# Design and realisation of the PRACLAY experimental gallery

# *Design et réalisation de la galerie expérimentale PRACLAY*

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ABSTRACT: Within the Belgian research programme for geological disposal of radioactive waste an experimental gallery was excavated to host a large scale heater test in Boom Clay. In this project, a gallery crossing was realised and the gallery has been excavated by a roadheader under the protection of a shield. The combination of geotechnical and (future) thermal loading of the concrete lining resulted in the use of several compressive materials. Geotechnical monitoring was carried out during construction.

*RESUME: Une galerie expérimentale à échelle réelle, destinée à un test de chargement thermique de l'argile de Boom, vient d'âtre achevée. L'expérience s'inscrit dans le contexte du programme de recherche belge pour l'évacuation géologique des déchets radioactifs. Le projet comprend la réalisation d'une carrure de renfort particulière et la galerie est excavée au moyen d'une machine à attaque ponctuelle à l'abri d'un bouclier. La combinaison des pressions de terre et de la future charge thermique implique l'utilisation de divers types de matériaux compressibles. Le chantier a fait l'objet d'une instrumentation exhaustive sur tous les composants.*

## 1 - INTRODUCTION: UNDERGROUND RESEARCH FOR THE DISPOSAL OF RADIOACTIVE WASTE

### *1.1 – Research at HADES URF*

The industrial production of nuclear electricity implies the management of the generated high level radioactive waste. In Belgium, the R&D programme on this topic was initiated at the Belgian nuclear research centre (SCK•CEN) in 1974. A tertiary clay formation called the "Boom Clay", present under the Mol-Dessel nuclear site between 190 m and 290 m, was selected as a potential host formation for the disposal of long lived HLW (High Level Waste). Preliminary laboratory research yielded promising results, thus it was decided to construct the underground research facility HADES (High-Activity Disposal Experimental Site) at 223 m depth.

The first construction phase started in 1980 and since then HADES has been expanded several times, Figure 1 shows the construction history (Bastiaens & Bernier, 2006). The primary purpose is conducting various in-situ experiments (on geomechanics, corrosion, migration, ...) to study the safety and feasibility of HLW disposal in the Boom Clay layer. HADES is currently managed by the EIG EURIDICE, an economic interest grouping between SCK•CEN and ONDRAF/NIRAS (the Belgian agency for radioactive waste and enriched fissile materials).

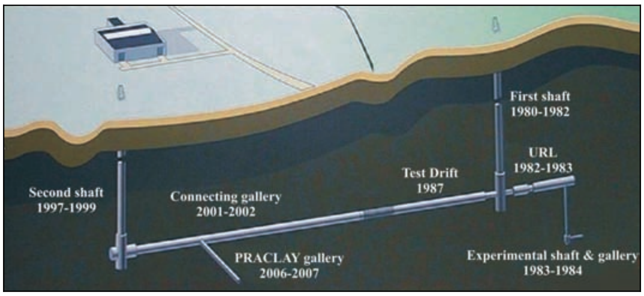

*Figure 1 - Construction history of HADES*

### *1.2 – The PRACLAY experiments*

The PRACLAY demonstration & confirmation experiments contribute to the Belgian research, development and demonstration programme to assess the safety and feasibility of geological disposal of radioactive waste in Boom Clay. Within this programme, the large scale PRACLAY heater test aims to verify that Boom Clay is suitable to host heat emitting radioactive waste. A 35 m long section of an experimental gallery in the underground research facility HADES will be heated during ten years (~80°C at the gallery extrados).

The heater test focuses on the response of the host rock to the thermal load. Figure 2 shows the experimental lay-out. In 2007, an important milestone was reached with the realisation of the PRACLAY gallery; a 45 m long drift with an external diameter of 2.5 m. The design was made by TRACTEBEL development engineering. Following an adjudication procedure, the construction contract was awarded to SMET Tunnelling. The design of the gallery needed to meet the specific requirements related to the heater test.

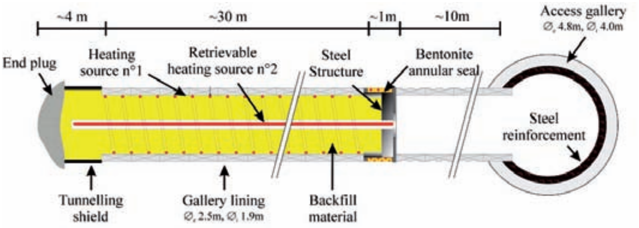

*Figure 2 - Overview of the PRACLAY heater test*

### *1.3 – Boom Clay*

Table 1 summarises the undrained geomechanical characteristics of undisturbed Boom Clay at the level of HADES (-223 m), considering a perfect elasto-plastic model type Mohr-Coulomb. Other important parameters such as hydraulic conductivity, porosity and water content are shown as well (NIRAS, 2001).

Table 1 – Undrained characteristics of Boom Clay

| Parameter | Unit | Value |
|---|---|---|
| Young's Modulus* (E) | MPa | 200 - 400 |
| Poisson coefficient ($\nu$) | / | 0.4 - 0.45 |
| Friction angle ($\varphi$) | ° | 4 |
| Cohesion (c) | MPa | 0.5 - 1 |
| Hydraulic conductivity (k) | m/s | $\sim 10^{-12}$ |
| Porosity | / | 0.39 |
| Water content | % vol | 30-40 |

* Tangential, at the origin

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. 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 ($K_o$~0.9).

## 2 - GALLERY CROSSING

The intersection structures between two perpendicular galleries are always a design challenge, mainly during the temporary construction phases. In this case, the main existing gallery has a 4.8 m external diameter whereas the perpendicular PRACLAY gallery is 2.5 m external. The ratio between both geometries corresponds to the rules of thumb used in similar projects in London Clay but similarities end there as the purposes of the present crossing structure are multiple:

- To demonstrate the construction feasibility of a secondary gallery by using a tunnelling machine that can fit in the main gallery without removing the main lining except at the opening (i.e. no starting chamber is needed).
- To avoid any additional clay convergence; in other words to maintain the existing extent of the excavated damage zone.
- To ensure the structural stability of the crossing while keeping the linings of both galleries independent (no connections).

