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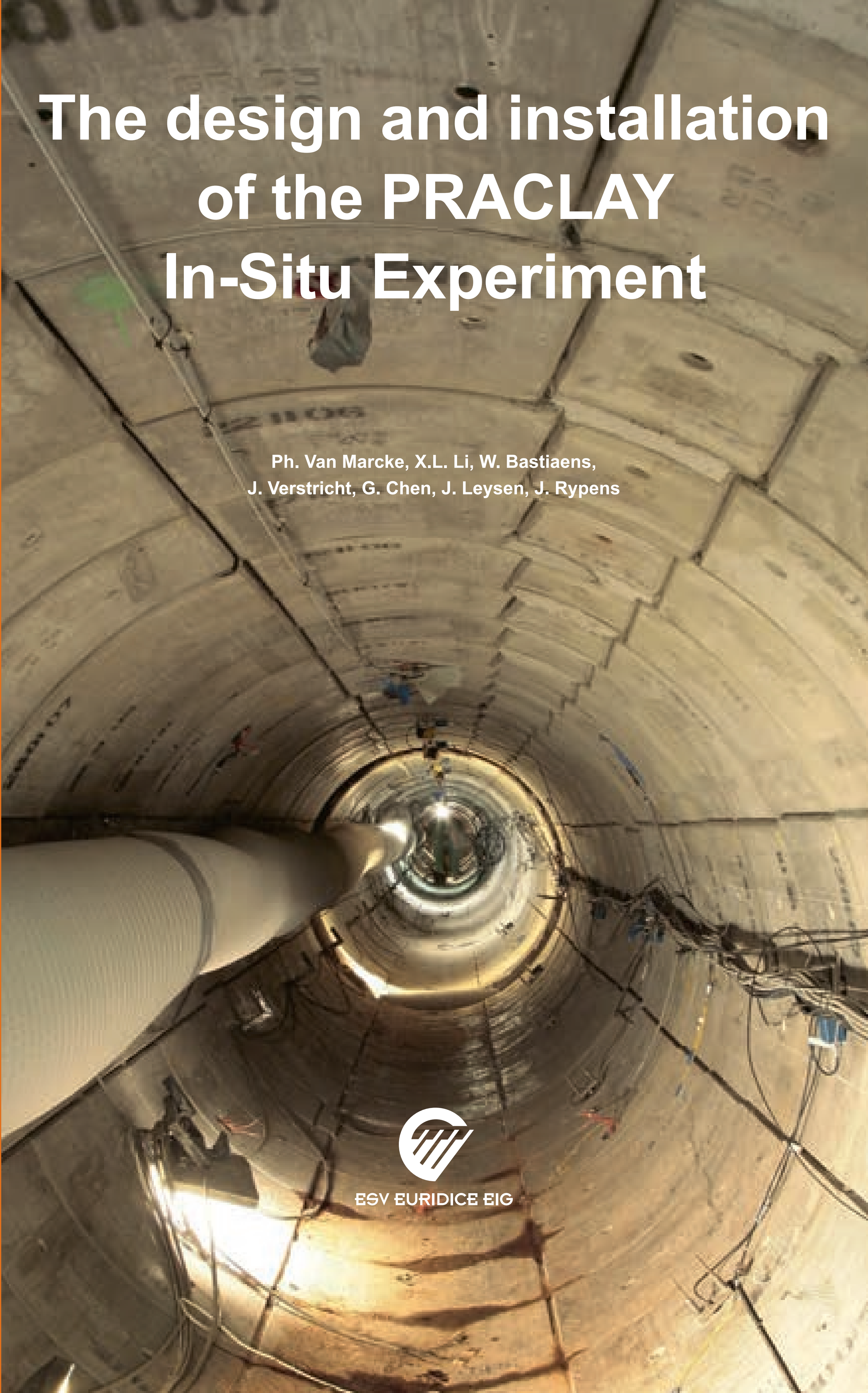

The design and installation of the PRACLAY In-Situ Experiment

Ph. Van Marcke, X.L. Li, W. Bastiaens,
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Scope and objectives of the report

This report describes the design and installation of the PRACLAY In-Situ Experiment, which is a continuation of the research that started in the 1970s on the Boom Clay as a potential host rock for the geological disposal of radioactive waste in Belgium. In 1980 work on building an underground research facility – the HADES Underground Research Facility – began in the Boom Clay at a depth of 225 m. The underground laboratory was extended in the decades that followed, demonstrating the feasibility of constructing galleries in clay at such a depth. Experiments, both in situ and in the laboratory, showed that the Boom Clay has a low hydraulic conductivity, a plastic character that gives it good self-sealing properties and a high capacity to retain radionuclides and, hence, to delay their migration towards the biosphere.

Building on these encouraging results, the PRACLAY project was launched in 1995. One goal was to demonstrate the feasibility of constructing galleries using industrial techniques, achieved with the construction of the Connecting gallery in 2001-2002. The next stage in the project was the development of a large-scale demonstration experiment of the reference design, including the use of a so-called supercontainer for the engineered barrier system, for the deep disposal of heat-emitting radioactive waste. To keep the possibility of switching over to alternative designs at a minimum cost, the idea of a single large-scale demonstration for one specific design was quickly abandoned. The original scope – the demonstration of the reference design for vitrified high-level waste or spent fuel – was reoriented to include the characterisation, verification, confirmation and demonstration of relevant elements of a disposal system and their behaviour by means of a combination of surface experiments and a large, more design-independent, in-situ experiment, the PRACLAY In-Situ Experiment.

The PRACLAY In-Situ Experiment comprises three tests. The **Heater Test** is designed to investigate the impact of a large-scale thermal load on the Boom Clay. High-level radioactive waste emits significant amounts of heat for hundreds or thousands of years. This thermal load leads to perturbations in the clay that might affect its performance as a host rock in the geological disposal concept for radioactive waste. The Heater Test is intended to be representative of a generic drift or gallery for the disposal of heat-emitting waste. To anticipate possible future changes in the repository design and because it is not possible to fully reproduce the time scale, the spatial scale and the boundary conditions of a real repository, the Heater Test was conceived to be as independent as possible of the final repository design and will be conducted under a well-controlled and a reasonably conservative combination of thermal, hydraulic and mechanical boundary conditions. This implies, among other requirements, quasi-undrained hydraulic conditions. These conditions are realised by the installation of water-saturated backfill sand in the heated part of the gallery and a hydraulic seal at the intersection between the heated and the non-heated part of the gallery. The design and installation of this seal constitutes the **Seal Test**.The Heater and Seal Test are housed in the PRACLAY gallery, situated perpendicular to the Connecting gallery. The construction of this gallery and its crossing with the Connecting gallery constitute the **Gallery and Crossing Test**, which is aimed at further demonstrating the feasibility of constructing an underground repository using industrial methods, and also examining the feasibility of constructing a crossing between two galleries without the use of a starting chamber.

Numerical simulations were used to determine the design criteria of the Heater Test. Based on these, design criteria for the hydraulic seal and the PRACLAY gallery were developed. Once the criteria for the complete PRACLAY In-Situ Experiment had been defined, the actual process of setting it up could start. This was done in three consecutive and distinct phases: the construction of the PRACLAY gallery, the fitting of the hydraulic seal and the installation of the heater and backfill material. The PRACLAY gallery was constructed in 2007. Once the hydraulic seal was fitted in 2010, the heating system and backfill material were installed in the heated section. The backfilling does not constitute an experiment in itself, since its only purpose is to create the thermal and hydraulic conditions required for the Heater Test. With the installation of the heater elements and backfill material in 2011, the set-up of the PRACLAY In-Situ Experiment was almost complete.

EURIDICE has summarised the design, preparation and actual installation of the experiment in this report. The aim of the report is to:

- ensure traceability and justification of all design and other choices since the initiation of the PRACLAY experiment through to completion of the process of setting up the experiment, including reasons why some choices or design options were ruled out;
- produce an as-built description of the different experiment components (gallery, hydraulic seal, heating system and instrumentation), which is of particular importance, as most parts of the experiment are not accessible while it is under way;
- define the objectives and success criteria of the experiment and position it within the more general R&D programme of ONDRAF/NIRAS on geological disposal of high-level and/or long-lived radioactive waste.

The full report consists of three parts:

- Part I: The PRACLAY gallery
- Part II: The hydraulic seal
- Part III: The heater and backfill material

Each part can be read and understood separately. Together, they encompass the complete installation of the PRACLAY In-Situ Experiment. Conclusions on the set-up of this experiment are included at the end of each part.

The report contains references to various other documents, such as strategic notes, numerical simulations and construction files. A list is given in the annexe. These documents can be obtained from EURIDICE on request.

Some initial observations on the hydromechanical response of the Boom Clay to the gallery excavation and on the behaviour of the hydrating bentonite in the hydraulic seal are included, but merely serve as preliminary results. It is not within the scope of this report to give an in-depth, systematic interpretation and analysis of the outcome of the PRACLAY In-Situ Experiment. This will be done at a later stage and will be the topic of future reports. Detailed evaluation of the instrumentation will also be carried out later and is outside the scope of this report.

The next milestone in the PRACLAY In-Situ Experiment is switching on the heating system and the actual start of the Heater Test.

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1. Introduction

For 40 years Belgium has been actively studying the long-term management of high-level and/or long-lived radioactive waste. A research programme was launched by the Belgian Nuclear Research Centre SCK•CEN at Mol in the early 1970s, and followed international recommendations to isolate radioactive waste from humans and the environment by means of geological disposal. This means that the waste is disposed of in a repository located in a geologically stable formation with appropriate characteristics. SCK•CEN chose to concentrate its efforts on investigating the poorly indurated Boom Clay layer because of the potentially favourable characteristics of this host rock. Because of the lack of experience in excavating underground facilities at a depth of some 200 metres in this type of clay, one of the main objectives of the initial research and development (R&D) programme was to assess and demonstrate the feasibility of building such a repository. This is why work on the underground research facility known as HADES (High-Activity Disposal Experimental Site) got under way in 1980 (Figure 1-1).

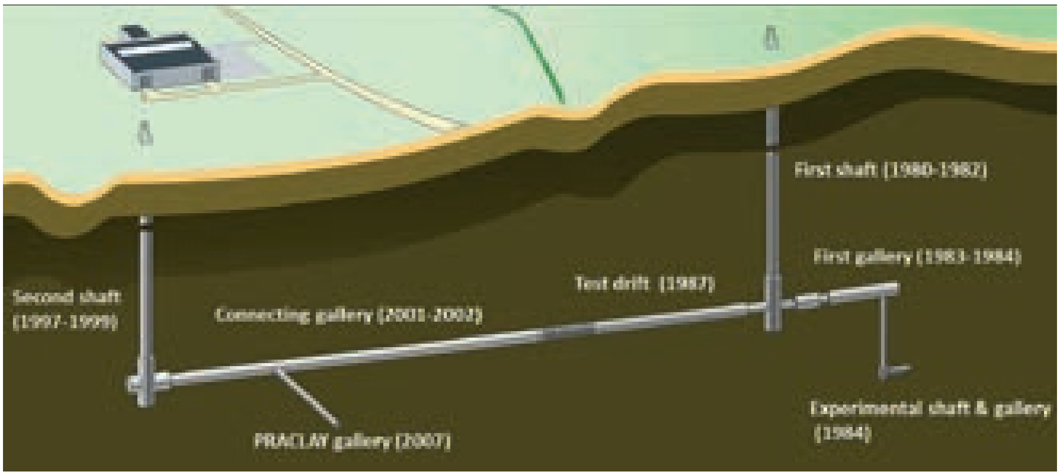


Figure 1-1 Construction history and layout of the HADES underground research facility.

In 1985 ONDRAF/NIRAS, the Belgian Agency for Radioactive Waste and Enriched Fissile Materials, took over the coordination of the R&D programme for the disposal of radioactive waste from SCK•CEN. Based on the promising results already obtained, ONDRAF/NIRAS decided to continue studying the Boom Clay beneath the Mol site as a potential host formation for the geological disposal of high-level and/or long-lived radioactive waste. The construction works carried out until then and the construction of the Test Drift a few years later (1987) showed that it was possible to build shafts in frozen aquifer sands and clay, and galleries in unfrozen clay. The feasibility of constructing galleries using industrial techniques had not yet been demonstrated, however. An expert assessment in the late 1980s confirmed that poorly indurated clays, and in particular the Boom Clay under the Mol site, could be considered for the disposal of high-level and/or long-lived waste, since they are able to offer effective protection in the very long term (*NIROND, 1989; SAFIR Evaluation Commission, 1990*). Water flow in the Boom Clay is limited due to the low hydraulic conductivity of the clay, the plastic character of the clay results in good self-sealing properties and moreover, the Boom Clay has a high capacity to retain many radionuclides by sorption and, hence, to delay the release of those radionuclides.

These encouraging results prompted ONDRAF/NIRAS and SCK•CEN to launch an ambitious demonstration project: the PRACLAY project [1][1]. The PRACLAY project was to be managed by

EURIDICE, the economic interest grouping created for that purpose in 1995 – though under the name "EIG PRACLAY" at that time – together with ONDRAF/NIRAS and SCK•CEN. At that time,the main objectives of the project were:

- to demonstrate the feasibility, from both a technical and an economic point of view, of constructing underground galleries similar, except in length, to the envisaged galleries, using industrial techniques that could also be employed to build an actual geological repository;
- to demonstrate the feasibility of constructing an intersection between access and disposal galleries;
- to install and operate a dummy gallery identical, except in length, to a disposal gallery containing high-level waste. This implied a simulation of the reference design for the engineered barrier system (EBS)[2] for high-level (heat-emitting) waste, which was, at that time, the SAFIR 2 design (NIROND, 1989). The heat-emitting waste was to be simulated by electrical heaters.
- to monitor the thermal, hydraulic and mechanical behaviour of the surrounding clay and the dummy engineered barrier system.

The first goal – to demonstrate the feasibility of constructing a gallery using industrial techniques – was achieved with the completion of the Connecting gallery in 2001-2002 (*Bastiaens et al., 2003*). Prior to the construction of this gallery, a second shaft had to be dug to be in compliance with mining regulations. The new shaft was excavated between 1997 and 1999 using industrial techniques, 90 metres from the end of the Test Drift (*De Bruyn et al., 2001*). The aquifer sands above the Boom Clay were frozen while the shaft was under construction, but the Boom Clay was excavated without freezing the clay. In 2002 the shaft was connected to the Test Drift by means of the Connecting gallery. For the first time ever, a gallery had been constructed in poorly indurated clay at a depth of 225 m using industrial techniques.

The next step in the research programme was the demonstration of the feasibility of the high-level waste reference design. In 2003 ONDRAF/NIRAS however reviewed the design of the EBS (NIROND, 2003). Three new EBS designs, illustrated in Figure 1-2, were considered:

- **Supercontainer**: the high-level waste is placed in a carbon steel overpack surrounded by a concrete buffer and an outer stainless steel envelope. This supercontainer is then horizontally placed in the disposal galleries, which are supported by concrete lining. Finally, the void space between the supercontainer and the gallery lining is backfilled with a cement-based material. The supercontainer has the key benefit that it is assembled on the surface and has adequate radiation shielding to be subsequently manipulated without the need for shielded handling equipment.
- **Borehole**: the waste, which is first placed in an overpack, is inserted from the disposal galleries directly into horizontal or vertical boreholes. This design has the minimum number of engineered barriers, giving almost direct contact of the waste package with the Boom Clay or with a casing (probably metallic), preventing collapse of the borehole. A buffer material may subsequently be used to fill the space between the overpack and the Boom Clay, preventing the annulus from becoming filled with water.
- **Sleeve**: a buffer (the sleeve) is first placed in the gallery, then the waste, once again in an overpack, is inserted into this sleeve. The sleeve could be a cement-based or bentonite material. The benefit of bentonite is that it would swell naturally to fill the gap to the overpack. With a concrete sleeve, there is a risk of leaving a gap between the overpack and the buffer, which would be filled with water.

1 A list of all documents related to the design and installation of the PRACLAY In-Situ Experiment is given in the annexe. These documents are referred to by placing the number of the document in the list between square brackets.

2 The EBS contains all engineered materials placed within the repository, including the waste forms, buffer materials, backfill and seals.

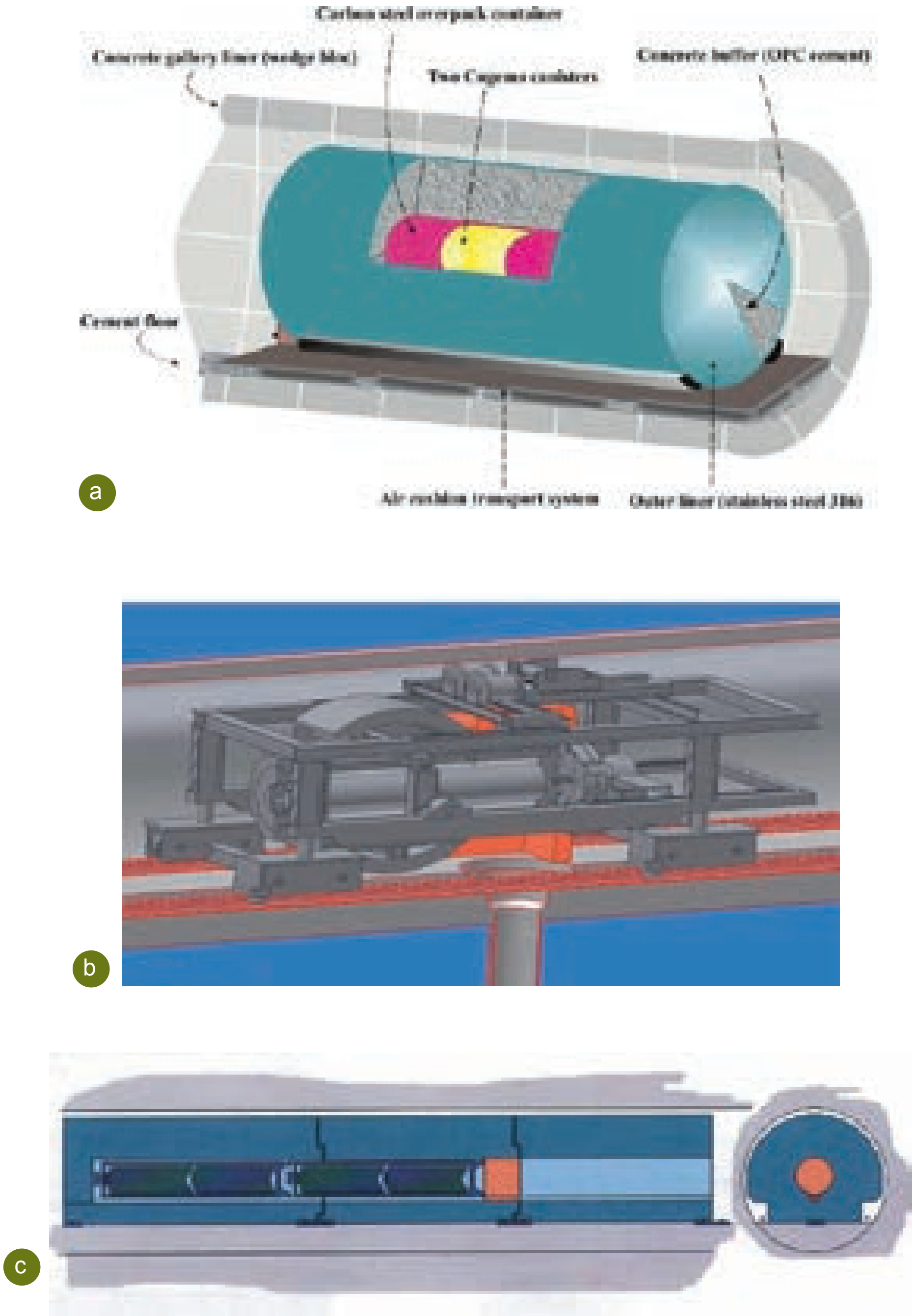


Figure 1-2 Three EBS designs considered by ONDRAF/NIRAS:
(a) Supercontainer; (b) Borehole; (c) Sleeve (*NIROND, 2003*).

The supercontainer was selected as the reference design for the EBS (*NIROND, 2004*). However, ONDRAF/NIRAS considers the other two options to be potentially interesting alternatives and therefore wishes to keep the possibility of switching over to these alternatives. This implied that a single large-scale demonstration experiment for one specific design was no longer an adequate R&D approach. The experiment was therefore reoriented to be as design-independent as possible in order to maintain its validity and representativeness in case of future changes in the repository design [2]. The original scope– the demonstration of the reference design for high-level waste – was expanded to include the characterisation, verification, confirmation and demonstration of relevant elements of the disposal system and their behaviour by means of a combination of surface and in-situ experiments among which the PRACLAY In-Situ Experiment.

The surface experiments consist of tests characterising the host formation, the components of the disposal system and the interaction between them, and tests demonstrating the feasibility of constructing these components of the disposal system. The OPHELIE mock-up (*Van Humbeek et al., 2009*) and the ESDRED full-scale backfill test (*De Bock et al., 2008*) form part of these surface experiments. The former was aimed at testing the original, and later abandoned, design of a disposal gallery backfill based on precompacted bentonite, the latter at demonstrating the feasibility of using a grout backfill, as considered in the supercontainer design. Furthermore, tests examining and demonstrating the feasibility of constructing a supercontainer were set up and are still on-going (*Areias et al., 2011*). The ATLAS-III test (*Chen et al., 2011*) is also part of the experimental programme. This short-term, small-scale in-situ heater test, is an intermediate step between the available knowledge on the THM behaviour and the large-scale Heater Test that is part of the PRACLAY In-Situ Experiment.

The PRACLAY In-Situ Experiment (Figure 1-3), as defined after the reference design decision in 2004, comprises three tests:

- the **Gallery and Crossing Test** to further examine and demonstrate the feasibility of constructing an underground repository using industrial methods, and also examine the feasibility of constructing a crossing between galleries;
- the **Seal Test** to examine the feasibility of creating a seal in a horizontal drift;
- the **Heater Test** to study the THMC responses of the Boom Clay to thermal impact.

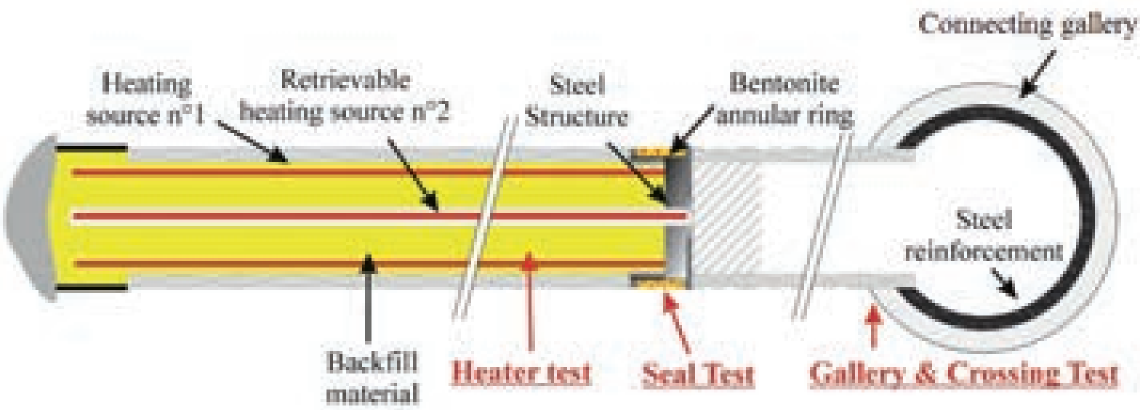


Figure 1-3 The PRACLAY In-Situ Experiment comprises three tests:
the Gallery & Crossing Test, the Seal Test and the Heater Test.

In 2007 the PRACLAY gallery was constructed perpendicular to the Connecting gallery. A hydraulic seal was fitted in the gallery in 2010, after which the primary heating system was installed. In 2011, the section of the PRACLAY gallery that will be used for heating was backfilled with sand and subsequently saturated with water, followed by the installation of the secondary heater beginning 2012. The full installation of the secondary heater, planned for early 2014, will complete the set-up of the PRACLAY In-Situ Experiment.

The Heater Test is intended to be representative of a generic drift or gallery for the disposal of heat-emitting waste. To anticipate possible future changes in the repository design and because it is not possible to fully reproduce the time scale, the spatial scale and the boundary conditions of a real repository, the Heater Test was conceived to be as independent as possible of the final repository design and will be conducted under a well-controlled and a reasonably conservative combination of thermal, hydraulic and mechanical boundary conditions. This implies, among other requirements, quasi-undrained conditions. These conditions are realised by the installation of water-saturated backfill sand in the heated part of the gallery and a hydraulic seal at the intersection between the heated and the non-heated part of the gallery.

The next chapter describes the design of the PRACLAY In-Situ Experiment. Subsequently the complete preparation and installation of the experiment, together with the technical and scientific achievements to date, are presented. Since the construction of the gallery, the fitting of the hydraulic seal and the installation of the heater and backfill material are three clearly distinct phases, they are discussed in three separate parts of the report which can each be read and understood individually:

- The PRACLAY gallery;
- The hydraulic seal;
- The heater and backfill material.

A list of all documents relating to the design and installation of the PRACLAY In-Situ Experiment is given in the annexe. The aim is to ensure traceability and justification of all design and other choices made over the years since the initiation of the PRACLAY experiment through to completion of the process of setting up the experiment. These documents are referred to by placing the number of the document in the list between square brackets (e.g. [x]).

2. Design of the PRACLAY In-Situ Experiment

This chapter first defines the objectives of the PRACLAY In-Situ Experiment and then describes the design process of all components in outline. The detailed specifications for the PRACLAY gallery, the hydraulic seal, the heater and the backfill material are given in the respective parts hereafter.

The objectives and the success criteria of the PRACLAY In-Situ Experiment are described in [3]. The preliminary design process and the preliminary design choices as explained in this chapter are discussed in more detail in the report on the design of the PRACLAY In-Situ Experiment [4], which also contains the scoping calculations on which these design decisions were based.

The complete design and installation process of the PRACLAY In-Situ Experiment was monitored by the Scientific Advisory Committee (SAC) supporting EURIDICE in its scientific tasks. Comments, questions and suggestions on the experiment were formulated during several meetings with the SAC. The minutes of the SAC meetings can be found in [5].

2.1. Objectives of the PRACLAY In-Situ Experiment

The main goal of the PRACLAY In-Situ Experiment is to examine the combined impact of mechanical disturbances caused by the gallery construction and a large-scale thermal load on the Boom Clay due to the heat emitting high-level waste. Such a combined mechanical and thermal load leads to perturbations in the clay and can affect its performance as a host rock in the geological disposal concept for heat-emitting radioactive waste. The impact of the combined load on the clay is examined and evaluated in the **Heater Test**. To cope with possible future changes in the repository design and because it is not possible to simulate the timescale, the spatial scale and the boundary conditions that apply for an actual repository, the test was designed to be as design-independent as possible and aims to impose THM conditions that are more penalising than expected in a real repository.

More specifically the goals of the **Heater Test** are to:

- demonstrate that liquefaction[1] of the Boom Clay will not occur around a repository of heat-emitting waste;
- assess the heat dissipation from a repository containing heat-emitting waste and, in particular, confirm the thermal properties of the Boom Clay at large scale;
- estimate the major consequences of the THM impact on the Boom Clay and the excavation-damaged zone, focusing primarily on the mechanical damage and hydraulic conductivity;
- assess the stability of the concrete lining under thermal conditions enveloping any design, taking into account the temperature criterion of T_{max}<100°C around the overpack (*Bel and Bernier, 2001*);
- increase knowledge of the performance and reliability of monitoring devices under thermal stress and heat;
- assess the thermally and excavation-induced geochemical perturbations and their impact on radionuclide transport-related parameters; this is not a priority, however, and should not jeopardise achievement of the above objectives.

[1] Liquefaction would be the consequence, in this context, of thermal pressurisation. One objective of the Heater Test is thus to demonstrate that, as the pore water pressure will increase due to the rapid, differential thermal expansion of the liquid and solid phases at the beginning of the thermal transient, the effective stress and the shear strength will not be reduced around a disposal gallery to a point at which the stability could be compromised.

Attaining the most critical conditions in terms of the THM response of a disposal system within the limits of what is reasonably achievable implies quasi-undrained hydraulic boundary conditions. This requires the installation of a hydraulic seal at the intersection between the heated and non-heated sections of the gallery and backfilling of the heated section with saturated sand. The installation of a hydraulic seal constitutes the **Seal Test**, the main goal of which is to hydraulically seal the heated section of the gallery and its surrounding excavation-disturbed zone from the non-heated section. The hydraulic seal is purpose-built for the PRACLAY Experiment and is not representative for seals in a geological disposal repository.

The Heater Test is housed in the PRACLAY gallery. The construction of this gallery and its crossing with the Connecting gallery constitutes the **Gallery and Crossing Test**. The feasibility of excavating a gallery in Boom Clay at a depth of 225 m using an industrial excavation technique has already been demonstrated in constructing the Connecting gallery. During work on the PRACLAY gallery, it was possible to optimise the excavation technique and further investigate the hydromechanical response of the Boom Clay to the excavation work.

The **Gallery and Crossing Test** aims to demonstrate:

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

The Gallery and Crossing Test, the Seal Test and the Heater Test make up the PRACLAY In-Situ Experiment.

The first step was to determine the requirements and design of the Heater Test. Once the experimental and boundary conditions were known, the gallery housing the test and the hydraulic seal could be designed.

2.2. Design of the PRACLAY Heater Test

The main purpose of the Heater Test is to simulate the thermal impact generated by heat-emitting high-level waste (HLW) on Boom Clay. Simulating the exact THM conditions as in an actual disposal site is not possible. The time period over which the thermal load applies is too long (several hundreds or thousands of years (*Sillen and Marivoet, 2006*)) and also the length of the repository galleries and the boundary conditions, such as the drainage conditions around the repository, are different. However, simulations also show that the most severe transient occurs and peak temperatures are reached already within the first 10 to 20 years after waste emplacement.

Because it is not possible to fully reproduce the time scale, the spatial scale and the boundary conditions of a real repository, the Heater Test will be conducted under a well-controlled and a reasonably conservative combination of thermal, hydraulic and mechanical boundary conditions. In addition, the design of the Heater Test has to be as independent as possible of the repository design to prevent any possible future changes in the repository design jeopardising the validity and representativeness of the test.

Numerical simulations were performed to estimate the temperature increase in the Boom Clay around a disposal gallery containing spent fuel and vitrified high-level waste (Figure 2-1) (*Sillen and Marivoet,* *2007*). The simulations considered the supercontainer as EBS. The maximum temperature increase, as obtained from these simulations, amounts to 59°C. As the in-situ temperature of the Boom Clay is 16°C at the depth of the underground laboratory, this corresponds to a maximum temperature of 75°C at the clay–lining interface of a disposal gallery for spent fuel. To be on the conservative side, it was decided to set the maximum target temperature at the clay–lining interface in the Heater Test slightly higher, at 80°C, corresponding to a temperature increase of 64°C.

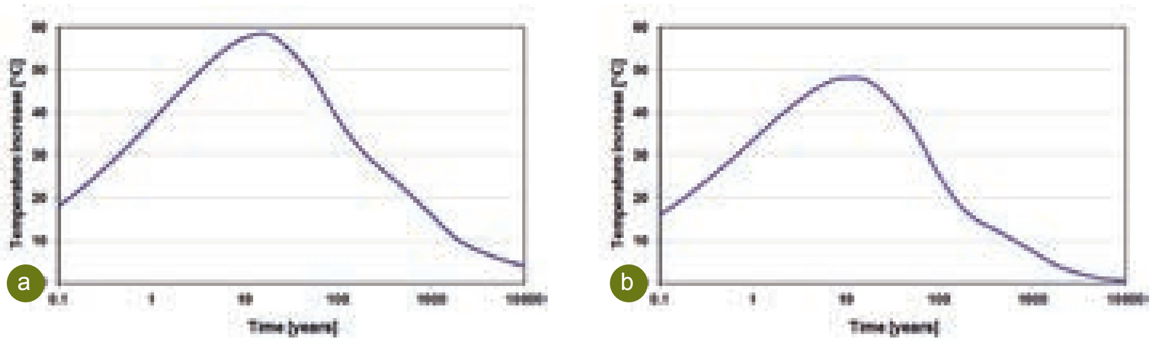


Figure 2-1 Temperature increase around a disposal gallery containing supercontainers with (a) spent fuel and (b) vitrified high-level waste.

To check whether this scenario with the supercontainer as EBS is also representative for the sleeve and borehole design, radial profiles of the temperature increase around a disposal gallery for spent fuel were calculated for all three EBS configurations. The borehole configuration required a 3D model, whereas the supercontainer and sleeve design could both be simulated with a 2D axisymmetric model. As a result, the temperature profiles obtained for the supercontainer and sleeve design were similar. The temperature profiles after 1 and 10 years of heating are shown in Figure 2-2. The Boom Clay–lining interface is approx. 1.2 m from the edge of the waste canister. These simulations show that the temperature profile in the clay is almost similar for the different designs under an equivalent thermal load. Hence, the target temperature profile to be achieved in the Heater Test is representative for the three EBS designs.

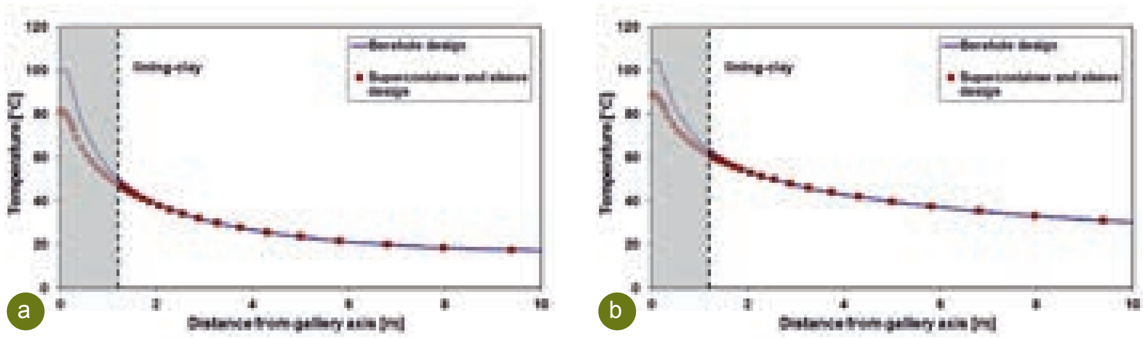


Figure 2-2 Temperature increase in a midplane around a disposal gallery for spent fuel for different EBS designs (the shaded area represents the disposal gallery): (a) after 1 year of heating; (b) after 10 years of heating.

Figure 2-1 also shows that the maximum temperature around a disposal gallery for spent fuel is obtained after approx. 20 years. In the PRACLAY Heater Test the target temperature of 80°C will be obtained as soon as possible. The temperature increase rate is, however, limited by the thermal gradient over the gallery lining that results from heating. When the target temperature is achieved abruptly, a high temperature gradient over the lining may induce high compressive stresses at intrados (inner surface) and high tensional stresses at extrados (outer surface) (Figure 2-3). These stresses will be minimised by progressive heating in which the temperature is increased step by step to the target temperature. The rate at which the temperature is increased will however still be faster than in an actual repository.

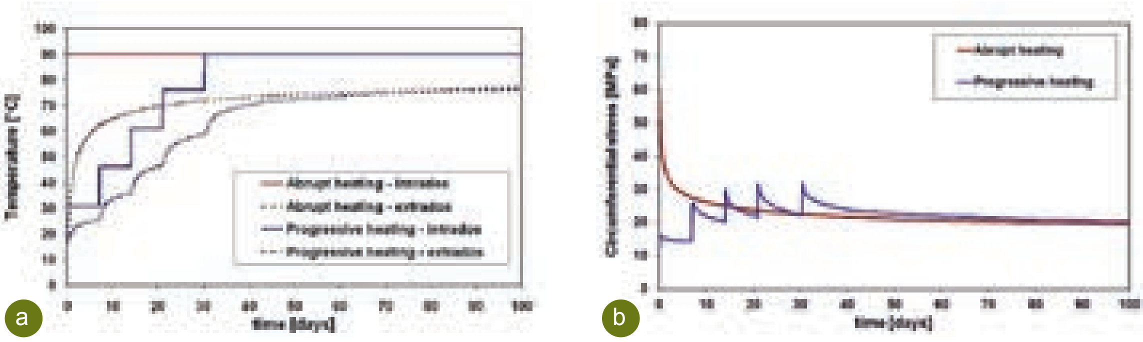


Figure 2-3 (a) The temperature at intrados and extrados of the gallery with abrupt and progressive heating; (b) Circumferential stresses at the lining extrados with abrupt and progressive heating.

Two possible heat source terms were considered: a constant heat flux (250 W/m) and a variable heat flux ensuring a constant temperature (80°C) at the clay–lining interface (Figure 2-4). A variable flux ensuring a constant temperature is the most effective and a constant temperature may be advantageous for the subsequent interpretation of in-situ measurements and for the subsequent THM modelling, as the boundary conditions of the test are simpler to implement in models. It was therefore decided to use a heater that produced a near-constant temperature of 80°C at the clay–lining interface.

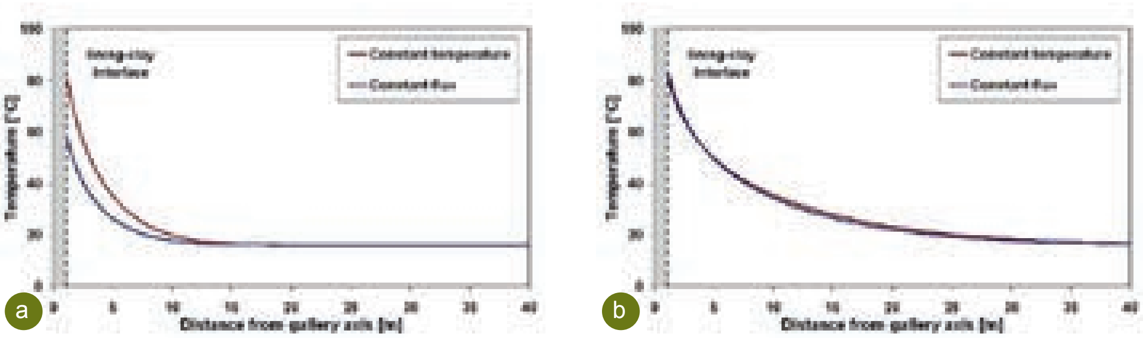


Figure 2-4 Radial temperature profiles in a midplane around the heated gallery for a constant temperature and a constant heat flux at the clay–lining interface: (a) after 1 year of heating; (b) after 10 years of heating.

Subsequently the scoping calculations focused on optimising the length of the heated gallery section. Figure 2-5 shows the radial temperature profiles for different heated gallery lengths at the middle of the heated section using a variable heat source, ensuring a fixed temperature of 80°C at the clay–lining interface. No significant gain in representativeness is obtained by increasing the length from 24 to 32 m. The length of the heated gallery section was therefore set at 30 m. As such a central section is obtained that has uniform conditions in the longitudinal direction, i.e. that is unaffected by end effects.

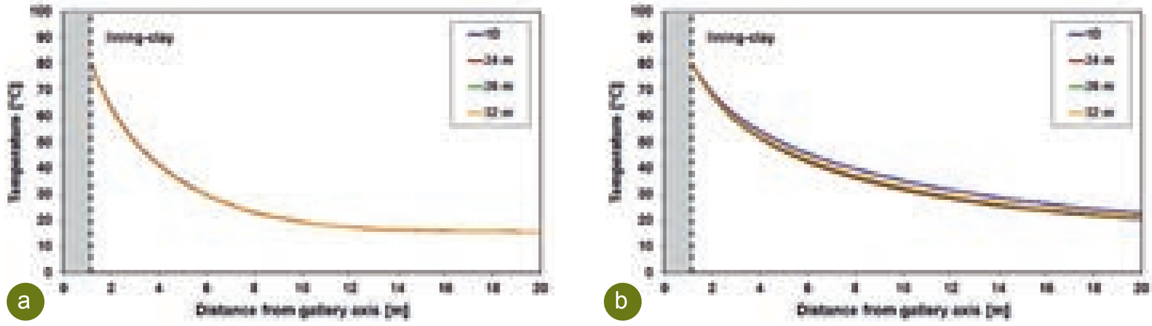


Figure 2-5 Radial temperature profiles in a midplane around the heated gallery for a constant temperature and for different lengths of the heated gallery section (the 1D scenario which is more representative for an actual repository, is also included): (a) after 1 year of heating; (b) after 10 years of heating.

An important goal of the Heater Test is to verify that the pore water pressure increase during heating does not lead to liquefaction of the Boom Clay. Undrained boundary conditions during the Heater Test lead to higher pore water pressures in the clay and are therefore more critical than drained boundary conditions. Figure 2-6 shows the difference in pore water pressure around the gallery in the midplane of the heated section in scenarios where the gallery is drained and undrained. The overpressure is much more pronounced when the gallery is undrained. The components inside the heated section of the PRACLAY gallery are thus to be saturated as much as possible to create an undrained boundary.

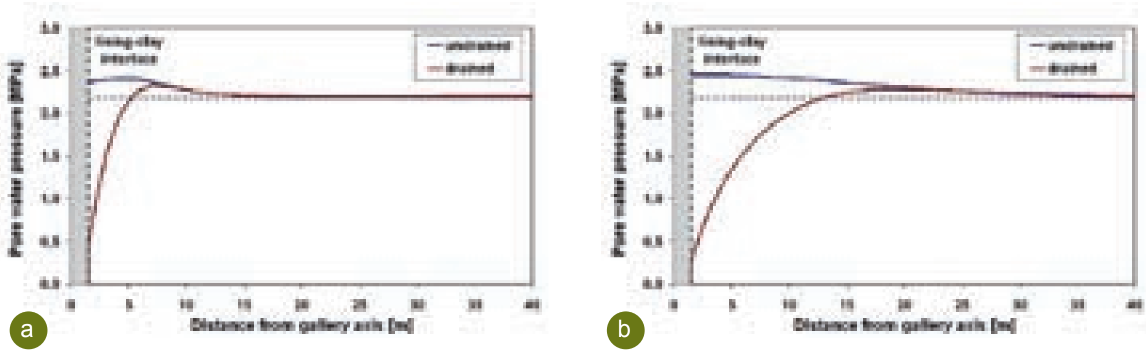


Figure 2-6 Pore water pressure profiles in a midplane around the heated gallery in scenarios where the gallery is drained and undrained: (a) after 1 year of heating; (b) after 10 years of heating.

To achieve undrained boundary conditions, a hydraulic seal also has to be installed at the intersection between the heated and non-heated sections of the PRACLAY gallery. The seal has to hydraulically cut off the heated section from the non-heated section of the gallery to maintain high pressures in the clay around the heated section. The design of the hydraulic seal is explained below (see section 2.3).

In conclusion, the following design criteria for the PRACLAY Heater Test were defined based on scoping calculations:

- imposing a constant temperature of 80°C at the gallery extrados (outer surface) and increasing the temperature progressively to the target temperature;
- heating a 30 m gallery section;
- creating a quasi-impermeable hydraulic boundary at the intersection between the heated and non-heated sections of the gallery;
- saturating the components inside the PRACLAY gallery as much as possible

Once these design criteria for the Heater Test were determined, the design of the hydraulic seal and the PRACLAY gallery was developed.

2.3. Design of the hydraulic seal

A quasi-impermeable boundary is required at the intersection between the heated and non-heated sections of the PRACLAY gallery. This is achieved by fitting a hydraulic seal, which has to not only close the PRACLAY gallery, but also hydraulically cut off the heated section from the non-heated section of the gallery. The hydraulic seal consists of a stainless steel structure closing off the heated part of the gallery from the rest of the underground infrastructure and an annular bentonite ring placed against the clay (Figure 2-7). Bentonite has a very low hydraulic conductivity and swells when it is hydrated. The swelling pressure exerted by the hydrated bentonite on the clay will lower the hydraulic conductivity of the clay around the seal.

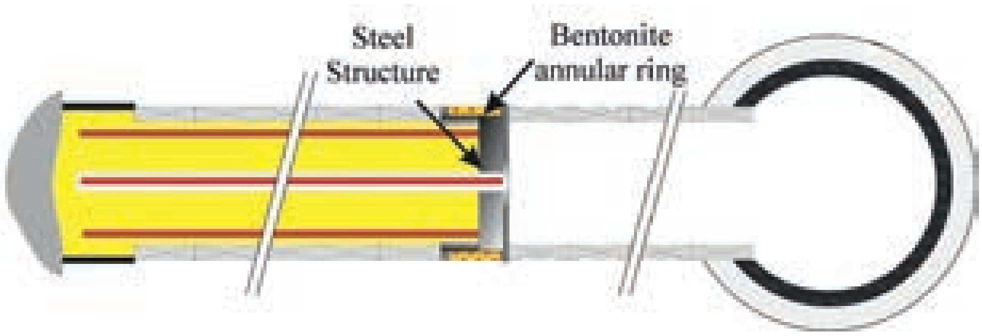


Figure 2-7 The hydraulic seal closing off the heated part of the PRACLAY gallery consists of a stainless steel structure and an annular bentonite ring.

A bentonite seal was chosen rather than, for example, a technical seal consisting of an inflatable packer, in order to examine its behaviour. This could provide relevant information for the design of seals in an actual disposal facility [3].

Figure 2-8 shows the pore water pressure profiles in the midplane of the heated section for different seal lengths and for an impermeable disposal gallery (representing undrained conditions). It was concluded from these figures that a length of 1 m for the seal was sufficiently effective and that the gain in representativity obtained by further increasing the seal length was outweighed by the extra cost and complexity of a larger seal.

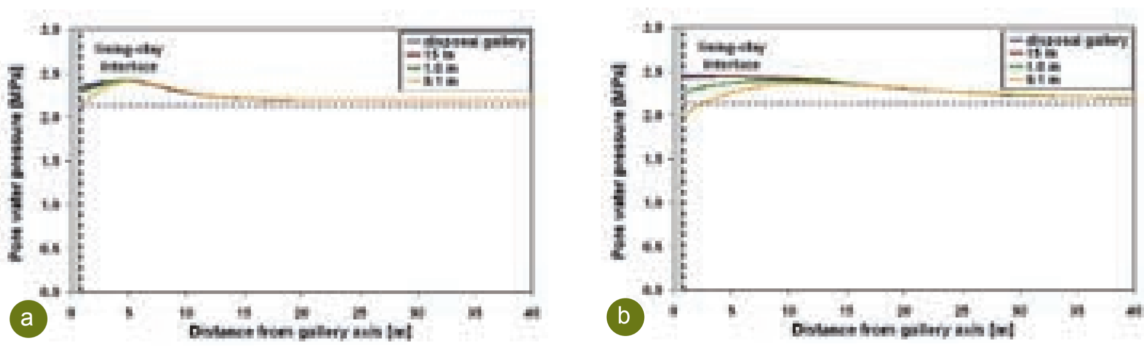


Figure 2-8 Pore water pressure profiles in a midplane around the heated gallery for different lengths of hydraulic seal (the reference case of an impermeable disposal gallery is also included): (a) after 1 year of heating; (b) after 10 years of heating.

The hydraulic seal is located at a distance of 10 m from the Connecting gallery to limit the mutual interactions between the Heater Test and the Connecting gallery. As the length of the heater was already set at 30 m, the minimum length of the PRACLAY gallery was fixed at 40 m.

2.4. Design of the PRACLAY gallery

A new gallery needed to be built to house the Heater Test. The existing galleries of HADES were not considered suitable for the following reasons [4]:

- The lining was not designed to sustain the thermal load resulting from the Heater Test.
- The installation of instrumentation is complicated, as the existing galleries are not designed for this purpose.
- The period over which the clay around the gallery would remain drained before the start of the Heater Test was too long to reproduce the desired critical conditions.
- The experiment would disturb and complicate the operations and on-going experiments in HADES. The laboratory length occupied would be too large and would limit the space available for other future experiments.

Constructing a new gallery perpendicular to the existing galleries also offered the occasion of creating a crossing between two galleries similar to the crossings planned in the reference repository design. The construction of the crossing between the PRACLAY gallery and the Connecting gallery required a reinforcement ring because the lining of the latter gallery is designed to allow openings of maximum 200 mm. The creation of a larger opening in the lining of the Connecting gallery would endanger its stability. It was decided to use a reinforcement ring with an internal diameter of 3.5 m so as not to narrow too much the Connecting gallery at the crossing. For economic reasons and because of the presence of adjacent instrumentation in the clay, the length of the reinforcement ring was limited to 3.8 m. The maximum allowable diameter for an opening in the Connecting gallery when using a reinforcement ring meeting these requirements was 2.55 m. The nominal diameter of the PRACLAY gallery at extrados (outer surface) was fixed at 2.50 m.

The start of the PRACLAY gallery was chosen between rings 32 and 35 of the Connecting gallery and the gallery was constructed towards the east [4]. These choices were made bearing in mind the existing instrumentation in the Connecting gallery and the interactions between the Heater Test, the other experiments running and the HADES infrastructure. The topography of the rings in the Connecting gallery (i.e. the variations in the internal diameter of the different rings of the Connecting gallery due to deviations in the placement of the wedge blocks) was also taken into account, as this determined the maximum external diameter of the reinforcement ring that could be installed.

The same excavation technique and type of lining as used for the construction of the Connecting gallery were selected for the PRACLAY gallery: excavating using an open-face tunnelling machine and installing a concrete wedge block lining. The design of the lining had to take into account a geotechnical load exerted by the clay on the lining and a thermal load due to the increased stresses in and on the lining during the Heater Test. A preliminary study of the stability of the gallery lining based on scoping calculations led to the following considerations and conclusions:

- The lining thickness was fixed at 0.30 m and thus the internal diameter of the PRACLAY gallery was set at 1.90 m. Increasing the lining thickness was not considered to be useful, as this would only slightly affect the stresses in the lining and would diminish the internal diameter of the gallery and the effective space inside the gallery.

- The length of the lining rings was set at 0.50 m, in contrast to the lining rings of the Connecting gallery, which were 1.00 m long. Such shorter segments are easier to handle and result in a shorter unsupported zone behind the tunnelling shield.

Compressive materials are incorporated into the lining (in and between lining rings) of the heated section, allowing for thermal expansion of the lining and thereby limiting thermally induced stresses. This avoids damage to the concrete wedge blocks and thus facilitates the safe access of the gallery after the Heater Test is stopped.

Two types of high-performance concrete (HPC)[1] were considered for the concrete segments: a standard HPC (C80/95) and a heavy HPC. The heavy HPC has a higher elastic modulus and thermal conductivity than standard HPC. Both types have almost the same compressive strength (approx. 80 MPa). Scoping calculations indicated that using a heavy HPC has no significant advantages. For a given thermal load, the maximum tangential stress in a heavy HPC is only slightly smaller than in a standard HPC. Moreover, it has a brittle behaviour at high deformation, which is unfavourable for the stability of the liner. It was therefore decided to use standard HPC rather than heavy HPC.

One of the objectives of the PRACLAY Heater Test was to characterise the thermal response of the lining–host rock interaction. In the design hypotheses, a conservative approach was used by assuming that the surrounding host rock prevents all radial movement of the lining. In reality, some divergence resulting from the thermal expansion of the clay and the lining, and thus less critical conditions, can be expected. Consequently, no compressive materials were incorporated into the lining rings of the last 3 m of the PRACLAY gallery. The segments of these rings are made of ultra-high performance concrete (UHPC). Their behaviour will be monitored during the Heater Test to study the lining–host rock interaction.

Since the hydraulic seal is installed after the construction of the PRACLAY gallery, an alternative lining in the zone of the future hydraulic seal is needed. On the one hand, a maximum percentage of the clay sidewall has to remain accessible to make sure the bentonite properly seals off. On the other hand, some support of the clay sidewall is needed to prevent convergence and instability. The lining rings next to the hydraulic seal do not contain compressible materials to avoid any lining movement around the seal. These rings are therefore made of UHPC concrete.

In conclusion, the following design criteria were defined for the PRACLAY gallery:

- The PRACLAY gallery is located between rings 32 and 35 of the Connecting gallery and is constructed eastwards.
- The diameter of the PRACLAY gallery is set at 2.50 m. A reinforcement ring is placed in the Connecting gallery prior to the excavation works to ensure the stability of the lining of the Connecting gallery.
- The excavation is carried out using an open-face tunnelling machine and 0.30 m thick concrete wedge blocks (standard HPC) are used as lining. The length of the lining rings is limited to 0.50 m. Compressive materials are incorporated into the gallery lining, allowing for some thermal dilatation and thus limiting the thermally induced stresses. An alternative lining is placed at the location of the hydraulic seal and at the last 3 m of the PRACLAY gallery.

[1] The American Concrete Institute (ACI) defines high-performance concrete as concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely when using conventional constituents and normal mixing, placing and curing practices. A commentary to the definition states that a high-performance concrete is one in which certain characteristics are developed for a particular application and environment.

3. The installation of the PRACLAY In-Situ Experiment

The installation of the PRACLAY In-Situ Experiment comprises, in chronological order, the construction of the PRACLAY gallery, the fitting of the hydraulic seal and the installation of the heater and backfill material. Since the work was completed in three consecutive and distinct phases, each of which is extensive, they are the subject of three separate parts:

- **Part I: The PRACLAY gallery**
- **Part II: The hydraulic seal**
- **Part III: The heater and backfill material**

Each part can be read and understood separately. Together, they encompass the complete installation of the PRACLAY In-Situ Experiment. All references and annexes of the full report, including the three parts, are listed at the end of the report.

Instrumentation is placed in the PRACLAY gallery lining, in the hydraulic seal and in boreholes in the Boom Clay around the PRACLAY gallery. The description and layout of all the instrumentation installed as part of the PRACLAY In-Situ Experiment is given in [6]. The instrumentation placed in the gallery lining and in the hydraulic seal is also described in the respective parts of this report.

PART I

The PRACLAY gallery

Summary

The construction of the PRACLAY gallery was successfully completed in 2007. Its main purpose is to host the PRACLAY Heater Test, but its construction also 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. Furthermore the possibility of resuming the excavation work after an interruption of a week was examined by means of a stop-and-go test.

The realisation of the crossing between the Connecting gallery and the PRACLAY gallery required the installation of a steel reinforcement ring in the Connecting gallery to guarantee the stability of the lining of the latter gallery. The reinforcement ring is composed of 11 cast steel segments. After a successful test assembly in the workshop, the segments were transported underground and reassembled in-situ.

The excavation was done using an open-face tunnelling machine similar to the one used for the construction of the Connecting gallery. The construction of a starting or mounting chamber was not necessary, as the tunnelling machine could be assembled in the Connecting gallery. Also, the underground assembly of the tunnelling machine was preceded by a test assembly on the surface.

The lining of the PRACLAY gallery consists of concrete wedge blocks (C80/95 concrete), also similar to the lining of the Connecting gallery. The design of the wedge blocks, however, had to take into account both a geotechnical load resulting from the pressure exerted by the clay formation and a thermal load resulting from the increased stresses in and on the lining during the Heater Test.

Compressive materials were incorporated into the gallery lining allowing some expansion of the lining and in that way limiting the thermally induced stresses. This avoids damage to the concrete wedge blocks and thus facilitates safe access to the gallery after the Heater Test is stopped. These compressive materials are used for this purpose (allowing subsequent access to the PRACLAY gallery), but are not envisaged for an actual repository. Polysiloxane sheets were placed between the lining rings in the heated part of the gallery and steel foam panels were inserted inside the lining rings. These panels have characteristic stress-deformation behaviour: they are relatively rigid under geotechnical loading, but they 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. Strain gauges, pressure and load cells, thermocouples and corrosion samples were embedded in some segments to monitor the behaviour of the gallery lining.

In a later phase, a hydraulic seal with a width of 1 m was installed in the PRACLAY gallery to hydraulically seal off the heated part of the gallery from the rest of the underground laboratory. This seal consists of a steel structure and bentonite blocks that are placed against the clay sidewall. To maintain the accessibility of the clay sidewall, an alternative lining was installed at the location of the hydraulic seal during excavation. The alternative lining consists of 4 steel rings, which make up the permanent part of the lining, and wood placed behind these steel rings as a temporary component of the lining.

The underground work started on 01.10.2007 with the cutting of the lining of the Connecting gallery where the PRACLAY gallery was going to be constructed. The tunnelling machine was then positioned in this opening and the excavation work was started. The construction of the PRACLAY gallery – 84 lining rings including the rings at the location of the hydraulic seal – was done between 04.10.2007 and 06.11.2007 and progressed more or less as expected. Except for the start-up phase (i.e. the construction of the first 11 rings), the stop-and-go test and the construction of the alternative lining at the location of the future

hydraulic seal, a progress rate of 2 m/day was aimed for and in general achieved. Only minor problems were encountered. These were mainly mechanical problems (e.g. oil leakage due to broken hoses) caused by the limited working space for equipment and personnel, which also complicated the process of rectifying any problems.

A stop-and-go-test was performed after the construction of ring 79 by suspending the excavation work for one week. The purpose of the stop-and-go test was testing the level of difficulty to restart the tunnelling machine. Restarting the tunnelling machine after a standstill could be difficult, as the friction between the clay and the shield increases with time due to the convergence of the Boom Clay around the shield. The thrust force required to push the shield forward after one week was about twice the normal thrust force. This was still only ca. 25% of the maximum available force and no problems resuming the excavation work were encountered.

Several measurements (in the clay, the gallery lining and the tunnelling machine) were carried out before, during and after the excavation of the PRACLAY gallery. They aimed at gaining as much information as possible on the performance of the excavation technique, the behaviour of the Boom Clay and the impact of the excavation on the clay. The results were in line with previous observations (mainly the observations done before, during and after the construction of the Connecting gallery) and confirm the highly coupled and anisotropic hydromechanical behaviour of the Boom Clay and known fracturing processes.

1. Introduction

The construction of the PRACLAY gallery is part of the PRACLAY In-Situ Experiment. Its main purpose is to host the PRACLAY Heater Test, but the construction of the gallery and its crossing with the Connecting gallery constitutes a test in itself, the **Gallery and Crossing Test**, the specific goals of which [3] are to examine:

- the feasibility of realising a crossing between two galleries without the need to construct a starting chamber for the assembly of the tunnelling machine. Such a starting chamber creates significant mechanical disturbances in the host formation and is more expensive;
- the feasibility of restarting the excavation after an interruption by means of a stop-and-go-test;
- the hydromechanical (HM) interaction between the lining and the Boom Clay.

The construction of the PRACLAY gallery was successfully completed in 2007. The design of the gallery, the tendering procedure, the actual construction and the technical and scientific achievements are discussed in this part of the report, which is structured as follows:

- *chapter 2* describes the design specifications of the gallery;
- *chapter 3* presents the tendering procedure;
- *chapter 4* gives an overview of the organisation of the work;
- *chapter 5* discusses the construction work;
- *chapter 6* presents the results of the measurement and research programmes carried out before, during and after the excavation work;
- *chapter 7* summarises the main conclusions and achievements.

