Forty years of investigation into the thermo-hydromechanical behaviour of Boom Clay in the HADES URL

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Abstract: The heat generated by high-level waste or spent fuel will create disturbances around a deep geological repository (DGR) containing these wastes. Since the 1990s, SCK CEN, EIG EURIDICE and ONDRAF/NIRAS have been characterizing the thermo-hydromechanical (THM) behaviour of Boom Clay and assessing the impact of the thermal disturbances. This research has included laboratory tests as well as *in situ* experiments in the HADES Underground Research Laboratory. The two types of tests have been complementary. Laboratory tests have allowed understanding of the THM behaviour and determination of associated values of the THM parameters of the clay under well-controlled boundary conditions and loading paths. This knowledge and the parameters were then validated and even improved by *in situ* tests which allowed investigation of the effects of temperature on the Boom Clay behaviour at large scales. This paper gives an overview of this research and presents the main findings. It also explains how the knowledge gained supports the design of a possible future DGR and contributes to assessing the extent and impact of the THM disturbances in the Boom Clay around a DGR.

The geological disposal of high-level waste (HLW) and/or spent fuel (SF) in Boom Clay has been studied for more than 40 years (ONDRAF/NIRAS 2013). This research was initiated in 1974 by the Belgian Nuclear Research Centre (SCK CEN). In these first years SCK CEN focused its research efforts on investigating the Boom Clay, a clay formation at a depth between 185 and 287 m below the site of SCK CEN in Mol. The Boom Clay is a poorly indurated clay. Its very low permeability, strong retention capacity for many radionuclides and chemical contaminants and self-sealing capacity make it a potentially suitable host clay formation for the disposal of radioactive waste.

Promising results on Boom Clay obtained in the laboratory led to the decision to construct the HADES Underground Research Laboratory (URL) at the site of SCK CEN. The HADES URL is built more or less in the middle of the clay formation at a depth of 225 m. Figure 1 summarizes the construction history of the HADES URL (Li *et al.* 2023).

Its construction started in the early 1980s with the First Shaft and First Gallery. An important extension was completed in 2001 with the construction of the Second Shaft and the gallery (called the ‘Connecting Gallery’) connecting this shaft to the already existing part of the URL. In 2007, the 45 m long PRACLAY Gallery was built perpendicular to the Connecting Gallery. This demonstrated the feasibility of constructing smaller-diameter galleries and crossings in Boom Clay using industrial techniques similar to those used for the Connecting Gallery (Van Marcke *et al.* 2013).

The HADES URL played an essential role in characterizing the thermo-hydromechanical (THM) behaviour of the Boom Clay. The construction of shafts and galleries provided an opportunity to observe and measure the clay’s response to these excavations (Bastiaens *et al.* 2003; Van Marcke *et al.* 2013). For example, before URL construction started, the Boom Clay mechanical behaviour at this depth was poorly understood. It was thought that the Boom Clay would not be able to sustain the excavation work (de Beer *et al.* 1977; Bastiaens *et al.* 2006). Therefore, it was frozen before the excavation. However, during the construction of the first gallery, the convergence of the clay turned out to be smaller than expected. This indicated that it was possible to excavate in unfrozen Boom Clay. This was

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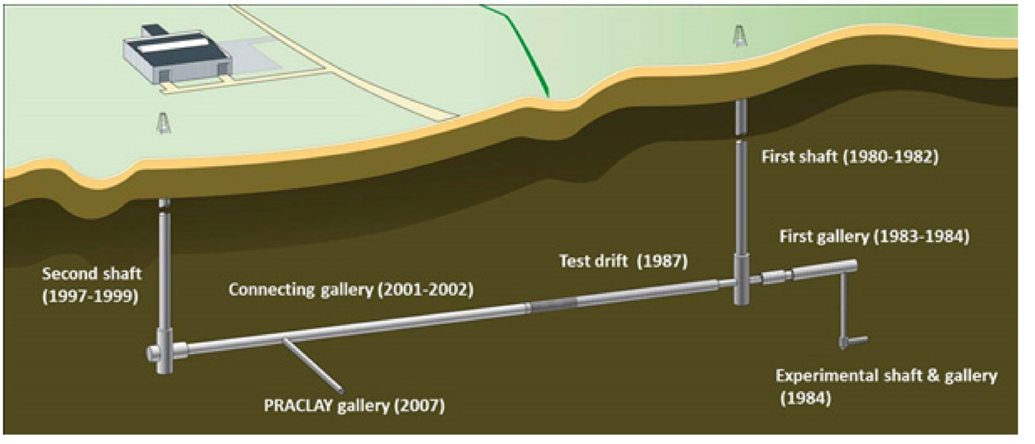

Fig. 1. Construction history of the HADES Underground Research Laboratory at Mol, Belgium.

successfully tested with the construction of the Experimental Shaft and Gallery.

The HADES URL has also allowed *in situ* experiments to be conducted. The ATLAS Heater Test was a small-scale test performed in the HADES URL between 1993 and 2012. Its goal was to investigate the THM behaviour of the clay and to determine its THM properties and parameters. In 2014, the PRACLAY Heater Test was launched in the PRACLAY Gallery (Fig. 2): a 33.5 m long section of the gallery was heated for 10 years at a temperature of 80°C at the interface between the gallery lining and the clay (Dizier *et al.* 2016, 2021). The main goal of the PRACLAY Heater Test is to refine the THM models and associated parameter values derived from the laboratory experiments and the ATLAS Heater Test and to confirm their relevance at different scales, from small scale to large scale *in situ* experiments (Chen *et al.* 2021, 2023*a*, *b*).

The construction of the HADES URL and the *in situ* experiments performed have allowed a good understanding of the THM behaviour of the Boom Clay as a complement to the laboratory results. The total vertical stress and porewater pressure at the depth of the URL in Mol are 4.5 and 2.25 MPa, respectively. The coefficient of earth pressure at rest, the K_0 value, is about 0.7 (Bernier *et al.* 2007; ONDRAF/NIRAS 2013). The Boom Clay is characterized by very low permeability (of the order of 10^{-12} m s^{-1}, Aertsens *et al.* 2004) and a limited hydraulic gradient over the formation. As a result, the transport of radionuclides mainly occurs via diffusion and advection is assumed to be negligible. In addition, measurements of the convergence of the HADES URL gallery lining particularly demonstrated the visco-elasto-plastic behaviour of the Boom Clay at that depth. This behaviour favours the Boom Clay's capacity to seal fractures (Bernier *et al.* 2007; Dizier *et al.* 2023). Furthermore, *in situ* experiments showed different responses depending on the orientations of the sensors (Chen *et al.* 2023*a*, *b*). This highlighted the anisotropic behaviour of the Boom Clay.

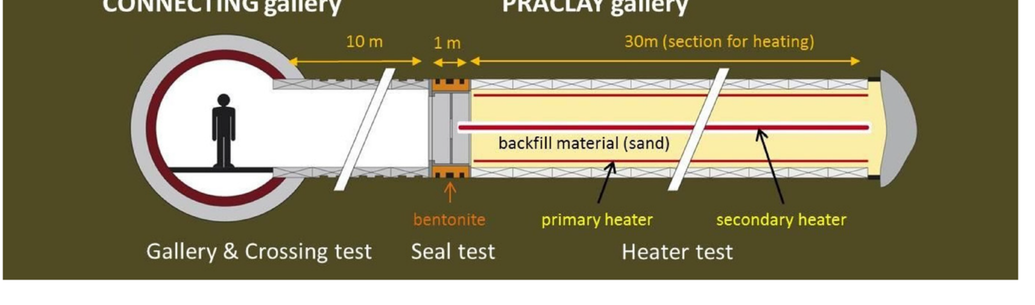

Fig. 2. The PRACLAY Gallery hosts the PRACLAY Heater Test.

State of knowledge on the THM behaviour of Boom Clay

The heat generated by HLW and/or SF will lead to perturbations in the clay around the deep geological repository (DGR). Figure 3 illustrates the range of processes (hydromechanical, thermal, chemical and biological) occurring in and around the DGR during the thermal phase, i.e. the phase during which the temperature of the host clay formation increases.

The increased temperature in the clay induces strong, coupled, hydromechanical perturbations, as also observed for Callovo-Oxfordian and Opalinus Clays (Villar *et al.* 2020). It leads to a volumetric expansion of both the porewater and the rock minerals. Because the thermal dilation coefficient of water is higher than that of the solid phase in a clay formation with low permeability, such as Boom Clay, the volumetric expansion results in an increase in porewater pressures and a variation of the mean stresses. This may cause a decrease in effective stress in the clay that can ultimately lead to fracturing. In that context, the studies on the effect of heat on the hydromechanical behaviour of the Boom Clay focus on the following three axes – how increasing temperature affects:

- the clay behaviour around the DGR (the intact clay);
- the clay behaviour within the excavation damaged zone (EDZ); and
- the extent of that EDZ (as a consequence of the two previous points).