### *2.1 – Geometry & Design*

The different constitutive elements of the structure had to comply with the following requirements:

- Weight and geometry compatibility with the access shaft (3 m internal diameter and 5 tons maximum payload.
- Maximum thickness of 22.5 cm, including construction/assembly tolerance (+/- 2 mm), deformation and lining irregularities. The internal diameter is 3.5 m and the external diameter 3.95 m.
- Short length (3.8 m) for economical reasons and the presence of adjacent experiments.
- Two circular openings are foreseen: ~2.5 m on one side (PRACLAY) and 0.8 m at the opposite side (future experiment).

The imposed material choice was a precast bolted steel structure (steel grade GS520). In addition to the ring's self weight, $\sigma_V$=3.0 MPa en $\sigma_H$=2.7 MPa was used in the design with a load safety factor of 1.2 and a material safety factor of 1.1.

The structural principle is based on several ribbed plates bolted with a significant number of M39 bolts (strength 10.9), locked in place by means of a predetermined tightening torque. The bolts are highly stressed due to the shear and tensile forces acting on the assemblies. Additional plates were added to increase the overall stiffness, mainly near the large opening.

The calculation was done by finite elements. The concrete lining is neglected due to the loss of the pre-existing normal force when the opening is created. The interface elements are reduced to equivalent springs based on the Boom Clay deformation modulus. The large opening of the structure undergoes centimetric deformation under these high loads so that an extra height was foreseen in order to guarantee the passage of the tunnelling machine. Figure 3 and 4 show the model and the bolting principles.

### *2.2 – Manufacturing*

SMET Tunnelling subcontracted the manufacturing of the structure to Allard Europe. It is composed of 11 cast steel segments. The first step was the construction of positive wooden moulds. These were made bigger than the designed size to compensate the shrinkage of steel. Then negative moulds were made in sand and the segments were cast. Afterwards, the segments were sandblasted and machined. Finally, the ring was assembled and milled as a whole (see Figure 5).

Throughout the construction process inspections were carried out: visual controls, dimensional measurements, hardness measurements, analysis of the chemical composition of the steel, tensile strength tests, magnetic and ultrasonic tests to detect any flaws. The measured yield values exceeded 700 MPa.

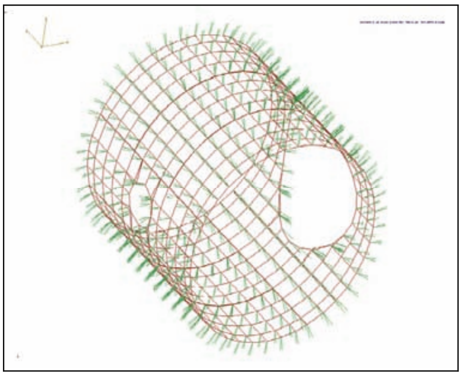

*Figure 3 - Finite element model of the reinforcement structure*

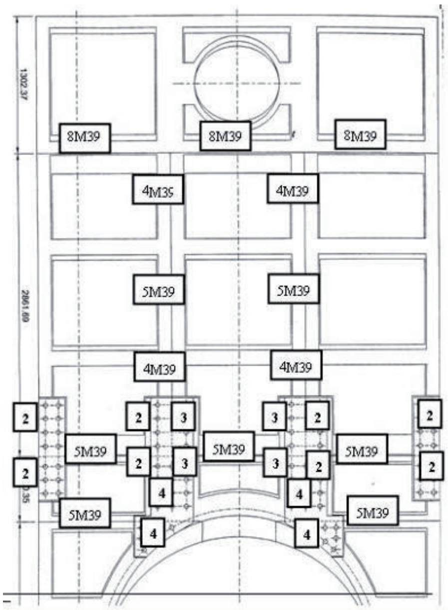

*Figure 4 – Detail of the bolts and additional plates*

*Figure 5 – Milling of the reinforcement structure as a whole*

### *2.3 – Assembly*

One after another, the 11 segments of the structure were transported to the underground facility. The underground assembly of the reinforcement ring was realised between 02.08.2007 and 14.08.2007. During the assembly, security bolts fixing the lining of the connecting gallery to the reinforcement ring were installed. This procedure made sure that the remaining parts of the lining stayed in place once the opening for the PRACLAY gallery was made. Once the bolts were placed, the annular space between the structure and the gallery lining - ranging from 0.1 to several cm - was filled with grout. This ensured a good load transfer of the host rock on the structure.

## 3 - EXCAVATION TECHNIQUE

The basic design principle is based on a continuous full face excavated rate of at least 2 m per day in order to comply with the creep behaviour of the clay. Calculation has shown that the clay behaves similarly at this pace than at a more industrial speed of about 10 to 15 m per day.

### 3.1 – Design

The tunnelling machine design is based on the need to have a smooth circular excavation profile at the rear, allowing the direct placement of the lining without the need to perform post-grouting. The majority of the face is excavated by means of a roadheader but the outer rim is cut by the edges of the shield when it moves forward. This ensures a smooth and circular excavation profile.

The fine-tuning of the shield's design involved three of its main characteristics: the diameter at the rear end, the oversize of the cutting head and the shape of the shield. These characteristics must provide an overexcavation to compensate for the convergence of the clay between its excavation and the installation of the lining. The convergence was determined by modelling which was supported by the experience gained from the excavation of the connecting gallery. As a result, the (initial) shield front and rear diameter were respectively 2585 and 2520 mm. The length of the shield was 2.4 m. In case of unexpected convergence, the oversize could be adjusted during the excavation.