2. Design specifications

The design of the PRACLAY gallery is mainly determined by the design requirements of the Heater Test. The following design criteria were eventually defined for the PRACLAY gallery [4]:

- The PRACLAY gallery is located between rings 32 and 35 of the Connecting gallery and is constructed eastwards.
- The diameter of the PRACLAY gallery is set at 2.50 m. A reinforcement ring is placed in the Connecting gallery prior to the excavation work to ensure the stability of the lining of the Connecting gallery.
- The excavation is done using an open-face tunnelling machine and 0.30 m thick concrete wedge blocks (standard HPC) are used as lining. The length of the lining rings is limited to 0.50 m, as shorter segments are easier to handle and result in a shorter unsupported zone behind the tunnelling shield. Compressive materials are incorporated in the gallery lining, allowing for some thermal dilatation and limiting the thermally induced stresses in the lining. At the location of the hydraulic seal, the installation of an alternative lining is required.

Figure 2-1 shows the geometry of the PRACLAY gallery design.

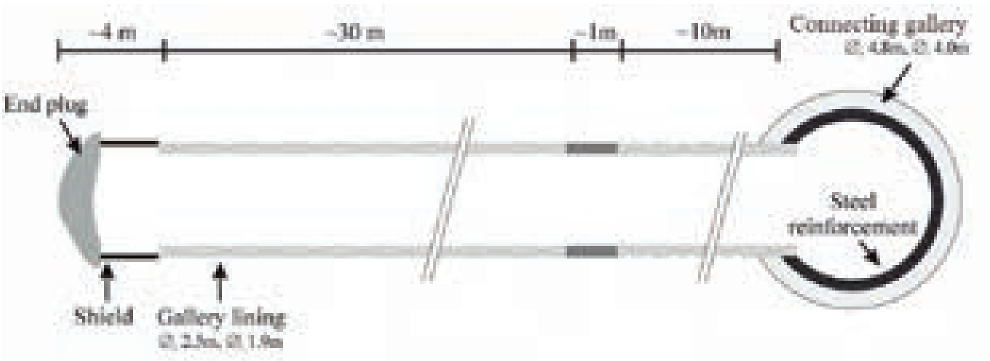


Figure 2-1: Geometry of the PRACLAY gallery.

Based on this general design the tendering specifications [7] were formulated, largely based on the design of the Connecting gallery and the experience gained from its construction (*Bastiaens et al., 2003*). The studies that led to the technical specifications were performed by TRACTEBEL in close cooperation with EURIDICE. The technical inspection agency SECO was also consulted during this stage. The most important specifications are listed hereafter.

2.1. Boom Clay characteristics

Since the design work for the gallery and the tunnelling machine largely depended on the geomechanical characteristics of the Boom Clay under the Mol site, a description of the relevant characteristics of the Boom Clay at this location was included in the tendering specifications.

The Boom Clay, or Boom Formation, belongs to the Rupelian period, which is the geological part of the Paleogene (Cenozoic) era that lasted from 34.2 to 28.7 million years ago. It is found below a depth of about 190 metres under the site of Mol, where it has a thickness of about 100 metres (Figure 2-2). It is surrounded by the overlying Neogene Aquifer and by the underlying Lower-Rupelian Aquifer. 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 septarias, are found in the marly bands occurring throughout the thickness of the formation (*De Craen, 1998; De Craen et al., 1999*).

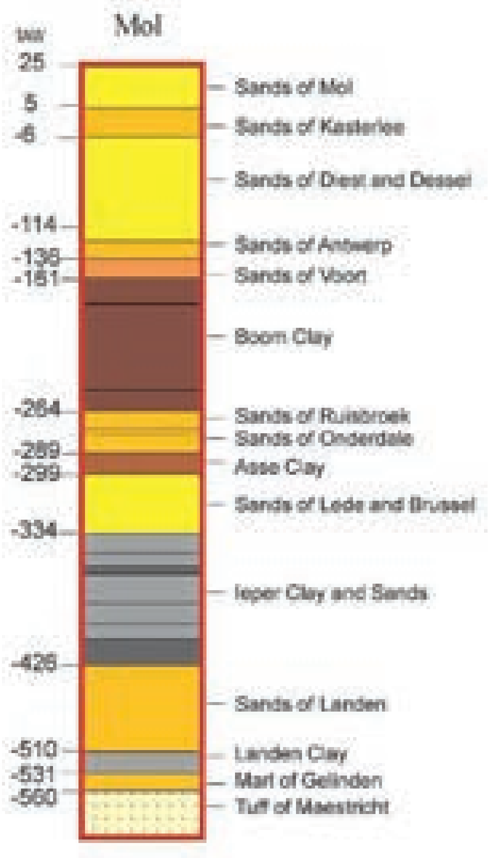


Figure 2-2: Stratigraphy under the site of Mol.

The Boom Clay mineralogy (*Laenen, 1997; De Craen et al., 2004; De Craen, 2005; Zeelmaekers, 2011*) is characterised by a wide variation in the content of clay minerals (from 30 to 70% by volume) due to its vertical lithological heterogeneity. The non-argillaceous fraction of the sediment consists of, in descending order of importance, quartz, feldspars, carbonates and pyrite. The content in organic matter ranges from 1 to 3% by weight. The volumetric water content ranges from 30 to 40%.

The undrained geomechanical characteristics of the Boom Clay at the depth of HADES are (*Horseman et al., 1987*):

- Young's modulus at the origin — E — 200 to 400 MPa
- Poisson's ratio — ν — 0.4 to 0.45
- Angle of friction — ϕ — 4°
- Cohesion — c — 0.5 to 1 MPa

The geotechnical identification parameters are:

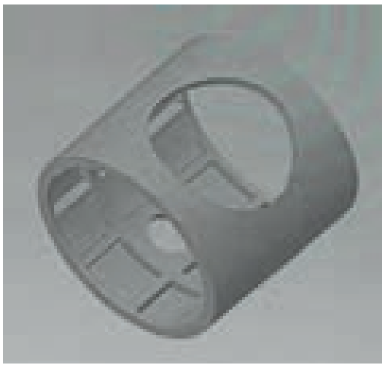
- Plastic limit — w_p — 23 to 29%
- Liquid limit — w_l — 55 to 80%
- Plastic index — IP — 32 to 51%

The Boom Clay displays elasto-visco-plastic behaviour (*Bastiaens et al., 2006; Coll et al., 2007; Cui et al., 2009; Le et al., 2007*) which results in a high convergence. At the depth of HADES, the total vertical stress and pore water pressure are respectively 4.50 and 2.29 MPa. The vertical stress is estimated to be slightly higher than the horizontal, which is 4.1 MPa (K_0~0.9) (*Bernier et al., 2007; Jia, 2009*). The hydraulic conductivity of the clay is in the order of 10^{-12} m/s.

2.2. Reinforcement structure at the gallery crossing

The installation of a steel reinforcement ring in the Connecting gallery at the crossing with the PRACLAY gallery was required to guarantee the stability of the lining of the Connecting gallery (Figure 2-3).

a



b

Figure 2-3: (a) The steel reinforcement ring; (b) the reinforcement ring as placed inside the lining of the Connecting gallery.

The requirements for the reinforcement structure were:

- a large opening (2.55 m diameter) at the east-side for the PRACLAY gallery and a small opening (0.80 m diameter) at the west-side for a future experiment;
- a length smaller than 3.8 m because of the presence of experiments in the adjacent rings of the Connecting gallery;
- a minimum internal diameter of 3.5 m so as not to narrow the Connecting gallery (4.0 m internal diameter) too much;
- dimensions compatible with the local dimensions of the Connecting gallery;
- ability to withstand the same geotechnical loads as the lining of the Connecting gallery (cf. Table 2.1);
- the underground assembly being preferably done without substantial welding operations;
- composed of segments whose weight and dimensions are compatible with the hoisting equipment of the second shaft.

These requirements were very strict, especially the minimum internal diameter of 3.5 m, which implies a maximum structure thickness of only 225 mm. As a result, the material demands for the precast steel and bolts were high and the assembly tolerances were strict. The specifications of the structure are listed in Table 2.1.

Dimensions	External diameter Internal diameter Length	3950 mm 3500 mm 3791 mm
Load case	Vertical load Horizontal load Safety coefficient load	3.0 MPa 2.7 MPa 1.20
Material	Yield strength of cast steel Bolts (M42) Safety coefficient material	520 MPa 10.9[1] 1.15
Tolerances	Radius (internal and external) Thickness	+/- 2 mm +/- 2 mm

Table 2.1: Specifications of the reinforcement ring

The design of the structure is developed by TRACTEBEL and is based on finite element calculations. The structure consists of cast steel segments that are bolted together. The structure has to be very rigid to fulfil the requirements. Therefore some of the joints on the inside of the ring are covered with bolted plates to increase the structure stiffness. The plates and segments and the segments mutually are bolted together with a high force (637 kN - 697 kN) because of the high shear and tensile forces acting on the assemblies. Specific finishing tolerances were imposed to ensure good contact between the plates and segments and the segments mutually.

The reinforcement structure was not designed to take any of the axial load that is exerted on the PRACLAY gallery (cf. section 2.3; Figure 2-4). Therefore the reinforcement structure and the Connecting gallery had to be independent of the PRACLAY gallery.

2.3. Gallery lining

The gallery lining is designed by TRACTEBEL in cooperation with EURIDICE. The design had to take into account a thermal load in addition to the geotechnical load:

- The geotechnical load is caused by the pressure the host rock exerts on the lining. In the short term this pressure is only a percentage of the in-situ stress due to the convergence and deconfinement of the clay around the excavation. The exact value of this percentage depends on several parameters such as gallery dimensions, amount of overexcavation, excavation rate, etc.
- A thermal load will arise in the concrete lining segments during the Heater Test. To limit this thermal load, compressive materials are incorporated in the lining allowing some thermal expansion of the lining.

[1] The code 10.9 means that the bolts need to have a minimum Tensile Ultimate Strength of 1040 MPa or a Tensile Yield Strength (0.2% deformation) of 940 MPa.

The load due to handling, storing and transporting the segments and due to the thrust force of the hydraulic jacks pushing the tunnelling shield forward was not incorporated in the design calculations. A maximum thrust force was imposed in the tender documents after the selection of the lining concrete to avoid damage during the gallery construction [7].

Furthermore several axial forces will act on the PRACLAY gallery (Figure 2-4). First the host formation exerts a pressure on the end plug and secondly the hydraulic seal undergoes an axial force due to the pore water pressure in the backfill material and due to the thermal expansion of the lining during the Heater Test. To limit the resulting axial displacement of the gallery, the following measures were taken:

- Circumferential grooves were placed on the extrados (outer surface) of the lining segment in the non-heated part of the PRACLAY gallery to increase the friction between the host rock and the lining (Figure 2-5). These grooves are not used in the heated part of the gallery as this would result in an increase of the stresses in the lining additional to the increased thermal stresses.
- The diameter of the end plug is 1 m larger than the gallery diameter. Consequently, the outer annulus of the plug is in contact with the clay and a reaction force is created in this zone when the formation exerts pressure on the end plug.
- A layer of compressive material was inserted between the end plug and the shield (shown in orange in Figure 2-4). This allows for some axial movement of the plug without influencing the PRACLAY gallery itself.

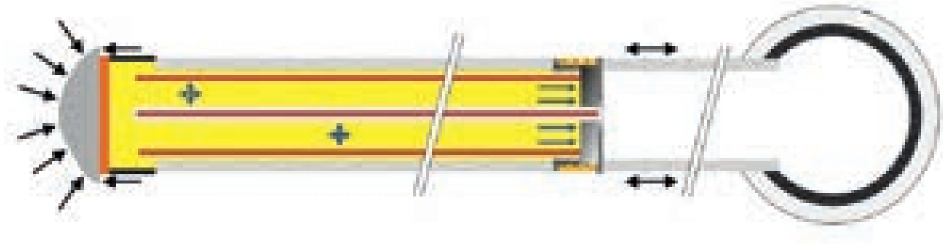


Figure 2-4: Axial forces acting on the PRACLAY gallery.

Figure 2-5: Grooved segments (the square opening in the segment extrados is for the installation of a pressure cell).

Figure 2-6 gives an overview of the different lining types or configurations that can be distinguished in the PRACLAY gallery. The different materials and lining zones are discussed hereafter. Also three special zones in the PRACLAY gallery can be defined: the future hydraulic seal, the tunnelling shield and the end plug.

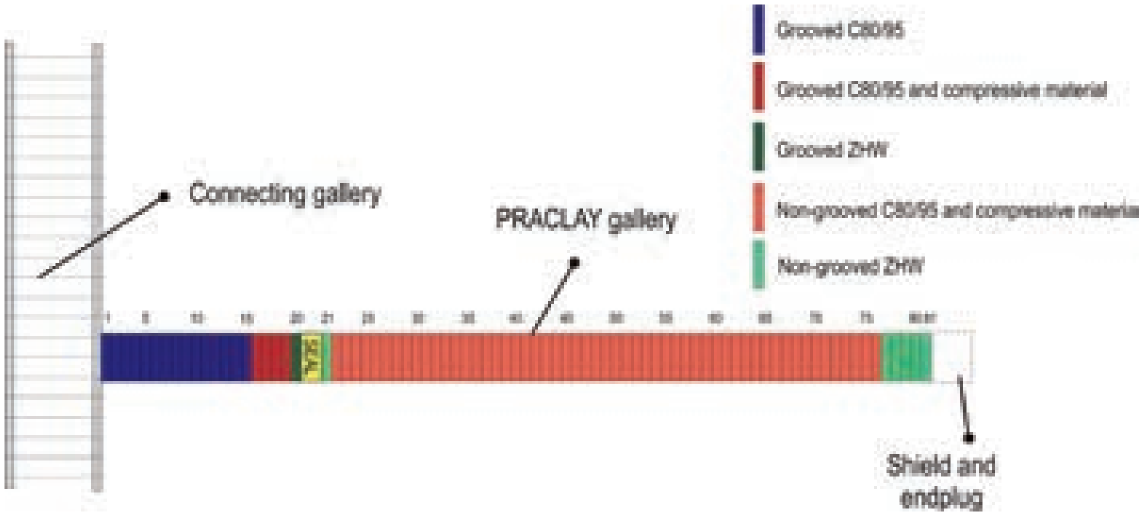


Figure 2-6: Zones with different types of lining.
"ZHW" stands for "zeer hoge weerstand", which is the Dutch translation for "UHPC".

2.3.1 WEDGE BLOCKS

In the design of the gallery lining, a geotechnical load of 2.5 MPa on the lining and an additional stress increase of 2 MPa due to the thermal load were considered. A safety coefficient of 1.35 was applied on the load taking into account a variation in the curvature of the segments induced by the convergence of the clay, a placement eccentricity of 20 mm and a geometrical loss of contact due to 2 chamfers of 20 mm. Also the thick tube effect was included. On the geotechnical load an additional safety coefficient was applied to take into account the anisotropy of the geotechnical load. Close to the Connecting gallery a coefficient for anisotropy of 1.4 was considered.

A safety coefficient of 1.3 on the strength of the concrete was applied, as is mandatory for prefabricated concrete. An additional coefficient of 1.2 was applied to take into account the lower ductility of non-reinforced concrete. To take into account long term effects, the strength was further reduced by a factor of 0.85. As a result, the theoretical allowable compressive stress was 43.59 MPa.

The design of the lining provided for a maximum reduction of 50 mm of the lining ring length (500 mm). This implies that boreholes of 50 mm can be drilled in the PRACLAY gallery lining. When the borehole is drilled at the interface between two rings, a borehole of 100 mm can be drilled.

These calculations led to the selection of C80/95 concrete. The complete design calculations are given in [7] and [8].

One of the objectives of the PRACLAY Heater Test was to characterise the thermal response of the lining–host rock interaction. In the design hypotheses a conservative approach was used by assuming that the surrounding host rock prevents all radial movement of the lining. In reality, some divergence of the lining resulting from thermal expansion and thus less critical conditions can be expected. Therefore, no compressive materials were incorporated in the lining rings of the last 3 m of the PRACLAY gallery. The segments of these rings are made of ultra-high performance concrete (UHPC). Their behaviour will be monitored during the Heater Test to study the lining–host rock interaction.

An overview of the lay-out of the wedge blocks is shown in Figure 2-7. The blocks had to meet the following requirements:

- The external diameter of the gallery lining is 2.5 m. The required lining thickness is 30 cm, which implies an internal gallery diameter of 1.9 m.
- The segments are 0.5 m long. Shorter segments also have the advantage that they are easier to handle and that the unsupported zone behind the shield is reduced.
- One key segment is used instead of two to make the assembly of a lining ring less complicated and also to reduce the number of gaps to be filled afterwards (a key segment is shorter than the other segments and the resulting gap has to be filled afterwards with mortar). On the other hand, the range in practicable lining diameter is reduced by using only one key segment.

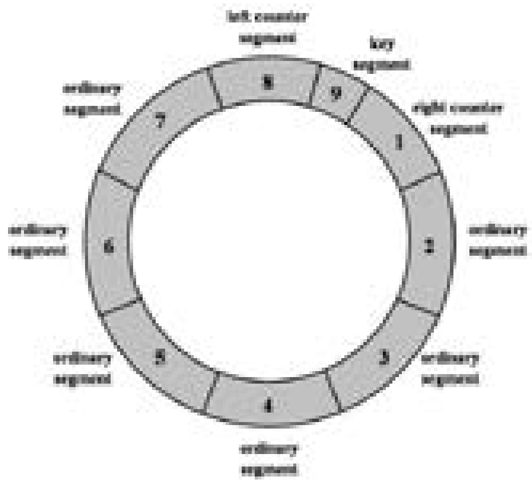


Figure 2-7: Lay-out of the wedge blocks.

Table 2.2 contains the fabrication tolerances of the wedge blocks.

Segment thickness	± 1.5 mm
Radius (internal and external)	± 1.5 mm
Circumferential length	± 1.5 mm
Surface tolerance	± 0.25 mm

Table 2.2: Fabrication tolerances of the lining segments.

Placement tolerances of 15 mm on the radial difference between two segments and 5 mm on their axial difference were specified (Figure 2-8).

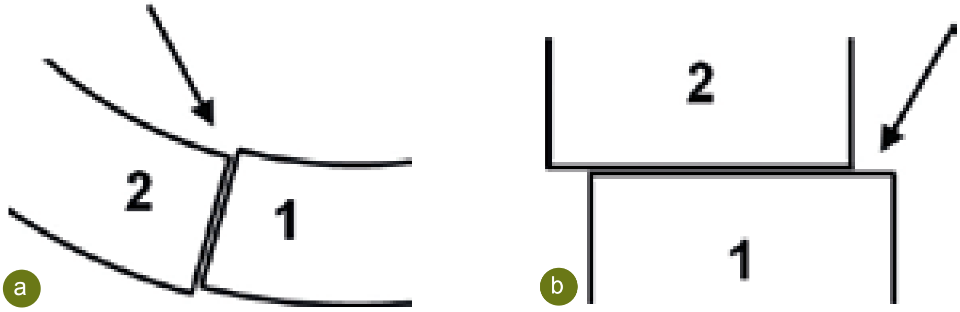


Figure 2-8: Placement tolerances of the wedge blocks:
(a) 15 mm on the radial difference; (b) 5 mm on the axial difference.

2.3.2 COMPRESSIVE MATERIALS

Several types of compressive materials are included in the lining of the PRACLAY gallery [9]. Compressive materials are placed between two adjacent rings to allow for steering corrections during the gallery construction and to avoid direct concrete-concrete contact. Otherwise spoiling of the concrete could occur when the tunnelling shield is pushed forward. Therefore polyethylene sheets are placed between two adjacent rings in the non-heated part of the gallery.

In the heated part of the gallery, compressive materials are installed in the gallery lining allowing for some thermal expansion to limit the thermally induced stresses. Polysiloxane sheets are placed between two adjacent lining rings in the heated part of the gallery, while materials with characteristic stress-deformation behaviour are placed in the lining rings in the zone affected by the Heater Test (this is the heated zone plus the 4 lining rings adjacent to the hydraulic seal in the non-heated part; 4 rings were estimated to be sufficient based on modelling). Their stress-deformation behaviour is as follows (Figure 2-9):

- A relatively rigid region up to 40 MPa limiting the material deformation before the heating phase. The maximum circumferential stress in the concrete before heating is estimated to be about 40 MPa, which is below the allowable stress level.
- A second region starting from 40 MPa allowing a significant deformation. A circumferential compression of about 10 mm for the complete ring is needed in the thermal phase to sufficiently limit the thermally induced stress. To have some reserve, 12 mm is taken as the minimum. Thus, the second region has to allow a deformation of 12 mm (per ring) without the stress exceeding 50 MPa. This is higher than the allowable stress of 43.59 MPa in the concrete segments, but is not considered to be problematic because the stress calculations are very conservative.

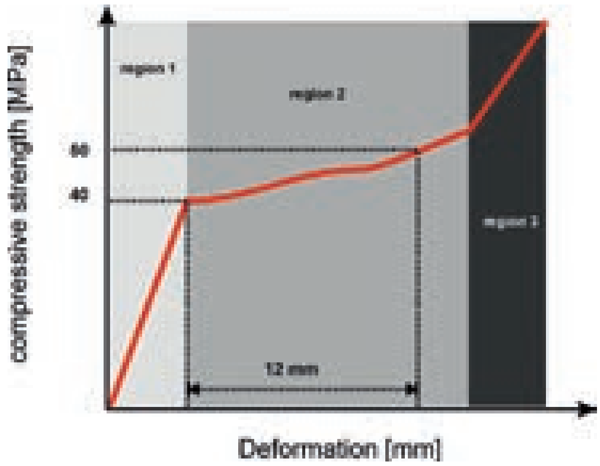


Figure 2-9: Characteristic stress-deformation behaviour of the compressive material placed in the lining rings in the zone affected by the PRACLAY Heater Test.

The selected compressive material is a stainless steel foam panel developed in cooperation with PORVAIR, which also manufactured the panels. For each ring, two foam panels were inserted: one between segments 1 and 2 and one between segments 7 and 8 (Figure 2-10). The joints are rectangular "panels" of approximately 300x250x50 mm³. The opposite faces of the foam panels are parallel. The tolerances on the dimensions of the panels are:

- +/- 1 mm on the thickness;
- +/- 2 mm on the width and length;
- the thickness variation at any location should not exceed 0.5 mm.

To provide the extra space for the metal foam panels, shorter wedge blocks were used in the lining rings containing these panels.

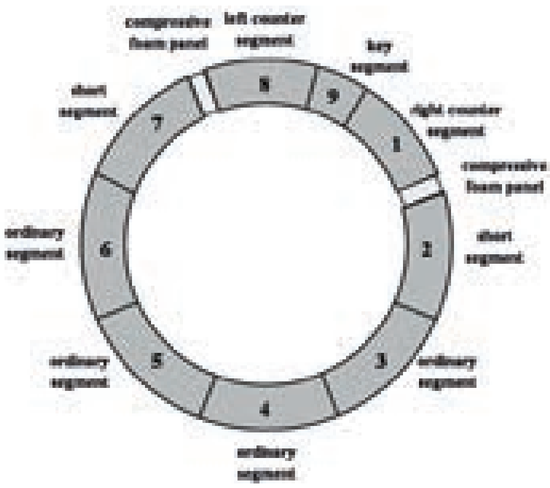


Figure 2-10: Lay-out of the wedge blocks of a ring with compressive materials.

As only a minor temperature increase is expected in the first few metres of the gallery, no foam panels were incorporated in the first 16 rings of the gallery. Nor were any foam panels placed in the two lining rings adjacent to the future hydraulic seal. The segments of these adjacent rings are made of C125/150 concrete (cf. section 2.3).

2.3.3 FUTURE HYDRAULIC SEAL

A hydraulic seal with a width of 1 m will be installed between rings 20 and 21 of the PRACLAY gallery. This seal consists of a steel structure and bentonite blocks that are placed against the clay formation. Bentonite has a very low hydraulic conductivity and swells when it is hydrated. The swelling pressure exerted by hydrated bentonite on the clay formation will reduce the hydraulic conductivity of the clay around the seal.

Evidently, bentonite can only exert its swelling pressure on the clay if it is placed in direct contact with the clay. Therefore no concrete lining can be placed in the zone of the hydraulic seal. Some kind of support in this zone is, however, necessary to prevent convergence of the clay and instability of the gallery sidewall before the seal is installed. The tunnelling shield is also pushed forward against the gallery lining during the excavation work. Therefore an alternative lining has to be placed to fulfil two contradictory requirements: on the one hand keeping a maximum percentage of the sidewall accessible for the bentonite and on the other hand providing sufficient support of the gallery sidewall and allowing the tunnelling shield to be pushed forward against the lining (cf. section 5.1.2.4).

It was left to the contractor to propose a design for this alternative lining.

2.3.4 SHIELD

The steel structure of the shield is abandoned at the end of the construction work, at which point it becomes part of the lining. Therefore it has to be designed to withstand the same load as the lining.

2.3.5 END PLUG

At the end of the PRACLAY gallery an end plug is installed. The end plug has a diameter 1 m larger than that of the gallery. In that way the outer annulus of the plug is in contact with the clay, which provides a reaction force for the clay pressure on the end plug (Figure 2-4).

The final excavation front is reinforced with a steel mesh (150x150 mm, Ø12 mm), which is subsequently shotcreted with C30/37 concrete. A 250 mm thick layer of compressive material is placed between the end plug and the shield to allow for some compression of the end plug (Figure 5-15) [9]. In that way the axial stresses in the PRACLAY gallery are limited. The compressive material is held together by a 10 mm thick steel plate, supported by steel profiles (HEB 100).

The compressive material has to have elastoplastic behaviour with a tangent Young's modulus of 3–4 N/mm² at between 2 and 4 MPa under the expected in-situ conditions, i.e. 90°C, confined and fully saturated with a pore water pressure of 2 MPa and a total pressure of up to 4 MPa.

Finally a tube with a diameter of 150 mm is placed in the compressive material and the concrete plug along the gallery axis for subsequent installation of a piezometer in the Boom Clay in parallel with the gallery axis.

2.4. Excavation of the gallery

Excavation is done using an open-face tunnelling machine. A minimum progression rate of 2m/24h, including the excavation work and placement of the lining, is required. At this rate the time-dependent convergence is limited. Contrary to the design of the reinforcement structure, which was described in detail in the tender documents [7; 10], the design of the shield was left to the contractor. The following requirements for the tunnelling shield were specified in the tender documents:

- Since the shield is abandoned at the end of construction and thus becomes part of the gallery lining, it has to withstand the same load as the gallery lining (cf. section 2.3.1).
- The maximum shield length is 2.4 m and the shield has to have a conicity of 10 mm on diameter.
- The extrados (outer surface) of the shield has to be coated with a Teflon-based paint (e.g. AMERCOAT) to reduce the friction between the shield and the host rock.
- The shield must be equipped with an anti-roll system.
- The shield has to be equipped with hydraulic jacks to move the shield forward by pushing it against the previously installed lining rings. The maximum pressure on the lining is 15000 kPa during normal operation and 25000 kPa in extraordinary situations (e.g. blocking of the shield or potentially after the stop-and-go test).

Based on a shield length of 2.4 m, EURIDICE determined the optimum diameter/required overexcavation to be between 2500 mm and 2550 mm at the rear end of the tunnelling shield [11]. Eventually the diameter of the tunnelling shield at the rear end was set at 2520 mm (Figure 2-11). As the conicity of the shield was 10 mm on diameter, the diameter of the tunnelling shield at the front end was 2530 mm. Cutting edges on the front end of the shield enable an adjustable additional overexcavation of between 10 mm and 50 mm on diameter to be achieved (see also section 5.1.3; Table 5.1).

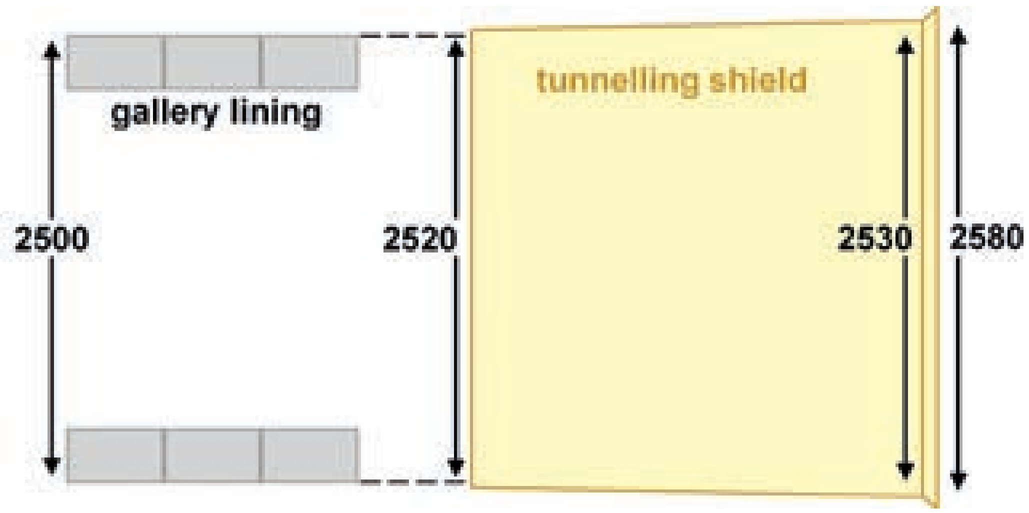


Figure 2-11: Design of the shield (figures are in mm).

The shield has to be instrumented to measure the following parameters:

- pressure in the hydraulic jacks;
- stroke of the hydraulic jacks;
- position and orientation of the tunnelling shield;
- convergence of the host rock around the tunnelling shield.

After ring 79, excavation has to be stopped and the front has to be stabilised. After maximum 7 days, an attempt will be made to restart the tunnelling process. This procedure is called the “stop-and-go test”. It aims to evaluate the difficulty of resuming excavation after a standstill due to, for example, a failure of the tunnelling equipment.

Before transporting the tunnelling shield and excavation equipment underground, a test assembly in the workshop must test all functionalities of the equipment. The shield is transported underground in parts and assembled in-situ. No mounting chamber is excavated.

2.5. Scientific programme and instrumentation

A scientific programme is set up to monitor the excavation work and to characterise the response of the clay to the excavation. The setting up of the instrumentation plan is described in [4] and the complete layout of all the instrumentation installed in the framework of the PRACLAY In-Situ Experiment is given in [6]. This section contains a global overview of the instrumentation that is installed 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. The results and conclusions of these measurements are given in chapter 6.

Prior to the excavation of the gallery, 6 instrumented piezometer boreholes (P30E, P33Id, P35E, P38E, P42E and P49E) were drilled around the future gallery and instrumented with several piezometer filters (50 mm long) complemented with thermocouples (Figure 2-12). Boreholes P35E, P38E, P42E and P49E are horizontal and parallel to the PRACLAY gallery, P30E is subhorizontal with an inclination of 7° downwards, and P33Id is inclined downwards over an angle of 45°. The boreholes, except P35E and P49E, have total pressure cells (flatjacks and/or biaxial stress meters) at the deep borehole end. Three boreholes (P30E, P35E and P42E) are also equipped with long filters (500 mm long) for geochemical characterisation.

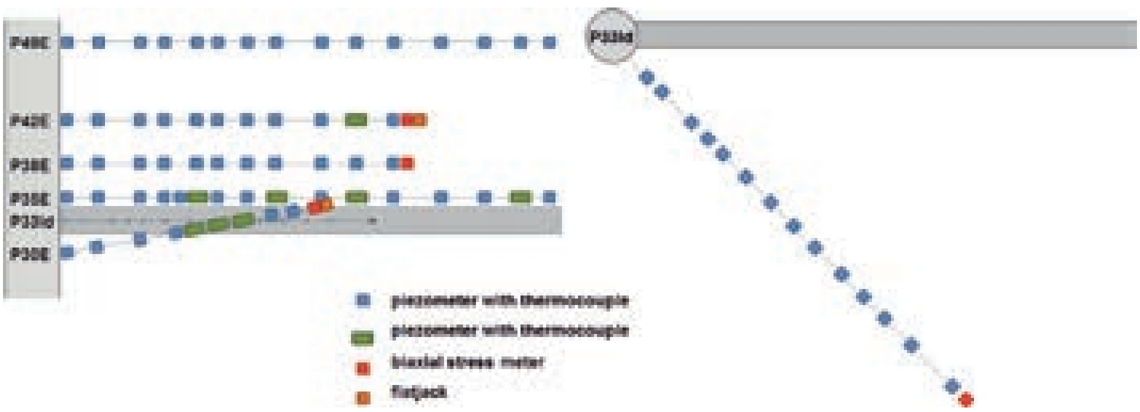


Figure 2-12: Piezometer boreholes drilled around the future PRACLAY gallery.

Furthermore an inclined borehole (P35Iu) was drilled to install an inclinometer. Microseismic sensors were placed in 3 boreholes drilled from ring 30 of the Connecting gallery (P30Iu, P30Ic and P30Id). After the construction of the PRACLAY gallery additional microseismic sensors were placed against the Boom Clay in holes drilled in some lining rings in the non-heated section of the PRACLAY gallery (i.e. the first 20 lining rings of the PRACLAY gallery). The layout of the seismic sensors is explained in [6].

Various instruments are embedded in the gallery lining (Figure 2-13):

- embedded vibrating wire strain gauges (4 lining rings) to measure the deformation of the segments;
- load cells between adjacent segments and pressure cells at the segment extrados (3 lining rings) to measure the pressure in and on the lining ring;
- thermocouples (10 lining rings) to measure the temperature in the lining;
- carbon steel and stainless steel corrosion samples (10 lining rings);
- piezometers at the extrados of ring 20 and ring 21 to measure the pore water pressure at the Boom Clay–gallery lining interface next to the hydraulic seal.

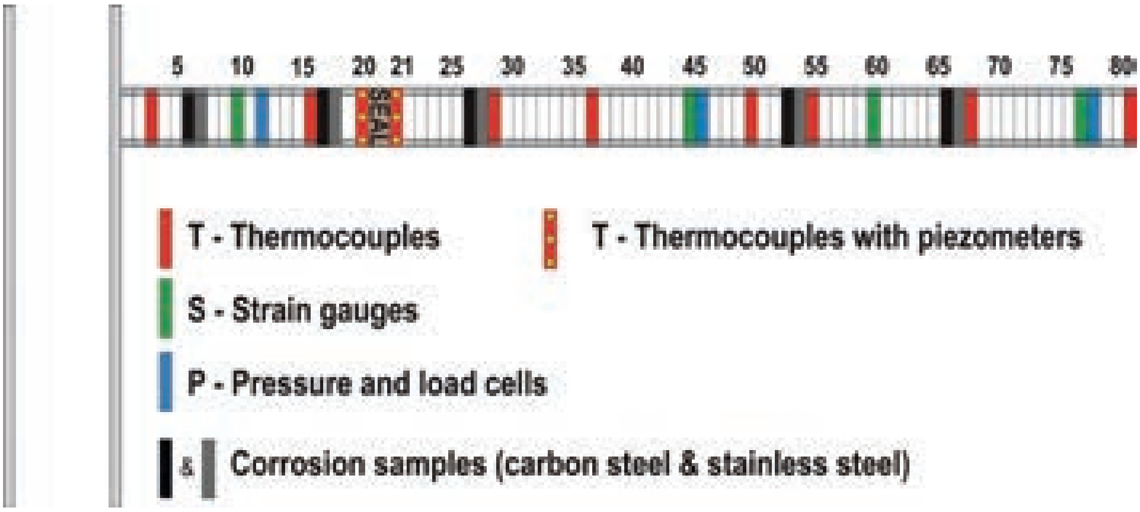


Figure 2-13: Instrumentation of the PRACLAY gallery lining.

How these sensors are included in the lining segments is explained in section 5.1.2 where the manufacturing of these segments is discussed.

After placement of the reinforcement ring, resistive strain gauges are glued on the steel reinforcement ring and on the lining of the Connecting gallery adjacent to the reinforcement ring (cf. section 6.1.1).

During the construction of the gallery, the following measurements and observations were performed:

- measuring the gallery diameter at some lining rings using an INVAR wire extensometer;
- observation of the excavation front and the unsupported clay sidewall behind the tunnelling shield, including systematically taking pictures of the clay sidewall to study the excavation-induced fractures and geological features;
- acquiring samples of clay blocks for laboratory characterisation and other experimental use.

After the construction of the PRACLAY gallery, additional instrumentation is placed to monitor the behaviour of the Boom Clay and the gallery lining during the Heater Test. This instrumentation is described in [6].

2.6. Safety

Safety is always an important issue in underground construction work. The tender documents [10] describe a series of specific points of interest for the contractor. Besides more conventional topics like noise and dust, attention has to be paid in this specific project to safety while transporting the equipment underground through the shaft and during underground assembly of the reinforcement structure and the tunnelling shield. Falling clay blocks at the excavation face and in the unsupported zone also pose a safety risk.

2.7. Comparison with the design of the Connecting gallery

The design of the PRACLAY gallery is mainly based on the design of the Connecting gallery. Table 2.3 summarises the main similarities and differences between the two galleries.

Item	Similarities with the Connecting gallery	Differences from the Connecting gallery
Gallery design	Similar design hypotheses were adopted	Dead-end gallery No starting chamber. A reinforcement ring had to be constructed to allow the crossing of the two galleries. Smaller dimensions. Besides geotechnical loads, thermal loads had to be considered as well. The PRACLAY gallery was constructed on an E-W axis (the Connecting gallery on a N-S axis)
Tunnelling shield	A cylindrical tunnelling shield was used. The shield was slightly conical. The shield was instrumented.	An anti-roll system was incorporated. More sophisticated position control. The instrumentation on the shield was more automated.
Excavation	Minimum progression rate of 2m/24h. The final profile was determined by the cutting edges at the front of the shield. Overexcavation could be adjusted by changing the position of these cutting edges. In the event of problems, the excavation face would be anchored and shotcreted.	The excavation method (manual or automated) was not defined by the principal. No ultimate solution was planned in the event of the tunnelling machine getting trapped[2].

2 For the construction of the Connecting gallery, it was planned to continue excavation manually if the shield became blocked.

Lining	Unreinforced concrete wedge-block lining. Lining was instrumented (more extensively than the lining of the Connecting gallery).	One key segment instead of two; 9 segments per ring instead of 12. Another type of concrete was used because of the different load case (thermal loads). Presence of compressive materials within the lining rings and between the lining rings.
Scientific programme	The host rock around the future gallery was instrumented. Measurements of the gallery behaviour were made during and after construction. Fracture and geological feature observation programme.	Available space was even more limited, so the scientific programme required much stricter coordination.

Table 2.3: Similarities and differences between the construction of the Connecting gallery and the PRACLAY gallery.

3. Tendering procedure

A restricted call for tenders was applied as tendering procedure for the construction of the PRACLAY gallery. Such a procedure was also used for the construction of the Connecting gallery. It proved to be the most appropriate tendering procedure, having the following advantages:

- The procedure entails a pre-selection of candidate contractors. This offers the advantage of being able to rule out contractors not qualified for this type of work.
- An evaluation of the tenders solely based on the cost, as would have been the case with a standard tendering procedure, would have been inadequate.

Table 3.1 gives the timeline of the procedure. As required by legislation, an official announcement was made in the Official Journal of the EU, followed by an announcement in the Belgian Official Gazette. Five candidates applied for the contract and were analysed at the prequalification stage, based on their certification, their legal situation and their economic, financial and technical capabilities. A maximum of 20 months between the signing of the contract and the provisional delivery was imposed.

All potential contractors passed the preselection and introduced a bid. These bids were analysed objectively according to the contract award criteria and weighting factors as defined in the invitation to tender letter and in the tender documents [10]. Finally the project was awarded to SMET Tunnelling in November 2005 and the contract was signed in January 2006.

01.04.2004	Announcement in the Official Journal of the European Union (ref. 2004/S 65-055447).
02.04.2004	Announcement in the Belgian Official Gazette (ref. N. 4261).
17.05.2004	Deadline for potential candidates to enter the procedure.
29.06.2004	Decision of the steering committee of EURIDICE about the prequalification of 5 potential candidates (ref. EURIDICE 04-033/BC).
17.12.2004	Invitation to tender letter sent to the 5 selected candidates (ref. EURIDICE MD/bp/04-260).
30.03.2005	Tender documents [10] given to the selected candidates.
09.08.2005	Original deadline for receipt of the bids. At the request of some of the candidates, this deadline was postponed to 13.09.2005 (ref. EURIDICE MD/bp/05-166).
13.09.2005	Receipt of the bids.
29.11.2005	Contract awarded
26.01.2006	Signing of the contract
01.02.2006	T_0

Table 3.1: Timeline of the tendering procedure.

SMET Tunnelling had envisaged 15 months between the signing of the contract and the provisional delivery. The provisional delivery was thus planned for April 2007.

4. General organisation of the work

The construction of the PRACLAY gallery involved four main parties. Besides SMET Tunnelling, contracted by EURIDICE for the construction work, the engineering office TRACTEBEL and the Technical Control Bureau for Construction SECO were also contracted. A detailed planning schedule for the project can be found in the construction documents [12].

The project teams involved in the construction of the PRACLAY gallery mainly comprised the following people:

- for EURIDICE:
  - > Marc Demarche, site manager and project manager, in charge of overall supervision and budgetary control of the project;
  - > Frédéric Bernier, scientific manager, in charge of all scientific aspects;
  - > Marc Buyens, safety coordinator, in charge of all safety aspects;
  - > Wim Bastiaens, project engineer, responsible for technical and administrative monitoring of the project and coordination between all parties;
  - > Jan Verstricht and Philippe Van Marcke, scientific engineers.

- for SMET Tunnelling:
  - > Bart Vanhout, project manager;
  - > Gert Van Gorp, Youri Demeulemeester and Bert Kustermans, project engineers;
  - > Guy Vangenechten, construction supervisor, responsible for correct and safe execution of the work.

- for TRACTEBEL:
  - > Alain Van Cotthem, lead engineer for the setting up of the technical specifications and for the construction work;
  - > Koen Nulens, assisting in the construction work;
  - > Carine Ramaekers, establishing the technical specifications.

- for SECO:
  - > Wim Defoort, supervisor;
  - > Luc Lauwers, site inspection.

From an organisational point of view, the whole construction project can be divided into four main types of activities, during which the various parties fulfilled different roles:

- the contract award procedure;
- the detailed design work;
- the construction work;
- the monitoring activities during the construction work.

4.1. Contract award procedure

The various aspects of the contract award procedure were the responsibility of the following parties:

- announcement of the project and prequalification in the framework of the restricted call for tender procedure: EURIDICE assisted by TRACTEBEL;

- setting up of the technical specifications: TRACTEBEL in close cooperation with EURIDICE;
- evaluation of the tenders submitted by the various candidate contractors: EURIDICE assisted by TRACTEBEL;
- administrative tasks: EURIDICE.

4.2. Detailed design work

The design phase that followed the contract award was used to turn the existing technical specifications into detailed work plans and procedures. This was done by SMET Tunnelling. Before the corresponding work could be started, these documents (proposals, plans, procedures and calculation notes) were submitted to EURIDICE for approval. TRACTEBEL was also consulted to check the technical correctness of these documents and their compliance with the technical specifications. SECO was consulted to check the stability calculations.

This procedure enabled EURIDICE to request modifications or clarifications from SMET Tunnelling whenever needed or to just approve the submitted documents. The approved documents are all included in the construction documents for the project [12].

4.3. Construction work

The construction work was executed by SMET Tunnelling under the supervision of EURIDICE. The installation of the reinforcement ring, the assembly of the shield and the underground equipment, and the construction of the gallery were all performed by the same team of workers. This team was under the supervision of the SMET Tunnelling construction supervisor, who was in turn assisted by the engineers involved in the studies, the design and the preparatory work.

The existing site infrastructure was adapted between January and July 2007 to meet the specific requirements of the underground work to be carried out. The existing lift was replaced by one with the necessary facilities, such as rails, mechanical locking devices and hoists facilitating the transport and handling of the materials and equipment to be used underground. A travelling crane was also erected on the surface to handle the heavy construction materials.

The underground assembly of the reinforcement ring and the tunnelling machine was carried out between August and October 2007. A work schedule of 12 hours a day for 5 days a week was maintained by one team of about 12 workers. The lining of the Connecting gallery was cut on 3 and 4 October 2007. From then on, a work schedule of 24 hours a day/7 days a week was introduced, involving 2 shifts of 12 hours. This was achieved by 3 teams of 8 workers. The main reason for this non-stop work schedule was to achieve the target excavation rate of 2m/24h. The faster the work progressed, the less convergence would occur and also the smaller the risk that the tunnelling machine would get trapped in the clay. The construction of the PRACLAY gallery was completed in 28 days, excluding the stop-and-go test and the construction of the end plug.

For the stop-and-go test, the excavation work was suspended for one week (30.10.2007 – 06.11.2007). A daily inspection was performed by the contractor and the principal.

After the stop-and-go test the last two rings, rings 80 and 81, were built on 06.11.2007.

The construction of the end plug (06.11.2007–15.11.2007) and demobilisation from the site (08.11.2007–07.12.2007) were completed with a work schedule of one 12-hour day shift.

4.4. Monitoring activities during the construction work

The construction work was monitored by means of daily and weekly meetings and by field inspections.

The *daily meetings* with SMET Tunnelling and the *regular meetings* between all four parties aimed to gain an overview of the progress of the work, discuss the encountered difficulties and any unsafe situations, and decide on actions to be taken. Two types of daily reports were made: activity reports and observation reports. The *activity reports* included the main activities, tests, observations and inspections performed, special events that had occurred during the activities, problems encountered during the work and possible solutions, any safety or technical issues that might influence the progress of the work and monitoring of the planning schedule. The *observation reports*, which were part of the activity reports, reported the observations made during the excavation and their analysis.

The *field inspections* were taken care of by EURIDICE, TRACTEBEL and SECO. SECO was in charge of the regular inspections of the execution of the civil engineering work with a view to preparing the documents needed by EURIDICE to obtain the 10-year warranty.

5. Construction of the PRACLAY gallery

The construction of the PRACLAY gallery can be subdivided into preparatory work and the actual excavation of the gallery. The main safety issues related to the construction work are discussed at the end of this chapter.

Detailed information (construction drawings, procedures, calculation notes, material specifications, meeting reports, etc.) on the construction of the PRACLAY gallery can be found in the construction documents for the gallery construction [12].

5.1. Preparatory work

The preparatory work involve the manufacturing of the main components of the PRACLAY gallery and the tunnelling machine: the steel reinforcement ring, the components of the gallery lining and the tunnelling shield.

5.1.1 REINFORCEMENT RING

The reinforcement ring was constructed by Allard and is composed of 11 cast steel segments that are moulded and assembled using bolts. The contractor proposed some adaptations to the initial design (cf. section 2.2). The number of identical segments was increased and hence fewer moulds for the construction of these segments had to be built. Moreover, fewer bolts were necessary in the new design and the use of M39 bolts was proposed instead of M42 bolts. Finally the position of the key segment was also changed.

Wooden positive moulds were first constructed (Figure 5-1). These were made larger than the designed size to compensate for the shrinkage of steel. Then the negative moulds were made in sand and the segments were cast. After production the segments were sandblasted and machined. Finally, the ring was assembled and milled as a whole (Figure 5-2).

Figure 5-1: Wooden positive moulds for the construction of the reinforcement ring.

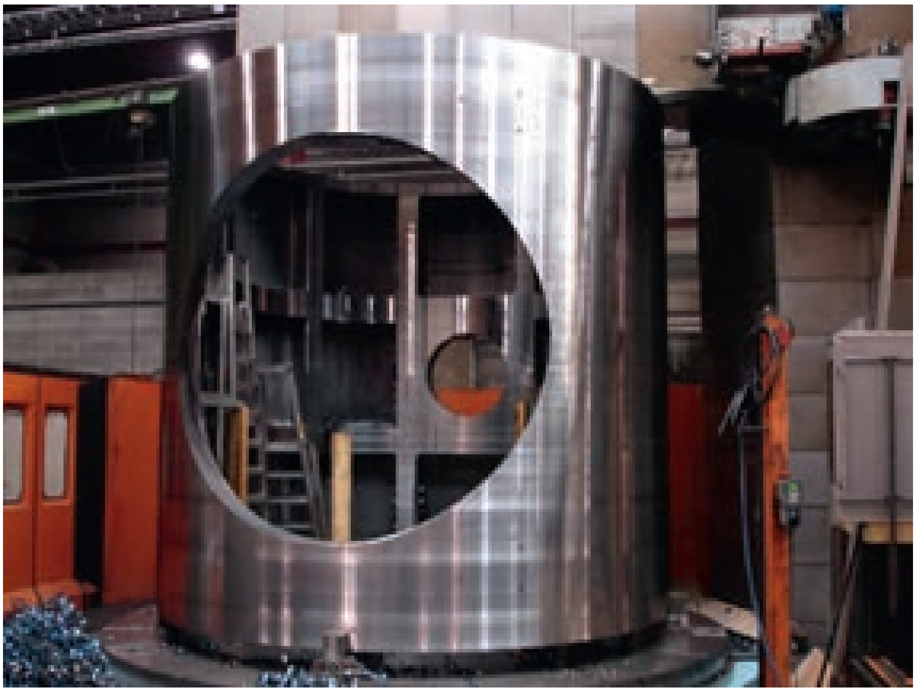


Figure 5-2: Test assembly of the reinforcement ring.

The segments were checked by TRACTEBEL during several inspections involving visual controls, geometrical measurements, hardness measurements using a metal hardness tester (Equotip), tensile strength tests, magnetic tests and ultrasonic tests to detect any faults. An analysis of the chemical composition of the steel was also performed. Some shrinkage cracks were detected and repaired by welding. The mechanical and geometrical specifications were met.

Attention had to be drawn to two other aspects of the construction of the reinforcement ring: the pre-tension induced in the bolts during assembly and the friction between the segments [13]. To determine whether the maximum torque applied on the bolts during the assembly of the reinforcement ring is sufficient to achieve the required pre-tension in the bolts, the relationship between the moment applied by the torque and the pre-tension in the bolts had to be determined. This was done by including a strain gauge in a bolt and measuring the stress in the bolt for a given torque. The measurements on the torque wrench that were used for the assembly of the reinforcement ring were performed on 31.07.2007.

Secondly, the segments were sandblasted to guarantee a friction coefficient of 0.5 between the contact surfaces of the segments mutually. The roughness of the contact surfaces was measured and proved to be sufficient. Therefore, and based on expert judgement, the friction between the segments was considered to be sufficient.

The construction of the reinforcement ring took longer than planned and resulted in a delay of 6.5 months. This delay was mainly caused by the additional design work and engineering of the ring and by a worldwide high demand for steel, which complicated the production process.

On 29.06.2007 a test assembly of the reinforcement ring was performed (Figure 5-2). The test was checked and approved by EURIDICE.

5.1.2 GALLERY LINING

The lining of the PRACLAY gallery is made of wedge blocks, some of which were instrumented. Compressive materials were placed between the rings and within the rings, allowing the lining to deform and in that way limiting the thermally induced stresses during the Heater Test. Where the hydraulic seal will be installed, an alternative lining was built. Compressive materials are also used between the tunnelling shield and the end plug to limit the axial stresses in the PRACLAY gallery.

5.1.2.1 WEDGE BLOCKS

All segments, except for the key segment, are 300 mm thick and 500 mm wide. Four different layouts for a lining ring are used (Figure 5-3):

- a lining ring with 6 ordinary segments, 2 counter key segments and 1 key segment;
- a lining ring with 4 ordinary segments, 2 short segments and 2 compressive foam panels, 2 counter key segments and 1 key segment;
- a lining ring with 6 short segments, three load cells, 2 counter key segments and 1 key segment;
- a lining ring with 4 short segments, 2 very short segments and 2 compressive foam panels, 3 load cells, 2 counter key segments and 1 key segment.

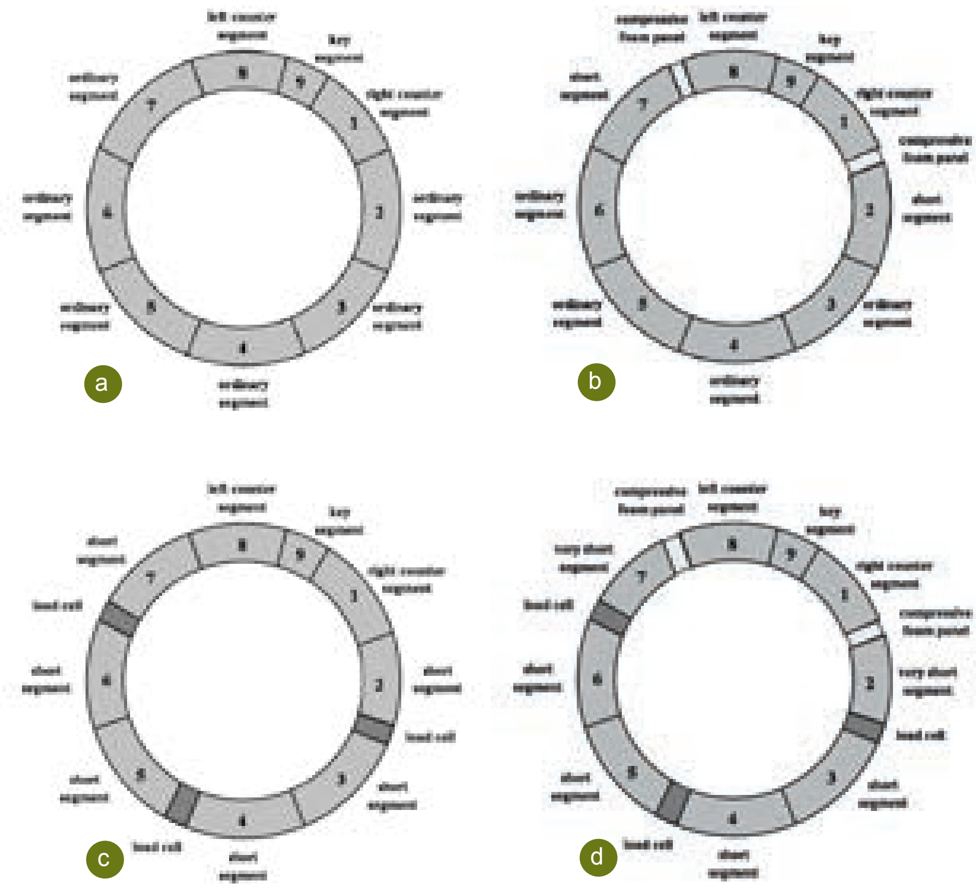


Figure 5-3: Layout of different lining ring configurations:
(a) ring containing only wedge blocks; (b) ring containing compressive foam panels;
(c) ring containing load cells; (d) ring containing compressive foam panels and load cells.

Figure 2-6 shows an overview of the use of these different layouts for the lining rings in the PRACLAY gallery. The segments of the rings in the non-heated part of the gallery (i.e. the first 20 rings) have circumferential grooves at the extrados (outer surface) (Figure 2-5) to increase the friction between the host rock and the lining (cf. section 2.3.1). This results in the following types of wedge blocks:

- *Ordinary segment*: length at extrados: 1004 mm; weight: ca. 320 kg.
- *Short segment (type 'B')*: length at extrados: 954 mm; weight: ca. 305 kg.
- *Very short segment (type 'C')*: length at extrados: 904 mm; weight: ca. 290 kg.
- *Left counter key segment:* length at extrados: between 767 mm (wedge-block leading edge) and 717 mm (wedge-block trailing edge); weight: ca. 250 kg.
- *Right counter key segment*: length at extrados: between 767 mm (wedge-block leading edge) and 717 mm (wedge-block trailing edge); weight: ca. 250 kg.
- *Key segment* (tapered segment): length at extrados: between 306 mm (wedge-block leading edge) and 392 mm (wedge-block trailing edge); width: 582 mm; weight: ca. 120 kg.

The dimensional tolerances on these blocks are:

- ± 1.5 mm on the length at extrados;
- ± 1.5 mm on the thickness;
- ± 1.5 mm on the width;
- 0.25 mm for the surface smoothness.

The fabricated key segments had a width of 582 mm, which is larger than needed. This offered flexibility to adjust the length of the key and thus also made it possible to adjust the external diameter of the lining ring. A decision table for the adjustment (if necessary) of the key segment width was made to enable a fast and appropriate decision to be made if required during the work. This decision table is shown in Figure 5-4.

The concrete of the lining is C80/95 concrete. In the last 3 m of the gallery (rings 76 to 81) and around the hydraulic seal (rings 20 and 21), no compressive materials allowing thermal expansion were used. The segments of these rings are UHPC concrete.

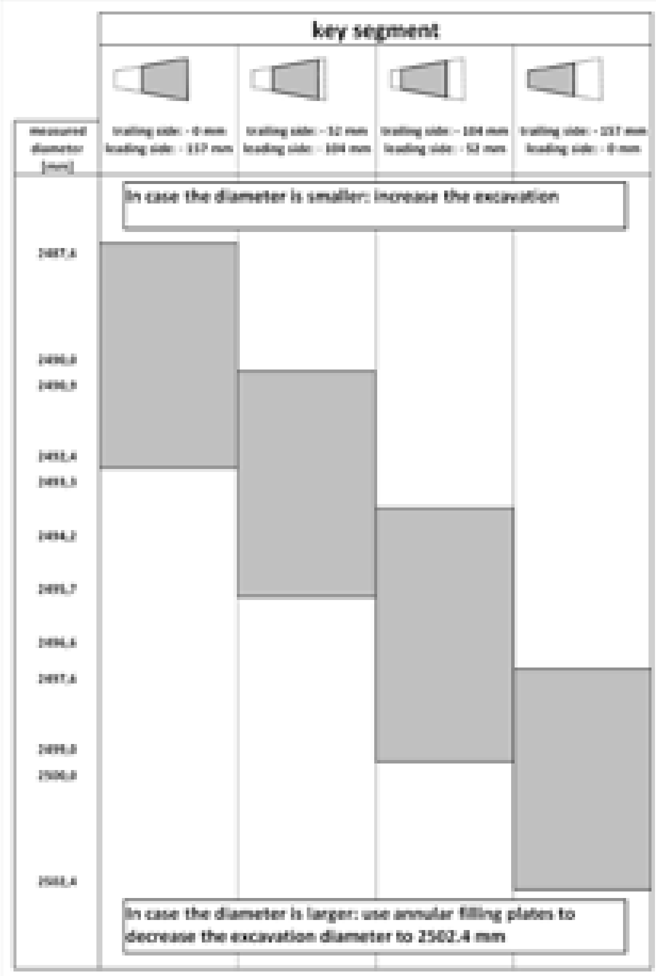


Figure 5-4: Decision table used during the excavation work.

The lining segments of the C80/95 type were manufactured by BUCHAN using BUCHAN moulds (Figure 5-5). These moulds were made of reinforced concrete, except their extrados, which was made of a removable steel framework. The surfaces between ordinary segments mutually and between ordinary segments and counter keys were made flat, while the surfaces between the keys and their counter keys were made slightly helical. A test assembly of two wedge block rings was carried out at BUCHAN and inspected by EURIDICE on 14.09.2006 prior to starting full-scale fabrication (Figure 5-6).

Figure 5-5: Fabricated concrete segment block in BUCHAN mould.

Figure 5-6: Test assembly of two wedge block rings.

