 *Interpretative modelling: actual and modelled temperature and pore pressure at a distance of 2 radii from the heated micro-tunnel, parallel (left) and perpendicular (right) to bedding*

As none of the teams could match the pressure drop due to the excavation of the micro-tunnel, the thermal pressurisation plot on Figure 6 helps comparing the models output during the heating phase. One can see that the models predict generally the anisotropic response to heating, but a large dispersion in the results remains, especially in the perpendicular orientation. Only the ULiège model could match the pressurisation magnitude in both directions.

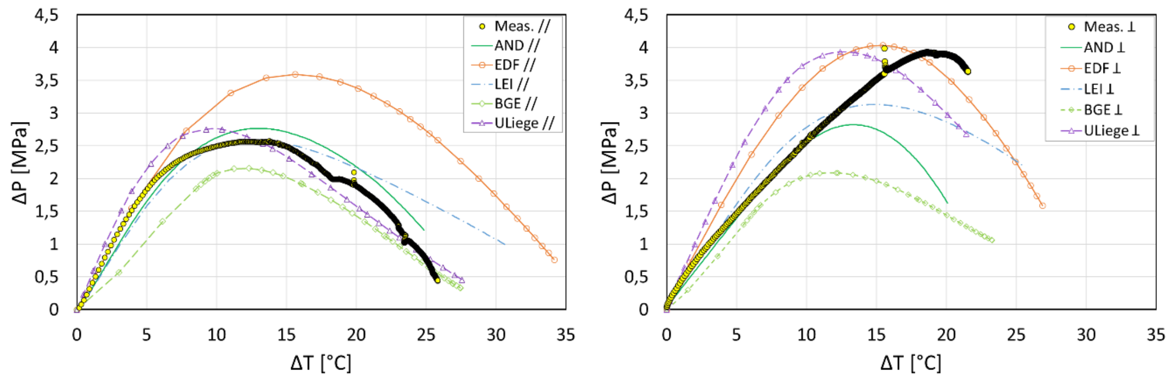

Figure 6 *Interpretative modelling: pore pressure increase vs. temperature increase at a distance of 2 radii from the heated micro-tunnel, parallel (left) and perpendicular (right) to bedding*

Further away from the micro-tunnel (Figure 7), models performed better for both temperature and pore pressure, as this zone is less affected by excavation-induced hydromechanical disturbance. This confirms that poro-elastic approaches provide acceptable results at greater distances from the micro-tunnel (models from Andra, BGE, and EDF). This is consistent with their use at the repository scale, as the most critical stresses and any risk of reaching tensile failure occur in the far field between disposal cells (Seyedi et al., 2021 and Simo et al., 2025b). Finally, far-field results obtained using 2D geometries with elastoplastic constitutive models (i.e., LEI and ULiège) were less affected by the null fluid flow and null thermal flux conditions in the out-of-plane direction.

