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Excavation induced fractures in a plastic clay formation: Observations at the HADES URF

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ABSTRACT

The Belgian research programme for geological disposal of radioactive waste focuses on the Boom Clay as the potential host rock formation. To examine the feasibility of constructing an underground repository in this clay layer, an underground research facility HADES has been constructed in several stages since 1980. The two galleries most recently excavated, the Connecting Gallery in 2002 and the Praclay Gallery in 2007, were constructed by means of an industrial method using a tunnelling machine. During these excavations the hydro-mechanical response of the clay was characterised.

A fracture pattern was observed consistently during the excavation of both galleries. The extent of this fractured zone was determined for the Connecting Gallery, but requires some further study. A strong hydro-mechanical coupling and a clear time dependency were noticed, even at an unexpectedly large distance from the excavation. Furthermore the Boom Clay responds in an anisotropic manner to the excavation due to anisotropy in the in situ stress state and the Boom Clay characteristics. Self-sealing processes were observed and appear to occur relatively fast.

1. Introduction

The geological disposal of radioactive waste has been studied in Belgium since the early seventies by the Belgian Nuclear Research Centre (SCK•CEN). The research is focused on the Boom Clay: a plastic clay layer that is found from a depth of 190 m under the site of SCK•CEN in Mol (in the northeast of Belgium) where it has a thickness of about 100 m. It has a low hydraulic conductivity (in the order of 10^{-12} m/s) and displays a plastic behaviour which results in self-sealing properties and a relatively high convergence when excavating galleries in it.

In 1980 SCK•CEN started the construction of the underground facility HADES at a depth of 225 m (Fig. 1). Its main purpose was to examine the feasibility of constructing such a repository and to provide SCK•CEN with an underground infrastructure for experimental research on the geological disposal of radioactive waste. Not much knowledge and experience on excavating in a deep plastic clay formation were available at that time. The work during this phase is therefore considered to be pioneering.

In 2002 the second shaft was connected with the existing underground infrastructure by the Connecting Gallery (80 m long and 4.8 m in external diameter). This was done in an industrial manner by the use of a tunnelling machine. Several measurement and research programmes were carried out before, during and after the construction works to characterise the hydro-mechanical response of the clay around the repository (Bastiaens et al., 2003; Bernier et al., 2003). In particular the fracture pattern resulting from the excavation was characterised. In 2007 the Praclay Gallery (45 m long and 2.5 m in external diameter) was constructed perpendicular to the Connecting Gallery. Again, the hydro-mechanical response was measured and characterised.

This paper discusses these measurements and observations. First the Boom Clay characteristics are given, then the used excavation technique is described after which the hydro-mechanical observations are presented.

2. Boom Clay characteristics

The Boom Clay is a silty clay characterised by a structure of bands that are several tens of centimetres thick, reflecting mainly cyclical variations in grain size (silt and clay content) due to fluctuations in the wave action on the sedimentation medium and to variations in the carbonate and organic matter contents. Typical concretions, known as septaria, are found in the marly bands occurring throughout the thickness of the formation.

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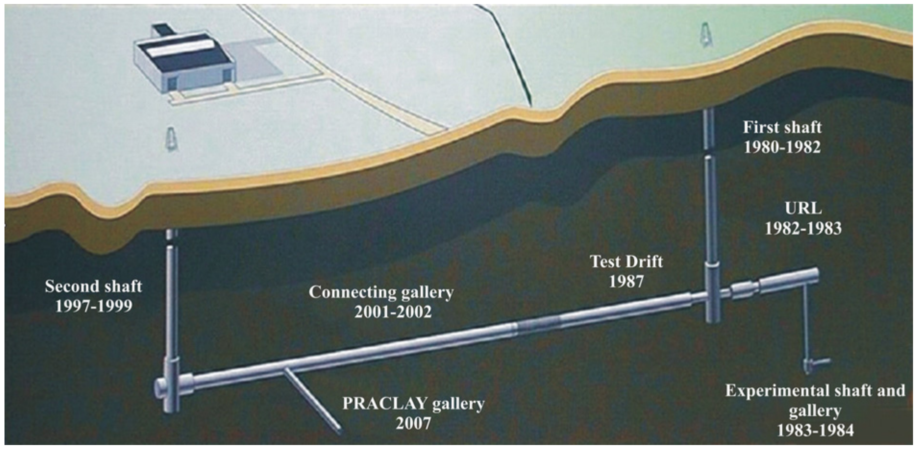

Fig. 1. Construction history of the underground research facility HADES.