However, two problems arose in the production process of the C80/95 concrete:

- The characteristic strength[3] was not systematically achieved during load tests performed on cubic samples (150×150×150 mm) 28 days after production. This was solved by adapting the production process. The already fabricated segments were rejected and rebuilt.
- Some segments did not meet the surface tolerance of 0.25 mm. This was due to the rubber in the moulds, which caused discontinuities on the segment surface. The contact surface between the segments in the ring was thus smaller and would cause higher stresses in the segments. To compensate for these higher stresses, the tolerance on the placement of the segments was reduced from 20 mm to 15 mm (Figure 2-8).

Since BUCHAN did not succeed in fabricating the segments of the UHPC concrete, these segments were made by SOCEA using the BUCHAN moulds [14; 15]. The UHPC segments were composed of the patented high quality concrete BSI®-CERACEM from EIFFAGE.

5.1.2.2 SEGMENT INSTRUMENTATION

Some segments were instrumented with the following sensors (Figure 2-13; section 2.5):

- embedded strain gauges
- external pressure and segment load cells
- thermocouples
- corrosion samples

Two types of strain gauges were used: vibrating wires and optical fibres. The vibrating wires were installed circumferentially on both the intrados (inner surface) and the extrados (outer surface). These strain gauges are placed in two configurations: configuration A with 4 strain gauges and configuration B with 8 strain gauges (Figure 5-7a). In addition, an optical fibre was installed in the longitudinal direction. The strain gauges are mounted on a support cage and placed in the mould (Figure 5-7b).

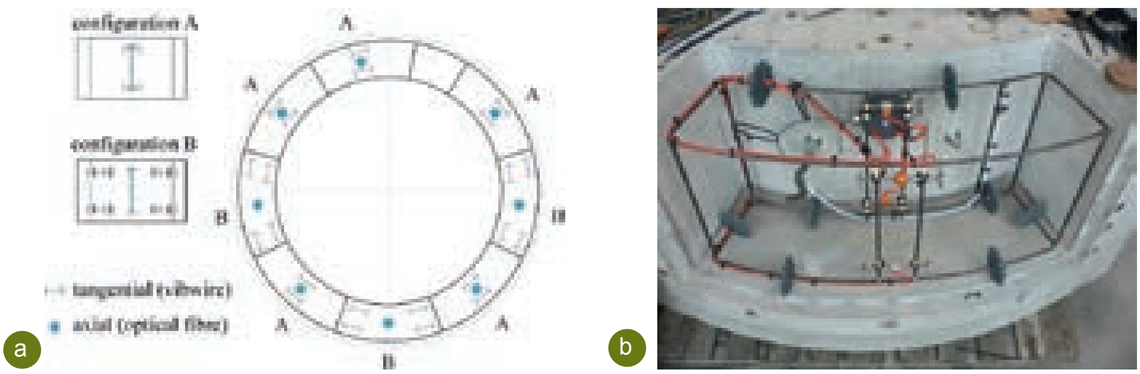


Figure 5-7: (a) Configuration of strain gauges embedded in the lining; (b) Support case placed in the segment mould for the installation of the strain gauges.

The radial pressure exerted on the gallery lining is measured by pressure cells that are mounted in the segments after the segment has been unmoulded. Therefore an opening was left in the segment extrados when casting the segment, into which the pressure cell was subsequently placed (Figure 5-8). The load cells to measure the circumferential stresses in the lining were cast in concrete segments 100 mm thick (Figure 5-9). These segments were placed between two segments during the installation of the lining. The configuration of the pressure and load cells is shown in Figure 5-3.

[3] The compressive strength of concrete is given in terms of the characteristic compressive strength of 150 mm size cubes tested at 28 days. The characteristic strength is defined as the strength of the concrete below which not more than 5% of the test results are expected to fall. This concept assumes a normal distribution of the strengths of the samples of concrete.

Figure 5-8: Opening in the segment extrados for pressure cell.

Figure 5-9: (a) 100 mm thick lining segment containing a load cell;
(b) lining segment containing the load cell in the lining ring.

The rings that are equipped with thermocouples contain four segments with three thermocouples each. These are installed on a support cage which is placed in the mould. In rings 20 and 21, openings are provided for the installation of pore water pressure sensors.

Finally 10 segments are equipped with corrosion samples. These samples are 200 by 300 mm in size and are placed in the middle of the segment. 5 samples are made of P239 carbon steel, the other 5 are made of 316L hMo stainless steel. These samples were chemically cleaned in advance to remove impurities.

5.1.2.3 COMPRESSIVE MATERIALS

Several compressive materials were glued onto the segments before their installation to allow some thermal expansion of the lining. This avoids damage to the concrete wedge blocks and consequently facilitates safe access to the gallery after the Heater Test is stopped.

In the heated part of the gallery and the 4 adjacent rings in the non-heated part, a chemically compatible compressive material was placed between the rings to absorb the thermal stresses. This was an 8 mm thick silicon rubber plate (polysiloxane) (Figure 5-10a). Laboratory tests were carried out to determine the behaviour of this material, both at room temperature and at elevated temperature. In the other part of the gallery, 3 mm thick polyethylene sheets were placed between the lining rings to allow for steering corrections when necessary (Figure 5-10b).

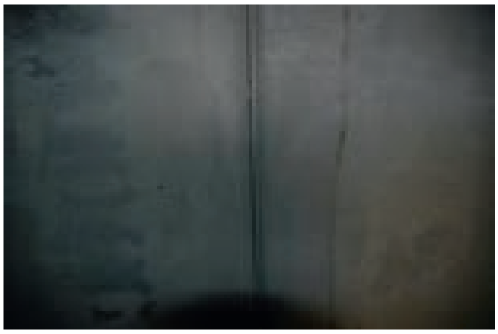


Figure 5-10: (a) 8 mm thick silicon rubber sheet and
(b) 3 mm thick polyethylene sheet placed between the rings.

Metal foam panels are used in rings 16 to 75 (except for rings 20 and 21 around the hydraulic seal). This material was developed in cooperation with PORVAIR. The stress-deformation behaviour of the metal foam panels exhibits relatively rigid behaviour below 40 MPa. The deformation before heating is therefore limited. At stresses between 40 and 55 MPa – stresses that might be reached during the heating phase – the foam undergoes a deformation of 5 mm. As two panels are inserted in one ring, this corresponds to a tangential deformation of 10 mm in total. This is necessary to keep the stresses in the lining allowable during the heating phase.

The stress-deformation behaviour of two metal foam samples was determined in a load cell [16]. A foam panel was cut in two for this purpose. This was necessary to be able to achieve pressures above 40 MPa in the foam panel with the available load cell. In the test applied on sample A, the head of the load cell was fixed and no differential displacement could occur (Figure 5-12a). In the test applied on sample B, the head of the pressure cell could rotate and follow a differential displacement. The results of both tests are shown in Figure 5-11.

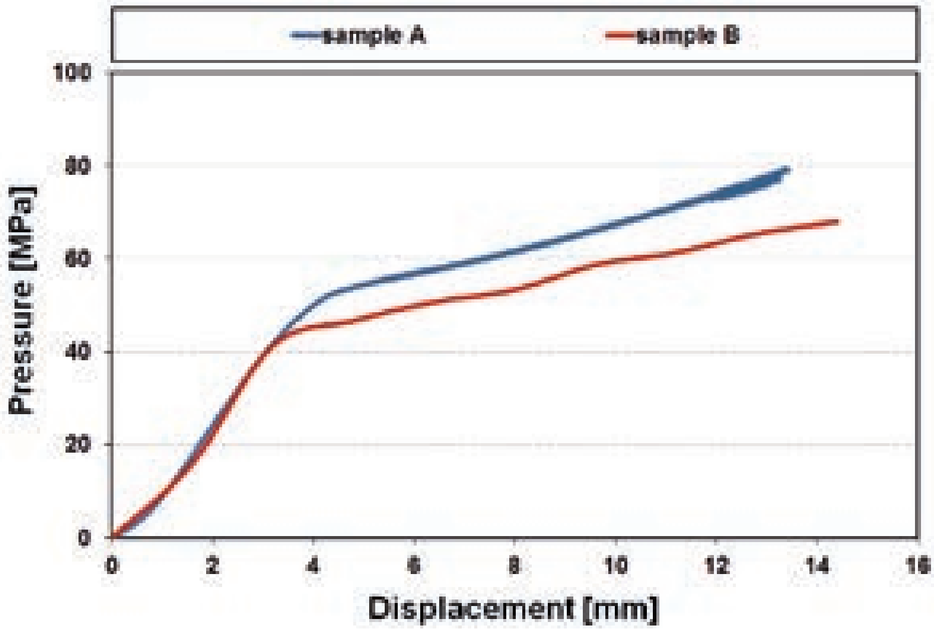


Figure 5-11: Stress-deformation determined by a load test on
two metal foam samples.

The stress-strain behaviour of sample A becomes more compressible at a pressure of approximately 50 MPa. This is higher than the required 40 MPa. As a result the deformation between 40 MPa and 50 MPa is limited to approximately 1 mm. Taking into account the fact that two metal foam samples were placed in one ring, this corresponds to a total displacement of 2 mm. The test was stopped at a pressure of 80 MPa because the limit of the load cell was reached.

Sample B was tested with a rotating head and was able to deform more. A crack was induced at the tip of the sample and the complete sample finally cracked at a pressure of 68 MPa (Figure 5-12b). From a pressure of 42 MPa the material becomes more compressible and between 40 MPa and 50 MPa a displacement of 3 mm was achieved, which corresponds to a total displacement of the complete ring of 6 mm.

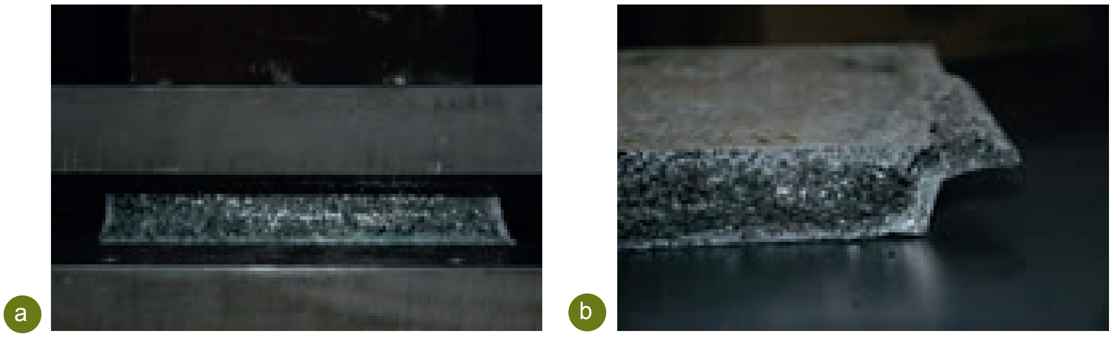


Figure 5-12: Load test with fixed load cell head (a)
and with rotating load cell head on metal foam samples (b).

The total tangential displacement of 2 mm and 6 mm derived from both tests is smaller than the required 12 mm (Figure 2-9). The test is not, however, completely representative for the situation that will occur in the lining during the Heater Test at an elevated temperature of 80°C.

5.1.2.4 LINING AT THE HYDRAULIC SEAL

At the location where the hydraulic seal will be installed, the lining consists of a permanent and a temporary part. The permanent part is made of 4 steel rings, 80 mm wide and 110 mm thick. Between these rings, wood is placed to support the clay. The wood will be removed before the installation of the hydraulic seal. As the hydraulic seal is 1 m wide, the alterative lining is composed of two lining rings. Steel plates 300 mm thick are placed at the sides of both rings.

Figure 5-13a illustrates this alternative lining. The four steel rings make up the permanent part. These are connected by steel plates between the rings to avoid buckling of the rings. The temporary part consists of wood placed behind a small steel edge welded to both sides of each steel ring. These two lining rings are, like the normal concrete lining rings, composed of 9 segments (Figure 5-13b) that are linked to each other by a "pin-hole connection" (Figure 5-13c). The lining not only has to support the clay, it also serves as a structure against which the shield can be pushed forward. Therefore the alternative lining has to be able to transfer the thrust force of the shield to the already built gallery lining. The transfer of this force is achieved by cylinders inserted between the steel plates at the sides of the rings (Figure 5-13d). These cylinders have to be removed before the installation of the hydraulic seal. Therefore the cylinders of the second ring were filled with sand. After the completion of the gallery construction, the stresses on these cylinders of the second ring were released by removing the sand. This was done by flushing the sand out with air. Once the stresses on the cylinders were relieved, the cylinders could be dismantled. Attention was drawn to the fact that the sand in the cylinders was equally pre-compressed to avoid differential deformation of the cylinders during the construction work.

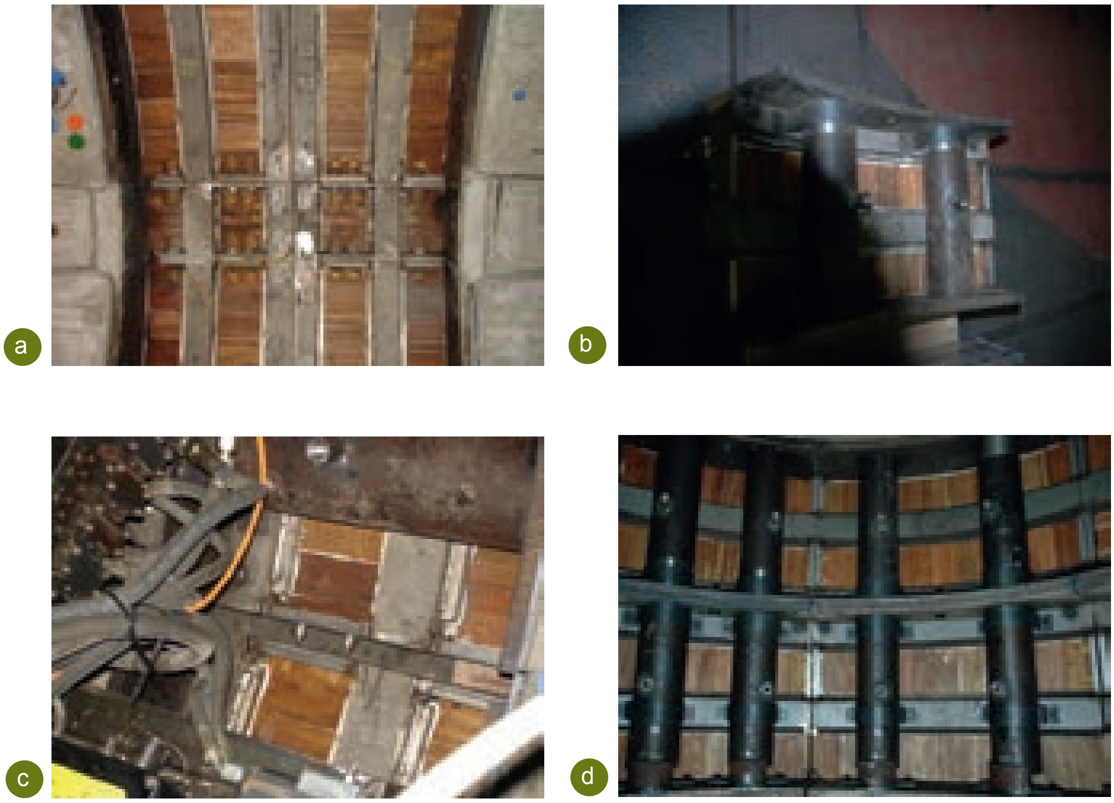


Figure 5-13: Alternative lining at the location of the future hydraulic seal: (a) the lining consists of a permanent part (4 steel rings) and a temporary part (wood placed between the steel rings); (b) the lining rings are composed of 9 segments; (c) these segments are interlinked by a pin-hole connection; (d) steel plates with steel cylinders inserted in between are placed at the side of both rings to transfer the thrust force of the shield.

The segments of the alternative lining were fabricated by SMET Tunnelling. A test assembly on the surface was carried out and inspected by EURIDICE on 28.09.2007 (Figure 5-14).

Figure 5-14: Test assembly of the alternative lining.

5.1.2.5 COMPRESSIVE MATERIAL INSERTED IN THE END PLUG

The compressive material placed between the tunnelling shield and the end plug has to limit the axial stresses in the PRACLAY gallery (cf. section 2.3.5). The material is designed and manufactured by SOLEXPERTS and is based on HIDCON elements, which are also used in other tunnelling projects (e.g. Lötschberg) (Figure 5-15). A test programme was performed to optimise the composition and shape of the HIDCON elements and to ensure the elements meet their requirements [17]. The concrete behaviour is elastoplastic with a tangent Young's modulus of 3–4 N/mm² at between 2 and 4 MPa (Figure 5-16). The material was tested under the expected conditions, i.e. at 90°C, confined and fully saturated.

Figure 5-15: Test assembly of the wall of compressive concrete installed at the end of the PRACLAY gallery.

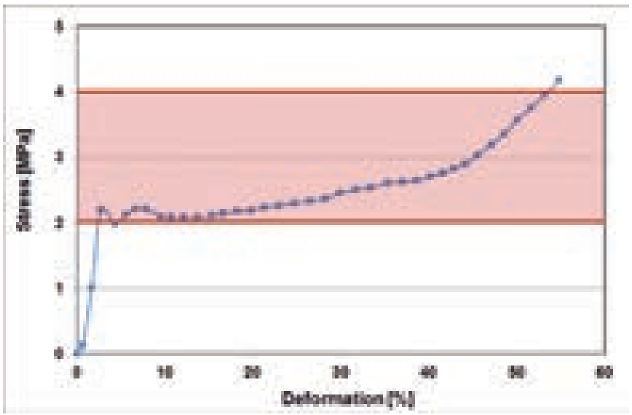


Figure 5-16: Stress-deformation behaviour of the compressive material used in the end plug.

5.1.3 TUNNELLING SHIELD

The design and geometry of the tunnelling shield are illustrated in Figure 2-11. The fine-tuning of the design involved the specification of the following characteristics determining the overexcavation: the diameter at the rear end, the oversize of the cutting edge and the shape of the shield (i.e. the conicity of the shield). A given overexcavation is needed to compensate for the convergence of the clay. An estimation of the convergence of the clay during the excavation was obtained by modelling the behaviour of the clay formation around the excavation [11]. The modelling was supported by the experience gained from the excavation of the Connecting gallery. This resulted in an estimated overexcavation of 18 to 35 mm on diameter. Assessing the exact instantaneous convergence in advance is difficult, however. It depends for example on the overexcavation and on the excavation rate. Therefore the possibility to adjust the overexcavation was incorporated in the design of the tunnelling shield. The front of the shield consists of 8 cutting edges whose position could be altered independently (Figure 5-17). These cutting edges are fixed by bolts placed in a sleeve (Figure 5-18a) in which the edges can, after having unscrewed these bolts, move forward or backward. Steel plates between the cutting edges and the shield help keeping the cutting edges in place during excavation (Figure 5-18b).

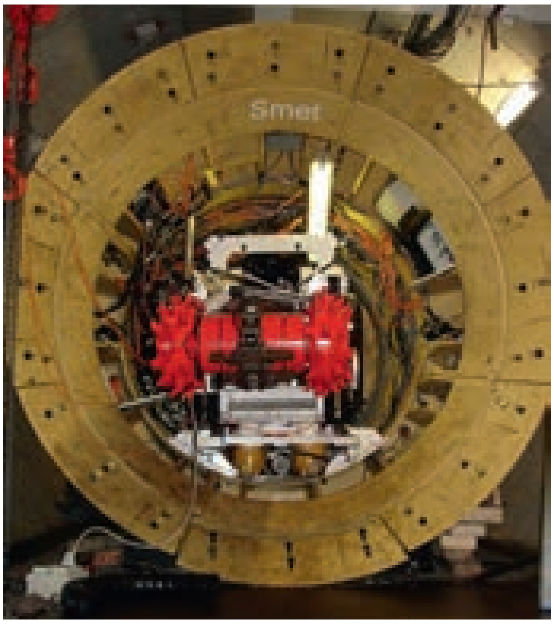


Figure 5-17: The shield consists of 8 cutting edges whose position can be changed independently.

Figure 5-18: (a) The cutting edges can move forward and backward in a sleeve; (b) steel plates are placed between the cutting edges and the shield to prevent the cutting edges moving back.

The relationship between the thickness of the inserted steel plates and the oversize is given in Table 5.1. The maximum additional overexcavation that can be achieved is 51 mm on diameter.

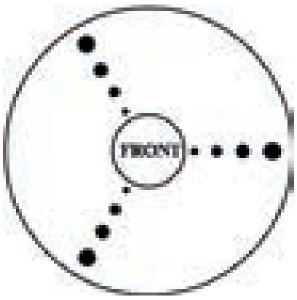
thickness steel plates [mm]	additional overexcavation [mm on diameter]
10	8
20	17
30	25
40	34
50	42
60	51

Table 5.1: Achieved additional overexcavation in relation to the thickness of the steel plates placed between the cutting edges and the shield.

The convergence that occurs in the unsupported zone behind the shield was estimated at 8 to 15 mm on diameter [11]. Therefore the diameter of the shield was increased by 20 mm. To reduce the friction between the shield and the clay, the tunnelling shield was made slightly conical (10 mm on diameter) (Figure 2-11) and coated with a Teflon-based paint (e.g. AMERCOAT).

12 small openings in the shield were provided to enable the measurement of the convergence of the clay around the shield. The openings are grouped into three sections, 120° apart, and located at an axial distance of respectively 500, 910, 1320 and 1730 mm from the rear end of the shield. A schematic overview of this configuration and a picture of one line of openings are shown in Figure 5-19. Optical laser distance sensors continuously measured the distance to the clay formation. The position and the roll of the shield were determined by a tachymeter placed in the Connecting gallery in front of the entrance of the PRACLAY gallery and mirrors placed on the tunnelling shield. Also the thrust forces and the stroke of the hydraulic jacks were measured. In summary, the following parameters were continuously monitored and recorded every 30 seconds:

- date, time, ring number and excavated distance
- horizontal and vertical deviation from the theoretical gallery axis
- roll of the shield
- convergence of the clay around the shield
- thrust pressures in the hydraulic jacks
- stroke of the hydraulic jacks

a


b


Figure 5-19: Openings in the shield to measure the convergence of the clay.

The concrete wedge blocks of the lining are placed using the circular erector behind the shield (Figure 5-20).


a


b

Figure 5-20: Circular erector for the placement of the segment blocks.

Prior to being transported to the underground laboratory, all tunnelling equipment (shield, roadheader, erector, rail tracks and hydraulics) was assembled on the surface to check all the functions and the geometry of the machinery, separately and as a whole, and to provide an opportunity to make the necessary adjustments prior to starting the work. The test assembly was particularly essential, as the limited volume of the Connecting gallery was going to make underground assembly of the tunnelling machine one of the most difficult steps of the project. Important tests were the manipulation of a lining segment and the insertion of a key into the corresponding pocket of the shield.

The assembly of the tunnelling machine was checked and approved by EURIDICE on 24.05.2007 (Figure 5-21).

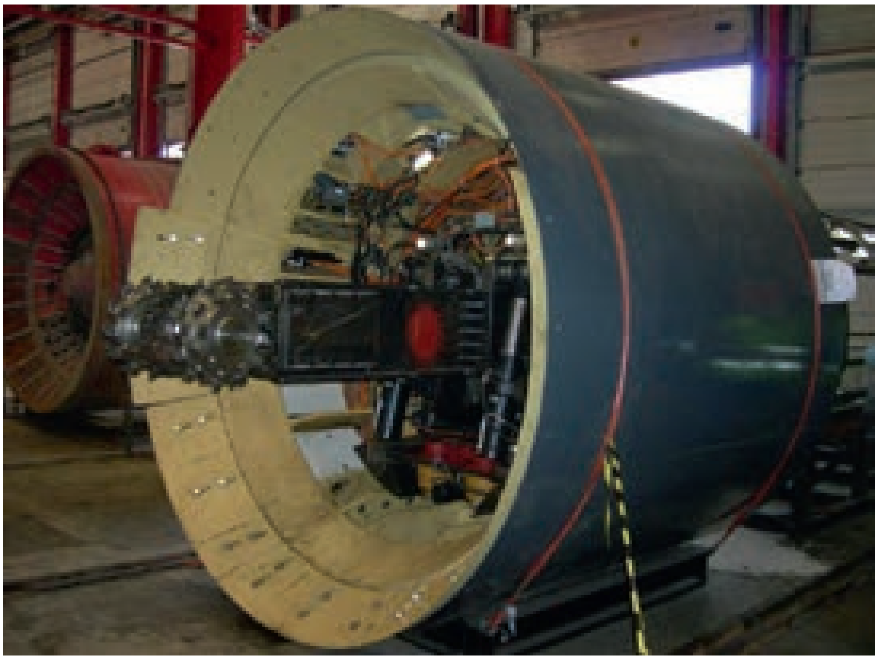


Figure 5-21: On-surface test assembly of the tunnelling machine.

5.2. Construction work

The construction of the PRACLAY gallery can be divided into two consecutive phases:

- placement of the reinforcement ring and assembly of the tunnelling machine;
- excavation and construction of the gallery

Besides these phases, the assembly of the lining for the hydraulic seal, the stop-and-go test and the excavation of the end plug are described separately. The main problems encountered during the construction work are listed at the end of this section.

5.2.1 PLACEMENT OF THE REINFORCEMENT RING AND ASSEMBLY OF THE TUNNELLING MACHINE

The reinforcement ring was assembled underground between 02.08.2007 and 14.08.2007 (Figure 5-22). Once the structure was assembled, security bolts were placed fixing the lining of the Connecting gallery to the reinforcement ring. This ensured that the remaining parts of the lining of the Connecting gallery stayed in place once the opening for the PRACLAY gallery was made. After the safety bolts were placed, the annular space between the structure and the gallery lining – ranging from 0.1 cm to several centimetres – was filled with grout to ensure a good load transfer of the host rock on the structure.

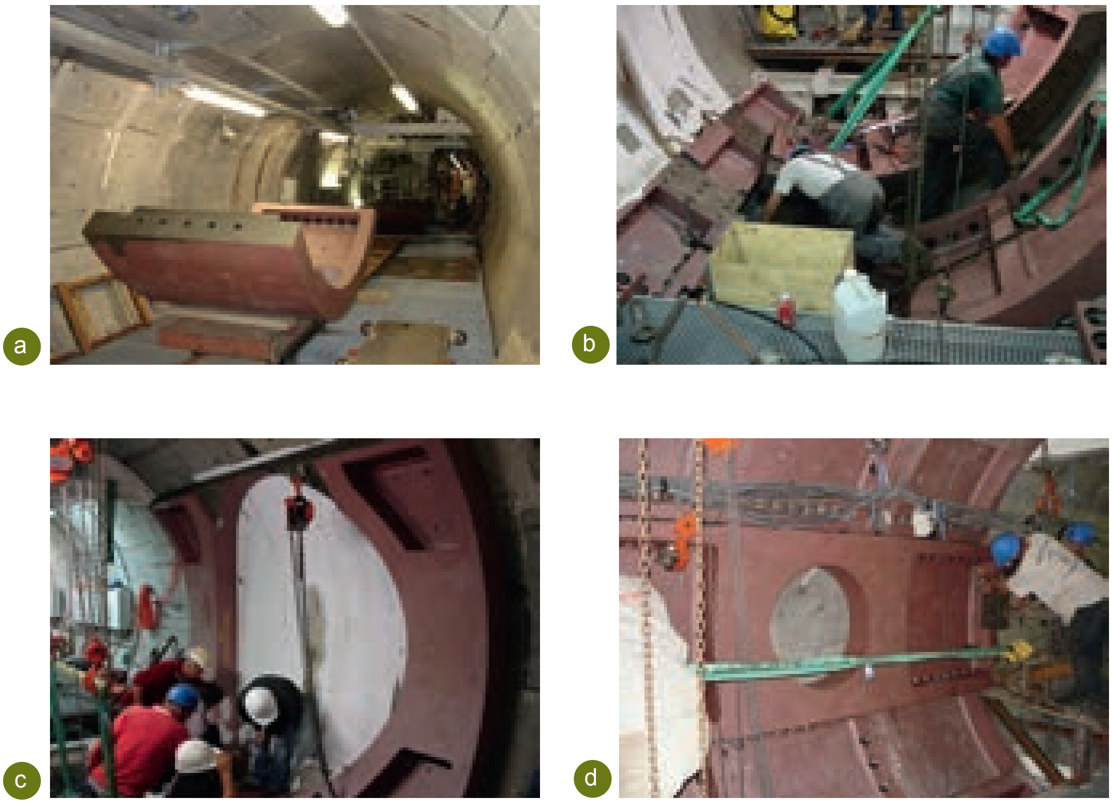


Figure 5-22: Underground assembly of the reinforcement ring.

The tunnelling machine was reassembled underground between 28.08.2007 and 05.10.2007 (Figure 5-23). The shield was assembled on a 'cradle' parallel to the axis of the Connecting gallery.

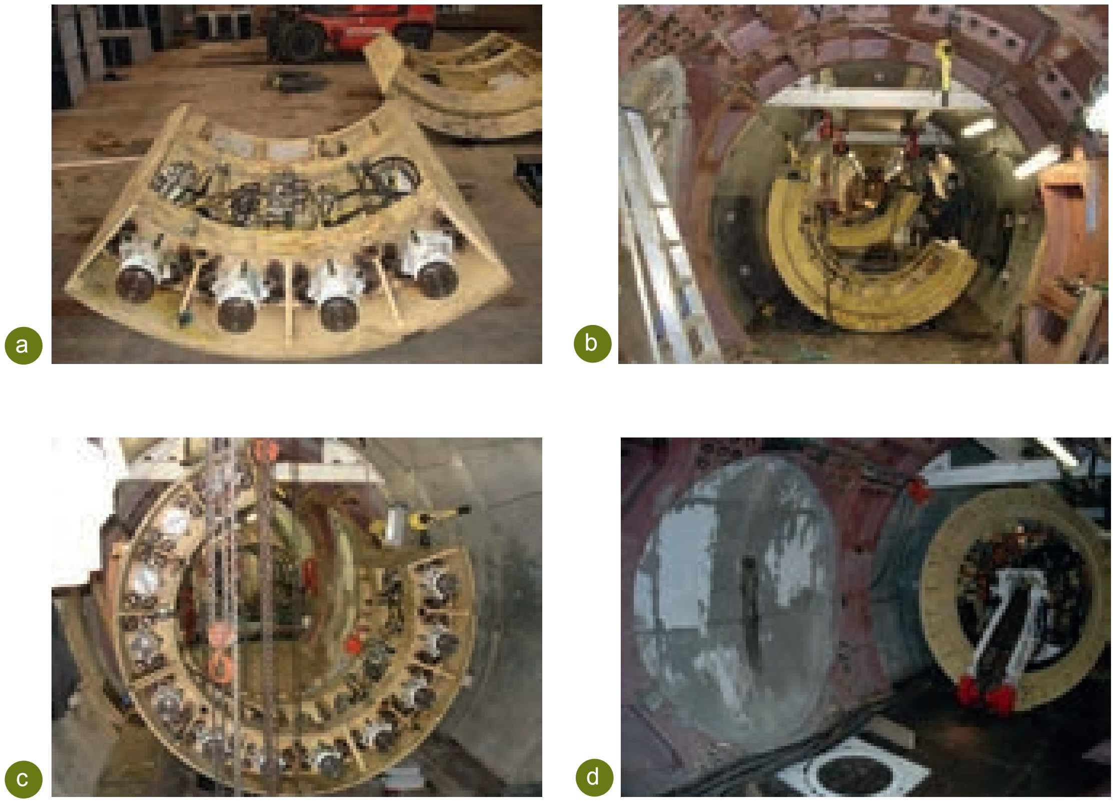


Figure 5-23: Assembly of the tunnelling machine.

On 01.10.2007 and 02.10.2007 the opening for the PRACLAY gallery was made in the eastern side of lining rings 32 to 34 of the Connecting gallery (Figure 5-24). The cradle carrying the machine was then positioned into the large opening of the reinforcement ring (Figure 5-25). The other parts of the equipment were installed stepwise during the start-up phase when the required space was made available.

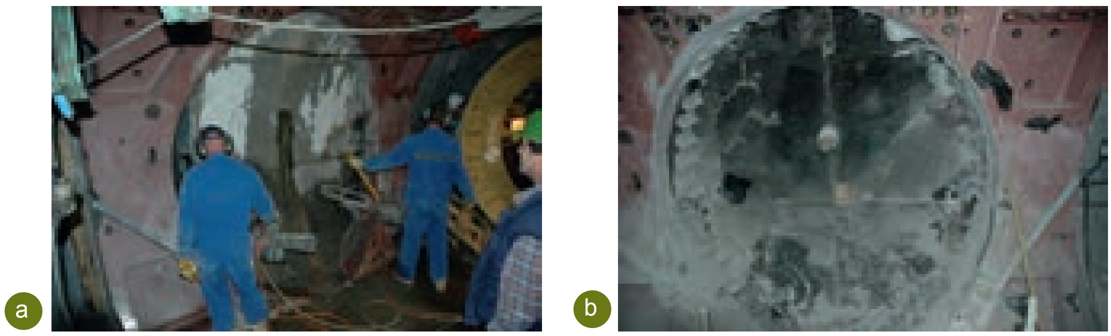


Figure 5-24: Cutting of the lining of the Connecting gallery
to make the opening for the PRACLAY gallery.

Figure 5-25: Positioning of the tunnelling machine into the large opening of the reinforcement ring.

The tunnelling shield was an open-face shield with hydraulic jacks to push the shield forward against the already installed lining. In the start-up phase, when there was no lining yet installed, a special structure was used to enable the pushing forward of the shield. This structure was built on 03.10.2007 and 04.10.2007 (Figure 5-26). The structure remained in place after the excavation work was finished (until the installation of the hydraulic seal; cf. part II of the report on the installation of the PRACLAY In-Situ Experiment – The hydraulic seal).

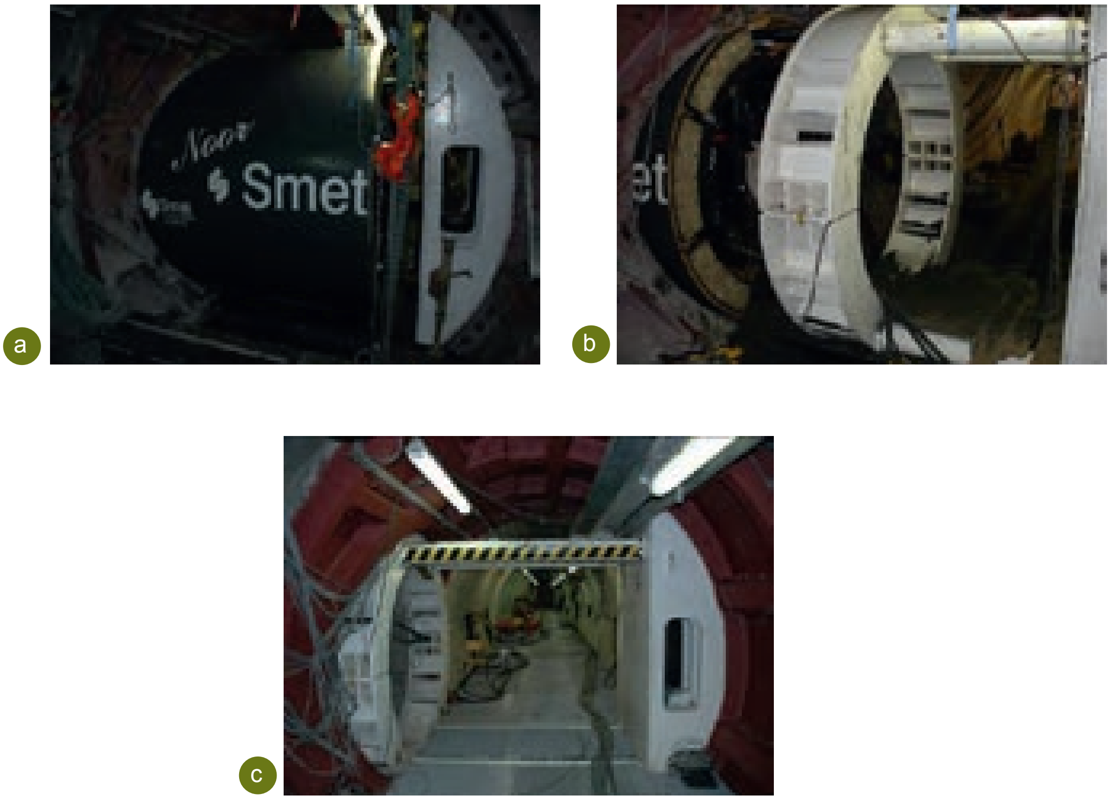


Figure 5-26: Structure against which the shield is pushed forward in the start-up phase.

5.2.2 CONSTRUCTION OF THE GALLERY

The construction of the PRACLAY gallery – 84 lining rings including the rings for the hydraulic seal – between 04.10.2007 and 06.11.2007 progressed more or less as expected. Apart from the start-up phase (i.e. the construction of the first 11 rings), the stop-and-go test and the construction of the lining at the hydraulic seal, a progress rate of 2 m/day, or 6 h/ring, was aimed for. From ring 15 on, the achieved construction rate complied in general with the target rate. Figure 5-27 shows the progress of the PRACLAY gallery construction. Rings 21 and 22 are the alternative rings for the hydraulic seal. As they differed from the other rings and were more complicated to fit, their construction time was longer. The peak at ring 67 was caused by a breakdown of the electric generator.

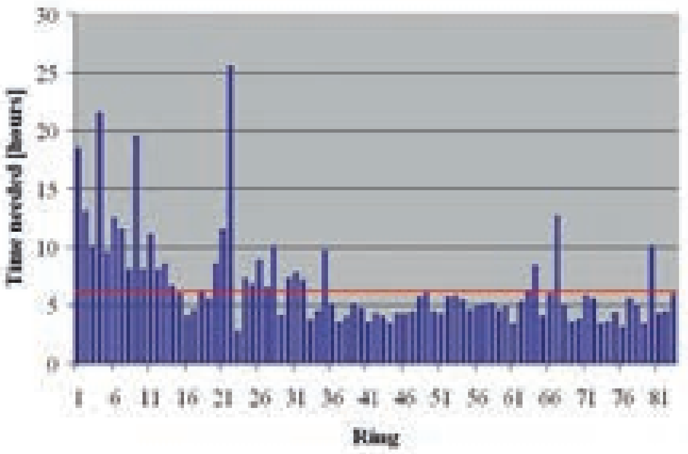


Figure 5-27: Excavation and construction time of the lining rings of the PRACLAY gallery (the red line marking the target progress of 6 h/ring).

The construction of the rings of the PRACLAY gallery proceeded according to the following sequence:

- *Excavation of the clay over a distance of half a metre*, the total length of the unsupported zone thus being 0.6 metres. This entails several iterations of the following three steps (Figure 5-28):
  - > excavation of the Boom Clay by the roadheader over a distance of ca. 20 cm, with simultaneous evacuation of the clay by the conveyor of the roadheader and direct loading into wagons that are pushed by hand on the rail tracks built at the rear of the tunnelling machine as it progresses;
  - > forward movement of the shield, pushed by the jacks on the already installed lining, with simultaneous smooth trimming of the excavated profile by the cutting edge, the cuttings falling onto the bottom of the gallery. The shield can be steered by the jacks;
  - > evacuation of the cuttings being scooped onto the head of the roadheader.

a

b

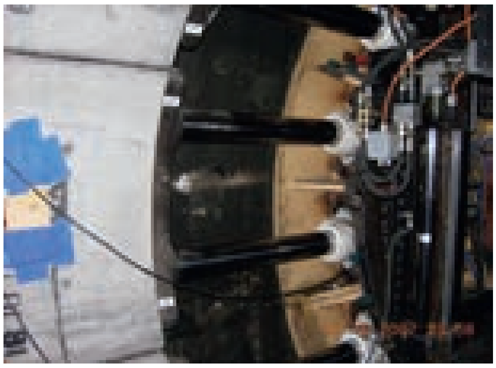


Figure 5-28: Excavation cycle: (a) drilling the clay front; (b) pushing the shield forward against the already built lining; (c) removal of the clay cuttings to the rear end of the tunnelling machine; (d) evacuation of the clay by wagons.

- *Measurements, observations and transport of the segments to the front* (Figure 5-29):
  - > measurements of the excavated diameter;
  - > taking pictures of the sidewalls and the excavation front to observe and measure the fractures induced;
  - > filling of the large cavities, if any, in the excavated profile with wood or polyethylene;
  - > transport of the segments to the rear of the tunnelling machine on purpose-built carts. These carts are pushed manually. The transport sequence of the segments has to match their placement sequence.

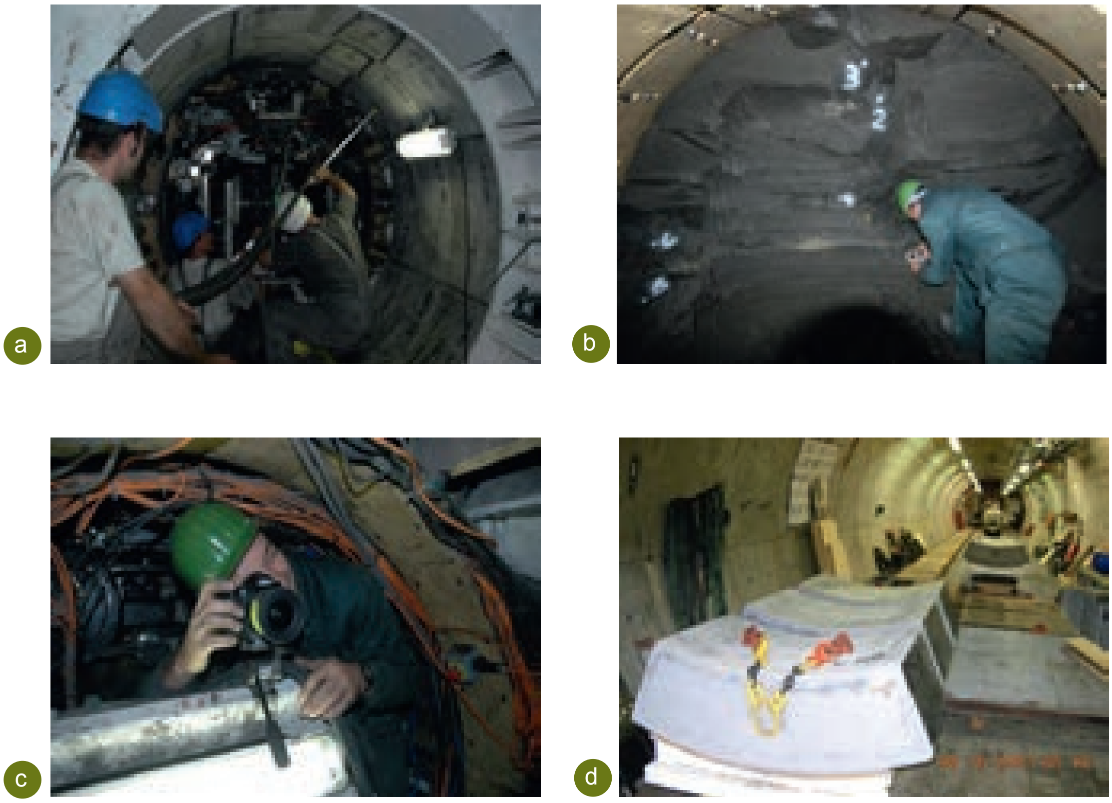


Figure 5-29: (a) Measuring the excavated diameter; (b) observations at the excavation front; (c) taking pictures of the excavation front; (d) transporting the segments to the front.

- *Placement of the segments* (see also Figure 5-3):
  - > segment 4 is brought to the erector at the back of the tunnelling shield by the cart and hoisting devices;
  - > placement of segment 4 by the erector on the bottom of the gallery and holding it in place against the corresponding segment of the previous ring by the thrust pressure of the jacks;
  - > repetition of these first two steps for segments 5, 6, 3, 7 and 2;
  - > pulling of the key (segment 9) in the pocket of the shield;
  - > placement of segments 8 and 1;
  - > insertion of the key into its final position, with expansion of the ring against the excavated clay profile. The contact surfaces of the key segment and the adjacent counter key segments have a helicoidal shape, ensuring correct positioning of the key segment as it is pushed into the ring (Figure 5-30).

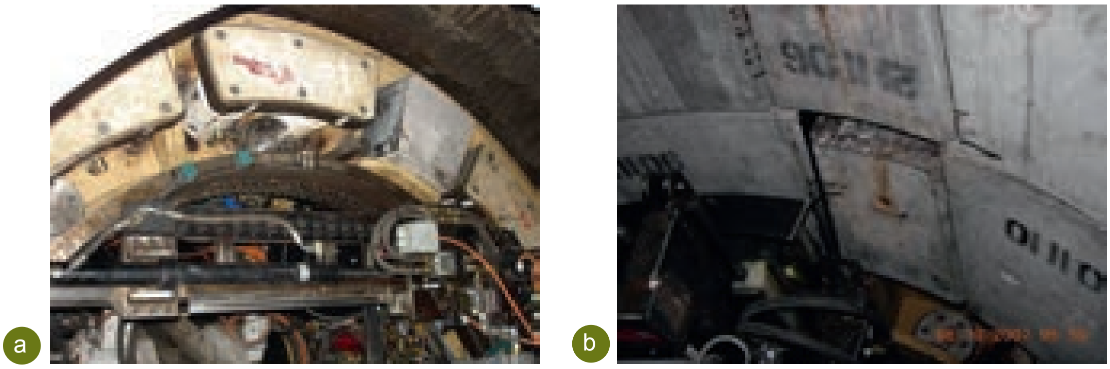


Figure 5-30: Insertion of the key segment: (a) the key segment is placed in a key holder in the tunnelling machine; (b) the key segment placed inside the lining ring.

When the excavation was started, all cutting edges were moved out over 60 mm. This corresponded to an additional overexcavation of 51 mm on diameter on top of the overexcavation of 30 mm on diameter resulting from the geometry of the shield (Figure 2-11). 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. In contrast, vertical convergence was 20 to 30 mm less than expected. As a consequence of the smaller vertical convergence, the overexcavation at the top and at the bottom was too large (Figure 5-31). Therefore the upper cutting edge was moved to 45 mm after the construction of ring 13. Overexcavation at the top and to a lower extent at the bottom still remained too large, however. The top cutting edge was further brought back to 30 mm and the lower cutting edge to 45 mm for the excavation of rings 33 to 81. By doing so the shield cut a slightly elliptical profile in order to end up with a more circular profile behind the shield. A more detailed discussion on the observed clay convergence can be found in section 6.3.

Figure 5-31: Gap between clay sidewall and lining ring 12 because of the excessively large overexcavation at the top.

The position of the tunnelling shield was continuously monitored by the tachymeter. Correcting the position of the shield and hence the excavation direction could be done to some extent only by pushing the shield forward with some jacks.

An information sheet containing the following data was filled in for all rings for traceability reasons:

- time of construction;
- information about the segments used (production date and mould);
- position and orientation of the ring;
- placement tolerances of the different segments;
- the diameter of the excavation and the ring.

Excavation of the PRACLAY gallery caused stress redistribution in the lining of the Connecting gallery next to the opening for the PRACLAY gallery. Two days after the start of the excavation work, a crack was observed in ring 31, adjacent to the reinforcement ring (Figure 5-32a). Four days later a crack in ring 30 was also noticed (Figure 5-32b). Neither of these cracks developed any further and no additional stability measures had to be taken. If the stress levels had become too high in the neighbouring lining rings, mitigating measures would have had to be taken. For this purpose, two 1 m wide steel reinforcement rings, constructed by PONCIN, were available on site (Figure 5-33). These rings were kept in stock underground during the excavation work to reduce reaction time in the event of a problem.

a b

Figure 5-32: Crack in the lining of the Connecting gallery after cutting the opening for the PRACLAY gallery: (a) ring 31; (b) ring 30.

Figure 5-33: Additional reinforcement rings.

5.2.3 INSTALLATION OF THE ALTERNATIVE LINING FOR THE HYDRAULIC SEAL

The lining where the hydraulic seal will be erected was constructed on 16.10.2007 and 17.10.2007 (Figure 5-34). The segments are different from ordinary concrete segments (cf. section 5.1.2.4) and were more difficult to fit. As a result their placement took significantly longer (approximately 36 hours for both rings, including the excavation time).

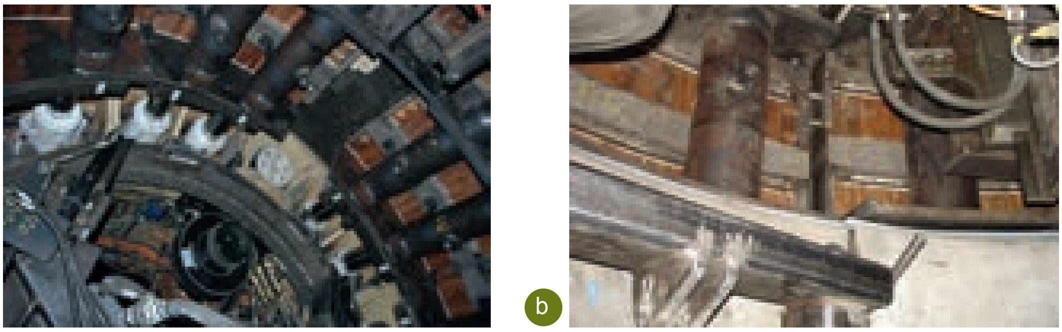


Figure 5-34: Assembly of the alternative lining at the location of the future hydraulic seal.

5.2.4 THE STOP-AND-GO TEST

On 30.10.2007, after the construction of ring 79, the excavation work was stopped. During any stand-still the friction between the clay and the tunnelling shield increases due to the convergence of the Boom Clay around the tunnelling shield. The purpose of the stop-and-go test was to test the level of difficulty restarting the tunnelling machine. To limit such difficulties, the shield was given a slightly conical shape and had a Teflon-based coating.

The excavation front was stabilised during the stop-and-go test using six 8-metre glass-fibre anchors (Figure 5-35). The boreholes for the anchors were drilled manually using a pneumatic drill mounted on a carriage. The anchors were then placed in the boreholes, which were subsequently injected with a resin to ensure good contact between the clay and the anchor. The drilling of the boreholes took longer than expected, mainly because the open surface of the drillhead was too small to efficiently remove the cuttings. The drillhead was therefore replaced by a more open drillhead, through which the cuttings could be removed more rapidly. Should the anchors have proved insufficient, the use of shotcrete was planned as an additional measure to stabilise the front. This was not necessary, however.

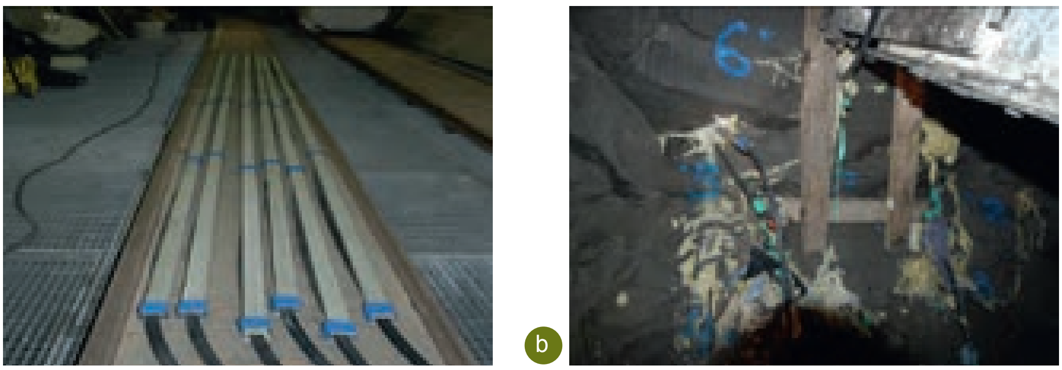


Figure 5-35: Anchors (a) were installed during the stop-and-go test to stabilise the excavation front (b).

One week later, on 06.11.2007, the excavation work resumed. The thrust force needed to push the shield forward was about twice the normal thrust force (cf. section 6.5). This was still only ~25% of the maximum available force.

5.2.5 CONSTRUCTION OF THE END PLUG

Upon completion of the excavation work, the tunnelling shield remained in place and all recoverable components were removed. The diameter of the end plug was designed to be 1 m larger than the diameter of the PRACLAY gallery (cf. section 2.3.5). To achieve this, the roadheader was extended to reach a wider excavation area (Figure 5-36).

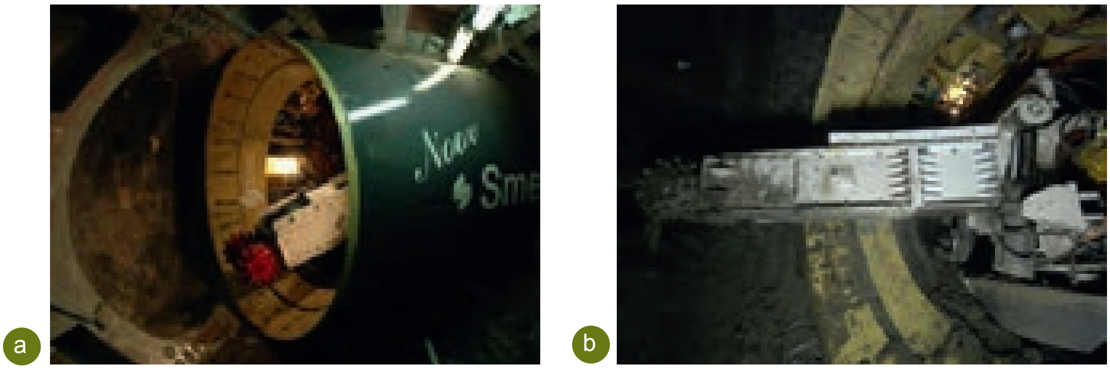


Figure 5-36: To achieve the larger excavated diameter of the end plug, the roadheader was extended: (a) picture of the roadheader at the beginning of the excavation work; (b) picture of the extended roadheader.

Once the final face was excavated, the excavation front was reinforced with a steel mesh (150x150 mm, Ø12 mm), which was subsequently shotcreted with C30/37 concrete (Figure 5-37). Then a 250 mm thick wall consisting of compressive blocks was built in front of the tunnelling shield. The purpose of the compressive wall is to allow some axial movement of the plug without influencing the PRACLAY gallery itself (cf. section 2.3.5). The compressive material is held together by a 10 mm thick steel plate, supported by steel profiles (HEB 100) (Figure 5-39). In the centre of the wall a tube was placed for the subsequent installation of a piezometer (Figure 5-38). Before finishing the complete construction of the compressive wall, the space behind the wall was filled with concrete (Figure 5-40).

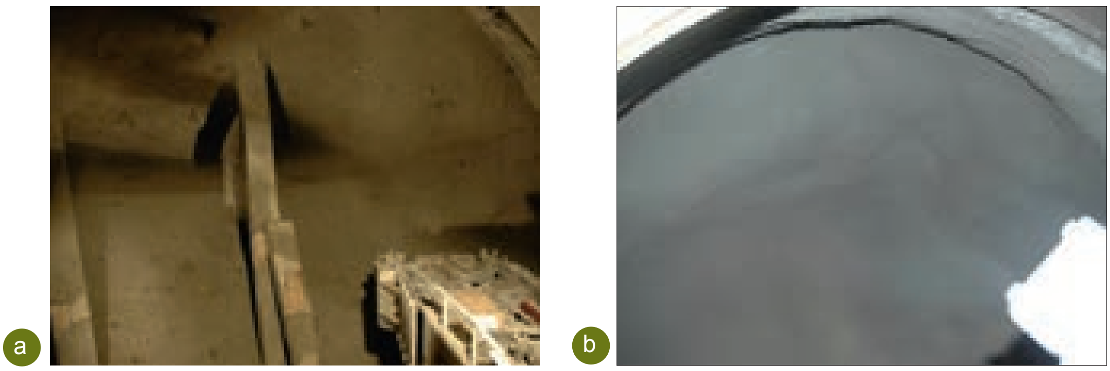


Figure 5-37: The final front was reinforced with a steel mesh (a) and shotcreted (b).

Figure 5-38: A wall of compressive blocks was built and the space behind it filled with concrete. A tube was placed in the centre for the subsequent installation of an instrumented borehole.

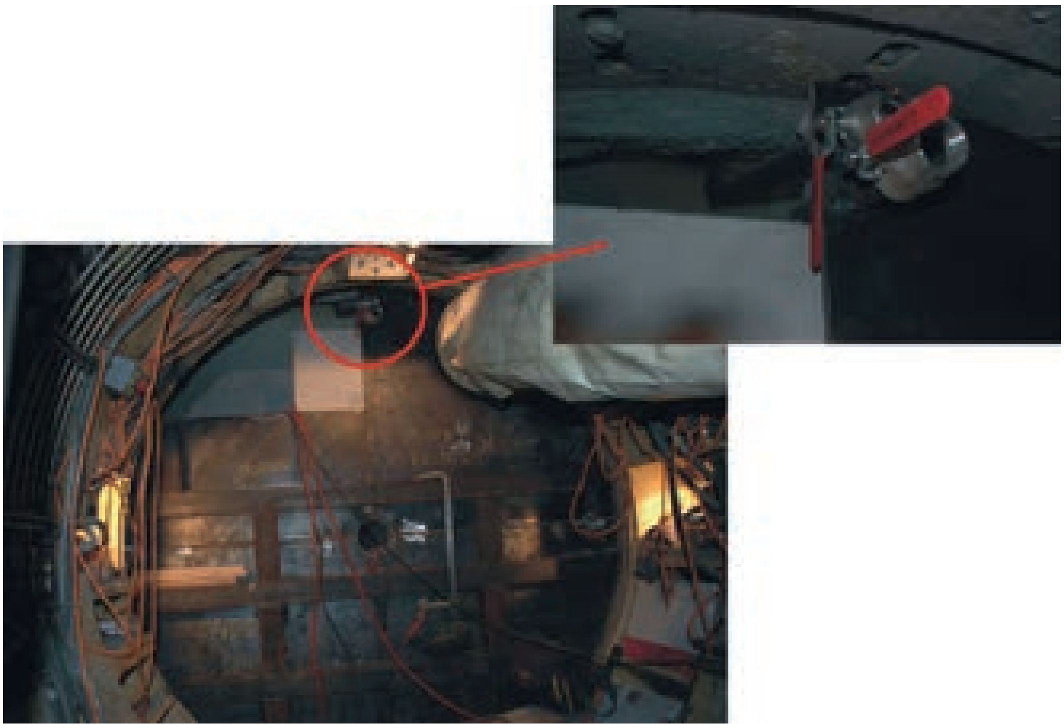


Figure 5-39: Reinforcement structure with tap on top to inject the last concrete.