### 3.2 – Manufacturing

The machine was constructed by SMET. Prior to the transport to the underground facility, all tunnelling equipment (shield, roadheader, erector, rail tracks and hydraulics) was assembled in the same configuration as for the actual excavation (see Figure 6). This allowed checking all functions and the geometry of the machine, separately and as a whole. It provided an opportunity to make any necessary adjustments before starting the underground works. The test assembly was all the more needed due to the limited assembly space in the connecting gallery. Amongst others, the manipulation of a lining segment and the insertion of a key into the corresponding pocket of the shield were tested.

### 3.3 – Assembly

After the test assembly, the tunnelling equipment was disassembled and all parts were transported to the underground facility. The underground re-assembly took place between 28.08.2007 and 08.10.2007. The shield was assembled on a 'cradle' just next to the reinforcement structure, parallel to the axis of the connecting gallery. Once the concrete lining of the connecting gallery at the location of the PRACLAY gallery was removed (on 01.10.2007 and 02.10.2007), the cradle carrying the machine was positioned into the large opening of the reinforcement ring (see Figure 7). The other parts of the equipment were installed stepwise during the start-up phase when the required space was made available.

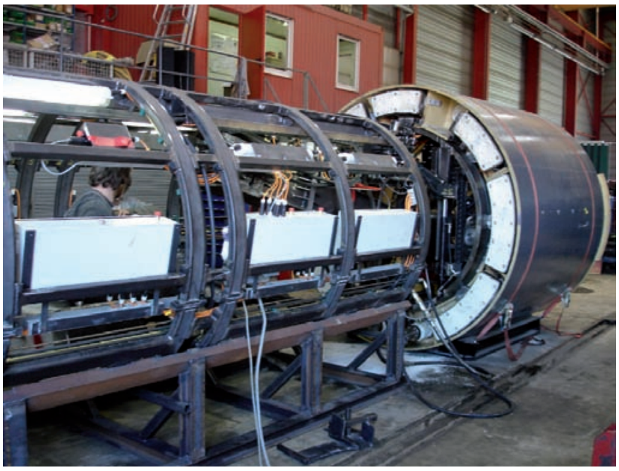

Figure 6 – Test assembly of the tunnelling equipment

Figure 7 – The tunnelling shield as it is being positioned into the reinforcement structure: the roadheader (painted red) is visible at the front of the tunnelling shield; Boom Clay is visible in the opening of the reinforcement structure

## 4 - GALLERY LINING

The design of the lining had to take into account two types of loading: "geotechnical" loading due to the pressure exerted on the lining by the surrounding rock and "thermal" loading which will occur during the operation of the PRACLAY heater test. Several innovative materials were used to cope with the related challenges. The gallery consists of 81 lining rings.

### 4.1 – Design & manufacturing

#### 4.1.1 – Current section

The gallery lining choice has been based on several requirements:

- The principle should be industrially proven.
- The material should be available and economically compatible with an application on an industrial scale (several kilometres of galleries are needed in a final repository).
- The concept must be tailored to absorb the effect of an intrados temperature of about 90 °C, both radially and longitudinally.

The lining used is of an expanded type ("wedge block system"). The expanded lining has been developed for cohesive soils with a stand-up time of several hours (as for the London subway in over-consolidated London Clay).

A ring consists of 8 concrete segments and one shorter wedge shaped key segment (see Figure 8). The introduction of the wedge expands the ring against the circular excavated profile inducing a post-stressing effect in the lining. The 30 cm thick concrete segments are unreinforced and unbolted. Each ring is independent and 50 cm in width. The key segments were 58 cm wide and were sawn to the correct dimensions on site. Depending on the diameter of the excavated profile behind the tunnelling shield, the front or rear end of the key segments was removed. This way a larger range of possible lining diameters was covered: 2488 – 2502 mm.

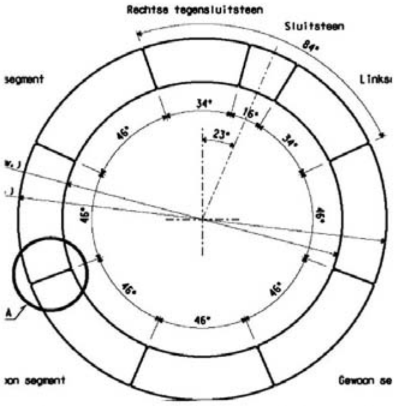

Figure 8 – Cross section of the PRACLAY gallery lining

The load levels have been chosen based on the current monitoring of the connecting gallery (wedge block system as well). The load on a current section at ambient temperature amounts to: $\sigma_V$ = 2.75 MPa and $\sigma_H$ = 2.5 MPa. A higher value has been taken close to the crossing to take into account the main gallery plastic zone and its higher circumferential stress.

These values induce compressive stress everywhere and also at the joints, where there is a direct concrete to concrete contact. As a consequence, the calculation choice is based on a continuous ring and may be done analytically with spreadsheets. The stress level reaches about 40 MPa, calling for a high quality concrete (C80/95). The material safety factor has been reduced to 1.2 (precast elements). Additional reduction factors have been applied due to the loss of ductility and long term effects.

Apart from stress anisotropy, the following effects and constraints have been included: thick tube effect, eccentricity at placement (2 cm misalignment), curvature reduction effect, geometrical loss of contact due to chamfers, reduced key length and future experimental borings with a maximal diameter of 6 cm.

Construction tolerances were +/-1.5 mm on the radius, thickness and length and +/- 0.25 mm on the surface flatness. SMET Tunnelling subcontracted the manufacturing of the moulds and the C80/95 segments to BUCHAN.