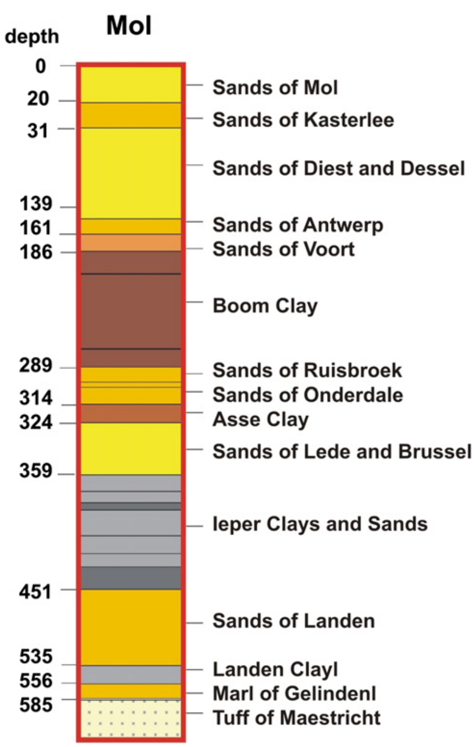

Fig. 2. Geological section under the Mol site.

Table 1
Undrained geomechanical characteristics of the Boom Clay at the depth of HADES.

Property	Unit	Value
Young's modulus tangential at the origin	E	200–400 MPa
Poisson's ratio	ν	0.40–0.45
Unconfined compressive strength	UCS	2 MPa
Angle of friction	φ	4°
Cohesion	c	0.5–1.0 MPa
Plastic limit	w_p	23–29%
Liquid limit	w_l	55–80%
Plastic index	IP	32–51%
Hydraulic conductivity	k	$\sim 10^{-12}$ m/s
Porosity	n	39%
Water content	w	30–40 vol%

The formation belongs to the Rupelian which is the geological part of the Tertiary Period with an age between 36 and 30 million years. It is found at a depth of about 190 m under the SCK•CEN site of Mol where it has a thickness of about 100 m (see Fig. 2). 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.

Due to its vertical lithological heterogeneity the mineralogy of the Boom Clay is characterised by a wide variation in the content of clay minerals (from 30 to 70% volume, dry matter). In descending

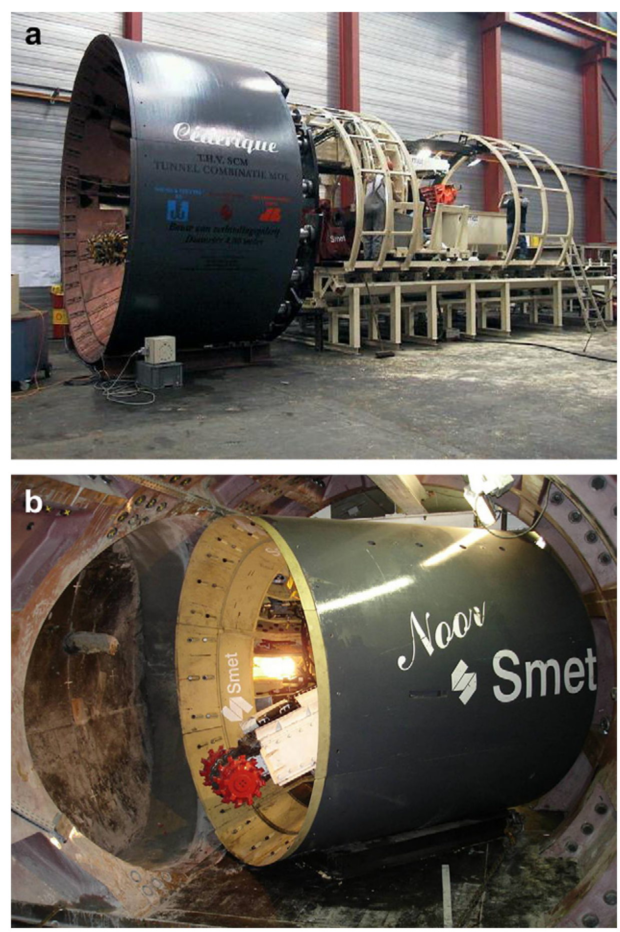

Fig. 3. Tunnelling machine used for the excavation of (a) the Connecting Gallery and (b) the Praclay Gallery.

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.

The Boom Clay displays furthermore a visco-elasto-plastic behaviour (Bastiaens et al., 2006; Coll et al., 2007; Cui et al., 2009; Le et al., 2007), such that its convergence in the longer term is high. At the level of HADES, total stress and pore water pressure are respectively 4.5 and 2.2 MPa. The vertical stress is estimated to be slightly higher than the horizontal ones ($K_0 \sim 0.9$). The undrained geomechanical characteristics of the Boom Clay at the depth of the existing facilities are given in Table 1 (Horseman et al., 1987).

3. Excavation by means of a tunnelling machine

Both the excavation of the Connecting Gallery and the Praclay Gallery were performed by the use of a tunnelling machine (Fig. 3). This machine consists of a roadheader with drillhead which is placed under the protection of a shield.