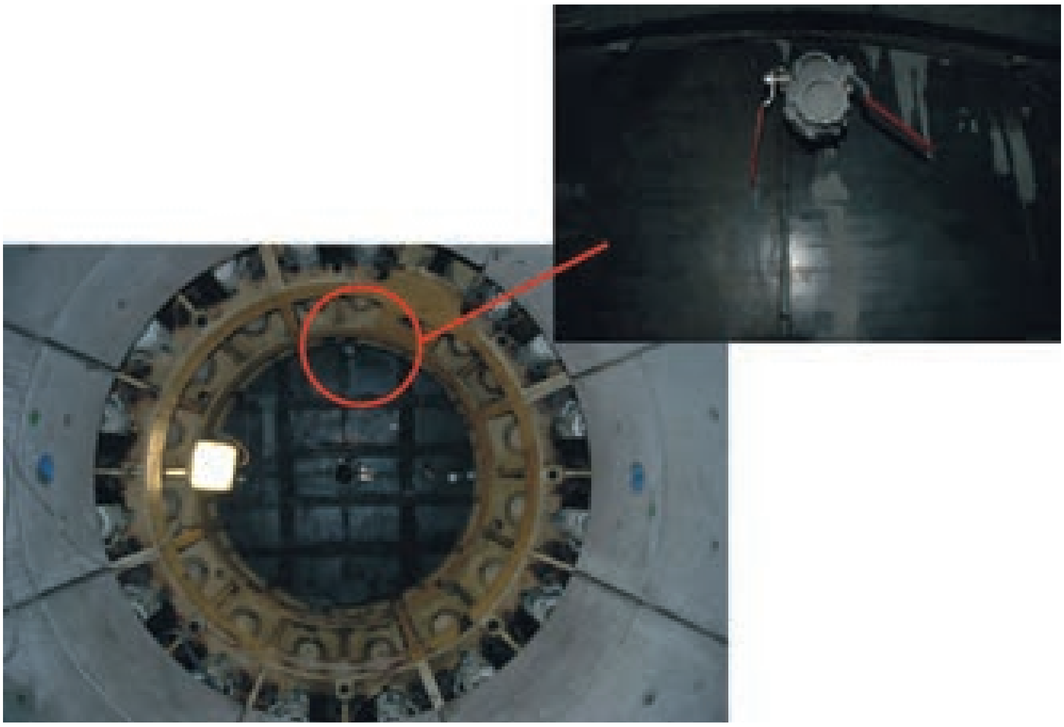


Figure 5-40: Abandoned shield and the reinforcement structure of the end plug with the tap through which the space behind the structure is filled with concrete.

5.3. Problems encountered and their solutions

Most of the problems encountered during the construction of the PRACLAY gallery were satisfactorily remedied on the spot. For other problems, suggestions for future excavations are given.

The following problems linked to the tunnelling machine were encountered:

- *Difficulties retracting the anti-roll system of the shield* during excavation. The anti-roll system, consisting of two fins that could protrude from the shield (Figure 5-41), was used after the stop-and-go test to test its functionality. For this purpose, the left fin was pulled out. However, automatically retracting the fin, as planned, turned out to be impossible and the fin had to be pushed back in manually.
  Suggested remedy:
  > using a stronger system to handle the fins

Figure 5-41: Anti-roll system of the shield.

- *Adjusting the position of the cutting edges to increase or decrease overexcavation was performed manually and was difficult.* To adjust overexcavation, the position of the cutting edges had to be changed. This was done manually by unscrewing the bolts in the cutting edges, moving the cutting edges and re-tightening the bolts. To be able to move the cutting edges forward, the clay in front had to be removed and this was also done manually. During this operation, workers had to come close to the front, which is better avoided because of the risk of falling clay blocks in the excavation front.
  Suggested remedy:
  > incorporating an automated system to adjust the position of the cutting edges

- *The action radius of the roadheader was too wide.* The roadheader sometimes excavated outside the design diameter, resulting in undesirable overexcavation (Figure 5-42).
  Suggested remedy:
  > automatically limiting the action radius of the roadheader

Figure 5-42: Excessively large overexcavation due to the action radius of the roadheader being too wide.

- *Measuring the convergence of the host rock around the tunnelling shield did not go well.* The openings in the shield through which the convergence of the host rock was measured got obstructed by clay particles and hence the convergence measurements often gave poor results.
  Suggested remedy:
  > facilitating the inspection and cleaning of the holes through which the convergence is measured

- *Mechanical problems and delays due to the small excavation diameter.* The small excavation diameter limited the space for equipment and personnel. This regularly resulted in delays (e.g. oil leakage due to broken hoses). Rectifying these problems also turned out to be more complicated and time-consuming because of the limited working space.

The following problems linked to the lining were encountered:

- Squeezing out of the key segment by the neighbouring segments
  Remedy:
  > fixing the key using wooden wedges placed between the key and the neighbouring segments

The following problems linked to the clay formation were experienced:

- *Safety and construction issue due to clay blocks falling from the formation.* Excavation-induced fractures (cf. section 6.2) caused blocks of clay to fall out of the excavation front and the sidewalls (Figure 5-43), thereby creating cavities in the roof and sidewalls. Relatively little fallout was encountered, certainly compared to the construction of the Connecting gallery. This was mainly because the excavation diameter was much smaller (2.5 m compared to 4.8 m).
  Remedy:
  > excavating the upper part of the front before its lower part, which reduced the number of blocks coming off and, consequently, the number of cavities;
  > removing loose blocks;
  > limiting the time workers had to be near the front to the strict minimum.

Figure 5-43: Risk of clay block coming off the excavation front.

5.4. Safety aspects

To minimise and/or control the risks associated with the underground construction work, special requirements and instructions were imposed by the authorities in charge of the supervision of underground activities, namely the Ministry of Work and Employment. In practice, it was the responsibility of the safety officer to take all the necessary measures to ensure safety.

The main safety issues related to the construction of the PRACLAY gallery and the measures taken in this respect were the following:

- risks associated with transports in the shaft:
  > ban on the simultaneous transport of persons and heavy materials in the shaft;
  > compulsory use of trapdoors in the lift cage for the transport of personnel;
  > use of a special double-locking system in the lift (one in the floor and one at both exits) for the transport of the wagons meant for carrying the clay blocks and for the transport of the carts meant for carrying the lining segments;
  > request not to fill the wagons above their edge, to avoid any risk of pieces falling out during transport;

- risks associated with the assembly of the reinforcement ring and shield, where all parts had to be assembled from the inside. Above ground they could be assembled from the outside using a forklift or a jenny:
  - > development of an assembly scenario based on the experience gained during the test assembly on the surface and illustration with a full storyboard instructing the underground workers;

- risks associated with falling clay blocks, either from the front or from the unsupported zone:
  - > regular detailed inspections of the front, with removal of all unstable clay blocks, and constant inspection during interventions close to the front in order to call the workers back in time should there be any doubt about its stability;
  - > reinforcement of the front during the stop-and-go test with anchors (Figure 5-35).

Because of the limited working space in the PRACLAY gallery, the workers were allowed to wear a safety cap instead of a safety helmet.

6. Measurements and observations related to the construction of the PRACLAY gallery

Several measurements were carried out before, during and after the excavation of the PRACLAY gallery. They aimed to gain as much information as possible on the performance of the excavation technique, the behaviour of the Boom Clay and the impact of the excavation on the clay. This information was gained through observations and measurements of the clay, the lining and the tunnelling machine. Together with the modelling work that was and still is being performed, these data contribute to a better understanding of the behaviour of the Boom Clay formation and to improve the tunnelling technique.

The instrumentation programme (see also section 2.5) consisted of:

- measurements in the clay
  - multifilter piezometers (pore water pressure) and total pressure cells (flatjacks and/or biaxial stress meters) located in boreholes in the clay formation
  - 3 boreholes for seismic measurements
  - 1 borehole containing an inclinometer (displacement)

- measurements on the reinforcement ring and on the lining of the Connecting gallery near the opening of the PRACLAY gallery
  - strain gauges

- measurements in the lining of the PRACLAY gallery
  - embedded strain gauges
  - external pressure and segment load cells
  - thermocouples
  - corrosion samples
  - seismic sensors

- measurements and observations during or related to the excavation
  - position and orientation of the shield
  - convergence of the host rock
  - pressures and stroke of the hydraulic jacks
  - position of the lining segments
  - observations of the sidewalls and the excavation front including 3D pictures of the front.

This chapter presents the measurements and observations related to the excavation of the PRACLAY gallery.

6.1. Stress and pore water pressure measurements

The hydromechanical response of the Boom Clay is monitored and characterised by means of instrumentation around the PRACLAY gallery and instrumentation embedded in the gallery lining. Pore water pressures are measured using piezometers located along several boreholes (P30E, P33Id, P35E, P38E, P42E and P49E) (Figure 2-12). Total stresses in the clay are measured using flatjacks placed in boreholes P30E and P42E. Furthermore strain gauges in the lining segments of rings R0, R10, R45, R60 and R77, pressure cells at the lining extrados and load cells inside lining rings R12, R46 and R78 give information on the stresses in and on the gallery lining. The instrumented lining segments are shown in Figure 2-13. Strain gauges are also placed on and around the steel reinforcement ring.

First the stress change in the reinforcement ring is discussed. Then the hydromechanical response of the Boom Clay is presented and finally the stress evolution on and in the lining of the PRACLAY gallery is discussed.

6.1.1 STRESS INCREASE IN THE REINFORCEMENT RING

Strain gauges are placed on the steel reinforcement ring and on the lining of the Connecting gallery adjacent to the reinforcement ring (Figure 6-1a). On the reinforcement ring the strain gauges are all placed in a rectangular rosette configuration (at each location 3 strain gauges are placed together at an angle of 45° from each other) (Figure 6-1b).

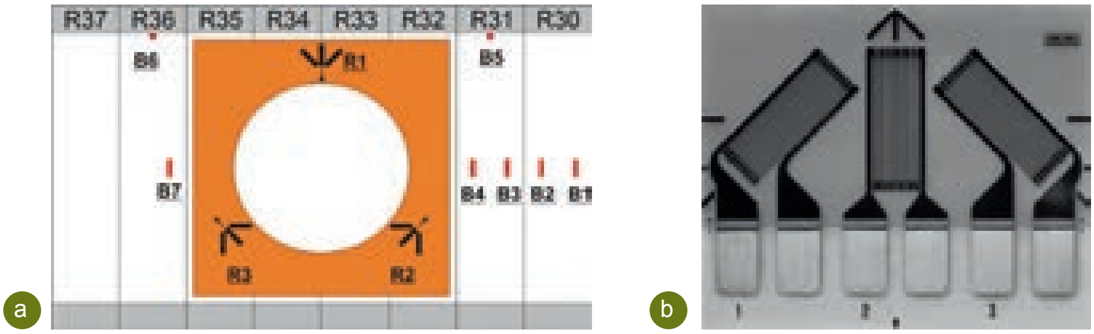


Figure 6-1: (a) Strain gauges on the steel reinforcement ring and the lining of the Connecting gallery around the opening for the PRACLAY gallery; (b) Rectangular rosette configuration of the strain gauges placed on the reinforcement ring.

Figure 6-2 shows the stress change measured by the strain gauges placed on the reinforcement ring. A clear change in stresses can be observed on 01.10.2007 when the lining of the Connecting gallery was cut (Figure 5-24). A second abrupt change occurs as the excavation starts on 04.10.2007. By the end of the excavation work the stresses in the steel reinforcement ring are stabilised.

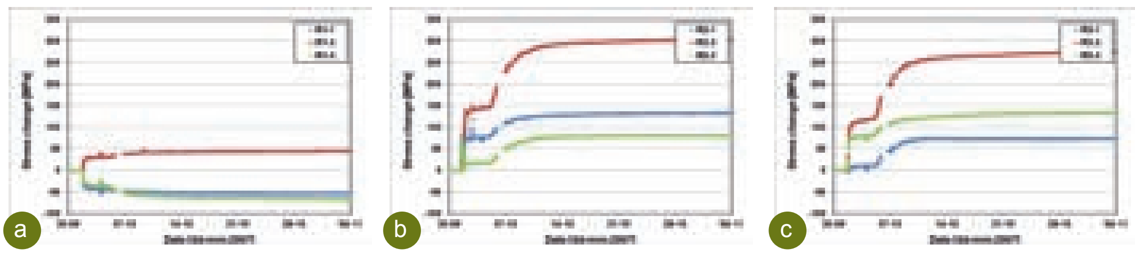


Figure 6-2: Stress variation (a positive sign is an increase in compressive stress) in the steel reinforcement ring as measured by the strain gauges: (a) rosette R1, (b) rosette R2 and (c) rosette R3.

Based on these measurements, the principal stresses around the reinforcement ring induced by the gallery excavation were calculated. Figure 6-3 shows these stresses at the end of the excavation of the PRACLAY gallery. These measurements are consistent with the stresses around an opening in a plate that is subjected to a compressive stress in one direction. Figure 6-4 shows these stresses around an opening obtained by modelling.

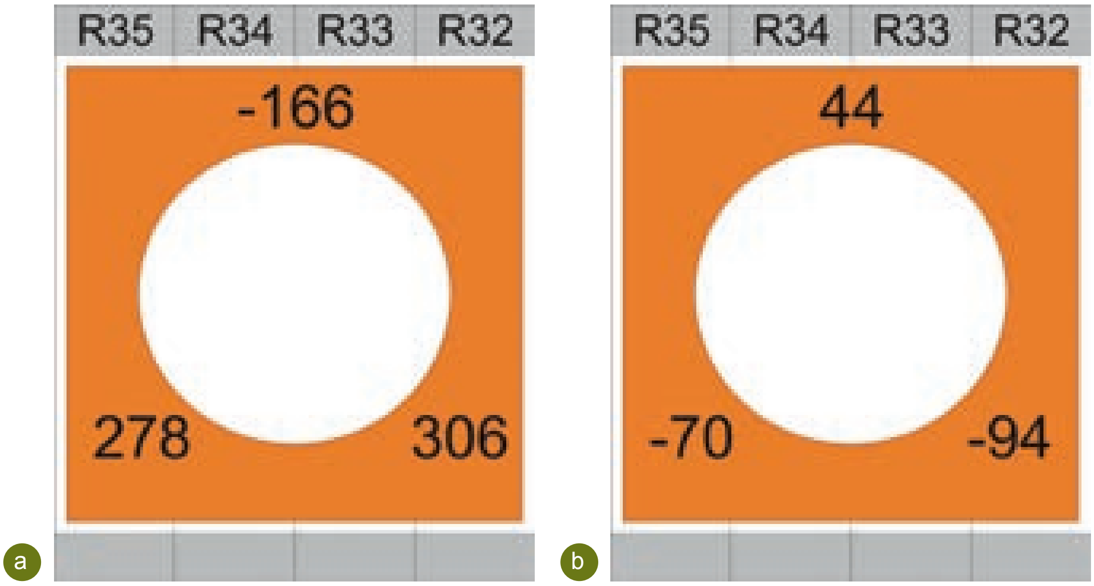


Figure 6-3: Stresses around the reinforcement ring after the excavation of the PRACLAY gallery (positive values indicate compressive stress; negative values indicate tensile stress): (a) tangential; (b) radial.

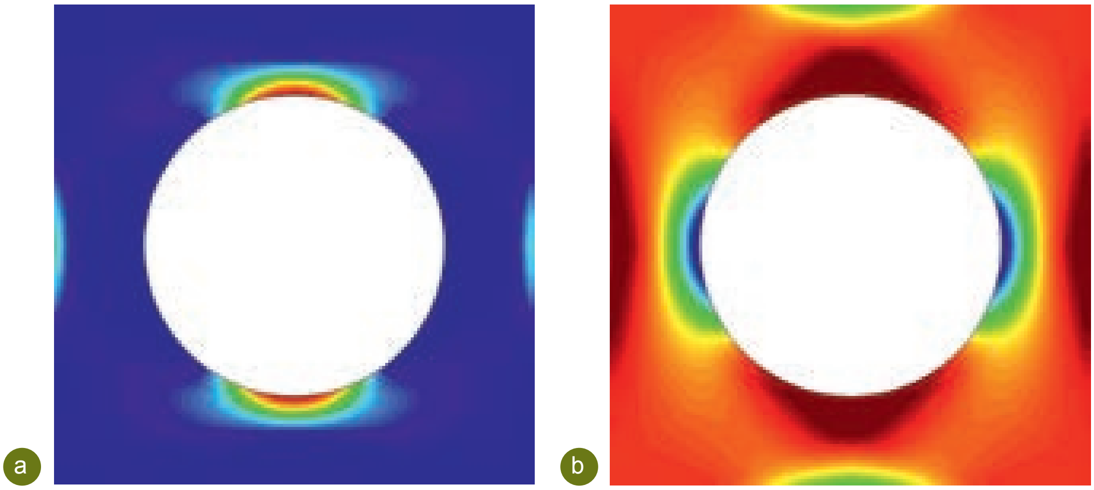


Figure 6-4: Modelled stresses around an opening in a plate subjected to compressive stress in one direction (vertical): (a) principal minimum (tensional) stress; (b) principal maximum (compressive) stress.

Figure 6-5 shows the stress change measured by the strain gauges on the lining rings of the Connecting gallery adjacent to the reinforcement ring.

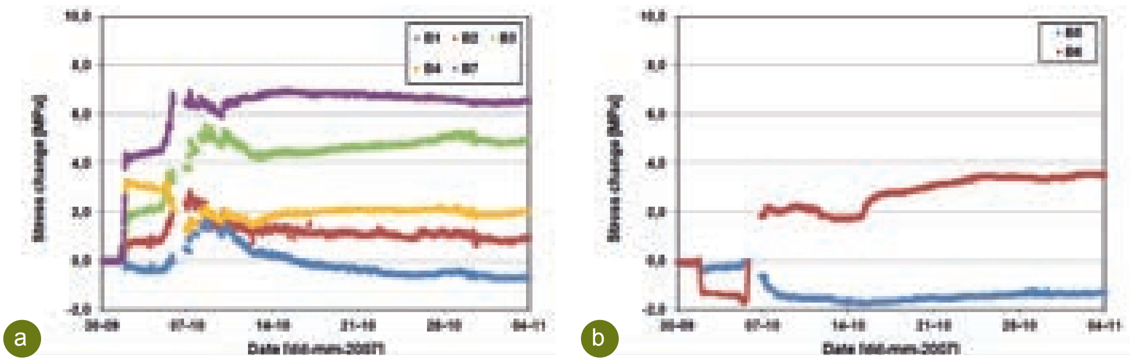


Figure 6-5: Stress variation (a positive sign is an increase in compressive stress) in the lining rings of the Connecting gallery adjacent to the steel reinforcement ring as measured by the strain gauges: (a) strain gauges B1, B2, B3, B4 and B7 at mid height of the Connecting gallery, (b) strain gauges B5 and B6 at the top of the Connecting gallery.

The strain gauges at mid height measure a stress increase on 01.10.2007 (cutting of the lining of the Connecting gallery), as do the strain gauges on the reinforcement ring. This increase is bigger for the strain gauges placed closer to the reinforcement ring. A second increase in the measured stresses can be observed on 06.10.2007 (start excavation) except for strain gauge B4, which measures a decrease in stress. Two days after the start of the excavation a crack was observed in ring 31 (same ring as strain gauges B3, B4 and B5), adjacent to the reinforcement ring (Figure 5-32a). Four days later a crack in ring 30 (above strain gauges B1 and B2) was also noticed (Figure 5-32b). After 07.10.2007 (building first ring of the PRACLAY gallery; excavation progress: ca. 3 m) all strain gauges reveal a decrease in stresses, after which the stresses evolve towards stabilisation.

The stress evolution measured by strain gauges B5 and B6 placed on top of the Connecting gallery is less straightforward. A stress decrease can be observed in strain gauge B6 on 01.10.2007 (cutting of the lining of the Connecting gallery). No significant change in stress is measured by strain gauge B5. On 04.10.2007 (start excavation) a very small additional decrease is measured by strain gauge B6 and on 05.10.2007 a gradual decrease is observed by strain gauge B5 and an abrupt increase by strain gauge B6.

6.1.2 HYDROMECHANICAL RESPONSE OF THE CLAY TO THE EXCAVATION

The stress and pore water pressure response in the clay to the gallery excavation was measured by flatjacks and piezometers placed in the clay. Some representative stress and pore water pressure measurements are presented here. Figure 6-6 shows the location of these flatjacks and piezometers.

Figure 6-6: Piezometers and flatjacks are installed in boreholes drilled from the Connecting gallery. The piezometers and flatjacks from which the measurements are here presented are marked by red circles and green squares respectively.

The stress response of the clay to the excavation measured by the flatjacks in boreholes P30 and P42 is shown in Figure 6-7. The flatjacks in borehole P30 are placed ca. 2.75 m below the PRACLAY gallery extrados, while the flatjacks in borehole P42E are placed next to the gallery, in a horizontal plane, at a distance of ca. 6.75 m from the gallery extrados. A drop in stresses is measured in P30E before the start of the excavation. This is due to the extraction of pore water in neighbouring filters for chemical analysis of the pore water.

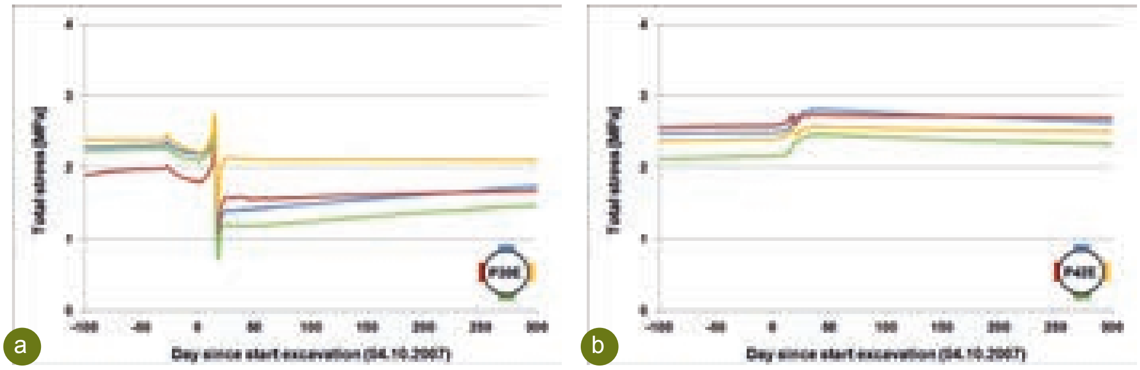
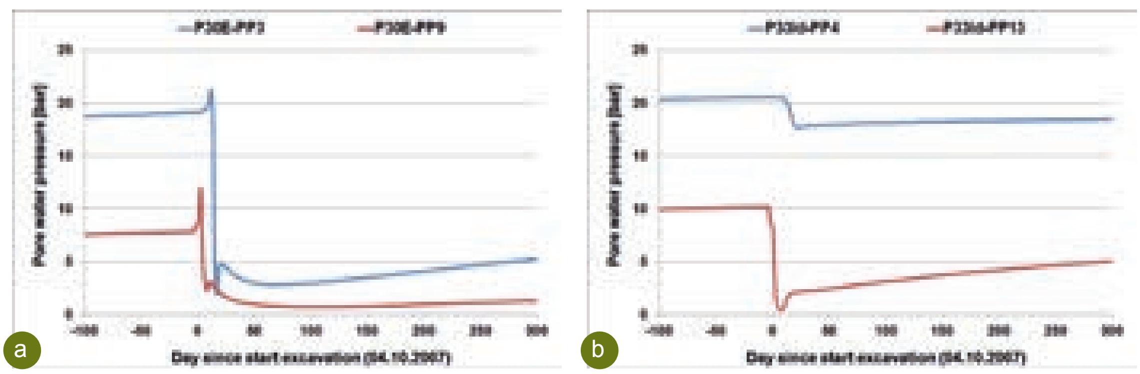


Figure 6-7: Total stress measured in boreholes (a) P30E (2.75 m below the PRACLAY gallery extrados; 26 m from the Connecting gallery extrados) and (b) P42E (6.75 m from the PRACLAY gallery extrados; 33 m from the Connecting gallery extrados).

All flatjacks observe a stress increase as the excavation front approaches, followed by a sudden decrease in stress as the excavation front passes by. These changes are more pronounced for the flatjacks in borehole P30E, which is closer to the gallery. The decrease in stresses results in dilatation of the clay and instantaneous convergence of the clay towards the opening. In addition to this instantaneous convergence, a time-dependent convergence results from the consolidation and creep behaviour of the clay (cf. section 6.3). Once the lining is placed, further convergence of the clay is prevented, and creep and consolidation of the clay occurs.

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 6-8 shows the pore water pressure measured at several distances from the PRACLAY gallery and at a distance of 4 m and 20 m respectively from the Connecting gallery. Except for piezometers P33Id-PP13, P30E-PP3 and P33Id-PP4, which lie below the PRACLAY gallery, all piezometers lie in a horizontal plane (or quasi-horizontal for P30E-PP9) along the axis of the PRACLAY gallery.



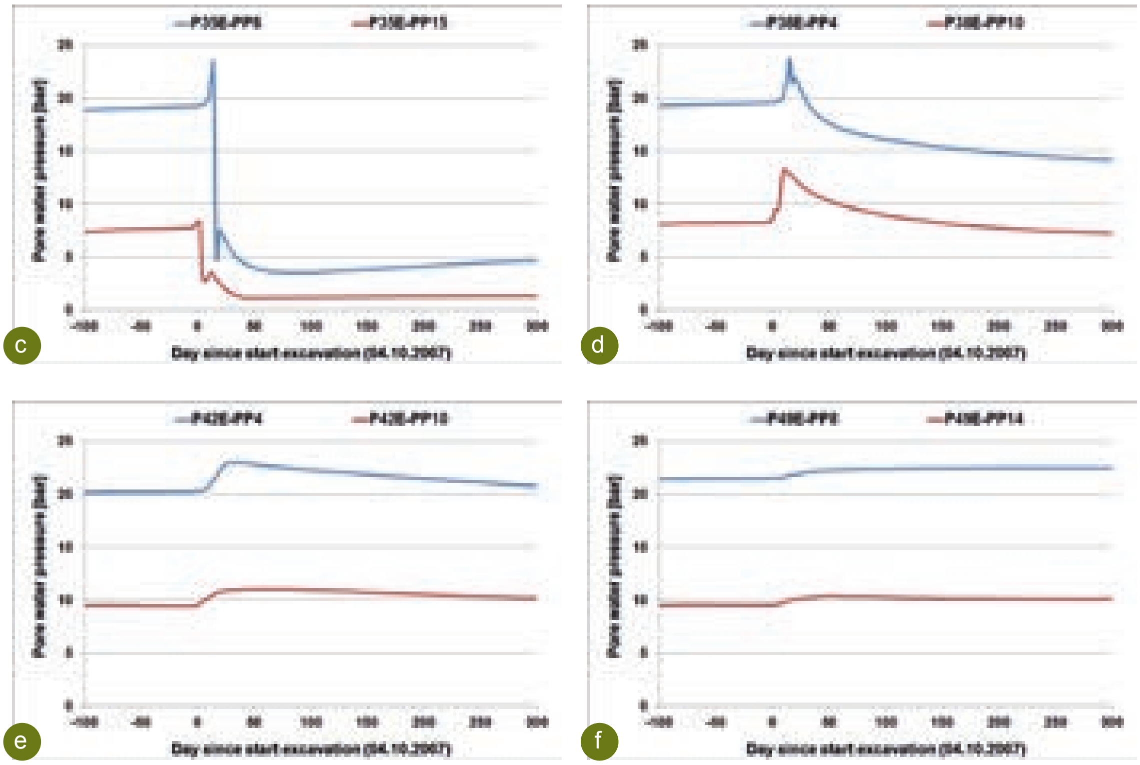


Figure 6-8: Pore water pressure measurements
(blue curve: ca. 20 m from extrados Connecting gallery; red curve: ca. 4 m from extrados Connecting gallery) (the distance to PRACLAY gallery extrados is mentioned in brackets): (a) P30E-PP3 (ca. 1.15 m below) and P30E-PP9 (ca. 1.25 m); (b) P33Id-PP4 (ca. 20 m below; horizontal distance to the extrados of the Connecting gallery is ca. 20 m, the total distance to the extrados of the Connecting gallery, however, is ca. 30 m) and P33Id-PP13 (ca. 2.85 m below); (c) P35E-PP8 and P35E-PP15 (both ca. 0.75 m); (d) P38E-PP4 and P38E-PP10 (both ca. 2.75 m); (e) P42E-PP4 and P42E-PP10 (both ca. 6.75 m); (f) P49E-PP8 and P49E-PP14 (both ca. 13.75 m).

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 on the 11-day figures compared to 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.

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

For piezometers placed next to the gallery (in a horizontal plane along the gallery axis) and at a sufficiently short distance from the gallery (less than 3 m) – these are the piezometers of boreholes P35E and P38E and piezometer P30E-PP9 – an increase in pore water pressure as the excavation front approaches can be seen. This corresponds to the compaction of the clay as the excavation front approaches. The magnitude of this pressure increase decreases for piezometers further from the gallery. The increase is not observed by piezometers placed further than 6 m from the gallery axis (piezometers of boreholes P42 and P49). 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.

Further away from the PRACLAY gallery (piezometers of boreholes P42 and P49) a gradual increase is observed when the gallery excavation passes by. The increase results from the stress redistribution around the excavation. The increasing stresses here, as opposed to the decreasing stresses closer to the gallery, indicate that the zone of plastic deformation does not reach up to these piezometers. The gradual increase is followed by a gradual decrease as the clay consolidates.

A different response can be seen in the piezometers placed in borehole P33Id below the gallery. There is no pore water pressure increase as the excavation front approaches. A drop in pore water pressure corresponding to the decompression of the clay as the excavation passes can be observed. This drop is followed by a gradual increase due to the consolidation of the clay. Remarkably, piezometer P30E-PP3, which is also placed below the gallery, but very close to the gallery extrados (ca. 1.15 m), shows the same response as the piezometers placed in a horizontal plane.

6.1.3 STRESSES ON AND IN THE GALLERY LINING

Finally, the pressure build-up on the gallery lining is measured by strain gauges (in the lining segments of rings R10, R45, R60 and R77), pressure cells at the extrados of lining segments R12, R46 and R78 and load cells placed inside lining rings R12, R46 and R78. The measured strains in the lining rings were converted to calculate the stresses in these rings from the knowledge of Young’s modulus and of the creep deformation of the C80/95 and UHPC concrete:

- The strain-stress relationship of the concrete has been derived from laboratory tests by the Magnel Laboratory. The average value of the secant Young’s modulus on two cylindrical samples for each concrete type was 43.3 GPa for the C80/95 concrete and 55.5 GPa for the UHPC concrete. The tested samples were then loaded until failure, which led to an average compressive strength of 104.1 N/mm2 (minimum of 98.7 N/mm2) for the C80/95 concrete and an average compressive strength of 172.0 N/mm2 (minimum of 168.6 N/mm2) for the UHPC concrete. These measured compressive strengths confirmed the 95 percentile of the compressive strength previously determined on cubic samples for both types of concrete (cf. section 5.1.2.1).
- Creep tests were carried out by the Magnel Laboratory on the concrete segments to determine the creep deformation in the total deformation measured by the strain gauges [18]. The creep tests carried out on 2 samples showed that corrections of up to 20% had to be applied to the strain gauge readings from the instrumented segments.

Figure 6-9 shows the circumferential stresses deduced from strain gauges placed close to the intrados and extrados of the lining segments of rings 10, 45, 60 and 77, as measured 2 years after the gallery construction (on 01.11.2009). A reduction of 20% was applied on the stresses measured by the strain gauges to correct for the creep of the concrete segments. The measurements reveal the presence of a bending moment in the lining segments.

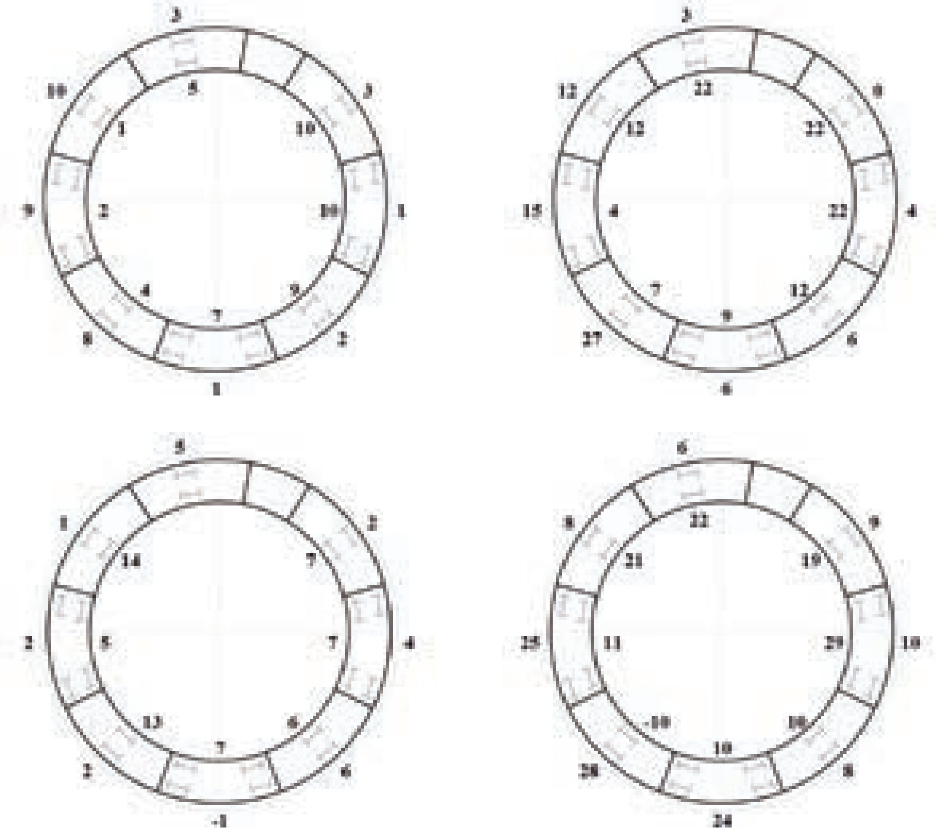
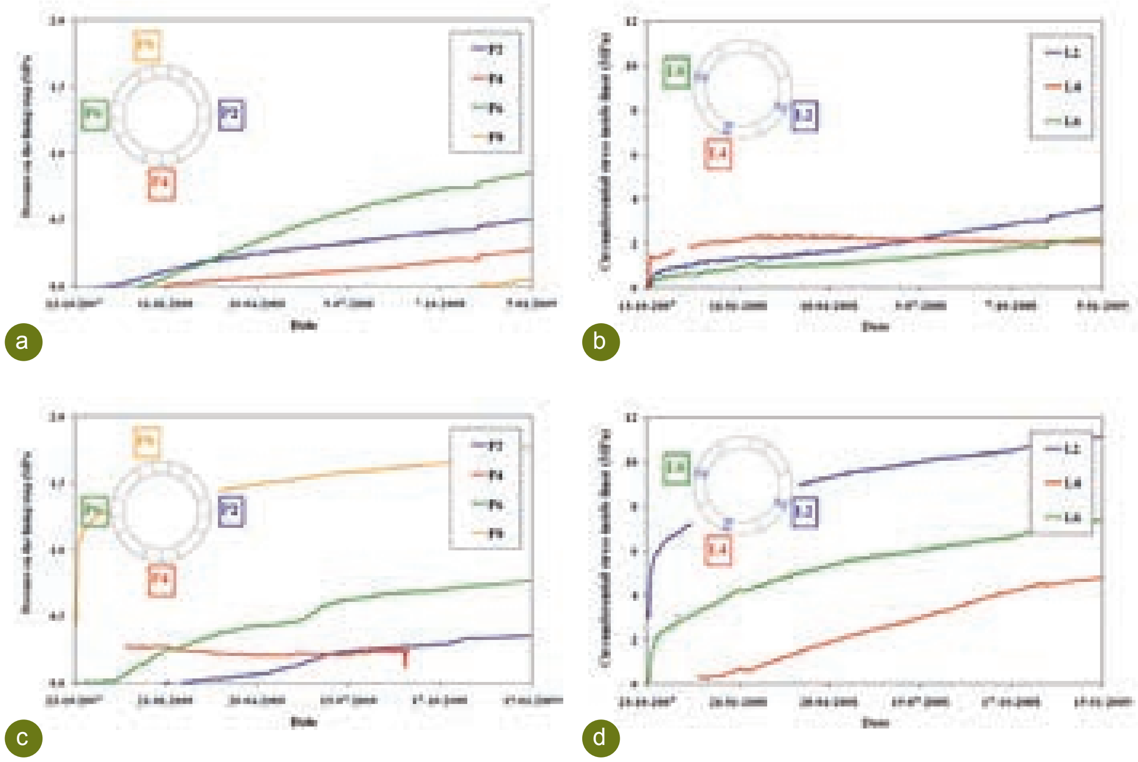


Figure 6-9: Average measured stresses (in MPa) at the intrados and extrados of the lining segments of rings 10, 45, 60 and 77, as measured on 01.11.2009 (2 years after the gallery construction).

Figure 6-10 shows the stresses measured in and on lining rings 12, 46 and 78 by the load and pressure cells respectively.



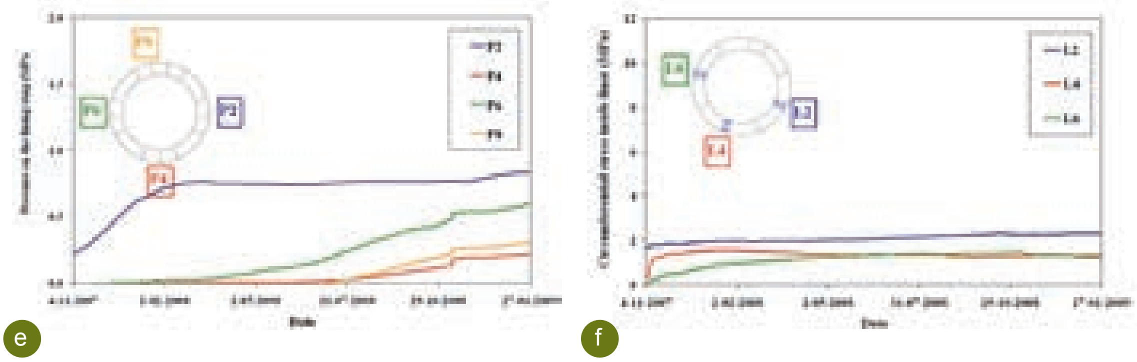


Figure 6-10: Measured stresses in and on lining rings 12, 46 and 78.

6.2. Fracture characterisation

The fracture pattern induced by excavation was characterised by systematic observations of the excavation front [19]. For this purpose, the dip and the dip direction of the fractures in the excavation front were measured whenever it was possible to do so safely (Figure 6-11a) and 3D stereographic pictures of the excavation front were made (Figure 6-11b).

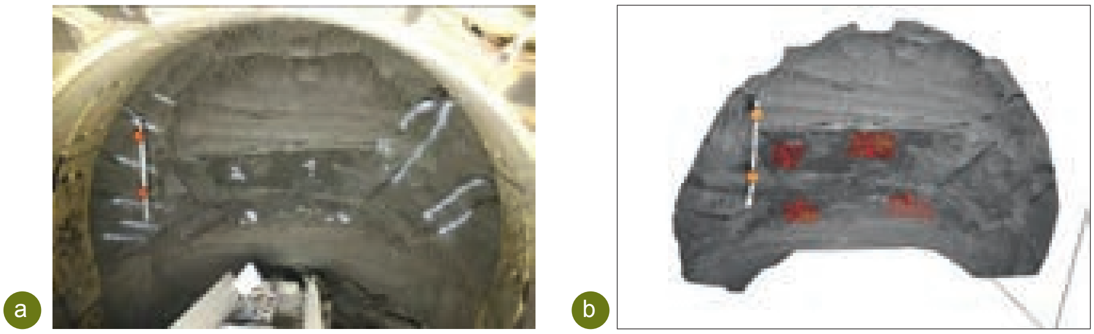


Figure 6-11: (a) The dip and dip direction of the fractures in the front were measured;
(b) stereographic pictures were taken to reconstruct a 3D image of the excavation front.

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 6-12a). When a best fit was performed on this stereographic data two poles became apparent (Figure 6-12b), revealing two conjugated fracture planes that intersect at mid-height of the gallery: one in the upper part, dipping ca. 45° towards the excavation direction (east), and the other in the lower part, dipping ca. 45° towards the opposite direction (west) (Figure 6-13). A similar fracture pattern was also observed when the Connecting gallery was excavated.

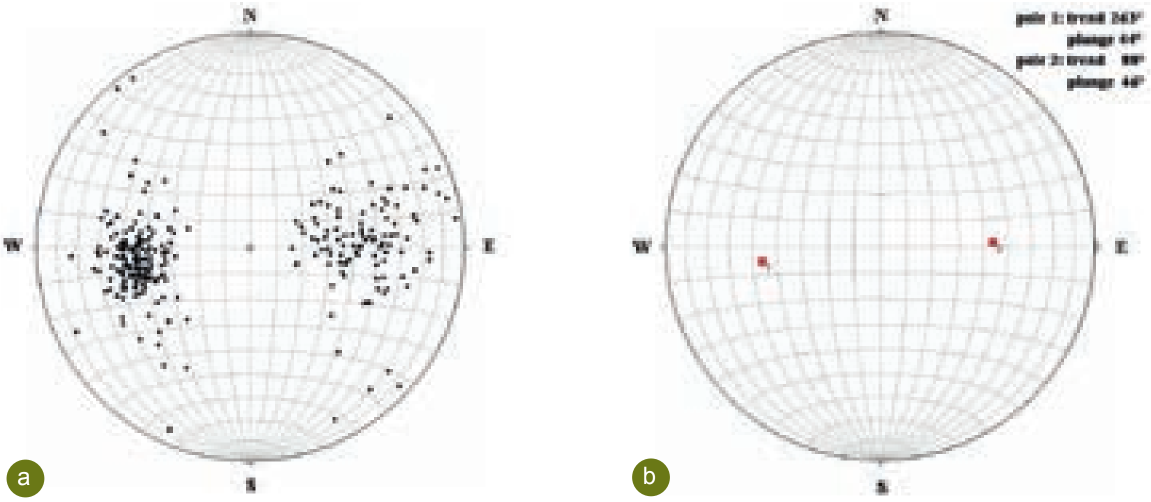


Figure 6-12: (a) Measured and (b) fitted poles to fracture planes plotted on stereographic plot.

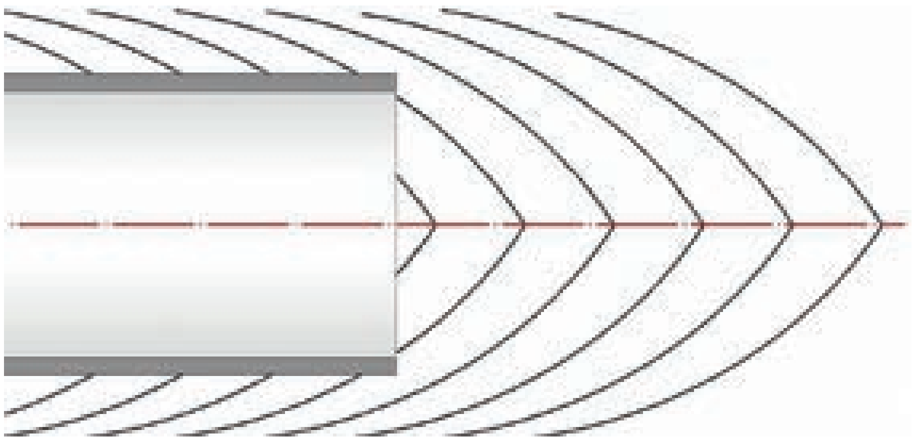


Figure 6-13: Observed fracture pattern (vertical cross section).

The induced fracture pattern was also characterised from observations of the excavation sidewalls [19]. This was done by taking pictures of the complete sidewall after every excavation cycle (Figure 6-14) and subsequently plotting the position and direction of the fractures (Figure 6-15).

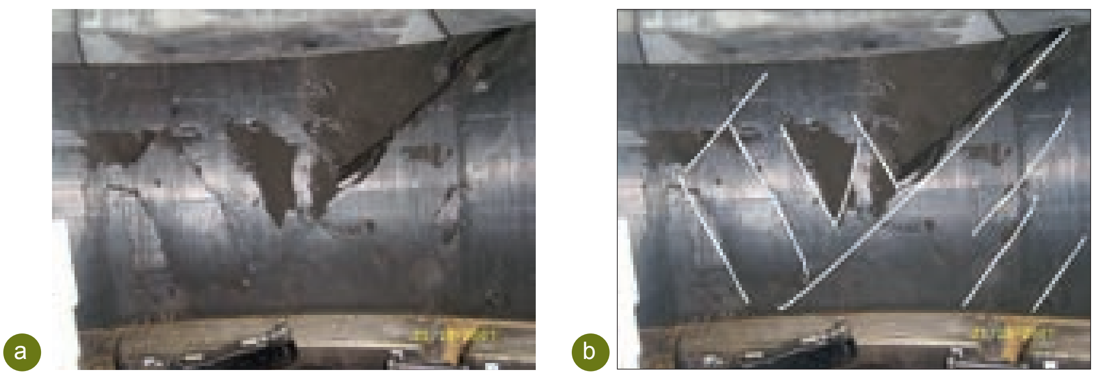


Figure 6-14: (a) Picture of the sidewall and
(b) identification of the fractures.

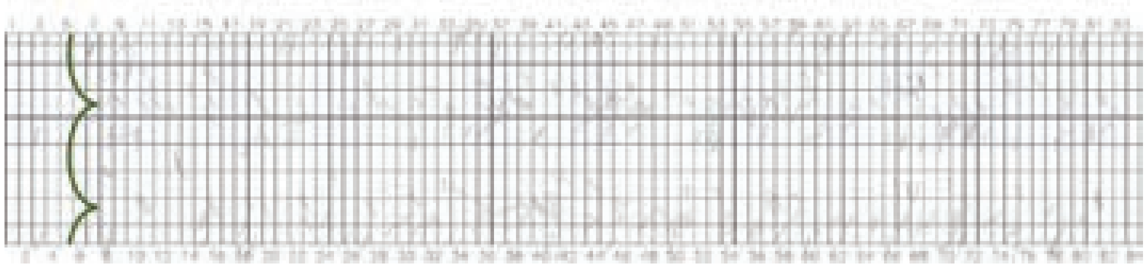


Figure 6-15: Plot of the observed fractures in the sidewalls of the gallery excavation (the theoretical trace of 2 flat planes (the one in the top segments dipping 45° down and the one in the bottom segments dipping 45° up) cutting a cylinder is indicated in green).

If the fracture pattern is simplified to two flat fracture planes (one dipping 45° east, the other 45° west) having their strike perpendicular to the gallery axis, the theoretical trace on the excavated profile in the unsupported zone can be calculated as the intersection of these planes with a cylinder. The observed fracture traces in the unsupported zone are quite similar (Figure 6-15).

All the information on the fracture map has also been digitised, making it possible to calculate the average trace orientation and to determine the shape of the fracture more quantitatively. A histogram of the cumulative length of fractures as a function of their orientation is made for each segment (see Figure 2-7 for the positions of the segments). To filter out the impact of small and very local fractures, only fractures with a length above an arbitrarily chosen threshold length of 500 mm were taken into account. Figure 6-16 shows these histograms together with the angle east-dipping fractures of 45° make on the top segments and the angle west-dipping fractures of 45° make on the bottom segments. In the segments at mid-height, where both fracture planes intersect (i.e. segments 2 and 6), both fracture planes are visible.

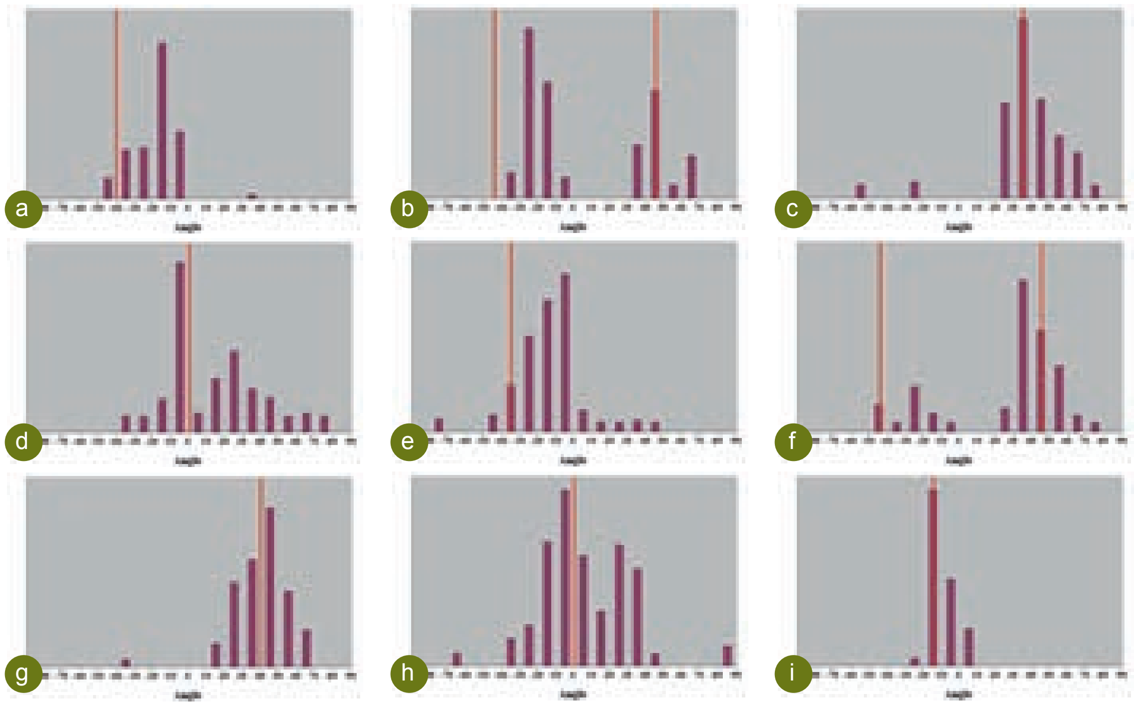


Figure 6-16: Histogram of the cumulative length of the fractures in the different sections with a length greater than 500 mm. A red line indicates the theoretical angle of the intersection between the segment plane and an east-dipping fracture plane of 45° in the upper part and a west-dipping fracture plane of 45° in the lower part: (a) segment 1; (b) segment 2; (c) segment 3; (d) segment 4; (e) segment 5; (f) segment 6; (g) segment 7; (h) segment 8; (i) segment 9.

The histograms generally confirm the fracture pattern shown in Figure 6-13. The fracture characterisation resulting from the excavation of the PRACLAY gallery thus confirms the fracture pattern observed during the excavation of the Connecting gallery. This pattern was consistently observed along the gallery except for the first few metres, where the pattern was distorted because of the fractures induced by a borehole drilled from the Connecting gallery along the axis of the PRACLAY gallery before the excavation of the latter (Figure 6-17) (cf. section 2.5). The similarity between the fracture pattern observed around two perpendicular horizontal galleries indicates that the difference in in-situ horizontal stress is small.

Figure 6-17: Fractures induced by the central borehole.

It is difficult to assign a value to the spacing of the fractures based on the plot of the fractures observed in the sidewalls (Figure 6-15). Nevertheless the spacing can be estimated to be in the order of centimetres to decimetres. Another parameter that is difficult to determine is the radial extent of the fractures. An attempt was made to determine the radial extent of the excavation-induced fractures based on boreholes drilled from the PRACLAY gallery (cf. section 2.5). These drillings passed the fractured zone around the gallery and cores were taken from the first 1.5 m of the boreholes drilled (Figure 6-18). It was not, however, possible to distinguish between fractures in the cores that were induced by the excavation of the PRACLAY gallery and fractures that originated from the drilling itself.

Figure 6-18: Cores from the first 1.5 m of boreholes drilled around the Praclay gallery were taken to examine the radial extent of the fractured zone around the gallery. Fractures were observed in these cores but it was not possible to distinguish between fractures induced by the excavation of the gallery and fractures originating from the drilling itself.
(a) 0 – 0.5 m in PG50Id; (b) 0.5 – 1.0 m in PG50Id; (c) 1.0 – 1.5 m in PG50Id.

An indication on the extent of the fractured zone could, however, be obtained from the sulphate concentrations in the filters placed in the vicinity of the gallery. The pyrite present in the clay oxidises in the fracture planes and sulphate is formed in the pore water. Thus, when a fracture extends up to a filter, the filter measures increased sulphate concentrations in the pore water. Fifteen 0.5 m long filters are placed in borehole P35E at a horizontal distance of 0.6 m from the gallery lining. However, no increased sulphate concentrations are measured in these filters indicating that the fractures around the PRACLAY gallery do not extend up to a radial distance of 0.6 m in a horizontal plane.

Since the PRACLAY gallery is constructed perpendicular to the Connecting gallery, the excavation of the PRACLAY gallery passes through the fractured zone induced by the construction of the Connecting gallery. These fractures were observed in the first few metres of the PRACLAY gallery excavation (Figure 6-19). At first sight the fractures appear to curve in an opposite direction to that expected. This is because the fracture trace is the intersection between the fracture plane and the excavation front, which has a spherical shape. These fractures were observed up to an excavation distance of 6 m. This is well beyond the previously determined radial extent of the fractured zone around the Connecting gallery of 1 m (*Bastiaens et al., 2003*).

Figure 6-19: Fractures visible in the excavation front of the PRACLAY gallery excavation during the first few metres of the excavation: (a) 1 m from extrados Connecting gallery; (b) 2.5 m from extrados Connecting gallery; (c) 4 m from extrados Connecting gallery; (d) 5.5 m from extrados Connecting gallery.

It is possible that microfractures up to that extent were induced during the excavation of the Connecting gallery, but these were not observed in the cores taken radially around the Connecting gallery. However, because of the stress redistribution created by the excavation of the PRACLAY gallery, these microfractures might have formed macrofractures. Or the in-situ stress state in this zone did not reach, but came close to the critical state due to the excavation of the Connecting gallery. The later excavation of the PRACLAY gallery remobilised the stress path so that the in-situ stresses reached the critical state and fractures were formed. 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.

6.3. Convergence measurements

The radial convergence of the host clay rock was modelled in advance and the shield was designed to achieve overexcavation of between 30 and 80 mm on diameter (cf. section 5.1.3; Figure 2-11). This overexcavation can be adjusted by changing the position of the cutting edges. Table 5.1 contains the overexcavation for different positions of the cutting edges.

The instantaneous radial convergence was continuously measured by ultrasonic measurements on the shield. Therefore three series of four openings, placed 120° apart, were provided in the shield (Figure 5-19). The performance of the ultrasonic measurements appeared to be poor, however. Clay cuttings trapped in the openings or fallout from the sidewall might have distorted the measurements.

The convergence was also visually inspected by observing the contact between the clay and the shield at the rear end of the shield. Initially all cutting edges were moved out over 60 mm, resulting in an overexcavation of 81 mm on diameter. The clay did not make contact with the shield over the whole circumference of the shield. At the top and at the bottom of the shield there was a gap between the clay and the shield (Figure 5-31). Therefore the top cutting edge was brought back to 45 mm after the placement of ring 13. In that way an overexcavation of 68 mm was achieved in the vertical direction of the excavation. This configuration of the cutting edges was maintained until ring 32. As there was still a gap between the clay and the shield at both the top and the bottom of the excavation, the top and bottom cutting edges were moved back over another 15 mm, resulting in an overexcavation of 55 mm on diameter in the vertical direction. After this adaptation the clay touched the shield over the whole circumference of the shield.

The convergence occurring between the excavation front and the rear end of the tunnelling shield was thus larger in the horizontal direction than in the vertical direction. The same phenomenon – but to a lesser extent – was observed during the excavation of the Connecting gallery (*Bastiaens et al., 2003*). It is assumed to be due to a combination of the fracture pattern that develops ahead of the excavation front, the anisotropy in in-situ stresses and the mechanical properties of the Boom Clay. Also the bedding plane plays a role in the observed anisotropy of the clay convergence.

The axial displacement of the clay host rock as a result of gallery excavation was determined by monitoring the position of 6 wooden cylinders installed in the clay along the axis of the PRACLAY gallery prior to the PRACLAY gallery excavation. The initial position of the cylinders was topographically determined during their installation. As soon as the cylinders could be seen in the excavation front during the gallery excavation, their position was measured again. The position measurements were performed with an accuracy of +/- 0.5 mm. Table 6.1 shows the initial position and the displacements of the 6 cylinders. No results were obtained for the second cylinder.

Distance to intrados Connecting gallery [m]	Axial displacement [mm]	Horizontal transverse displacement [mm]	Vertical transverse displacement [mm]
3.916	41	8	15
5.662	-	-	-
7.048	62	7	14
9.029	38	2	5
10.397	29	2	2
11.732	35	4	3

Table 6.1: Measured displacements of the wooden cylinders.

The axial displacement is in the order of tens of millimetres. Theoretically no transverse displacement is expected. The measured transverse displacements might have been a real displacement or might be due to the overall accuracy of the complete experimental setup. In the case of the latter, these displacements give an indication of the accuracy of the measurements.

The axial displacement of some marked points in the excavation front during the stop-and-go-test were also monitored (Figure 6-20).

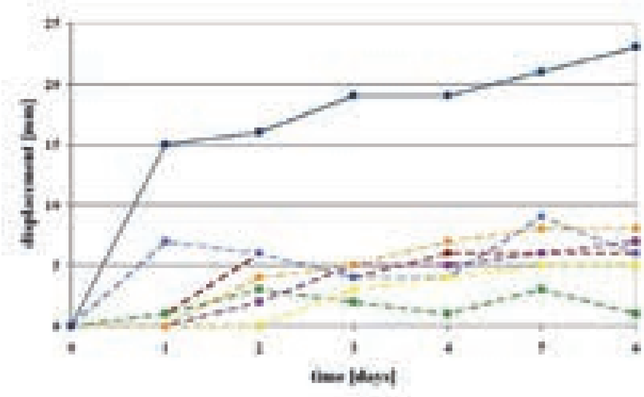


Figure 6-20: Measured displacement of marked points in the excavation front during the stop-and-go test (full line is the point in the centre of the front, the dashed lines are more to the edge of the front).

The axial convergence in the centre of the excavation front is larger than at the edges. The axial displacements at the points at the edge are of the same order of magnitude. The axial displacement in the centre occurs mainly during the first day.

6.4. Positioning and deformation of the lining

The position of the gallery axis during the excavation was measured by a total station placed in the Connecting gallery in front of the opening for the PRACLAY gallery (Figure 6-21). A vertical and horizontal deviation

Figure 6-21: Total station to measure the position of the gallery axis during the excavation work.

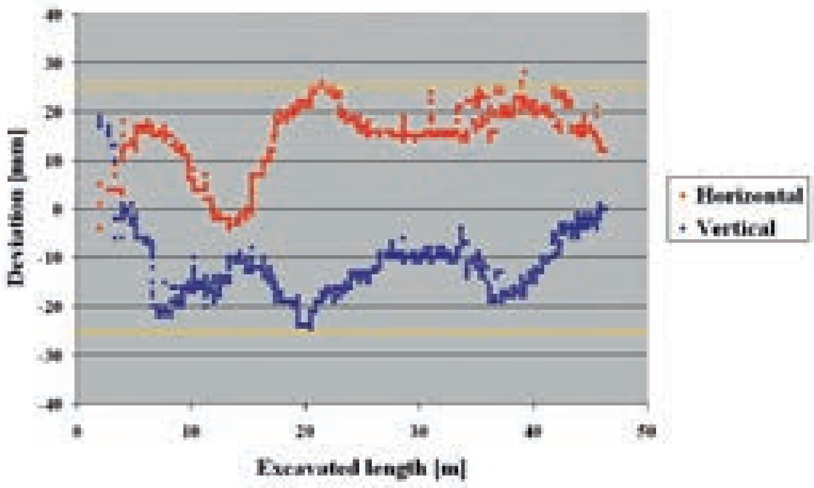


Figure 6-22: Vertical and horizontal deviation from the theoretical gallery axis.
The allowed tolerance was 25 mm, indicated by the yellow lines.

from the design axis position of 25 mm was allowed. The initial horizontal and vertical deviations were respectively 5 mm and 18 mm (Figure 6-22). The final deviation in the horizontal and vertical direction amounted to 9 mm and 2 mm respectively. The maximum horizontal deviation was 26 mm. This was, however, only reached over a distance of less than 1 metre. The vertical deviation remained within tolerance over the whole excavation distance, reaching a maximum of 25 mm.