### 4.1.2 Influence of thermal loading

The high thermal load and the uncertainty about the amount of divergence of the clay (if any) induce an additional load according to $\Delta\sigma = E * \alpha * \Delta T$. Depending on the hypothesis, the resulting stress can amount to about 50 MPa in addition to the normal load case. Instead of using even higher concrete strengths or thicker segments, it was decided to include two 5 cm thick elasto-plastic joints within the rings subject to the thermal load. The transition between the elastic and plastic behaviour should occur above the stress level induced by the ground pressure of the surrounding rock, this means above 40 MPa. In other words, after construction of the gallery these joints should remain rigid and it is only when the thermal loading starts (cf. start of the PRACLAY heater test), that their deformation is needed.

The material chosen and tested is a specific stainless steel foam panel. This material was developed in cooperation with PORVAIR, which also produced the panels. Figure 9 shows a cross section of such a panel. Its stress-deformation behaviour is shown in Figure 10. Because very large forces are needed to compress these panels, the compression test shown had to be performed using a press not specifically designed for this purpose. Consequently, the resolution of the test is low. However, the desired behaviour is illustrated: the flat zone of the curve at 40 MPa corresponds to the heat loading phase, limiting additional stresses in the concrete and hence protecting its integrity.

Not all rings affected by the thermal loading of the heater test were equipped with foam panels though. As an experiment to study the interaction between the lining and the surrounding clay, some rings were installed without the foam panels. The design team is hopeful that some divergence of the clay will occur during the operational phase of the heater test, avoiding the need for these expensive joints in the future. These rings were composed of a patented high quality concrete (160 MPa on cube): BSI®-CERACEM from Eiffage. This solution was applied for the six last rings of the gallery. The same moulds were used as for the C80/95 segments, manufacturing was subcontracted to SOCEA.

Along the axis of the PRACLAY gallery, thermal expansion (and subsequent loading) is also important. A chemically compatible compressive material was placed between the rings to absorb the thermal stresses: 8 mm thick silicone rubber sheets. Laboratory tests were carried out to determine the behaviour of this material, both at room temperature and at elevated temperature. 3 mm thick PP sheets were introduced in between the lining rings to allow for steering corrections when necessary.

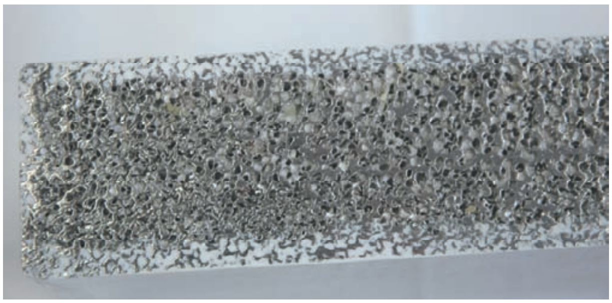

*Figure 9 – Cross section of a stainless steel foam panel*

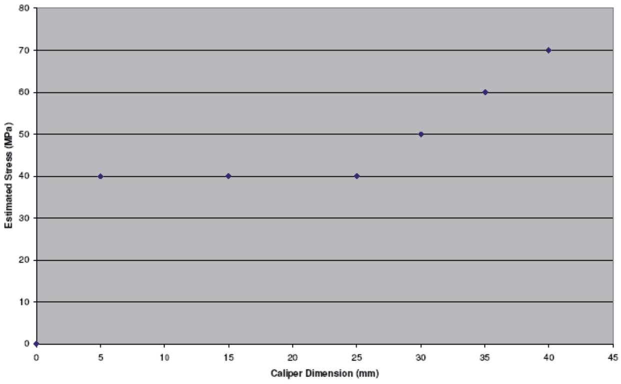

*Figure 10 – Compression results of a stainless steel foam panel*

### 4.1.3 End plug

At the end of the excavation the tunnelling shield was left in place and all recoverable components were removed. The final face was given a hemispherical shape and a concrete end plug (C30/37) was installed. The end plug is subject to long term pressure from the surrounding clay, adding to the longitudinal stress level. Some measures were taken to limit these stresses:

- The diameter of the end plug is 1 m larger than that of the gallery itself. Consequently, the outer annulus of the plug is in contact with the clay and a reaction force will be created in this zone when the formation exerts pressure on the end plug.
- Furthermore, a custom made wall of compressive concrete blocks was built between the shield and the end plug (see Figure 11). The initial thickness of the wall is 25 cm. This material was designed and manufactured by SOLEXPERTS, based on HIDCON elements also used in other tunnelling projects (e.g. Lötschberg). The concrete's behaviour is elasto-plastic with a specified yield level between 2 and 4 MPa (see Figure 12). The material was tested under the expected conditions i.e. at 90 °C, confined and fully saturated.

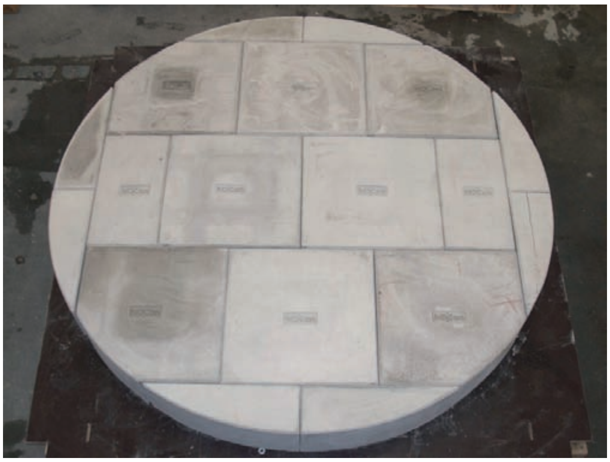

*Figure 11 – Test assembly of the wall of compressive concrete which was installed at the end of the PRACLAY gallery, the diameter of the wall is 2.4 m and its thickness 0.25 m*