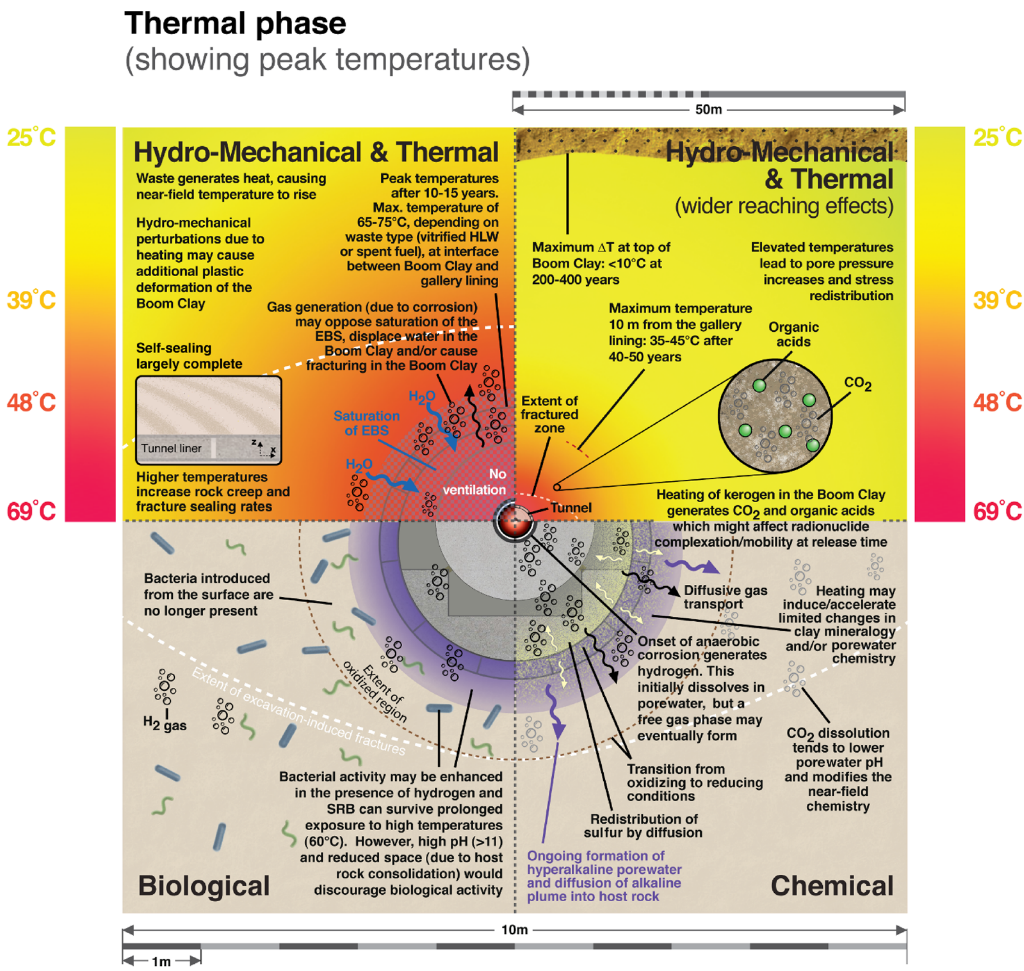

Fig. 3. Transverse cross-sections through a disposal tunnel for heat-emitting waste and the surrounding Boom Clay, illustrating the hydromechanical, thermal, biological and chemical processes occurring in the disturbed zone during the thermal phase (Harvey *et al.* 2011). EBS, engineered barrier system; HLW, high-level waste; SRB, sulfate-reducing bacteria.

This was done using a large number of laboratory tests, such as oedometer tests, triaxial tests, creep tests, permeameter tests (e.g. Baldi *et al.* 1988; Sultan 1997; Delage *et al.* 2000; Le 2008; Lima 2011). These laboratory tests were complemented by *in situ* experiments (as detailed in Bernier *et al.* 2007) and by back-analysing the stresses in the segmental concrete lining of the HADES URL galleries (Dizier *et al.* 2023). The THM behaviour was further studied through different *in situ* heater tests, more specifically the CACTUS, ATLAS and PRACLAY tests. These latter are discussed below.

Laboratory tests and *in situ* experiments have both been instrumental in characterizing the Boom Clay's THM behaviour. Laboratory tests have allowed values to be determined for the THM properties of the clay under well-controlled boundary conditions and loading paths. In parallel, *in situ* tests have allowed validation of the obtained parameters and properties and their improvement under more realistic conditions. This also allowed investigation of the upscaling effects of the laboratory test. In that way, laboratory and *in situ* tests have contributed in an iterative manner to refine understanding of the Boom Clay THM behaviour and its THM parameters and properties. For example, early laboratory tests assumed that THM behaviour of Boom Clay was isotropic, but analysis of the *in situ* heater test results showed that this behaviour was in fact anisotropic (Chen *et al.* 2011, 2023*a*). In turn, additional laboratory tests have been done to better characterize this transversely anisotropic behaviour, for example by loading the samples in different directions (mainly parallel and perpendicular to the bedding plane) (Dao 2015). Finally, it is worth pointing to the role that numerical simulations have played in characterizing the THM behaviour of Boom Clay. Several models have been developed that are capable of capturing the main observations from laboratory tests and *in situ* tests (Chen *et al.* 2023*a*, *b*). This strengthens the confidence in our understanding of the THM behaviour of Boom Clay.

Laboratory tests

The THM behaviour of clay is characterized by a coupling between thermal, hydraulic and mechanical processes. The most important characteristics of the THM behaviour of the Boom Clay are elaborated below based on the coupling between these different processes.

Thermal properties. The heat is mainly transferred by conduction in the clay that can be defined by two parameters:

- the thermal conductivity which defines the dissipation of heat; and
- the volumetric heat capacity, a storage parameter.

The thermal conductivity of Boom Clay is cross-anisotropic: the one parallel to the bedding plane (i.e. subhorizontal, λ_h) is higher than the one perpendicular to it (i.e. vertical, λ_v).

Until now, there has been a limited number of laboratory test setups to determine the thermal conductivity of Boom Clay. In most of them, the thermal conductivity is determined with a needle probe on samples without confining stress. In those conditions, Djeran *et al.* (1994) estimated an average thermal conductivity value of 1.44 W (m K)$^{-1}$. Dao (2015) completed this estimation by measuring the thermal conductivity in clay samples located at different distances from the Connecting Gallery. It was observed that the thermal conductivity decreases in the first metres from the gallery lining: the measured λ_h ranges from 1.34 to 1.61 W (m K)$^{-1}$ and the measured λ_v from 0.82 to 1.06 W (m K)$^{-1}$. Unfortunately, such an approach is imperfect because removing the *in situ* stress can disturb the sample and modify the contact between the clay particles. As a result, the density may change, which in turn may affect the measured thermal conductivity.

With the aim of improving the thermal conductivity estimation and avoiding the negative effects of the needle probe technique, Lima (2011) derived a thermal conductivity from the numerical interpretation of a heating pulse test on a hydrated Boom Clay sample under constant volume conditions. This led to a value of 1.60 W (m K)$^{-1}$, which is in agreement with the estimation of Van Cauteren (1994), who proposed a thermal conductivity value of 1.60 W (m K)$^{-1}$ based on a back-analysis of early *in situ* heating tests (i.e. CERBERUS and CACTUS) in the HADES URL. This value can be considered as a geometric mean of λ_h and λ_v.

The order of magnitude of the thermal conductivity was later confirmed and refined by analysing *in situ* heater tests. A small-scale *in situ* heater test, called ATLAS, was conducted in four phases (i.e. ATLAS I–IV) from 1993 to 2012 in the HADES URL. This small-scale test was followed by a large-scale one: the PRACLAY Heater Test, which has been running since 2014. These two tests yielded a large number of measured temperatures at different distances and directions from the heat source that allowed derivation of the cross-anisotropic thermal conductivity values (Charlier *et al.* 2010; Chen *et al.* 2011, 2023*a*; Garitte *et al.* 2014).

Table 1 summarizes the thermal conductivity values obtained from the laboratory and *in situ* tests. The specific heat of Boom Clay is estimated to be about 1450 J (kg K)$^{-1}$ by Buyens and Put (1984). The uncertainty surrounding this value is considered low according to Garitte *et al.* (2014).

Thermo-mechanical coupling behaviour. Many studies focused on the thermo-mechanical behaviour

Table 1. *Thermal conductivity values of the Boom Clay*

Reference	Laboratory or *in situ* test	Thermal conductivity (W (m °C)$^{-1}$)			Note
		λ_h	λ_v	λ_{mean}	
Djeran *et al.* (1994)	Laboratory test			1.44	No confining stress
Dao *et al.* (2015)	Laboratory test	1.34–1.61	0.82–1.06		No confining stress
Lima (2011)	Laboratory test			1.60	Confined, hydrated
Buyens and Put (1984)	Terhaegen *in situ* test			1.69	Boom Clay at a depth of 6 m below ground surface
Van Cauteren (1994)	CERBERUS and CACTUS *in situ* tests			1.60	
Charlier *et al.* (2010)	ATLAS III *in situ* test	1.75	1.25	1.56	
Chen *et al.* (2011)	ATLAS III *in situ* test	1.65	1.31	1.53	
Garitte *et al.* (2014)	ATLAS III *in situ* test	1.55	1.06	1.37	
Chen *et al.* (2023*a*)	ATLAS IV and PRACLAY *in situ* tests	1.90	1.20	1.63	

of soils, clay and claystone. The general processes will not be recalled in this paper, but a synthesis of the thermo-mechanical behaviour of fine-grained soil can be found in François (2008) and in Villar *et al.* (2020), where experimental results are also included for Opalinus Clay and Callovo-Oxfordian claystone.

The behaviour of clay submitted to heat is mainly governed by the coupling between the solid skeleton, the clay particles and the fluid phase. The volumetric dilation of a solid is much lower than that of the fluid phase (water) filling the pore space. As a consequence, the fluid phase dilates more than the solid phase during heating and tends to occupy more space, generating excess porewater pressure owing to its low permeability. This excess pressure reduces the effective stresses and may cause the failure of the sample.