The excavated diameter and the internal diameter of the gallery were manually measured for each ring using an extensometer (Figure 6-23). Figure 6-24 and Figure 6-25 show the measured diameters. There is a difference between the vertical and the horizontal diameter. The average horizontal and vertical diameter of the excavated profile is respectively 2506 and 2525 mm. This is in line with the previously discussed convergence measurements and observations (cf. section 6.3). Also the impact of the reduction in the vertical overexcavation after ring 32 can be seen on the vertical diameter of the excavated profile. The average horizontal and vertical internal diameter of the gallery is respectively 1898 and 1906 mm.

Figure 6-23: Manual measurement of the diameter of the gallery.

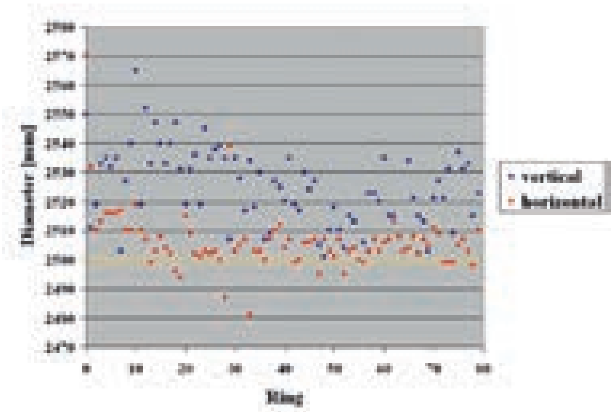


Figure 6-24: Measured vertical and horizontal diameter of the excavated profile.

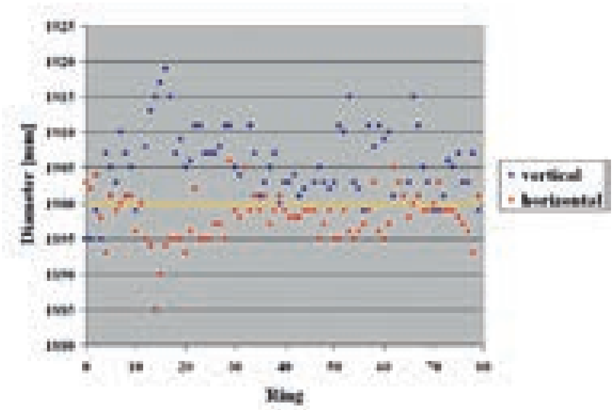


Figure 6-25: Measured vertical and horizontal internal diameter of the gallery.

Subsequently, regular measurements of 12 distances between marked points fixed on the segments (Figure 6-26) were performed on some lining rings with Invar wires to monitor changes in the diameter and the shape of the lining. The rings on which these measurements were performed were rings 4, 10, 19, 22, 33, 45, 60 and 77. Each time a newly erected ring was measured, two distances on all the previously selected rings were measured again. More distances were checked when there was a significant difference between consecutive measurements.

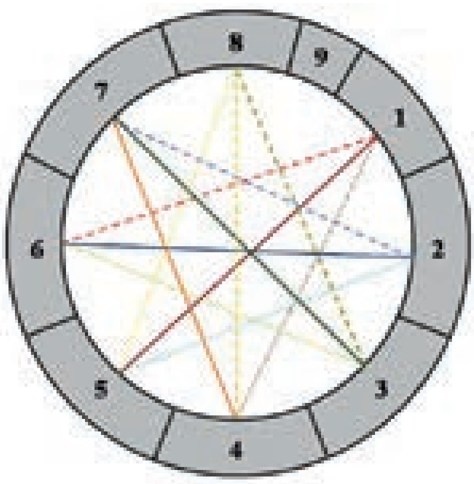


Figure 6-26: Measured distances between marked points fixed on the segments of lining rings 4, 10, 19, 22, 33, 45, 60 and 77.

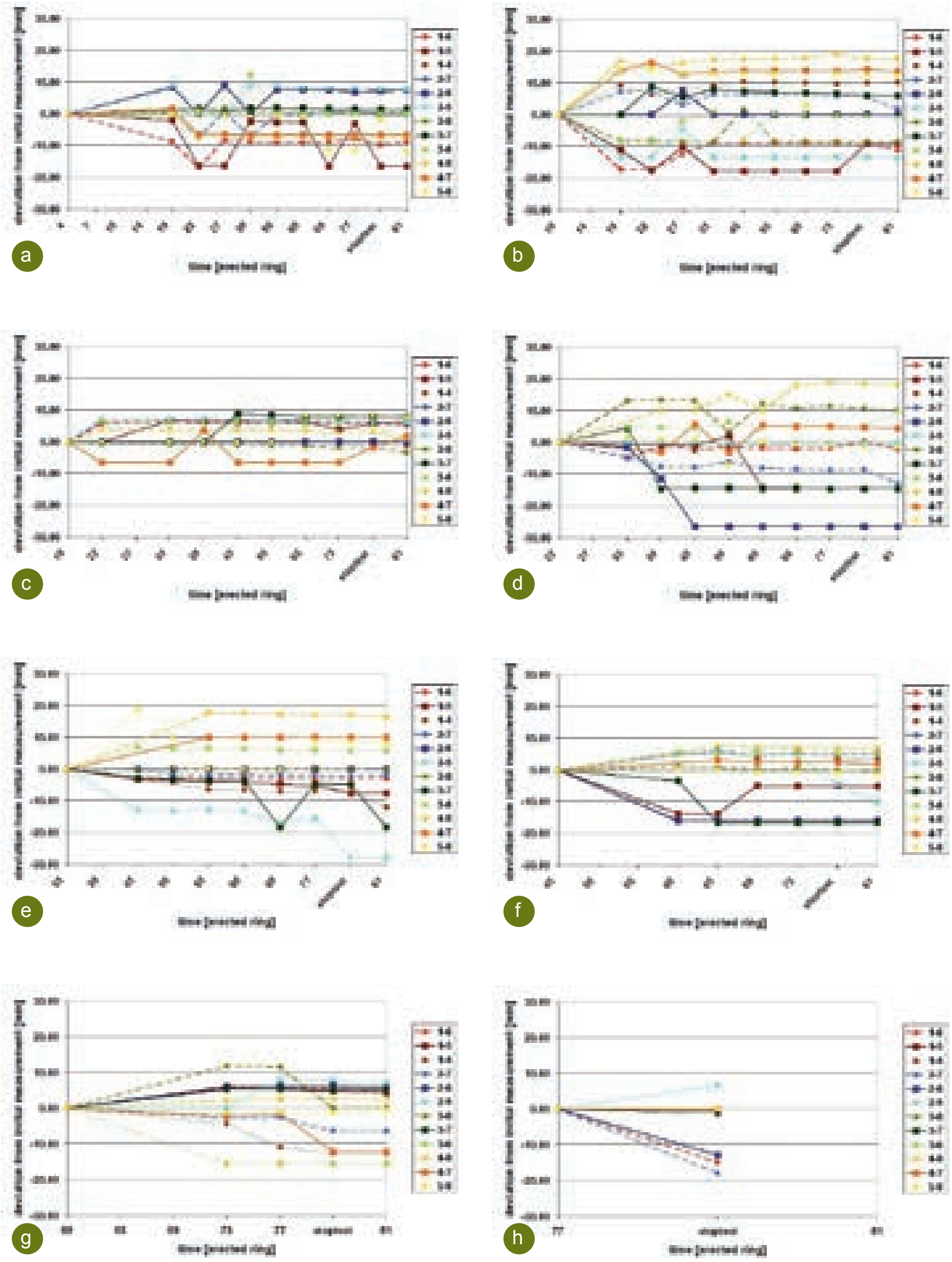


Figure 6-27: Distance measurements on lining rings: (a) ring 4; (b) ring 10; (c) ring 19; (d) ring 22; (e) ring 33; (f) ring 45; (g) ring 60; (h) ring 77.

These measurements do not reveal any deformation of the lining, which is consistent for all measured lining rings. For example the distances between segments 2 and 5 and segments 3 and 7 decreased in 4 of the rings measured and increased in the other 4 rings. The deformation, resulting from the increasing clay pressure on the lining due to the convergence and consolidation of the clay, also depends on the initial position of the lining ring in relation to the excavated opening, which is evidently different for every lining ring. The deformation is always smaller than 2% of the initially measured length value and on average the deformation was 0.4% of the initially measured length. The plots also reveal that the deformation mainly, and almost exclusively, occurs between the first (i.e. initial) and the second measurement.

6.5. Tunnelling machine measurements

The tunnelling shield was equipped with a real-time data-acquisition system to continuously record and check the position of the shield, the convergence of the host rock, the roll of the shield, the pressures in the hydraulic jacks and the stroke of the hydraulic jacks (cf. section 5.1.3). The convergence measurements, the position of the shield, i.e. the gallery axis, were discussed in sections 6.3 and 6.4.

The rotation of the shield was determined by means of a topographical survey of the tunnelling shield. The rotation as a function of the excavated length is given in Figure 6-28. Positive angles indicate a clockwise rotation when looking towards the end of the PRACLAY gallery.

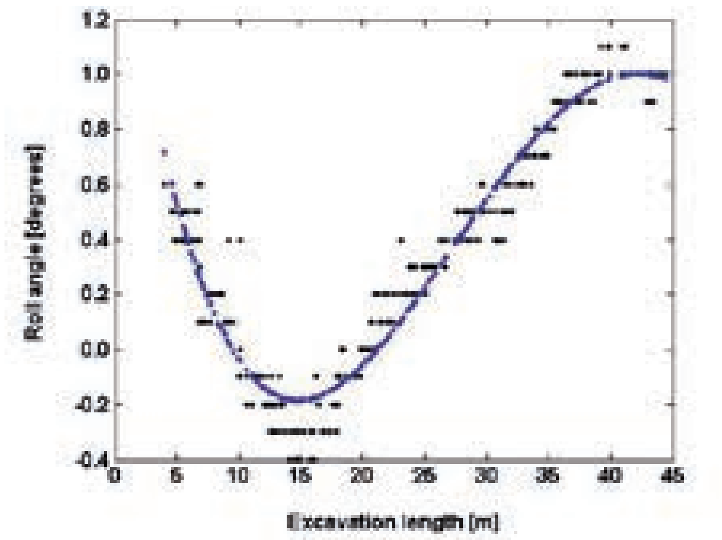


Figure 6-28: Measured rotations of the shield (black) and a trendline (blue) through these measurements.

A retractable fin was placed on both sides of the shield (Figure 5-41). The fin on the left side of the tunnelling shield (looking towards the end of the PRACLAY gallery) was pulled out after the stop-and-go-test (ring 80; excavated distance: 40 m). The impact of the fin is clearly visible in Figure 6-28, as the clockwise rotation changes to a counter-clockwise rotation after the fin is pulled out.

The force to move the shield forward is delivered by 8 pairs of hydraulic jacks. These jacks were designed to deliver a maximum pressure of 700 bars, corresponding to a force of 850 kN or 85 tonnes each. The pressure in the jacks, and hence the force exerted by the jacks, was monitored during the excavation (Figure 6-29). Most of the time the total force required to move the shield forward lay between 1000 and 1500 kN, which was approximately ten times smaller than the nominal total force of 13600 kN (16x850 kN). The exerted force was higher after the stop-and-go test (when the excavation work was suspended for 1 week), i.e. 3083 kN, which is about twice the force that was exerted during excavation. This is still well below (4.5 times) the nominal total force of 13600 kN.

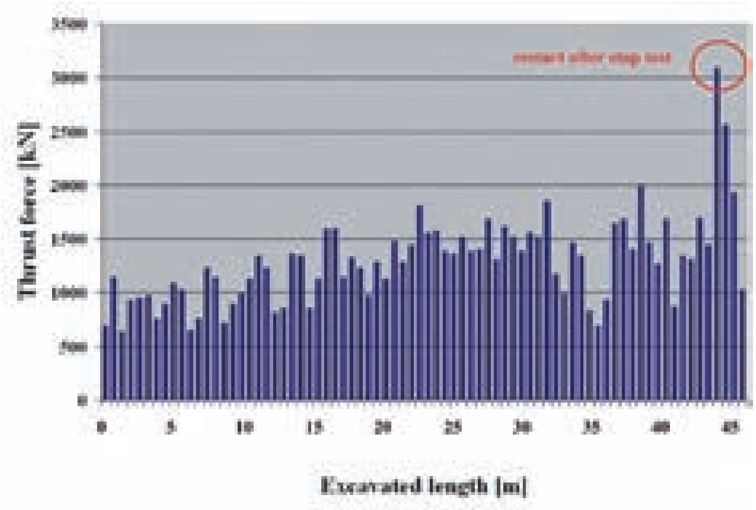


Figure 6-29: Thrust force exerted by the hydraulic jacks on the gallery lining.

6.6. Geology of the Boom Clay layer

The geological strata at Mol are nearly horizontal, dipping slightly towards the north. Since the Boom Clay itself has a layered structure, it has been possible to monitor its dip. During the construction of the Connecting gallery the vertical position of septaria layer mS 140 was measured on a north-south axis. This led to an average (apparent) dip of 0.4° along the north-south axis.

The PRACLAY gallery lies along an east-west axis and the excavation offered the possibility to measure the vertical position of the septaria layer mS140 in that direction. The measurements of the vertical position of the septaria layer on the sidewalls of the excavation reveal a dip of 0.2° to the east (Figure 6-30).

Figure 6-30: Septaria layer mS 140 visible in the excavation front.

7. Conclusions

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 and 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.

Besides being a test in itself, the gallery has to host the Heater Test and its construction is therefore a first step in the realisation of this test. The design criteria for the gallery are mainly determined by the Heater Test, which aims to verify the suitability of Boom Clay as a host rock for the geological disposal of heat-emitting radioactive waste. The existing galleries of HADES were not suitable to host this test and therefore a new gallery, perpendicular to the Connecting gallery, had to be constructed. Its location was determined by the existing instrumentation in the Connecting gallery and the interactions between the Heater Test, the other running experiments and the HADES infrastructure.

7.1. Gallery design

The tender specifications were largely based on the design of the Connecting gallery and the experience gained from the construction of this gallery. 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.

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

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. To limit the thermal stresses in the lining, compressive materials are incorporated in 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 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.

7.2. Gallery construction

The actual construction of the gallery was performed 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.

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 thrust force. This was still only ~25% of the maximum available force.

7.3. Scientific lessons

Several measurements (in the clay, the lining and the tunnelling machine) were carried out before, during and after the excavation of the PRACLAY gallery. They aimed to gain as much information as possible on the performance of the excavation technique, the behaviour of the Boom Clay and the impact of the excavation on the clay. The results were in line with previous observations and confirm the highly coupled and anisotropic hydromechanical behaviour of the Boom Clay and known fracturing processes.

Piezometers placed below the gallery show a more gradual decrease below the gallery axis as the excavation front approaches. The different pore water pressure response beside and below the gallery reveals the anisotropic behaviour of the clay. The anisotropic pore water pressure response can result from the anisotropic mechanical characteristics of the clay and/or from the anisotropy in in-situ stresses in the clay.

The same highly coupled and anisotropic hydromechanical behaviour of the Boom Clay was observed during the construction of the Connecting gallery. Also the excavation-induced herringbone-like fracture pattern observed around the Connecting gallery (*Bastiaens et al., 2007*) was evident from the fracture observation programme carried out for the PRACLAY gallery excavation. The detailed analysis of the gathered information revealed the same fracture pattern that was consistently observed along the gallery except for the first few metres where the gallery passes the excavation-disturbed zone induced by the earlier construction of the Connecting gallery. An attempt was made to determine the radial extent of these fractures by examining cores taken from the clay around the PRACLAY gallery. It was not, however, possible to distinguish between fractures in the cores that were induced by the excavation of the gallery and fractures that originate from the core drilling itself.

Overexcavation could be adjusted during the gallery construction by changing the position of the cutting edges of the tunnelling shield. Good contact between the clay and the rear end of the shield was obtained with a vertical overexcavation of 55 mm on diameter and a horizontal overexcavation of 81 mm on diameter. The radial convergence in the near field around the excavation (i.e. between the excavation front and the rear end of the tunnelling shield) was thus larger in the horizontal direction than it was in the vertical direction. The same phenomenon – but to a lesser extent – was observed during the excavation of the Connecting Gallery. It is assumed to be due to a combination of the fracture pattern that develops ahead of the excavation front, the anisotropy in in-situ stresses and the mechanical properties of the Boom Clay. Also the bedding plane plays a role in the observed anisotropy of the clay convergence.

PART II

The hydraulic seal

Summary

A hydraulic seal was installed in the PRACLAY gallery in 2010. The installation is part of the PRACLAY In-Situ Experiment and its main purpose is to hydraulically cut off the heated part of the PRACLAY gallery from the non-heated part, thus creating a quasi-impermeable hydraulic boundary at the intersection between the two parts. Such a quasi-impermeable boundary is required to achieve conservative conditions during the Heater Test. The hydraulic seal also has to allow watertight feed-through of the instrumentation placed in the upstream part of the PRACLAY gallery, and of the cables of the heating system that is placed in a later phase.

The design of the hydraulic seal is mainly determined by the design of the PRACLAY gallery and the Heater Test. The seal is installed 10 m from the Connecting gallery to limit the mutual interactions between the Heater Test and the Connecting gallery.

The hydraulic seal is purpose-built for the PRACLAY Experiment and is not representative of seals in a geological disposal repository. A bentonite-based hydraulic seal was chosen instead of, for example, a technical seal consisting of inflatable packers, as a bentonite-based seal might be envisaged as an actual repository seal. By installing such a seal, lessons could be learnt about the behaviour of the bentonite.

The seal consists of a steel structure closing off the heated part of the gallery from the rest of the underground infrastructure, and an annular ring of compacted bentonite placed against the clay. Bentonite was chosen as a sealing material because of its intrinsically low permeability (when compacted to a suitable dry density) and its swelling capacity, which helps seal the excavation-induced zone around the seal. Scoping calculations proved that a seal length of 1 m is sufficiently effective and that no significant gain is obtained by further increasing the length of the seal.

To maintain the accessibility of the clay sidewall at the location of the hydraulic seal, an alternative lining was installed during the construction of the PRACLAY gallery. The alternative lining consisted of four steel rings with wood placed behind these steel rings as a temporary component of the lining. The wood was removed before the installation of the hydraulic seal.

The steel structure consists of two flanges that are placed against the concrete lining next to the hydraulic seal. Because the flanges are too large to be installed in one piece, they are composed of four segments that are assembled in-situ. After both flanges are installed, an annular ring of bentonite blocks is erected between the flanges and the clay sidewall. Subsequently a steel cylinder is placed inside the annular bentonite ring and between the two flanges. In that way the bentonite is enclosed between the two flanges, the cylinder and the Boom Clay. Filters are placed on the extrados (outer surface) of the cylinder to artificially hydrate the bentonite. The bentonite will mainly be hydrated by water from the Boom Clay.

A circular plate placed in the cylinder closes off the heated part of the PRACLAY gallery. Because this part of the gallery still has to remain accessible before the start of the Heater Test – this is needed for the assembly of the cylinder to the flanges during the seal installation and for the installation of the heater and backfill material in the PRACLAY gallery after the seal installation – a manhole is placed in the centre of the plate. Before the start of the Heater Test the manhole is closed by welding a closing plate onto it. The plate in the cylinder has several openings for the feed-through of the instrumentation and the heating system placed in the upstream part of the gallery.

It was decided to use precompacted MX80 bentonite blocks. The choice of this type of bentonite was mainly based on literature data on its swelling capacity, water retention potential and 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, AECL's URL) and in the laboratory (by CEA, CIEMAT, CERMES and SKB). Furthermore it is a Na-bentonite, which makes it chemically compatible with the Boom Clay, whose pore water is sodium dominated. The desired initial dry density of the bentonite, which affects its swelling pressure and its saturated permeability, was determined by scoping calculations.

The installation of the hydraulic seal started on 13.01.2010 and on 11.02.2010 the first phase of the underground installation of the seal was finished. The second phase comprised the welding of the closing plate onto the manhole of the hydraulic seal. This was 20 months later, between 29.09.2011 and 13.10.2011, after the heating system and the backfill material were installed in the heated part of the PRACLAY gallery.

Instrumentation was placed in the bentonite blocks to gain information on the bentonite hydration and to be able to evaluate the performance of the hydraulic seal. This report includes measurements until August 2011. The measurements indicate that the bentonite hydration is evolving in the right direction. The bentonite hydration is ongoing and since most bentonite is still unsaturated, there is still substantial potential for further bentonite swelling as the hydration process continues.

1. Introduction

The installation of the hydraulic seal in the PRACLAY gallery is part of the PRACLAY In-Situ Experiment. Its main purpose is to create a quasi-impermeable hydraulic boundary at the intersection between the heated part of the PRACLAY gallery and the non-heated part during the Heater Test [3]. Such a quasi-impermeable boundary is required to achieve conservative conditions for the Heater Test.

The installation of a horizontal seal is also used to examine the feasibility of installing such a seal and in particular to test the contact zone between the seal and the host rock.

The installation of the hydraulic seal was successfully completed in 2010. The preparation process, including the design of the seal and the tendering procedure, the actual installation and the technical and scientific achievements are discussed in this report, which is structured as follows:

- *chapter 2* discusses the design specifications of the seal;
- *chapter 3* describes the tendering procedure;
- *chapter 4* gives an overview of how the work was organised;
- *chapter 5* presents the construction and installation work;
- *chapter 6* discusses the results of the measurement and research programmes carried out during and after the seal installation;
- *chapter 7* summarises the main conclusions, evaluates the achievements and provides recommendations for future work.

2. The design of the hydraulic seal

The hydraulic seal has to hydraulically cut off the heated part of the PRACLAY gallery from the non-heated part. This is achieved by physically closing off the heated part of the gallery and by lowering the hydraulic conductivity of the clay around the seal to a value lower than the undisturbed in-situ hydraulic conductivity. This is done using a bentonite-based hydraulic seal. This type of seal was preferred to, for example, a technical seal consisting of inflatable packers, as a bentonite-based seal might also be included in the repository design for the disposal of radioactive waste. By installing such a seal, lessons could be learnt about the behaviour of the bentonite.

The hydraulic seal consists of a steel structure closing off the heated part of the gallery from the rest of the underground infrastructure, and an annular ring of bentonite placed against the clay (Figure 2-1). Precompacted bentonite has low permeability and a high swelling capacity. When the bentonite is hydrated, the swelling pressure exerted against the clay will locally lower the hydraulic conductivity of the clay and close any fractures present around the hydraulic seal. Furthermore the hydraulic seal has to allow watertight feed-through of the instrumentation placed in the upstream part of the PRACLAY gallery, and of the heater cables of the PRACLAY heating system.

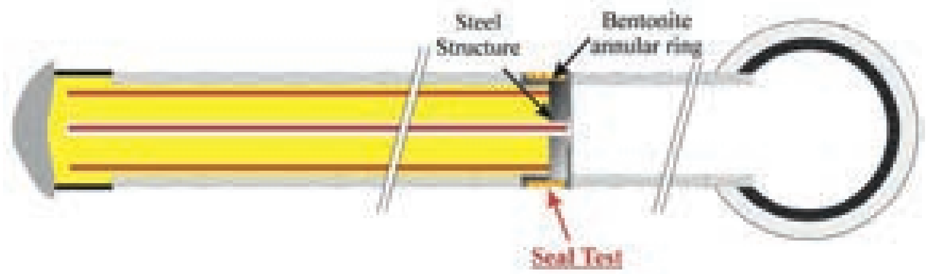


Figure 2-1: The hydraulic seal closing off the heated part of the PRACLAY gallery consists of a steel structure and an annular ring of bentonite.

The design of the hydraulic seal is mainly determined by the design of the PRACLAY gallery and the Heater Test. The following design criteria were eventually defined for the hydraulic seal [4]:

- a length of 1 m for the seal was sufficiently effective and no significant gain was obtained by further increasing its length;
- the seal will be located at a distance of 10 m from the Connecting gallery to limit mutual interactions between the Heater Test and the Connecting gallery.

Based on these requirements, a design was developed and tendering specifications were formulated. A tendering procedure was launched, but did not lead to the award of the contract and a new call for tenders was issued. As part of the new procedure, the design was also optimised. This time the tendering procedure led to the award of the contract. Section 2.1 describes both designs for the hydraulic seal in detail. The history of the tendering procedure is discussed in chapter 3.

The scope of the tendering procedure encompassed the construction of the steel structure and its installation together with the bentonite. The bentonite blocks were not part of the scope of the tendering procedure for the hydraulic seal and were ordered by EURIDICE. The specifications of the bentonite blocks are given in section 2.2.

The complete design was also presented to an expert panel. The findings of the panel are summarised at the end of this chapter (section 2.3).

2.1. Design specifications

First the conditions and requirements for the seal are summarised. This is followed by a brief description of the design specifications in the first tendering procedure and a more detailed description of the second design, which was eventually implemented. The technical specifications of both designs were prepared by TRACTEBEL ENGINEERING, in close cooperation with EURIDICE.

2.1.1 CONDITIONS AND REQUIREMENTS

The hydraulic seal is placed in the PRACLAY gallery at a distance of 10 m from the crossing with the Connecting gallery. The nominal inside diameter of the gallery is 1900 mm. Due to the tolerances on the placement of the concrete wedge blocks during the construction of the gallery, the internal diameter varies. The minimum diameter in the relevant section (i.e. the first 10 m) is ca. 1870 mm.

At the location of the hydraulic seal, the gallery had an alternative lining consisting of four steel rings, which were the permanent part of the lining (Figure 2-2a). These were connected by steel plates between them to avoid buckling of the rings. The temporary part consisted of wood, which was placed behind a small steel edge welded to both sides of each steel ring. The alternative lining was composed of 9 segments that are connected to each other by a "pin-hole connection" (Figure 2-2b). Before the installation of the hydraulic seal, the wood from the alternative lining was removed to make the Boom Clay sidewall accessible for bentonite.

a

b

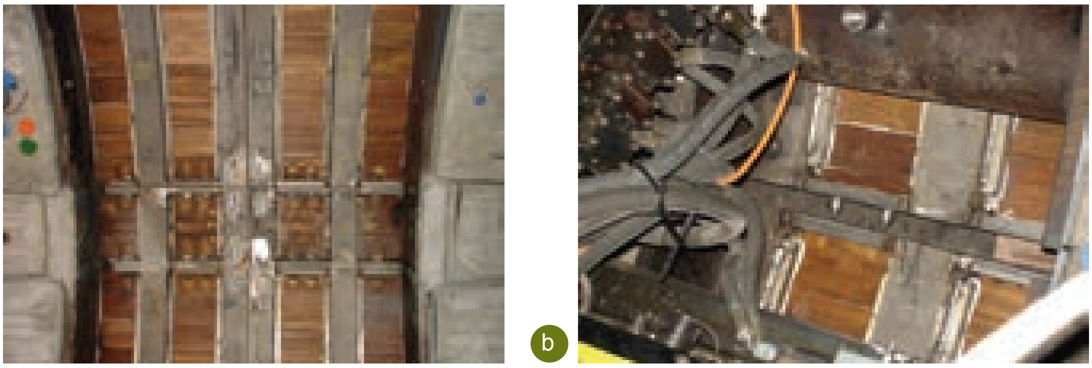


Figure 2-2: Alternative lining where the hydraulic seal will be erected:
(a) the lining consisted of a permanent part (4 steel rings) and a temporary part (wood placed between the steel rings); (b) the segments of the alternative lining were connected by a pin-hole connection in the steel plates between the rings.

The radial swelling pressure of the bentonite has to be sufficiently high to ensure good compaction of the clay around the seal, but it has to be limited as well to avoid fracturing the clay. In the design hypothesis, the steel structure of the hydraulic seal will be subjected to a radial pressure of 5 MPa caused by the bentonite. This value is based on the assumption that a uniform pressure distribution is obtained. In the case of an elliptical pressure distribution, the radial pressure varies between 4 and 6 MPa. The design furthermore assumes a maximum pore water pressure of 3.5 MPa and a maximum temperature of 90°C on the upstream side[1] of the hydraulic seal. On the downstream side, atmospheric pressure and a temperature of 16°C are the prevailing conditions.

The hydraulic seal also has to allow watertight feed-through of the instrumentation placed in the upstream part of the PRACLAY gallery.

The bentonite has to fulfil the following requirements:

- its minimum swelling pressure is 2.5 MPa to avoid the creation of negative effective stresses around the hydraulic seal during the Heater Test (the maximum pore water pressure in the Boom Clay around the hydraulic seal during the Heater Test is estimated at 2.5 MPa);
- its maximum swelling pressure is 6 MPa to avoid fracturing the clay or compromising the integrity of the stainless steel structure of the hydraulic seal;
- its hydraulic conductivity in the saturated state is as low as possible (at least lower than the conductivity of undisturbed Boom Clay (≈ 10^{-12} m/s) and preferably one order of magnitude lower).

2.1.2 DESIGN SPECIFICATIONS IN THE FIRST TENDERING PROCEDURE

The first design for the hydraulic seal is shown in Figure 2-3. A ring of bentonite with a thickness of 170 mm is placed against the Boom Clay sidewall and enclosed by a steel structure. A manhole in the centre of the steel structure provides access to the upstream side of the structure for the installation of the heater and backfill material in the PRACLAY gallery. After their installation the manhole is closed by welding a closing plate onto the structure. The four large pipes are for instrumentation feed-through. The smaller pipes are for backfill installation and saturation of the backfill. No artificial hydration of the bentonite was planned. For more details on the design, refer to the design specifications in the tender documents and the design calculations performed by ULg [20].

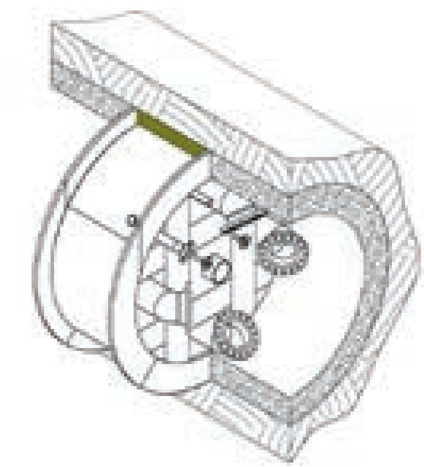


Figure 2-3: First design of the hydraulic seal: bentonite (shown in green) is placed against the Boom Clay, after which the components making up the steel structure are assembled by welding.

[1] The upstream side of the hydraulic seal is the side of the heated part of the PRACLAY gallery. The downstream side is the side towards the Connecting gallery.

The installation of this structure starts by placing the bentonite blocks. Then the annular steel ring, which is made of 4 segments to allow their transport through the first 10 m of the PRACLAY gallery, is assembled in-situ by welding. These welding operations are thus performed after the placement of the bentonite and close to the bentonite. This would result in significant heating of the bentonite (up to 200°C), causing it to lose some of its swelling capacity locally. The effect of heating the bentonite was examined in laboratory tests (*Villar, 2004*). The welding is also performed at 4 locations and over the complete axial length of the cylindrical structure. This might create a preferential pathway along the hydraulic seal.

Therefore a new design was worked out in which the welding operations after placement of the bentonite are limited. The bentonite layer in the new design is also thicker and more bentonite can be installed.

2.1.3 DESIGN SPECIFICATIONS IN THE SECOND TENDERING PROCEDURE

The general design of the hydraulic seal is illustrated in Figure 2-4, in which a cross-section of the PRACLAY gallery at the location of the hydraulic seal is shown for the different steps of the seal installation. In Figure 2-4a a cylinder is placed in the gallery behind the location of the hydraulic seal (green: Boom Clay, grey: neighbouring concrete lining, black: steel rings of the permanent part of the gallery lining at the location of the hydraulic seal; brown: wood and steel plates making up the temporary part of the gallery lining at the location of the hydraulic seal; red-orange: cylinder). The cylinder has an external diameter of 1840 mm and can pass through the gallery, which has a minimum diameter in the relevant section of ca. 1870 mm (cf. section 2.1.1). The cylinder is closed in the middle by a plate with a manhole measuring 570x570 mm. After the cylinder is placed behind the location of the hydraulic seal, the temporary part of the lining at the location of the hydraulic seal is removed (Figure 2-4b) and a flange is placed against the concrete lining on the downstream side (Figure 2-4c; red-orange: flange). Subsequently a flange is placed against the concrete lining on the upstream side (Figure 2-4d; red-orange: flange). Both flanges have the same external diameter as the PRACLAY

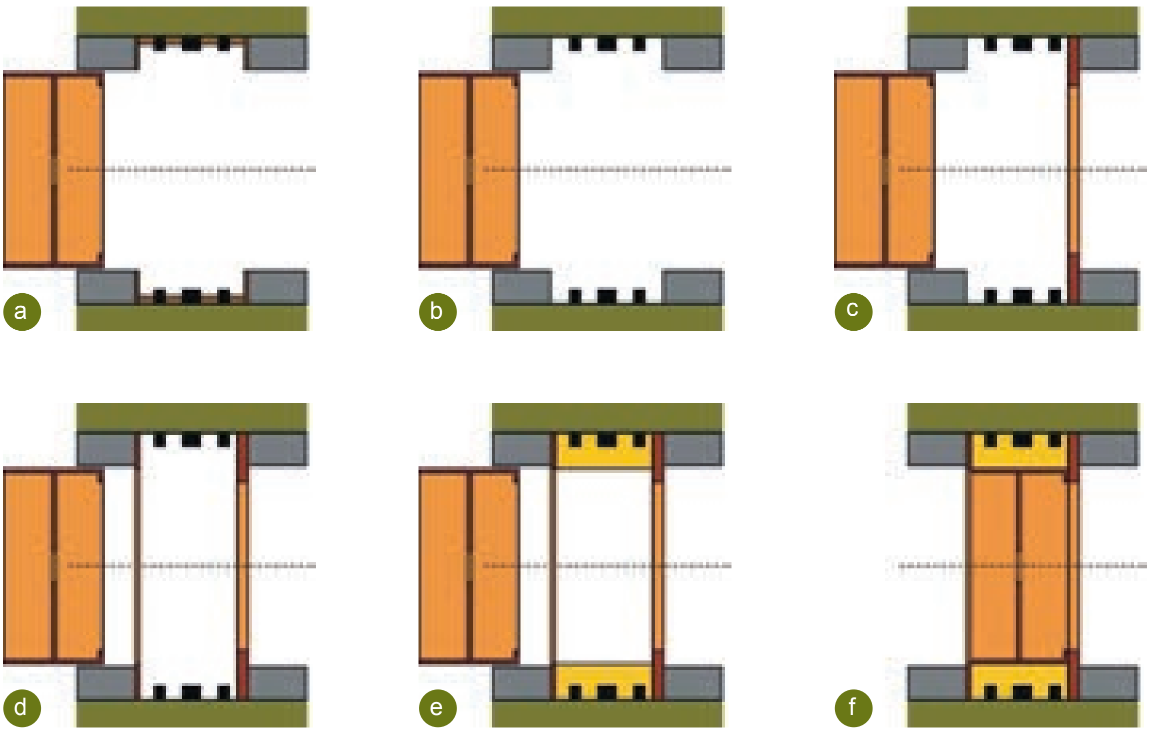


Figure 2-4: Schematic overview of the different steps of the hydraulic seal installation in a cross-section of the PRACLAY gallery at the location of the hydraulic seal (the left side of the drawings is the upstream side).

gallery, i.e. 2500 mm. The inner diameter of the downstream flange is, however, smaller than the inner diameter of the upstream flange. Because the flanges are too large to be installed in one piece, they are constructed in four segments and welded together in-situ. After both flanges are installed, bentonite blocks are placed between the flanges against the clay (Figure 2-4e; yellow: bentonite blocks). Finally the cylinder is pushed in against the downstream flange and welded to the two flanges (Figure 2-4f).

These different parts of the steel structure of the hydraulic seal – the flanges and the cylinder – are discussed below. No negative tolerances on their thicknesses were allowed and when machining (cutting, welding, etc.) was performed on these parts, it had to be guaranteed that the design thickness would be maintained.

The detailed design can be found in the technical specifications for the hydraulic seal [21].

2.1.3.1 DOWNSTREAM FLANGE

The downstream flange is 100 mm thick, and has an external diameter of 2500 mm and an internal diameter of 1580 mm. The material for the flange is stainless steel (SA182-F51). The flange is constructed in four segments, which are assembled in-situ by welding. Before the flange is placed against the concrete lining, any irregularities on the contact surface of the concrete lining have to be filled (e.g. using polypropylene sheets). This flange has 20 openings (see Figure 2-5), which are positioned circumferentially to allow feed-through of the instrumentation placed in the bentonite blocks.

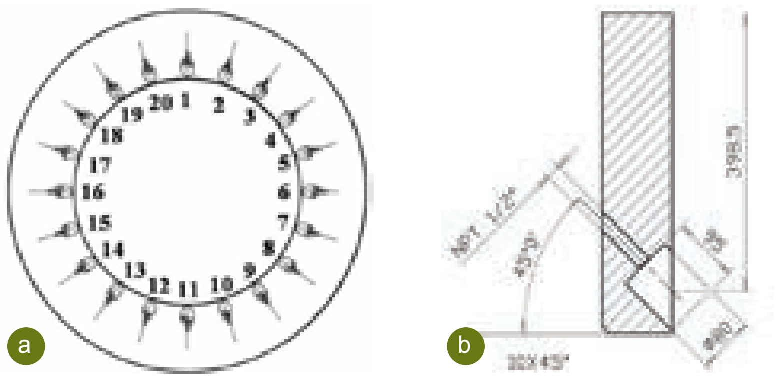


Figure 2-5: (a) 20 openings are positioned circumferentially along the downstream flange for bentonite instrumentation feed-through ; (b) detailed view of a flange opening.

2.1.3.2 UPSTREAM FLANGE

The upstream flange is 40 mm thick, and has an external diameter of 2500 mm and an internal diameter of 1844 mm. The material for the flange is stainless steel (SA240-304). This flange is also constructed in four segments, which are welded. The flange is not placed against the lining, but is positioned parallel and concentrically to the downstream flange at a distance equal to the length of the cylinder minus 20 mm. The 20 mm provides an overlap between the upstream flange and the cylinder to weld these parts together.

2.1.3.3 CYLINDER

The cylinder is 930 mm long, and has a wall thickness of 40 mm and an external diameter of 1840 mm (Figure 2-6a). No positive tolerance on the external diameter is allowed to ensure the feasibility of passing the cylinder through the upstream flange. At its downstream end, the cylinder has a 40 mm thick flange with an internal diameter of 1580 mm, equal to the inner diameter of the downstream flange.

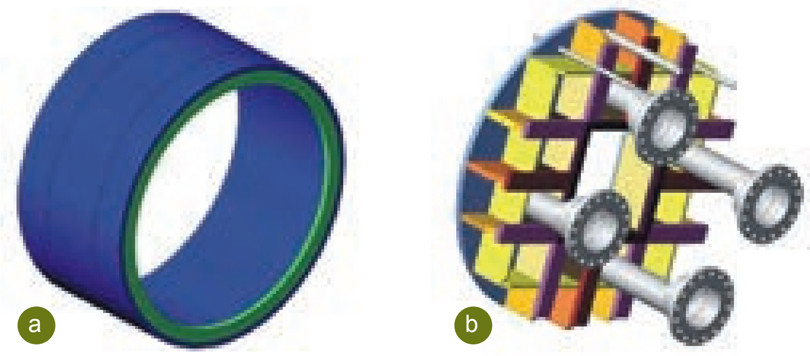


Figure 2-6: (a) Cylinder with flange on the downstream side; (b) plate in the cylinder with stiffeners, pipes and square manhole in the centre.

The cylinder is closed in the middle by a 30 mm thick plate (Figure 2-6b) equipped with stiffeners. There is a square 570x570 mm manhole in the centre. The upstream side of the cylinder has to remain accessible for the hydraulic seal installation and for the subsequent installation of the heater and backfill material in the PRACLAY gallery. After the heater and backfill installation the manhole is closed by welding a closing plate onto it. This closing plate has a central opening of 221 mm in diameter, through which a central tube housing part of the heater will be inserted. The material used for the cylinder (including the plate, stiffeners and closing plate) is stainless steel (SA240-304).

The plate in the cylinder has different openings for the feed-through of the instrumentation and the heating system placed in the upstream part of the gallery (Figure 2-6b). After the installation of the cylinder and its assembly to the flanges, pipes are welded in these openings. The smaller pipes at the top of the plate are to be fitted with collars. The four larger pipes are to be fitted with reducing unions 6” to 10” and flanges and counter-flanges with bolting and gaskets at the end (downstream side) to ensure a good seal.

Filters are placed on the extrados (outer surface) of the cylinder for the artificial hydration of the bentonite. The configuration of the injection system is shown in Figure 2-7. Two rings of filters are installed: in cross-

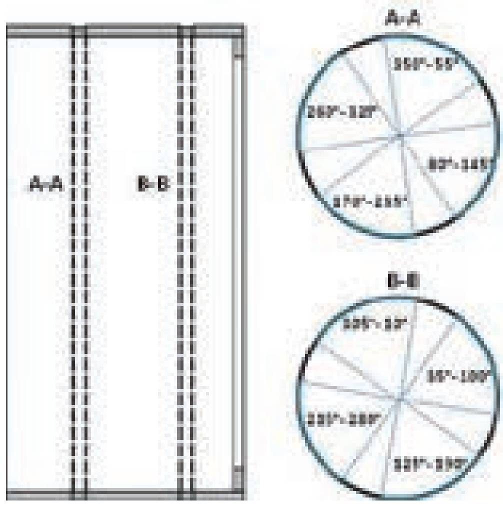


Figure 2-7: Layout of the filters placed at the extrados of the cylinder.

section A-A and in cross-section B-B. The filters do not cover the complete circumference. They cover 4 radial sections of 65° with an offset of 45° between cross-section A-A and cross-section B-B.

The filters are 50 mm wide and 3 mm thick (Figure 2-8). They are placed in an opening leaving 1 mm void above and below the filter. Each filter is fed by two channels 6 mm in diameter, one on each side of the filter section.

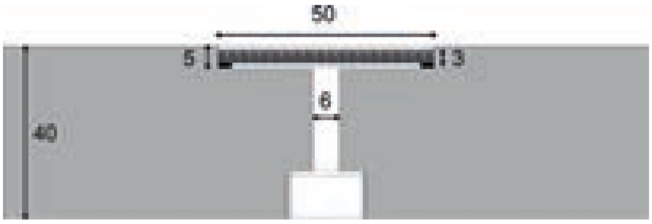


Figure 2-8: Filter dimensions.

The filters need to have a high grade efficiency[2] to avoid them being clogging by the bentonite. The filters are SIKA-R1 AX having a grade efficiency$_{x=98\%}$ of 1.8 µm. This means that very fine particles (in the order of micrometres) cannot penetrate the pores of the filter material.

2.2. Bentonite blocks

The bentonite blocks have to exert a sufficiently high swelling pressure on the Boom Clay to create a quasi-impermeable zone around the hydraulic seal. The minimum swelling pressure[3] is 2.5 MPa to avoid negative effective stresses in the Boom Clay around the hydraulic seal, as the maximum pore water pressure during the Heater Test is estimated at 2.5 MPa. The maximum swelling pressure is 6 MPa. Higher swelling pressure might lead to fracturing of the clay around the seal. Furthermore its hydraulic conductivity in the saturated state is as low as possible (at least lower than the conductivity of undisturbed Boom Clay ($\approx 10^{-12}$ m/s) and preferably one order of magnitude lower) (cf. section 2.1.1).

In the context of geological disposal of nuclear waste, different types of bentonite have been studied, such as FoCa clay, Febex S-2 and MX80. For the selection of the type of bentonite, no strict criteria were defined and followed. It was decided to use MX80 bentonite based on the following arguments:

- MX80 bentonite compacted to the correct dry density presents sufficiently high swelling and water retention potential and sufficiently low hydraulic conductivity;
- MX80 bentonite is a sodium-dominated bentonite and is thus compatible with the Boom Clay, whose water chemistry is also sodium dominated (14 mM $NaHCO_3$);
- the interaction between MX80 bentonite and Boom Clay has not been studied yet and relevant experience with and information on this type of bentonite exists from its use in other experiments in underground research facilities (Mont Terri, Bure, ASPO, AECL's URL) and in the laboratory (by CEA, CIEMAT, CERMES and SKB).

[2] The grade efficiency is a measure to indicate the efficiency with which particles in a mixture of solids and fluids are separated. This efficiency mostly depends on the size of the particles and is expressed by the grade efficiency curve (ASTM F795).

[3] Swelling pressure in this context means the pressure the bentonite exerts on the clay when the bentonite is hydrated. As the Boom Clay around the bentonite ring will be compressed during hydration of the bentonite, the bentonite can expand and the term swelling pressure, as used in this report, is not the swelling pressure of the bentonite in perfectly confined conditions.

The MX80 is compacted into blocks, which are assembled into different rings of bentonite (Figure 2-4e). The layout of these bentonite rings is shown in Figure 2-9. Four rings of bentonite form an outer layer with an internal and external diameter of respectively 2280 mm and 2500 mm. Seven rings form an inner layer with an internal and external diameter of respectively 1860 mm and 2260 mm. Between the inner and outer layer and between the steel cylinder and inner layer is a technological gap of 10 mm. This leads to a theoretical ratio of 11% for the initial void volume to the initial bentonite volume.

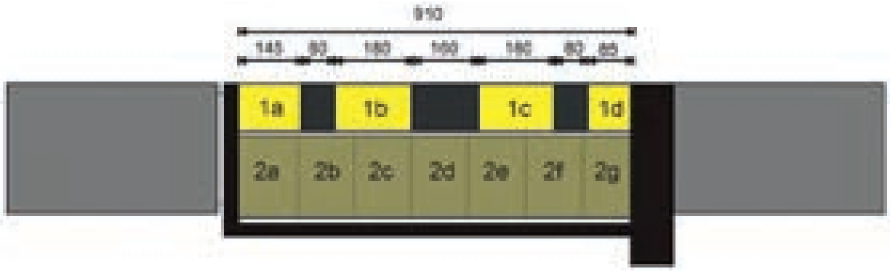


Figure 2-9: Layout of the annular bentonite ring.

The most important parameter to be determined for the bentonite is its initial dry density. This parameter determines its swelling pressure and its final saturated hydraulic conductivity. The desired initial dry density was determined by scoping calculations, taking into account the technological void and the interaction with the Boom Clay [22]. An initial dry density of 1.8 t/m³ was selected, resulting in a final swelling pressure of ca. 4 MPa (Figure 2-10). The saturated hydraulic conductivity is 10^{-13} m/s, which is one order of magnitude smaller than the in-situ hydraulic conductivity of Boom Clay.

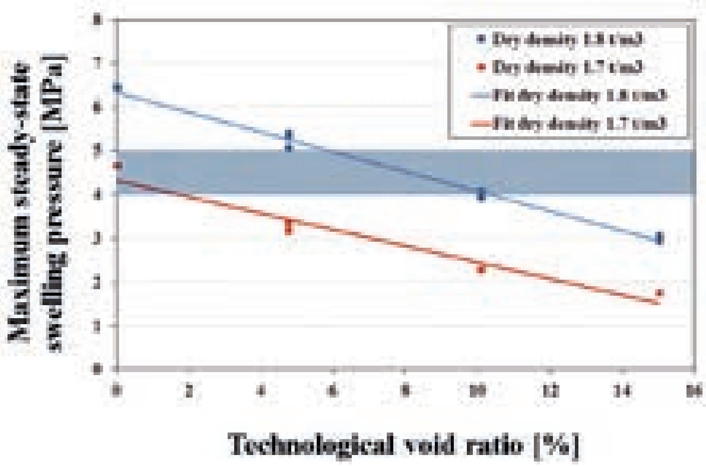


Figure 2-10: Swelling pressure as a function of the technological void and for different initial dry densities (from scoping calculations).

Figure 2-11 shows the modelled swelling pressure generated by the fully saturated MX80 (initial dry density: 1.8 t/m³; technological void: 11%) on the Boom Clay interface [22]. The steel rings of the alternative lining at the location of the hydraulic seal have a significant effect on the swelling pressure. As these rings cannot move outward, an inhomogeneous distribution of the swelling pressure on the clay is obtained. Allowing the outward movement of the steel rings would make the swelling pressure distribution more homogeneous (Figure 2-11). The sharp changes in the pressure profile result from the numerical model used.

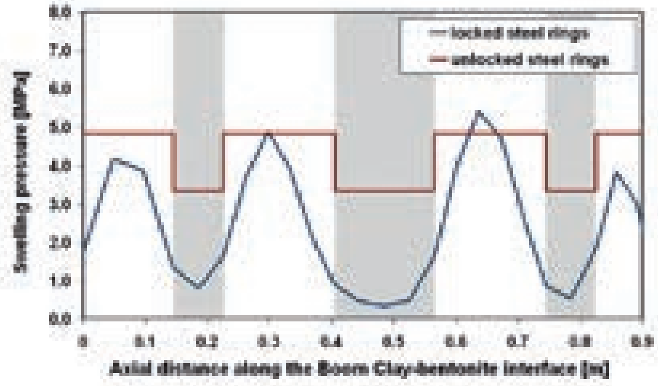


Figure 2-11: Pressure exerted by the bentonite along the Boom Clay–bentonite interface in the event of locking and unlocking the steel lining rings (indicated by the grey bars).

The saturation degree in the bentonite before full saturation is quite inhomogeneous due to the localised injection filters and the presence of the steel rings (Figure 2-12). Figure 2-13 shows the calculated hydration time required to achieve an overall degree of saturation in the bentonite (this is the degree of saturation of the least saturated location in the bentonite). The initial saturation of the bentonite blocks is 84% [22].

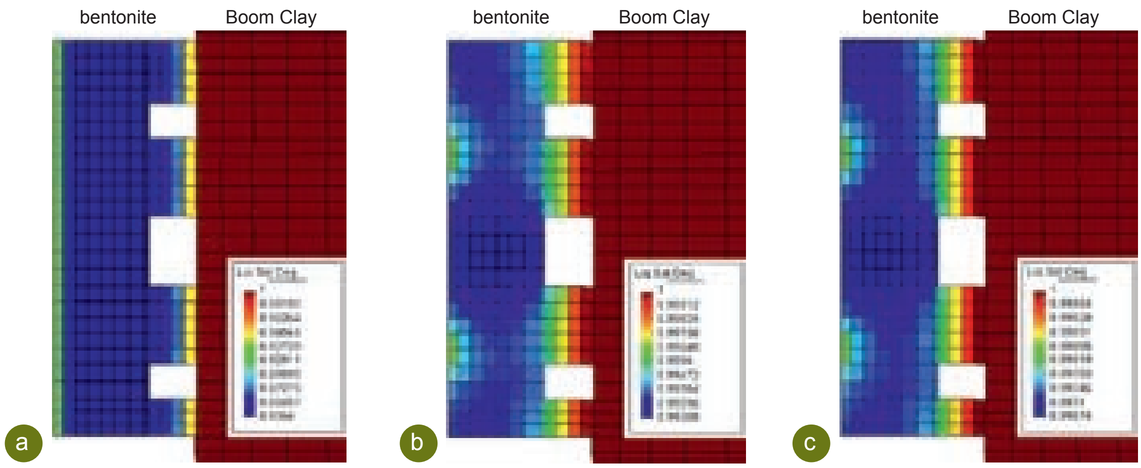


Figure 2-12: Distribution of the degree of saturation in the bentonite (the steel rings are coloured white): (a) after 1 day of hydration; (b) after 1 year of hydration; (c) after 1.5 years of hydration.

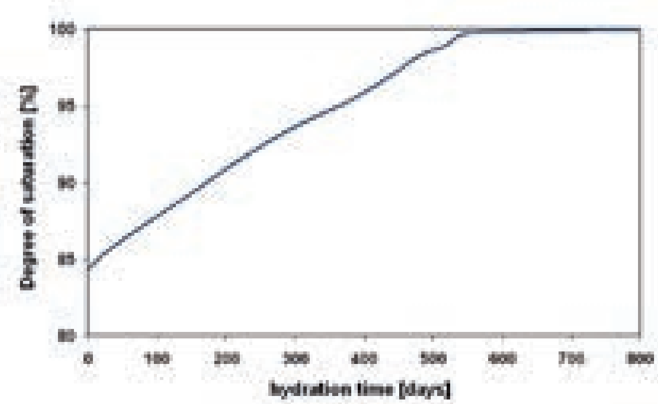


Figure 2-13: Degree of saturation of the least saturated location in the bentonite as a function of the time after starting the hydration (according to modelling).

Also some laboratory tests were performed to evaluate the hydraulic resistance of the bentonite–Boom Clay interface and to evaluate the hydration process on the bentonite surface, as it is believed that the performance of the seal greatly depends on the interface characteristics. The hydraulic resistance of the bentonite–Boom Clay interface was examined in laboratory percolation tests at 20 and 80°C at CERMES [23]. All tests indicated that the hydraulic resistance of the soil-wall interface was higher than 5 MPa. As these tests are not completely representative of the real case, other tests will be performed in a later phase to evaluate the hydraulic resistance of this interface.

Another potential risk was the disintegration of the bentonite during hydration. This was also tested by placing MX80 bentonite blocks in a transparent cell, filling the cell with water and observing the hydration of the bentonite. It was concluded from these simple tests that there is no risk of disintegration of the blocks during hydration [24].

To be able to monitor the behaviour of the bentonite during its hydration, instrumentation is placed in the bentonite [6]. The following sensors were to be installed:

- 16 total pressure cells (flatjack);
- 10 total pressure cells (Kulite);
- 35 thermocouples;
- 21 piezometers of which 13 have a moisture sensor embedded;
- 3 extensometers;
- 3 Hukseflux thermal conductivity probes.

In addition 12 strain gauges are placed on the steel rings of the alternative lining at the location of the hydraulic seal. The sensors are placed in 3 sections (Figure 2-14). The sensor layout of these sections is shown in Figure 2-15. The extensometers are placed in different sections (indicated in red in Figure 2-14).

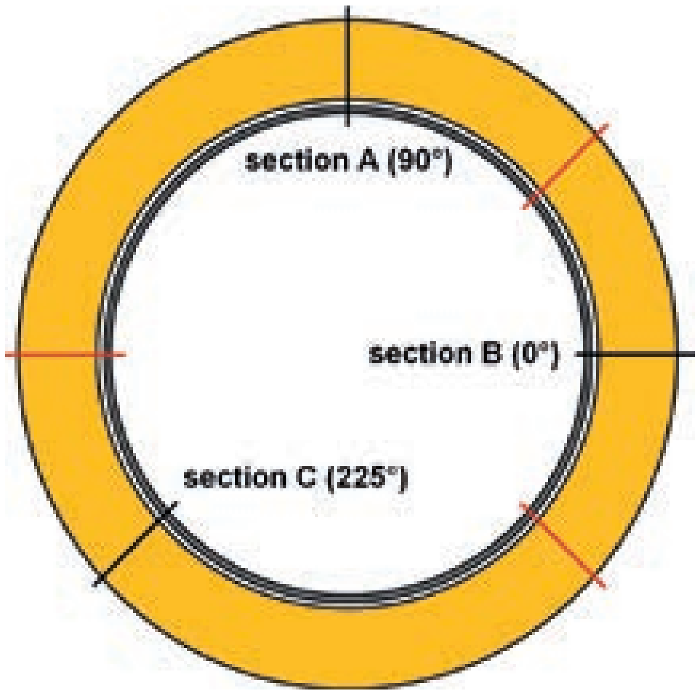


Figure 2-14: Overview from the downstream side of the instrumented sections in the bentonite rings (the red lines indicate the position of the extensometers).

The feed-through of the sensor cables is done through 20 openings placed in the downstream flange (cf. section 2.1.3.1; Figure 2-5).

Figure 2-15: Instrumentation in the different sections:
(a) section A; (b) section B; (c) section C.

2.3. Expert panel on seal design

An expert panel was gathered with the purpose of:

- obtaining feedback on the design of the hydraulic seal;
- identifying the most critical issues related to the performance of the hydraulic seal;
- getting recommendations on how to test the performance of the hydraulic seal;
- identifying the main issues and open questions related to the Seal Test.

The expert panel was composed of the following participants:

- Prof. Yujun Cui (CERMES, France);
- Dr. David Dixon (AECL, Canada);
- Dr. Claude Gatabin (CEA, France);
- Dr. Maria Villar (Ciemat, Spain).

A meeting with the experts was held on 23.06.2008 and 24.06.2008 at EURIDICE. Beforehand a report on the design of the hydraulic seal and its role in the PRACLAY In-Situ Experiment was prepared and handed over to the experts [24].

In conclusion, no fundamental flaws in the design of the hydraulic seal were identified by the experts. Some suggestions for further optimisation were made, some of which were taken into account in the design of the hydraulic seal or in the design of the Heater Test. The most important remarks and suggestions from the expert panel and the measures taken in this respect are listed below:

- In the design of the seal, the downstream flange is placed against the gallery lining. The upstream flange is placed at a given distance from the downstream flange and will not touch the gallery lining. The gap between the upstream flange and the lining has to be filled to minimise the risk of creating a preferential pathway along this interface. As the steel structure will be subjected to a water pressure of 3.5 MPa on its upstream side, a small displacement of the seal is possible. Therefore the use of a swelling material to fill the gap is recommended.
  > The gap was filled with mortar (cf. Figure 5-30d).

- An air bleeding system should be provided during the bentonite hydration. Also hydrating from bottom to top is advised to facilitate the evacuation of air. Moreover, notwithstanding the fact that the simple tests observing bentonite hydration in cells indicated that there is no risk of the bentonite blocks disintegrating during hydration, a low injection pressure should be applied to avoid erosion of the blocks. The injection of hot water can be envisaged to accelerate the hydration process.
  > The water injection was done from bottom to top and at a low pressure. Air venting was done with the piezometers placed in the upper part of the bentonite. Injecting hot water is difficult, but heating elements were placed at the intrados (inner surface) of the cylinder. It was later decided not to heat the bentonite, as this might complicate interpretation of the bentonite hydration process and further installation work of the PRACLAY In-Situ Experiment (cf. section 5.2.5).

- The steel rings should be unlocked, allowing them to move outwards and achieve a more homogenised swelling pressure distribution on the Boom Clay sidewall (cf. section 2.2).
  > The rings were unlocked at two locations (cf. section 5.2.1).

