The construction of the HADES underground research laboratory and its role in the development of the Belgian concept of a deep geological repository

Xiangling Li[1]*, Bernard Neerdael[2‡], Didier Raymaekers[3] and Xavier Sillen[3]

[1]EURIDICE, European Underground Research Infrastructure for Disposal of Nuclear Waste in Clay Environment, Boeretang 200, B-2400 Mol, Belgium

[2]SCK CEN, Belgian Nuclear Research Centre, Institute for Environment, Health and Safety, Belgium

[3]ONDRAF/NIRAS, Belgian Agency for Radioactive Waste and Enriched Fissile Materials, Kunstlaan 14, B-1210 Brussels, Belgium

XL, 0000-0001-7266-2108
‡Retired
*Correspondence: xiang.ling.li@euridice.be

Abstract: When the Belgian Nuclear Research Centre (SCK CEN) launched a research, development and demonstration programme on geological disposal in the 1970s, it was not certain if a deep geological repository could be constructed in poorly indurated clay. This was tested by constructing the HADES underground research laboratory (URL) in Boom Clay, 225 m below SCK CEN's site in Mol. The construction history of the URL reflects how the understanding of the Boom Clay increased and how the excavation techniques and design of the gallery lining improved. It demonstrated that shafts, galleries and crossings between galleries can be constructed using industrial techniques. It also allowed characterization of the hydromechanical response of the clay and the clay disturbances induced by the excavation. This increased understanding is also reflected in the evolution of the geological disposal concept considered in Belgium. The current disposal concept foresees the installation of seals in the shafts and galleries. The HADES URL also offered the opportunity to test possible seal designs and develop a better understanding of the behaviour of bentonite, a possible seal material, owing to its swelling capacity, under *in situ* conditions.

The research in the field of the long-term management of high-level and/or long-lived radioactive waste was initiated in 1974 in Belgium by the Belgian Nuclear Research Centre (SCK CEN). The research is focused on the Boom Clay: a poorly indurated clay layer that is found between 185 and 287 m below the site of SCK CEN in Mol. A decade later the responsibility for the definition and management of a research, development and demonstration (RD&D) programme was transferred to Belgian National Agency for Radioactive Waste and Enriched Fissile Material (ONDRAF/NIRAS). Today, geological disposal of these wastes in a poorly indurated clay is still the reference concept considered by ONDRAF/ NIRAS (ONDRAF/ NIRAS 2013; ONDRAF/NIRAS 2019*d*) for its RD&D programme. It is also used as a basis to evaluate what could be the future cost of such a solution for the long-term management of radioactive waste in Belgium, in the absence of a decision by the Belgian authorities on the principle of geological disposal, let alone on a host rock and a site. Two clay layers are considered to support and illustrate the generic RD&D programme of ONDRAF/NIRAS: the Boom Clay and the Ypresian clays.

The Boom Clay Formation belongs to the Rupelian, which is the geological part of the Tertiary Period with an age between 36 and 30 myr. It is found at a depth of about 185 m under the SCK CEN site of Mol, where it has a thickness of about 100 m. The Boom Clay layer is almost horizontal (it dips 1–2% towards the NE) and water-bearing sand layers are situated above and below it (Fig. 1).

Boom Clay is a silty clay characterized by a structure of bands that are several tens of centimetres thick, reflecting mainly cyclical variations in grain size (silt and clay content) owing to fluctuations in the wave action on the sedimentation medium and to variations in the carbonate and organic matter contents. Typical calcareous concretions, known as septaria, are found in the marly bands occurring throughout the thickness of the formation. Owing to its vertical lithological heterogeneity, the mineralogy of the Boom Clay is characterized by a wide variation in the content of clay minerals (from 30 to 70%

From: Li, X. L., Van Geet, M., Bruggeman, C. and De Craen, M. (eds) 2023. *Geological Disposal of Radioactive Waste in Deep Clay Formations: 40 Years of RD&D in the Belgian URL HADES.*
Geological Society, London, Special Publications, **536**, 159–184.
First published online February 16, 2023, https://doi.org/10.1144/SP536-2022-101

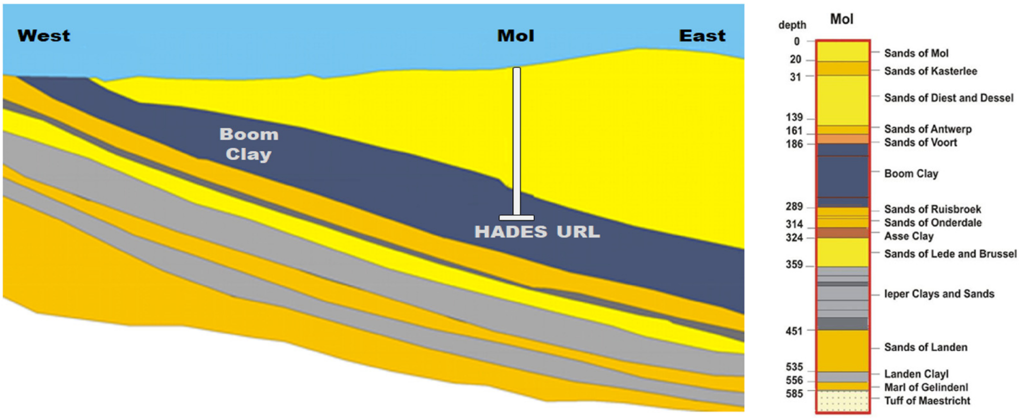

Fig. 1. Geological section under the Mol site.

volume, dry matter). In descending order of importance, the non-argillaceous fraction of the sediment consists of quartz, feldspars, carbonates and pyrite. The organic matter content ranges from 1 to 3% weight, dry matter. The water content ranges from 30 to 40% volume.

Boom Clay has a low hydraulic conductivity (on the order of 10^{-12} m s^{-1}) and displays a visco-elasto-plastic behaviour. This results in a relatively high convergence when excavating galleries in it and a capacity for self-sealing. At the level of HADES, the total stress and pore water pressure are respectively 4.5 and 2.25 MPa. The vertical stress is estimated to be higher than the horizontal one with a coefficient of earth pressure at rest of K_0 *c.* 0.7. The unconfined compressive strength is about 2–2.5 MPa.

In the early days of the research, it was questionable if it was possible to excavate a deep geological repository (DGR) in poorly indurated clay. That is why SCK CEN decided to construct the HADES (High-Activity Disposal Experimental Site) underground research laboratory (URL) in Boom Clay. The HADES was constructed at SCK CEN's site in Mol at a depth of 225 m. Its main purpose was to examine the feasibility of constructing a DGR in Boom Clay and to provide SCK CEN with a URL to conduct *in situ* experiments, including at large scale.

This paper presents the construction history of the HADES URL, as well as the lessons learned in terms of how the Boom Clay responds to the excavation and operation of the URL. The URL also offered the opportunity to perform sealing experiments. These have provided valuable information for designing repository seals and assessing their performance. Finally, the paper describes how the Belgian concept for geological disposal has evolved and how lessons learned from the construction of the HADES URL and from *in situ* experiments conducted there have contributed to the DGR design.

Construction of the HADES URL

The construction history of the HADES URL reflects how the understanding of the Boom Clay increased and how the excavation techniques and design of the gallery lining improved (Fig. 2). When the construction of the First Shaft started in 1980, there was little or no knowledge on and experience of excavating in a deep plastic clay formation at such depth. The construction of the shaft and the first galleries of the URL was therefore pioneering work. The goal was to demonstrate that it was possible to excavate galleries in Boom Clay at 225 m depth.

After this goal was achieved, the focus shifted to demonstrating that galleries could be constructed using industrial methods with minimum disturbance to the host rock. These methods were applied for the construction of the Second Shaft and the Connecting and PRACLAY galleries. They demonstrate how the HADES URL has enabled the testing, demonstration and optimization of technologies to construct, operate and close a DGR in poorly indurated clay.

The First Shaft (1980–82)

Before the construction of the First Shaft, the only knowledge about the mechanical behaviour of Boom Clay was based on lab tests on Boom Clay cores taken at the Mol site (De Beer *et al.* 1977). The Boom Clay was at that time expected to have a very plastic response and to more or less behave like toothpaste (Bastiaens *et al.* 2006). Therefore, it was decided to freeze not only the overlying sand aquifer prior to shaft sinking, but also the Boom

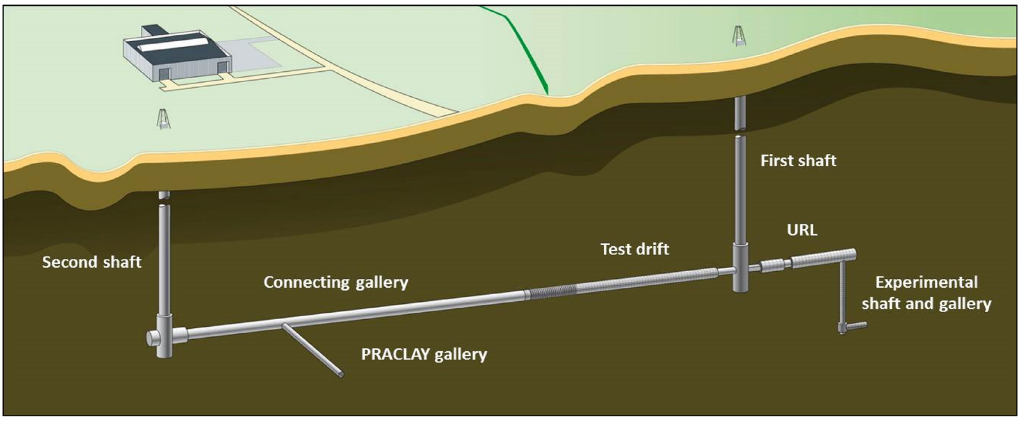

Fig. 2. Layout of the HADES underground research laboratory (URL).

Clay itself. The freezing was done by circulation of a $CaCl_2$ brine cooled to about −25°C through freezing tubes drilled around the circumference of the later excavation (Fig. 3).

The internal diameter of the shaft was limited to 2.65 m, as it was designed only for experimental purposes. Because of its small diameter, the shaft had to be excavated semi-manually using pneumatic hammers (Fig. 4), as a mechanical excavation was not feasible. The depth of the shaft is 230 m, the digging of the shaft started on 1 October 1980 and ended on 2 September 1982; consequently, an average excavation digging rate about 0.5 m/week was achieved.

The shaft lining consists of two 40 cm thick concrete layers. To make the lining watertight, a 5 mm thick polyethylene (PE) membrane was placed between the two concrete layers.

The shaft sinking proceeded as planned until the top of the Boom Clay. In the frozen clay mass, however, displacements of the unlined shaft wall reached up to 1 cm/day. The freezing (−12°C at the wall) was unable to prevent the movement of the clay towards the excavation, and therefore did not prevent the build-up of pressure on the lining. It was therefore necessary to modify the design by reducing the diameter of the crossing chamber from 6 to 4 m. The shaft water tightness was also not completely successful as water leaks were observed. This was probably due to the PE membranes in between the two concrete layers, which were damaged by clay settlement after thawing. The leaks were successfully remediated by injecting polyurethane.

The URL gallery and experimental excavations (1983–84)

The first gallery (26 m long and 3.5 m in diameter) was excavated manually in frozen clay at a depth of 225 m. The excavation was again done semi-manually using pneumatic hammers (Fig. 5a). Owing to limited knowledge, high safety factors and conservative values were used in the design calculations for the shaft and gallery linings (Fig. 5b; De Bruyn and Neerdael 1991). Cast iron segments with a thickness of 20 cm were used as the gallery lining. Some segments had openings providing access to the host clay for the various experiments. At the end of the gallery a 2.5 m thick concrete plug was

Fig. 3. Freezing tubes used to freeze the sand aquifer and Boom Clay before the excavation of the First Shaft.

Fig. 4. Semi-manual excavation of the First Shaft.

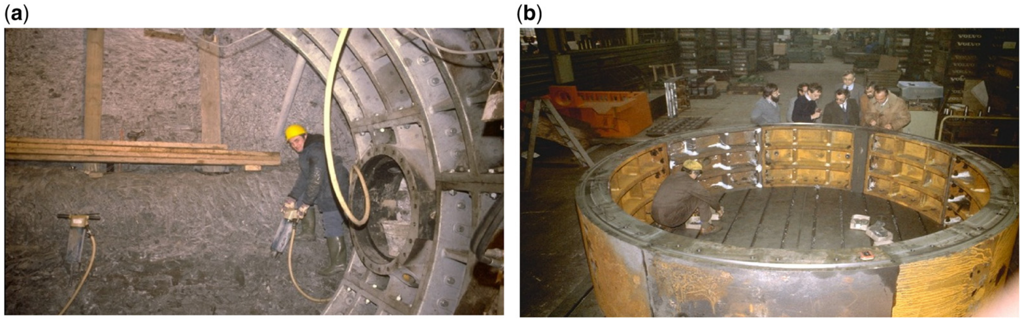

Fig. 5. (**a**) Semi-manual excavation of the URL gallery (an opening in the cast iron segment providing access to the clay can be seen next to the worker), and (**b**) cast iron lining used for this gallery.

constructed. In the end, an average excavation rate of only 1 m/week was achieved (Neerdael *et al.* 1991).