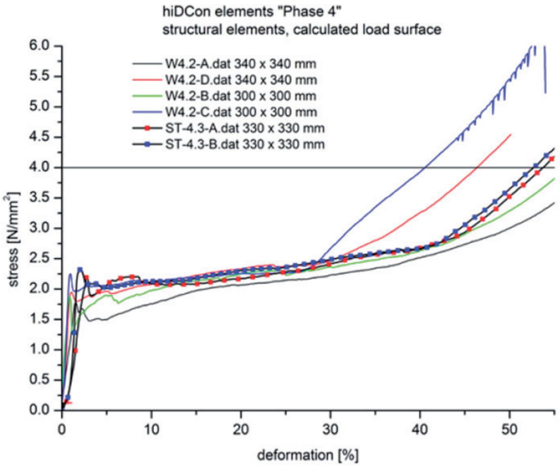

*Figure 12 – Stress-deformation tests on compressive concrete.*

### *4.2 – Installation procedure*

Several excavation steps (~15 cm each) were performed up until an unsupported zone of some 60-70 cm was present behind the tunnelling shield. Next, the lining segments were installed by using a rotary erector mounted on the rear of the tunnelling shield (see Figure 13). The installation started with the bottom segments. In the meanwhile the key segment ("wedge") was installed in a dedicated pocket in the tunnelling shield. Once all other segments were in place (the top ones were kept in place by the hydraulic jacks of the shield), the key segment was pushed into the ring, expanding it against the excavated clay profile. The contact surfaces of the key segment and the adjacent counter key segments have a helicoidal shape, ensuring a correct positioning of the key segment as it is pushed into the ring.

The different types of compressive materials (foam panels, silicone rubber and PP sheets) were glued onto the segments before their installation. The concrete end plug was poured in place, using the wall of compressive concrete and a steel plate as a formwork.

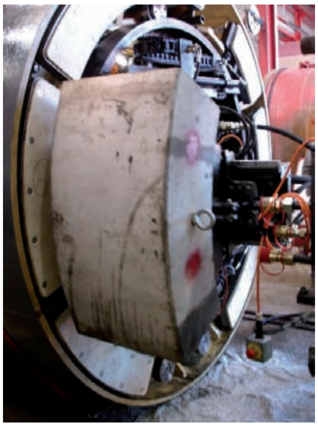

*Figure 13 – Segment manipulation with the rotary erector*

## 5 - REALISATION OF THE GALLERY

### *5.1 – Excavation and construction process*

The actual construction of the gallery was performed during October and November 2007. The combination of the small diameter of the PRACLAY gallery and the important amount of equipment needed resulted in a very limited amount of working space. All available space was used (see Figure 14). As a result, minor problems such as broken ducts etc. occurred relatively often. Furthermore, the limited space complicated the repairs.

This was also reflected in a lower progress rate than achieved during the excavation of the connecting gallery. Figure 15 shows the time needed for the excavation and installation of each ring. Taking into account the width of the lining rings (0.5 m) the target rate of 2m/24h corresponds with a maximum of 6h/ring. The graph shows that after a (expected) start-up zone of 5-10 m, the target rate could be reached about 90% of the time. There were two major exceptions. The first was the zone where a special structure was installed for the future construction of a hydraulic seal needed to seal off the PRACLAY heater test from the rest of HADES. A second one was related to a break down of an electrical generator.

In the start-up zone, the convergence of the clay between its excavation and the installation of the lining was influenced by the altered stress conditions near the crossing. Beyond the start-up zone, horizontal convergence was in line with the predictions. On the contrary, vertical convergence was 2-3 cm less than expected. This seems contradictory to the fact that the vertical in-situ stresses are higher than the horizontal ones. However, stresses are significantly altered around an excavation face and furthermore, excavation induced fractures can play an important role in this phenomenon. As will be discussed in section 6.2.3 the strike of the observed fractures is generally perpendicular to the axis of the PRACLAY gallery. These fractures originate several metres ahead of the excavation face; in this way the clay undergoes some relaxation in the vertical sense before it is reached by the tunnelling machine. The same phenomenon – but to a lesser extent - was observed during the excavation of the connecting gallery (Bastiaens et al., 2003).

As a consequence of the lower than expected vertical convergence, the positions of the cutting knives at the front of the tunnelling shield were adjusted. To cope with the observed anisotropic convergence, the overexcavation was reduced at the top and bottom of the shield. This way, the shield cut a slightly elliptical profile in order to end up with a more circular profile behind the shield.

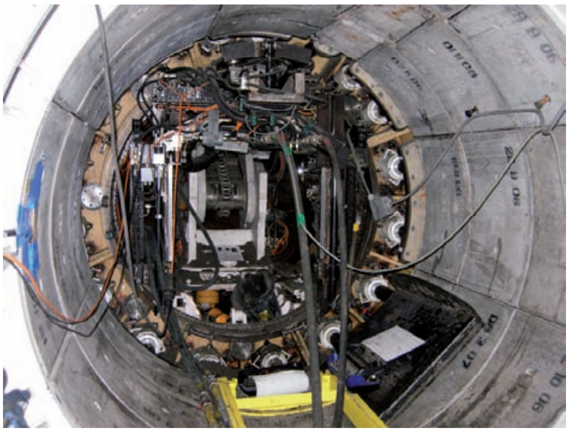

*Figure 14 – Rear view of the tunnelling shield (start-up phase)*

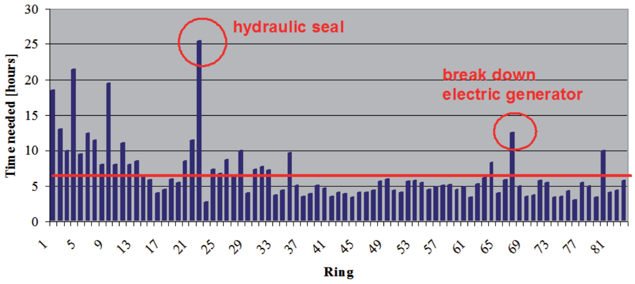

*Figure 15 – Time needed for each lining ring: the targeted excavation rate was reached most of the time*

### *5.3 – Tunnelling stop-test*

On 30.10.2007, after the installation of ring 79, the excavation works were stopped for one week. The purpose of the stop was to test the level of difficulty to restart the tunnelling machine in case of an operational halt. Indeed, during such a stand-still the Boom Clay around the shield converges and the friction between the clay and the shield increases. Measures taken to limit the difficulties of restarting the shield in such a case are its slightly conical shape and its Teflon-based coating.