Fig. 4 shows the different steps in the excavation procedure. The roadheader moves along the clay front and the majority of the face is removed (Fig. 4a). Once all the clay within the reach of the roadheader is removed (Fig. 4b), the complete tunnelling machine is pushed forward against the already placed lining (Fig. 4c). By doing so the outer rim of the excavation face is cut by the edges of the shield. This ensures a smooth and circular excavation profile. When the tunnelling machine has progressed over a sufficiently large distance, a new lining ring can be placed by the use of an erector (Fig. 5). The placement of the lining as soon as possible after the excavation minimises the convergence. Also the use of a rigid and expanding type of lining (see further) avoids further convergence and the need to perform post-grouting.

The lining of the galleries consists of concrete wedge blocks (Fig. 6a). The segments are unreinforced and unbolted and each ring is independent. By introducing shorter, wedge shaped segments the ring can be expanded against the circular excavated profile and in that way a post-stressing effect in the lining can be induced (Fig. 6b). The dimensions of the key segment can be

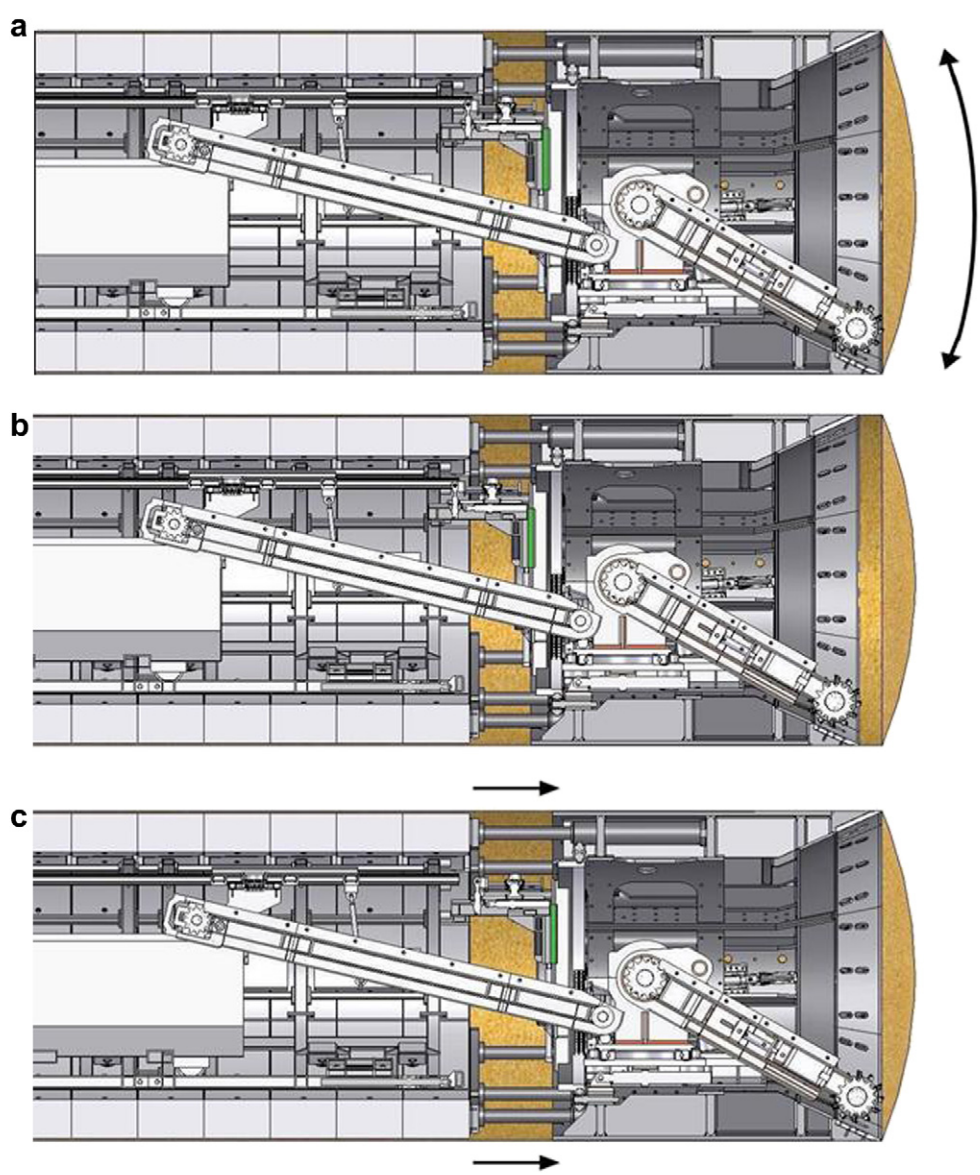

Fig. 4. Excavation phases: (a) the roadheader is moved along the clay front to remove the clay; (b) all the clay is removed within the reach of the roadheader; (c) the tunnelling machine is pushed forward against the already built lining. Once the tunnelling machine has sufficiently progressed, a new lining ring can be installed.