The tubes to freeze the clay prior to the excavation of the URL gallery were drilled from the First Shaft. They were not drilled parallel to the future gallery, but had a conical configuration. Freon freezing units were used with brine temperature of −32°C. The first measured displacements at the frozen excavation front were close to 3 mm/day. Freezing the clay prior to the excavation, however, was costly and induced perturbations in the clay.

The further the excavation progressed, the further the clay at the centre of the excavation front was from the freezing tubes. Towards the end of the URL gallery, it was observed that the clay in the centre of the excavation front was not frozen. However, the clay here did not behave as plastically as expected. This observation was confirmed in reconnaissance boreholes drilled in unfrozen clay.

Following these observations, it was decided to excavate a small experimental shaft and gallery in unfrozen clay (Fig. 6). The shaft was 24 m deep from the level of the URL gallery. This was deep enough to be outside the frozen clay and the damaged zone around the gallery. Close to the lowest level, an 8.5 m long gallery was excavated. Both excavations have a 2 m external diameter. Apart from excavating in unfrozen clay, a lining consisting of 30 cm thick concrete blocks was used instead of cast iron. Wooden plates were placed between the blocks to allow for some deformation of the lining and thus limit the stresses on the lining. No major difficulties were encountered as the creep of the unfrozen clay was lower than expected.

The Test Drift (1987)

With the construction of the experimental shaft and gallery, it was demonstrated, at a small scale, that it was possible to excavate galleries in unfrozen clay. It was also proven that a concrete lining could be used, which is less costly than a cast iron lining. This excavation method and lining were applied on a larger scale with the construction of the 65 m long Test Drift in 1987. The Test Drift has an internal diameter of 3.5 m and a 60 cm thick lining consisting of concrete blocks with wooden plates in between.

This demonstrated the feasibility of constructing galleries in unfrozen clay using a concrete lining at a scale representative of a DGR. However, the excavation techniques used were still semi-manual and an

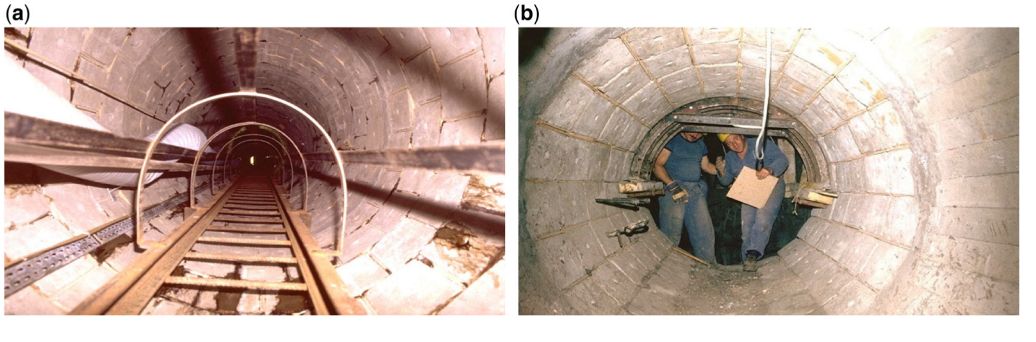

Fig. 6. (**a**) Experimental shaft and (**b**) experimental gallery.

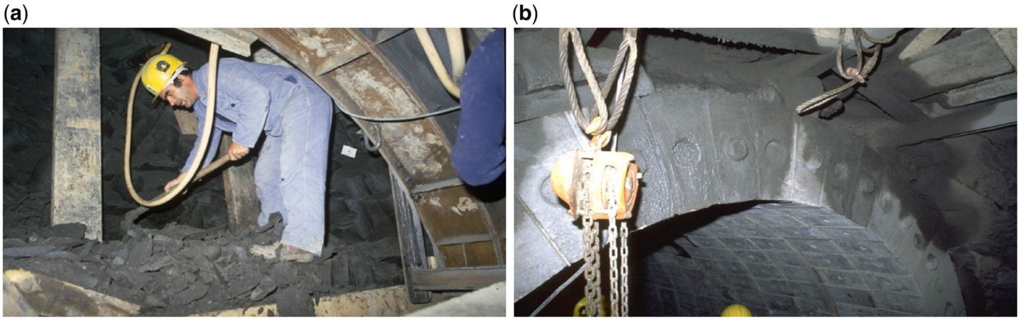

Fig. 7. (**a**) Semi-manual excavation of the Test Drift, and (**b**) lining consisting of concrete blocks with a relatively large over-excavation at the top of the lining.

excavation rate of only 2 m/week was achieved (Fig. 7; Neerdael *et al.* 1991; Bernier *et al.* 2007*a*, *b*). Another disadvantage of this excavation method was the large over-excavation needed to insert the concrete blocks at the top of the lining (Fig. 7b). This gap above the lining was filled with grout, but this method nevertheless resulted in a relatively large excavation damaged zone (EDZ) at the top.

The last 12 m of the Test Drift were lined with sliding steel ribs (TH-profiles; Fig. 8). Each lining ring consists of four steel profiles interconnected with 'friction clamps'. When the ground pressure on the lining exceeds a threshold, the ribs can slide, thereby limiting the loads at the cost of additional convergence, following the convergence/confinement theory. This type of lining was constructed in co-operation with Andra as part of their programme on the mechanical behaviour of deep clay formations (Rousset 1988, 1990) and to test the gallery support methods (Armand *et al.* 2023).

The Second Shaft (1997–99)

In the 1990s it was decided to expand the HADES URL. The Belgian mining authorities requested for safety reasons the construction of a second shaft before approving any extension of the URL. Therefore, the Second Shaft was constructed which was connected to the already existing galleries by the so-called Connecting Gallery.

Fig. 8. Section of the Test Drift which is lined using steel sliding ribs.

As by now the feasibility of excavating in unfrozen clay had been demonstrated, only the aquifer sands and the top of the transition zone were frozen. Sixteen freezing pipes were equally spaced on a 7 m diameter circle. The pipes were anchored into the top of the clay layer to a depth of 191 m. Two freezing groups using ammonia as the coolant were installed, each with a capacity of 250 kW, and $CaCl_2$ brine was pumped through the circuit at a temperature of −27°C.

The layout of the second shaft is shown in Figure 9. From the surface to the top of the Boom Clay the shaft has an external diameter of 4.5 m and an internal diameter of 3.0 m (Ramaeckers *et al.* 2000). From the top of the Boom Clay (at about 200 m depth) the shaft enlarges to external and internal diameters of respectively 10.3 and 5.0 m to allow the construction of the starting chamber of the Connecting Gallery.

The shaft was drilled using a jack hammer mounted on a work platform (Fig. 10a). An average excavation rate of 6 m/week was achieved. The lining in the aquifer sands consists of 20–40 cm thick shotcrete. At the top of the Boom Clay a concrete foundation was made upon which 30 cm thick prefabricated concrete rings were placed from the bottom to the top (Fig. 10b). These rings have an 8 mm steel impermeable membrane at their extrados (this is the outer side of the lining). The steel membranes were welded onsite. An annular gap of 10 cm was left between the inner and outer linings and filled with asphalt. The asphalt homogenizes the stresses on the inner lining and thus guarantees an isotropic loading of the inner lining. Furthermore, the asphalt also provides long-term waterproofing of the shaft.

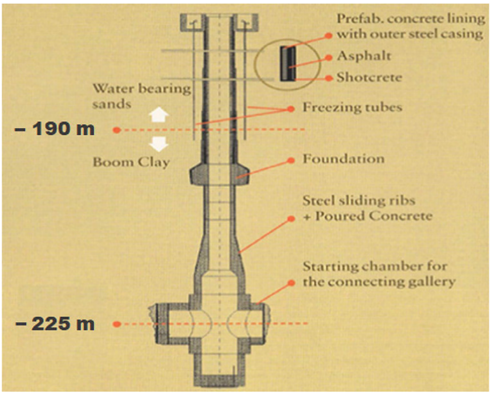

Fig. 9. Layout and design of the second shaft of the HADES URL.

In the shaft section excavated in Boom Clay, a primary lining of steel sliding ribs was placed during the excavation (Fig. 10a). In a later phase reinforced concrete with a minimum thickness of 80 cm was cast *in situ* from the bottom to the top.

Two problems arose during the construction of the second shaft. First, some clay collapsed and unexpected large shear planes were observed during the construction of the starting chambers at the bottom of the shaft (Bastiaens *et al.* 2003). The lack of active support during excavation of the starting chambers and the low excavation rate certainly favoured the development of the fractures and the detachment of clay blocks. A second problem concerns the asphalt layer that was poured between the inner and outer lining in the aquifer sands. After 5 years the asphalt level had dropped by *c.* 10 m, indicating asphalt leakage. As the inner lining is dimensioned for an isotropic load, guaranteed by the asphalt layer, refilling of the asphalt was needed.

The Connecting Gallery (2001–02)

From the Second Shaft, the 85 m long Connecting Gallery with an internal diameter of 4 m was constructed towards the Test Drift. This gallery was constructed using industrial techniques and trying to minimize the convergence of the clay (Bastiaens *et al.* 2003).

The excavation was done using a road header which was placed in a tunnelling shield (Fig. 11). The shield provides temporarily support to the clay around the excavated opening. The front edge of the shield smoothly carves out the excavation profile to a perfect circle while the clay inside the shield is excavated by the road header. The tunnelling shield moves forward by hydraulic jacks that push it forward against the lining that has already been built behind the shield.

The assembly of the lining is done at the rear end of the shield where there is a small unsupported zone. The lining consists of segments that are assembled to form a ring. This ring is expanded against the excavated clay massif by inserting one or more key segments or ‘wedge blocks’ (Fig. 12). Unreinforced

(**a**) (**b**)

Fig. 10. Excavation of the second shaft: (**a**) jack hammer assembled on hydraulic arm and steel sliding ribs as primary lining in the Boom Clay; (**b**) prefabricated concrete rings for the inner lining in the aquifer sands.

Fig. 11. Open-face tunnelling machine used for the construction of the Connecting Gallery during a test assembly on the surface.

concrete was chosen as the lining material. The high radial isotropic stresses on the lining induce a very low bending moment and it works almost exclusively in compression.

The lining and shield have almost the same diameter and thus the required over-excavation is very limited. Furthermore, the wedge block rings are expanded against the clay and therefore no additional annular grouting is necessary. The technique thus minimizes the excavation disturbed zone. It is only applicable in a narrow range of impervious homogenous clay-like media. This technique had already been used in the London clay (underground metrolines) and in the Boom Clay (technical crossings under the Scheldt River), although at much shallower depths.

The technique for constructing the Connecting Gallery was for the first time applied in a poorly indurated clay at a depth of 225 m. Owing to the plastic nature of the clay, it converges relatively rapidly. It was therefore important to maintain a fast construction rate to limit the clay convergence and to avoid entrapment of the shield in the clay. Therefore, a working regime of 24 h a day and 7 days a week was established. This resulted in an average construction rate of 3 m/day. The progress rate was limited by the capacity of the shaft hoisting system to remove the excavated materials. The measured radial convergence of the Boom Clay was in the order of tens of millimetres on radius, which is considered acceptable in terms of hydromechanical disturbances.

(a) (b)

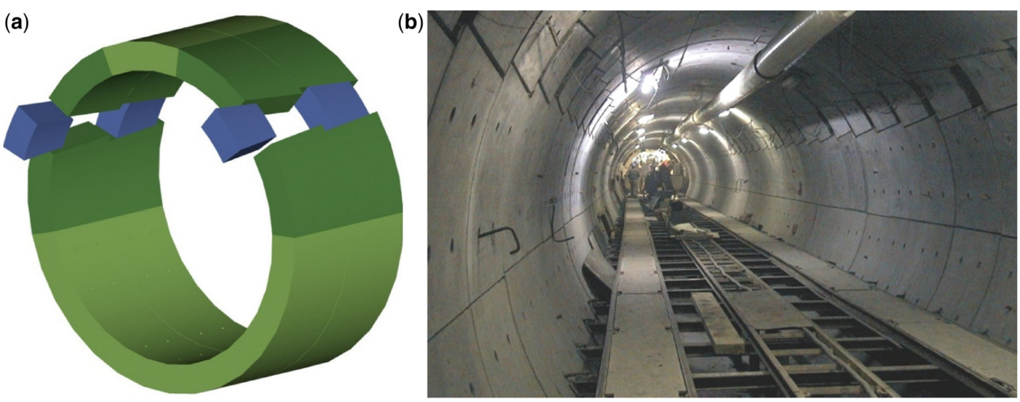

Fig. 12. (**a**) Principle of the construction of a wedge-block lining ring by inserting key elements in the ring and (**b**) the concrete wedge-block lining of the Connecting Gallery.

The PRACLAY Gallery (2007)

In 2007 the same type of lining and construction technique were used for the construction of the PRACLAY Gallery (Van Marcke *et al.* 2013). The PRACLAY Gallery has a smaller diameter (1.9 m internal diameter; Fig. 13a). A construction rate of 2 m/day was achieved and the clay convergence was on the same order of magnitude as for the Connecting Gallery.

The lining consisted of 30 cm thick unreinforced concrete segments. The PRACLAY Gallery hosts the large-scale PRACLAY Heater Test, to study the effect on the Boom Clay of the thermal loading that would be imposed by heat-emitting vitrified high-level waste or spent nuclear fuel. The gallery lining needs to withstand a thermal load (Dizier *et al.* 2016; Chen *et al.* 2022). To limit the stress increase in the lining during the Heater Test, compressible materials were inserted in the gallery lining (Fig. 13b). The performance of the lining will be evaluated during the PRACLAY Heater Test.