The excavation front was stabilised during the stop test using six 8-metre glass-fibre anchors. The boreholes for the anchors were drilled manually by a pneumatic drill mounted on a carriage. The anchors were then placed in the boreholes and injected afterwards by a resin to assure a good contact between the clay and the anchor. On 06.11.2007, the excavation works restarted. The thrust force needed to push the shield forward was about twice the normal thrust force. Still, this was only ~25% of the maximum available force.

## 6 - SCIENTIFIC PROGRAMME

### *6.1 – Monitoring the crossing*

Due to the excavation of the PRACLAY gallery, a stress redistribution occurred. In some places stresses were lower than before, but in other places 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. Therefore additional reinforcement was available and the lining of the connecting gallery was monitored to evaluate whether it was necessary to actually install them. 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 16 shows the location of the surface strain gauges at the gallery crossing.

Two days after the opening of the lining of the connecting gallery a crack was observed in one of the segments of ring 31, adjacent to the reinforcement ring. Four days later also a crack in a segment of ring 30 was noticed. Both cracks however did not grow further and no additional stability measures had to be taken.

As expected, the highest stresses in the steel structure were measured near the 2.5 m diameter opening, at locations R2 and R3 (see Figures 16 and 17). They amount up to ~300 MPa. The graph 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. If one looks into detail, the second increase consists of several smaller steps, these correspond to the alternating steps of excavation and lining installation.

Similar results were obtained by the strain gauges installed on the surface of the concrete lining next to the reinforcement structure (see Figure 18). The same two events are visible: removal of the lining and start of the excavation. Maximum stress increase measured was some 8 MPa.

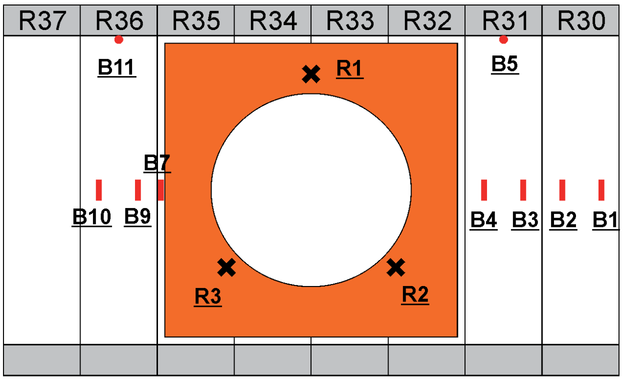

*Figure 16 – Location of strain gauges at the gallery crossing*

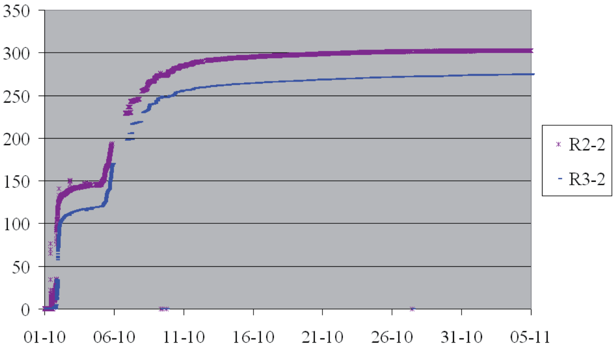

*Figure 17 – Stress measurements [MPa] on the reinforcement structure during the excavation (locations R2 and R3)*

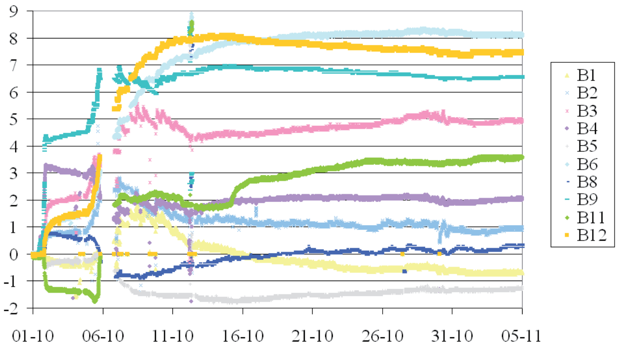

*Figure 18 – Stress measurements [MPa] on the concrete lining next to the reinforcement structure*

### *6.2 – Monitoring the host rock*

#### 6.2.1 – Measurement set-up

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 up to a depth of 45 m. Because these sensors were already installed before the construction of the gallery they registered the HM response of the Boom Clay during the excavation. When looking at the HM behaviour of a clay formation, one of the important and highly sensitive parameters is the pore water pressure Figure 19 shows the locations of all installed pore pressure sensors; this article will discuss the results of one specific example.

#### 6.2.2 – Measurements during tunnelling

Figure 20 shows the pore pressures measured by piezometer P35E which runs parallel to the PRACLAY gallery, at a distance of only 0.7 m. Sixteen measurement points are present, at distances between 1 (sensor 16) and 45 m (sensor 1) from the connecting gallery. Figure 20 shows two graphs. The one on the top shows pore pressure measurements at piezometer P35E as a function of time. The other graph shows the same measurements but as a function of the relative (horizontal) position of the sensor with respect to the excavation face.