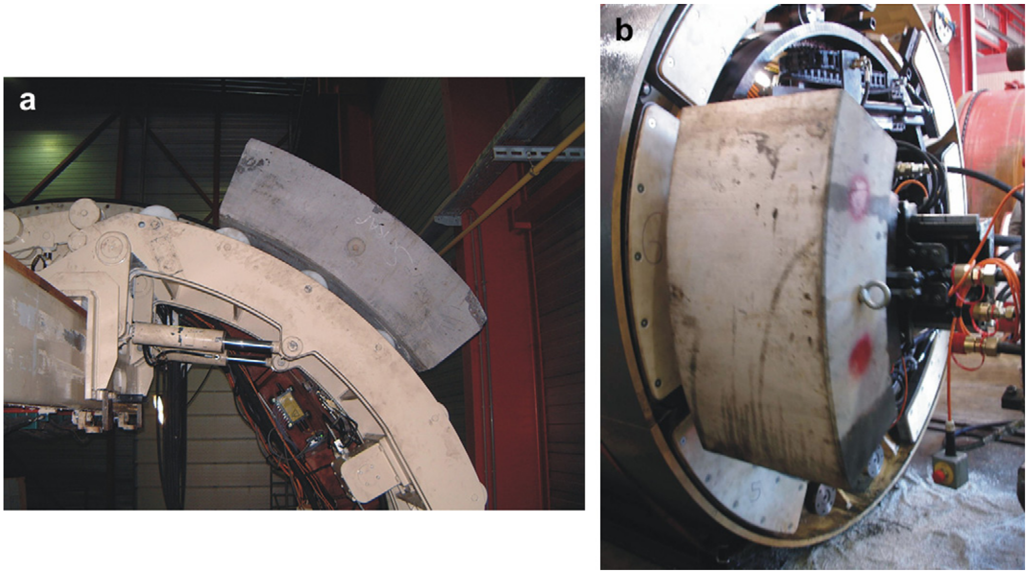

Fig. 5. Erector of the tunnelling machine used to place the gallery lining segments: (a) bird-wing erector used when constructing the Connecting Gallery; (b) rotary erector used for the construction of the Praclay Gallery.

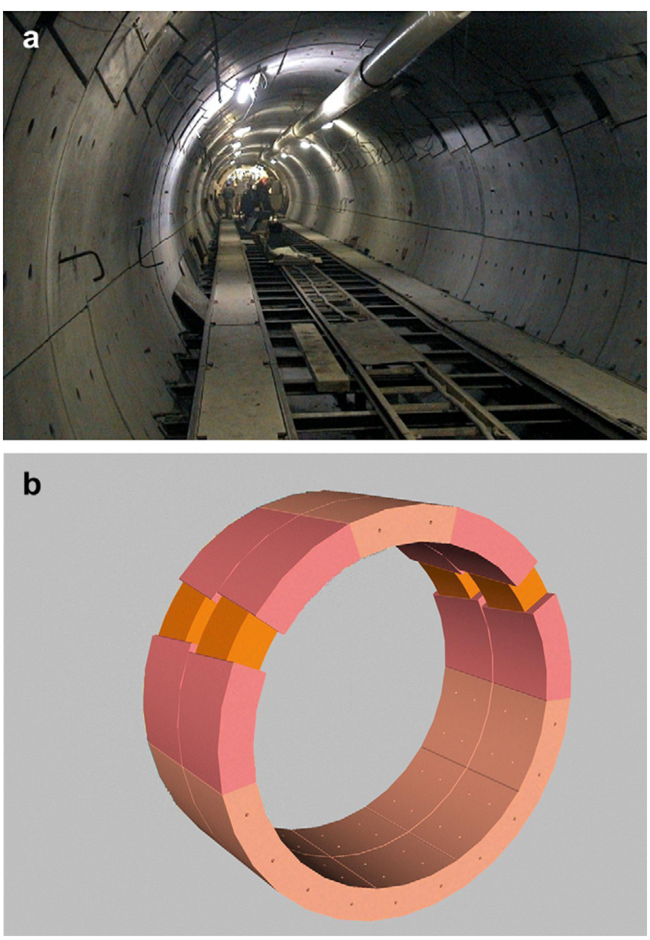

Fig. 6. (a) Picture of the Connecting Gallery showing the concrete wedge blocks making up the gallery lining. (b) By using key segments the lining can be expanded and the diameter of the lining can be adjusted according to the diameter of the excavated profile.

adjusted by sawing the segment at its front or at its back end. This allows adjusting the diameter of the expanding lining to the diameter of the excavated profile.

The Connecting Gallery was excavated at a rate of 3 m/day while the excavation rate of the Praclay Gallery was 2 m/day. Achieving a mean excavation rate of 10 m/day is assumed to be realistic for a future repository when also a larger access shaft will be available for transporting cuttings and material.