The PRACLAY Gallery was constructed perpendicular to the Connecting Gallery and thus a crossing between the two galleries needed to be constructed. This crossing was realized by installing a steel reinforcement ring in the Connecting Gallery before excavating the PRACLAY Gallery (Fig. 14). The ring consisted of 11 cast steel segments. These segments were bolted together and the annular space between the structure and the gallery lining was filled with grout to ensure a good load transfer of the host rock on the structure.

This demonstrates the feasibility of constructing such crossings. However, such steel reinforcement rings are very expensive and it was attempted to minimize the amount of steel in the repository as the anaerobic corrosion of steel will lead to hydrogen gas generation. The ring also reduces the internal diameter of the Connecting Gallery at the crossings.

At the very end of the PRACLAY Gallery, a stop-and-go test was performed. The excavation works were stopped for one week to test the level of difficulty of restarting the tunnelling machine in the case of stopping. During such a standstill the Boom Clay around the shield converges and the friction between the clay and the shield increases. After one week of standstill the excavation works were restarted. The thrust force needed to push the shield forward was about twice the normal thrust force, but this was still only 25% of the maximum available force. The works could restart without any problem.

Hydromechanical response of the Boom Clay to gallery excavation

The excavation of shafts and galleries will disturb the clay in which these are constructed. The clay will converge towards the openings and the stresses and pore water pressures in the clay will change, which can cause fracturing of the clay. This may in turn affect the clay's permeability. Characterizing this EDZ and evaluating its impact on the clay properties will be an important part of a safety assessment for geological disposal.

Therefore, an extensive research programme was established to monitor the hydromechanical response of the Boom Clay to the excavations of the Connecting and PRACLAY galleries and to characterize the EDZ. Pore water pressures, host rock stresses and displacements were measured. The fractures induced by the excavations were also mapped and examined. In addition, specific research was done to characterize the self-sealing behaviour of the Boom Clay.

(a) (b)

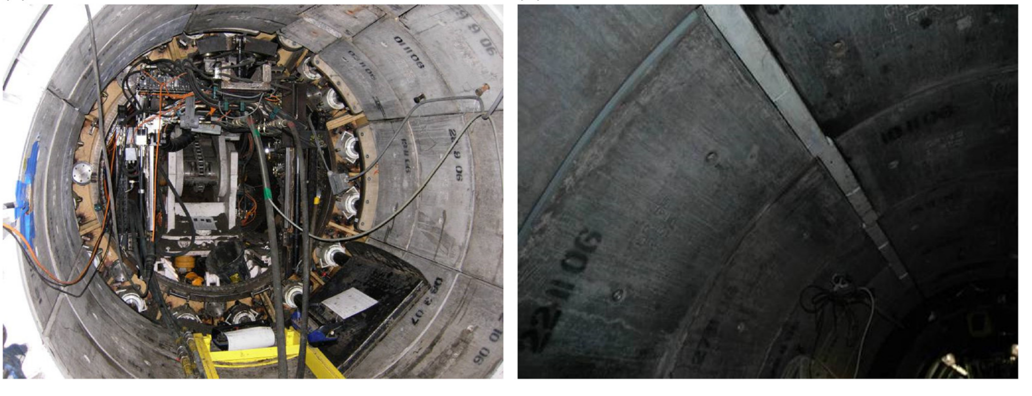

Fig. 13. (**a**) Rear view of the tunnelling shield excavating the PRACLAY Gallery, and (**b**) compressible materials (white blocks) in the lining to limit the thermally induced stresses.

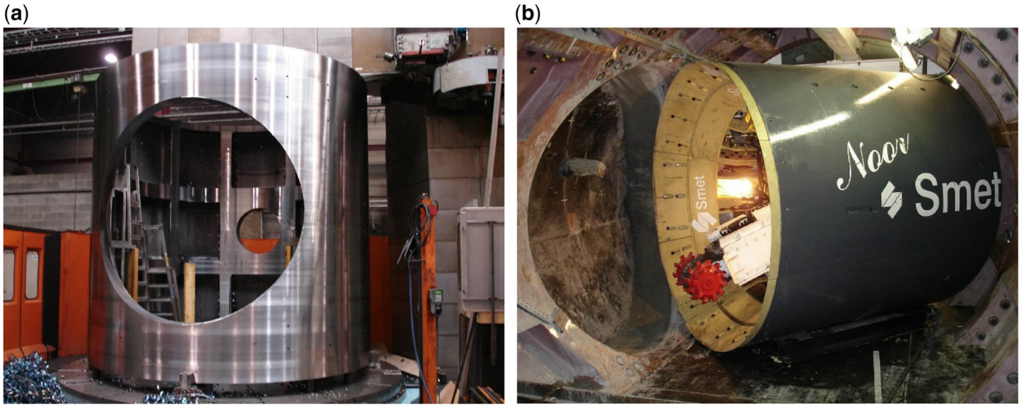

Fig. 14. (**a**) The reinforcement ring during a test assembly in the workshop and (**b**) positioning of the tunnelling machine inside the opening of the reinforcement ring.

Characterization programme for the Connecting Gallery

Within the framework of the EC CLIPEX instrumentation programme (Clay Instrumentation Programme for the Extension of an Underground Research Laboratory), a series of instrumented boreholes were drilled from the Second Shaft and the Test Drift prior to the construction of the Connecting Gallery (Fig. 15). Because this gallery was excavated from the Second Shaft towards the Test Drift, boreholes drilled from the Test Drift allowed sensors to be installed ahead of the excavation front. The sensors installed in the clay were displacement, pore water and total pressure sensors. In addition, strain gauges in the lining segments of the gallery enabled the monitoring of stresses in the lining.

All pore water pressure sensors installed from the Test Drift registered a similar evolution (Fig. 16). When the excavation front approaches, there is a progressive increase in the pore water pressure. This is due to the undrained contractant behaviour of the clay as the stress field becomes less isotropic as the excavation front approaches. Owing to the low hydraulic conductivity of the clay (Yu *et al.* 2013), the pore water cannot dissipate sufficiently fast and the pore water pressure increases as well. This gradual increase is followed by a sharp drop when the excavation front has come very close and the clay decompresses. This illustrates the hydromechanical coupling behaviour of the Boom Clay. Once the gallery lining is placed, further convergence of the clay is prevented. Pore pressures then slowly evolve as water is drained from the far field towards the EDZ

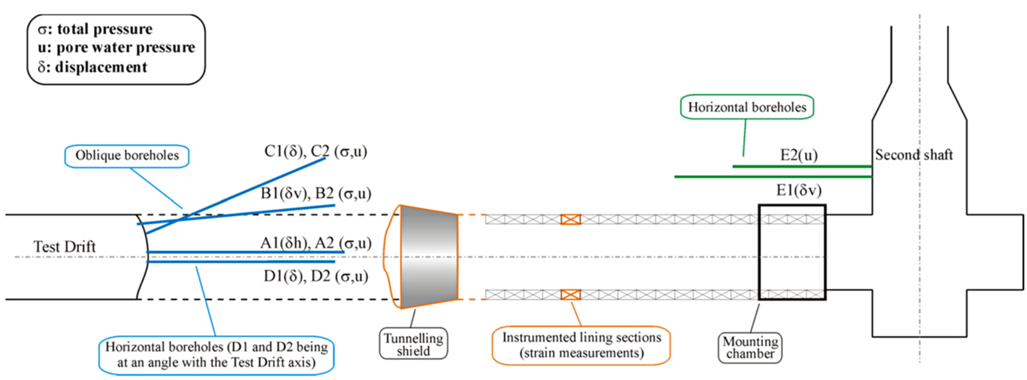

Fig. 15. Instrumented boreholes are drilled from the Test Drift and the Second Shaft to monitor the hydromechanical response of the clay to the construction of the Connecting Gallery.

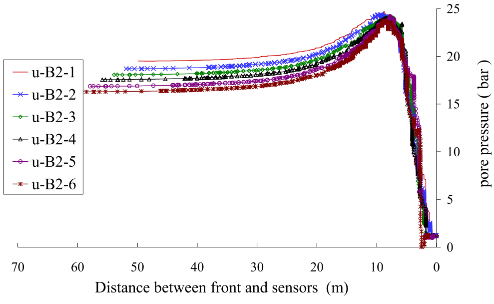

Fig. 16. Pore water pressure measurements of an inclined piezometer installed from the Test Drift.

and the gallery. As drainage proceeds, the clay progressively consolidates.

At about the same time as the start of the EC SELFRAC project (Fractures and Self-Healing within the Excavation Disturbed Zone), the Connecting Gallery was constructed. The main objective of the EC SELFRAC project was to understand and to quantify the fracturing and the sealing/healing processes (Bernier *et al.* 2007*a*, *b*). A significant effort was therefore made to observe, photograph and map the fractures in the excavation front and sidewalls of the Connecting Gallery during its construction. This resulted in a detailed database describing fracture type (tension, shear, etc.) and orientation over the whole length of the gallery (Bastiaens *et al.* 2003; Mertens *et al.* 2004). A herringbone-like fracture pattern was consistently observed. Also, some cored borings were carried out after the tunnel was constructed. They indicated a radial fracture extent of about 1 m. Field observations and numerical modelling showed that the fractures originated some 6 m ahead of the excavation face (Fig. 17).

Soon after the construction of the Connecting Gallery, three 40 m long piezometers, equipped with 10 or so filters each, were installed in the clay from the Connecting Gallery: one downward, one horizontal and one in between these two with a downward inclination of 45°. The measurements from the horizontal and vertical piezometers showed that the pore water pressures were affected respectively 20 and 40 m from the Connecting Gallery. The anisotropy of this hydraulically influenced zone can be explained by the anisotropic mechanical properties of the clay and the anisotropic stress state (K_0 ~0.7; Bernier *et al.* 2003).

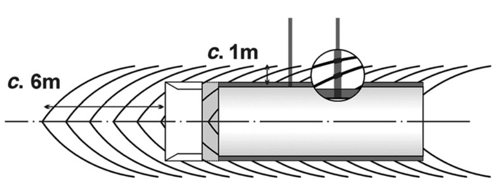

Fig. 17. Observed fracture pattern around the Connecting Gallery (vertical cross-section). The fractures are believed to originate about 6 m ahead of the excavation front and their radial extent is estimated to be about 1 m.

The hydraulic conductivity around the Connecting Gallery was measured. It appeared that an increase of 2–3 times the undisturbed value could be observed within the first 6–8 m around the gallery. However, the measured conductivities tend to return to their undisturbed values. This shows the self-sealing capacity of the Boom Clay as further discussed below.

Characterization programme for the PRACLAY Gallery

Before the construction of the PRACLAY Gallery, boreholes were drilled from the Connecting Gallery to install stress, pore water pressure and displacement sensors. Strain gauges were also embedded in segments of the PRACLAY Gallery (Verstricht *et al.* 2022).

The observations and measurements were in line with those of the characterization programme for the Connecting Gallery. They confirmed the highly coupled and anisotropic hydromechanical behaviour of the Boom Clay and known fracturing processes. Also the large extent of the hydraulically influenced zone was observed (Li *et al.* 2006; Van Marcke *et al.* 2013).

It was tried to determine the radial extent of these factures from cores taken around the gallery but it was not possible to make a distinction between fractures induced by the excavation of the gallery and fractures induced by the drillings themselves. An indication on the extent of the open fracture zone can, however, be derived from the sulfate concentrations as measured in pore water from the filters placed in the vicinity of the gallery. The clay in a fracture plane oxidizes and sulfate is formed in the pore water as the oxygen comes into contact with pyrite in the Boom Clay. Thus, when a fracture extends up to a filter, the filter will measure increased sulfate concentrations in the pore water. Fifteen 0.5 m long filters were placed in a horizontal borehole drilled from the Connecting Gallery at a distance of 0.6 m from the PRACLAY Gallery extrados. No increased sulfate concentrations were measured in these filters, indicating that open fractures around the gallery do not extend beyond a radial distance of 0.6 m (Van Marcke *et al.* 2013; De Craen *et al.* 2008, 2011).

Characterizing the Boom Clay self-sealing behaviour

During the consolidation of the clay around the excavation, a self-sealing process occurs as the open fractures close progressively. This results from the swelling of the clay when it rehydrates and from its visco-plastic behaviour. Evidence of self-sealing of Boom Clay was observed from coring and instrumentation campaigns as the clay appeared to close spontaneously against the borehole casings. Open boreholes close up completely and if there is a cased opening in the gallery lining, the Boom Clay will be squeezed out through this opening into the gallery (ONDRAF/NIRAS 2013; Fig. 18).

Within the EC SELFRAC project, both lab tests and *in situ* measurements were done to better understand the sealing process of Boom Clay (Bernier *et al.* 2007*a*, *b*). The fast self-sealing of Boom Clay was demonstrated in the lab using an artificially fractured clay sample. A computed tomography image of the sample was taken after it was fractured. The sample was then left to saturate and after 4.5 h another computed tomography image was taken. The images show the closure of the fracture (Fig. 19).