Before the start of the excavation, the pore pressure values largely depend on the distance between the sensor and the connecting gallery. Indeed, the disturbed zone of the connecting gallery regarding pore pressures has an extent of several tens of metres (Bastiaens et al., 2006). According to the elasto-visco-plastic theory, the variation of the pore water pressure during the underground excavation is linked to the volumetric deformation of the massif via the coupling effect. For all sensors in Figure 20 pore pressure rises when the excavation front approaches that specific sensor. When the front is at about 2 m, pressures start to decrease. Some metres after the front has passed the sensor, pressures increase and later decrease again.

The first increase is attributed to the undrained contractant behaviour of the clay. Stresses increase ahead of the front, compressing the clay (decrease of pore volume). Since the clay's very low permeability, water can only be expelled very slowly and the pore pressure increases. The drop phenomenon close to the front results from the high decompression of the massif and the accompanying fractures and volumetric dilatations (increase of the pore volume). Once the lining is placed (about 3 m behind the front), reconsolidation starts. Similar observations were made in the CLIPEX project studying the HM response during the excavation of the connecting gallery (Bernier et al., 2002).

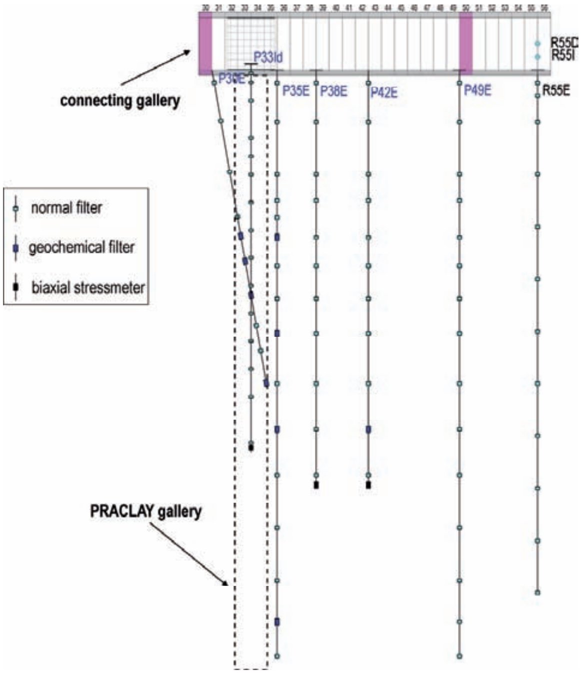

*Figure 19 – Lay-out of the piezometers installed around the PRACLAY gallery*

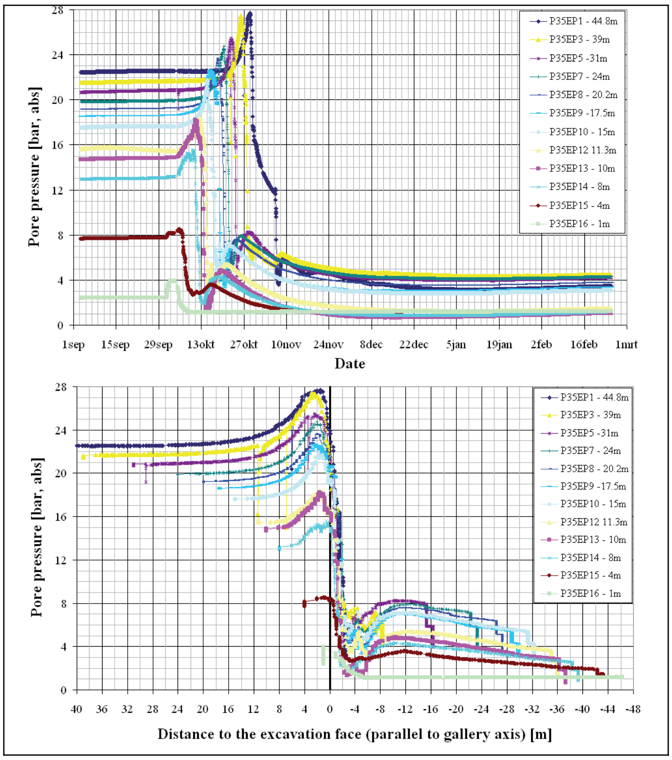

*Figure 20 – Pore pressure measurements at P35E as a function of time (top) and the relative position of the sensor (bottom)*

### 6.2.3 – Excavation induced fractures

During the excavation of the connecting gallery, a fracture observation programme was carried out. This resulted in the description of the herringbone-like fracture pattern shown in Figure 21 (Bastiaens et al., 2007). A similar observation programme was carried out during the excavation of the PRACLAY gallery. The front and excavated profile of the gallery were observed and photographed systematically. The detailed analysis of the gathered information is currently ongoing, the first results indicate a similar fracturation than observed before. Figure 22 shows the excavation faces of the PRACLAY and connecting gallery. In both cases, conjugated fracture planes are present that meet each other at the middle of the gallery. As expected, a more complicated situation was encountered near the crossing.

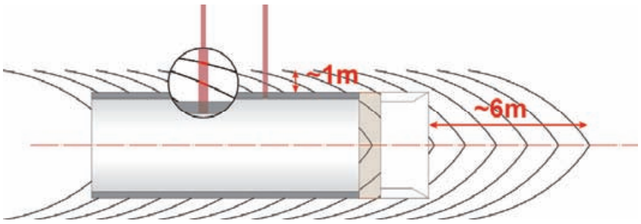

*Figure 21 – Fracture pattern observed during the excavation of the connecting gallery*