- The performance of the seal should be tested before starting the Heater Test. The following tests or analyses can contribute to an evaluation of the seal performance: an overall analysis of the results from the instrumentation placed in the bentonite, testing the hydraulic reaction between the different filters placed in the bentonite, gas build-up tests using the filters and measurements of the hydraulic conductivity.
  > The performance of the seal was tested before starting the Heater Test (cf. section 6.2).

More detailed information on the feedback from the expert panel can be found in the report by the expert panel [25].

3. Tendering procedure

A restricted call for tenders was applied as contract award procedure for the construction and installation of the hydraulic seal. This procedure was also used for the construction of the Connecting and PRACLAY galleries and it proved to be the most appropriate tendering procedure, having the following advantages:

- The procedure entailed a pre-selection of candidate contractors. This offered the advantage of being able to rule out contractors not qualified for this type of work.
- An evaluation of the tenders solely based on the cost, as would have been the case with a standard tendering procedure, would have been inadequate.

An official announcement was made in the Belgian Official Gazette on 25.05.2007. Only one candidate applied and after having passed the pre-selection, submitted a bid for a total price of ca. 495,000 euros. This bid was rejected because the price was considered to be too high. The cost of manufacturing the steel structure of the hydraulic seal and its underground installation had been pre-estimated to be between 150,000 and 200,000 euros. The bid price was thus about 3 times the estimate.

A new tendering procedure, a negotiation procedure, was launched and published in the Belgian Official Gazette on 13.12.2007 [26]. As part of the new procedure, the design of the hydraulic seal was also optimised (cf. section 2.1).

Three candidates applied, two of which passed the pre-selection. After the tender documents were given to the potential contractors, one candidate withdrew from the tendering procedure and eventually only one potential contractor submitted a bid. After negotiation, the candidate was asked to submit a BAFO (Best And Final Offer). The price of the BAFO amounted to ca. 570,000 euros. This was accepted based on the following arguments:

- The PRACLAY Heater Test has to be started as soon as possible to provide initial results for Safety and Feasibility Case 1 in 2013. The start-up of this test awaits the installation of the hydraulic seal.
- The earlier tendering procedure launched resulted in a similar outcome, where only one bid was received and was much higher than the estimated cost. It appears to be unlikely that a substantially lower price will be obtained and it is difficult to find candidates with the necessary know-how to be able to execute the underground installation.
- The estimation was based on a preliminary design and probably underestimated the complexity and scale of the construction work and underground installation.

The contract was finally awarded to SMET TUNNELLING in October 2008. Table 3.1 gives the history of the complete tendering procedure.

25.05.2007	Announcement in the Belgian Official Gazette (ref. N. 5879)
30.06.2007	Deadline for potential candidates to enter the procedure
07.08.2007	Decision of the steering committee of EURIDICE about the prequalification of 1 potential candidate (ref. EURIDICE 07-032/BC)
07.08.2007	Invitation to tender letter sent to the selected candidate, including the tender documents [26] (ref. EURIDICE MD/bp/07-240)

10.09.2007	Original deadline for receipt of the bids. Because of the specific nature of the contract, the deadline was postponed until 26.09.2007 (ref. EURIDICE MD/bp/07-253).
26.09.2007	Receipt of the bid
20.11.2007	Rejection of the bid by the steering committee of EURIDICE and decision to relaunch the contract based on a negotiation procedure without prior notification (ref. EURIDICE 07-048/BC)
13.12.2007	Announcement in the Belgian Official Gazette (ref. N. 16809)
16.01.2008	Deadline for potential candidates to enter the procedure
18.03.2008	Decision of the steering committee of EURIDICE about the prequalification of 3 potential candidates (ref. EURIDICE 08-004/BC and HVH/bp/08-129)
18.03.2008	Invitation to tender letter sent to the 2 selected candidates (ref. EURIDICE MD/bp/08-135)
11.06.2008	The tender documents were given to the 2 selected candidates (ref. EURIDICE PDP/bp/08-160 and PDP/bp/08-161)
17.06.2008	Withdrawal of one candidate from the tendering procedure
11.07.2008	Receipt of the bid
29.08.2008	Invitation letter to submit a Best And Final Offer (ref. EURIDICE PDP/bp/08-182)
10.09.2008	Receipt of the BAFO
23.09.2008	Decision of the steering committee of EURIDICE to award the contract (ref. EURIDICE 08-032/BC)
13.10.2008	Award of the contract to SMET TUNNELLING (ref. EURIDICE PDP/bp/08-203)
20.10.2008	Signing of the contract (T_0)

Table 3.1: Timeline of the tendering procedure.

4. General organisation of the work

The construction and installation of the hydraulic seal involved four main parties. SMET TUNNELLING, together with its subcontractor STORK MEC, was contracted by EURIDICE for the execution of the project. Engineering office TRACTEBEL ENGINEERING was contracted to provide EURIDICE with technical assistance. A detailed planning schedule for the project can be found in the construction documents [27].

The project teams involved in the installation of the hydraulic seal mainly comprised the following people:

- for EURIDICE:
  - > Peter De Preter, site manager and project manager, in charge of overall supervision and budgetary control of the project;
  - > Xiangling Li, scientific manager, in charge of all scientific aspects;
  - > Pascal Deboodt, safety coordinator, in charge of all safety aspects;
  - > Philippe Van Marcke, project engineer, responsible for technical and administrative monitoring of the project and coordination between all parties;
  - > Jan Verstricht, scientific engineer.

- for SMET TUNNELLING:
  - > Bart Vanhout, project manager;
  - > Wouter Roels, project engineer;
  - > Guy Vangenechten, construction supervisor, responsible for correct and safe execution of the work.

- for STORK MEC:
  - > Kevin Bollaert, project engineer.

- for TRACTEBEL ENGINEERING:
  - > Alain Van Cotthem, lead engineer for the setting up of the technical specifications and for the construction work;
  - > Zohra M'Talssi, contract manager;
  - > Geneviève Brennet, design engineer;
  - > Arturo Suarez, performing quality checks.

The whole project can be divided into three main phases characterised by different kinds of activities and during which the various parties fulfilled different roles:

- the design of the hydraulic seal and the contract award procedure;
- the construction work;
- the underground installation work and the monitoring activities during construction.

4.1. Design development and contract award procedure

The various aspects of the contract award procedure were the responsibility of the following parties:

- development of the initial design: TRACTEBEL ENGINEERING in close cooperation with EURIDICE;
- announcement of the project and prequalification in the framework of the restricted call for tender procedure: EURIDICE assisted by D-Consult and TRACTEBEL ENGINEERING;

- setting up of the technical specifications: TRACTEBEL ENGINEERING in close cooperation with EURIDICE;
- evaluation of the tenders submitted by the various candidate contractors: EURIDICE assisted by D-Consult and TRACTEBEL ENGINEERING;
- administrative tasks: EURIDICE.

4.2. Construction work

The construction of the steel structure of the hydraulic seal was done by STORK MEC as a subcontractor of SMET TUNNELLING. The existing technical specifications were also turned into detailed work plans and procedures by STORK MEC. These plans and procedures were checked by TRACTEBEL ENGINEERING for technical correctness and compliance with the technical specifications, and had to be approved by EURIDICE and TRACTEBEL ENGINEERING before the corresponding work could be started. Quality checks of the structure during the construction work were performed by TRACTEBEL ENGINEERING.

4.3. Underground installation and monitoring of the work

The installation work was executed by SMET TUNNELLING, except for the installation of the bentonite, which was done by EURIDICE with the assistance of SMET TUNNELLING. The welding operations were performed by STORK MEC as a subcontractor of SMET TUNNELLING. Passivation of the welds was done by SMET Jet as a subcontractor of STORK MEC. Furthermore GEOMODUS was contracted by SMET TUNNELLING to assist in the positioning of the flanges (cf. sections 5.2.2 and 5.2.3) and JAMES WALKER was present during the assembly of the downstream flange to assist in using the resin (cf. section 5.2.3).

From the removal of the temporary lining at the location of the hydraulic seal until the assembly of the cylinder to the downstream flange, a work schedule of 24 hours a day/7 days a week was introduced, involving 2 shifts of 12 hours. This schedule was followed to minimise the convergence of the clay after the removal of the temporary lining and to minimise the drying of the bentonite blocks during their installation. The preparatory work (such as the adaptation of the site infrastructure and the transport of the seal components underground) and the welding of the cylinder to the upstream flange and the pipes to the cylinder were performed by one team of workers, who maintained a schedule of 12 hours a day for 5 days a week.

The installation work was monitored by means of daily and weekly meetings between EURIDICE and SMET TUNNELLING and by field inspections, which aimed to gain an overview of the progress of the work, discuss the encountered difficulties and any unsafe situations, and decide on actions to be taken.

5. Construction and installation of the hydraulic seal

The construction and installation of the hydraulic seal can be subdivided into (1) the construction of the hydraulic seal, including the fabrication of the bentonite blocks, and (2) its actual underground installation. The main safety issues related to the installation work are discussed at the end of this chapter.

Detailed information (construction drawings, procedures, calculation notes, material specifications, meeting reports, etc.) on the construction and installation of the hydraulic seal can be found in the construction documents for the hydraulic seal [27].

5.1. Construction of the hydraulic seal components

The hydraulic seal mainly consists of two parts: a steel structure and bentonite blocks. The steel structure was manufactured by STORK as a subcontractor of SMET TUNNELLING. The bentonite blocks were fabricated by MPC.

5.1.1 STEEL STRUCTURE

The construction of the steel structure was planned to start 3 months after the signing of the contract and the complete construction would take about 15 weeks. The bottleneck was the long delivery period for the stainless steel for the downstream flange. During the construction work, quality checks, mostly weld inspections, were performed by TRACTEBEL ENGINEERING. The as-built plans of the steel structure can be found in the construction documents [27].

After the signing of the contract two significant design changes were made:

- the assembly of the segments of the downstream flange by welding was abandoned and replaced by assembly using bolts, gaskets and a resin (cf. section 5.1.1.1);
- the assembly of the segments of the upstream flange by welding was abandoned as well and replaced by assembly using bolts (cf. section 5.1.1.2).

Besides these two changes, some smaller adjustments were made during the construction phase:

- the inner diameter of the upstream flange was increased from 1840 mm to 1844 mm to facilitate the passage of the cylinder through the flange;
- 3 openings were made in the cylinder to allow the installation of an extensometer in the bentonite (cf. section 2.2);
- opening T3 was enlarged from 62 mm in diameter to 150 mm in diameter and a plug was made to close off this opening;
- the dimensions of several welds were changed.

After all components of the steel structure – the cylinder, the flanges, the closing plate and the pipes – had been constructed a test assembly was performed in the workshop to test their compatibility and to check the feasibility of assembling them (cf. section 5.1.1.3).

5.1.1.1 DESIGN CHANGE DOWNSTREAM FLANGE

In the initial design the 4 segments of the downstream flange were to be assembled using a full penetration weld. Because the flange is placed against the lining of the gallery, welding can only be done from one side of the flange. Welding over the whole thickness of the flange (100 mm) from only one side would result in excessively large deformations on the flange and would thus obstruct the assembly of the flange and the cylinder. Therefore an alternative design was needed in which no welds, or at least only relatively small welds not jeopardising the assembly of the cylinder and the flange, would be used.

The design has to provide a connection between the segments that is significantly strong (the forces working on the structure are given in section 2.1.1) and that is watertight. After consulting some companies specialising in sealing products, an alternative design was worked out by JAMES WALKER (see Figure 5-1) [28].

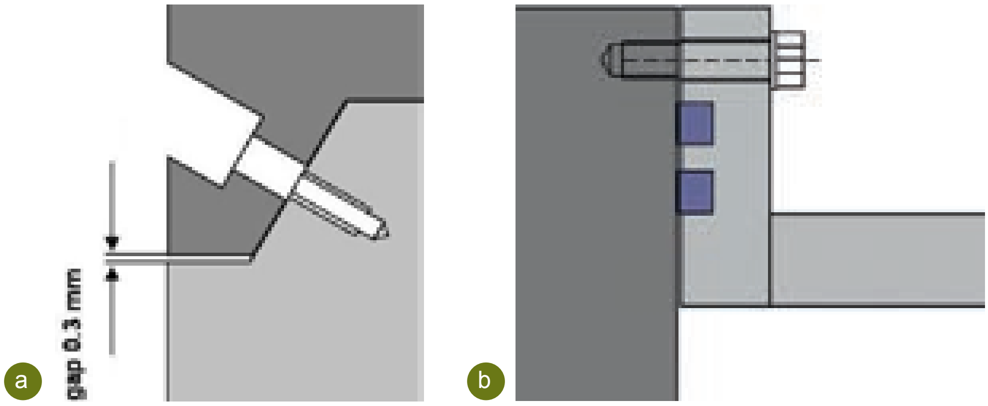


Figure 5-1: Alternative design for: (a) the assembly of the segments of the flange using bolts and a resin applied in a 0.3 mm gap; (b) the assembly of the cylinder (light grey) to the downstream flange (dark grey) is done using two gaskets (blue) and bolts.

The segments are equipped with a "sloping tooth" and are connected by 3 bolts for each segment connection. The watertightness of the connection is achieved using a resin that is applied in a gap of 0.3 mm. The resin is composed of 2 components: a hardener (Weicon AN305-18) and an activator spray speeding up the curing of the product. Both components are mixed in-situ, after which the two-component resin can be worked for 2 hours. The curing time is 36 hours. The resin is chemically compatible with the stainless steel of the flange and keeps its functionality under the experimental conditions of 3.5 MPa water pressure and 90°C. A one-component product (Weicon AN302-18) is applied on the thread of the bolts to guarantee their watertightness. The holes for the bolts are subsequently filled with a two-component resin (Weicon TI).

When welding the cylinder to the flange, the temperature might exceed 90°C locally and this might damage the sealing resin applied during the assembly of the segments of the downstream flange. Welding was therefore also abandoned and the cylinder was to be bolted to the flange using M18 rotabolts with a tension control indicator set load of 13 tonnes. The watertightness of the connection is guaranteed by 2 gaskets that are placed in a specially made opening in the cylinder. The outer gasket protects the inner gasket during the bentonite hydration, while the inner gasket ensures watertightness. To ensure that the gaskets function properly, the surface roughness of the touching surfaces was specified at 0.8 Ra.

Some small-scale tests were performed with the resin by applying it on small stainless steel dummy samples to gain practice and confidence with the product [29].

The development of this alternative design took about 4 months [30]. An additional delay of 10 weeks resulted from the extra construction time that was needed to make the "sloping tooth" and the openings for the gaskets, and to achieve the stricter surface roughness requirements.

5.1.1.2 DESIGN CHANGE UPSTREAM FLANGE

As for the downstream flange, the segments of the upstream flange were likewise to be welded together. But again the risk of the design weld of 20 mm overly deforming the flange was considered to be too high. The flatness of the flange was not as crucial as for the downstream flange, but the deformations might reduce the inner diameter of the flange (1844 mm) and obstruct the passage of the cylinder (1840 mm in outer diameter) through the opening.

Consequently, an alternative assembly method for the segments of the upstream flange was also required [31]. In this design 2 segments are connected by placing a plate over their interface and bolting the plate to both segments (Figure 5-2). Two 5 mm welds at the top and bottom of the "assembly plate" are placed to make the connection watertight. These welds are considered to be sufficiently small not to overly deform the flange.

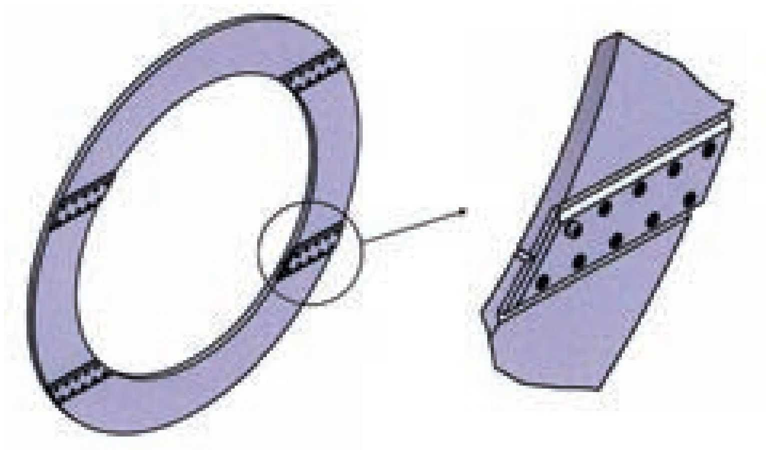


Figure 5-2: The segments of the upstream flange are connected by bolting a plate over the connection.

The development and construction of the alternative design for the upstream flange did not cause any delays in the overall planning of the project.

5.1.1.3 TEST ASSEMBLY

A test assembly was performed in the workshop of STORK to check the compatibility of the different components and the feasibility of assembling them. The test assembly was done in three phases. On 14.12.2009 the segments of the downstream flange were assembled and the flange was bolted to the cylinder. The eight filters placed at the extrados of the cylinder (cf. section 2.1.3.3) were tested on 23.12.2009. These filters appeared to have some fissures (Figure 5-3). These fissures were created when the filters were welded. The maximum length of the filter material SIKA R1AX that could be ordered was 300 mm. Several of these filters had to be welded together to achieve the required radial length of ca. 1000 mm. During this welding process, the pores of the very porous material joined up and formed fissures due to the traction created by welding.

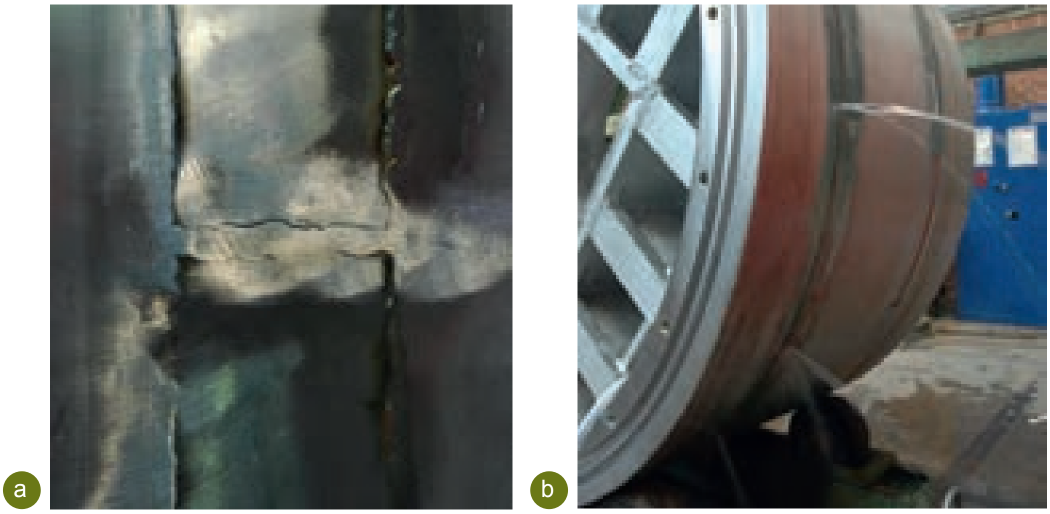


Figure 5-3: (a) Fissure in the filter; (b) Water leakage through fissures in the filters during the testing of the filters.

These fissures were treated on 12.01.2010 with a resin (Weicon HB300), which had to cure for 48 hours. On 14.01.2010 the filters were tested again. The filters functioned well and a uniform water outflow was obtained.

Finally on 07.01.2010 the following aspects were successfully checked:

- assembly of segments of the downstream flange (Figure 5-4a-c);
- assembly of the downstream flange to the cylinder with the 2 gaskets placed in their designated groove in the cylinder (Figure 5-4d);
- assembly of the upstream flange (Figure 5-4e-f);
- passage of the upstream flange over the cylinder.

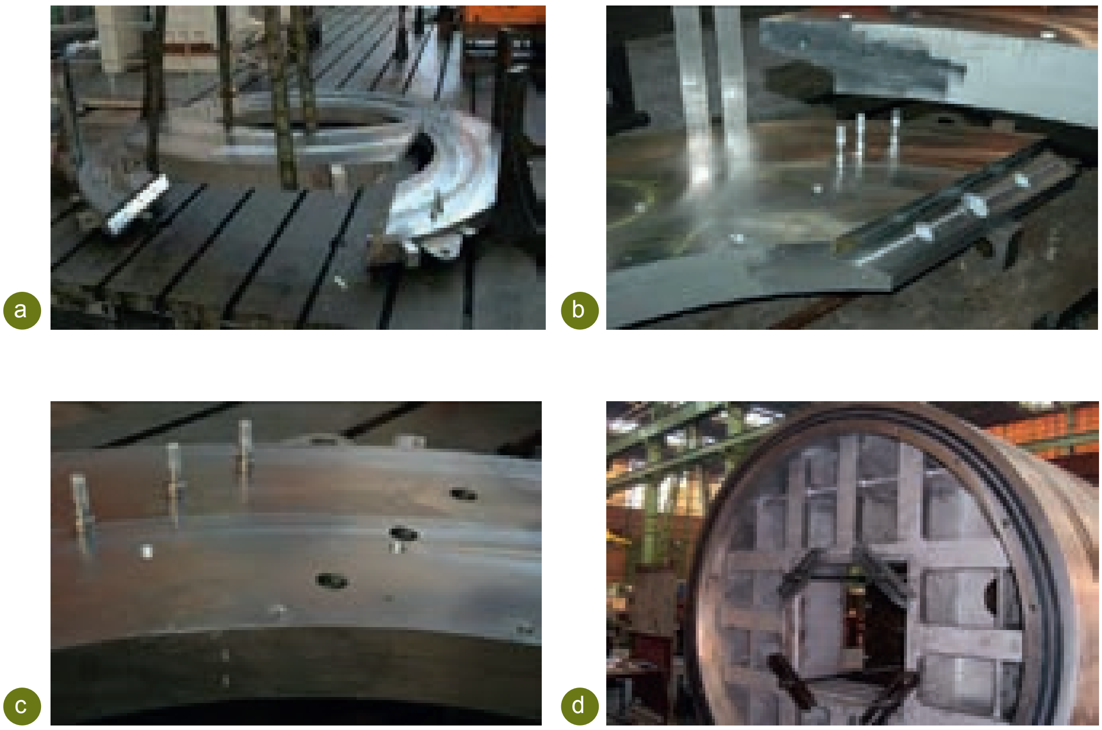


Figure 5-4: Test assembly in the workshop:
(a) assembly of the four segments of the downstream flange; (b) the segments are assembled using a “tooth” connection that is bolted; (c) tight connection between the segments; (d) placing of the two gaskets in their designated groove in the cylinder flange; (e) assembly of the four segments of the upstream flange; (f) the segments are assembled by bolting a closing plate over the connection between the segments.

The test was checked by EURIDICE, SMET TUNNELLING and JAMES WALKER. TRACTEBEL ENGINEERING inspected the steel structure in the workshop on 12.01.2010. Once all parties had given their approval, the components of the steel structure were transported to EURIDICE on 12.01.2010.

5.1.2 BENTONITE BLOCKS

The bentonite blocks were fabricated by MPC in December 2008. The blocks were compacted using steel moulds (made by TELLUS). Because of the high cost of these moulds, only 2 types of blocks are made: outer layer blocks and inner layer blocks (Figure 5-5). The outer blocks are 190 mm wide and 110 mm thick. The inner blocks are 134 mm wide and 200 mm thick. The outer layer has an internal diameter of 2280 and an external diameter of 2500 mm. The inner layer has an internal diameter of 1860 mm and an external diameter of 2260. The inner blocks also have a bulge and hole so that they can slot into each other. The outer layer blocks weigh approximately 8.6 kg, the inner layer blocks approximately 13.0 kg. The blocks were cut to their desired dimensions in-situ (cf. section 5.2.4).

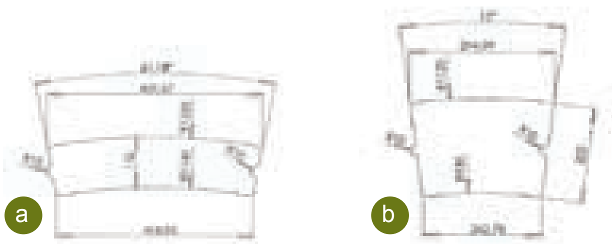


Figure 5-5: Two types of bentonite blocks are made: (a) blocks for the outer bentonite layer and (b) blocks for the inner bentonite layer.

The CEA mould used in the large-scale ESDRED mock-up test was re-used as the inner layer mould. The thickness of this mould limited the available thickness of the bentonite mixture in the mould to 230 mm. When the bentonite mixture was compressed into bentonite blocks, the thickness was reduced by a factor of 1.8. The compaction was however done in different steps. By using 3 compaction steps the desired width of 190 mm was achieved. In the first two compaction steps the blocks were compressed at a pressure of 45 MPa, while in the last compaction step a pressure of 60 MPa was applied [32].

CEA was contracted to perform some checks and tests on the blocks [33]. The following parameters were determined or verified in the CEA laboratory before the blocks were fabricated:

- the compaction pressure and initial degree of saturation;
- the post-swelling of the blocks;
- the final swelling pressure taking into account a technological void of 10–15%.

During fabrication, the dimensions and homogeneity of one out of every 20 blocks were checked. Also one block was sent to CEA to determine its swelling pressure in the lab for different values for the technological void [33].

After fabrication the blocks were wrapped in film to prevent them from dehydrating (Figure 5-6). They were transported to the site on 23.12.2008. There the blocks were stored in a climatised area at a constant temperature of 19°C and 60% humidity.

Figure 5-6: (a) Outer layer bentonite block; (b) Inner layer bentonite block.

After the delivery of the blocks it was realised that the extrados of the wood of the temporary part of the alternative lining at the location of the hydraulic seal was placed 10 mm more to the interior than the extrados of the steel rings (Figure 5-7). The wood was therefore 100 mm thick and had an external diameter of 2480 mm instead of 2500 mm. The diameter of the clay sidewall was therefore 2480 mm instead of 2500 mm. To correct this mismatch, the blocks from the outer layer were scoured over 10 mm at their extrados.

Figure 5-7: The alternative lining at the location of the hydraulic seal
during a test assembly on the surface.

As a result the original layout (Figure 2-9) is slightly adjusted, as the outer layer of bentonite is 100 mm thick instead of 110 mm and has an external diameter of 2480 mm instead of 2500 mm.

5.2. Installation of the hydraulic seal

After the test assembly in the workshop, the components of the steel structure were transported to the site of EURIDICE on 12.01.2010. On 13.01.2010 the cylinder was brought to the underground laboratory. Because the cumulative weight of the cylinder and the lift cage used for personnel and material transport exceeded the allowable weight on the cable, the cage was removed from the cable and the cylinder was directly hung on the cable (Figure 5-8a). Once in the underground laboratory the cylinder was moved on rails and positioned in front of the opening of the PRACLAY gallery (Figure 5-8b). The other parts of the steel structure, such as the segments of the flanges, were brought down with the lift cage.

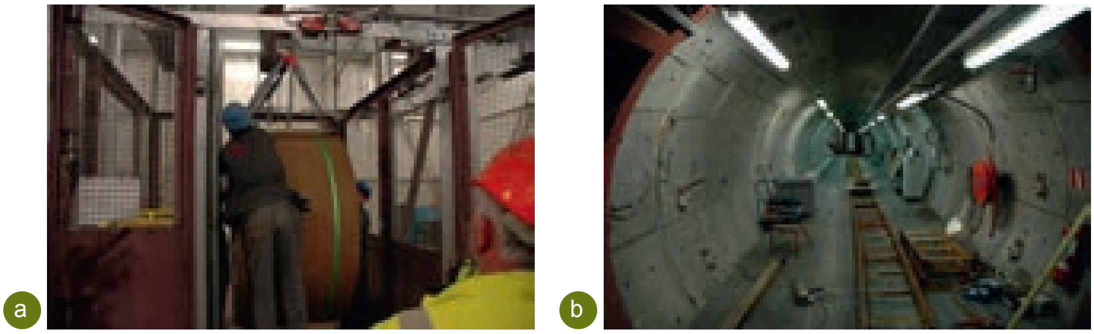


Figure 5-8: (a) The cylinder was lowered to the underground laboratory by hanging it directly on the lift cable; (b) In the underground laboratory the cylinder was transported on rails from the shaft to the opening of the PRACLAY gallery.

Before the cylinder could be placed in front of the opening of the PRACLAY gallery, the structure placed in the reinforcement ring at the crossing between the Connecting gallery and the PRACLAY gallery was removed (Figure 5-9). This structure was installed for the construction of the PRACLAY gallery and enabled the tunnelling shield to be pushed forward in the start-up phase of the excavation. The steel stamps (marked with yellow-black tape; cf. Figure 5-9) obstructed the positioning of the cylinder in front of the PRACLAY gallery. The complete structure also had to be removed to give access to an opening on the opposite side of the reinforcement ring for a future gas experiment.

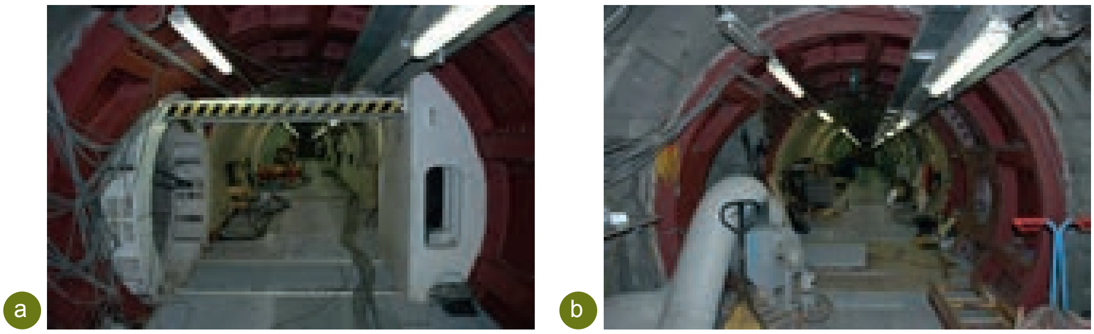


Figure 5-9: (a) Structure placed in front of the PRACLAY gallery to enable the tunnelling shield to be pushed forward in the start-up phase of the PRACLAY gallery excavation; (b) The structure was removed to be able to place the cylinder in front of the PRACLAY gallery.

On 15.01.2010 the cylinder was inserted into the PRACLAY gallery and placed ca. 2 m upstream of the location of the hydraulic seal (Figure 5-11b). This was done using a hoisting table (Figure 5-10). The table consists of two I-profiles that are placed in the central opening. The vertical position of these I-profiles could be manually altered by the jacks at both ends of the table. The table has wheels and can thus be moved horizontally. The complete table can be assembled and dismantled relatively easily (without the need for large equipment). The table was also used for the erection of the flanges (cf. sections 5.2.2 and 5.2.3) and the assembly of the cylinder to the flanges (cf. section 5.2.5).

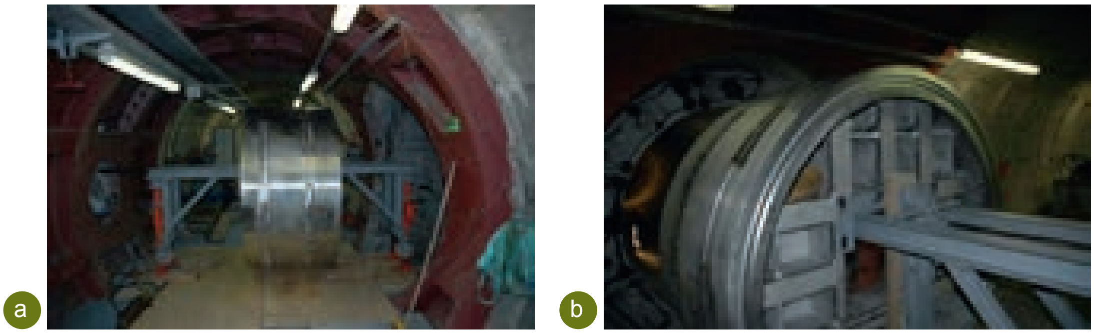


Figure 5-10: (a) Hoisting table on wheels used to transport the cylinder; (b) The table consists of two I-profiles that are placed in the central opening of the cylinder. The vertical position of the profiles can be altered.

To make sure the cylinder could pass through this section of the PRACLAY gallery, a wooden mockup cylinder with the same diameter as the steel cylinder (1840 mm) was made and transported through the gallery on 20.11.2008 (before starting construction of the cylinder in the workshop) (Figure 5-11a) [34]. The 4 cut-outs in the mockup cylinder are made to avoid the need to remove all cables in the gallery for this test.

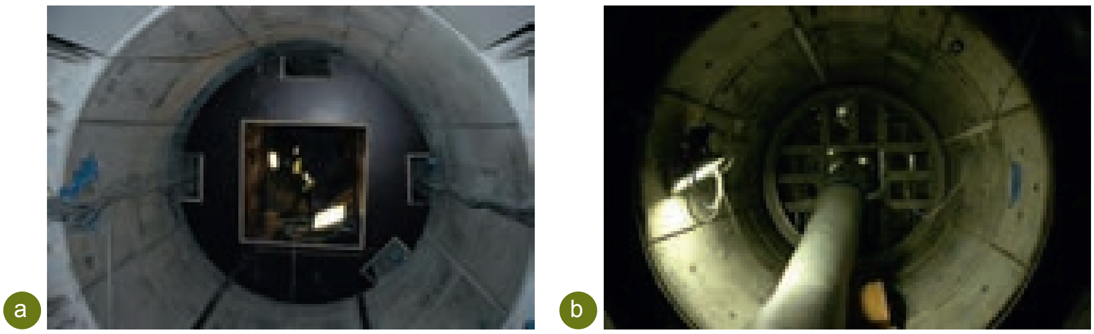


Figure 5-11: (a) Wooden mockup cylinder to test the feasibility of passing the steel cylinder through the PRACLAY gallery; (b) The steel cylinder is placed about 2 m behind the location of the hydraulic seal.

Once all components had been brought underground and the cylinder placed behind the location of the seal, the actual underground installation could start. Five different phases in the seal installation can be distinguished (Figure 2-4):

- removal of the temporary part of the gallery lining at the location of the seal;
- erection of the downstream flange;
- erection of the upstream flange;
- placement of the bentonite blocks;
- assembly of the cylinder to the flanges and welding of the tubes (I1 to I4) to the cylinder.

Between 29.09.2011 and 13.10.2011, 20 months later, after the installation of the heater and the backfill material, the central plate was welded onto the cylinder and the PRACLAY gallery was completely closed off.

5.2.1 REMOVAL OF THE TEMPORARY PART OF THE GALLERY LINING

The alternative lining at the location of the hydraulic seal consists of a permanent and a temporary part (Figure 2-2). The permanent part is made of 4 steel rings (these rings will be referred to as ring 1 to ring 4, ring 1 being the most downstream ring, ring 4 the most upstream ring, and rings 2 and 3 the two rings in between). Between these rings, wood is placed to support the clay. Also part of the temporary lining are 300 mm thick steel plates that are placed against the adjacent concrete lining ring.

First the wood and the steel plate between ring 1 and the concrete lining were removed. For this purpose, the small steel rib keeping the wood in place was taken out using a grinding disc. The wood was then removed by drilling holes in the middle of it (Figure 5-12a). The removal of the lateral steel plates between the steel rings turned out to be difficult. The thickness of these plates demanded a relatively large grinding disc. Because the use of a large grinding disc for the removal of the steel ribs was considered to be unsafe, plasma burning was used to take out these plates (Figure 5-12b).

a

b


Figure 5-12: Removal of the temporary part of the lining at the location of the hydraulic seal: (a) the steel ribs behind which the wood is placed were removed using a grinding disc and the wood was cut with a drill;
(b) the lateral steel plates were removed by plasma burning.

When holes were drilled in the wood, a groove of about 3 centimetres deep was made in the clay (Figure 5-13a). To avoid this damage to the clay, a small tube was placed over the drill rod, preventing the rod from going any deeper once it had cut through the wood (Figure 5-13b).

a

b


Figure 5-13: (a) Groove in the clay made when drilling the wood of the temporary lining;
(b) A small tube was placed over the drill rod, preventing it from cutting into the clay.

After the erection of the downstream flange, the wood and the steel plate on the upstream side were removed using the same procedure. Once the upstream flange had also been erected, the wood between the middle rings was taken out. The removal of the temporary part of the lining was done in this sequence and not all at once to minimise the convergence of the clay and the risks associated with any instability of the gallery wall (i.e. fallout of clay blocks).

The 4 steel lining rings that remain in place are composed of segments. The neighbouring segments of the first and the second and of the third and fourth ring are connected by two lateral plates placed between them. These plates are fixed by "pin-hole connection" (Figure 2-2b). This connection prevents the segments of the lining ring moving outwards during the swelling of the bentonite and a rather heterogeneous pressure distribution exerted by the bentonite on the clay is obtained (cf. section 2.2). Allowing the rings to move outwards would result in a more homogeneous pressure distribution. Therefore the steel plates are removed at two locations in the ring (Figure 5-14a). When the plates are removed, the maximum free length increases and this might lead to buckling of the ring. Therefore a further two steel plates are welded between the ring to replace the plates to be removed (Figure 5-14b). These steel plates are independent of each other and thus do not prevent the outward movement of the segments.

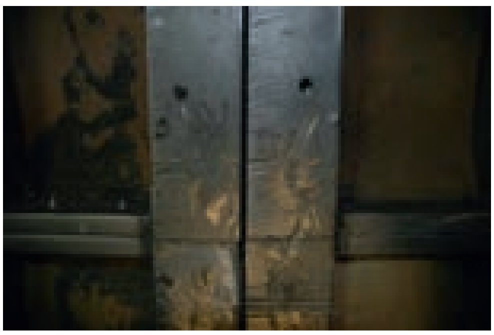
a

b

Figure 5-14: (a) The steel lateral plates between the rings;
(b) New steel plates are placed around the steel plates that were to be removed.

When the wood in the two middle sections was removed, the two rings in the middle (ring 2 and ring 3) that are placed against each other and are independent of each other, started to move outwards, leaving an opening between them (Figure 5-15a). To prevent them moving further apart, they were bolted together in 4 places (Figure 5-15b). The plates were removed after the outer bentonite layer was installed and once no further movement was possible (cf. section 5.2.4).

a



b

Figure 5-15: (a) Opening between rings 2 and 3 after removal of the wood around these rings; (b) Plates bolted over the rings to prevent them moving further apart.

5.2.2 ERECTION OF THE DOWNSTREAM FLANGE

Before the downstream flange could be erected at its location, some clay at the gallery sidewall had to be scraped off. The segments of the flange would be assembled by bolting them together and applying a resin on their interface to make it watertight (cf. section 5.1.1.1). The curing time of the resin was 2 hours, which limited the assembly time and complicated the operation. Moreover once the segments with resin are brought together, they cannot be moved back again. Therefore a “dry” assembly was first performed in which the complete flange was put together without adding the resin. The aim was to test the feasibility of the assembly procedure and minimise the assembly time once the resin was applied.

First the top segment was brought into place using the hoisting table. The segment was fixed about 2 cm higher than its final position (Figure 5-16a). The bottom segment was then placed in its correct position with the assistance of a surveyor and fixed to the gallery floor (Figure 5-16b). Finally the 2 middle segments were put in place (Figure 5-16c) and all segments were bolted together (Figure 5-16d).

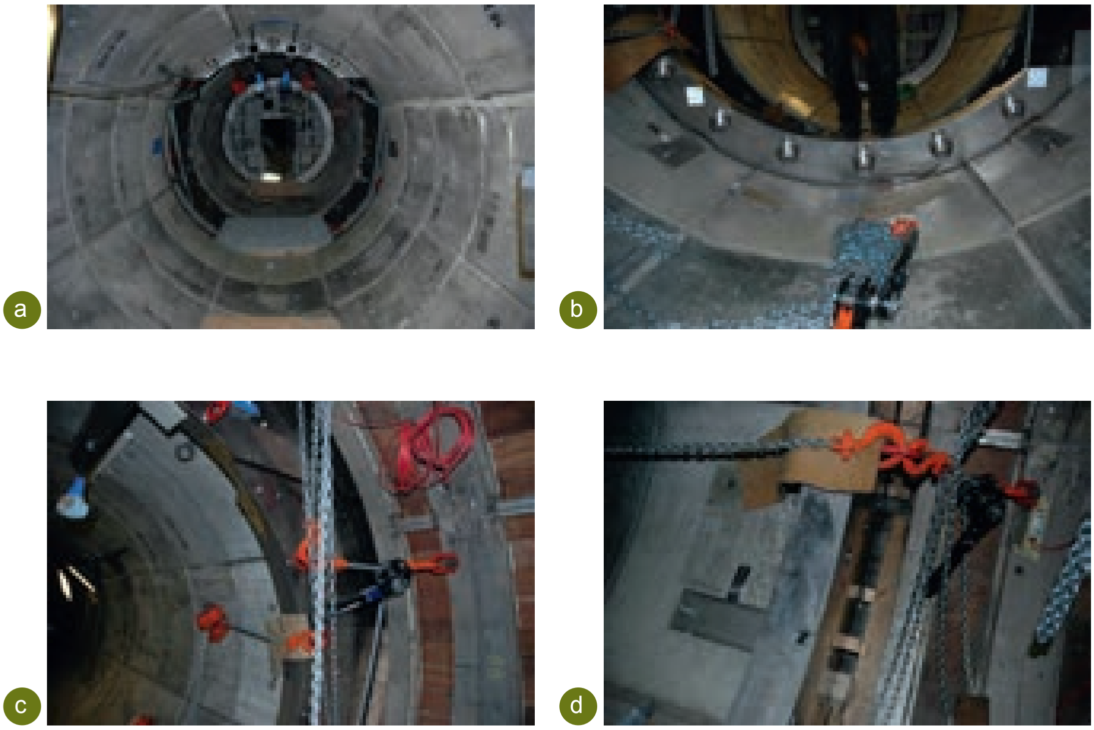


Figure 5-16: (a) The top segment is brought into place and held a little higher than its final position; (b) the bottom segment is already in its correct position and fixed to the gallery floor; (c) the middle segments are positioned; (d) the flanges are bolted together without using resin.

Now that the assembly had been found to be feasible, the middle segments were unbolted and moved back. The resin (Weicon AN305-18) was then applied to the surface of the “sloping tooth” (Figure 5-17a). This was all done with the assistance of JAMES WALKER. Once the flange was assembled, the holes for the bolts were filled with Weicon TI (Figure 5-17b). The flange was then covered with wooden plates to protect it while erecting the upstream flange (Figure 5-17d). Any gaps between the gallery lining and the downstream flange were filled with the polypropylene sheets that were also used between the lining rings during the gallery construction. This was not planned or strictly needed, but it was preferred to avoid direct contact between the flange and the concrete lining.

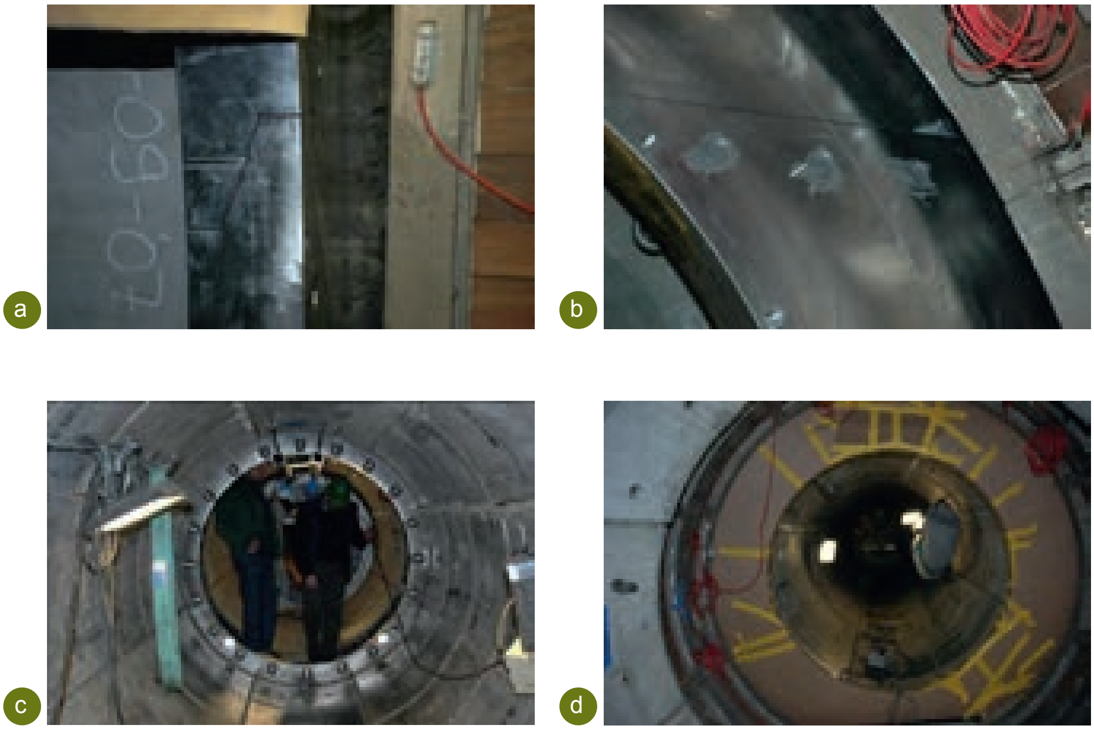


Figure 5-17: (a) The connection between the flange segments is made watertight by applying a resin on their interface; (b) the holes for the bolts assembling the segments are filled with another resin; (c) downstream side of the flange; (d) upstream side of the flange covered in protective wooden sheets.

5.2.3 ERECTION OF THE UPSTREAM FLANGE

The assembly of the upstream flange is less complicated because the segments are less heavy and no resin is used. For the subsequent assembly of the cylinder to both flanges, it was however crucial to accurately position the upstream flange relative to the downstream flange. The upstream flange had to be placed:

- parallel to the downstream flange;
- concentric to the downstream flange;
- at a distance of 910 mm (measured between the inner sides of both flanges).

Therefore the bottom segment is directly placed in its correct position with the assistance of the surveyor and fixed to the gallery floor (Figure 5-18a). Here, too, some clay at the gallery sidewall had to be scraped off. Efforts were made to keep the amount removed to a minimum, but locally too much clay was removed (Figure 5-18b). This was later filled with a clay slurry (cf. section 5.2.4). The right middle segment, the top segment and the left middle segment were then placed and bolted together using “assembly plates” (Figure 5-18c and Figure 5-18d). After the erection of the upstream flange, its position was again checked by the surveyor.

Figure 5-18: (a) The bottom segment is placed in its correct position and fixed to the gallery floor; (b) some clay had to be removed from the gallery sidewall; (c) the top and middle segments are put in place; (d) assembly plates are bolted over the interface between the segments.

Subsequently a weld was placed over the edges of the assembly plates to make them watertight. During the welding process the inner diameter of the flange was frequently measured to guarantee that no deformations reducing the internal diameter of the flange occurred, as this might obstruct the passage of the cylinder through the upstream flange. After the welding of the assembly plates the welds were checked using a penetration product (Figure 5-19a). Subsequently the welds were passivated using a gel instead of more liquid passivation products, which might contaminate the Boom Clay. Finally the holes in the assembly plates where the bolts were placed were filled with a resin to close them (Figure 5-19b). This was not strictly necessary for the watertightness of the flange, but it was done as an extra measure.

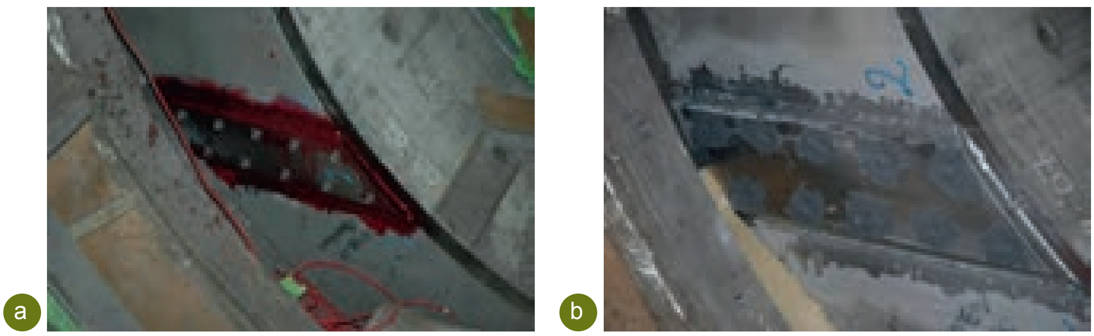


Figure 5-19: (a) Checking the welds on the assembly plate using a penetration product; (b) The welds are passivated and the holes for the bolts in the assembly plates are filled with a resin.

5.2.4 PLACEMENT OF THE BENTONITE BLOCKS

Before the installation of the bentonite blocks a detailed installation protocol was worked out [35]. The bentonite blocks are placed in 2 layers (Figure 2-9). The outer layer is composed of 4 rings that are placed between the steel lining rings against the clay. The inner layer contains 7 rings. Two technological gaps of 10 mm are expected: one between the outer and inner layer and the other between the inner layer and the steel structure. The outer rings are composed of 17 blocks, the inner rings of 24 blocks. The blocks were given a number indicating the ring in which they are placed (e.g. 1b) and then their position in this ring (e.g. 1b-11) (Figure 5-20).

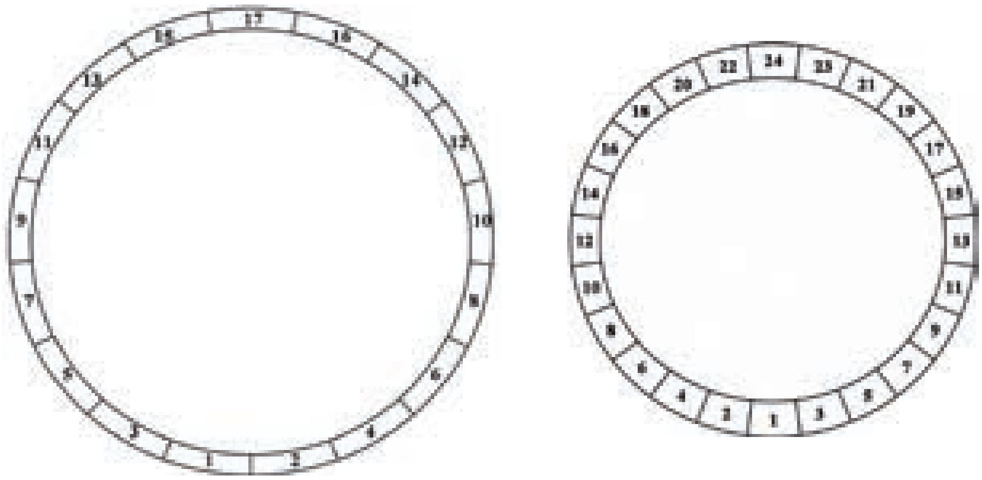


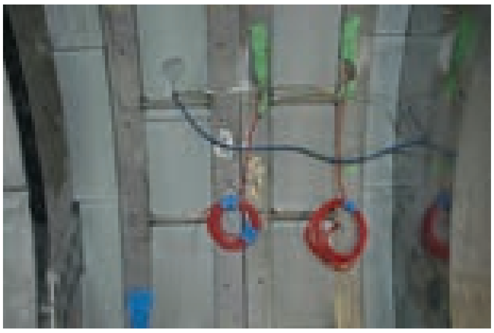
Figure 5-20: Numbering of the bentonite blocks in the (a) outer ring and (b) inner ring.

Figure 5-21: The bentonite blocks were shaped in-situ to enable their placement in the annular bentonite ring and to enable the installation of sensors in the blocks.

Two types of bentonite blocks were manufactured: outer layer blocks and inner layer blocks (cf. section 5.1.2). Before their installation most blocks needed some "shaping" to enable their placement in their designated position in the annular bentonite ring (Figure 5-21). Rings 1a, 1d and 2g are smaller than the width of the bentonite blocks of the inner and outer layer and the blocks were sawn to the correct width. Other blocks needed to be shaped because of the steel plates between the steel rings, because of the assembly plates used for the assembly of the upstream flange and because of the sensors and cables in the blocks.

The outer rings are not self-supporting, as the rings are interrupted by plates between the lining rings (Figure 5-22a). The outer ring blocks placed in the upper part are supported by small INOX plates welded to the lining rings (Figure 5-22b).

a

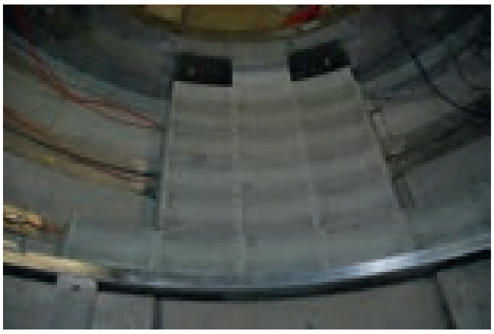


b

Figure 5-22: (a) The outer bentonite rings are not completely self-supporting, as the rings are interrupted by steel plates; (b) The outer ring blocks in the upper part are kept in place by INOX plates welded to the lining rings.

The inner rings are completely composed of bentonite blocks forming a self-supporting structure (Figure 5-23a). Between the inner and outer ring a void of 10 mm is expected. To achieve this in the lower part, some INOX plates were placed between the inner and outer ring (Figure 5-23b). First the lower blocks of all inner rings were placed.

a



b

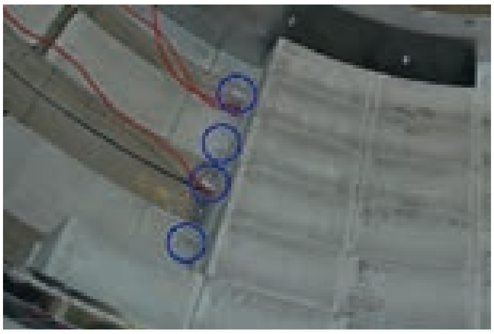


Figure 5-23: (a) Bottom part of the inner bentonite rings; (b) To achieve the technological void between the outer and inner ring, small INOX plates (indicated by blue circles) are placed under the outer blocks.

Subsequently a floor was placed above the lower blocks and an arch structure was used to install the blocks in the upper part (Figure 5-24a). The arch was two inner rings wide (ca. 270 mm) and its height could be adjusted. The blocks were placed on top of the structure. When one ring was finished and supporting itself, the arch was lowered and the construction of a new ring could start. Mostly the inner blocks placed at the bottom were a few millimetres (usually no more than 1 or 2 mm) further outwards than anticipated in the theoretical layout. Because all the blocks had to remain outside the opening through which the cylinder had to pass (cf. section 5.2.5), the ring could not be lowered as a whole and the diameter was also increased by a few millimetres. As a result the circumferential length of these rings increased and when the last block in the ring was placed (block 24; cf. Figure 5-20b), the ring was not self-supporting (Figure 5-24c). This was solved by placing a sawn bentonite "sheet" between the upper blocks of the ring (Figure 5-24d).

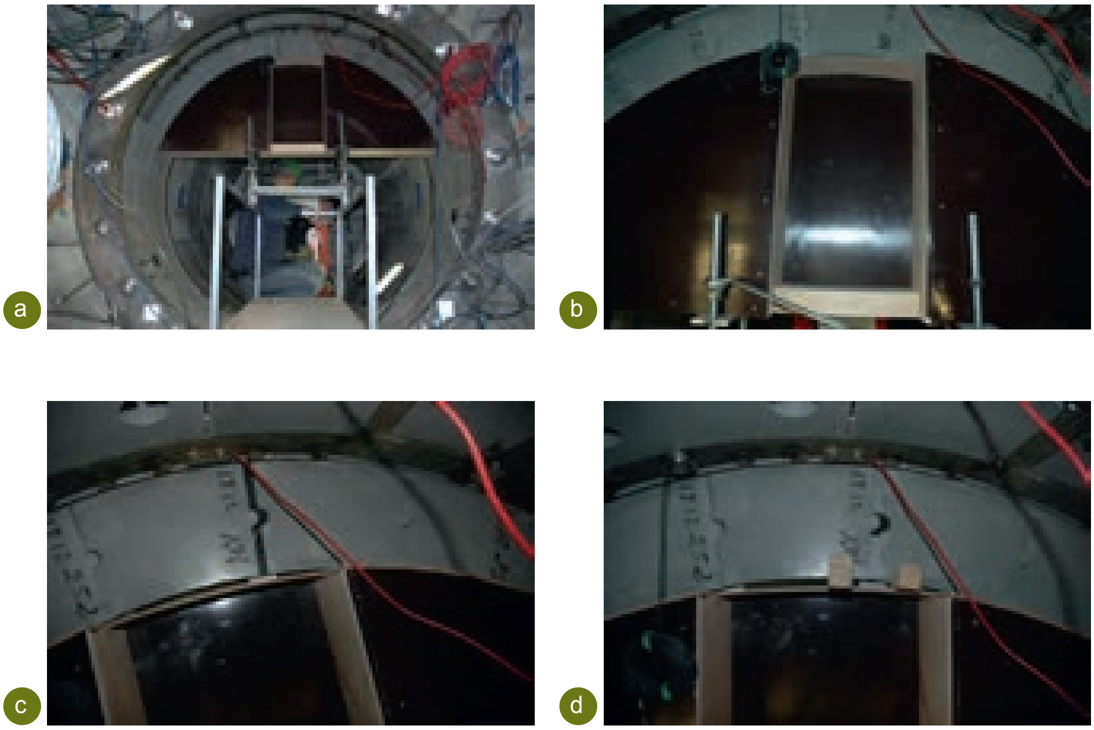


Figure 5-24: (a) and (b) A support arch is used to place the upper part of the blocks of the inner ring; (c) The inner rings were slightly larger than anticipated and as a result the final block did not touch both of its neighbouring blocks; (d) A small bentonite sheet was sawn and placed in the ring to fill the gap.

The last block was shaped as a key element and brought in from below. The block was kept in place by a rod drilled into the clay. Wooden wedges were placed between the upper blocks of the last ring and the downstream flange. The ring was self-supporting without the wedges, but they were placed as an extra measure. Just before the cylinder was placed against the downstream flange (cf. section 5.2.5), these wedges were removed.

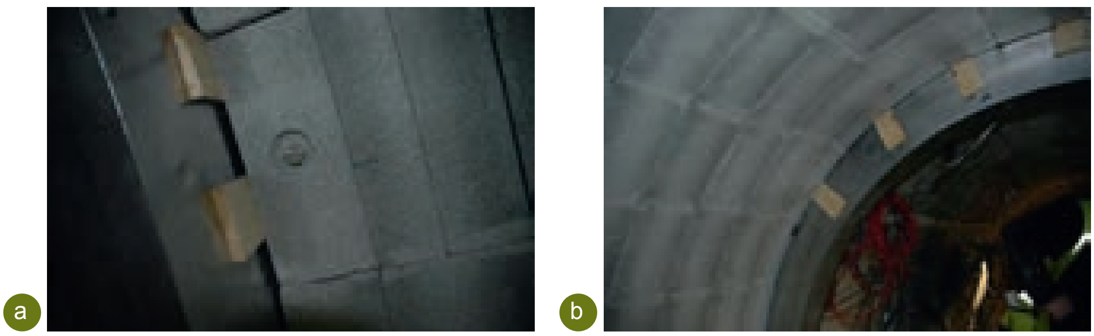


Figure 5-25: Wooden wedges were placed between the inner ring 2g and the downstream flange as an extra support for the inner rings.