The sealing was also confirmed by measuring the hydraulic conductivity of the sample. After a few months the conductivity returned to the same order of magnitude as the undisturbed value (10^{-12} m s^{-1}). As mentioned above, this was also observed by *in situ* measurements of the hydraulic conductivity around the Connecting Gallery.

Another experiment monitored how the EDZ around a partially cased borehole evolved. This was done by drilling a central borehole from the Test Drift (Fig. 20). Four 8.2 m long observation boreholes were drilled around the central borehole. Seismic and acoustic transmitters and receivers were installed in the observation boreholes between 5 and 8 m depth. The receivers could detect disturbances and reveal the evolution of Boom Clay sealing around the central borehole.

These tests showed that the fractures in the EDZ around a gallery will close over time and that the hydraulic conductivity of the clay in this zone restores to its undisturbed value.

Buffer and sealing experiments

The current geological disposal concept considered by ONDRAF/NIRAS foresees the installation of seals in the shafts and galleries. The purpose of these seals is to create a physical barrier to the waste. This contributes to waste isolation and helps to compartmentalize the repository which, in turn, can limit the impact of incidents if they occur in one part of the repository (ONDRAF/NIRAS 2013). The specific requirements for these seals remain to be defined, but experiments have been conducted in the HADES URL to test possible seal designs and develop a better understanding of the behaviour of clay-based materials, more specifically the bentonite, a possible seal material owing to its swelling capacity upon hydration under *in situ* conditions.

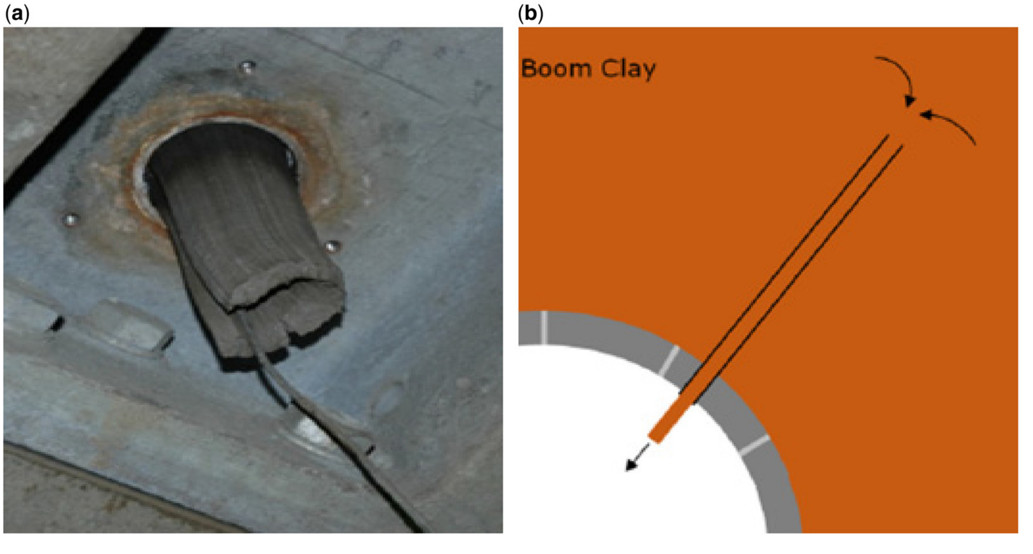

Fig. 18. (**a**) Creep of Boom Clay into the HADES URL; and (**b**) schematic representation of creep of Boom Clay. Source: ONDRAF/NIRAS (2013).

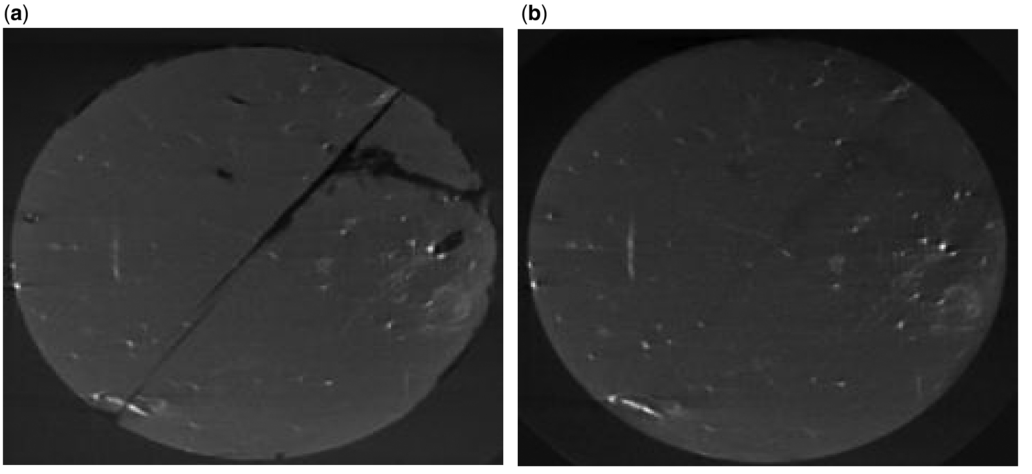

Fig. 19. Computed tomography images of an artificially fractured Boom Clay sample: (**a**) immediately after fracturing; and (**b**) a few hours after the sample was left to saturate.

The BACCHUS 1 and 2 experiments

The BACCHUS experiments investigated the thermo-hydro-mechanical behaviour of the clay host rock and clay-based buffer and sealing materials, in the context of the disposal of heat-emitting waste (Bernier and Neerdael 1996; Bernier *et al.* 1995). This was done by installing a heater down a vertical borehole (Fig. 21). The borehole section where the heater was placed was not lined. The annular void between the heater and the clay was filled by ring-shaped blocks of a compacted FoCa clay (a calcium bentonite from the Paris Basin)–sand–graphite mixture. Above the heater, a sealing plug was placed composed of four circular blocks of Boom Clay which were recompacted to a density equivalent to the *in situ* density. The cables of instrumentation passed through a tube placed in the centre of this plug.

The test set-up was installed in November 1988 and in March 1989 the heater was switched on increasing the temperature at the buffer-host rock interface to 100°C. The heating phase lasted until June 1990. After switching on the heater, the hydration of the compacted clay and mixture was monitored, together with the swelling pressure and temperature at the interface with the clay host rock (Neerdael *et al.* 1992).

In 1993 the complete test set-up was retrieved and another test set-up, called BACCHUS 2, was installed. The sealing material consisted of a mixture of Boom Clay pellets and powder. The powder–pellet ratio and the density, size and water content of the pellets will control the behaviour of the sealing material. There was no thermal loading in this test. Its main aim was to study the hydration processes of the buffer and interaction between the buffer and the clay host rock (Bernier and Neerdael 1996).

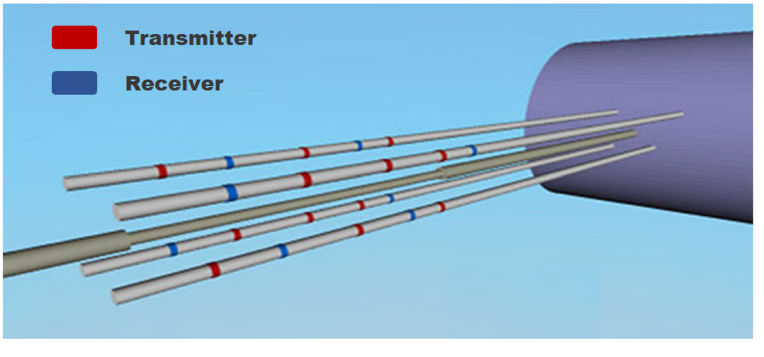

Fig. 20. 3D illustration of the central borehole and the four instrumented boreholes drilled from the Test Drift.

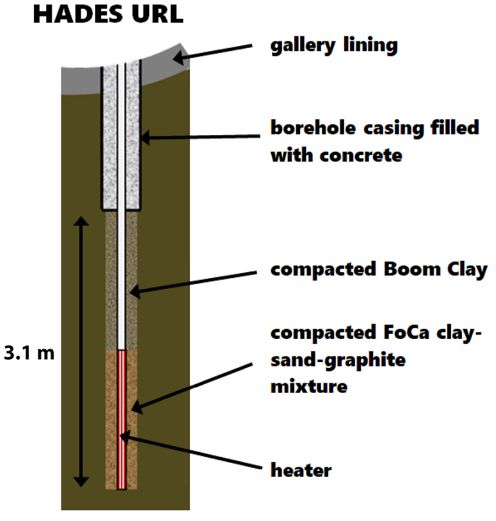

Fig. 21. Schematic view of the BACCHUS Experiment 1.

Both tests allowed study of the evolution of the thermal-hydro-mechanical behaviour of the used materials during the saturation process and optimization of the installation of the clay-based materials (Bernier and Neerdael 1996).

The RESEAL Experiment

For this experiment a bentonite seal was installed in a small experimental shaft (diameter: 2 m) (Fig. 22) (Volckaert *et al.* 2000; Van Geet *et al.* 2009). Before installing the seal, the bottom of the shaft was filled with grout. The concrete lining at the location of the seal was removed over a vertical length of 2.2 m and this section of the shaft was then filled with a mixture of 50% powder and 50% highly compacted pellets of FoCa clay. A 1 m high concrete lid was placed on top of the seal to keep it in place.

The goal was to demonstrate the feasibility of installing a seal with a hydraulic conductivity not higher than that of undisturbed Boom Clay. The powder–pellet mixture was optimized beforehand in the laboratory to obtain a good balance between saturation time, swelling pressure, hydraulic conductivity and ability to be compacted (Van Geet *et al.* 2005; Villar *et al.* 2005).

It took about 6 years to fully saturate the seal. After saturation, the hydraulic conductivity of the EDZ around the seal and of the seal itself were in the range of the hydraulic conductivity of the undisturbed host formation. The hydromechanical evolution was monitored by measuring total stress, water pressure, relative humidity and displacements. Two gas breakthrough tests were performed by injecting gas on a filter in the middle of the seal. After these two tests, the hydraulic conductivity at the injection filter came back to its original value, demonstrating the good self-sealing capacity of the FoCa clay.

The experiment demonstrated that it is feasible to install a seal in a shaft in Boom Clay and showed that the seal was effective. It also increased the knowledge of the parameters influencing the *in situ* hydromechanical behaviour of bentonite. It was also learned that it took longer than originally expected to reach full saturation and that artificial hydration only has a limited effect on this duration (Van Geet *et al.* 2008, 2009).

The PRACLAY Seal Test

The PRACLAY Heater Test requires undrained conditions. These conditions are realized by installing a seal at the intersection between the heated and the

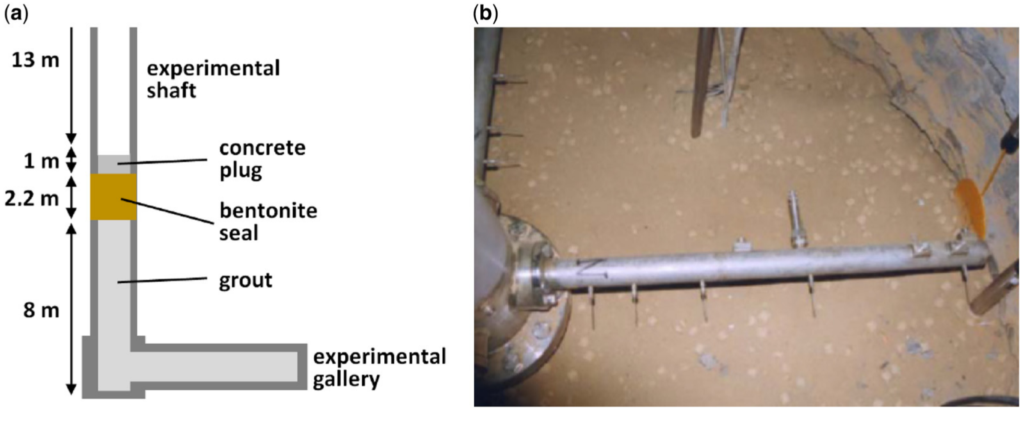

Fig. 22. (**a**) Layout of the RESEAL experiment in the HADES URL, and (**b**) a picture of the FoCa clay and part of the instrumentation that was installed in the seal.

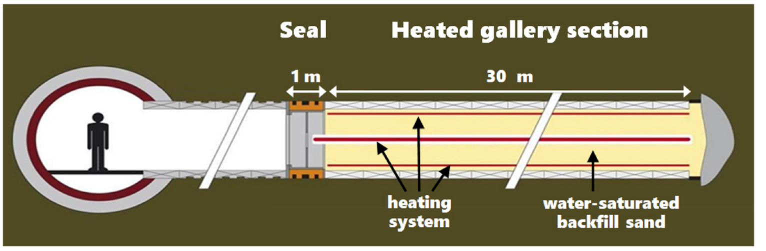

Fig. 23. Cross-section of the PRACLAY Gallery which hosts a heater and seal test.

non-heated part of the gallery (Fig. 23; Van Marcke 2013; Van Marcke *et al.* 2014).

The seal consists of an annular ring of compacted bentonite placed against the clay and a stainless-steel structure enclosing the bentonite and closing off the heater part (Fig. 24). This seal design is oriented to creating the required boundary conditions for the heater test and is not meant as a prototype for a seal in a disposal facility.