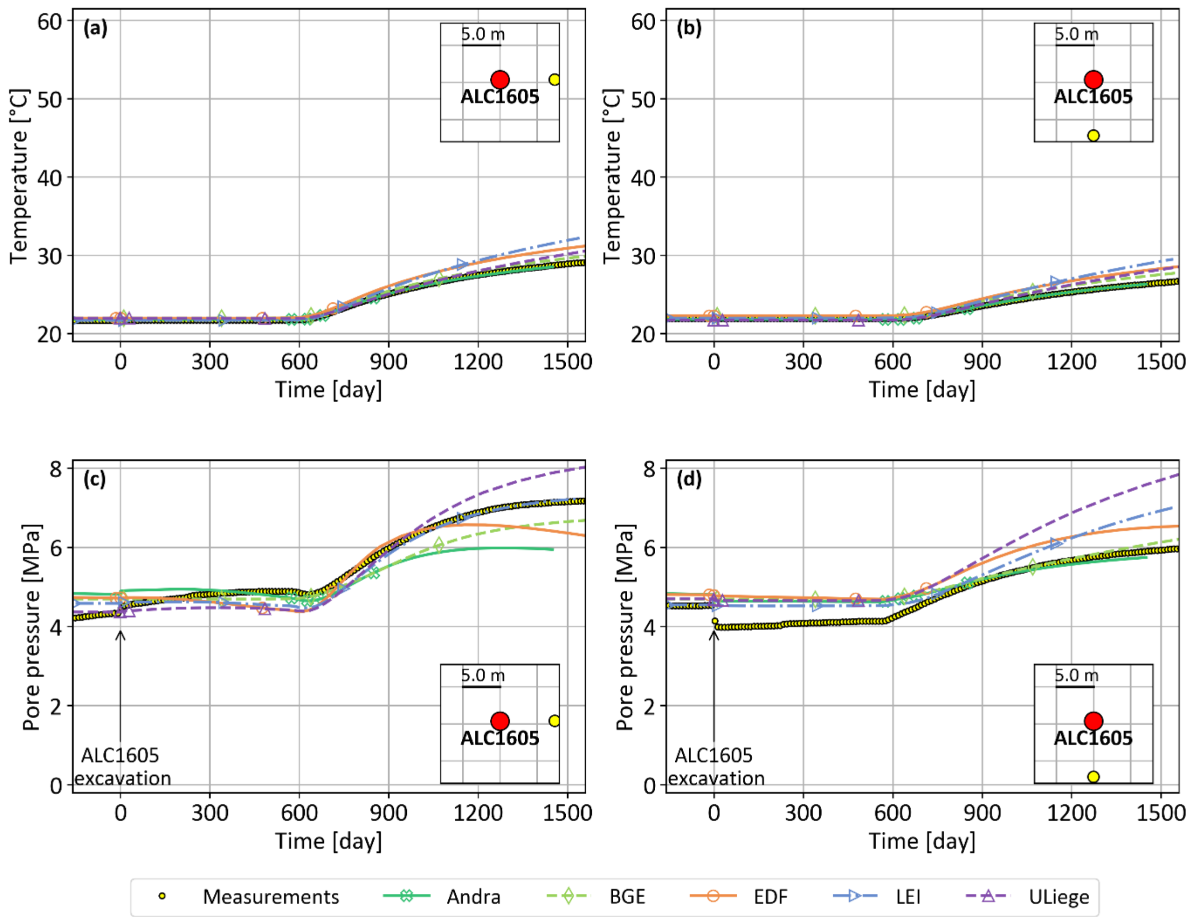

Figure 7 *Actual and modelled temperature and pore pressure in the far field, parallel (left) and perpendicular (right) to bedding*

2.2 The large scale in situ PRACLAY Heater test

Four teams modelled the large-scale PRACLAY Heater test: BGE, ULiège, UPC, and EURIDICE/SCK CEN. The benchmark exercise began with an academic case in which the constitutive law and parameters were fixed. The results of this initial step showed good agreement among the teams when modelling the experiment using the same constitutive assumptions. In all cases, the anisotropy of the mechanical and transport properties of the clay was considered, with anisotropic intrinsic permeability and thermal conductivity. The elastic behaviour was modelled using cross-anisotropic elasticity.

For the second phase, two teams — ULiège and UPC — went further by modelling the experiment using advanced tools. ULiège employed an isotropic strain-hardening Drucker–Prager elastoplastic model. An Excavation Damaged Zone (EDZ) with increased permeability was introduced, and the parameters of the undisturbed clay were optimized to better capture in-situ measurements. They also implemented a strain-dependent isotropic evolution of the hydraulic permeability tensor and a strain-dependent elastic modulus to reproduce the stiffness degradation curve (Song et al., 2025). UPC, on the other hand, used the advanced Hyperbolic Mohr–Coulomb (HMC) model (Manica 2018, 2021), which includes hardening–softening behaviour and a nonlocal formulation. They also applied the "air gap" approach to represent the contact between the host clay and the concrete lining.

Table 2: Modelling teams, codes and particularities in the modelling

Team	**Finite element software**	**Model geometry**	**Mechanical constitutive model**	**Permeability evolution**	**Artificial EDZ**
BGE	OpenGeoSys	2D PS	Drucker-Prager elastoplastic model	/	/
ULiège	Lagamine code	2D PS	Drucker-Prager elastoplastic model + strain dependent shear modulus	Strain dependent	Explicit zone with high permeability
UPC	CODE_BRIGHT	2D PS	Advanced Hyperbolic Mohr-Coulomb (HMC) constitutive model with hardening-softening and nonlocal formulation	Kozeny-Carman	/
EURIDICE	COMSOL Multiphysics	2D PS	Drucker-Prager elastoplastic model	/	/