The instrumentation was placed in the blocks by shaping the blocks and then inserting the instrumentation in each block to be installed (Figure 5-26). Sometimes the sensors were glued onto the blocks. The cables of the sensors are passed through 20 openings in the downstream flange (Figure 5-26; see also Figure 2-5).

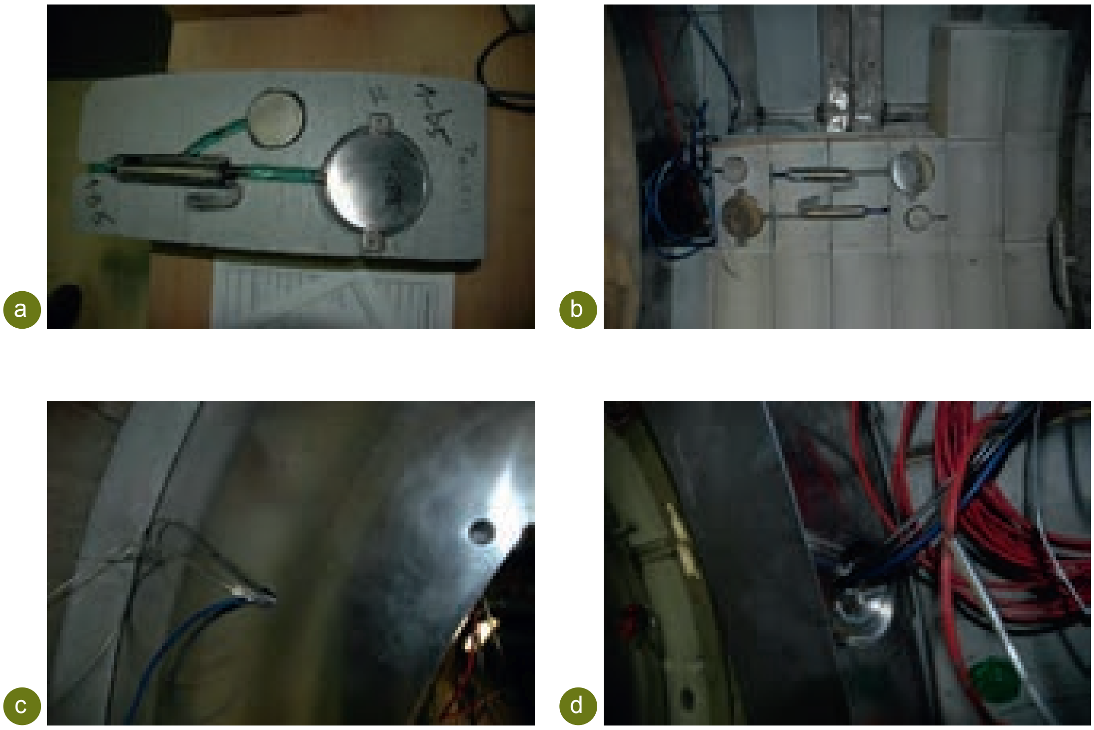


Figure 5-26: (a) The instrumentation was placed in the blocks before they were installed; (b) Flatjacks and filters on the intrados of the inner bentonite ring; (c) Opening on the inside of the downstream flange for instrumentation cable feed-through; (d) Opening on the outside of the downstream flange for instrumentation cable feed-through.

During installation the position of the blocks, and more particularly their distance to the centre of their circle, was measured to ensure the feasibility of passing the cylinder through the rings of bentonite. This position was measured using a measuring tool that was placed on both flanges and against which the distance to the circle centre could be measured (Figure 5-27). The measuring tool was also used to measure the distance from the clay sidewall to the gallery axis. Sometimes clay had to be scraped off to make room

Figure 5-27: (a) A measuring tool was made that could be placed over both flanges to get a reference against which the position of the blocks could be measured; (b) Scraping of clay.

for the block to be placed. In other cases voids in the clay wall were filled with a slurry of Boom Clay cuttings and water. When an amount of water equal to 30% of the weight of the cuttings was added to these cuttings, a manageable slurry was obtained.

For the installation of each block, the following procedure was followed:

- measure the diameter of the Boom Clay wall using a measuring strip (scrape off clay or fill voids in the clay sidewall if necessary) and measure the dimensions of the opening where the bentonite block will go;
- saw the bentonite block to the right dimensions;
- weigh and measure the block;
- put instrumentation in the block;
- install the block;
- measure the position of the block using the measuring strip;
- place instrumentation cables (feed-through of the cables of the seal sensors is done through 20 openings placed in the downstream flange as illustrated in Figure 2-5; the openings are numbered starting from the top opening and counting clockwise).

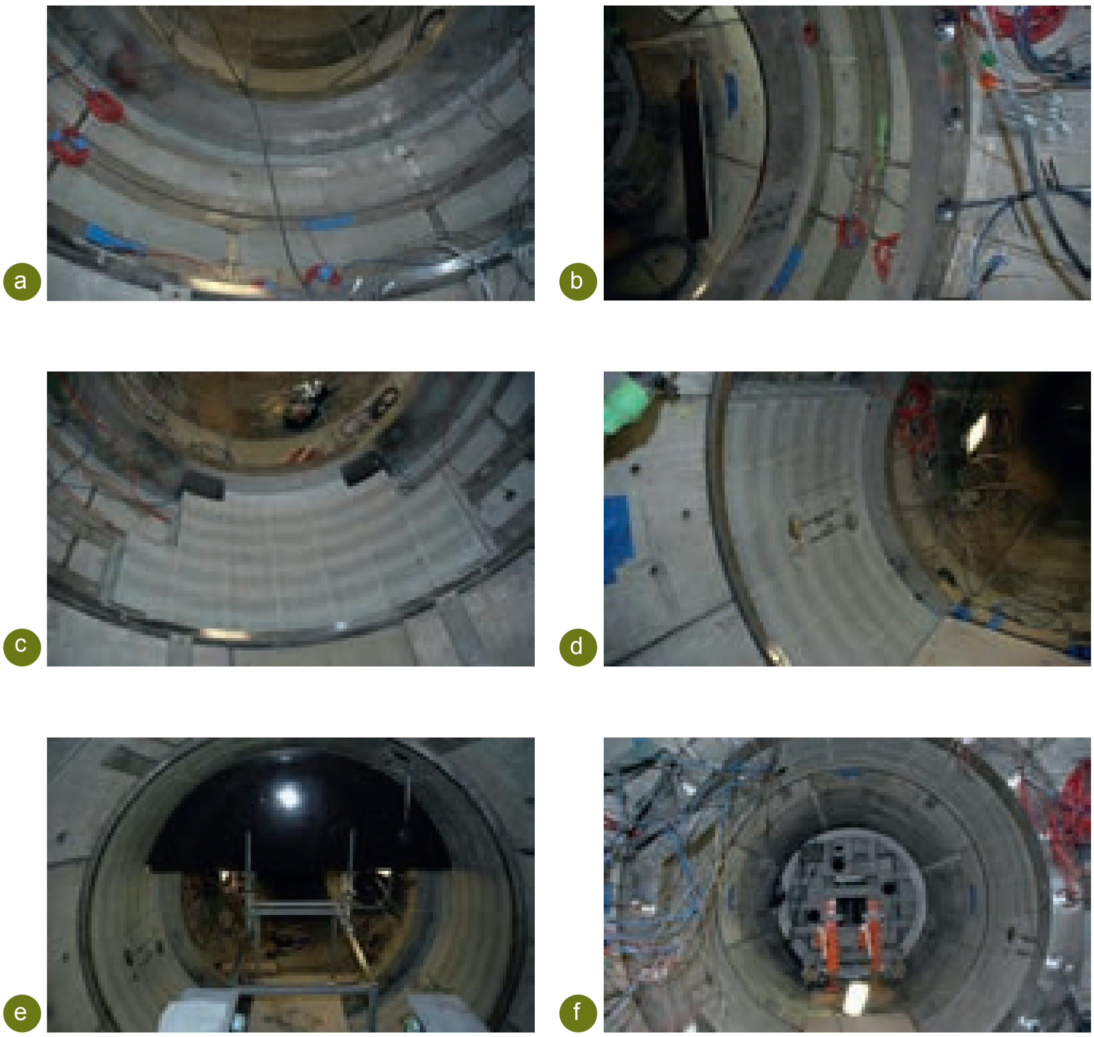


Figure 5-28: Overview of the progress of the bentonite installation.

The complete installation of the bentonite took 5 days (24 working hours/day), during which time 236 blocks were installed (Figure 5-28). The total installed bentonite weight amounted to 3,200 kg. The void-bentonite ratio was ca. 8%, which was smaller than the designed 11%. The reason for this was that less bentonite was lost during its installation than expected.

Because the instrumentation layout as initially planned (cf. section 2.2) was not always feasible, the layout was slightly adjusted. The as-built layout of the instrumentation sections is given in [6].

5.2.5 ASSEMBLY OF THE CYLINDER TO THE FLANGES AND CLOSURE OF THE CYLINDER

The cylinder was moved through the upstream flange and the ring of bentonite up to its position against the downstream flange using the hoisting table (Figure 5-29a). The margin between the inner diameter of the upstream flange and the extrados of the cylinder was 4 mm on diameter. This required a very precise movement of the cylinder (Figure 5-29d). Two gaskets were placed in their designated groove in the cylinder (Figure 5-29c). They were first lubricated with grease to ensure that each was more or less evenly distributed over the radial length of the groove, thus minimising the tensional friction stresses in the gaskets. The complete movement of the cylinder through the upstream flange took approximately 1 hour. Once the cylinder was placed against the flange, both parts were bolted with a fixed torque (350 kNm), compressing the gaskets and sealing the interface between the cylinder and the downstream flange (Figure 5-29d).

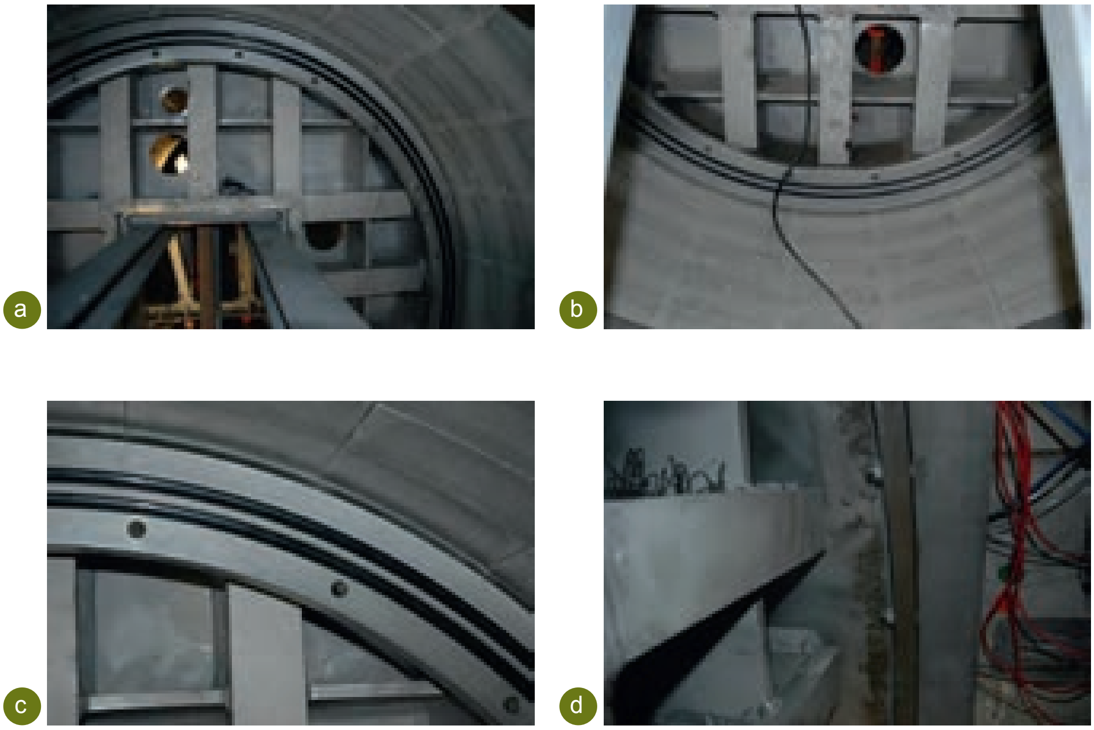


Figure 5-29: (a) The cylinder was introduced into the opening of the flange and the bentonite ring using the hoisting table; (b) The small margin between the upstream flange and the cylinder demanded a very accurate movement of the cylinder; (c) Gaskets were placed in their designated groove;
(d) The cylinder was bolted to the downstream flange.

The cylinder was then welded to the upstream flange and the 4 pipes were inserted into the openings in the plate of the cylinder and welded to this plate (Figure 5-30a, Figure 5-30b and Figure 5-30c). Finally the opening between the upstream flange and the gallery lining, approximately 17 mm, was filled with mortar (Figure 5-30d).

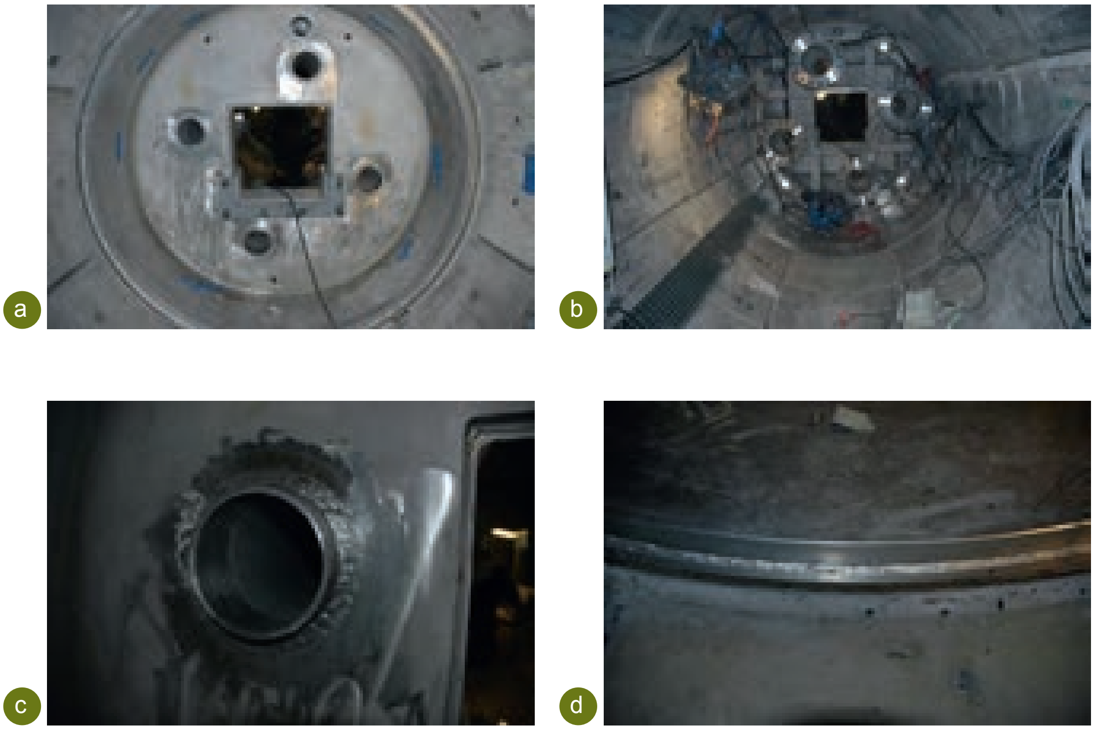


Figure 5-30: (a) Upstream view of the hydraulic seal ; (b) Downstream view of the hydraulic seal; (c) The pipes were welded to the cylinder; (d) The cylinder was welded to the upstream flange and mortar was placed in the gap between the flange and the lining.

The openings in the downstream flange for the feed-through of the bentonite instrumentation were sealed with resin (Weicon Easy-Mix Metal) (Figure 5-31a). Heating cables (covered by insulating material) were attached to the cylinder to heat the bentonite during the artificial hydration stage and in that way speed up the hydration (Figure 5-31b). It was later decided not to do this as the heating of the bentonite might complicate the interpretation of the bentonite hydration process and the further installation work of the PRACLAY In-Situ Experiment (i.e. the heater and backfill material).

Three openings in the cylinder were provided to install the displacement transducers (instrumentation sections D; cf. section 2.2). Holes were drilled in the bentonite to install the displacement transducers, one end of which is placed in the clay sidewall around the bentonite. One transducer could not be installed, as a stainless steel plate used for the bentonite installation was in the way.

The 4 pipes were closed by bolting blind flanges to the pipes. This was done after the flanges were equipped with the necessary instrumentation feed-throughs (cf. part III of the report on the installation of the PRACLAY In-Situ Experiment – The heater and backfill material).

During the artificial hydration of the bentonite (cf. section 6.2), 2 leaks were observed at the junction between the bottom downstream segment, the 2 middle downstream segments and the cylinder [36]. The location of these leaks is shown in Figure 5-32. The leak on the left was more severe than the one on the right.

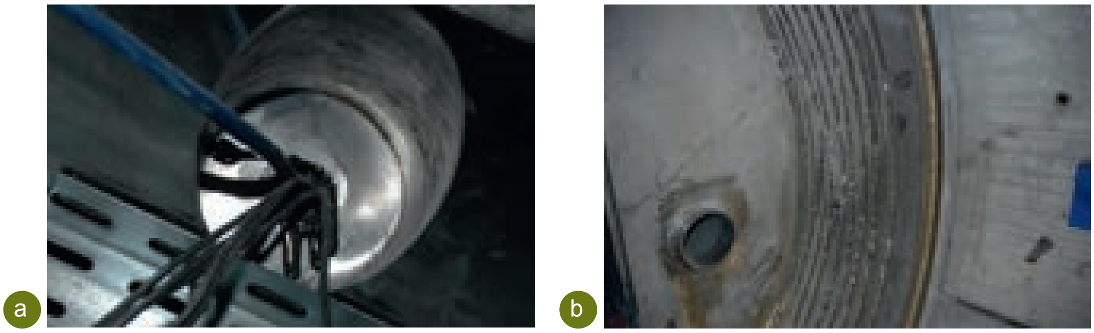


Figure 5-31: (a) Resin (black product) sealing the feed-through openings in the downstream flange; (b) Heating cables placed against the cylinder (cables are placed both on the downstream and on the upstream side).

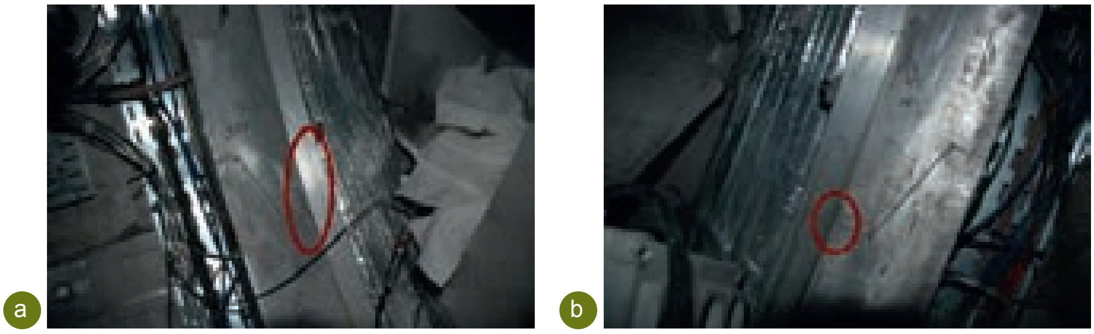


Figure 5-32: Location of the leaks in the hydraulic seal during the artificial hydration: (a) at the junction between the bottom downstream segment, the left middle downstream segment and the cylinder; (b) at the junction between the bottom downstream segment, the right middle downstream segment and the cylinder.

On 19.08.2010 another resin (MS polymer Flex 310M Classic) was applied circumferentially on the junction between the downstream flange and the cylinder to seal this leak (Figure 5-33).

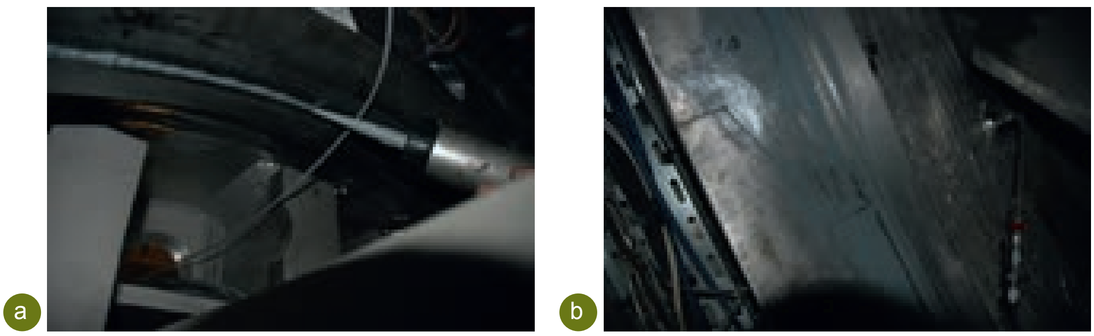


Figure 5-33: Resin applied on the junction between the cylinder and the downstream flange.

Finally, after complete installation of the backfill material and the heating system, the cylinder was closed between 29.09.2011 and 13.11.2011 by moving a plate over the central tube against the opening in the cylinder. Subsequently the plate was welded onto the cylinder and the central tube (Figure 5-34). During the welding operation, protective fireproof blankets were placed over all cables coming out of the hydraulic seal.

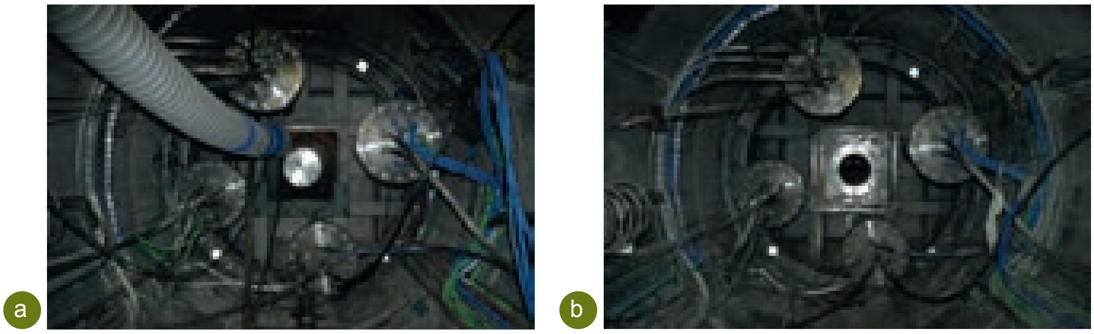


Figure 5-34: A central plate was welded onto the hydraulic seal and the central tube to close the manhole: (a) before the welding of the central plate; (b) after the welding of the central plate.

5.3. Safety aspects

The main safety issues related to the installation of the hydraulic seal and the measures taken in this respect were the following:

- risks associated with dust and hazardous gases during welding, grinding and burning operations:
  > the wearing of an oxygen mask (Figure 5-35a);

- risks associated with the application of the resins:
  > the wearing of masks and gloves;

- risks associated with the weld passivation:
  > the wearing of gloves and protective clothes and a ban on non-essential personnel in the gallery during the passivation (Figure 5-35b);

- risks associated with falling clay blocks from the gallery sidewall after removing the temporary part of the alternative lining:
  > visual inspections of the sidewall;
  > the temporary part of the lining is not removed earlier than necessary (cf. removal sequence described in section 5.2.1).

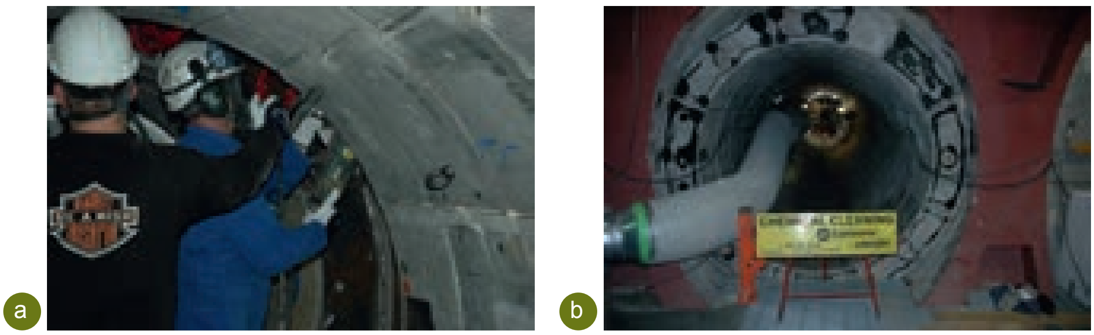


Figure 5-35: (a) It was compulsory to wear an oxygen mask and protective gloves for operations during which dust and hazardous gases could be produced; (b) During passivation only essential personnel were allowed in the gallery.

Furthermore the PRACLAY gallery was continuously ventilated by extracting air. Because of the limited working space in the gallery, the workers were allowed to wear a safety cap instead of a safety helmet.

The health and safety plan for the installation of the PRACLAY hydraulic seal can be found in [37].

6. Measurements related to the behaviour of the hydraulic seal

Instrumentation was placed in the bentonite blocks to gain information on the bentonite hydration and to be able to test and evaluate the performance of the hydraulic seal. The instrumentation programme (see also section 2.2 – Figure 2-14 and Figure 2-15 – and section 5.2.4) consists of:

- 35 thermocouples;
- 21 piezometers of which 13 have a moisture sensor embedded;
- 16 total pressure cells (flatjack);
- 10 total pressure cells (Kulite);
- 2 extensometers.

Furthermore 12 strain gauges were placed on the steel rings of the alternative lining at the location of the hydraulic seal prior to the installation of the hydraulic seal. The strain gauges made it possible to monitor the stress changes in the steel rings during the hydraulic seal installation and the bentonite hydration. This report only includes measurements until August 2011.

A workshop called "PRACLAY Heater switch-on" was held on 23.11.2011 and 24.11.2011 at EURIDICE. The objective of the workshop was to discuss the appropriate moment for the PRACLAY heater to be switched on and to start the Heater Test. Beforehand a report on the performance of the hydraulic seal was prepared and handed over to the workshop participants [38]. The report contains a more detailed description and interpretation of the bentonite hydration, supported with modelling results, than given here. Also a report on the workshop output was compiled [39].

6.1. Stress changes in the steel lining rings

Before the hydraulic seal installation work started, 12 strain gauges, 3 on each ring, were placed on the steel lining rings of the lining at the seal location (Figure 6-1).

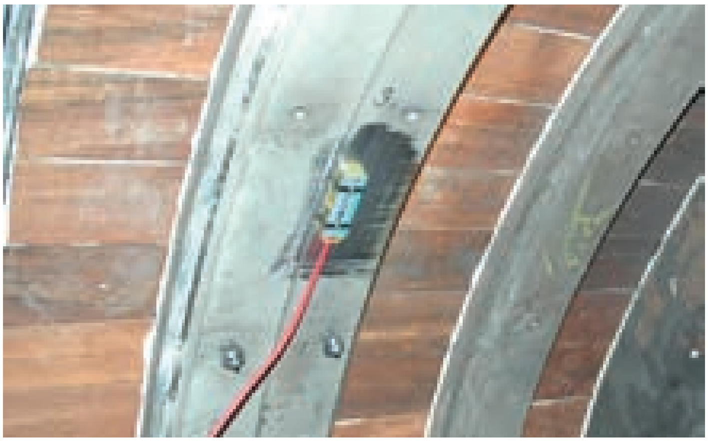


Figure 6-1: Strain gauge placed on steel lining ring.

The stress changes measured by these strain gauges during the seal installation are shown in Figure 6-2. The rings are numbered from the downstream to the upstream side. The pink bars indicate the periods in which respectively:

- the wood on the downstream side of ring 1 was taken out (first bar);
- the wood on the upstream side of ring 4 was removed (second bar);
- the replacement of the steel lateral plates between rings 1 and 2, and 3 and 4 (third bar);
- and finally the wood between rings 1 and 2 and between rings 3 and 4 (fourth bar) was removed.

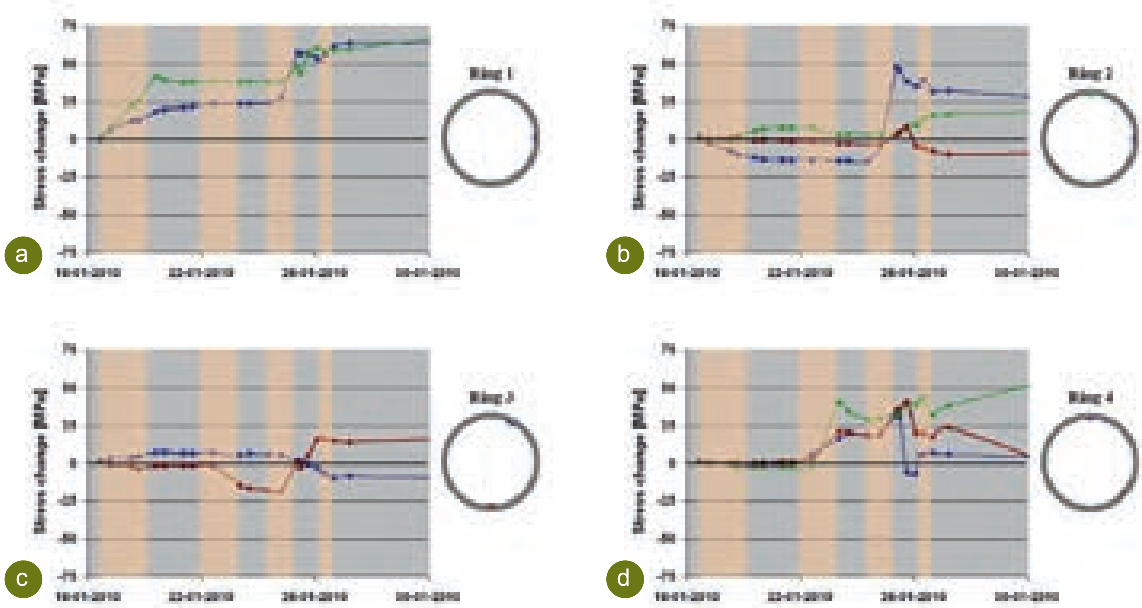


Figure 6-2: Measured stresses (a positive change is a reduction in compressive stress, a negative change is an increase in compressive stress) in the lining rings: (a) ring 1; (b) ring 2; (c) ring 3; (d) ring 4.

The effect of the removal of the wood can clearly be observed on the strain gauge measurements:

- ring 1: A clear decrease in stress is measured when the wood on the downstream side is removed and when the steel lateral plates are replaced. The strain gauge that was placed at the bottom of this ring got damaged during the seal installation work.
- ring 2: Here, too, a clear decrease can be seen in the strain gauge placed at the side of the ring when lateral plates between the rings are removed. In the other strain gauges the stress changes are not so clear. The stress measured on the lowest strain gauge even seems to increase. The changes measured in these strain gauges are however relatively small.
- ring 3: An increase in the stress at the bottom can be seen when the wood on the upstream side of ring 4 is removed. This increase, which cannot be explained, is followed by the expected decrease in stress when the wood beside this ring is taken out. The stress variations in the strain gauge on the upper side of the ring are not consistent with the measurements at the bottom, but are rather small. The strain gauge that was placed at the side of this ring was damaged and lost.
- ring 4: The stress decrease when the wood on the upstream side of this ring is removed is clearly visible. Stress changes are also measured later on but these are not entirely consistent and cannot clearly be related to the removal of the wood in the lining.

These measurements will be taken into account in a more extensive study that will be done on the stresses in and on the gallery lining in general and that will mainly be based on the stress measurements in and on the lining of the PRACLAY gallery (cf. section 6.1 in part I of the report on the installation of the PRACLAY In-Situ Experiment – The PRACLAY gallery).

6.2. The bentonite hydration

The bentonite is hydrated by pore water coming from the Boom Clay and by water injected through filters placed on the extrados of the cylinder (Figure 6-3) (cf. section 2.1.3.3). Two rings of filters are installed: in cross-section A-A and in cross-section B-B. The filters do not cover the complete circumference. They cover 4 radial sections of 65° with an offset of 45° between cross-section A-A and cross-section B-B. The total surface area for artificial injection (surface area of the filters) is 0.42 m². The total surface area for natural hydration (contact surface area between bentonite and Boom Clay) is ca. 4.6 m².

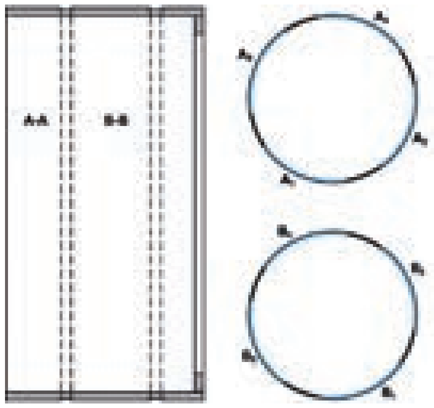


Figure 6-3: Layout of the injection filters (section A-A is on the upstream side, section B-B on the downstream side).

On 07.04.2010 the hydration of the bentonite was started by connecting filters A1 and B1 to a pressure vessel filled with synthetic Boom Clay water (Figure 6-4). At an injection pressure of 3 bar, 15 l of water were injected over ca. 2.5 hours (flowrate = 6 l/hour). The injection pressure was then increased to 4 bar resulting in the injection of 8 l of water in ca. 1 hour. The injection was stopped for that day (after having injected 23 l). No water leaking from the hydraulic seal was observed.

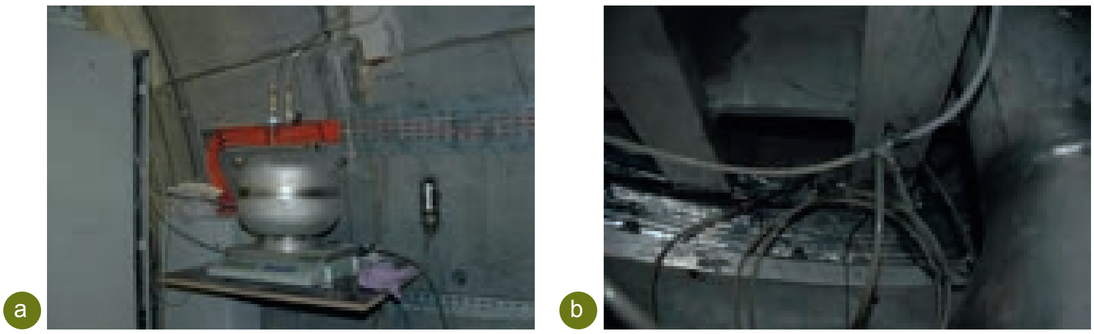


Figure 6-4: (a) Pressure vessel filled with synthetic water and placed on weighing scales to monitor the injected amount of water; (b) Connection between the filters on the seal extrados and the injection hoses.

On 08.04.2010 the injection was restarted at a pressure of 2 bar, resulting in a flowrate of 6 l/hour. After 1.5 hours a significant amount of water (several litres) had leaked into the gallery, both downstream and upstream of the seal, but mainly downstream (Figure 6-5). The injection was continued and the amount of water in the gallery did not seem to increase. Later that day filters A2 and B2 were connected as well. On

09.04.2010 all filters were connected and the hydration was continued during the daytime. The hydration was stopped for the weekend (10.04.2010 and 11.04.2010).

Figure 6-5: Water leakage in the gallery on the 2nd day of the artificial hydration:
(a) downstream; (b) upstream.

On 12.04.2010 the hydration was restarted at a pressure of 3 bar. Water appeared to leak from the seal through 2 leaks at the interface between the cylinder and the connection between the bottom segment and the 2 middle segments of the downstream flange (Figure 6-6). It could not be determined whether the interface between the cylinder and the connection between the top segment and the middle segments of the downstream flange was watertight, as the water level in the seal did not reach up to this height. The artificial hydration was nevertheless continued and was performed around the clock thereafter.

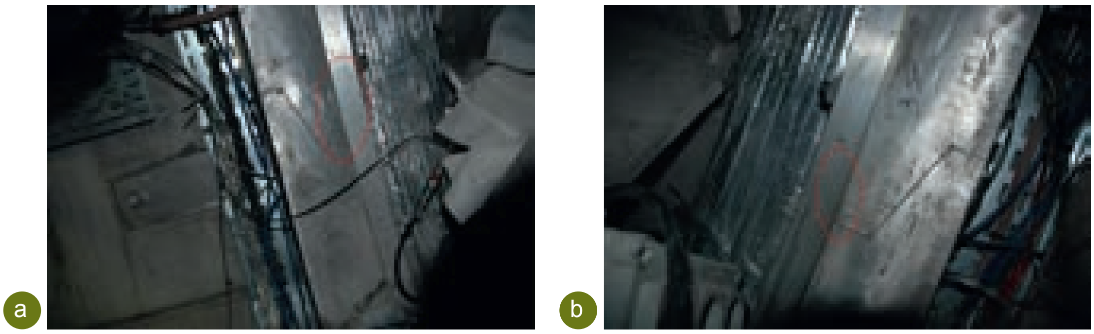


Figure 6-6: The location of the leakage of water from the seal on 12.04.2010 at
(a) the interface between the cylinder and the bottom and left segments of the downstream flange and
(b) the interface between the cylinder and the bottom and right segments of the downstream flange.

By 19.04.2010 the bentonite around the cylinder had been sufficiently hydrated to close the annular space between the cylinder and the clay. As a result the flow rate of injected water at an injection pressure of 3 bar was very small. There was no further water leakage from the seal. Probably the bentonite had been sufficiently swollen to close the leaks. Still, it was decided to apply resin over the interface between the cylinder and the downstream flange. This was done on 19.08.2010 (cf. section 5.2.5).

Figure 6-7 shows the measured injection rate of the artificial hydration since 23.04.2010 (no visible leaks have occurred since this date). The short-term variations, which are sometimes substantial, are due to the sensitivity of the scales to disturbances (vibrations due to underground activities) and other external causes (for example replacement of the vessel to refill it). A decreasing trend in the injection rate over the long term is however clear.

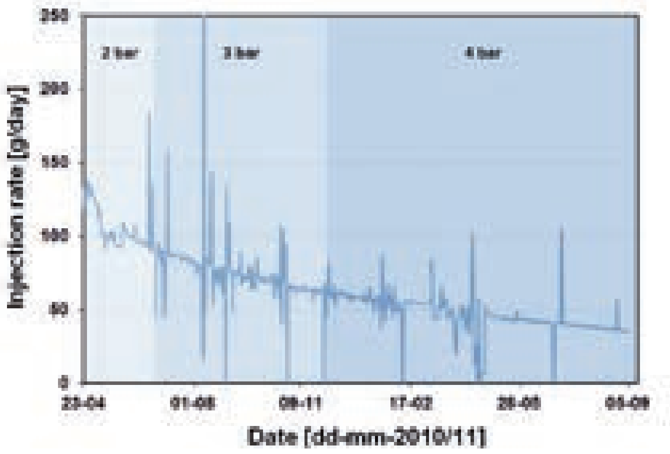


Figure 6-7: Measured injection rate of the artificial hydration of the hydraulic seal.

Between 23.04.2010 and 06.09.2011 ca. 31 litres of water were artificially injected into the seal and the injection rate decreased from 130 g/day to 35 g/day. The injection pressures were increased from 2 bar to 4 bar, but this had no impact on the injection rate. This is because the injection rate is mainly determined by the suction of the bentonite. The initial suction pressure, as measured in the laboratory [33], is ca. 60 MPa and is much higher than the applied injection pressure.

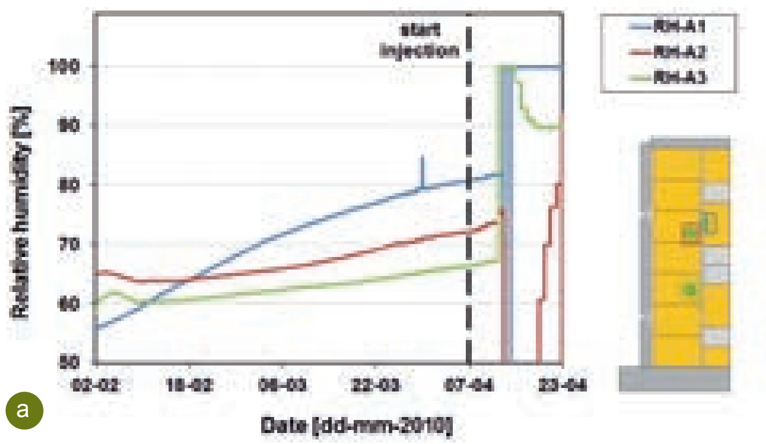
The evolution in the following parameters is monitored during the hydration of the bentonite:

- relative humidity in the bentonite annular ring;
- stresses in the bentonite annular ring;
- pore water pressures in the bentonite annular ring;
- pore water pressures in the Boom Clay around the seal;
- displacements in the bentonite annular ring.

The sensors and their layout are given in sections 2.2 and 5.2.4. The evolution in these parameters is discussed in the sections below.

6.2.1 RELATIVE HUMIDITY IN THE BENTONITE RING

The relative humidities measured in the 3 sections of the bentonite ring are shown in Figure 6-8.



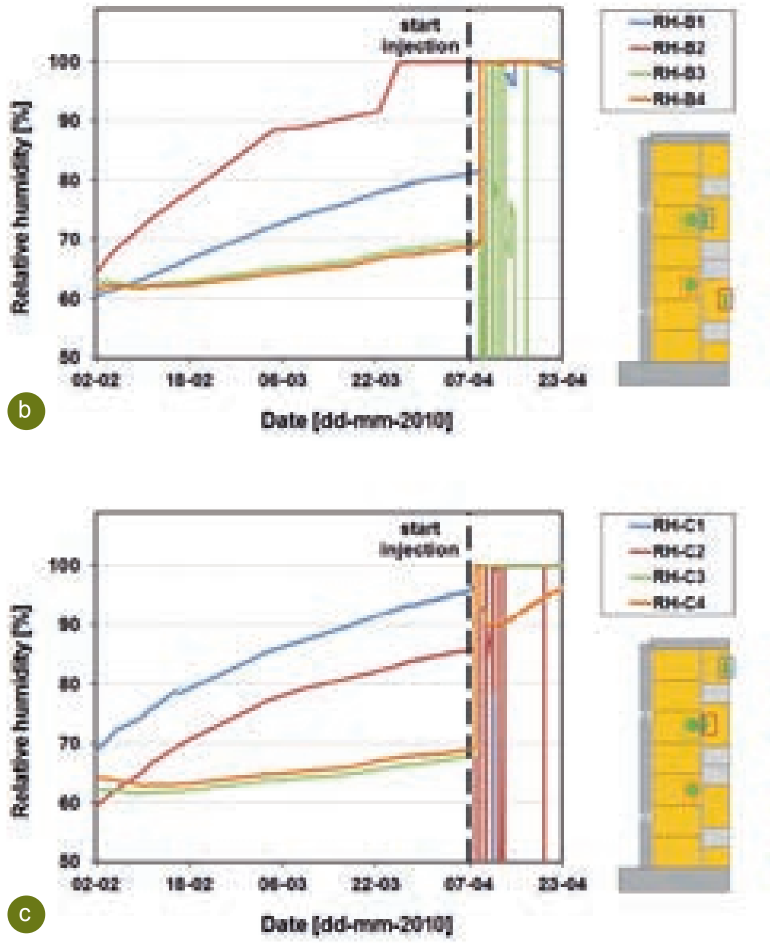


Figure 6-8: Measured relative humidity: (a) section A-A (top section); (b) section B-B (middle section); (c) section C-C (bottom section).

After the assembly of the cylinder to the downstream flange on 02.02.2010 (cf. section 5.2.5), the bentonite ring was enclosed in the steel structure. The relative humidity measurements were then between 55 and 68%. Since then all relative humidity sensors have shown an increase. It can be observed that the increase occurs faster for the sensors closer to the Boom Clay sidewall. The relative humidity sensor placed against the Boom Clay sidewall in the middle section B-B (RH-B2) reached 100% relative humidity 52 days after the enclosure of the bentonite ring. The other relative humidity sensor that is placed against the Boom Clay sidewall in the bottom section C-C (RH-C1) reached 96% relative humidity by 07.04.2010 when the artificial hydration started.

The artificial hydration was started on 07.04.2010 by connecting the bottom hydration filters to the vessel containing the injection water. On 08.04.2010 all sensors on the bottom section C-C reached 100% relative humidity over a timespan of 6 hours: first the sensor placed against the Boom Clay (RH-C1), then the sensor placed in the void between the inner and outer bentonite ring (RH-C2), and finally almost simultaneously the sensors placed in the inner bentonite ring (RH-C3 and RH-C4). Subsequently the humidity sensors of section C-C failed. The sensors in sections A-A and B-B had not yet been affected by the artificial hydration, which was started at the bottom part of the bentonite.

On 09.04.2010 all the injection filters were connected and in the following hours the relative humidity sensors on the middle section B-B also reached 100%. The sudden increase in humidity occurred almost instantly after the connection of the hydration filters to the water vessel. On 12.04.2010 filters RH-A2 and

RH-A3 in the top section measured 100% relative humidity, followed by sensor RH-A1 one day later on 13.04.2010. Furthermore, the sensors in sections A-A and B-B did not give reliable measurements after having reached 100% relative humidity.

The failure of the sensors once they came in contact with water was expected. It is known that this kind of sensor is fragile once flooded with water. This had already been mentioned by the expert panel on the seal design (cf. section 2.3) [24].

The interpretation of the measured relative humidity is not straightforward. The observed evolution in the relative humidity indicates a rather fast hydration process. Scoping calculations based on the assumed water retention capacity, relative permeability and initial state of the bentonite indicate that a water volume of ca. 35 l would be used in the bentonite hydration and that the suction inside the bentonite would decrease significantly in such a short time if the relative humidity measurements corresponded to the real progress of the hydration front.

But during this phase only a limited hydration process was expected, as the water flux from the Boom Clay towards the bentonite by advection is very small due to the low hydraulic conductivity of the bentonite and Boom Clay. Such a limited hydration also appears from the measured swelling pressures observed during the first 2 months (cf. section 6.2.2). Probably the relative humidity sensors, which are placed along the technological void and the bentonite interfaces, measure the relative humidity of the air in the voids between the bentonite blocks rather than the relative humidity of the bentonite blocks themselves.

6.2.2 STRESSES IN THE BENTONITE RING

The evolution in the stresses (all stress values are relative) in the bentonite ring and the stresses exerted by the bentonite on the Boom Clay and the steel structure of the hydraulic seal is given in Figure 6-9 to Figure 6-13. Sensor PK-C3, placed in the inner bentonite ring, failed on 09.05.2010 and the later measurements are not included in Figure 6-12. The recent drop measured by PG-B2 (Figure 6-9) might be due to a leaky flatjack. Also the low value shown by PK-A2 probably does not reflect an actual phenomenon, and is likely to be a sensor anomaly as well.

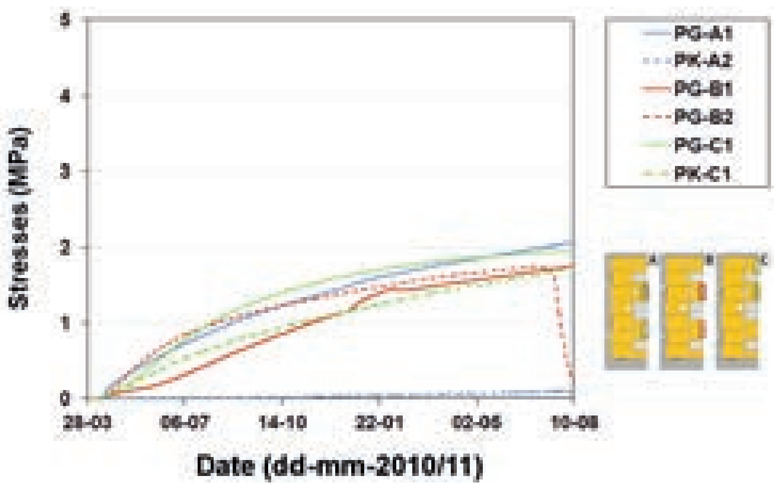


Figure 6-9: Radial stresses measured at the interface between the bentonite and the Boom Clay sidewall.

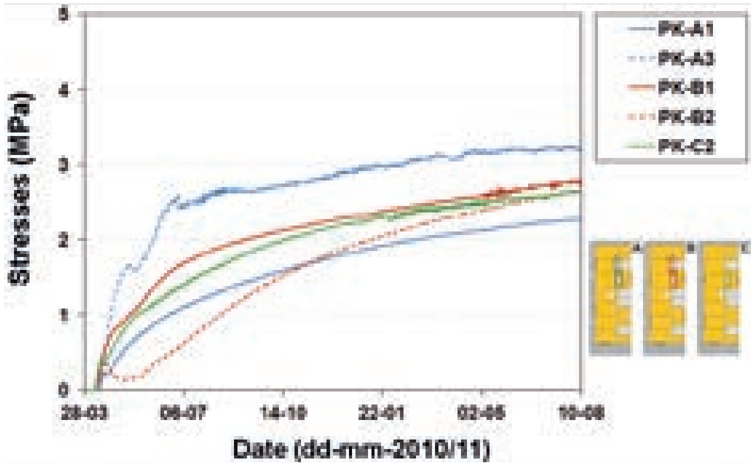


Figure 6-10: Radial stresses measured in the void between the inner and outer bentonite rings.

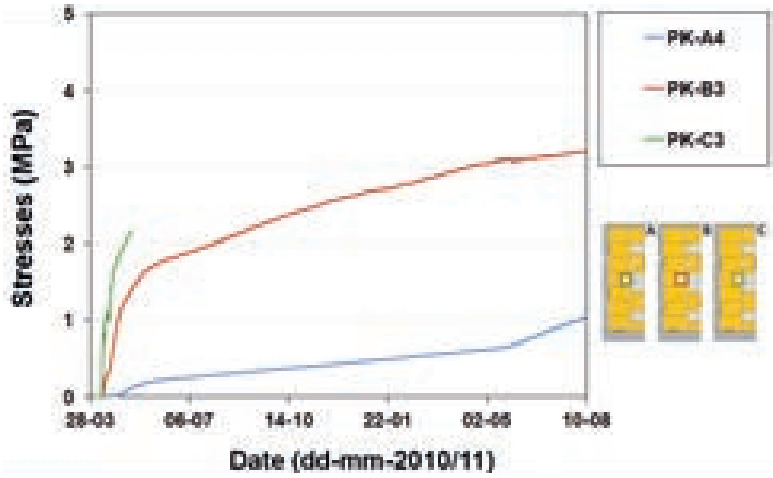


Figure 6-11: Circumferential stresses measured in the inner bentonite ring.

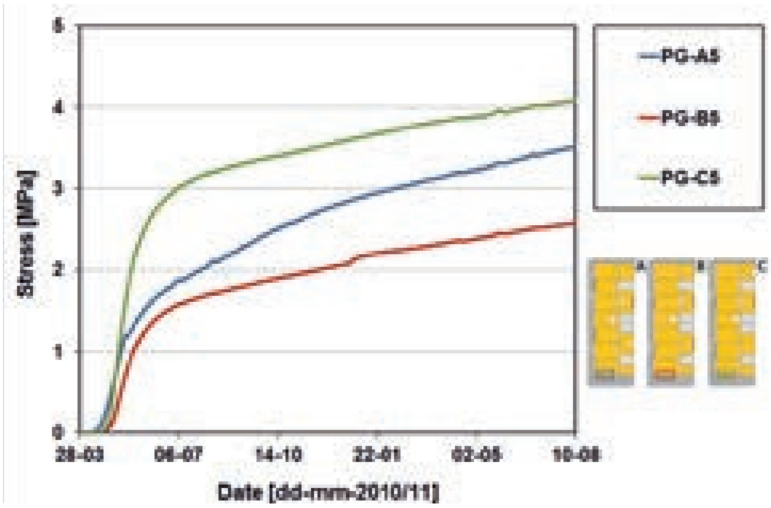


Figure 6-12: Axial stresses measured at the interface between the bentonite and the downstream flange.

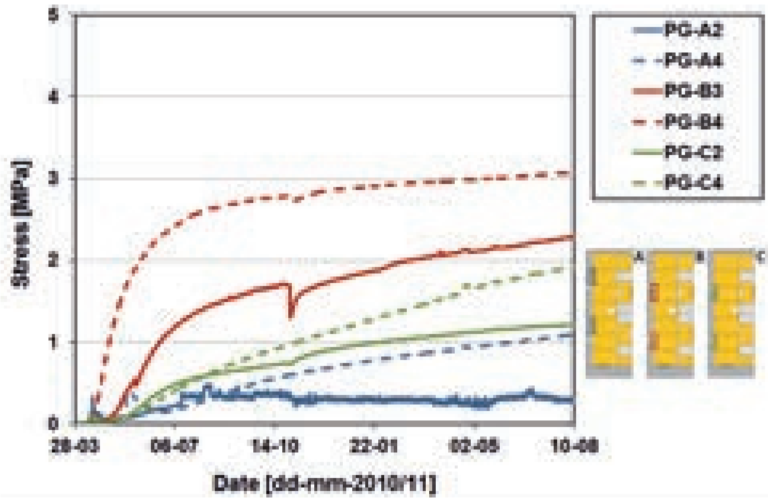


Figure 6-13: Radial stresses measured at the interface between the bentonite and the steel cylinder.

Although the rate of increase differs for the different sensors, all sensors, except for sensors PK-A2 and PG-A2, show a clearly increasing trend. These stress increases started a few days after the start of the artificial hydration, which indicates that in the first days of artificial hydration a closure of the voids took place. After all voids were closed, the stresses in the bentonite ring started increasing. This is consistent with the observed leakages during the first few days of the artificial hydration.

The measured radial stresses exerted by the bentonite on the Boom Clay sidewall (Figure 6-9) range from almost 1.5 MPa up to almost 3 MPa. The measured radial stresses on the steel structure of the hydraulic seal (Figure 6-13) vary from almost 1 MPa to 3 MPa and the measured axial stresses on the downstream flange (Figure 6-12) lie between 2.6 MPa and 4.1 MPa. The higher stresses in the axial direction can be explained by the absence of voids in the axial direction, by the mechanical constraints of the flange and by the compaction direction during the fabrication of the bentonite blocks, which may induce anisotropic swelling properties in the short term (the blocks were compacted in their axial direction).

The current stress increase rate at the bentonite–Boom Clay interface is ca. 10-12 bar/year, inside the bentonite ca. 7.5-9 bar/year, and at the bentonite–steel cylinder interface ca. 3-11 bar/year. The stress increase at the interface between the bentonite and the steel cylinder was higher in the beginning and is flattening out. The rate of stress increase at the interface between the bentonite and the Boom Clay is more constant than at the bentonite–steel cylinder interface. This could be explained by the availability of water, as the total surface area for natural hydration is ca. 10 times the surface area for artificial hydration.

It is interesting to observe that all sensors placed along the same interface show more or less the same stress increase rate, including the sensors placed against the steel rings (PK-A3 and PK-B2). This suggests that an unlocking of the steel rings (cf. section 2.2; Figure 2-11) did take place. The "unlocking" event might be the explanation for the drop in stresses seen in both sensors PK-A3 and PK-B2. This drop occurs earlier for PK-B2, which might be due to the fact that this sensor is placed closer to where the unlocking occurred.

The measured stresses are quite inhomogeneous. This can be attributed to several factors, such as the presence of the steel rings, the mechanical boundary conditions around the hydraulic seal (including the initial contact between the bentonite and the Boom Clay), the anisotropy of bentonite due to the bentonite compaction and the anisotropy of Boom Clay. The inhomogeneity is largest at the bentonite–steel cylinder interface. This might be due to the fact that artificial hydration is probably a more inhomogeneous process than natural hydration at the bentonite–Boom Clay interface (cf. hydration sequence and observed leakages during the start-up of the artificial hydration).

Since October 2010 interventions have been performed on the filters at the bentonite–Boom Clay and bentonite–steel cylinder interfaces (cf. section 6.2.3). The filters were saturated and subjected to overpressure. These water pressure increases led to stress decreases in nearby stress sensors (such as PG-B3).

6.2.3 PORE WATER PRESSURES IN THE BENTONITE RING

Piezometer filters in the bentonite make it possible to monitor the evolution in the pore water pressures in the bentonite (all pore pressure values are absolute). Figure 6-14 to Figure 6-17 show the measured pore water pressures, respectively, at the interface between the bentonite and the steel cylinder, in the void between the outer and inner bentonite rings, in the inner bentonite ring and at the interface between the bentonite and the Boom Clay. Since October 2010 some manipulations have been performed on several filters to gain better insight into bentonite status and behaviour.

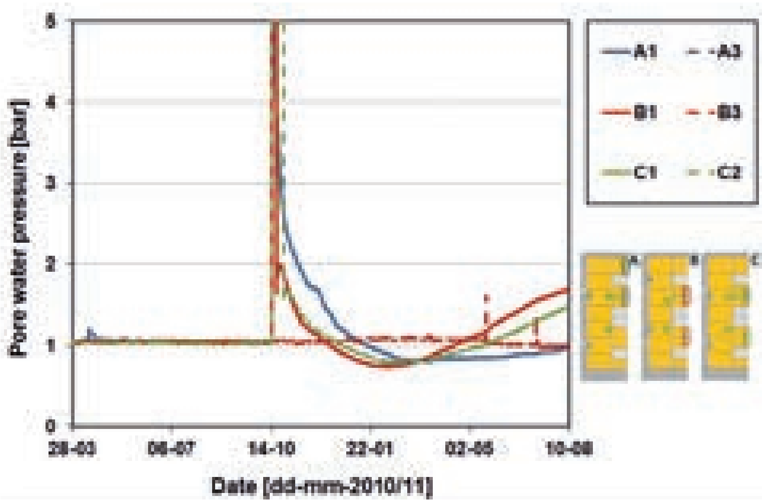


Figure 6-14: Measured pore water pressures at the interface between the bentonite and the Boom Clay.

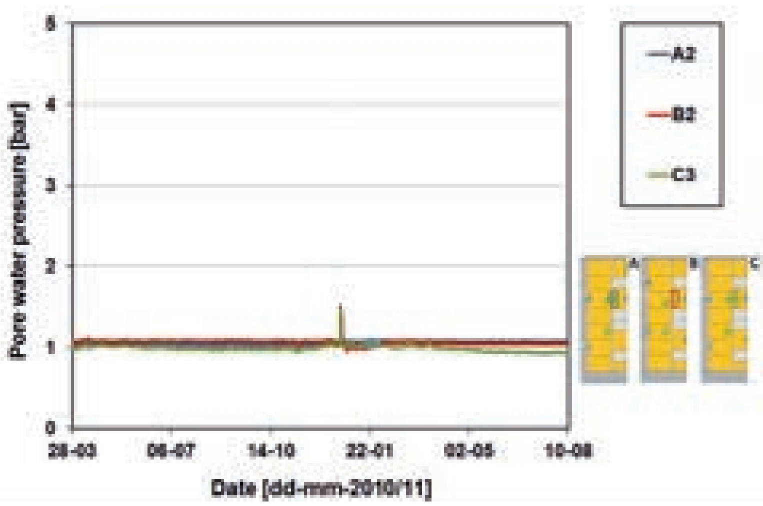


Figure 6-15: Measured pore water pressures in the void between the inner and outer bentonite rings.

