Gallery & Crossing test	The construction of the PRACLAY gallery	
Type of test: Construction techniques Hydro-mechanical interactions between the concrete lining and the Boom Clay	**Collaborations:** Smet Tunnelling SECO Tractebel Engineering	**Period:** 2007

BACKGROUND

The construction of the HADES laboratory is important in order to be able to study and demonstrate the technical feasibility of geological disposal in poorly indurated clay formations like the Boom Clay. With the construction of the Connecting gallery (2001-2002), the feasibility of excavating galleries using industrial tunnelling techniques was demonstrated (Figure 1).

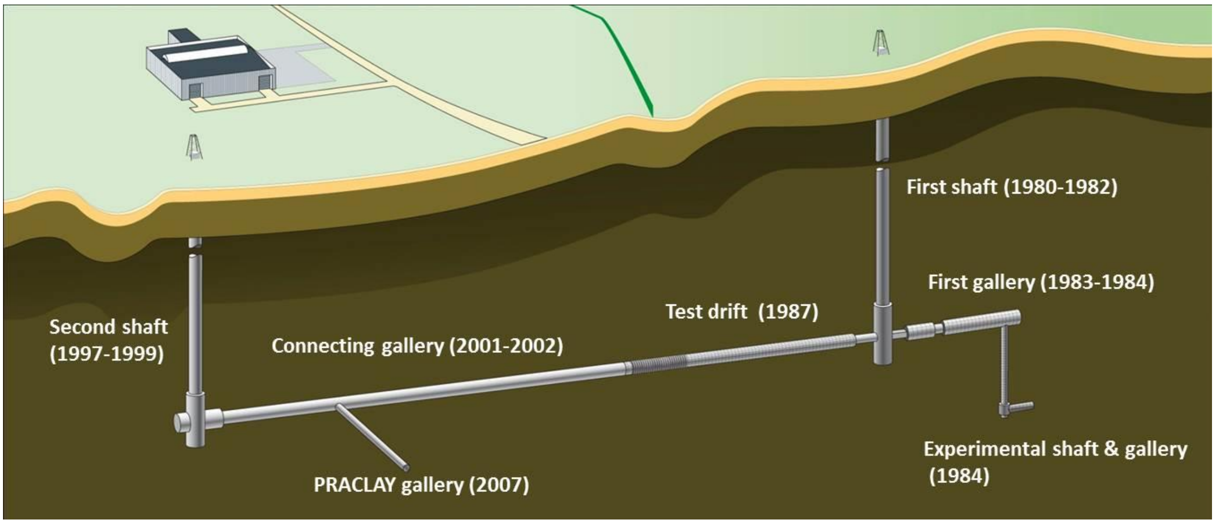

Figure 1 - Layout of the construction of the HADES underground research laboratory

The current design by ONDRAF/NIRAS of the repository for geological disposal of category B & C waste contains disposal galleries that are perpendicular to a central gallery. Where these galleries connect, gallery crossings need to be constructed. The construction of these crossings in a plastic clay host rock at great depth (more than 200 m) poses a technological challenge and its feasibility needs to be demonstrated. The construction of the PRACLAY gallery and its crossing with the already existing

Connecting gallery constitutes the **Gallery and Crossing test**. The PRACLAY gallery is designed to host the **Heater test,** to study the impact of heat on the THM behaviour of the Boom Clay on a scale that is representative of an actual waste repository, and the **Seal test,** to provide the hydraulic boundary conditions for the Heater test and to explore the possibility of closing off galleries. Together, these three tests make up the **PRACLAY In-Situ Experiment (Figure 2)**.

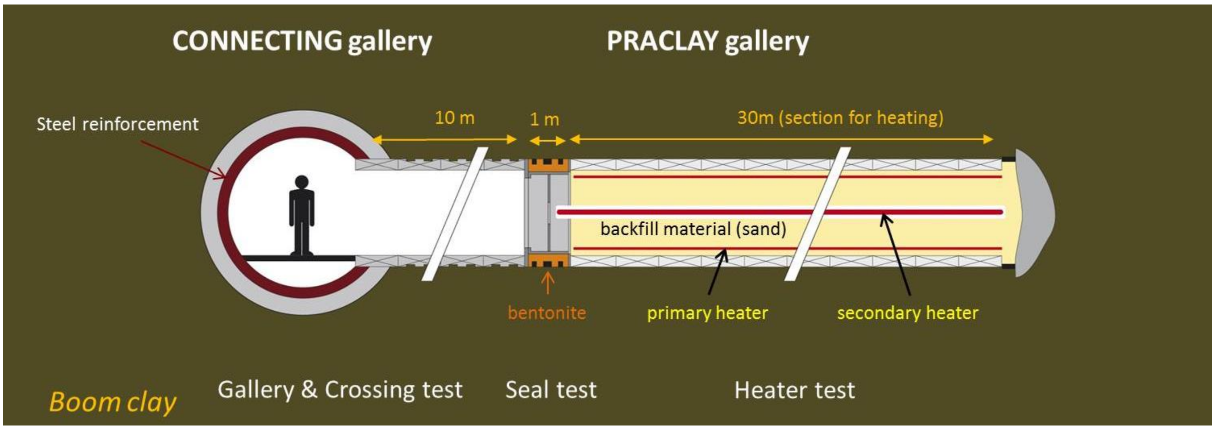

Figure 2 - The set-up of the PRACLAY In-Situ Experiment

OBJECTIVES

The specific objectives of the Gallery & Crossing test are to:

- Demonstrate the feasibility of constructing a crossing between two galleries without using a mounting chamber for the assembly of the tunnelling machine, since such a chamber creates significant mechanical disturbances in the host formation and is more expensive;
- Demonstrate the possibility of restarting the excavation process after an interruption by means of a stop-and-go test;
- Study the hydro-mechanical (HM) interaction between the lining and the Boom Clay.

During work on the PRACLAY gallery, it was possible to optimise the industrial excavation technique and further investigate the HM response of the Boom Clay to the excavation work.

TIMING

Underground assembly of a reinforcement ring at the crossing: August 2007
Construction of the PRACLAY gallery: October – November 2007
Stop-and-go test: 30/10/2007 – 6/11/2007

INSTALLATION OF THE REINFORCEMENT RING

The **crossing** between the Connecting gallery (4.8 m external diameter) and the PRACLAY gallery (2.5 m external diameter) could only be achieved by placing a steel reinforcement ring in the Connecting gallery at the crossing before making the opening for the PRACLAY gallery in the lining of the Connecting gallery. The reinforcement ring is composed of 11 cast steel segments, which were transported underground and assembled in situ (Figure 3).

(a)

(b)

(c)

(d)

Figure 3 - Underground assembly of the reinforcement ring

DESIGN and CONSTRUCTION of the PRACLAY gallery

The **design of the PRACLAY gallery** is largely based on the design of the Connecting gallery and the experience gained from the construction of this gallery.

The **PRACLAY gallery was excavated** using an open-face tunnelling machine whose design was based on the need to have a smooth circular excavation profile at the rear to allow direct placement of the lining without the need to perform post-grouting. The majority of the excavation front was excavated by means of a roadheader but the outer rim of the front was cut by the edges of the shield when it moved forward. This ensured a smooth, circular excavation profile.

The construction of a mounting chamber was not necessary, as the tunnelling machine could be assembled in the Connecting gallery (Figure 4). The underground assembly of the tunnelling machine was preceded by a test assembly on the surface.

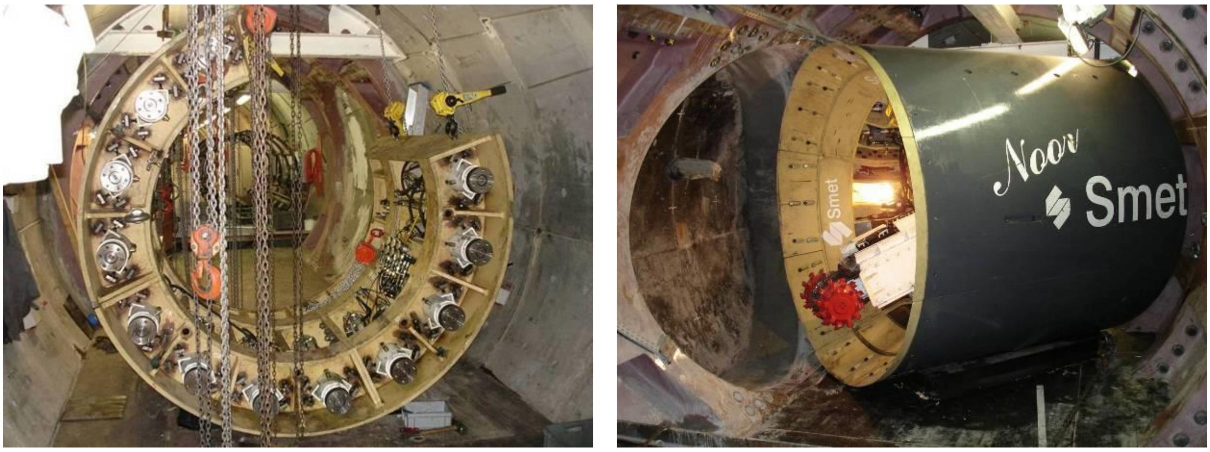

Figure 4 -- Underground assembly of the tunnelling machine and positioning in front of the entrance.