The results of the first phase, with imposed parameters, showed that the temperature evolution is well captured by the modelling teams as it can be seen in Figure 8 with the results of ULiège. On the contrary, the pore pressure evolution is underestimated both horizontally and vertically during the heating phase as shown in Figure 9. The locations of the sensors mentioned in Figure 8 to 12 are given in Table 3

Table 3: Offset from the sensors to the Praclay gallery (PG)

Sensor	**Horizontal distance from PG**	**Sensor**	**Vertical distance from PG**
CG35	2.24m	PG50D-1	20.99m
CG38	4.69m	PG50D-2	16.99m
CG42	8.97m	PG50D-3	12.99m
CG49	16.14m	PG50D-4	10.99m
		PG50D-5	8.99m
		PG50D-6	6.99m

		PG50D-7	4.99m
		PG50D-8	2.99m from PG
		PG50D-9	1.99m from PG
		PG50D-10	1.49m from PG

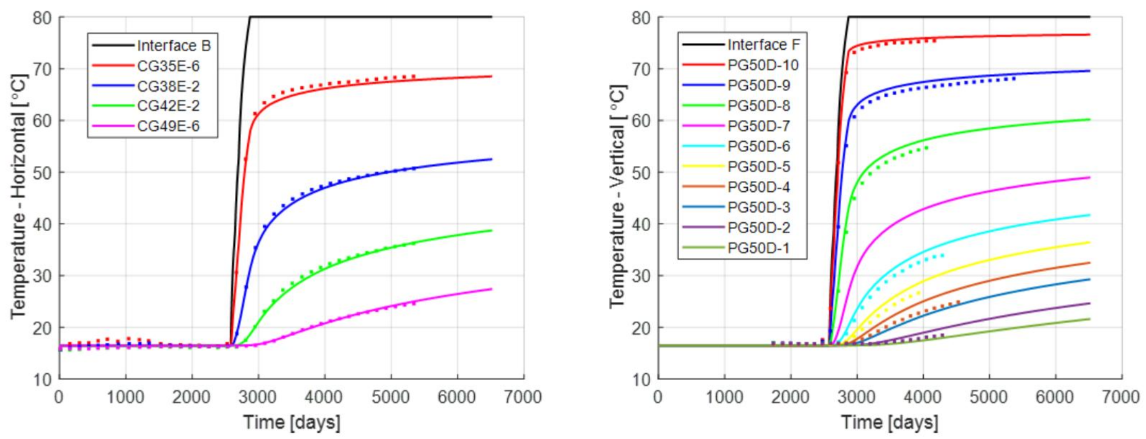

Figure 8 *Comparison between the experimental (dots) and the numerical (solid line) temperature evolution in the horizontal and in the vertical direction for the first case of the benchmark with fixed parameters obtained by ULiège in deliverable D7.6 (de Lesquen et al., 2024)*

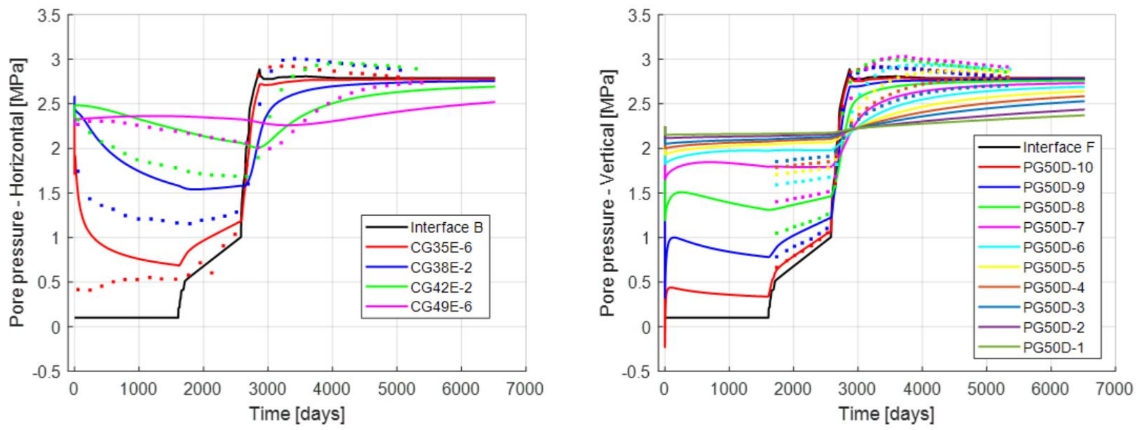

Figure 9 *Comparison between the experimental (dots) and the numerical (solid line) pore water pressure evolution in the horizontal and in the vertical direction for the first case of the benchmark with fixed parameters obtained by ULiège in deliverable D7.6 (de Lesquen et al., 2024)*