Figure 4a shows the results of two undrained triaxial tests on Boom Clay, where one sample was heated under undrained conditions at a given deviatoric stress. Figure 4b presents the excess porewater pressure induced by the undrained shear test with and without the effect of heating. Two samples were sheared under normally consolidated conditions. At a given moment, the load was stopped for one of the two samples and heated. Because of the undrained conditions, the generated excess pore pressure conducted the stress path towards the critical state line, characterizing the plastic behaviour and the failure of the sample (Hueckel *et al.* 2009). During the TIMODAZ project (Delage *et al.* 2010), Monfared (2011) showed that undrained heating can be responsible for the reactivation of a pre-existing shear band during the thermal pressurization of a hollow cylinder in Boom Clay. Nevertheless, the

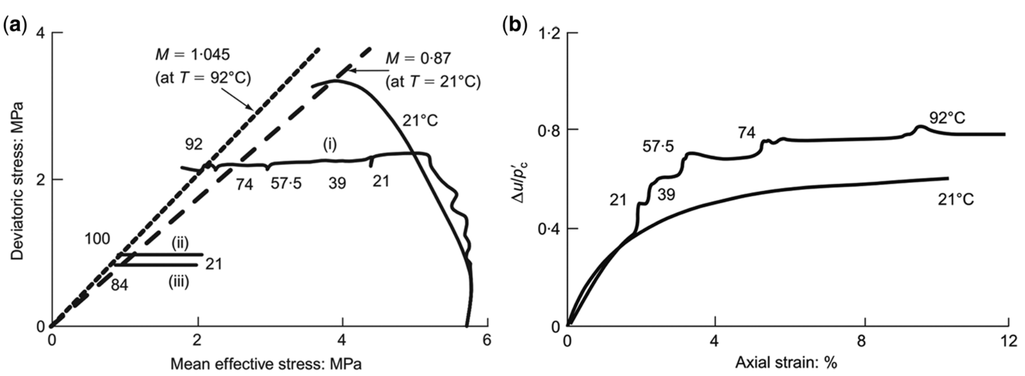

Fig. 4. (**a**) Stress path in the (p', q) plane during undrained thermal failure for Boom Clay, where p' refers to the mean effective stress and q refers to the deviatoric stress, and (**b**) excess porewater pressure generation (Hueckel *et al.* 2009).

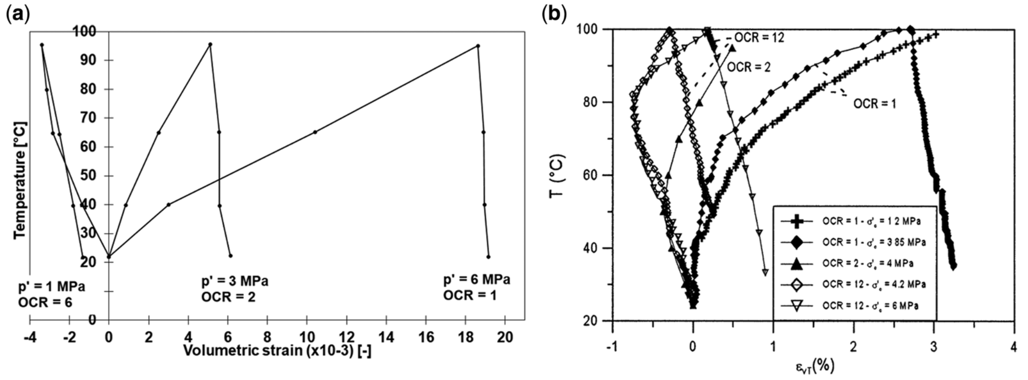

Fig. 5. Drained heating tests on Boom Clay samples at different confining stresses. Source: (**a**) after Baldi *et al.* (1991) and (**b**) after Sultan (1997). OCR, overconsolidation ratio.

effect of an elevated temperature on the shear strength properties remains unclear for fine-grained soils. Some authors found an increase in the critical state parameters, M, while others observed a decrease of M with temperature (Hueckel *et al.* 2009). For Boom Clay, based on undrained heating test performed by Baldi *et al.* (1991) and re-interpreted by Hueckel *et al.* (2009), an increase in M was observed (Fig. 4a). However, this finding was obtained based on one unique test with a specific stress path. Additional triaxial tests at different temperature levels should be performed to support this conclusion.

The mechanical behaviour of Boom Clay submitted to heating/cooling phases has been studied for a long time (Baldi *et al.* 1987, 1988, 1991; Sultan 1997; Cui *et al.* 2000; Delage *et al.* 2000). Figure 5 presents drained heating tests on Boom Clay samples at different confining pressures. The contractive/dilative behaviour may be seen in both cases. For normally consolidated and slightly overconsolidated samples, the behaviour remains contractive during the heating phase, while for highly overconsolidated samples dilation followed by contraction is observed.

In addition of this dilative/contractive behaviour, clayey soils undergo variation of their elastic limit with temperature. In the case of fine-grained soils, the preconsolidation pressure decreases with the increase in temperature. This is shown in Figure 6, illustrating the evolution of the preconsolidation pressure in two oedometer tests, one at ambient temperature and one at 80°C (Le 2008).

Moreover, when a clay sample is submitted to a temperature increase, an overconsolidation effect can occur. Figure 7 shows the evolution of the void ratio as a logarithmic function of the effective stress when the clay is heated at a constant pressure and then reloaded at high temperature. It is observed that the slope of the reloading path (at 70°C) changes before coming back to the previous slope, indicating that an overconsolidation process occurs (Cui *et al.* 2000).

Thermo-hydraulic coupling behaviour. The hydraulic conductivity is also affected by temperature, and more specifically, the viscosity of water decreases with the increase in temperature. As a consequence, the hydraulic conductivity will normally increase with temperature (e.g. Delage *et al.* 2000; Lima 2011). This change in water viscosity with temperature only affects the hydraulic conductivity of the clay, but not its intrinsic permeability, as experimentally shown by Delage *et al.* (2000) and Lima (2011).

Laboratory tests were performed to study the self-sealing capacity of the Boom Clay (Bastiaens *et al.* 2007). These tests performed under constant volume conditions in permeameter cell revealed the Boom Clay's capacity to rapidly seal fractures. Chen *et al.* (2014), by exposing Boom Clay samples (damaged and intact samples) to a heating cycle from 20 to 80°C, showed that there is no positive or negative impact of temperature on the sealing/healing properties of the clay under such conditions.

Heater tests in the HADES URL

Laboratory tests have allowed investigation of the THM behaviour and determination of the related THM parameters and properties of Boom Clay under well-defined and controlled boundary conditions and loading paths. Laboratory tests are performed on a relatively small volume of soil and they can be easily repeated to increase confidence in the experimental results.

In situ tests, on the other hand, allow consideration of a larger and therefore more representative volume of soil, but their number and thus

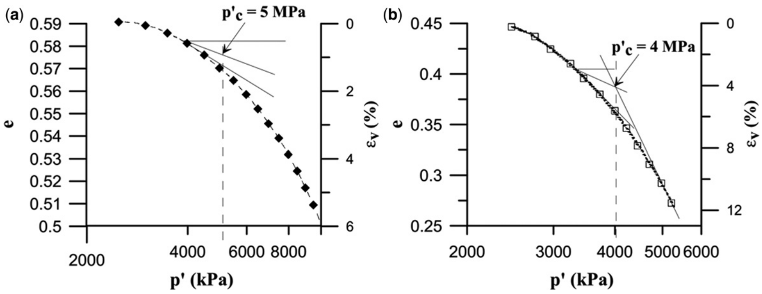

Fig. 6. Preconsolidation pressure of Boom Clay samples: (**a**) at ambient temperature and (**b**) at 80°C (Le 2008).

replicability are limited. The interpretation of *in situ* tests is generally done by back-analysing the *in situ* measurements using numerical simulations derived from the knowledge about THM behaviour, parameters and properties obtained from laboratory tests. In that sense, both tests are complementary. Furthermore, *in situ* tests can be conducted at different scales to explore the upscaling effect of the THM knowledge.

CACTUS Heater Test (1990–94). The main objective of the CACTUS experiment ('Characterization of Clay Under Thermal Loading in Underground Storage') was to study the THM behaviour of the Boom Clay formation around a vertical linear thermal source. This source simulated the thermal release of a 50 year-cooled COGEMA vitrified HLW canister (the main characteristics of these HLW canisters are summarized in ONDRAF/NIRAS 2001).

The CACTUS programme was composed of two *in situ* tests (CACTUS I and II) implemented in different sections in HADES URL separated from each other by a distance of about 25 m. The experimental setups of both tests are, however, similar. An overview of the setup is presented in Figure 8. The central borehole with the heater is surrounded by six instrumented boreholes to monitor the THM behaviour of

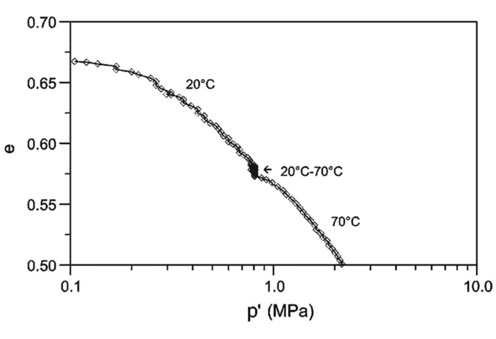

Fig. 7. Overconsolidation effects observed on Boom Clay during isotropic compression (Cui *et al.* 2000).

the Boom Clay by measuring the variation in the temperature, porewater pressure, total stress, displacement and water content. The peripheral instrumentation was installed in order to record the hydromechanical parameters prior to drilling the central borehole.