The **lining** used is of an expanding type: the “wedge-block system”. The wedge-block segments are made of C80/95 concrete. The design of the lining had to take into account two types of loading: "geotechnical" loading resulting from the pressure exerted on the lining by the surrounding rock, and "thermal" loading that will occur during the operation of the PRACLAY Heater test (target temperature of 80°C at gallery extrados). To limit the thermal stresses in the lining, compressive materials are incorporated into the lining, allowing some thermal expansion of the lining. This avoids damage to the concrete wedge blocks and allows safe access to the gallery after the Heater test is stopped. Compressive polysiloxane sheets are placed between adjacent lining rings in the heated part of the gallery and steel foam panels are inserted inside the lining rings. These panels have characteristic stress-deformation behaviour: they are relatively rigid under geotechnical loading, but they could undergo significant deformation once thermal loading is superimposed on geotechnical loading. In the last 3 m of the gallery and around the hydraulic seal, no compressive materials were used. The wedge blocks of these rings consist of high-strength concrete.

The **construction of the gallery** was completed in October and November 2007. The combination of the small diameter of the PRACLAY gallery and the large amount of equipment resulted in a very limited working space. As a result, minor problems, such as broken ducts, occurred relatively often and the limited space complicated repairs. This was also reflected in a lower progress rate than achieved during the excavation of the Connecting gallery. Nevertheless, the target rate of 2 m/day was in general reached, except for a start-up zone of 5 to 10 m.

STOP-AND-GO test

With two more lining rings to erect, the excavation work was suspended for one week. The purpose of this **stop-and-go test** was testing the level of difficulty to restart the tunnelling machine in the event of an operational halt. During such a standstill, the Boom Clay around the shield converges and the friction between the clay and the shield increases. To limit the difficulties of resuming the tunnelling work, the shield was given a slightly conical shape and had a Teflon-based coating. After a one-week standstill, excavation was resumed. The thrust force needed to push the shield forward was about twice the normal level. This was still only about 25% of the maximum available force, however.

SCIENTIFIC PROGRAMME

A scientific programme was set up to monitor the excavation work and to gain information on the performance of the excavation technique, the behaviour of the Boom Clay and the impact of the excavation on the clay.

- **Monitoring the crossing**

Due to the excavation of the PRACLAY gallery, stress redistribution occurred. In some places stresses were lower than before, but in others the stress level increased. At the level of the crossing, the ground pressures were borne by the steel reinforcement structure. In order to evaluate the behaviour of the crossing, it was equipped with strain gauges. Due to the relatively limited length of the reinforcement structure, the Connecting gallery lining beyond the reinforced zone (rings 32-35) could also experience an increased load. Additional reinforcement was therefore available and the lining of the Connecting gallery was monitored to evaluate whether it was necessary to actually reinforce it. Ring 30 of the Connecting gallery was built with segments containing embedded strain gauges. Moreover, strain gauges were fixed on the intrados of the Connecting gallery lining close to the reinforcement structure. Figure 5 shows the location of the surface strain gauges at the gallery crossing.

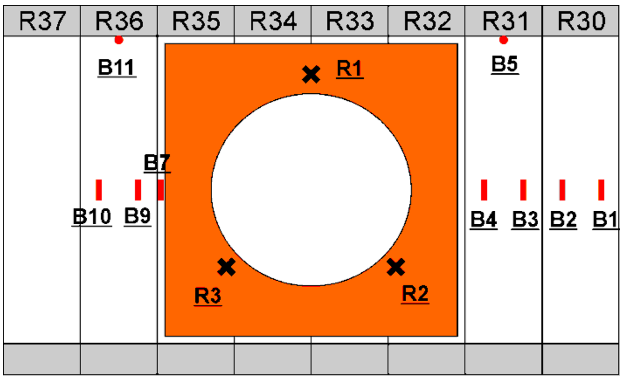

Figure 5 - Location of the strain gauges at the gallery crossing. The white circle in the middle represents the entrance to the PRACLAY gallery

As expected, the highest stresses in the steel structure were measured near the 2.5 m diameter opening, at locations R2 and R3. They reached up to approx. 300 MPa. The graph in Figure 6 shows that stresses increased in two steps. The first step corresponds to the removal of the Connecting gallery lining at the level of the 2.5 m opening. The second increase occurred when the excavation actually started. Looking at this in more detail, the second increase consists of several smaller steps; these correspond to the alternating steps of excavation and lining installation.