To understand the source of discrepancies between the experimental and numerical results, several modifications to the initial case were implemented. Figure 10 compares the experimental and numerical evolution of pore water pressure in the horizontal and vertical directions for a case in which an artificial EDZ is created around the tunnel, with permeability increased by a factor of 1.5 compared to the prescribed value, and where the stiffness outside the EDZ corresponds to the undisturbed Boom Clay stiffness as defined by Chen et al. (2023). This comparison shows that the evolution of pore water pressure during the heating phase is better captured in both the horizontal and vertical directions.

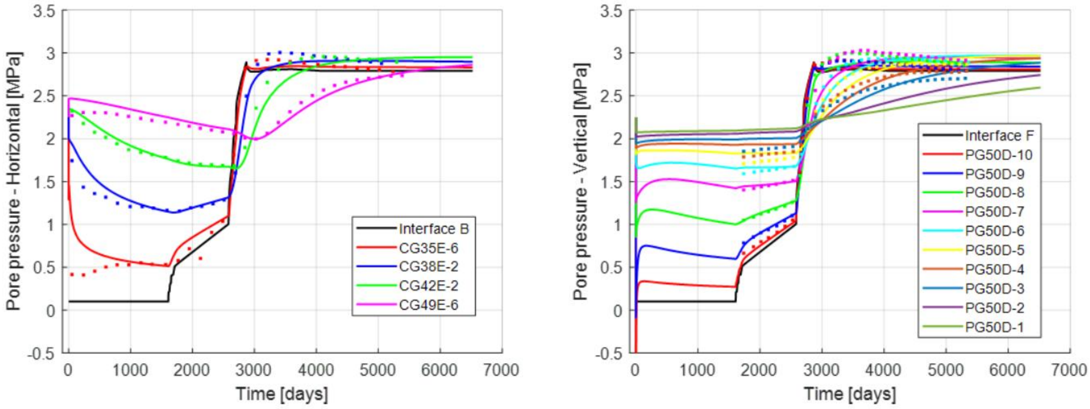

Figure 10 *Comparison between the experimental (dots) and the numerical (solid line) pore water pressure evolution in the horizontal and in the vertical direction obtained by ULiège when modifying the permeability and the stiffness of the clay host rock (with the use of an artificial EDZ)*

When implementing their advanced models, both teams (ULiège and UPC) successfully reproduced the anisotropic response of the clay host rocks to excavation and heating as observed in Figure 11 and Figure 12.

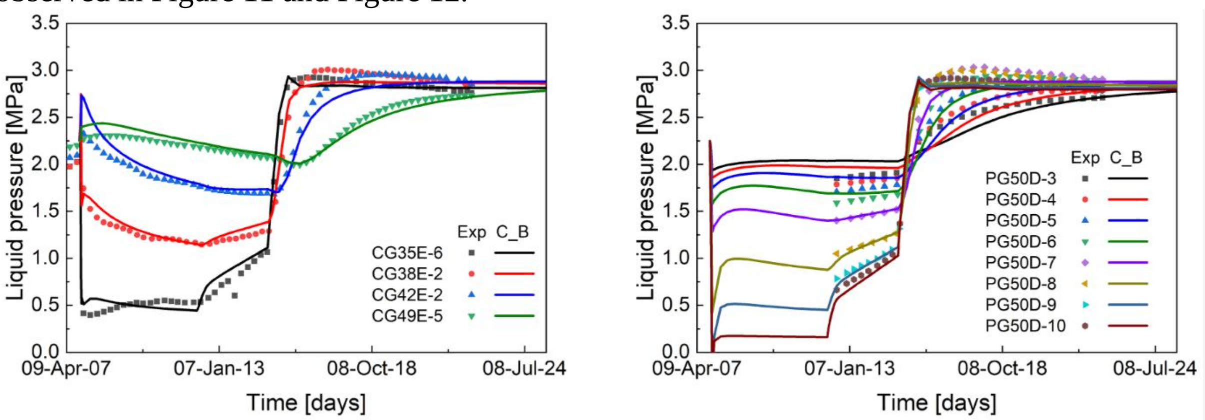

Figure 11 *Pore pressure evolution around the PRACLAY gallery in the horizontal and vertical directions obtained with the HMC constitutive model, comparison between the experimental (dots) and the numerical (solid line) results (UPC results in deliverable D7.6, de Lesquen et al. 2024)*