The CACTUS I was a preliminary test. The first heating phase started in September 1990 and lasted for 47 days. The heater power varied from 4000 to 1200 W. The second heating phase started in March 1991 and lasted until January 1992. A constant heating power of 1200 W was applied. The CACTUS II test was run from February 1992 until March 1993 and also applied a constant power of 1200 W. The complete measurements of two tests can be found in Picard *et al.* (1994).

For both tests, similar THM responses were observed (Bernier and Neerdael 1996). When heating started, a fast increase of porewater pressure was observed, followed by dissipation and stabilization towards the initial values. A decrease in the water content was also noted. During cooling, the porewater pressure decreased to a value much lower than the initial one, followed by an increase to an equilibrium state. The water content increased during cooling.

A fast increase of total pressures was observed with the same magnitude as for the porewater pressure at the same location. It further remained nearly constant during the heating. The heating phase was also accompanied by an increase of density. The extensometer records show displacements ranging from 0.5 to 1 mm between two reference points at 1 m distance. During the cooling phase, a fast decrease of the total pressure was observed followed by a slow stabilization and a decrease in the density.

The THM coupling models were developed within the framework of the EC INTERCLAY II project (Trentesaux 1997). Numerical analysis indicated that the heat transfer in Boom Clay was mainly through heat conduction and was not affected by the hydromechanical processes. The thermal conductivity (1.7 W $(m\ K)^{-1}$) and diffusivity (6×10^{-7} m^2 s^{-1}) can reproduce the *in situ* temperature

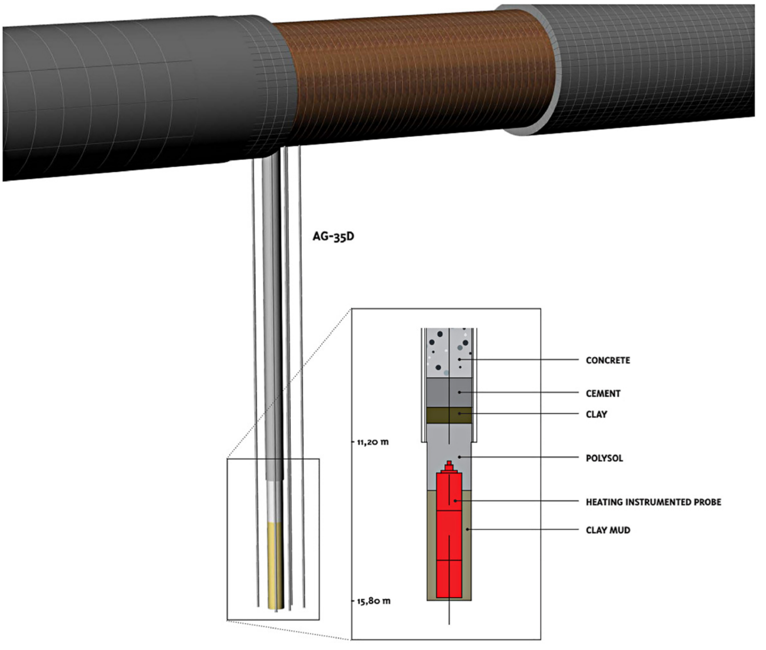

Fig. 8. Overview of the CACTUS experiments (CACTUS I). Source: ©EIG EURIDICE ESV.

measurements quite well. However, the modelling of the porewater pressure and stress variation remained challenging as test setup and conditions were complex and difficult to model with sufficient accuracy.

The CACTUS tests provided valuable data for understanding the THM coupling behaviour of the Boom Clay. Several lessons could also be drawn from these tests:

- The test setup should be as simple as possible, not involving too many materials. This lesson was incorporated into the design of the ATLAS Heater Test, which focused on the host clay formation.
- Sufficient sensors need to be installed, particularly near the heater, to capture the THM responses. This led to the installation of a dense network of sensors in the near field around the PRACLAY Gallery. It also turned out to be important to carefully select sensors that are sufficiently sensitive to measure the parameter variations expected and are suitable for the conditions in which they will operate (Verstricht *et al.* 2023).
- From a numerical point of view, a large part of the THM coupled processes cannot be neglected in the numerical modelling, such as for instance the non-linear thermal dilation coefficient or the evolution of the hydromechanical properties in the excavation damaged zone. These lessons were also drawn from the ATLAS and PRACLAY Heater Tests.

ATLAS Heater Test (1993–2012). The ATLAS Heater Test was carried out in four phases between 1993 and 2012. The goal of these tests was to assess the hydromechanical effects of a thermal load on the Boom Clay (Chen *et al.* 2023*a*, *b*). To facilitate the interpretation of the test results, the test setup was designed to have well-defined boundary conditions and a simple geometry. This ensured that the test responses depended only on the Boom Clay properties and not on the test setup itself, as was the case for the CACTUS test. In that test the heater was not in direct contact with the clay. Figure 9 presents a schematic view of the test setup. The test setup for the first two phases, ATLAS I (1993–96) and ATLAS II (1996–97), consists of a heater borehole (TD89E) and two horizontal observation boreholes (TD85E and TD93E). In 2006, the setup was expanded by drilling two additional observation boreholes: one horizontal (TD98E) and one inclined downward (TD97E). The heater was subsequently switched on from April 2007 to April 2008. This heating phase is called ATLAS III. To further examine the anisotropic THM response, an additional inclined observation borehole, TD90Iu, was drilled above the heater borehole TD89E in 2010. The fourth heating phase of the ATLAS Heater Test, ATLAS IV, lasted from 2011 to 2012.

Because of the small diameter of the heater borehole and considering that the heating load is moderate and progressively changed, the THM disturbance

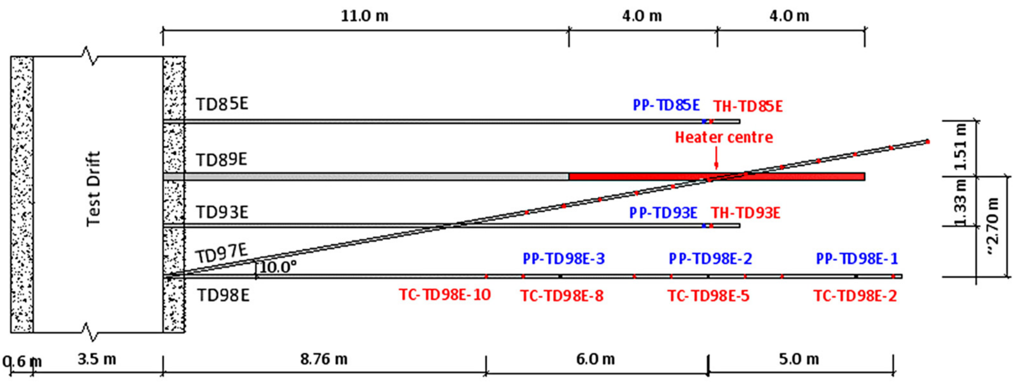

Fig. 9. Schematic horizontal view of the ATLAS Heater Test setup (Chen *et al.* 2023*b*).

of the clay is limited. Therefore, the THM responses monitored during the ATLAS Heater Test mainly depend on the less disturbed Boom Clay properties and are more representative of the far-field THM behaviour of the Boom Clay.

The test provided a large amount of high-quality data on the temperature and porewater pressure, based on which some noteworthy observations were made. Differences in the porewater pressure response were seen for sensors in a horizontal place with the heater compared with sensors in a vertical plane. In particular, an instantaneous but temporary porewater pressure decrease after increasing power and a temporary porewater pressure increase after cooling were noticed.

To enhance the understanding of the THM responses in the Boom Clay to heating, coupled THM numerical analyses were carried out for the ATLAS Heater Test (François *et al.* 2009; Chen *et al.* 2011, 2023*a*, *b*). For the ATLAS III heater test, a three-dimensional coupled THM model was established incorporating constitutive laws with consideration of the transverse THM anisotropy. A set of transversely anisotropic parameters (Table 2) were obtained with which the modelling could well reproduce the measured porewater pressure (Fig. 10) and temperature from the ATLAS III heater test. In Table 2, the values of the elastic moduli are high compared with those obtained in laboratory tests because the clay studied in the *in situ* experiment is representative of the far field where elastic moduli at small strain can be considered. The numerical interpretation also indicated that the instantaneous but temporary porewater pressure variations after increasing power and cooling were due to the mechanical anisotropy (Charlier *et al.* 2010; Chen *et al.* 2011).

PRACLAY Heater Test (2014–ongoing). To confirm and refine the knowledge gained from laboratory tests and the ATLAS Heater Test to a scale and conditions that are more representative of a real DGR, it was decided to perform a large-scale heating test: the ‘PRACLAY Heater Test’. During this test, a 33.5 m long section of the PRACLAY Gallery was heated for 10 years at a temperature of 80°C at the interface between the gallery lining and the Boom Clay (Fig. 2; Van Marcke *et al.* 2013; Dizier *et al.* 2016, 2021). Many sensors were installed in and around the PRACLAY Gallery (Verstricht *et al.* 2023).