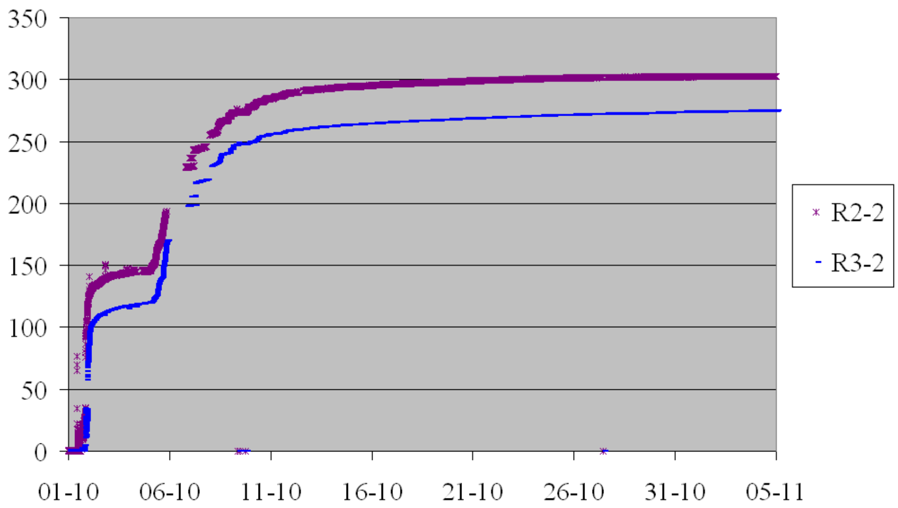

Figure 6 - Stress measurements [MPa] on the reinforcement structure during excavation (locations R2 and R3)

Similar results were obtained by the strain gauges installed on the surface of the concrete lining next to the reinforcement structure (Figure 7). The same two events are visible: removal of the lining and start of the excavation. The maximum stress increase measured was some 8 MPa.

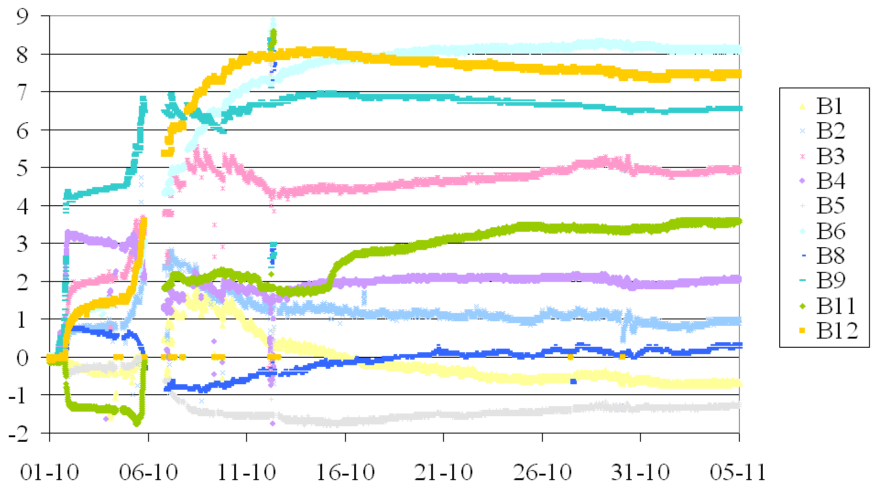

Figure 7 - Stress measurements [MPa] on the concrete lining next to the reinforcement structure

- **Monitoring the host rock**

Prior to the excavation of the PRACLAY gallery several types of sensors were installed in the surrounding host rock. Measured parameters include pore water pressure, total stress, displacement, temperature, pore water chemistry and seismic parameters. In total, eleven boreholes were drilled and equipped from the Connecting gallery, some down to a depth of 45 m. Since these sensors were already installed before the construction of the gallery, they registered the HM response of the Boom Clay during excavation.

When looking at the HM behaviour of a clay formation, one of the important and highly sensitive parameters is the pore water pressure. Due to the low permeability of the clay, undrained behaviour prevails in the short term and the volumetric deformations that result from the stress redistribution directly cause changes in the pore water pressure. Pore water pressures were measured at several distances around the gallery. Figure 8 shows the locations of all pore pressure sensors (normal filters) installed in the different instrumented boreholes surrounding the PRACLAY gallery.