It was decided to use MX80 bentonite compacted into blocks. The bentonite is chosen as seal material for its good swelling capacity upon hydration and for its low permeability. Relevant experience and information with this type of bentonite exists from its use in other experiments in underground research facilities (Mont Terri, Bure, ASPO and AECL URLs) and in the laboratory by CEA (Atomic Energy Commission, France; Gatabin *et al.* 2006), CIEMAT (the Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, Spain; Villar 2005; Villar *et al.* 2005), CERMES (the geotechnical group of Laboratoire Navier, Ecole des Ponts ParisTech, France; Tang 2005) and SKB (Swedish Nuclear Fuel and Waste Management Company; Borgesson and Hernelind 1999). Furthermore, it is a Na-bentonite which makes it chemically compatible with Boom Clay water. The initial dry density of the bentonite (1.8 t m^{-3}), which affects its swelling pressure and its saturated permeability, was determined by scoping calculations (Chen and Li 2011; Chen *et al.* 2012).

The hydraulic seal was installed in 2010. The bentonite was then hydrated both artificially through injection filters in the seal structure and naturally by water from the clay host rock. The hydration occurred very slowly, confirming the observation made in the RESEAL Experiment. By the end of 2014, the bentonite swelling pressure was sufficiently high to create the conditions required to start the heater test.

During the heating phase the pore water pressures inside the PRACLAY Gallery increased to 2.7 MPa. The seal closed off the gallery as intended and maintained the water pressure inside the heated section of the gallery. The high pore water pressure gradient over the seal (from non-heated to heated section) indicates that the seal is fulfilling its role in creating quasi-undrained hydraulic boundary conditions (Dizier *et al.* 2016, 2021). Despite the successful installation of the PRACLAY Seal, the assembly of the seal components in a very limited workspace turned out to be far from straightforward, revealing the complexity of such underground operations.

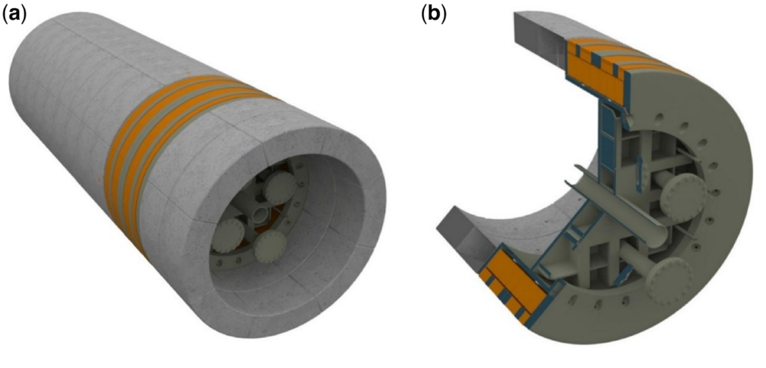

Fig. 24. Schematic drawing of the PRACLAY seal in the HADES URL: (**a**) the PRACLAY Gallery lining and the hydraulic seal; and (**b**) and cross-section of the steel structure and bentonite ring drawn in orange.

Downloaded from https://www.lyellcollection.org by Guest on May 04, 2025

Evolution of the Belgian geological disposal concept

Following international recommendations to isolate radioactive waste in a DGR, SCK CEN launched an RD&D programme on geological disposal in the 1970s, with financial support from the European Commission. SCK CEN chose to concentrate its efforts on investigating the poorly indurated Boom Clay. The characteristics of this clay formation met the broad criteria defined for potential host formations at European level (Commission of the European Communities 1980) and it was present at convenient depth and thickness under SCK CEN's site in Mol.

The 'HADES' concept

During the first years, lab tests were conducted on core samples and drilling and seismic campaigns were launched from the surface. However, the benefit of constructing a URL soon became apparent. The URL would allow testing of whether it is feasible to construct a DGR in Boom Clay and would make it possible to conduct *in situ* measurements and experiments. At that time, developing the repository concept and constructing the URL were essentially seen as one project. This is reflected in some of the design choices for the HADES URL. An example is its exact depth. This is not at midplane depth, which would have been a logical choice, but a few metres above that. The reason can be found in the repository design at the time: high-level waste packages would be disposed of in vertical or inclined tubes below that gallery (Fig. 25, ONDRAF/NIRAS 1989).

In turn, the early designs reflect the technologies and materials used in the first phase of the construction of the URL. These were also largely influenced by the prevailing knowledge (at the time) of the mechanical behaviour of Boom Clay at depth. High loads were anticipated on the shaft and gallery lining in the clay, which was perceived as a mechanically weak material with a considerable potential for creep and thus rapid closure of unsupported cavities.

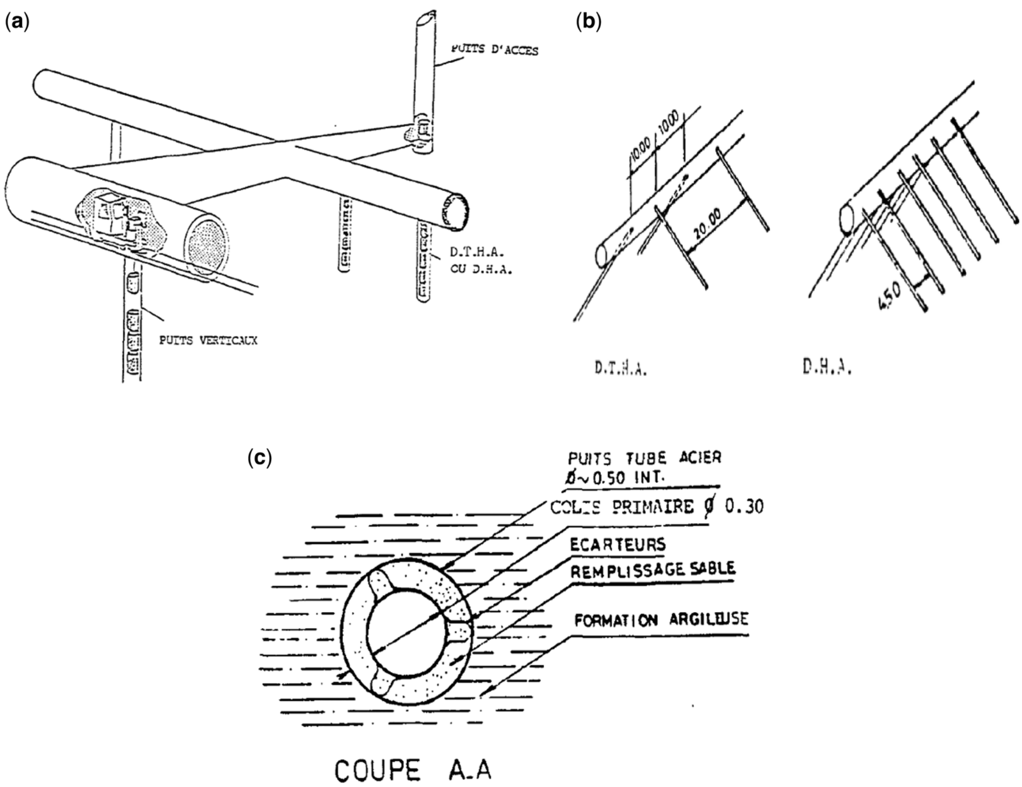

Fig. 25. Early designs of a deep geological repository for high level waste in Boom Clay ('HADES/radial' concept): (**a**) general layout for high level waste (D.H.A.) and heat emitting high level waste (D.H.T.A.); (**b**) alternative layout with inclined disposal tubes (lengths are in metres); and (**c**) cross-section of a disposal tube and waste package, with metallic spacers ('écarteurs') and sand backfill.

Part of this perception can probably be traced to an early lab test programme considering the low-permeability porous media and its pore water as a single 'lumped' material for all practical purposes, and thus missing part of the hydromechanical couplings that affect the clay's behaviour during excavation.

To provide the required strength and stiffness while limiting the lining thickness, cast iron segments were then preferred over a thicker concrete lining which would have reduced the effective diameter or required a larger excavation and more extensive freezing. Disposal tubes would have cutting edges and be pushed segment by segment into the clay through openings in the cast-iron lining using hydraulic jacks. Segments would be welded together while the clay cuttings would be continuously removed from the advancing tube. Some sort of plug would be cast at the bottom of the tube before inserting the waste packages. The tube would be closed by backfilling with sand and sealing/shielding at its top.

One could also note that, compared with current repository designs, the engineered barriers in the early repository concepts were reduced to the bare essentials, consisting of the primary waste package (e.g. for vitrified high-level waste, the stainless steel COGEMA canister), the metallic disposal tube and its end plugs. This reflects the weight attributed to the clay host layer as the primary barrier and to a lesser extent the slow dissolution of the high-level waste matrices for ensuring the long-term performance of the disposal system.

The disposal concept for intermediate-level long-lived waste (ILW) was equally basic at this pioneering time (Fig. 26, ONDRAF/NIRAS 1989). In contrast, most techniques used for the sinking the first shaft of the HADES URL through the highly permeable aquifer overlying the host rock and the shaft design were found very effective and are still those considered today. These were improved during the construction of the Second Shaft of the URL.

The 'axial' concept

The 1980s were marked by important evolutions of the repository concept. The commissioning of the HADES URL and experience gained during this pioneering phase profoundly changed the way future excavations in the Boom Clay were planned. Also, ONDRAF/NIRAS was established in 1980. This agency became responsible for developing solutions for the long-term management of all radioactive waste in Belgium. In line with its mission, ONDRAF/NIRAS gradually got involved in the development and operation of the HADES URL and progressively took over the development of the repository concept.

When excavating the First Shaft in frozen clay, large displacements were encountered. These perturbations to the clay host rock, the high cost and other related problems caused by the freezing technique led to the conclusion that a technique to excavate in unfrozen clay was necessary. The construction of the experimental shaft and gallery drift from the end of the URL were the first promising indications that underground works in unfrozen Boom Clay were not only possible, but even easier than in frozen clay. This was confirmed by the construction of the Test Drift in 1987.

At the same time, it became increasingly recognized that the behaviour of both the clay and its pore water had to be considered for understanding their combined mechanical behaviour. Hence, significant progress was made in the characterization and understanding of the hydromechanical couplings that determine the behaviour of Boom Clay. This

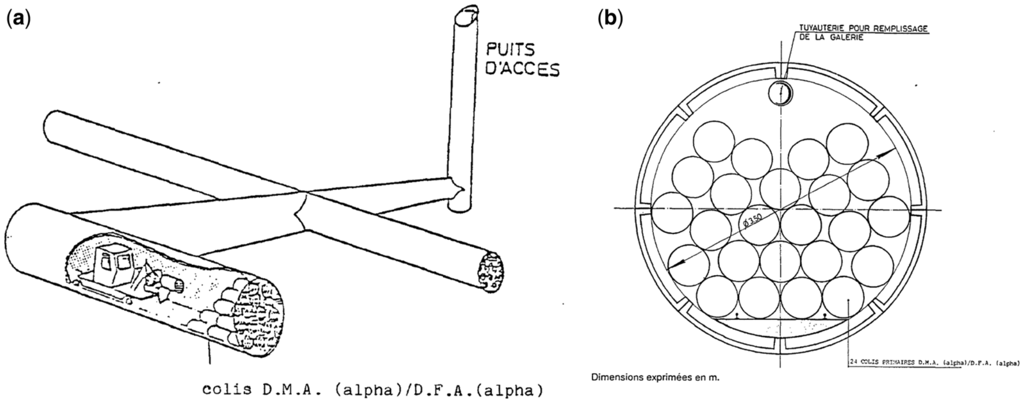

Fig. 26. (**a**) Early layout for the disposal of intermediate-level long-lived waste (ILW) in Boom Clay; and (**b**) cross-section of a disposal gallery ('HADES' concept).

increased confidence in the possibility of constructing a DGR in Boom Clay using more conventional deep tunnelling techniques that led to the proposal of a new repository design (Fig. 27, ONDRAF/NIRAS 1989).

This was called the 'axial' concept because high-level waste would be disposed in long, horizontal, concrete-lined galleries instead of in short vertical or inclined disposal tubes. The fact that it was also referred to the 'Belgian' concept rather than the 'HADES' concept perhaps indicates a change of mind about the role of the HADES URL: from a mock-up repository towards a testbed for technologies for DGR construction and a laboratory to study the clay's response to the various thermal, hydraulic, mechanical and chemical perturbations to which it would be exposed to.

The 'SAFIR 2' concept

The 1990s were marked by refinements of the Belgian concept and the preparation of new extensions of the HADES URL with the Second Shaft and the Connecting Gallery. During that period, repository concepts were also being developed in several other countries. Most of these considered the use of bentonite for key components of the engineered barrier system such as backfills, buffers, plugs and seals. Bentonite was also proposed as buffer material in the Belgian concept, as can be seen in the repository concept presented in SAFIR 2 report (Fig. 28, ONDRAF/NIRAS 2001).

The SAFIR 2 concept implements the idea of a multi-barrier system with clear and complementary roles assigned to the different engineering barrier system (EBS) components. The waste packages were to be pushed by a robot into long steel disposal tubes along or parallel to the gallery axis (Fig. 28b, c). These tubes were to be designed to ensure that no groundwater would come into contact with the packages until the end of the thermal phase. This is the phase during which the host rock is at an elevated temperature (i.e. higher than 25°C) owing to the heat generated by the waste. This phase lasts several hundreds to thousands of years for vitrified high-level waste and spent fuel, respectively. This would ensure that waste package corrosion and radionuclide diffusion through the pore water of the bentonite and the host clay after failure of the packages would occur in (near) isothermal conditions.