The test is intended to be representative of a generic disposal gallery for heat-emitting waste, and not to exactly simulate the conditions expected for the current repository design. This is done to

Table 2. *A set of Boom Clay thermo-hydromechanical parameters obtained from the numerical interpretation of the ATLAS III Heater Test*

Direction to the bedding plane	Thermal conductivity (W (m K)$^{-1}$)	Intrinsic permeability (m^2)	Young modulus (MPa)	Thermal expansion coefficient of porewater (°C^{-1})
Parallel	$\lambda_{par} = 1.65$	$k_{i\ par} = 4.0{\cdot}10^{-19}$	$E_{par} = 1400$	3.4×10^{-4}
Perpendicular	$\lambda_{per} = 1.31$	$k_{i\ per} = 2.0{\cdot}10^{-19}$	$E_{par} = 700$	

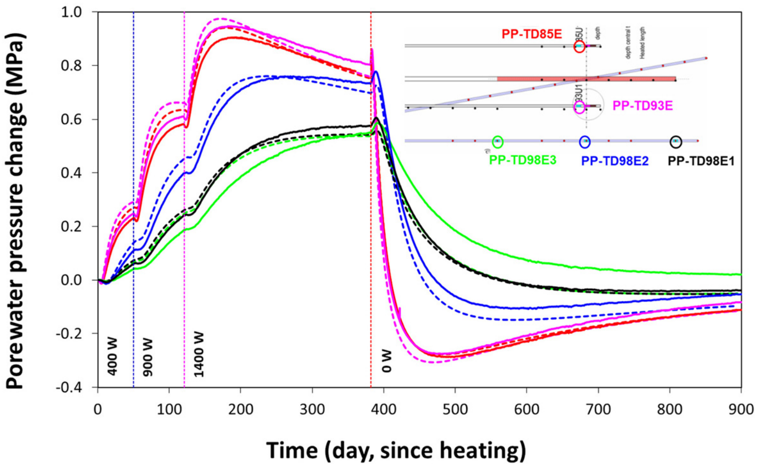

Fig. 10. Comparison of porewater pressure at some points between measurements and modelling (Chen *et al.* 2011).

make sure that the test remains valid if the design changes in future. It is also not possible to fully reproduce the time scale, the spatial scale and the boundary conditions of a real repository. Therefore, the test is conducted under a reasonably conservative combination of thermal, hydraulic and mechanical conditions.

In the ONDRAF/NIRAS reference design for geological disposal, a maximum temperature of 72°C is reached after *c.* 15–20 years at the interface between the clay and the lining of a disposal gallery containing spent fuel (Dizier 2018). In the PRACLAY Heater Test, the clay at the lining interface was heated to a temperature of 80°C in around 9 months. As the maximum temperature in the test is higher and reached more quickly, the thermal conditions imposed in the Heater Test are assumed to be conservative.

As for the hydraulic conditions, it was attempted to achieve undrained boundary conditions as these are more penalizing than drained boundary conditions. At the clay–lining interface, this was realized by backfilling the PRACLAY Gallery with water-saturated sand and pressurizing it to 1.0 MPa before the start of the heater test. At the intersection between the heated and the non-heated part of the gallery, a bentonite-based hydraulic seal was installed. The seal had to hydraulically cut off the heated part of the PRACLAY Gallery from the rest of the HADES URL.

During the start-up phase of the test, between November 2014 and August 2015, the heating power was increased in steps from 250 to 350 W m^{-1} and finally 450 W m^{-1}. Since August 2015, the stationary heating phase has started, during which a constant temperature of 80°C is kept at the lining–clay interface.

The evolution of the temperature and porewater pressure in the vertical and horizontal directions (monitored from a downward and horizontal borehole in the middle section of the heated gallery) is shown in Figure 11. The rate at which the clay temperature increases depends on its position relative to the gallery axis. At a distance of 2 m, the temperature increased quickly during the start-up phase, but then this increase slowed down. Further away the increase was slower.

By the end of 2021, the thermally affected zone had extended in both directions to a depth of more than 16 m in the Boom Clay. At a given time the temperature rise extends further in the horizontal direction than in the vertical one. These observations clearly indicate an anisotropic heat transfer conduction mechanism through the Boom Clay, as already observed in the smaller-scale ATLAS test.

For the piezometers closest to the concrete lining (CG35E-6 and PG50D-9), the porewater pressure increased from its initial value of about 1 MPa before heating to a value close to 3 MPa at the end of the start-up phase (August 2015). Since the start of the stationary phase, the porewater pressure close to the lining has remained nearly constant but it continued to increase in the clay. Over time, the peak in porewater pressure has gradually shifted away from the gallery further into the Boom Clay. The peak of maximum excess porewater pressure in the Boom Clay was reached around 2017 in piezometer CG38E-2. Since then, the excess porewater pressure has been dissipating in the surrounding environment.

A difference of evolution was noticed between the vertical (from the PRACLAY Gallery) and the horizontal piezometers (from the Connecting Gallery). More particularly, a short decrease followed

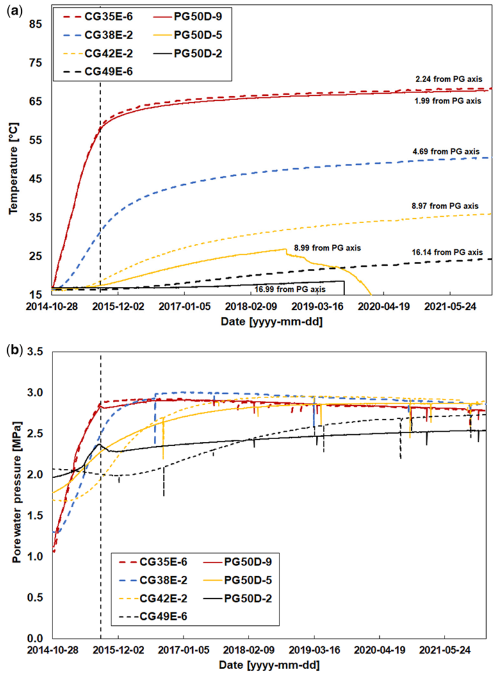

Fig. 11. Evolution of the measured (**a**) temperatures and (**b**) porewater pressures at the middle section of the heated part of the PRACLAY Gallery (PG) in both horizontal and vertical directions (horizontal boreholes were drilled from the Connecting Gallery and the vertical downward borehole was drilled from the PRACLAY Gallery).

by a re-increase of porewater pressure was observed at the beginning of the heating for some horizontal piezometers (CG49E-2 and CG49E-6) as a consequence of the mechanical anisotropic properties of the clay. These phenomena were also observed during the ATLAS Heater Test and confirm the anisotropic response of the clay (Charlier *et al.* 2010; Chen *et al.* 2011).

Figure 12 presents the evolution of the porewater pressure at a distance of 22 m from the PRACLAY Gallery axis. Excess porewater pressures are generated during the heating, indicating that the hydraulic affected zone extends beyond 22 m. Porewater pressures had been decreasing owing to the drainage by the gallery. When the PRACLAY Heater Test was started, this decrease slightly accelerated. Later, however, well into the stationary phase, the porewater pressures started to increase. All of these observations confirm that the anisotropy is an important aspect for understanding the porewater pressure evolution around a heat source in Boom Clay.

To evaluate the impact of large-scale thermal loading on the intrinsic permeability of the Boom Clay, *in situ* permeability tests have been performed on 14 filters from five boreholes CG30E, CG35E, CG38E, CG42E and CG49E around the PRACLAY Gallery (Fig. 13; Chen *et al.* 2022). These tests were carried out before and during the PRACLAY Heater Test. Figure 14 shows the evolution of intrinsic permeability with temperature. It can be seen that there is almost no change in intrinsic permeability with a temperature increase up to 50°C. Since the permeability is dominated by the porosity and structure of the Boom Clay, this observation implies that there is no significant change in the porosity and structure of the Boom Clay, even with a temperature increase of up to 50°C.

A horizontal profile of the Boom Clay intrinsic permeability around the heated PRACLAY Gallery is presented in Figure 15. The results are from five

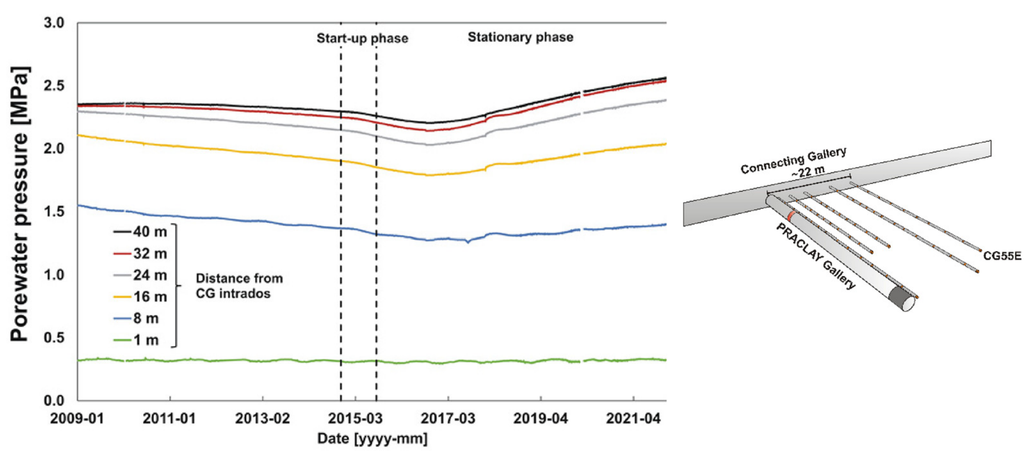

Fig. 12. Measured porewater pressures along a borehole drilled from the Connecting Gallery (CG) at a distance of approximately 22 m from the PRACLAY Gallery axis.