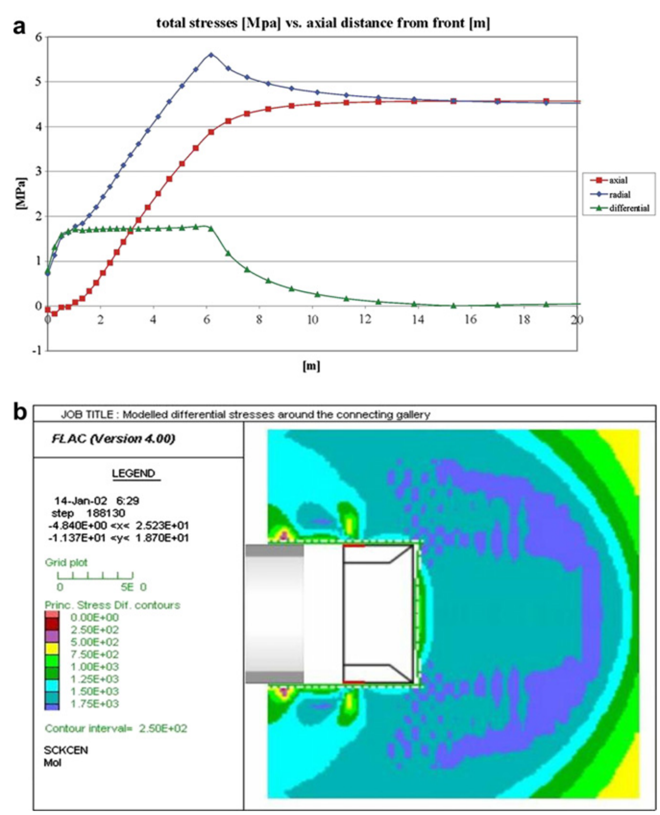

Fig. 7. Modelled stresses along the gallery axis ahead of the excavation front: (a) axial, radial and differential stresses; (b) differential stresses.

4. Hydro-mechanical response of the Boom Clay to the excavation

The excavation of a gallery results in differential stresses that are relatively high compared to the strength of the Boom Clay (Table 1). Fig. 7 shows the stresses around an excavation as obtained by a perfect elasto-plastic model using the parameters from Table 1. The finite difference code FLAC2D was used to compute the stresses for this model.

These high differential stresses result in shear fractures which were, during the excavation of both the Connecting as the Praclay Gallery, systematically observed on the sidewalls of the excavation as well as on the excavation front (Fig. 8).

These observations revealed a fracture pattern similar in both excavations (Fig. 9). The pattern consists of two conjugated fracture planes: one in the upper part dipping towards the excavation direction and the other in the lower part dipping towards the opposite direction. These fracture planes intersect at mid-height of the gallery and they are slightly curved. Their intersection both with a vertical and a horizontal plane passing through the gallery axis is a curve. Due to the anisotropy of the stresses in the clay – the vertical stresses are higher than the horizontal stresses – this curve is much more pronounced vertically than horizontally. The distance between successive fractures is a few decimetres. These observations are consistent with observations from earlier excavations such as the Test Drift (Mertens et al., 2003, 2004).

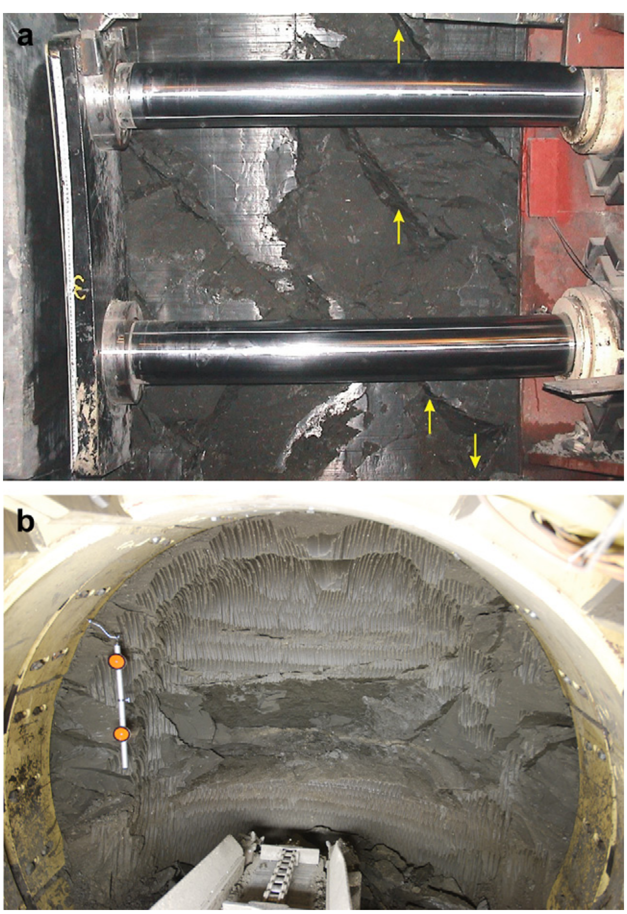

Fig. 8. Fractures observed (a) on the sidewalls (Connecting Gallery) and (b) the excavation front (Praclay Gallery).