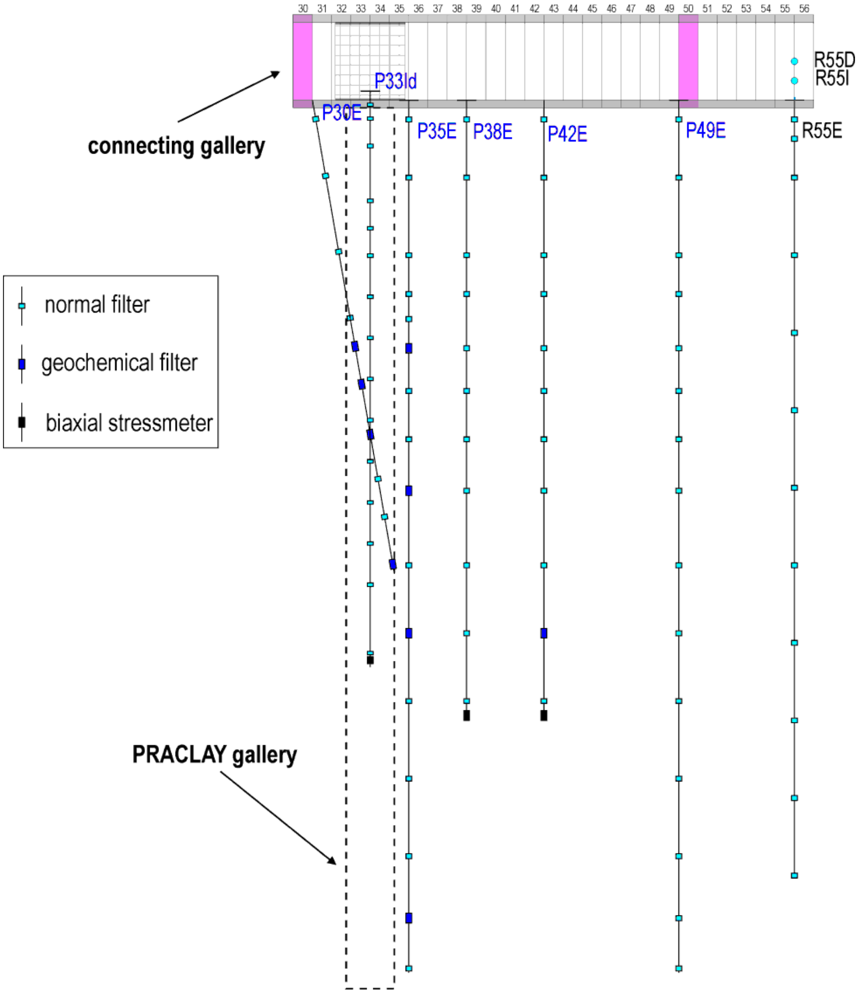

Figure 8 - Layout of the instrumented boreholes installed around the PRACLAY gallery. The normal filters are used to measure pore water pressure.

Before the start of excavation, the pore water pressure values largely depend on the distance between the sensor and the Connecting gallery. Indeed, the disturbed zone of the Connecting gallery regarding pore water pressures covers several tens of metres (Bastiaens et al., 2006). According to the elasto-visco-plastic theory, the variation in the pore water pressure during underground excavation is linked to the volumetric deformation of the clay host rock via the coupling effect.

The pore water pressure response in the clay to the excavation work is determined by the distance and the position of the piezometer with respect to the excavation (i.e. whether the piezometer is placed next to or below the gallery). The latter reveals the anisotropic nature of the Boom Clay.

Figure 9 shows the measurements of two piezometer filters in borehole P35E, which runs parallel with the PRACLAY gallery at a distance of 0.75 m. The first filter is located 4 metres from the Connecting gallery, and the second 20 metres from the Connecting gallery. The observations in borehole P35E are representative of sensors in a horizontal plane along the gallery axis and at a sufficiently short distance from the gallery (less than 3 m).

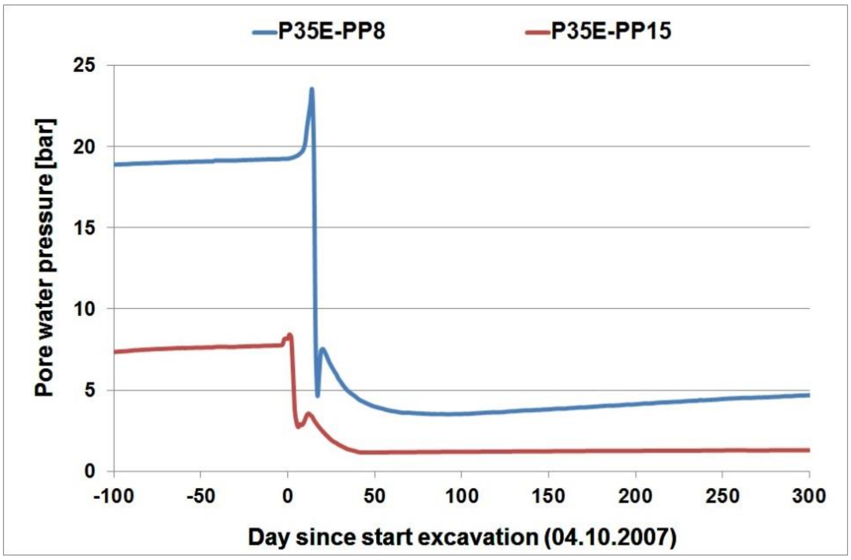

Figure 9 - Pore water pressure measurements in borehole P35E (blue curve: approx. 20 m from the Connecting gallery; red curve: approx. 4 m from the Connecting gallery).

The excavation front passed at a distance of 4 m from the Connecting gallery on 09.10.2007, and 20 m from the Connecting gallery on 20.10.2007. This results in a horizontal shift of the blue curve compared with the red curve. The measurements show that there is no significant impact of the distance to the Connecting gallery on the changes in pore water pressures, as the blue and red curves follow (qualitatively) the same trend in each Figure.