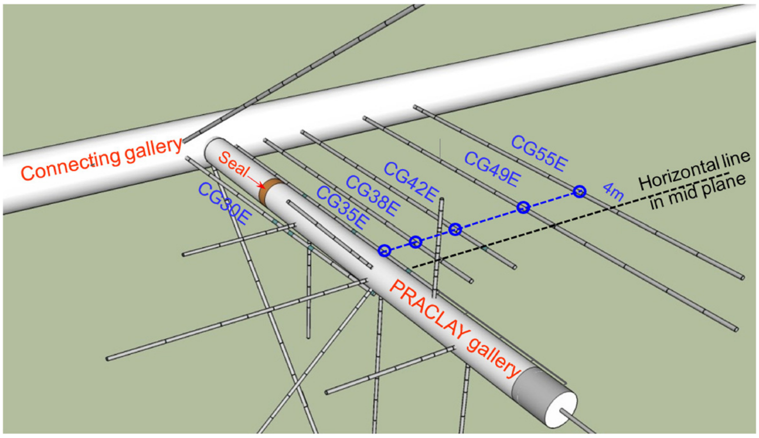

Fig. 13. Filters from boreholes CG35E, CG38E, CG42E, CG49E and CG55E selected for *in situ* permeability tests.

filters located along the blue dashed line in Figure 13. They are all at a distance of 24 m from the Connecting Gallery lining. These filters are located around the mid plane of the heated gallery, i.e. the plane perpendicular to the PRACLAY Gallery axis and through the middle of the heated gallery (see black dashed line in Fig. 13). For these filters, the temperature and the permeability were measured from 2013 to 2016 (before heating or when temperature increase was very limited) and from 2020 to 2021 (during heating) (Fig. 15). This shows that the intrinsic permeability measured at most filters remains almost constant with increasing temperature. This again demonstrates that there is no detrimental thermal influence on the intrinsic permeability of the Boom Clay. All of these observations are consistent with those of our previous laboratory tests (Delage *et al.* 2000; Chen *et al.* 2014) and small-scale *in situ* ATLAS Heater Test.

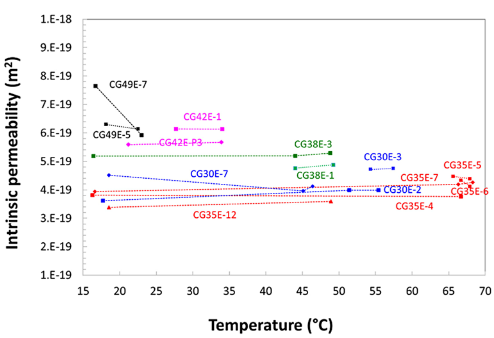

Fig. 14. Intrinsic permeability in function of the temperature based on measurements from boreholes CG30E, CG35E, CG38E, CG42E and CG49E.

Application of THM knowledge to real repository simulation

The Belgian Research, Development and Demonstration programme on the geological disposal of HLW and/or SF considers disposal in poorly indurated clay as the reference solution. The concept

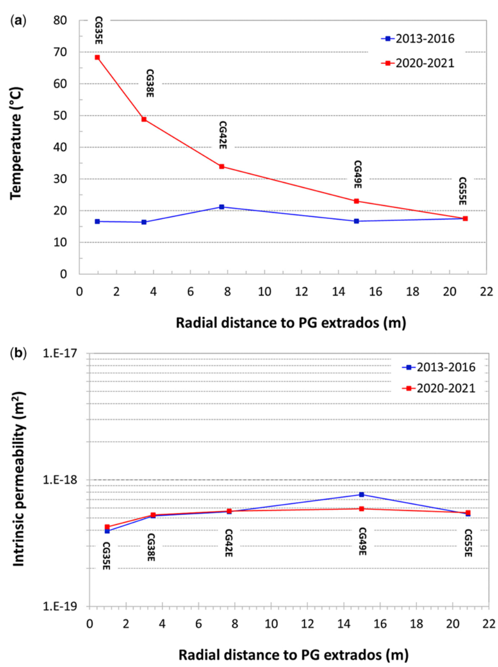

Fig. 15. Profiles of (**a**) temperature and (**b**) intrinsic permeability along the filters at a distance of 24 m from the Connecting Gallery lining. PG, PRACLAY Gallery.

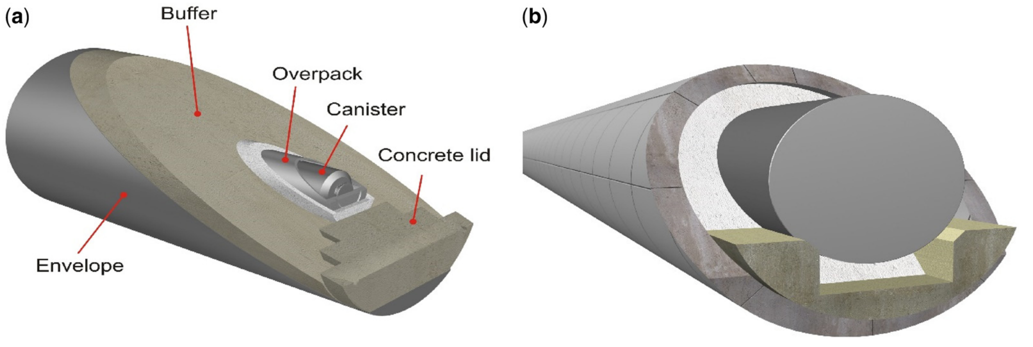

Fig. 16. Schematic drawing of (**a**) a supercontainer containing a vitrified high-level waste canister and (**b**) a supercontainer placed in a disposal gallery, which is then backfilled (ONDRAF/NIRAS 2013).

studied is the so-called 'supercontainer concept'. It entails conditioning the waste in 'supercontainers' with a 30 mm thick carbon steel overpack surrounded by a concrete buffer (Fig. 16). The overpack has to ensure complete waste containment during at least the thermal phase. The concrete buffer may, in turn, be enclosed in a 6 mm thick stainless steel envelope (ONDRAF/NIRAS 2013, 2020).

The dimensions of the supercontainers vary depending on the waste they contain. The largest and heaviest supercontainer has a diameter of 2150 mm, is 6250 mm long and weighs 69 t. These are transported along a waste shaft to the DGR and placed in a horizontal disposal gallery (Fig. 17). As waste disposal progresses, the repository is progressively closed by backfilling the disposal galleries.

A minimum distance between adjacent disposal galleries is necessary to avoid interference between processes around adjacent galleries (Fig. 17). Examples of possible interferences are the excavation disturbed zone or the generation of gas. This leads to a minimum spacing of 50 m between the galleries containing non heat-emitting waste. High-level waste and SF, however, will emit heat for hundreds to even thousands of years, as can be seen in Figure 18. There needs to be sufficient distant between adjacent disposal galleries to limit the temperature increase in the surrounding host clay formation. A distance of 120 m between the galleries is considered sufficient.

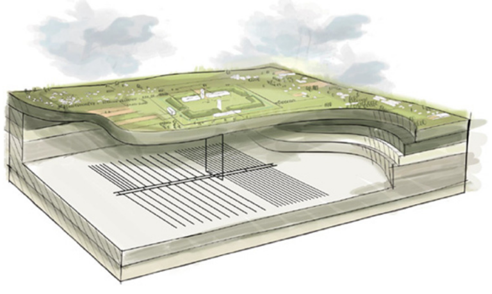

Fig. 17. Layout of the deep geological repository (ONDRAF/NIRAS 2020).

Numerical simulations of a geological disposal facility have assessed the THM impact on the clay host formation. An example of such simulations for a repository at a depth of 400 m showed that the temperature increased quickly around the disposal gallery before rising slowly into the clay massif thanks to the heat dissipation (Fig. 19). These simulations used the THM parameters defined in Dizier *et al.* (2016) and are performed with the finite element model developed with COMSOL multiphysics. The model considers the entire DGR history from the excavation of the galleries until the end of thermal phase 2000 years after the disposal of the supercontainer.

A close look into the evolution of the temperature obtained by this numerical modelling of a geological disposal facility showed that the temperature variation at the clay–lining interface has a maximum value of 50°C, the peak of the temperature being reached after one or two decades (Fig. 20a). The change in slope during the cooling period is influenced by the neighbouring galleries, which only affect the long-term cooling and have no consequence for the peak temperature.

At the clay–lining interface, significant excess porewater pressures occur, as can be seen in Figure 20a. The porewater pressure rises quickly to a value close the undisturbed value, which is 4 MPa in this case (for a repository at a depth of 400 m).

The analysis of the variation of the state of mechanical stress in Figure 20b shows that the excavation process generates plastic strain, which is consistent with the formation of an EDZ observed during the excavation of the connecting gallery in the HADES URL. The variation in temperature affects the mechanical state of stress by accumulating additional plastic strain around the gallery. This

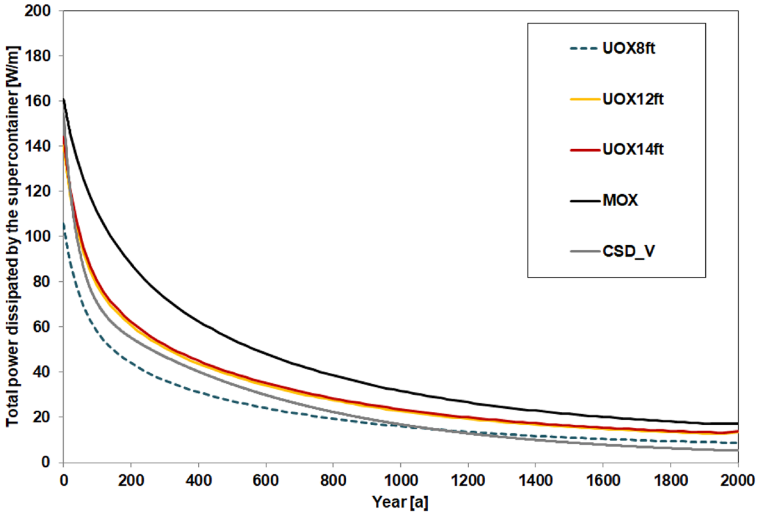

Fig. 18. Estimation of the heat fluxes applied at the gallery wall considering a cooling period of 85 years before the deposit. The time zero corresponds to the beginning of the thermal phase. Source: in Dizier (2018).