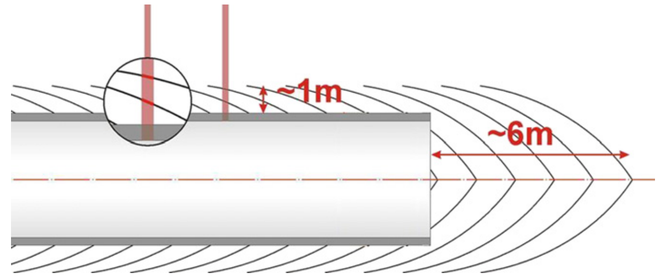

Fig. 9. Fracture pattern observed in the Connecting Gallery. A similar pattern was observed for the Praclay Gallery. The radial extent of the fracture pattern around the Connecting Gallery was estimated at 1 m, the axial extent at 6 m. The extent of the fractures around the Praclay Gallery still needs to be evaluated.

The radial extent of the fractured zone around the Connecting Gallery was determined from cores taken around the gallery. Fractures were found up to a distance of about 1 m (Fig. 9). The axial extent was found by modelling and appeared to be about 6 m. This figure was confirmed when the Connecting Gallery reached the Test Drift (Fig. 1): about 6 m from the end of the Test Drift fractures induced by the excavation of the latter were observed.

The extent of the fractured zone around the Praclay Gallery still needs to be evaluated. This will be done when instrumentation around the gallery is placed. However, piezometers placed parallel to the Praclay Gallery at a horizontal distance of 0.75 m did not drop to atmospheric pressure and thus suggest that the fractures do not extend up to 0.75 m in a horizontal plane.

Since the Praclay Gallery is constructed perpendicular to the Connecting Gallery, the excavation of the first passes through the fractured zone induced by the construction of the latter. These fractures were observed in the first few metres of the Praclay Gallery excavation (Fig. 10). At first sight, with the naked eye, the fractures appeared to curve in a direction opposite to that expected. This is because the fracture is the intersection between the fracture plane and the excavation front which is spherical. These fractures were observed up to an excavation distance of 6 m. This is well beyond the formerly determined radial extent of 1 m. Possibly microfractures up to that extent were induced during the excavation of the Connecting Gallery, but were not observed in the cores taken radially around the Connecting Gallery. As a result of the stress redistribution created by the excavation of the Praclay Gallery these microfractures might have formed macrofractures. Another hypothesis is that the fractures induced by the excavation of the Connecting Gallery in 2002 were reactivated and their extent increased due to additional stress redistribution by the Praclay Gallery excavation. At the crossing, and especially at the level of the fractures, other stress orientations exist ahead of the face than those that are present beyond the start-up zone during the excavation.

Fig. 11 shows the pore water pressure as function of the radial distance to the Connecting Gallery. The pore water pressures are measured by two piezometers around the gallery and are plotted as a percentage of the undisturbed in situ pressure at their location. The gallery lining is shown as well. The pore water pressure distribution around the gallery is remarkably large and anisotropic. The hydraulically disturbed zone (HDZ) in a horizontal plane seems to range up to about 20 m into the host rock. In a vertical plane however, an equilibrium pressure is not reached even at 40 m. The values are all significantly lower than 100%. This is probably due to the disturbance caused by the installation of the piezometer itself.

Because of the decreased stresses near the excavation (Fig. 7), the clay will converge towards the excavation. An instantaneous convergence results from the elasticity of the clay while the creep behaviour of the clay gives rise to a time-dependent convergence.

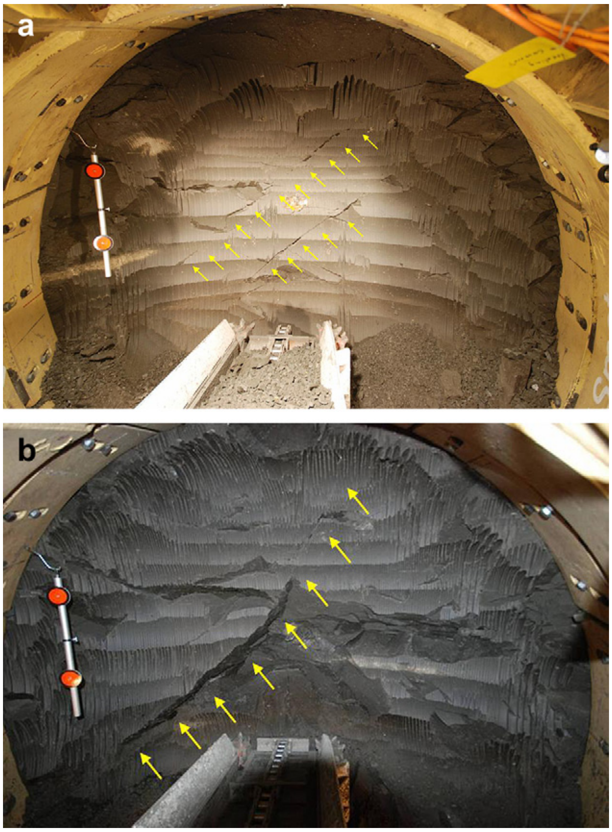

Fig. 10. (a) Excavation front of the Praclay Gallery 0.5 m from the Connecting Gallery. (b) Excavation front of the Praclay Gallery 4.0 m from the Connecting Gallery.