For piezometers placed next to the gallery, an increase in pore water pressure as the excavation front approaches can be seen. This corresponds to compaction of the clay. The magnitude of this pressure increase decreases for piezometers further from the PRACLAY gallery. The increase is not observed by piezometers placed further than 6 m from the PRACLAY gallery axis. The pressure drop phenomenon close to the front results from the high decompression of the clay and the accompanying fractures and volumetric dilatations (increase in the pore volume). Then a sudden increase can again be observed. This corresponds to the placement of the gallery lining and results from the counter-pressure that is exerted on the clay when the key segment is inserted. Thereafter consolidation of the clay takes place and the pore water pressure evolves towards equilibrium with the in-situ stress state. Similar observations were made in the CLIPEX project studying HM response during the excavation of the Connecting gallery (Bernier et al., 2002).

- **Excavation-induced fractures**

The fracture pattern induced by the excavation was characterised by systematic observations of the excavation front. For this purpose, the dip and dip direction of the fractures in the excavation front were measured whenever it was possible to do so safely (Figure 10) and 3D stereographic pictures of the excavation front were taken.

Figure 10 - (a) The dip and dip direction of the fractures in the excavation front were measured; (b) stereographic pictures were taken to reconstruct a 3D image of the excavation front

Shear planes, recognisable by their shiny, slickensided surface, were observed in several excavation fronts. The poles of these fractures were drawn on a stereographic plot (Figure 11a). When a best fit was performed on this stereographic data two poles became apparent (Figure 11b), revealing two conjugated fracture planes that intersect at mid-height of the gallery: one in the upper part, dipping about 45° in the excavation direction (east), and the other in the lower part, dipping about 45° in the opposite direction (west).

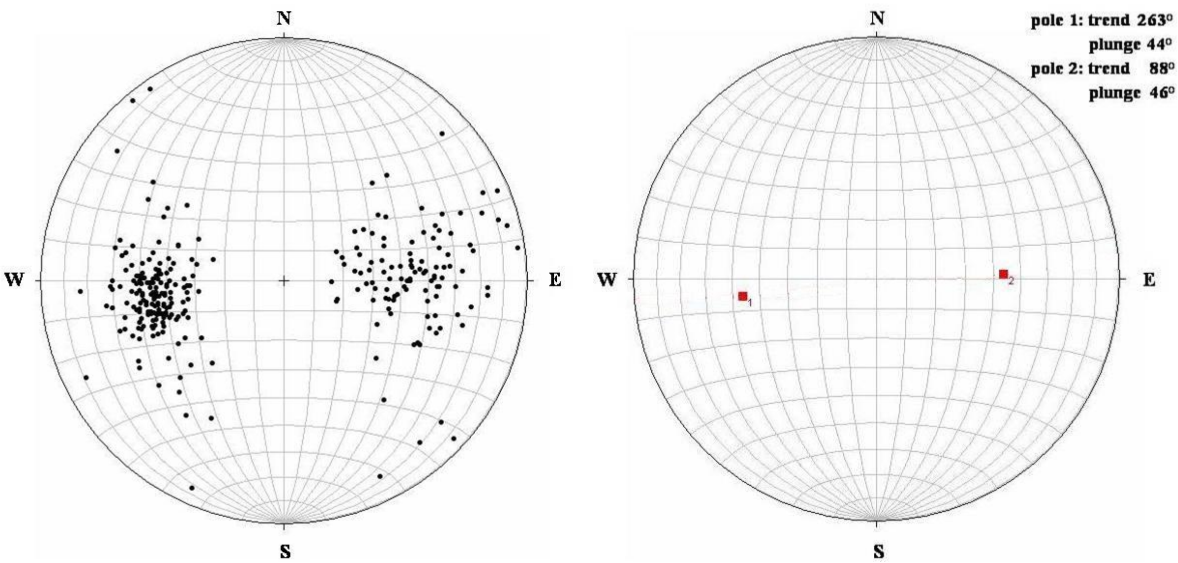

Figure 11 - (a) Measured and (b) fitted poles to fracture planes plotted on stereographic plot

The induced fracture pattern was further characterised from observations of the excavation sidewalls. An analysis of these observations made during the excavation of the PRACLAY gallery confirms the fracture pattern observed during the excavation of the Connecting gallery (Figure 12). The similarity between the fracture pattern observed around two perpendicular horizontal galleries indicates that the difference in in-situ horizontal stresses is small.

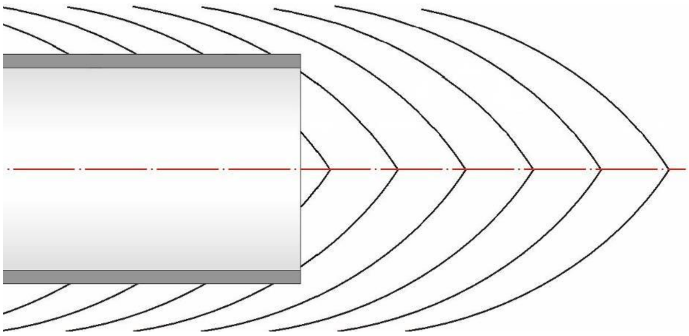

Figure 12 - Fracture pattern observed during the excavation of the Connecting gallery

- **Monitoring the gallery lining**

About 40% of the lining rings contain one or more specially equipped segments. In some segments, sensors were embedded during manufacturing: thermocouples, strain gauges (vibrating wire and optical), pressure cells and load cells. Some segments contain corrosion samples and some lining rings were equipped for wire extensometer measurements. Figure 13 gives an overview of the various instruments embedded in the gallery lining. Figure 14 shows the support case for the strain gauges.