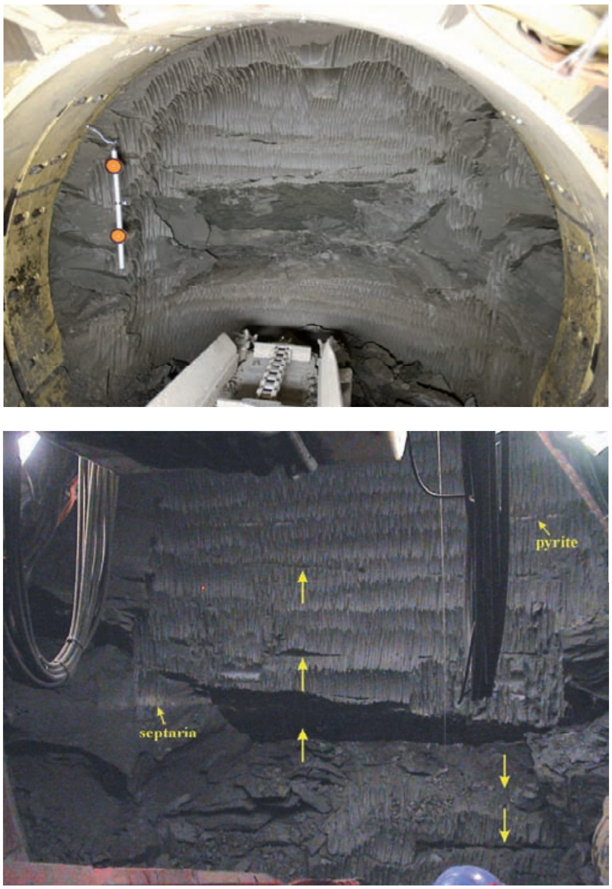

*Figure 22 – Excavation face of the PRACLAY gallery (top) and the connecting gallery (bottom)*

## 6.3 – Monitoring the gallery lining

### 6.3.1 – Measurement set-up

About 40% of the lining rings contain one or more specially equipped segments. In some segments, sensors were embedded during the 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 23 shows some pictures of the manufacturing process of the instrumented segments.

### 6.3.2 – Results

Figure 24 shows strain measurements by embedded strain gauges 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). At present, measured strains are between 200 and 360 µstrain. According to the technical specifications of the concrete, Young's modulus should be about 65 MPa. The measured strains thus correspond to stresses between 13 and 23 MPa. Tests to verify the value of Young's modulus will be carried out on concrete cores taken out of some spare segments.

Due to the progressive loading of the lining by the surrounding clay formation strains increase 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 is visible. The sensors near the intrados behave differently than those at the extrados: a varying bending moment is present inside the lining. Other segments (at other positions inside the lining) show a different behaviour. The results reflect the transition phase towards a stable loading of the gallery by the clay formation. For the connecting gallery, a more or less stable loading was obtained after roughly 12 months.

Generally, the strains show a continued increase up to present. At least part of this continued increase is caused by creep of the concrete. Therefore, creep tests are being carried out on concrete cores to quantify this phenomenon and enable a correct interpretation of the stresses within the lining.

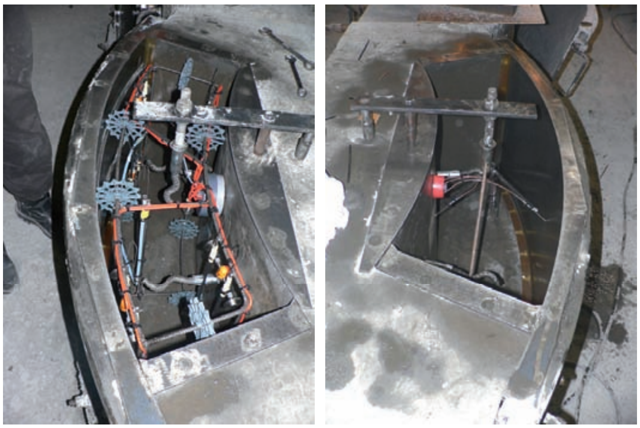

*Figure 23 – Segment moulds equipped with vibrating wire strain gauges (left) and thermocouples (right) prior to concrete casting*

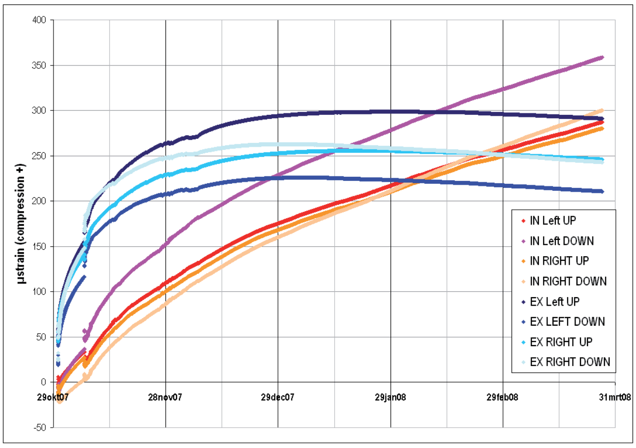

*Figure 24 – Strains inside the PRACLAY gallery lining, measured by embedded strain gauges in ring 77*

## 7 - CONCLUSIONS

The successful realisation of the gallery crossing and the PRACLAY gallery itself constitute an important milestone in the Belgian research programme for the geological disposal of HLW. The design proved to be adequate although it was evidenced that from a practical point of view, the gallery diameter of 2.5 m was at the low end of what is feasible using this construction technique. Some years ago, the same technique was success for the construction of a 4.8 m gallery at HADES. Since the future disposal galleries have an intermediate diameter, their construction feasibility can be considered proven.

Several compressive materials were used throughout the gallery. Their performance can only be evaluated in the future, more specifically during the operation of the PRACLAY heater test when a large part of the gallery will be subject to thermal loading.

During the excavation, the response of the clay formation was monitored. The results were in line with previous observations and confirm the highly coupled HM behaviour of the Boom Clay and known fracturing processes. The complex stress redistribution at the crossing zone was monitored as well.

Future work comprises further interpretation of the measurements during the excavation and the installation, operation and interpretation of the large scale in-situ PRACLAY heater test.

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