This dilatation, combined with the undrained conditions on the short term, can result in negative pore water pressures.

In spite of the higher vertical stresses, the convergence appeared to be higher in the horizontal direction than in the vertical direction. This can be explained by the shape of the fracturation pattern. Since the dip directions of the fractures are roughly parallel to the gallery axis, vertical de-stressing can assumed to be partly affected by fracturing ahead of the excavation. This in turn reduces the vertical convergence afterwards. However, the clay at the sides of the gallery converges as if no fracturing had occurred and thus the horizontal convergence is larger.

Once the lining is placed, the convergence of the clay will result in an increase of the pressure exerted by the clay on the lining (Fig. 12). This pressure build-up is monitored through embedded vibrating wire strain gauges. Four gallery lining rings are assembled with these strain-gauged segments. The strain measured by these gauges is converted into mechanical stress in the segments, which on its turn can be related to the total pressure in the host rock acting on the lining.

During the consolidation of the clay around the excavation, self-sealing occurs as the open fractures close progressively due to the creep behaviour of the clay and to its swelling when it rehydrates. Evidence of the 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 an open casing (not closed at the end) is installed in a borehole, the Boom Clay flows inside the tube (Bernier et al., 2006).

Within the SELFRAC EC project (Bernier et al., 2006), the fast self-sealing capacity of Boom Clay has been demonstrated and visualised by means of X-ray CT. Fig. 13a shows the CT image of a Boom Clay sample shortly after an artificial fracture was created and before saturation of the sample. Fig. 13b gives an image of the sample 4.5 h after saturation. Closure of the fracture is clearly observed. Sealing was confirmed by measuring the hydraulic conductivity measurement of the sample which returned to the same order of magnitude as the undisturbed value ($\sim 10^{-12}$ m/s) after a few months.

In situ experiments have also revealed sealing processes in the Boom Clay. Two years after the excavation of the Connecting Gallery, sealing had reduced the radial extent of the fractured zone from 1 m to less than 0.6 m.

An impact of the ventilation of the gallery on the fracturing or a desaturation of the Boom Clay around the gallery has not been observed in the HADES URL. Moreover, a laboratory mock-up test, PHEBUS (Robinet et al., 1998), was setup to study the desaturation of the Boom Clay due to ventilation. In the test a controlled humidity air (33% humidity) was cycled in an orifice drilled in a cylinder sample and the hydric exchange between the air and Boom Clay was measured. After dismantling also the moisture profile of the mock-up was measured. The desaturation zone appeared to be very limited.

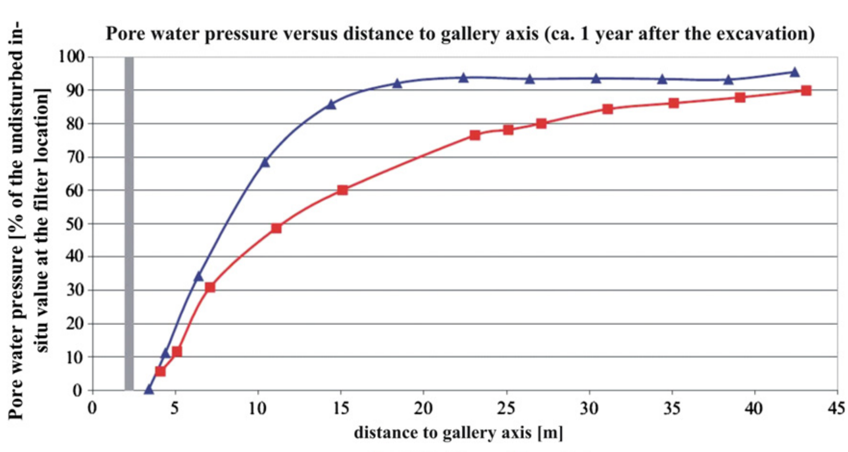

Fig. 11. Pore water pressure in function of the distance to the excavation. The pore water pressure is expressed as a percentage of the undisturbed in situ value.