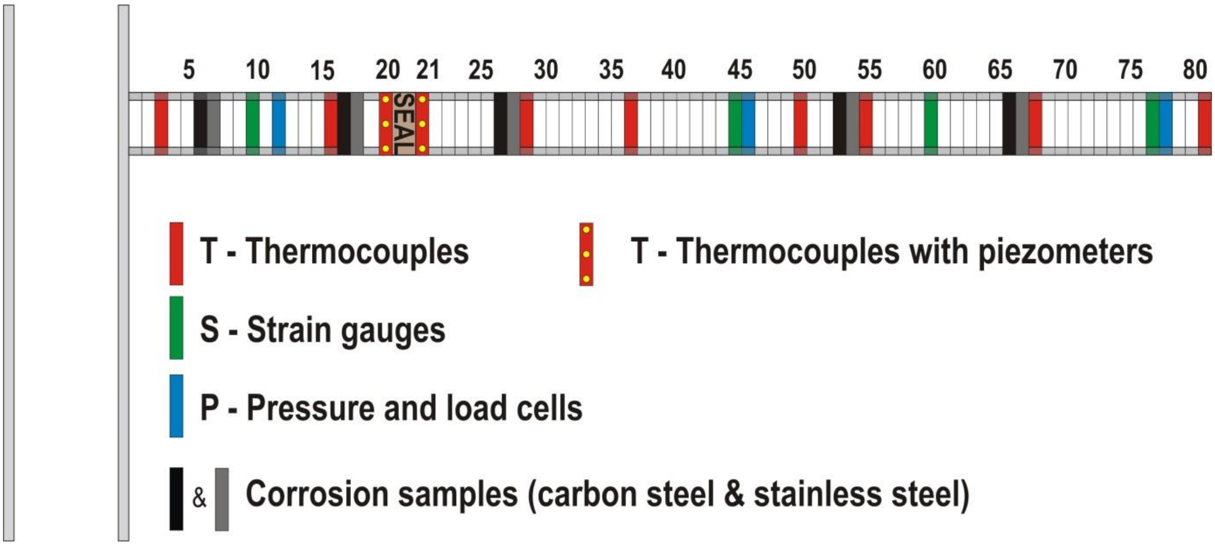

Figure 13 - Instrumentation of the PRACLAY gallery lining

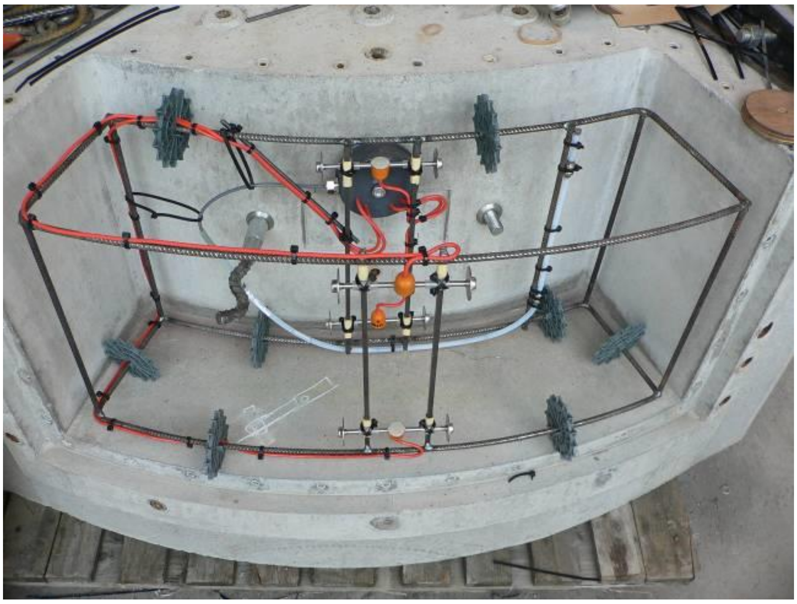

Figure 14 - Support case placed in the segment mould for the installation of the strain gauges

Figure 15 shows strain measurements during the first five months after installation of the gallery lining. These are the measurements made by strain gauges embedded in one of the segments of ring 77 of the PRACLAY gallery, notably the utmost right segment. Ring 77 is one of the high-strength rings (CERACEM®) near the end of the gallery. This segment contains eight vibrating wire strain gauges, four near the extrados (blue graphs) and four near the intrados (orange/pink graphs).