Bentonite blocks would be installed around the tubes to mechanically protect them and limit the transport of solutes through the EBS. Sand would be mixed in with the bentonite to limit the swelling pressure upon hydration.

The lining of the galleries in the SAFIR 2 concept was to be constructed using the 'wedge block' technique (Fig. 12). This design was successfully tested with the construction of the Connecting and PRACLAY Gallery. This confirmed that the SAFIR 2

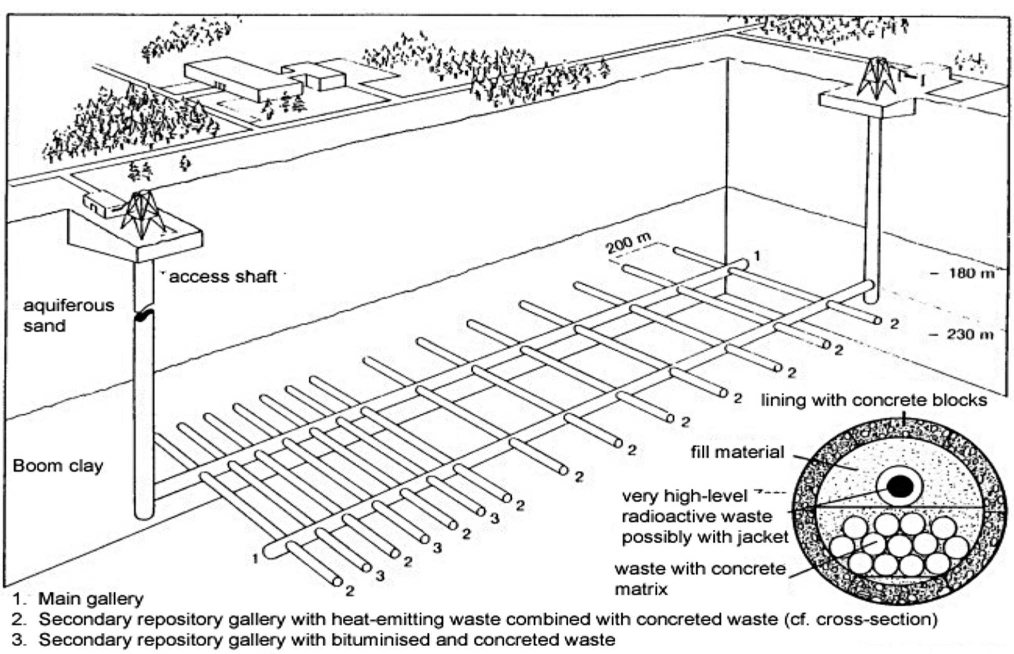

Fig. 27. The 'axial' or 'Belgian' repository concept as of 1989.

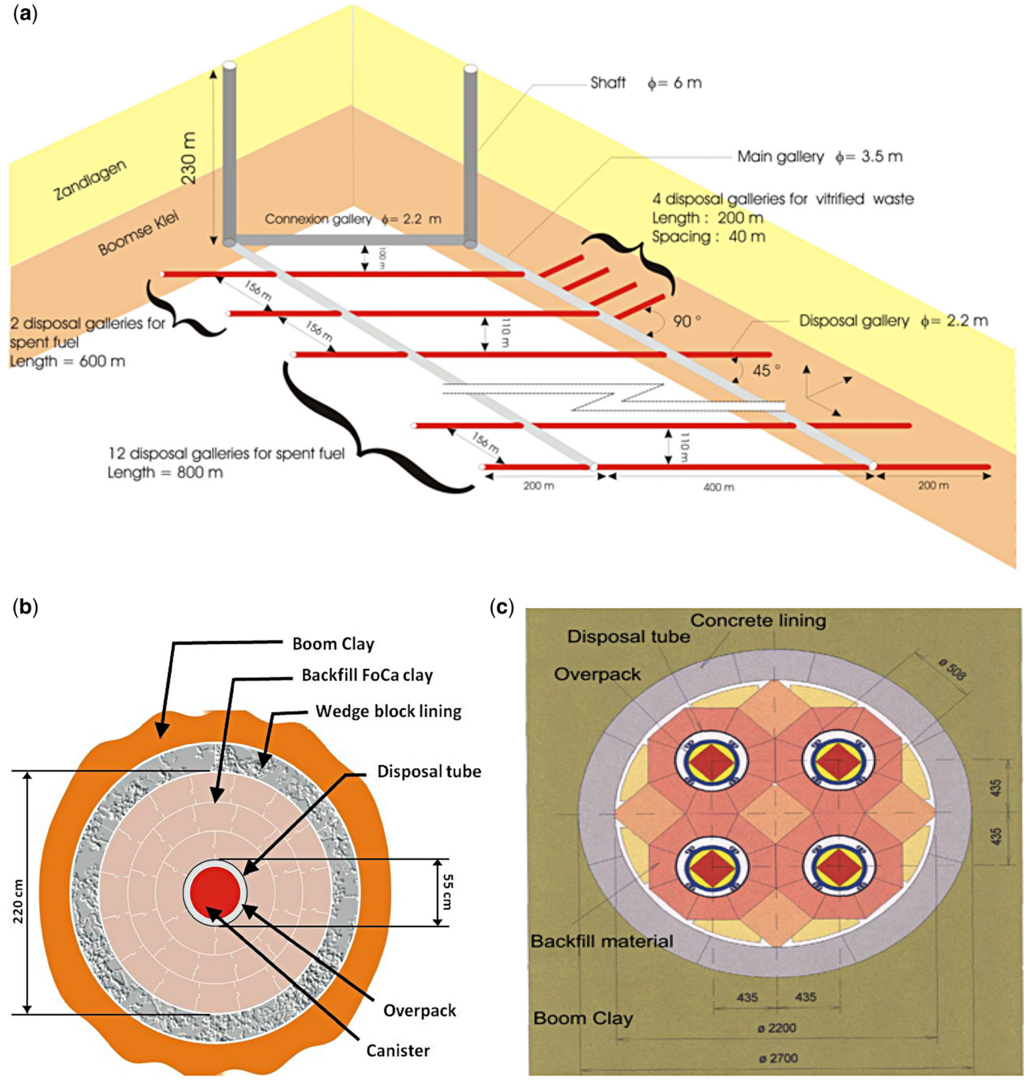

Fig. 28. SAFIR 2 repository concept for the disposal of spent fuel and vitrified high-level waste: (**a**) repository layout (note the 45° crossings between the access galleries and the disposal galleries for spent fuel, to accommodate the length of the disposal package during transport through galleries of limited diameters); (**b**) cross-section of a disposal gallery for vitrified waste; and (**c**) cross-section of a disposal gallery for spent fuel.

concept could be constructed using industrial excavation techniques.

The number of parallel disposal tubes and the spacing between the disposal galleries for the different types of heat-emitting wastes (vitrified waste, uranium oxide (UOX) and mixed oxide (MOX) spent fuel) were optimized to limit the thermal impact on the surrounding host rock. Over the years, several *in situ* experiments at different scales were conducted in the HADES URL to determine the admissible thermal loading of the clay in the near field of a repository, culminating with the PRACLAY Heater Test (Chen *et al.* 2022; Li *et al.* 2022).

A peer review of the SAFIR 2 concept was organized in 2003 (OCDE/AEN 2003). The review revealed several weaknesses in the EBS design. There were concerns about the practicalities of constructing the bentonite buffer and the 200 m long disposal tubes and of installing and possibly retrieving waste packages in these tubes. This is further complicated by the thermal stresses induced in the tube during the thermal phase that could lead to deformations of the tube.

With respect to long-term retardation of radionuclide migration after failure of the waste packages, the contribution of a bentonite buffer with a thickness of about 1 m would be marginal compared with that of the geological clay barrier. Moreover, the characterization of the hydromechanical behaviour of the Boom Clay demonstrated the excellent self-sealing capacity of the Boom Clay (Bernier *et al.* 2007*a*, *b*). This meant that the fractures in the EDZ close rapidly and that the very low permeability of the clay in the EDZ is restored, and that it is not necessary to install a swelling buffer to avoid preferential radionuclide migration through the EDZ.

The primary function of the buffer was thus to provide a controlled chemical environment that would contribute to maximizing the lifetime of a metallic containment barrier around the primary waste packages. However, a surface model of the SAFIR 2 EBS design was built as part of the OPHELIE experiment (Van Humbeeck *et al.* 2009). The experiment revealed the complex behaviour of the EBS and the possible negative impact of some processes on the corrosion resistance of metal components. It was concluded that the crucial function of the central tube, namely to ensure complete waste containment during the thermal phase, could not be guaranteed. This led to the abandonment of the SAFIR 2 EBS design.

The current Belgian repository concept

Several alternative concepts were proposed and a multi-criteria decision analysis was performed to select a new reference concept (ONDRAF/NIRAS 2004). The purpose of developing a number of different concepts and selecting one reference concept was to build a broad basis to justify the selection.

The new design consists of the use of 'supercontainers' for HLW and SF and 'monoliths' for ILW. This design is illustrated in Figure 29 (see ONDRAF/NIRAS 2019*a*, *b* for the details of the design and role of each component).

The supercontainer consists of a carbon steel overpack that has to guarantee waste containment during the thermal phase. This overpack is surrounded by a buffer of Portland cement concrete, which creates a highly alkaline environment and passivates the carbon steel of the overpack. This results in slow and uniform corrosion of the overpack. The concrete buffer also provides radiological shielding (Bel *et al.* 2006). A stainless steel envelope is used as a mould to construct the buffer and to provide added mechanical strength during the transportation and handling of the supercontainer.

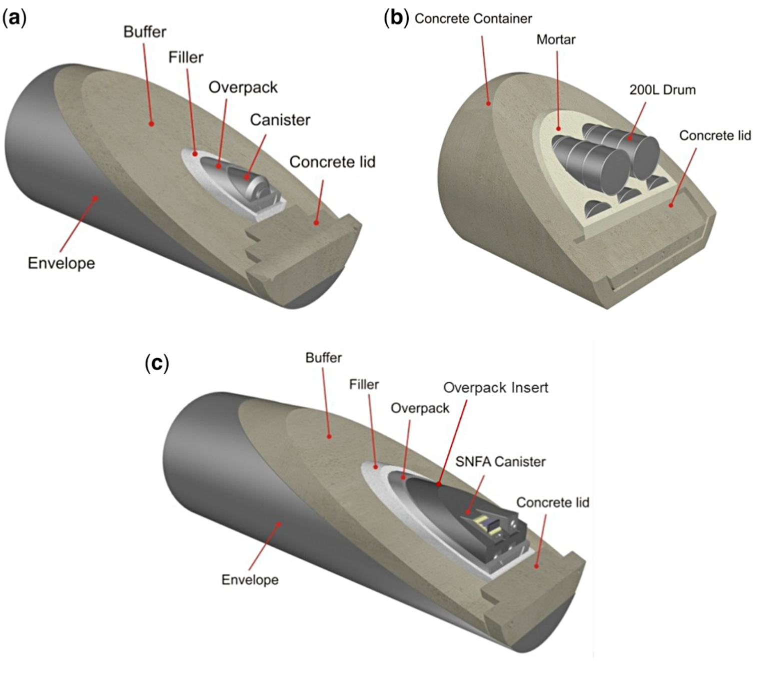

Fig. 29. Design of the supercontainer and of the monolith: (**a**) supercontainer for vitrified high-level waste; (**b**) monolith for ILW; and (**c**) supercontainer for spent fuel. Source: adapted from ONDRAF/NIRAS (2019*a*, *b*).

The monolith is made from a concrete caisson. After the primary waste packages are placed in this caisson, it is backfilled with a mortar immobilizing the primary waste packages and closed by a concrete lid. The monoliths have a cylindrical shape with a flat base allowing their disposal on a support structure in the disposal gallery. The concrete container and lid need to be sufficiently thick to provide the required radiological shielding.

In the 2000s, it also became clear that Mol was not to be considered as a preferred potential site for a DGR, but only as reference for RD&D purposes. ONDRAF/NIRAS began to investigate other host formations, such as the poorly indurated Ypresian clays. This all led to the need for a more generic disposal concept. The reference design, however, was still one in poorly indurated clays (Boom Clay and Ypresian clays), at depths that could possibly exceed that of the HADES URL.

This led to iterations in the design of the supercontainer and monolith-based EBS and, in recent years, to an optimization of the layout. An overall view of the current repository concept is shown in Figure 30 (ONDRAF/NIRAS 2019*c*). Parallel access galleries have been adopted instead of an earlier layout where there was only one single-access gallery. Using parallel galleries offers operational safety advantages.

The shafts are scaled up versions of the Second Shaft of the HADES URL. They are planned to be sunk through frozen aquifer layer(s). During the excavation of the shaft, a first shotcrete or prefabricated concrete lining will be installed. Once the top of the clay is reached, a foundation will be built. On this foundation, a secondary concrete lining will be installed from the bottom to the top. A steel liner and asphalt between the first and secondary lining will make the shaft watertight (Fig. 31; ONDRAF/NIRAS 2019*c*).