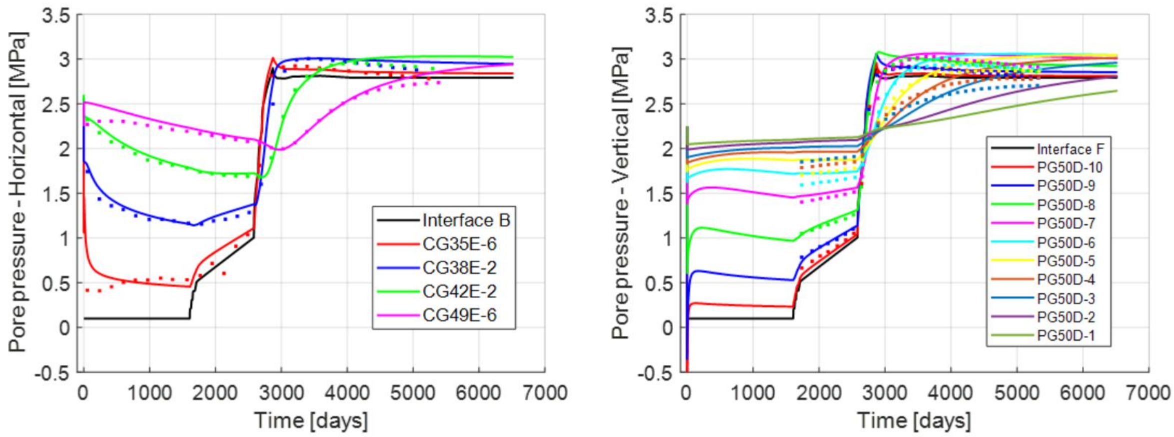

Figure 12 *Pore pressure evolution around the PRACLAY gallery in the horizontal and vertical directions depending on the permeability and stiffness modification as a function of the strain (Song, 2025)*

Overall, the evolution of temperature and pore pressure in the far field was well captured using a poro-elasto-plastic approach, and very consistent results were obtained with different finite element codes. This consistency increases confidence in the robustness of the models and their ability to support the design of deep geological repositories. More advanced models are however required to account for processes occurring near the tunnels, including changes in hydraulic and mechanical properties within the EDZ, their strain dependency and creep. The modelling exercises highlighted the key role of parameters such as the stiffness of both intact and damaged clay rock, as well as the permeabilities in these zones, in accurately reproducing the measurements.

3. Discussion

Two clay host rocks identified to host radioactive waste disposals in Europe were studied in this project: the Boom Clay (BC), which is a poorly indurated Oligocene clay, and the Callovo-Oxfordian (COx) which is a well-consolidated claystone of Jurassic age. The Boom Clay's hydro-mechanical properties are characterised by permeabilities around 10^{-19} m^2 and Young's moduli of 0.2 GPa perpendicular to bedding and 0.4 GPa parallel to bedding whereas the COx permeability is one order of magnitude lower at 10^{-20} m^2 and its stiffnesses are much higher at 7 GPa perpendicular to bedding and 10 GPa parallel to bedding (Villar et al., 2025). Their thermal properties are however similar with thermal expansion coefficients of 1 vs. 1.25 10^{-5} $°C^{-1}$ and solid phase specific heats of 769 vs. 790 J/kg/K respectively; their anisotropic thermal conductivities are also similar parallel to bedding (1.65±0.05 vs. 2.0±0.1 W/m/K) and equal to 1.30±0.05 W/m/K perpendicular to bedding.

The maximum temperatures at the excavation wall are expected in both concepts around 80°C; given the thermal conductivity anisotropy, at an offset (corresponding to the ratio of the distance to the excavated diameter) of 2, the temperature is down to 45-50°C in a horizontal plane and slightly over 40°C in a vertical plane. Because of its higher permeability and plasticity, the resulting pore pressure increase in the BC is however much smaller at 3 MPa compared to 6 MPa in the COx claystone. The anisotropic effect is clearer in the COx, with a much higher pressure in the vertical plane than in the horizontal plane

Despite their different mechanical properties, Armand et al. (2023b) showed that the hydromechanical processes related to the excavation of galleries are similar in the BC and in the COx, and they displayed how the experience gained in one URL could be transposed to another one. The large-scale in-situ heating tests studied here show that the thermal responses are also similar in poorly indurated clay and indurated claystone. All these clays behave under quasi-undrained conditions due to their very low hydraulic conductivity. Nevertheless, even when the thermal load and thermal response are comparable, the effects on the hydraulic response are greater in indurated claystone than in poorly indurated clay. These effects are a consequence of the lower hydraulic conductivity, which limits pore water pressure dissipation in indurated claystone.