Due to the progressive loading of the lining by the surrounding clay formation, strains increased rapidly during the first weeks. About one week after the start of the measurements, the effect of restarting the tunnelling works after the stop test was visible. The sensors near the intrados behaved differently to those at the extrados: a varying bending moment is present inside the lining. Other segments (at other positions inside the lining) display a different behaviour. The results reflect the transition phase towards a stable loading of the gallery by the clay formation.

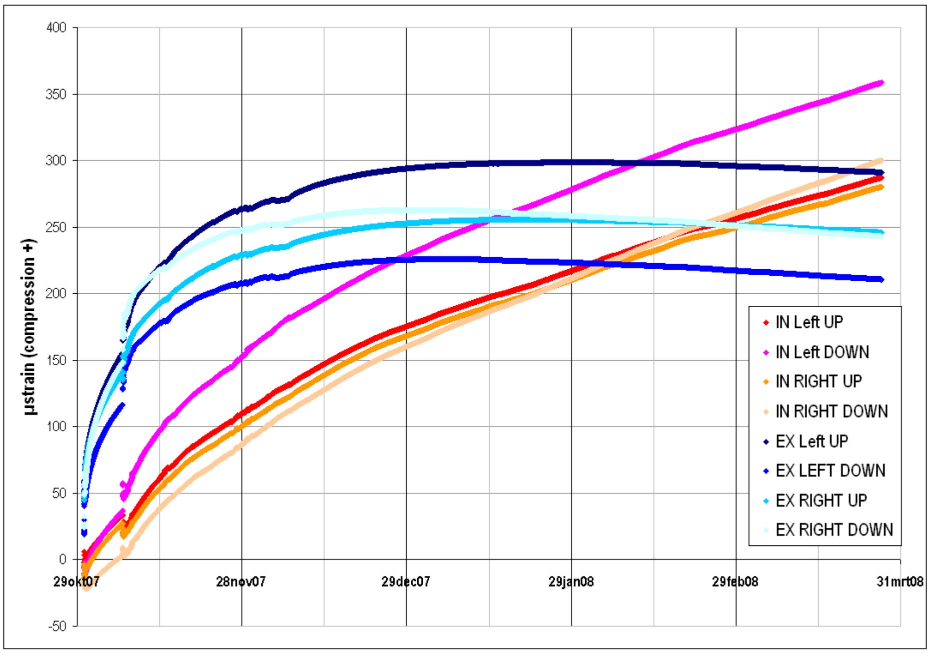

Figure 15 - Strains inside the PRACLAY gallery lining, measured by strain gauges embedded in ring 77

CONCLUSION

With the construction of the gallery crossing and the PRACLAY gallery itself, the first of the three tests making up the PRACLAY In-Situ Experiment was successfully accomplished. This test, the so-called Gallery & Crossing test, aimed to further examine and demonstrate the construction of an underground repository using industrial methods and the feasibility of constructing a crossing between two galleries. The design proved to be adequate and the construction feasibility can be considered proven.

Several measurements (at the crossing, in the clay and in the lining) were carried out before, during and after the excavation of the PRACLAY gallery. The aim was to gain as much information as possible about the performance of the excavation technique, the behaviour of the Boom Clay and the impact of excavation on the clay. The results were in line with previous observations and confirm the highly coupled and anisotropic hydro-mechanical behaviour of the Boom Clay and known fracturing processes.

PUBLICATIONS

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

Bastiaens W., Bernier F., 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, Amsterdam, Netherlands, 15-17 June 2005 / International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE), London, United Kingdom, Taylor & Francis, pp. 795-801, 2006.

Bastiaens W., Bernier F., Li X.L., An overview of long-term HM measurements around HADES URF. In: Proceedings of The Internation Symposium of the International Society for Rock Mechanics on Multiphysics Coupling and Long Term Behaviour in Rock Mechanics, Liège, Belgium, 9-12 May 2006 / International Society of Rock Mechanics, London, United Kingdom, Taylor & Francis, pp. 15-26, 2006.

Bastiaens W., Bernier F., Li X.L., SELFRAC: Experiments and conclusions on fracturing, self-healing and self-sealing processes in clays: Clays in natural & engineered barriers for radioactive waste confinement, Tours, France, 14-18 March 2005. In: Physics and Chemistry of the Earth, 32:8-14, pp. 600-615. ISSN 1474-7065, 2007.

Bernier F., Li X.L, Verstricht J., Barnichon J.D., Labiouse V., Bastiaens W., Palut J.M., Ben Slimane K., Ghoreychi M., Gaombalet J., Huertas F., Galera J.M., Merrien K., Elorza F.J., Davies C., CLIPEX. Report EUR 20619, Luxembourg: Commission of the European Communities, 2002.

Salehnia F., Collin F., Li X., Dizier A., Sillen X., Charlier R. Coupled modeling of Excavation Damaged Zone in Boom clay: Strain localization in rock and distribution of contact pressure on the gallery's lining. In: Computers and Geotechnics, 69(2015), pp. 396-410. ISSN 0266-352X