It is proposed to excavate the disposal and access galleries using the same techniques that were successfully applied for the construction of the Connecting and PRACLAY Gallery: an open face tunnelling machine and a lining composed of prefabricated concrete segments and keys. This has been found to be effective in ensuring good contact between the lining and the clay and minimizing clay convergence.

Monitoring of deformations and pressures on the Connecting and PRACLAY galleries showed that the stresses in the lining will increase in time (Dizier *et al.* 2023). For these reasons, and also to allow for uncertainties about the depth of the (generic)

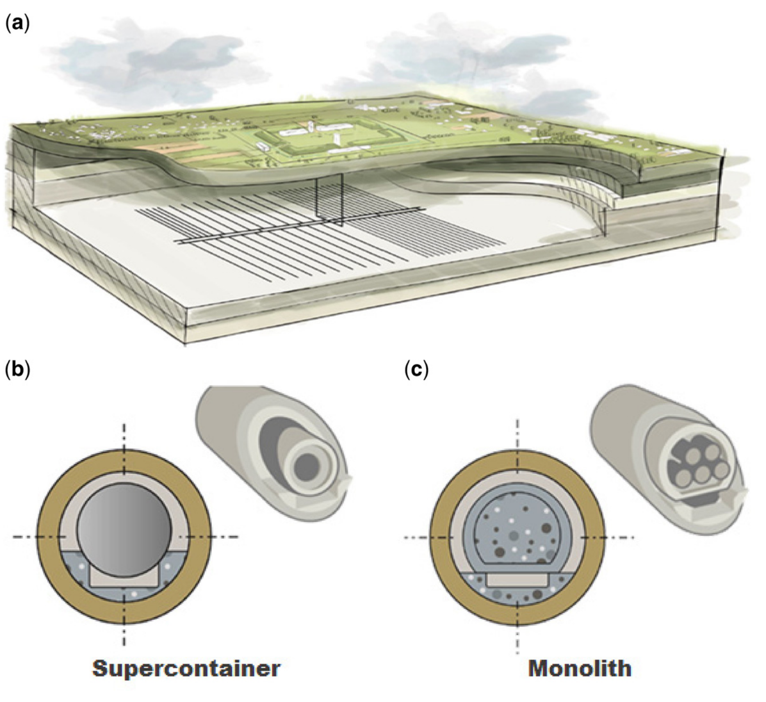

Fig. 30. The current Belgian repository concept for spent fuel, vitrified high-level waste and intermediate-level long-lived waste: (**a**) layout; (**b**) cross-section of a disposal gallery for vitrified high-level waste encapsulated in supercontainers; and (**c**) cross-section of a disposal gallery for ILW primary packages in monoliths. Source: adapted from ONDRAF/NIRAS (2019*c*).

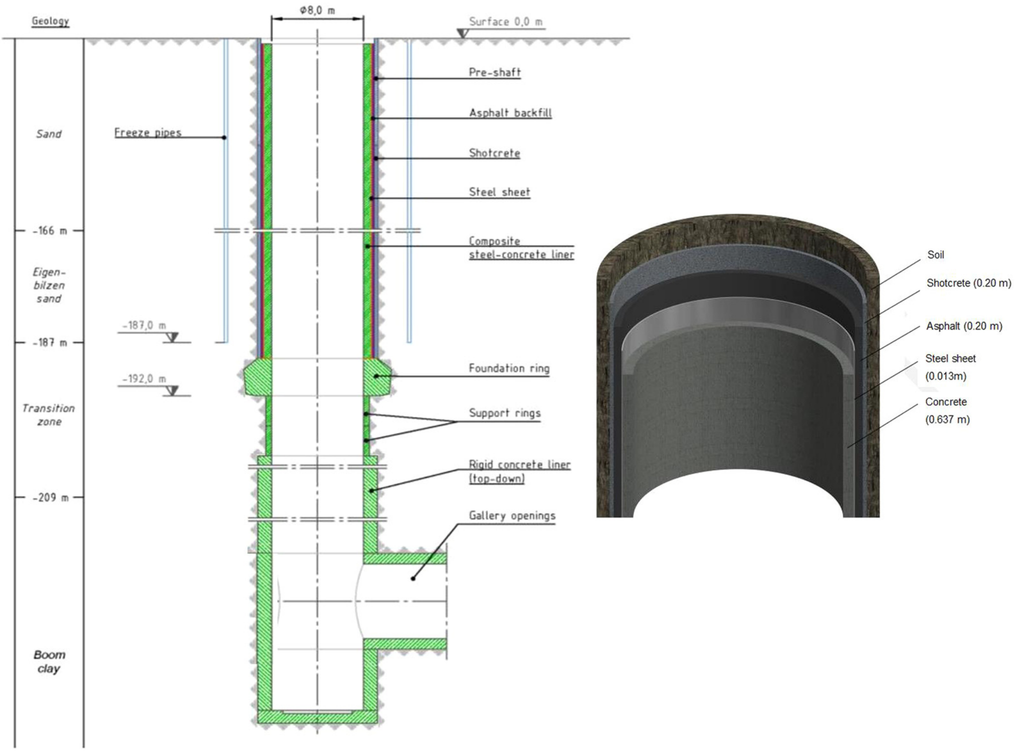

Fig. 31. Current concept for the shafts of a repository in poorly indurated clays in Belgium and detail of the components of the watertight shaft wall for the crossing of aquifers. Source: ONDRAF/NIRAS (2019*c*).

repository and host rock properties (Boom Clay or Ypresian clays at a generic location), a composite lining concept is proposed. The lining is designed to withstand the poorly indurated clay pressure at two different stages in the repository lifetime (ONDRAF/NIRAS 2019*c*). A primary lining is installed at the moment of the excavation. The design consists of a wedge block lining with compressible elements between the concrete segments (Fig. 32). The compressible elements can be thought of as a modern equivalent of the wooden plates installed between concrete blocks in the lining of the Test Drift. They allow the lining to deform. This will limit the stresses inside the lining at the cost of some additional convergence.

In a second phase, the compressible elements of the primary lining are blocked and, if necessary, a secondary concrete lining is cast *in situ* (Fig. 32c). The combination of the two linings is designed to withstand the long-term pressures on the lining. This would allow for a long operational period (expected for the access galleries) and facilitate the reversibility/retrievability of the wastes, which may be a legal or stakeholder requirement.

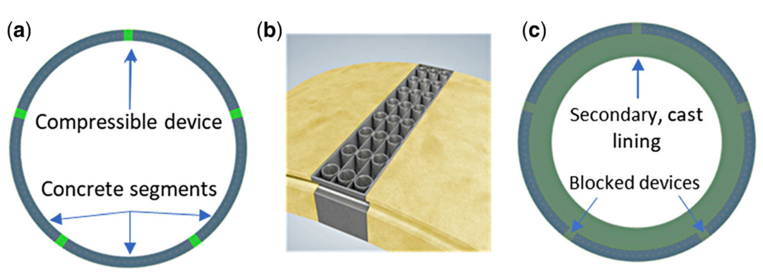

Fig. 32. Current generic (site-independent) concept for the lining of access galleries: (**a**) first phase lining; (**b**) detail of the compressible devices; and (**c**) secondary lining.

In previous concepts, gallery crossings were conceived as 'double crossings' with disposal galleries on both sides of the access galleries. Based on design calculations and measurements around the crossing between the Connecting and PRACLAY Gallery, very high stresses are expected in the lining of an access gallery at these double crossings. That is why a repository layout with T-crossings was adopted in the current repository concept (ONDRAF/NIRAS 2019*c*).

The crossing between the Connecting and PRACLAY Gallery was realized using a steel reinforcement ring. This reinforcement ring is a permanent structure. In a real repository, any such structures are planned to be temporary. The envisaged construction sequence for the gallery crossings is illustrated in Figure 33. These steps are:

(1) installation of a removable steel frame;
(2) removal of the concrete lining at the position of the future disposal gallery;
(3) starting of the excavation and installation of a thick, high-strength and reinforced concrete;
(4) removal of the steel frame, assembly of the tunnel boring machine and continuation of the disposal gallery excavation using a wedge block lining.

Finally, all geological repository designs include sealing structures. These contribute to isolating the waste by creating a physical barrier. They also compartmentalize the repository, which can help limit the impact of potential incidents in one part on the other parts of the repository (ONDRAF/NIRAS 2013). Sealing systems in different disposal concepts have different functions, depending on the concept, the type of host rock, requirements by stakeholders, etc. In most concepts, the sealing structures are also designed to hydraulically cut off a possible EDZ that could otherwise potentially act as a preferential pathway for radionuclide migration. This is generally achieved by removing part of the lining and installing bentonite-based seals or plugs in contact with the surrounding host rock.

Several generic experiments have been performed in the HADES URL to evaluate the performance of bentonite as a sealing material. One of the main goals was demonstrating that the bentonite–clay interface would not act as a preferential pathway for flow and solute transport. While not representative of an actual seal design for a repository, the PRACLAY seal demonstrated that such an interface could remain virtually watertight despite the high hydraulic and thermal gradients it was subjected to, with a difference in excess of 2.5 MPa and 60°C between the two sides of the 1 m long seal. In actual repository designs, the cumulated length of the plugs and seals would be considerably longer, so that the hydraulic resistance along the repository structures would be comparable with that of the geological barrier.

At this stage, no exhaustive requirements have been defined for the seals in the generic Belgian concept. Nevertheless, some preliminary designs have

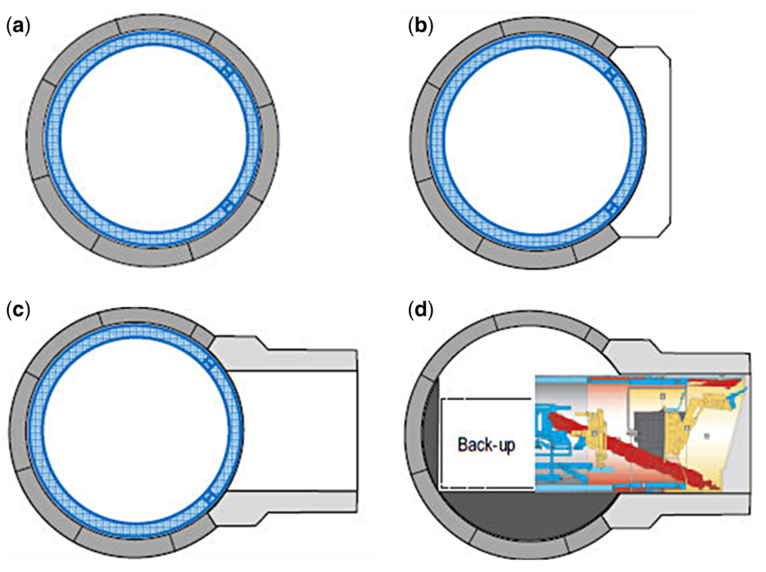

Fig. 33. Four steps to construct a T-crossing: (**a**) installation of a removable steel frame; (**b**) removal of the concrete lining at the position of the future disposal gallery; (**c**) starting of the excavation and installation of a thick, high-strength and reinforced concrete; and (**d**) removal of the steel frame, assembly of the tunnel boring machine and continuation of the disposal gallery excavation using a wedge block lining. Source: ONDRAF/NIRAS (2019*c*).

been proposed (see ONDRAF/NIRAS 2019*c* for details). They are based on classical bentonite-based seal designs. The design requires the installation of a temporary lining at the location of the future seal. This section of the lining is then removed before the seal is installed so that the bentonite can be placed directly against the clay host rock. Because of the self-sealing capacity of poorly indurated clays, swelling plugs and seals may not be strictly necessary. Therefore, concrete-based plugs and seals could prove to be a viable alternative. This, however, remains to be further evaluated.

Conclusions

The research on the geological disposal of radioactive waste in Belgium dates back to the 1970s. SCK CEN launched an RD&D programme and chose to concentrate its efforts on investigating the poorly indurated Boom Clay below its site in Mol. At the time, it was questionable if a DGR could be constructed in poorly indurated clay. Therefore, SCK CEN decided to construct the HADES URL in Boom Clay 225 m below at its site.

The construction of the First Shaft started in 1980. The sand aquifers above the clay were frozen to avoid water infiltration during shaft sinking. However, also the clay itself was frozen because it was expected to have a very plastic response and would more or less behave like toothpaste. The first gallery was excavated in frozen clay for the same reason. The excavation was done semi-manually using pneumatic hammers and 20 cm thick cast iron segments were used as the gallery lining.

It was, however, observed, among other from reconnaissance boreholes drilled in unfrozen clay, that Boom Clay did not behave as plastically as expected. This led to the decision to excavate a small experimental shaft and gallery in unfrozen clay. In addition, the 20 cm thick cast iron segments were replaced as gallery support by 30 cm thick concrete blocks. This excavation method and lining were applied on a larger scale with the construction of the 65 m long Test Drift in 1987. This demonstrated the feasibility of constructing galleries in unfrozen clay using a concrete lining at a scale representative of a DGR.

However, the excavation techniques used were still semi-manual and an excavation rate of only 2 m/week was achieved. Another disadvantage of this excavation method was the large over-excavation needed to insert the concrete blocks at the top of the lining. Constructing a DGR in an economically feasible way requires an industrial excavation technique. Such a technique was applied in 2001 for the Construction Gallery.