Several benchmarks have already shown that consistent results could be obtained by various codes using a simple poro-elastic approach (Seyedi et al., 2021, Plúa et al, 2021, Simo et al., 2025). As this type of model is conservatively used to design a safe spacing between the disposal tunnels in high-level waste repositories, these previous results helped increase the confidence in the models and codes and illustrated the robustness of the method. The present benchmark confirmed that more advanced approaches are necessary to model numerically the processes affecting the clay rocks in the vicinity of the tunnels. The excavation-damaged zone may be represented explicitly by predefining a zone with reduced properties around the gallery or may be computed in an elastoplastic model by introducing a dependency of the mechanical and hydraulic properties with the strain. This benchmark exercise showed that two such advanced models developed by UPC and ULiège could reproduce accurately the pore pressure evolution around the PRACLAY Heather test in the Boom Clay.

Advanced models are often developed for a specific clay formation (Vu et al., 2025). The benchmark gave an opportunity to test one of them on two very different clay types, as ULiège ran its coupled local second gradient model on the two proposed cases. Compared to other models, this Drucker-Prager elastoplastic model considers a strain-dependent water permeability and the HSsmall model (Brinkgreve et al., 2007) is used to represent the stiffness evolution with strain (Song, 2025). A thermally induced strength degradation was also implemented in the ALC1605 case, but with a maximum temperature below 50°C in the formation, its effect is not deemed significant. Reference is made to Song (2025) for more details on this constitutive model development. Despite some limitation due to its 2D geometry in a complex 3D setup, the model also gave some satisfactory results in the well-consolidated COx claystone. This showed that it is possible for a single model to accurately capture the THM responses around both the ALC1605 and PRACLAY heater tests, which is quite remarkable. It illustrated a common understanding of THM processes in poorly indurated clay and in claystone and provides some keys for transferring knowledge from one clay formation to another.

Conclusion

A benchmark organised in the framework of the EURAD HITEC project and involving seven European modelling teams gave an opportunity to compare the outputs from six finite element codes. Very consistent results were obtained with the elastic models on a series of generic cases investigating the impact of heating on the behaviour of clay host rocks, especially in the far-field. This outcome increases the confidence in models and codes and illustrates their robustness to contribute to the design and the safety of deep geological repositories for radioactive waste. More advanced models are however needed to represent the behaviour of the rocks in the near-field area that is affected by some damage and fracturing during the excavation of the tunnels.

Two full-scale in-situ heating experiments were modelled, the ALC1605 experiment in the COx claystone and the PRACLAY Heater test in the Boom Clay. In both cases, the teams successfully managed to reproduce the anisotropic response of the clay host rocks to excavation and heating. The evolutions of temperature and pore pressure were well modelled in the far-field with a poro-elastic approach. Two approaches were used to model the excavation-induced fracture network: a simplified poro-elastic approach with higher permeability and reduced mechanical properties in a predefined EDZ around the tunnels, and more advanced elasto-plastic models with strain-dependent permeability and stiffness. The latter models gave very good results on the PRACLAY Heater test case, but their 2D geometries could not perfectly represent the 3D complexity of the ALC1605 case. This benchmark highlighted how advanced models are needed to better reproduce the processes occurring in the near field around the tunnels (e.g., modification and strain-dependency of hydraulic and mechanical properties within the EDZ, creep).

Remarkably, an elasto-plastic model gave good results both in the poorly indurated Boom Clay and in the well-consolidated Callovo-Oxfordian claystone. This shows that even though these clay formations have different histories and properties, they share a common behaviour when exposed to the THM processes related to the disposal of high-level radioactive waste. This finding gives more confidence in THM process understanding in clays and provides some keys for transferring knowledge from one clay formation to another.

Acknowledgements

The HITEC project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 847593. The authors would also like to thank the organising committee of the 9th Clay Conference in Hannover for the opportunity to present their work.

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

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