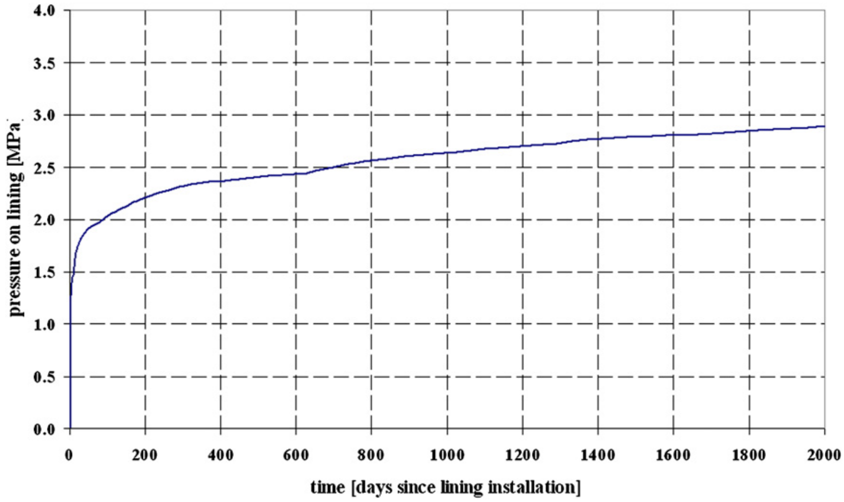

Fig. 12. Evolution of the average pressure exerted on a lining ring of the Connecting Gallery.

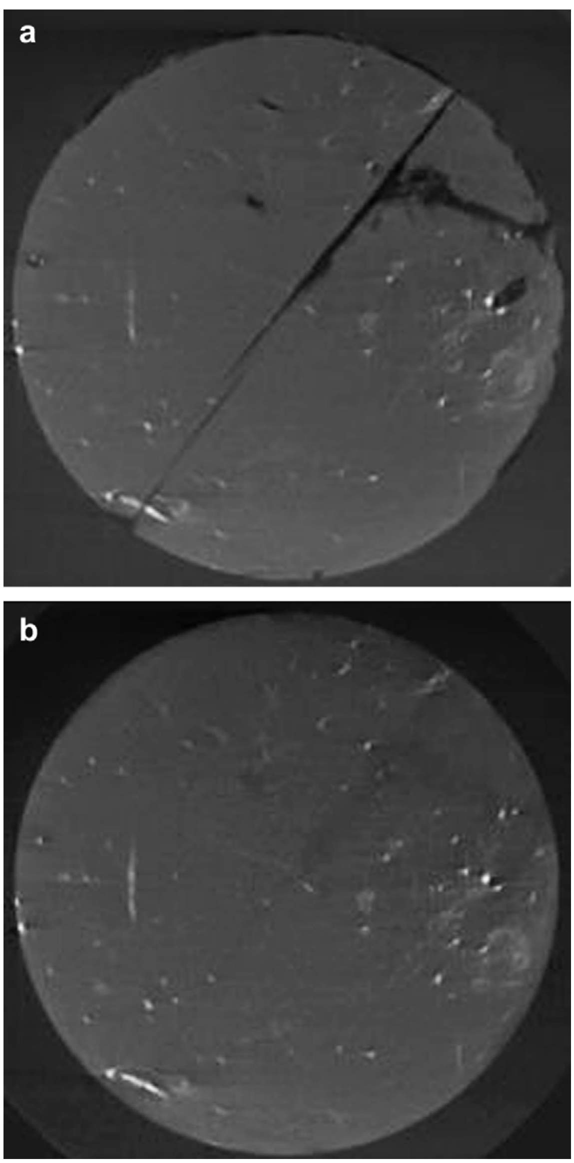

Fig. 13. (a) CT image of an artificially fractured Boom Clay sample. (b) CT image of the same sample after a few hours of saturation.

5. Conclusions

In the framework of the Belgian research programme for the geological disposal of radioactive waste, an underground research facility has been built in the Boom Clay layer at a depth of 225 m. The response of the Boom Clay to the excavation of a gallery was observed and characterised during the excavation of the Connecting Gallery in 2002 and the Praclay Gallery in 2007.

The excavation induces fractures in the surrounding clay layer. These fractures are created according to a pattern consisting of two conjugated fracture planes: one in the upper part dipping towards the excavation direction, the other in the lower part dipping towards the opposite direction. The fractures curve towards the excavation. The extent of this fractured zone depends on the diameter of the excavated gallery. For a gallery of 4.8 m, the radial extent appeared to be 1 m. The extent of the fractures around the Praclay Gallery (2.5 m in external diameter) still needs to be determined.

Furthermore in situ measurements and numerical modelling were performed to characterise the geomechanical behaviour of the clay. A strong hydro-mechanical coupling and a clear time dependency were noticed, even at an unexpectedly large distance from the excavation.

Once the lining is placed, the consolidation of the clay results in an increase of the pressure exerted by the clay on the lining and open fractures close progressively. In other words, self-sealing processes occur in the Boom Clay and they occur relatively fast. These processes reduce the extent of the fractured zone around the Connecting Gallery from 1 m to 0.6 m within one year.

Finally, the hydro-mechanical response of the clay appeared to be anisotropic. This was attributed to anisotropy in in situ stress conditions and in the hydro-mechanical properties of the Boom Clay.

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