The gallery was excavated using an open-face tunnel boring machine. This technique had already been used in the London clay (underground lines) and in the Boom Clay (technical crossings under the Scheldt River), although at much shallower depths. With the construction of the Connecting Gallery, it was the first time that this technique was applied in a poorly indurated clay at a depth of 225 m. An average construction rate of 3 m/day was achieved and the over-excavation was minimal, although the inner diameter of the Connecting Gallery was larger than that of the Test Drift.

In 2007 the same types of lining and construction techniques were used for the construction of the PRACLAY Gallery perpendicular to the Connecting Gallery. This demonstrated the feasibility of constructing a gallery crossing.

During the successive construction stages of the HADES URL, the hydromechanical response of the Boom Clay to the excavations was monitored. Pore water pressures, host rock stresses and displacements were measured. Also, the EDZ was characterized and fractures induced by the excavations were mapped and examined.

This provided insight into the highly coupled and anisotropic hydromechanical behaviour of the Boom Clay and its self-sealing behaviour. The fast self-sealing of Boom Clay was demonstrated both in the lab and *in situ*. Tests showed that open fractures in the EDZ can be expected to close over time and that the hydraulic conductivity of the clay in this zone restores to its undisturbed value.

The current geological disposal concept considered by ONDRAF/NIRAS foresees the installation of seals in the shafts and galleries. The purpose of these seals is to create a physical barrier against fluid flow and preferential radionuclide transport through the repository infrastructures. Sealing experiments have been conducted in the HADES URL to test possible seal designs and develop a better understanding of the behaviour of bentonite, a possible seal material, under *in situ* conditions. These experiments showed that it is feasible to install a shaft and gallery seals in Boom Clay. They also increased the knowledge about the parameters influencing the *in situ* hydro mechanical behaviour of bentonite.

All this knowledge gained – about excavation techniques, shaft and gallery linings, the hydromechanical behaviour of clay – has supported the development of a geological disposal concept in Belgium. This increased understanding is reflected in the evolution of the repository design. In the early days, developing the repository concept and constructing the URL were essentially seen as one project. Over time, when it became clear that Mol was not to be considered as a preferred potential site for a DGR, a more generic disposal concept was developed. ONDRAF/NIRAS began to investigate other host formations, such as the poorly indurated Ypresian clays.

Today, the generic repository design that serves as a reference for the RD&D and for the estimation of the possible future cost of geological disposal in Belgium is still one in poorly indurated clays and the lessons learned from the HADES URL remain highly relevant. The shafts in the current DGR concept are scaled up versions of the Second Shaft of the HADES URL and the galleries are planned to be excavated using the same techniques that were successfully applied for the construction of the Connecting and PRACLAY Gallery.

Acknowledgements The authors would like to express their appreciation to all colleagues who have contributed over the past 40 years to the construction of the HADES URL and to the development of the concept for a deep geological repository.

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper, except from the agencies to which the authors are affiliated.

Author contributions **XL**: writing – original draft (lead), writing – review & editing (equal); **BN**: writing – original draft (equal), writing – review & editing (equal); **DR**: writing – review & editing (equal); **XS**: writing – original draft (equal), writing – review & editing (equal).

Funding This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

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

Armand, G., Plas, F., Talandier, J., Dizier, A., Li, X.L. and Levasseur, S. 2023. Contribution of HADES URL to the development of the Cigéo project, French industrial centre for geological disposal of high-level and intermediate long-lived radwaste in a deep clay formation. *Geological Society, London, Special Publications*, **536**, https://doi.org/10.1144/SP536-2022-98.

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**. ESV EURIDICE, Mol.

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*, 2006, London, 795–801.

Bel, J.J., Wickham, S.M. and Gens, R.M. 2006. *Development of the Supercontainer Design for Deep Geological Disposal of High-Level Heat Emitting Radioactive Waste in Belgium*. MRS Online Proceedings Library.

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., Volckaert, G. and Dardaine, M. 1995. Demonstration of the in-situ application of an industrial clay based backfill material (BACCHUS 2), SCK•CEN report **R-3068**.

Bernier, F., Li, X.L. *et al*. 2003. Clay Instrumentation Programme for the Extension of an underground research laboratory, Final Report, **EUR-20619-EN**, EC contract FI4W-CT96-0028, European Commission, Luxembourg.

Bernier, F., Li, X.L. and Bastiaens, W. 2007*a*. 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

Bernier, F., Li, X.L. *et al*. 2007*b*. Fractures and self-sealing within the excavation disturbed zone in clays (SELFRAC), Final Report, **EUR-22585**, EU contract FIKW-CT2001-00182, European Commission, Luxembourg.

Borgesson, L. and Hernelind, J. 1999. *Coupled thermo-hydro-mechanical calculations of the water saturation phase of a KBS-3 deposition hole*. SKB Technical Report **TR-99-41**.

Chen, G. and Li, X.L. 2011. Numerical study of the PRACLAY Seal test in Mol, Belgium. *Proceedings of the 2nd International Symposium on Computational Geomechanics (COMGEO I)*, 27–29 April, Cavtat-Dubrovnik, 640–649.

Chen, G., Verstricht, J. and Li, X.L. 2012. Numerical modeling of the in situ PRACLAY seal test. comparison between model and measurement. *In*: Mancuso, C., Jommi, C. and D'Onza, F. (eds) *Proceedings of the Second European Conference on Unsaturated Soils in Naples, Italy, June 2012, E-UNSAT 2012*. Springer, **2**, 333–341, https://doi.org/10.1007/978-3-642-31343-1

Chen, G.J., Li, X.L., Dizier, A., Verstricht, J., Sillen, X. and Levasseur, S. 2022. 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

Commission of the European Communities 1980. *European catalogue of geological formations having suitable characteristics for the disposal of solidified HLW and/or long-lived radioactive waste*, CEC Report EUR **6891**.

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.

De Bruyn, D.J. and Neerdael, B.A. 1991. The HADES project – ten years of civil engineering practice in a plastic clay formation. *In*: Dexter-Smith, R. (ed.) *International Conference on Civil Engineering in the Nuclear Industry, Windermere, 1991*. Thomas Telford, London. 39–50.

De Craen, M., Van Geet, M., Honty, M., Weetjens, E. and Sillen, X. 2008. Extent of oxidation in Boom Clay as a result of excavation and ventilation of the HADES URF: experiment and modelling assessments. International Meeting on Clays in Natural and Engineered Barriers For Radioactive Waste Confinement, Lille, 2007. *Physics and Chemistry of the Earth*, **33**, S350–S362.

De Craen, M., Honty, M. *et al*. 2011. Overview of the oxidation around galleries in Boom Clay (Mol, Belgium) – Status 2008, **SCK CEN-ER-189**.

Dizier, A., Chen, G., Li, X.L., Leysen, J., Verstricht, J., Troullinos, I. and Rypens, J. 2016. The start-up phase of the PRACLAY Heater test. EURIDICE Report **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**, in review.

Gatabin, C., Touze, G., Billaud, P., Imbert, C. and Guillot, W. 2006. *ESDRED PROJECT-MODULE 1, Selection and THM characterisation of the buffer material*. Technical Report.

Li, X.L., Bastiaens, W. and Bernier, F. 2006. The hydromechanical behaviour of the Boom Clay observed during excavation of the Connecting Gallery at Mol site. *In*: *EUROCK 2006, Multiphysics Coupling and Long Term Behaviour in Rock Mechanics. Proceedings and Monographs in Engineering, Water and Earth Sciences, London, British Indian Ocean Territory*, **1**, 467–472.

Li, X.L., Dizier, A., Chen, G.J., Verstricht, J. and Levasseur, S. 2022. 40 years of investigation into the thermo-hydromechanical (THM) behaviour of Boom Clay in the HADES URL. *Geological Society, London, Special Publications*, **536**, https://doi.org/10.1144/SP536-2022-103

Mertens, J., Bastiaens, W. and Dehandschutter, B. 2004. Characterisation of induced discontinuities in the Boom Clay around the underground excavations (URF, Mol, Belgium). *Applied Clay Science*, **26**, 413–428, https://doi.org/10.1016/j.clay.2003.12.017

Neerdael, B.A., De Bruyn D.J., Mair R.J. and Taylor R.N. 1991. *The HADES project at Mol: Geomechanical behaviour of Boom Clay*. Workshop on Pilot Tests on Radioactive Waste Disposal in Underground Facilities, Braunschweig.

Neerdael, B., Meynendockx, L. and Voet, M. 1992. The Bacchus backfill experiment at the Hades underground research facility at Mol, Belgium, **EUR-14155**, Final Report EC contract FI4W-CT96-0028. European Commission, Luxembourg.

OCDE/AEN 2003. *SAFIR 2: Belgian R&D Programme on the Deep Disposal of High-level and Long-lived Radioactive Waste: an International Peer Review, Radioactive Waste Management*. Éditions OCDE, Paris, https://doi.org/10.1787/9789264103467-en

ONDRAF/NIRAS 1989. *Safety Assessment and Feasibility Interim Report (SAFIR)*, Report submitted to the Secretary of State for Energy.

ONDRAF/NIRAS 2001. *SAFIR 2: Safety Assessment and Feasibility Interim Report 2*. Report NIROND **2001-06 E**.

ONDRAF/NIRAS 2004. *Multicriteria analysis on the selection of a reference EBS design for vitrified high level waste*. Report NIROND **2004-03 E**.

ONDRAF/NIRAS 2013. *ONDRAF/NIRAS Research, Development and Demonstration Plan for the geological disposal of high-level and/or radioactive waste including irradiated fuel if considered as a waste. State-of-the-art report as of December 2012*. Report NIROND-TR **2013-12 E**.

ONDRAF/NIRAS 2019*a*. *Design and construction of the monolith B for category B wastes*. Report NIROND-TR **2017-10 E V3**.

ONDRAF/NIRAS 2019*b*. *Design and construction of the monolith B for category B wastes*. Report NIROND-TR **2017-11 E V**3.

ONDRAF/NIRAS 2019*c*. *Design and Construction of the Geological Disposal Facility for Category B and Category C Wastes*. Report NIROND-TR **2017-12 E V3**.

ONDRAF/NIRAS 2019*d*. Scénario de référence pour la gestion à long terme des déchets des catégories A, B et C (période tarifaire 2021–2023). Technical Note **2019-2447**.

Ramaeckers, C., Van Cotthem, A. and De Bruyn, D.J. 2000. Construction d'un second puits à Mol dans le cadre des études pour l'enfouissement géologique des déchets hautement radioactifs en Belgique. *Tunnels et ouvrages souterrains*, **162**, 315–325.

Rousset, G. 1988. *Comportement mécanique des argiles profondes, application au stockage de déchets radioactifs*. PhD thesis, École Nationale des Ponts et Chaussées.

Rousset, G. 1990. Les sollicitations à long terme des revêtements des tunnels. *Revue Française de Géotechnique*, **53**, 5–20, https://doi.org/10.1051/geotech/19900 53005

Tang, A.M. 2005. *Effet de la température sur le comportement des barrières de confinement*. PhD thèses, Ecole Nationale des Ponts et Chaussées, Paris, France.

Van Geet, M., Volckaert, G. and Roels, S. 2005. The use of microfocus X-ray computed tomography in characterising the hydration of a clay pellet/powder mixture. *Applied Clay Science*, **29**, 73–87, https://doi.org/10.1016/j.clay.2004.12.007

Van Geet, M., Bastiaens, W. *et al*. 2008. Installation and evaluation of a large-scale in-situ shaft seal experiment in Boom Clay. *Science and Technology Series*, **334** (Andra), 95–109.

Van Geet, M., Bastiaens, W. *et al*. 2009. *RESEAL II A large-scale in-situ demonstration test for repository sealing in an argillaceous host formation – Phase II*. Final report, **EUR 24161 EN**.

Van Humbeeck, H., Verstricht, J., Li, X.L., De Cannière, P., Bernier, F. and Kursten, B. 2009. *The OPHELIE mock-up Final report*. EURIDICE Report **09-134**.

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**, Mol, Belgium.

Van Marcke, P., Li, X.L., Chen, G.J., Verstricht, J., Bastiaens, W. and Sillen, X. 2014. Installation of the PRACLAY seal and Heater. *Geological Society, London, Special Publications*, **400**, 107–115, https://doi.org/10.1144/SP400.4

Verstricht, J., Nackaerts, D., Li, X.L., Leonard, D., Levasseur, S. and Van Geet, M. 2022. 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. 2005. *MX-80 bentonite, thermo-hydro-mechanical characterization performed at CIEMAT in the context of the Prototype project*. CIEMAT Technical Report.

Villar, M.V., Imbert, C. *et al*. 2005. *RESEAL II – a large scale in situ demonstration test for repository sealing in an argillaceous host rock – phase II: final report on laboratory tests*. SCK CEN report **ER-1**.

Volckaert, G., Dereeper, B. *et al*. 2000. A large scale in situ demonstration test for repository sealing in an argillaceous host rock. RESEAL project – Phase I. European Commission, Luxembourg, **EUR 19612**.

Yu, L., Rogiers, B., Gedeon, M., Marivoet, J., De Craen, M. and Mallants, D. 2013, A critical review of laboratory and in-situ hydraulic conductivity measurements for the Boom Clay in Belgium. *Applied Clay Science*, **75–76**, 1–12, https://doi.org/10.1016/j.clay.2013.02.018