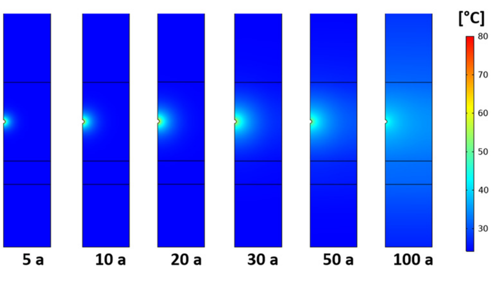

Fig. 19. Numerical assessment of the temperature distribution around one disposal gallery at several intervals after 5, 10, 20, 30, 50 and 100 years of radioactive waste disposal (Dizier 2018) (black line indicates the separation between the Boom Clay formations and the sandy aquifers above and below).

additional irreversible strain may modify the EDZ by extending the initial cracks, by increasing the hydraulic conductivity or by generating irreversible changes in the EDZ, affecting the favourable properties of the clay. However, permeability measurements during the PRACLAY Heater Test showed that the intrinsic permeability is not affected by the heating. This means that the additional plastic strains obtained during the thermal phase with the modelling have no, or very limited, effects on the favourable properties of the clay. Indeed, as the heating phase of the PRACLAY Heater Test is more conservative than the thermal phase around a DGR, a similar evolution of the plastic strains can be anticipated around the PRACLAY gallery with no effects on the measured permeabilities.

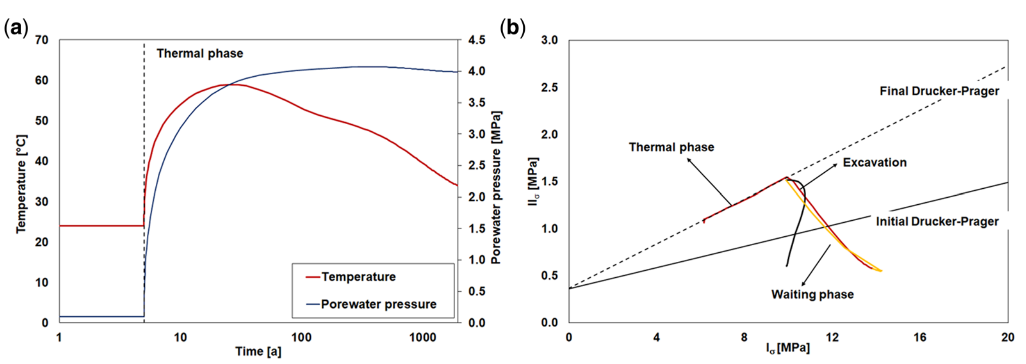

Fig. 20. (**a**) Porewater pressure and temperature evolution at the gallery wall obtained during a numerical prediction of the geological disposal facility. (**b**) Stress path in the plane of the first invariant of the effective stress tensor and the second invariant of the deviatoric effective stress tensor for a point on the gallery's wall (Dizier 2018).

Conclusions

When developing a geological disposal concept for HLW, it is necessary to characterize the THM behaviour of the host geological formation. The heat of the HLW will induce perturbations in the clay formation, which can affect its performance in containing the radioactive waste. The Belgian RD&D programme on geological disposal studies the Boom Clay as a potential host clay formation for a DGR. The THM behaviour of this poorly indurated clay has been characterized by laboratory tests and *in situ* experiments in the HADES URL.

Laboratory tests have allowed investigation of the THM behaviour and determination of the related THM parameters and properties of Boom Clay under well-defined and controlled boundary conditions and loading paths. Laboratory tests are performed on a relatively small volume of soil and they can be easily repeated to increase confidence in the experimental results. *In situ* tests, on the other hand, allow the consideration of a larger and therefore more representative volume of soil but their number and thus replicability are limited. The interpretation of *in situ* tests is generally done by back-analysing the *in situ* measurements using numerical simulations derived from knowledge about the THM behaviour, parameters and properties gained from laboratory tests. In that sense, both tests are complementary. Furthermore, *in situ* tests can be conducted at different scales to explore the upscaling effect of the THM knowledge. *In situ* heater tests were conducted to confirm or refine the THM parameters and property values obtained from laboratory tests and further test and evaluate the THM behaviour of the Boom Clay on a larger scale. The ATLAS Heater Test provided a large amount of high-quality data on the temperature and porewater pressure. Because of the small diameter of the heater borehole, the THM disturbance of the clay around the ATLAS heater was limited. Therefore, the THM responses mainly depend on the less disturbed Boom Clay properties and parameters and are more representative of the far-field THM behaviour.

The ATLAS Heater Test demonstrated the anisotropic THM behaviour of the clay and confirmed the strong coupling between its mechanical, hydraulic and thermal responses. To confirm and refine the knowledge gained from the ATLAS Heater Test to a scale and conditions that are more representative of a real DGR, the large-scale PRACLAY Heater Test was set up in a 33.5 m long section of the PRACLAY Gallery. The clay at the lining interface was heated to a temperature of 80°C in about 9 months. It is then kept at this temperature for 10 years. This maximum temperature is higher and it is reached faster than around a real DGR. This means that the thermal conditions imposed in the PRACLAY Heater Test are conservative. The PRACLAY Heater Test confirmed the observations from the smaller scale ATLAS Heater Test. It reconfirmed the importance of the clay's anisotropic THM behaviour in understanding the porewater pressure evolution in the clay.

In addition, it is worth pointing out the role that numerical simulations have played in characterizing the THM behaviour of Boom Clay. Several models have been developed and have proven to be capable of capturing the observations from laboratory tests and *in situ* tests (Charlier *et al.* 2010; Chen *et al.* 2023*a*, *b*). This strengthens the confidence in our understanding of the THM behaviour of Boom Clay.

This knowledge about the Boom Clay's THM behaviour is important for the design of a possible DGR in Boom Clay. It allows, for example, the minimum distance that is necessary between adjacent disposal galleries to avoid interference between thermal perturbations around them to be defined. Knowledge about the THM behaviour also contributes to the safety assessment as it is necessary to assess the extent and impact of the THM disturbances in the Boom Clay around a DGR.

Nevertheless, even if understanding of the THM behaviour of Boom Clay is already significant, there remain open questions that need to be examined from the perspective of DGR optimization. For example, the role of the anisotropy of the strength properties has not yet been investigated. Only very few triaxial tests have been performed with different orientations of the bedding (Dao 2015) and the results are difficult to interpret. Additional tests would be required to confirm the first observations. The creep behaviour of the clay is also not sufficiently understood, despite its role in DGR behaviour as suggested by several observations made around the HADES URL over the past 40 years (Dizier *et al.* 2023). In particular, for future interpretations of the long-term phase of the PRACLAY Heater Test, it would be useful to consider the viscosity of the clay in order to evaluate its effects and improve the accuracy of DGR models.

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Author contributions **XL**: writing – original draft (equal), writing – review & editing (equal); **AD**: writing – original draft (equal), writing – review & editing (equal); **GC**: writing – original draft (equal), writing – review & editing (equal); **JV**: writing – review & editing (supporting); **SL**: writing – original draft (lead), writing – review & editing (equal).

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Data availability The data that support the findings of this study are available from EIG EURIDICE, SCK CEN and NIRAS/ONDRAF but restrictions apply to the availability of these data, which were used under licence for the current study, and so are not publicly available. Data are, however, available from the authors upon reasonable request and with permission of EIG EURIDICE, SCK CEN and NIRAS/ONDRAF.

References

Aertsens, M., Wemaere, I. and Wouters, L. 2004. Spatial variability of transport parameters in the Boom Clay. *Applied Clay Science*, **26**, 37–45, https://doi.org/10.1016/j.clay.2003.09.015

Baldi, G., Borsetto, M. and Hueckel, T. 1987. *Calibration of mathematical models for simulation of thermal, seepage and mechanical behaviour of Boom Clay*. Commission of the European Communities. Nuclear Science and Technology EUR 10924.

Baldi, G., Hueckel, T. and Pellegrini, R. 1988. Thermal volume changes of the mineral–water system in low-porosity clay soils. *Canadian Geotechnical Journal*, **25**, 807–825, https://doi.org/10.1139/t88-089

Baldi, G., Hueckel, T., Peano, A. and Pellegrini, R. 1991. *Developments in modelling of thermo-hydro-mechanical behaviour of Boom Clay and clay-based buffer (vol. 2)*. Commission of the European Communities. Nuclear Science and Technology EUR 13365/2.

Bastiaens, W., Bernier, F., Buyens, M., Demarche, M., Li, X.L., Linotte, J.M. and Verstricht, J. 2003. *The Connecting gallery – the extension of the HADES underground research facility at Mol, Belgium*. EURIDICE report **03-294**.

Bastiaens, W., Bernier, F. and Verstricht, J. 2006. 25 years of underground engineering in a plastic clay formation: the HADES underground research facility. *Proceedings of the 5th International Conference of TC28 of the ISSMGE on Geotechnical Aspects of Underground Construction in Soft Ground*, London, 795–801.

Bastiaens, W., Bernier, F. and Li, X.L. 2007. SELFRAC: experiments and conclusions on fracturing, self-healing and self-sealing processes in clays. *Physics and Chemistry of the Earth*, **32**, 600–615, https://doi.org/10.1016/j.pce.2006.04.026

Bernier, F. and Neerdael, B. 1996. Overview of in-situ thermomechanical experiments in clay: concept, results and interpretation. *Engineering Geology*, **41**, 51–64, https://doi.org/10.1016/0013-7952(95)00032-1

Bernier, F., Li, X.L. and Bastiaens, W. 2007. Twenty-five years' geotechnical observation and testing in the Tertiary Boom clay formation. *Géotechnique*, **57**, 229–237, https://doi.org/10.1680/geot.2007.57.2.229

Buyens, M. and Put, M. 1984. Heat transfer experiment in Boom Clay. *9th European Conference on Thermophysical Properties*, 17–21 September, Manchester.

Charlier, R., Chalandar, S. *et al*. 2010. Deliverable D13 – annex 4. In situ heating test ATLAS in Mol. TIMODAZ project, F16W-CT-2007-036449.

Chen, G.J., Sillen, X., Verstricht, J. and Li, X.L. 2011. ATLAS III in situ heating test in boom clay: field data, observation and interpretation. *Computers and Geotechnics*, **38**, 683–696, https://doi.org/10.1016/j.compgeo.2011.04.001

Chen, G.J., Maes, T. *et al*. 2014. Thermal impact on damaged Boom Clay and Opalinus Clay: permeameter and isostatic tests with μCT Scanning. *Rock Mechanics and Rock Engineering*, **47**, 87–99, https://doi.org/10.1007/s00603-012-0334-y

Chen, G.J., Dizier, A., Li, X.L., Verstricht, J., Sillen, X. and Levasseur, S. 2021. Numerical prediction of the large-scale in situ PRACLAY Heater test in the Boom Clay. *Rock Mechanics and Rock Engineering*, **54**, 2197–2218, https://doi.org/10.1007/s00603-021-02405-2

Chen, G.J., Yu, L., Lefevre, C. and Nachaerts, D. 2022. *In situ hydraulic conductivity measurement for the Boom Clay around the Connecting gallery and PRACLAY gallery: test campaign 2020–2021*. EURIDICE report **EUR-PH-21-068**.

Chen, G.J., Li, X.L., Sillen, X. and Levasseur, S. 2023*a*. Determination of the anisotropic thermal conductivity of the boom clay based on a combined numerical interpretation of two in situ heater tests at different scales. *Acta Geotecnica*, **18**, 127–147, https://doi.org/10.1007/s11440-022-01555-z

Chen, G., Li, X., Dizier, A., Verstricht, J., Sillen, X. and Levasseur, S. 2023*b*. Characterization of Boom Clay anisotropic THM behaviour based on two heating tests at different scales in the HADES URL. *Geological Society, London, Special Publications*, **536**, https://doi.org/10.1144/SP536-2022-72

Cui, Y.J., Sultan, N. and Delage, P. 2000. A thermomechanical model for saturated clays. *Canadian Geotechnical Journal*, **37**, 607–620, https://doi.org/10.1139/t99-111

Dao, L.Q. 2015. *Etude du comportement anisotrope de l'Argile de Boom*. PhD thesis, Ecole des Ponts ParisTech, France.

Dao, L.Q., Cui, Y.J., Tang, A.M., Pereira, J.M., Li, X.L. and Sillen, X. 2015. Impact of excavation damage on the thermo-hydro-mechanical properties of natural Boom Clay. *Engineering Geology*, **195**, 196–205, https://doi.org/10.1016/j.enggeo.2015.06.011

De Beer, A., Carpentier, R., Manfroy, P. and Heremans, R. 1977. Preliminary studies of an underground facility for nuclear waste burial in a tertiary clay formation. *Rockstore Conference*, 1977, Stockholm. **3**, 771–780.

Delage, P., Sultan, N. and Cui, Y.J. 2000. On the thermal consolidation of Boom Clay. *Canadian Geotechnical Journal*, **37**, 343–354, https://doi.org/10.1139/t99-105

Delage, P., Bésuelle, P. *et al*. 2010. Deliverable D5. THM characterisation and input for simulation. TIMODAZ project, F16W-CT-2007-036449.

Dizier, A. 2018. Thermo-hydro-mechanical modelling of a C-waste geological repository. ESV EURIDICE, EUR_18_013 (EURIDICE Internal report).

Dizier, A., Chen, G.J., Li, X.L., Leysen, J., Verstricht, J., Troullinos, I. and Rypens, J. 2016. The start-up phase of the PRACLAY Heater Test. EUR_PH_16_025. Mol, Belgium.

Dizier, A., Chen, G.J., Verstricht, J., Li, X.L., Sillen, X. and Levasseur, S. 2021. The large-scale in situ PRACLAY Heater Test: first observations on the in situ thermo-hydro-mechanical behaviour of Boom Clay. *International Journal of Rock Mechanics and Mining Sciences*, **137**, 104558, https://doi.org/10.1016/j.ijrmms.2020.104558

Dizier, A., Scibetta, M. *et al*. 2023. Stability analysis and long term behaviour of deep tunnels in clay formation. *Geological Society, London, Special Publications*, **536**, https://doi.org/10.1144/SP536-2022-86

Djeran, I., Bazargan, B., Giraud, A. and Rousset, G. 1994. Etude experimentale du comportement Thermo-Hydro-Mecanique de l'argile de Boom. Report **ONDRAF 90/10/547**.

François, B. 2008. *Thermo-plasticity of soils at various saturation state: application to nuclear waste disposal*. PhD thesis, Ecole Polytechnique Fédérale de Lausanne.

François, B., Laloui, L. and Laurent, C. 2009. Thermo-hydro-mechanical simulation of ATLAS in situ large scale test in Boom Clay. *Computers and Geotechnics*, **36**, 626–640, https://doi.org/10.1016/j.compgeo.2008.09.004

Garitte, B., Gens, A., Vaunat, J. and Armand, G. 2014. Thermal conductivity of argillaceous rocks: determination methodology using in situ heating tests. *Rock Mechanics and Rock Engineering*, **47**, 111–129, https://doi.org/10.1007/s00603-012-0335-x

Harvey, L., Van Marcke, P., Kent, C., Wickham, S., Van Geet, M. and Sillen, X. 2011. Disturbed zone evolution around a geological repository for nuclear waste. *13th International High-Level Radioactive Waste Management Conference 2011*, 10–14 April 2011, Albuquerque, New Mexico, USA. *IHLRWMC 2011*, **2**, 984–991.

Hueckel, T., François, B. and Laloui, L. 2009. Explaining thermal failure in saturated clays. *Géotechnique*, **53**, 197–212, https://doi.org/10.1680/geot.2009.59.3.197

Le, T.T. 2008. *Comportement thermo-hydro-mécanique de l'argile de Boom*. PhD thesis, Ecole des Ponts ParisTech, France.

Li, X.L., Sillen, X., Raymaekers, D. and Neerdael, B. 2023. The construction of the HADES Underground Research Laboratory and its role in the development of the Belgian concept for a deep geological repository. *Geological Society, London, Special Publications*, **536**, https://doi.org/10.1144/SP536-2022-101

Lima, A. 2011. *Thermo-hydro-mechanical behaviour of two deep Belgian clay formations: Boom Clay and Ypresian Clays*. PhD thesis, Technical University of Catalunya.

Monfared, M. 2011. *Couplages température–endommagement–perméabilité dans les sols et les roches argileuses*. PhD thesis, Ecole Nationale des Ponts et Chaussées.

ONDRAF/NIRAS 2001. *SAFIR-2 Second Safety Assessment and Interim Report*. Belgian Agency for Radioactive Waste for Enriched Fissile Materials. Report **NIROND 2001-06 E**.

ONDRAF/NIRAS 2013. *Research, Development and Demonstration (RD&D) plan for the geological disposal of high level and/or long-lived radioactive waste including irradiated fuel if considered as waste*. State-of-the-art report as of December 2012. Belgian Agency for Radioactive Waste for Enriched Fissile Materials. Report **NIROND-TR 2013-12 E**.

ONDRAF/NIRAS 2020. *Design and Construction of the Geological Disposal Facility for Category B and Category C waste (V3)*. Technical Report **NIROND-TR-2017-12 E V3**. Category B&C. Brussels, Belgium.

Picard, J.M., Bazargan, B. and Rousset, G. 1994. *Essai thermo-hydro-mécanique dans une argile profonde: 'Essai Cactus'*, Final report, **EUR-15482**, European Commission, Luxembourg.

Sultan, N. 1997. *Etude du comportement thermo-mécanique de l'argile de Boom: expériences et modélisation*. PhD thesis, Ecole Nationale des Ponts et Chaussées, Paris, France.

Trentesaux, C. 1997. *Modelling of thermo-hydro-mechanical behaviour of the Boom Clay 'Cactus test'*, Final report, **EUR-17558**, European Commission, Luxembourg.

Van Cauteren, L. 1994. Evaluatie van de warmtegeleidbaarheid en de warmtecapaciteit van de Boomse klei, Nota 94-0605, ONDRAF/NIRAS.

Van Marcke, P., Li, X.L., Bastiaens, W., Verstricht, J., Chen, G.J., Leysen, J. and Rypens, J. 2013. The design and installation of the PRACLAY In-Situ Experiment. EURIDICE report **13-129**.

Verstricht, J., Nackaerts, D., Li, X.L., Leonard, D., Levasseur, S. and Van Geet, M. 2023. Assessment of long-term sensor performance based on a large THM experiment in the HADES URL. *Geological Society, London, Special Publications*, **536**, https://doi.org/10.1144/SP536-2022-87

Villar, M.V., Armand, G. *et al*. 2020. D7.1 HITEC. Initial State-of-the-Art on THM behaviour of i) Buffer clay materials and of ii) Host clay materials. Deliverable D7.1 HITEC. EURAD Project, Horizon 2020 no. 847593, 214.