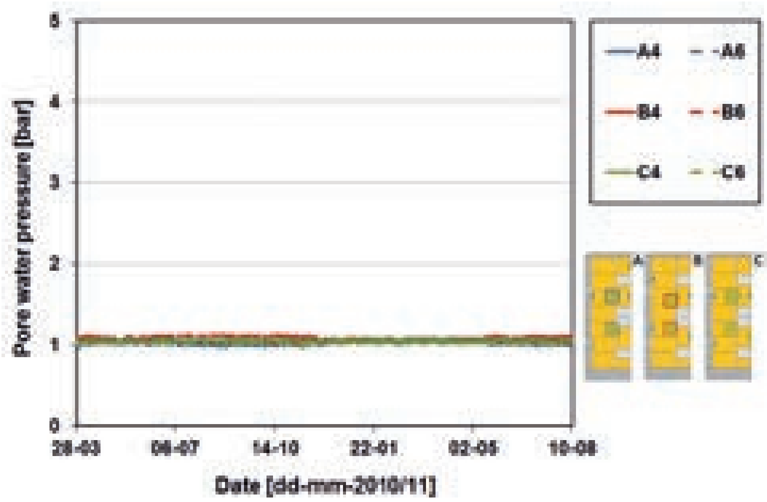


Figure 6-16: Measured pore water pressures in the inner bentonite ring.

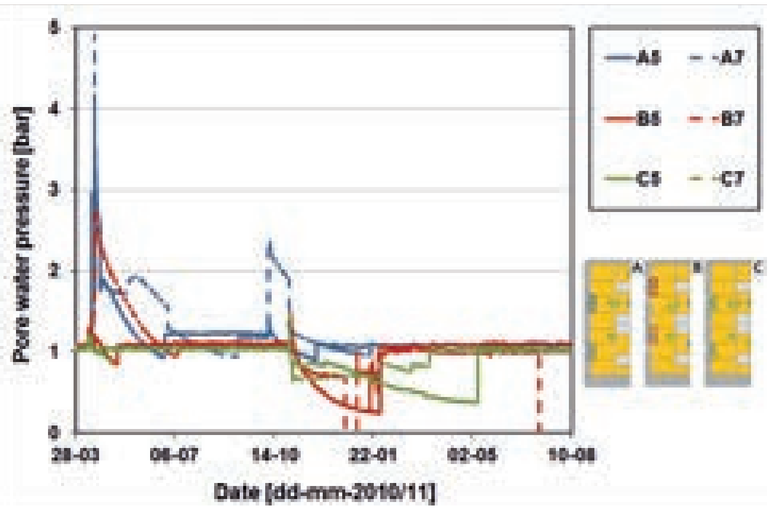


Figure 6-17: Measured pore water pressures at the interface between the bentonite and the steel cylinder.

Before the start of the artificial hydration no changes in pore water pressure in the bentonite ring can be observed. Once the artificial hydration is started on 07.04.2010 a sudden increase can be observed in all filters at the interface between the bentonite and the steel cylinder (Figure 6-17). These filters are close to the hydration filters in the steel cylinder through which the artificial hydration is performed. The magnitude of the increase differs strongly for the different filters. The increase is followed by a gradual decrease in the pore water pressures before the start of the artificial hydration, as the water is consumed by the bentonite hydration.

The filters at the interface between the inner and outer bentonite rings (Figure 6-15) and in the inner bentonite ring (Figure 6-16) have not yet shown a significant deviation from atmospheric pressure.

The pore water pressures between the inner and outer bentonite rings do not show any significant change during the whole period between the bentonite installation and October 2010. The same applies for the pore water pressures at the interface between the bentonite and the Boom Clay, except for filter PP-A1. The small increase on this filter cannot be explained and is probably a sensor anomaly.

The observed pore water pressure evolution is not always straightforward and is sometimes difficult to explain. Several filters indicate atmospheric pressures, but it is not clear if this applies to a gas, liquid or mixed pressure. Therefore some manipulations were performed on the filters to gain more insight into the status of the bentonite hydration. These consist of artificially saturating the filter with water to a certain overpressure and subsequently monitoring the evolution. The development of pressure below the atmospheric level would then indicate suction and unsaturated conditions in the zone around the filter.

All filters show more or less the same evolution: a sudden pore water pressure increase is observed as the filter is saturated, this increase being followed by a gradual decrease during which the pressure in some filters decreases below atmospheric pressure, indicating suction conditions around the filter.

The pore water pressures measured by filters A1, A3, B1 and C3 at the bentonite–Boom Clay interface decrease to values below 1 bar. After having reached a minimum, the pore water pressures steadily increase to values above 1 bar. Filters B3 and C1 were saturated as well, but although the pore water pressures decreased slightly there is no clear indication of suction.

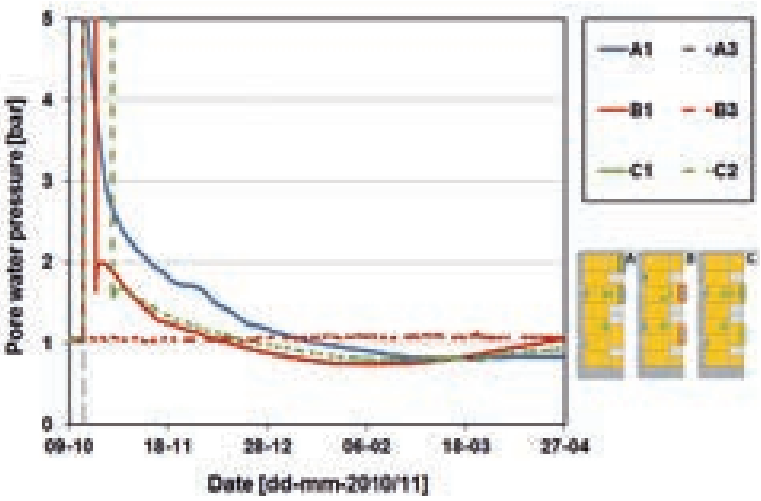


Figure 6-18, Figure 6-19 and Figure 6-20 show the evolution in the pore water pressures on the filters that were artificially subjected to overpressure.

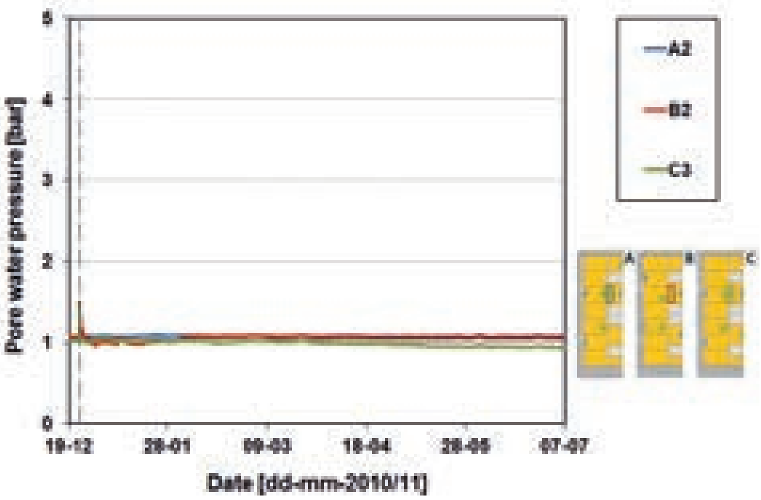


Figure 6-19: Measured pore water pressures in the void between the inner and outer bentonite rings after the manipulation of filters in this interface (the dashed line indicates the start of manipulation).

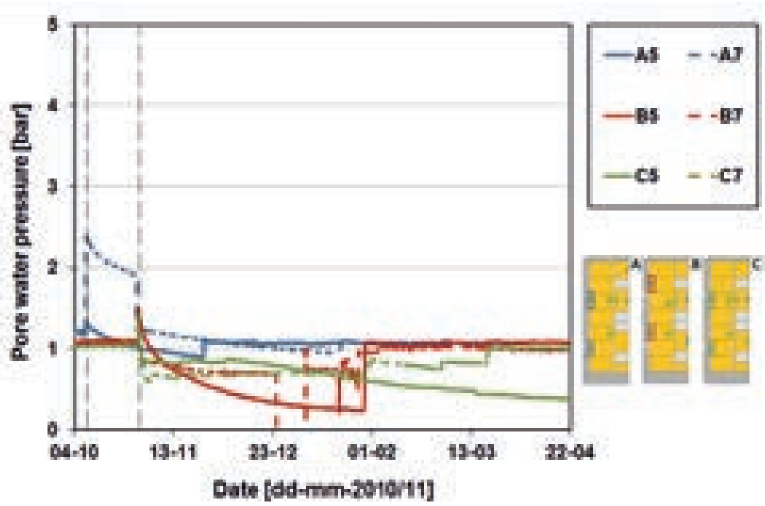


Figure 6-20: Measured pore water pressures at the interface between the bentonite and the steel cylinder after the manipulation of filters in this interface (the dashed line indicates the start of manipulation of filters A5-A7 and B5-B7-C5-C7 respectively).

The saturation of filters A2, B2 and C3 inside the bentonite also shows a slight increase immediately followed by a decrease, but also for these filters no clear indications of suction conditions around the filters can be observed. The manipulations performed on the filters at the bentonite–steel cylinder interface and at the bentonite–Boom Clay interface did not have any effect on the filters inside the bentonite.

For the filters placed at the bentonite–steel cylinder interface the peak in pore water pressure caused by saturating the filters is clearly followed by a gradual decrease. All filters measured suction pressures and eventually returned to atmospheric pressure. One remarkable aspect is the sudden increase in pore water pressure. This probably indicates gas entry as the pressure difference between the decreasing filter pressure and the environment (supposedly at atmospheric conditions) increased above the air entry value of the piezometer filter (estimated at about 0.1 bar – based on the manufacturer's specifications).

6.2.4 PORE WATER PRESSURES IN THE BOOM CLAY AROUND THE HYDRAULIC SEAL

Piezometers are available in the Boom Clay close to the hydraulic seal. Figure 6-21 shows the pore water pressures measured by these piezometers. Piezometer P30E-7 is placed at a distance of ca. 0.5 m from the hydraulic seal (somewhat inclined below the gallery), while piezometers P35E-12 and P35E-13 are respectively at a horizontal distance of ca. 0.75 m and ca. 0.9 m from the hydraulic seal.

At the start of the seal installation an increase in pore water pressure can be observed in piezometers P35E-PP12 and P35E-PP13 next to the hydraulic seal. An opposite change can be seen in piezometer P30E-PP7. These changes are induced by the removal of the wood from the alternative lining at the location of the hydraulic seal (cf. section 5.2.1). The difference in pore water pressure changes below and next to the gallery is explained by the anisotropic nature of the Boom Clay and shows again the complexity of the hydromechanical behaviour of the Boom Clay. This removal caused a stress release at the Boom Clay sidewall, which in turn contributed mainly to the decrease in the pore water pressure measured by P35E-PP12, P35E-PP13 and P30E-PP7. After the bentonite was placed and before the artificial injection, the contact between Boom Clay and bentonite was not perfect yet, so decreasing pore water pressures were still observed.

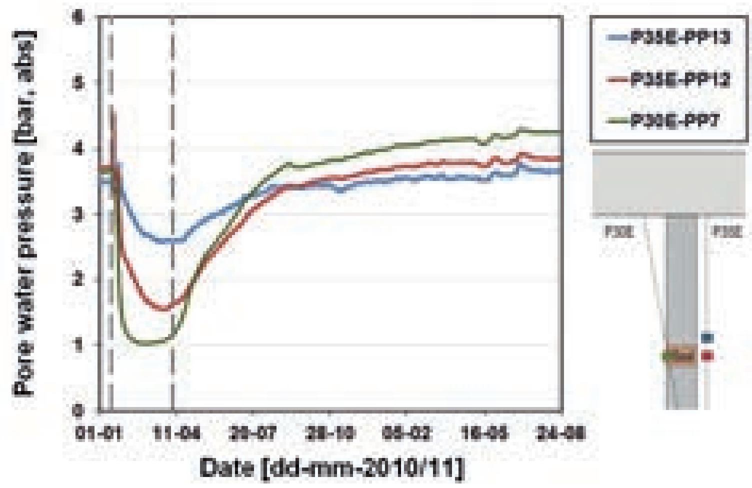


Figure 6-21: Measured pore water pressures in the Boom Clay close to the hydraulic seal (the dashed grey lines indicate the start of the seal installation and the start of the artificial hydration respectively).

As the bentonite gets more hydrated by the natural water from Boom Clay and artificial injection, it exerts a swelling pressure on the surrounding Boom Clay and this in turn results in a volumetric compaction of the Boom Clay and increasing pore water pressures. After ca. 8 months the pore water pressures have recovered to their value before the bentonite installation.

The hydraulic conductivity of the clay around these filters was measured by imposing a higher water pressure on the filters and measuring the water influx. The hydraulic conductivities obtained on all 3 filters were similar (order of magnitude of 10^{-12} m/s) to hydraulic conductivities measured in undisturbed Boom Clay.

6.2.5 DISPLACEMENTS IN THE BENTONITE RING

The displacements measured by the 2 extensometers in the bentonite ring are given in Figure 6-22. No significant displacement was measured before the start of the artificial hydration.

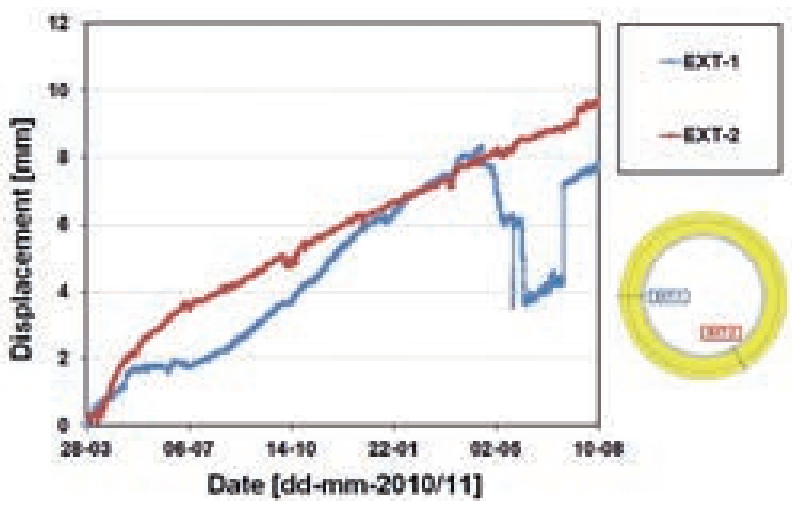


Figure 6-22: Measured radial displacement (an outward displacement is positive) of the bentonite ring.

Once the artificial hydration started, the extensometers measure an outward displacement. In the first few months this displacement is larger for the bottom extensometer EXT-2. This is consistent with the sequence of the artificial hydration, which was performed from bottom to top. Almost one year after the start of the artificial hydration the extensometers measured a displacement of 9.6 mm and 7.8 mm for the bottom and middle extensometer respectively. Uncertainty exists regarding the total displacement of the middle extensometer, as a failure occurred on this extensometer on 18.04.2011. This was repaired on 07.07.2011. However, the increasing trend for both extensometers is clear and still persists.

6.2.6 CONCLUSIONS FROM BENTONITE HYDRATION

During the natural hydration phase (before artificial injection) the relative humidity in the bentonite ring gradually increased. The increase in relative humidity is largest in the bentonite closer to the Boom Clay. However, the relative humidity sensors are placed along the technological void and the bentonite interfaces and probably measure the relative humidity of the air in the voids between the bentonite blocks and not the relative humidity of the bentonite blocks themselves. After the start of the artificial hydration all sensors reach 100% relative humidity and subsequently fail. No significant changes in stresses, pore water pressures or displacements are observed during this period.

With the start of the artificial hydration, synthetic Boom Clay water was injected into the bentonite ring. As there was no significant swelling of the bentonite before the start of the artificial hydration, the ring still contained voids and some of the injected water leaked out of the hydraulic seal. It is therefore not possible to accurately estimate how much water was injected during this period. By 19.04.2010 the bentonite around the cylinder had been sufficiently hydrated to close the annular space between the cylinder and the clay and there was no further water leakage from the seal. Measured stresses indicate that almost all the gaps in and around the seal were closed within 2 weeks of the start of the artificial hydration. The injection rate decreases with time.

The injection of water at the interface between the steel cylinder and the bentonite leads to an increase in the pore water pressures at this interface. This increase is followed by a gradual decrease in the pore water pressure value observed before the start of the artificial hydration. This decrease is caused by the consumption of the water by the bentonite. The pore water pressures between the inner and outer bentonite ring and at the interface between the bentonite and the Boom Clay are not significantly affected by the artificial hydration.

The stresses in the bentonite ring and at the interfaces between the bentonite and the cylinder and the bentonite and the Boom Clay also started to increase after the start of the artificial hydration. Except for some malfunctioning sensors, they all measure increasing stresses. The maximum radial swelling pressure (measurements until August 2011) has reached 3.1 MPa and most of the radial swelling pressures at the three interfaces (bentonite–steel cylinder, inner void, bentonite–Boom Clay) between 1.6 MPa and 3.1 MPa.

Furthermore, an outward displacement of 10 mm is measured at the bentonite–Boom Clay interface by the 2 extensometers.

As it was not clear whether the piezometers measured a gas, liquid or mixed pressure in the bentonite, several filters were artificially saturated with water to a certain overpressure. Subsequently the evolution in pore water pressure was monitored to gain more insight into the status of the bentonite hydration.

Depending on the location of the filters, different results were obtained and no clear picture of the saturation degree was obtained. The strongest reactions (i.e. tensiometer effect with development of suction down to deep levels and subsequent gas entry) were noticed around the central steel cylinder. This indicates that the influence of the hydration filters is only very local and has not yet caused a general saturation of the bentonite in contact with this cylinder. Inside the bentonite, the filters do not show any pronounced suction effect. This is somewhat surprising, as the saturation in this zone was considered to be the lowest.

The filters at the interface with the Boom Clay first showed negative pore pressures after saturation, but then measured gradually increasing pressure, with pore water pressure above 1 bar developing in this region. Suction in this zone has disappeared, indicating that the bentonite at the bentonite-Boom Clay interface is being saturated.

7. Conclusions

A hydraulic seal was installed in the PRACLAY gallery in 2010. With the installation of this hydraulic seal, the second test of the three tests making up the PRACLAY In-Situ Experiment was successfully accomplished. The main purpose of the hydraulic seal is to create a quasi-impermeable hydraulic boundary at the intersection between the heated part of the PRACLAY gallery and the non-heated part. Such a quasi-impermeable boundary is required to achieve the conservative conditions that are envisaged for the Heater Test. Furthermore the opportunity was taken to examine the feasibility of installing such a seal in an underground gallery.

The hydraulic seal consists of a steel structure closing off the heated part of the gallery from the rest of the underground infrastructure, and an annular ring of precompacted bentonite placed against the clay. The bentonite is hydrated and the swelling pressure exerted against the clay will locally lower the hydraulic conductivity of the clay. The hydraulic seal is about 1 m long, as scoping calculations proved that such a seal length is sufficiently effective and that no significant gain is obtained by further increasing the length of the seal.

To maintain the accessibility of the clay sidewall at the location of the hydraulic seal, an alternative lining was installed during the construction of the PRACLAY gallery. The alternative lining consisted of four steel rings and wood placed behind these steel rings as a temporary component of the lining. The wood was removed before the installation of the hydraulic seal.

7.1. Hydraulic seal design

The steel structure of the hydraulic seal consists of two flanges that are placed against the concrete lining next to the hydraulic seal. Because the flanges are too large to be installed in one piece, they are composed of 4 segments that were initially to be welded together in-situ. But as the welding of this segments was considered to pose a risk of significantly deforming the flanges, assembly by welding was replaced by mechanical assembly using bolts, gaskets and a resin.

After both flanges are installed, an annular ring of bentonite blocks is erected between the flanges and the clay sidewall. Subsequently a cylinder is placed inside the annular bentonite ring and between the two flanges. In that way the bentonite is enclosed between the two flanges, the cylinder and the Boom Clay. Filters are placed on the extrados of the cylinder for the artificial hydration of the bentonite.

A circular plate placed in the cylinder closes off the heated part of the PRACLAY gallery. Because this part of the gallery still had to remain accessible before the start of the Heater Test – this was needed for the assembly of the cylinder to the flanges during the seal installation and for the installation of the heater and backfill material in the PRACLAY gallery after the seal installation – a manhole is placed in the centre of the plate. Before the start of the Heater Test the manhole is closed by welding a closing plate onto it. The plate in the cylinder has several openings for the feed-through of the instrumentation and the heating system placed in the upstream part of the gallery.

MX80 bentonite was selected based on its swelling and water retention potential, its compatibility with Boom Clay and experience with this type of bentonite from other experiments in underground research facilities. The desired initial dry density of the bentonite, which affects its swelling pressure and its saturated permeability, was determined by scoping calculations. MX80 bentonite was compacted into bentonite blocks, which were installed in-situ into an annular ring of bentonite placed against the Boom

Clay. To be able to monitor the behaviour of the bentonite during its hydration, instrumentation was placed in the bentonite.

7.2. Seal construction and installation

The different components of the steel structure were manufactured in the workshop (of STORK MEC as a subcontractor of SMET TUNNELLING). After their construction they were assembled in the workshop during a test assembly to check the compatibility of the different components and the feasibility of assembling them. Subsequently they were transported to the site. The actual underground installation work started on 13.01.2010. On 11.02.2010 the first phase of the underground installation of the seal was finished.

The assembly of the heavy steel components (the heaviest single part weighed ca. 1.6 tonnes and the total weight of the assembled downstream flange was ca. 2.3 tonnes) in the very limited working space was not at all straightforward. Also the assembly of the bentonite ring composed of in total 236 blocks, or ca. 3200 kg of bentonite, was a complicated task. Nevertheless the complete installation work was performed successfully and without major difficulties in less than one month.

The second phase of the hydraulic seal installation comprised the welding of the closing plate onto the manhole of the hydraulic seal. This was 20 months later, between 29.09.2011 and 13.10.2011, after the heating system and the backfill material were installed in the heated part of the PRACLAY gallery.

7.3. Bentonite hydration

Instrumentation was placed in the bentonite blocks to gain information on the bentonite hydration and to be able to evaluate the performance of the hydraulic seal. This report only includes measurements until August 2011. These measurements indicate that the bentonite hydration is evolving in the right direction. The bentonite is swelling up to 10 mm towards the Boom Clay, the maximum radial swelling pressure has reached 3.1 MPa. The measured stresses indicate that almost all the gaps in and around the seal were closed shortly after the start of the artificial injection. At the bentonite–Boom Clay interface, pore water pressures higher than atmospheric pressure are measured, which indicates good saturation of this interface. Finally, the measured hydraulic conductivity of the Boom Clay around the seal is similar (order of magnitude of 10^{-12} m/s) to hydraulic conductivities measured for undisturbed Boom Clay.

The bentonite hydration is ongoing and since most bentonite is still unsaturated, there is still substantial potential for further bentonite swelling as the hydration process continues.

PART III

The heater and backfill material

Summary

The last phase in the installation of the PRACLAY In-Situ Experiment was started in 2011 with the installation of the heating system and backfill material. The heating system has to heat the clay at the gallery extrados (outer surface) from its in-situ temperature of 16°C to a temperature of 80°C and maintain the gallery–Boom Clay interface at this temperature for ca. 10 years. The saturated backfill material ensures quasi-undrained hydraulic boundary conditions at the interface between the Boom Clay and the gallery lining.

The heating system consists of a primary heater close to the gallery intrados (inner surface) and a secondary heater inside a central tube. Both of these are electrical heaters. The primary heater is inaccessible during the Heater Test and is therefore installed in a redundant manner, i.e. more heater elements are placed than strictly required. The secondary heater is a backup and remains accessible and replaceable at all times during the test. Besides these heating elements, a control system regulating the heating power is also part of the heating system. Each heating system has its own control system. The temperatures measured by thermocouples at the intrados and extrados of 7 lining rings serve as input for the control system.

Because of the larger heat dissipation at the two ends of the heated part of the PRACLAY gallery, a constant temperature along the extrados of this part can only be achieved when a higher power is applied at these two ends. Therefore the primary heating system is made up of three sections: a front-end section (the first few metres behind the hydraulic seal), a middle section of ca. 30 m and a far-end section (the last few metres of the PRACLAY gallery).

The secondary heater is placed in a central tube, which rests on a support structure. The support structure is made up of prefabricated components that are assembled in-situ. No welding is allowed to avoid damaging the instrumentation and heater cables.

During the start-up phase the temperature is increased step-wise and very slowly. The rate of the temperature increase is limited by the maximum allowable thermal gradient in the concrete lining. The maximum allowed difference between the intrados and extrados temperature of the lining during the start-up phase is 15°C. The temperature increase rate is nevertheless larger than around an actual disposal gallery for heat-emitting waste.

The saturated backfill material has a thermal conductivity higher than the thermal conductivity of the lining and Boom Clay to efficiently transfer the heat generated by the heating system. It also has sufficiently high hydraulic conductivity, allowing rapid homogenisation of the water pressures in the backfill material. Furthermore it has a narrow grain size distribution, limiting the density differences between the top and bottom due to segregation. Mol sand was selected as backfill material, with ca. 145 tonnes being required to fill the gallery. The sand was installed by blowing it in a dry state into the gallery. In a later phase the backfill sand was saturated by injecting water through 6 saturation filters placed at the bottom of the heated part of the PRACLAY gallery.

1. Introduction

In contrast to the construction of the PRACLAY gallery and the installation of the hydraulic seal, the installation of the heating system and backfill material in the PRACLAY gallery does not constitute an experiment in itself. Its only purpose is to achieve the thermal and hydraulic conditions required for the PRACLAY Heater Test.

The primary heating system and backfill material had been successfully installed in the PRACLAY gallery by October 2011. The secondary heating system was installed in a central tube during February 2012. However, at the moment of publication of this report, the design of the secondary heater is under revision. This part of the report discusses the requirements for the heating system and the backfill material, the tendering procedure for the heating system and the complete installation work. It is structured as follows:

- *chapter 2* describes the design specifications for the heating system and backfill material;
- *chapter 3* gives an overview of the tendering procedure for the construction and installation of the heating system;
- *chapter 4* explains the design and construction of the heating system and the selection of the backfill sand;
- *chapter 5* presents the installation work;
- *chapter 6* summarises the main conclusions, evaluates the achievements and provides recommendations for future work.

2. Specifications for the heating system and the backfill material

The heating system and backfill material are installed in the PRACLAY gallery to achieve the required thermal and hydraulic conditions for the PRACLAY Heater Test. The aim is to impose conservative conditions in terms of the thermo-hydromechanical (THM) response of the Boom Clay formation to a disposal system. These conditions were mainly determined by scoping calculations and are described in chapter 2 of the introductory part of this report.

The following design criteria were eventually defined for the Heater Test:

- imposing a constant temperature of 80°C at the gallery extrados and increasing the temperature progressively;
- a heated gallery section of 30 m;
- saturating as much as possible the components inside the PRACLAY gallery.

Based on these criteria for the Heater Test, and taking into account the design of the PRACLAY gallery and the hydraulic seal, the design specifications for the heating system [40] and the backfill material were developed. The design specifications for the heating system and the backfill material are discussed in the sections below.

2.1. The heating system

The heating system has to heat the clay at the gallery extrados from its in-situ temperature of 16°C to a temperature of 80°C and maintain the gallery–Boom Clay interface at this temperature for ca. 10 years. The heating system consists of a primary heater close to the gallery intrados and a secondary heater inside a central tube (Figure 2-1). Both of these are electrical heaters. The primary heater is inaccessible during the Heater Test and therefore needs to be installed in a redundant manner. The secondary heater is a backup and will remain accessible and replaceable at all times during the test.

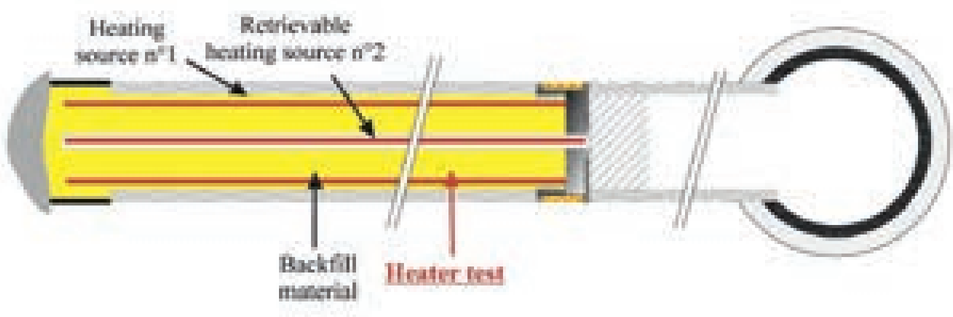


Figure 2-1: The heating system consists of a primary and a secondary system.

Besides the heater systems, a control system also has to be installed to regulate the heating power according to measured and target temperatures.

A preliminary design for the heating system was made, mainly based on the recommendations formulated in two studies performed by NRG/ECN [41; 42]. Heating by electrical heaters is preferred to an oil- or water-based heating system. In the latter system a hot fluid is circulated through a set of pipes. Achieving a flat temperature profile along the gallery is more difficult, as the heat output is larger at the beginning of the pipes than at the end and the pipes would have to be equipped with a temperature-controlled valve. Furthermore the life expectancy of oil- or water-based heating systems was estimated to be shorter because of the risk of leakage at the valve and pipe connections.

According to these studies, a thermal power of 250-400 W/m is needed during the stationary phase. To limit the thermal gradient over the concrete lining, the temperature has to be increased from 16°C to 80°C over a sufficiently long period. For a start-up phase of 100 days, during which the temperature is increased from 16°C to 80°C, the required power would amount to ca. 750 W/m. To obtain the flattest possible temperature profile, the larger losses at the ends have to be compensated for. Therefore the heater is divided into 3 separately controlled sections: a front-end section just behind the hydraulic seal, a middle section, the length of which should be maximised, and a far-end section at the end of the PRACLAY gallery.

The construction and installation of the primary heater and the control system were the subject of a tendering procedure (cf. section 3). The tender documents described the functional requirements and the necessary tolerances for the heating system. The design of the system was the responsibility of the contractor and was also part of the tendering procedure.

The secondary heater is installed inside a central tube. However, at the moment of publication of this report, the design of this heater is under revision. The final installation is planned for early 2014.

The sections below describe the functional requirements and the necessary tolerances as mentioned in the tendering procedure for the first heating system and the control system (sections 2.1.1 and 2.1.3). The specifications of the secondary heating system are given in section 2.1.2.

2.1.1 PRIMARY HEATING SYSTEM

Electrical heater cables have to be used for the primary heating system and electrical connections in the heated part of the gallery need to be avoided. Furthermore the number of individual heating elements is limited as the number of passages through the hydraulic seal is limited.

The overall heating system has to have a minimum service life of 10 years. The system thus needs to be mechanically robust and corrosion-proof, and must be suitable for a water-saturated (pressures up to 35 bar) and hot environment. The primary heating system has to be 100% redundant and the heater elements should be arranged in such a manner that the heterogeneity of the temperature field in the event of failure of a heating cable is limited.

The surface temperature of the heater cables has to be limited to 200°C so as not to damage the instrumentation cables in the gallery. To limit hot spots on the gallery lining intrados, the cables are installed at a distance of 100 mm from the gallery intrados. The temperature at the lining intrados has to remain below 95°C at all times.

Because of the larger heat dissipation at the two ends of the heated part of the PRACLAY gallery, a constant temperature along the extrados of this part can only be achieved when a higher power is applied at these two ends. Therefore the primary heating system is made up of three sections:

- a front-end section: the first few metres behind the hydraulic seal;
- a middle section: ca. 30 m;
- a far-end section: the last few metres of the PRACLAY gallery.

It was the responsibility of the contractor to determine the exact length of the three sections, taking into account the fact that the length of the middle section should be maximised.

During the start-up phase the temperature is increased step-wise and very slowly. The rate of the temperature increase is limited by the maximum allowable thermal gradient in the concrete lining. The maximum allowed difference between the intrados and extrados temperature of the lining during the start-up phase is 15°C.

Furthermore the temperature has to be increased in a homogeneous manner along the heated gallery section. The maximum temperature difference between any 2 given points of the lining extrados is 5°C for the middle section and 8°C overall.

It was the responsibility of the contractor to draw up a heating system and procedure for the start-up phase in compliance with the above constraints. The start-up phase should, however, be kept as short as possible, with a maximum of 6 months.

During the 10-year steady-state phase the following constraints apply:

- the maximum allowable temperature difference between the intrados and extrados of the lining is 10°C;
- the tolerance on the temperature at the lining extrados is ±2°C in the middle section and ±4°C overall;
- the tolerance on the mean temperature at the lining extrados is ±1°C in the middle section and ±2°C overall.

2.1.2 SECONDARY HEATING SYSTEM

At first the heating cables of the large-scale ESDRED mock-up (*De Bock et al., 2008*) were re-used as cables for the secondary heater. However, it was later decided not to use these cables as their length (31m) does not cover the complete heated section (33m). Therefore the design of the secondary heater is revised. The full installation is planned for early 2014.

2.1.3 CONTROL SYSTEM

The control system has to regulate the power of the heating elements to meet the temperature constraints described in section 2.1.1. The three sections of the primary heater have to be controlled separately.

An extensive network of temperature sensors is installed in the gallery lining and the surrounding clay. Seven lining rings in the heated part of the PRACLAY gallery (rings 21, 29, 37, 50, 55, 68 and 81; see Figure 2-2a) are instrumented with 12 thermocouples each (Figure 2-2b). The extrados and intrados sensor readings are made available as input for the control system.

The bottom (segment 4) thermocouples of ring 21, ring 50 and ring 68 appeared to be out of order and new thermocouples were installed in a hole drilled in bottom segment 4 of these rings. The hole was afterwards filled with mortar.

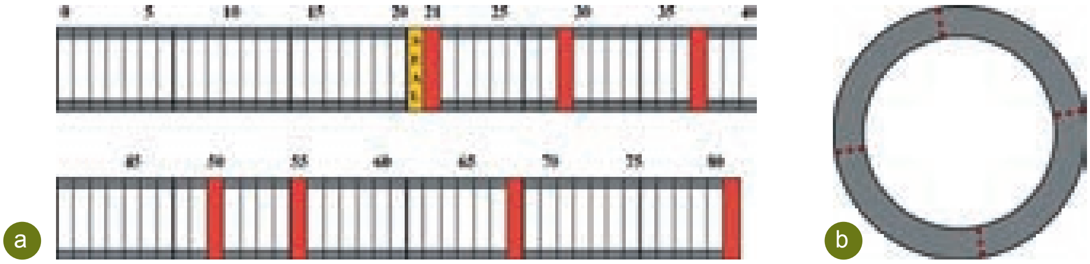


Figure 2-2: (a) Temperature sensors are installed in lining rings 21, 29, 37, 50, 55, 68 and 81 of the PRACLAY gallery; (b) the location of the individual sensors in each instrumented lining ring (looking upstream along the gallery).

In order to back-analyse the experimental results of the Heater Test, detailed knowledge of the heat source is of primary importance. Therefore, besides controlling the heater elements, the control system has to be able to determine the exact power that is delivered to the heating systems.

Several power conversion methods were identified in the ECN/NRG documents to drive the heater elements [41]. The choice of conversion method was left to the contractor, who has to detail and justify his choice.

2.2. Backfill material

With the installation of a saturated backfill material, together with the hydraulic seal, the required quasi-undrained boundary conditions at the interface between the gallery lining and the Boom Clay are achieved. The volume of the gallery section that has to be backfilled is ca. 100 m³. The requirements for the saturated backfill material are [4]:

- having a thermal conductivity higher than the thermal conductivity of the gallery lining and clay formation (being 1.5-1.7 W/m·K) to efficiently transfer the heat generated by the heating system towards the clay;
- having a sufficiently high hydraulic conductivity to allow rapid homogenisation of the water pressure in the gallery and to minimise the longitudinal gradient of the water pressure in the vicinity of the heater. Numerical simulations indicate that permeability of the order of 10^{-6} m/s is sufficiently high (Figure 2-3).
- having preferably a narrow grain size distribution to limit the density differences between the top and bottom of the backfill sand due to segregation.

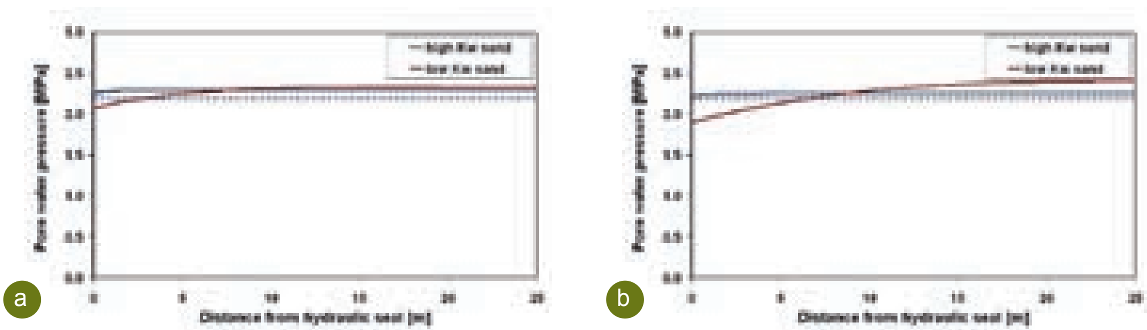


Figure 2-3: Water pressure in the backfill material along the heated section of the gallery for a backfill material with high conductivity (10^{-6} m/s) and low conductivity (10^{-10} m/s): (a) after 1 year of heating; (b) after 10 years of heating.

3. Tendering procedure for the heating system

A negotiation procedure without prior notification was applied as contract award procedure for the design, construction and installation of the primary heating system and control system (cf. section 2.1) [43]. Table 3.1 gives the timeline of the applied tendering procedure. Five companies were asked whether they were interested in submitting a bid:

- Bartec, Tessenderlo (B);
- ENON, Wijchen (NL);
- Mechaheat, Wijchen (NL);
- Thermocoax, Eindhoven (NL);
- TYCO THERMAL CONTROLS, Leuven (B)

All five confirmed their interest and the tender documents were sent. Only 2 potential contractors eventually submitted a bid. These bids were analysed objectively against the contract award criteria and weighting factors as defined in the tender documents. The 2 candidates were invited to take part in a negotiation round, after which they were both asked to submit a BAFO (Best And Final Offer). After receipt and analysis of the BAFOs, the contract was awarded to TYCO THERMAL CONTROLS in October 2009 and the contract was signed in January 2010.

27.04.2009	Invitation to participate in the negotiation procedure sent to 5 companies (ref. EURIDICE PDP/WP/bp/09-150)
29.05.2009	Deadline for potential candidates to enter the procedure
09.07.2009	The tender documents [43] were given to the 5 potential contractors (ref. EURIDICE WP/bp/09-177)
20.08.2009	Receipt of the 2 bids
31.08.2009	Invitation letter for negotiation round (ref. EURIDICE WB/bp/09-181)
03-04.09.2009	Negotiation round with the candidates
07.09.2009	Invitation letter to submit a Best And Final Offer by 21.09.2009 (ref. EURIDICE WB/bp/09-185)
11.09.2009	Original deadline for receipt of the BAFOs was postponed until 28.09.2009 (ref. EURIDICE WP/bp/09-188).
28.09.2009	Receipt of the BAFOs
26.10.2009	Decision of the steering committee of EURIDICE to award the contract (ref. EURIDICE WB/bp/09-202 and incoming mail ref. 09-208)
29.10.2009	Award of the contract to TYCO THERMAL CONTROLS (ref. EURIDICE WP/bp/09-205) and notification of the decision to the other candidate (ref. EURIDICE WP/bp/09-206)
22.01.2010	Signing of the contract (T_0)

Table 3.1: Timeline of the tendering procedure

4. Design of the heating system and selection of the backfill material

The design specifications for the heating system and the requirements for the backfill material were discussed in chapter 2. This chapter explains the design of the heating system and the selection of the backfill material. The subsequent installation of the heating system and backfill material is explained in chapter 5.

The secondary heater is placed in a central tube, which rests on a support structure. The construction of this central tube and its support structure is explained in section 4.3. At the moment of publication of this report, the design of the secondary heater is revised.

Detailed information (construction drawings, procedures, calculation notes, material specifications, meeting reports, etc.) on the construction and installation of the primary heating system and the control system can be found in the construction documents for the primary heating system and control system [44].

4.1. Primary heating system and control system

The specifications for the heating system and the control system are described in section 2.1. The primary heating system consists of electrical heaters placed 100 mm from the gallery intrados and is 100% redundant. The system is divided into three longitudinal sections along the length of the heated part of the PRACLAY gallery – the front-end section behind the hydraulic seal (1.4 m), the middle section (28.3 m) and the far-end section at the dead-end of the gallery (2.0 m) – and in each of these longitudinal sections the system is further divided into four cross-sections (a bottom and top section and two side sections) (Figure 4-1).

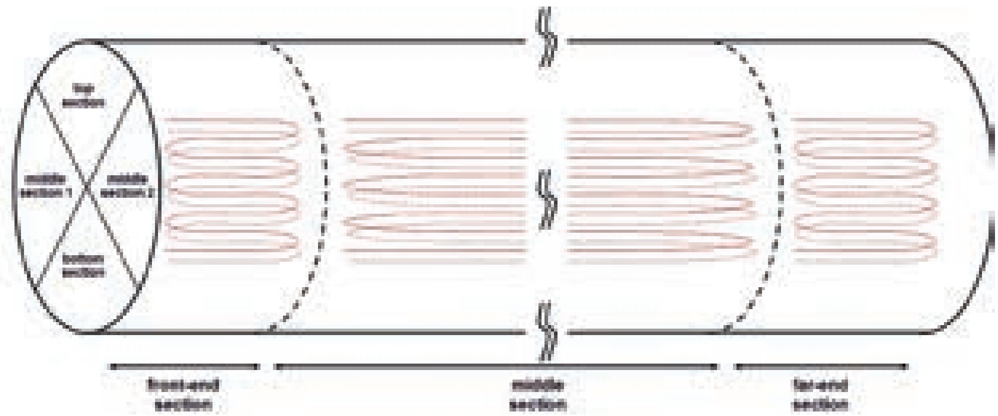


Figure 4-1: The heater layout is divided into 3 longitudinal sections and 4 cross-sections. In this figure only the heater cables (in red) in the middle section 2 are shown.

To achieve the required power, the heater cables have to be placed at an intermediate distance of 157 mm. For this purpose, one heater cable with 8 windings is placed in each section. As the primary heating system has to be 100% redundant, an extra heater cable, also with 8 windings, is installed. The windings of both cables in one section are placed in an alternating order (Figure 4-1). The intermediate distance between two cables then becomes 78.5 mm. The heater cables are not allowed to touch each other.

The heaters are electrical resistance elements in a metal sheath (Alloy 825) (Mineral Insulated (MI)). A product data sheet for the cables is given in [45]. Dual core heaters[1] are used in the front-end and far-end sections to achieve a sufficiently high resistance in these relatively short sections. Moreover the use of a dual core for the far-end enables only one cold lead[2] to be used to connect the heater cable to the power source. As the middle section is relatively long, single core heaters are used for this section.

The following heater elements are used in the three longitudinal sections:

- front-end section: 4x2 dual core elements (HAA2M13.2K) with a power of 24 W/m and a cable length of 12.2 m (length cold lead: 10 m)
- middle section: 4x2 single core elements (HAP1N37) with a power of 22 W/m and a cable length of 228 m (length cold lead: 15 m)
- far-end section: 4x2 dual core elements (HAA2M5600) with a power of 25 W/m and a cable length of 17.0 m (length cold lead: 40 m)

16 cold leads (diameter 7.3 mm) from the 16 dual core elements and 16 cold leads (diameter 6.4 mm) from the 8 single core elements are connected in the workshop to the heater cables using laser welding and are fed through the hydraulic seal (Figure 4-2).

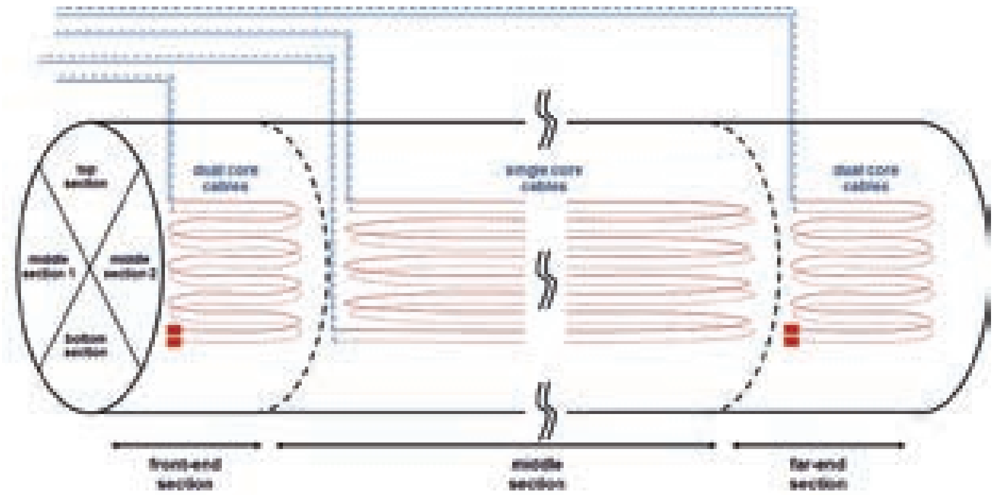


Figure 4-2: Cold leads connecting the heater cables to the power source.

The elements are certified to withstand pressures of up to 30 bars. The heater elements were checked by performing the Megger test[3]. The water pressure in the backfill material is limited to 35 bar (this is the water pressure taken into account in the design calculations of the hydraulic seal) by the safety valves (cf. section 4.2). Therefore the heater elements were tested by EURIDICE for pressures up to 40 bar and temperatures up to 90°C. The tests were Megger tests on the heater elements placed in a water vessel that could be heated.

The tests followed a test protocol specifying the pressure and temperature path to follow [46].

1 The heater elements consist of an electrical resistance wire in a stainless steel tube. Electrical insulation (Mineral Insulated (MI) Powder) is placed between the resistance wire and the tube to prevent short-circuiting. In single core heaters one wire is placed in the steel tube, while in dual core heaters the wire runs twice through the steel tube.

2 The cold lead connects the heater cable to the power source. It has to have a low electrical resistance compared to the heater cable to prevent the cold lead itself heating up.

3 With a Megger test, also known as an insulation resistance test, the resistance of the insulation of the heater cables is checked. At an applied voltage of 1000 V the insulation had to have a minimum resistance of 100 MΩ.

During the start-up phase the power to be delivered to the gallery lining per metre of heater cable is limited to 18 W/m, limiting the thermal gradient over the 300 mm thick gallery lining to 15°C. During the stationary phase the delivered power to the gallery lining per metre of heater cable is ca. 2 W/m.

The heater elements are driven by AC voltage and the power is regulated by switching the AC sine wave on or off for one or more periods within a fixed time (zero crossing firing technique). This system controls the primary heater and the three sections of the primary heater are controlled separately. Furthermore, the control system switches between the two redundant primary heating systems every 12 hours in order to prevent one of these systems being out of order undetected for longer than one day.

The system has to ensure that the temperature profiles required for the Heater Test are met (cf. section 2.1.1) and that the temperature limits of the heater cables and the gallery lining are not exceeded. These criteria are ranked in order of priority in case they might conflict with each other. The following criteria, in order of priority, apply during the start-up phase:

1. the temperature of the heater cables is lower than 200°C;
2. the temperature gradient over the concrete lining thickness is maximum 15°C;
3. the temperature differences at the lining extrados in the middle longitudinal section are smaller than 7°C;
4. the temperature differences at the lining extrados overall are smaller than 10°C;
5. the temperature of the concrete is lower than 95°C.

The following criteria apply during the stationary phase:

1. the temperature of the heater cables is lower than 200°C;
2. the temperature gradient over the concrete lining thickness is maximum 10°;
3. the average temperature at the gallery extrados in the middle longitudinal section is 80±2°C;
4. the temperature at the gallery extrados at any point in the middle longitudinal section is 80±3°C;
5. the overall average temperature at the gallery extrados is 80±4°C;
6. the temperature at the gallery extrados at any point is 80±6°C;
7. the temperature of the concrete is lower than 95°C.

The input for the control system comes from 56 thermocouples installed at the extrados and intrados in 7 lining rings of the heated part of the PRACLAY gallery (cf. section 2.1.3). The heating protocol, according to which the control system regulates the heating power, is described in a manual that is included in the construction documents [44]. The manual contains the instructions for operating the control system.

4.2. Selection of the backfill material

Mol M34 sand was selected as backfill material [47]. This sand has a dry density of 1.45 g/cm³ and thus, as 100 m³ of gallery had to be backfilled, 145 tonnes of Mol M34 sand was needed. The sand was bought from SIBELCO.

The calculated saturated thermal and hydraulic conductivity of the sand are respectively 2.5 W/m·K and $8.5 \cdot 10^{-4}$ m/s (for a dry density of 1.45 g/cm^3). These values are consistent with the requirements for the backfill sand as explained in section 2.2.

Furthermore, Mol M34 sand has a narrow grain size distribution (88% between 63 and 180 μm), which limits the density differences between the top and bottom of the backfill sand due to segregation. Segregation could lead to an insulating water layer at the top of the gallery and a less homogeneous temperature profile around the gallery. Some small-scale laboratory tests were performed on Mol M34 sand to examine the segregation of this material during saturation [48]. No segregation in the sand was observed during these tests. Numerical simulations also indicated that a hypothetical water layer of 100 mm at the top of the gallery only has a limited and very local effect on the temperature profile around the gallery [22].

The installation of the backfill sand was done by blowing the sand in a dry state through a hose on top of the PRACLAY gallery. The dry injection of the sand was done by a shotcreting machine that can also be used for sand-blasting. As the sand front progresses towards the hydraulic seal, the injection hose is pulled back. After the backfill is completely installed, the backfill material is saturated in a later phase (cf. chapter 5).

Dry installation is preferred to the injection of a sand-water mixture, as the latter would be a relatively complex operation. Dry installation is relatively easy and can be done by EURIDICE. This installation technique had also already been successfully applied by EURIDICE in the ESDRED mock-up (*De Bock et al., 2008*).

The injection technique was tested on-surface on 13.10.2009 (Figure 4-3). A sand flowrate of 3 m³/hour was achieved. The abrasiveness of the injected sand on cables was checked. No damage to the cable could visually be detected.

Figure 4-3: (a) Sand blown out of the injection tube;
(b) Testing the abrasiveness of the blown sand.

For the subsequent saturation of the backfill material, 6 saturation filters are placed at the bottom of the gallery. The filters consist of a 3 mm thick sintered steel plate measuring 100 x 50 mm. They are fixed to the gallery floor and fed individually by a single feeder tube. Also 5 vent filters at the top of the gallery are installed to enable the gallery air to be vented during the backfill saturation. The layout of the saturation and vent filters is given in Figure 4-4. The saturation system is described in more detail in [49]. Their feed-throughs are placed in the flanges of the hydraulic seal, as described in [6]. After saturation, the filters will serve as monitoring devices for the water pressure and allow the extraction of water samples from the backfill sand.

Figure 4-4: Layout of the saturation and vent filters
and the relief valves in the PRACLAY gallery.

A safety system preventing the water pressures going above 35 bar is also implemented [49]. It is based on 2 relief valves connected to saturation filters S2 and S6. The valves open at a pressure of 35 bar.

Tap water will be used to saturate the backfill sand. Initially synthetic Boom Clay water and degassing were considered. The exact chemical composition of the water was however found not to be significant, while degassing the water would only have a marginal influence on the THM conditions around the PRACLAY gallery [49]. Moreover, degassing might even have negative effects on the corrosion of the steel components in the gallery [49].

4.3. Support structure of the secondary heater

The secondary heater is placed in a central tube made of stainless steel (219 mm in diameter) (Figure 4-5). The tube is composed of sections of 3 m. The ends of the tube sections are fitted with a flange to enable the different sections to be bolted. These connections are made leaktight by placing a KLINGERIT plate of 2 mm between the flanges. A central opening of 221 mm in diameter in the hydraulic seal enables the central tube to be passed through the hydraulic seal.

The interior structure of the central tube is similar to that of the central tube of the ESDRED mock-up. In the central tube, 5 smaller tubes are placed: 4 tubes each housing one heater cable that can be replaced at any time and 1 tube that can be used to measure the alignment of the central tube. During their retrieval from the ESDRED mock-up, one cable got stuck. Therefore the cables are placed in a stainless steel casing and this casing is then pushed into the smaller tube. A 5th small tube is installed at the bottom so that the vertical and horizontal position of the tube can be measured during the Heater Test.
The central tube is placed on a support structure consisting of a central structure supporting the tube and a platform attached to the side. The structure is fixed in the lining by 10 mm plugs drilled in the lining. The platform is needed to enable workers to walk beside the central tube during the installation work. It consists of a permanent structure and wooden plates that are successively removed before the gallery is backfilled with sand (cf. chapter 5).

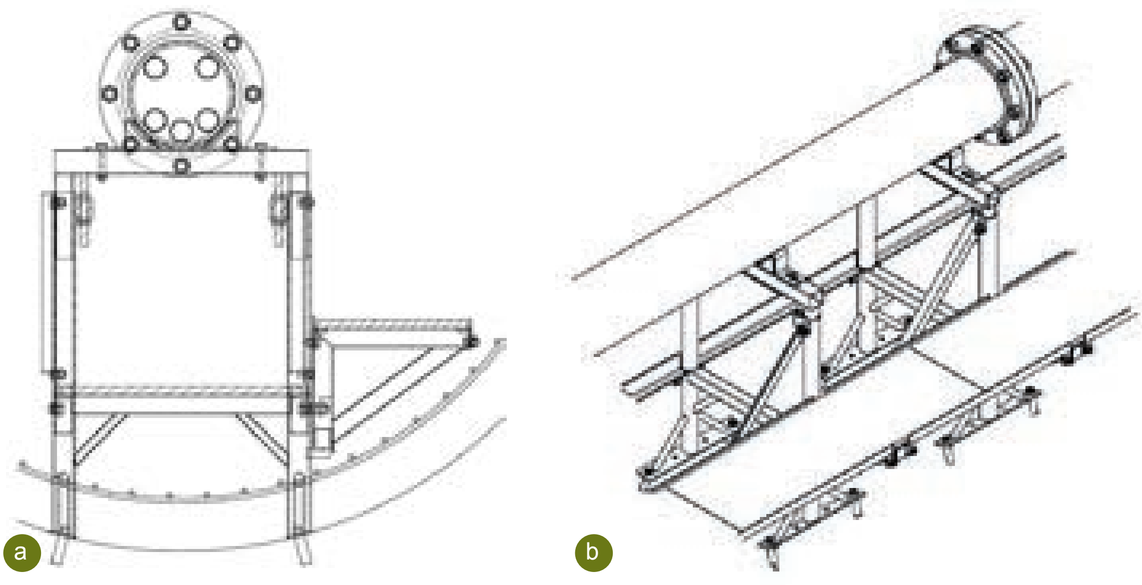


Figure 4-5: Central tube and support structure.

The support structure is made of a mild carbon steel (ST37). This type of steel is expected to sufficiently withstand corrosion [50]. Moreover, the mechanical integrity of this structure only has to be ensured until backfilling with sand takes places. Once backfilling is complete, the central tube is supported by the sand. Teflon is placed between the stainless steel central tube and the carbon steel structure to avoid galvanic coupling between the two materials.

The structure is made up of prefabricated components that are assembled in-situ. Assembly does not involve any welding so as not to damage the instrumentation and heater cables.

The detailed plans for the structure were made by the Drawing and Engineering Office of SCK•CEN [51]. The central tube sections were fabricated by the Mechanical Workshop of SCK•CEN. The floor and the support structure were fabricated by PROVAN. Figure 4-6 shows the fabricated components.

Figure 4-6: (a) and (b) Components of the support structure for the central tube;
(c) 3 m long section of the central tube in which 5 smaller tubes are placed;
(d) stainless steel casing for the secondary heater cables.

5. Installation of the heating system and backfill material

The installation of the heating system and backfill material comprises the following phases:

1. finalising instrumentation and feed-throughs;
2. installing the primary heater;
3. installing the secondary heater and its support structure;
4. backfilling with sand.

Figure 5-1 gives an overview of the sequence of the installation work.

Figure 5-1: Overview of the timing of the installation work.

As can be seen, the phases listed above are not performed in a strictly consecutive sequence as, for example, some instrumentation feed-through was still being done after the installation of the primary heater, or part of the support structure for the secondary heater had to be placed before the primary heater was completely installed. Nevertheless, the installation work generally follows the above-mentioned sequence and this chapter will be structured accordingly.

A logbook was kept during the installation work to keep track of all observations, actions and decisions made during this work [52].

5.1. Instrumentation and feed-throughs

A lot of instrumentation is placed in the heated part of the PRACLAY gallery. A complete overview of all instrumentation placed as part of the PRACLAY In-Situ Experiment is given in [6].

All the instrumentation cables – ca. 500 sensor cables or filter tubes – are grouped and passed through the seal using feed-throughs embedded in the 4 flanges that are bolted onto the 4 pipes of the hydraulic seal (Figure 5-2). Also the tube for the backfill installation and the tube for the backfill saturation are installed and passed through the hydraulic seal (cf. section 4.2).

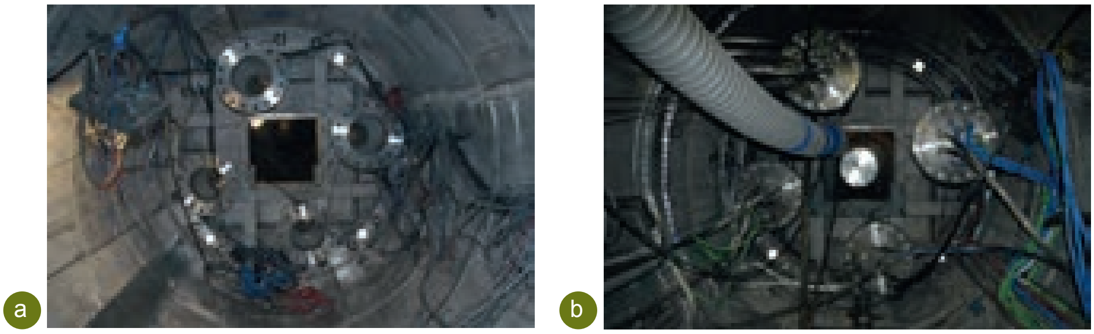


Figure 5-2: The instrumentation feed-throughs are embedded in 4 flanges bolted onto the hydraulic seal: (a) hydraulic seal after its installation; (b) hydraulic seal near the end of the backfill installation.

5.2. Primary heater and control system

Before installation of the primary heater cables, they are subjected to a Megger test. Then they are placed in a water vessel for a week, after which they are subjected to another Megger test. Only when the heater cable passed both tests was it approved for installation.

The primary heater cables are attached to circular rods previously installed in the gallery. These rods (wire diameter of 6 mm) are placed every 2 lining rings (equal to every metre) at a distance of 100 mm from the

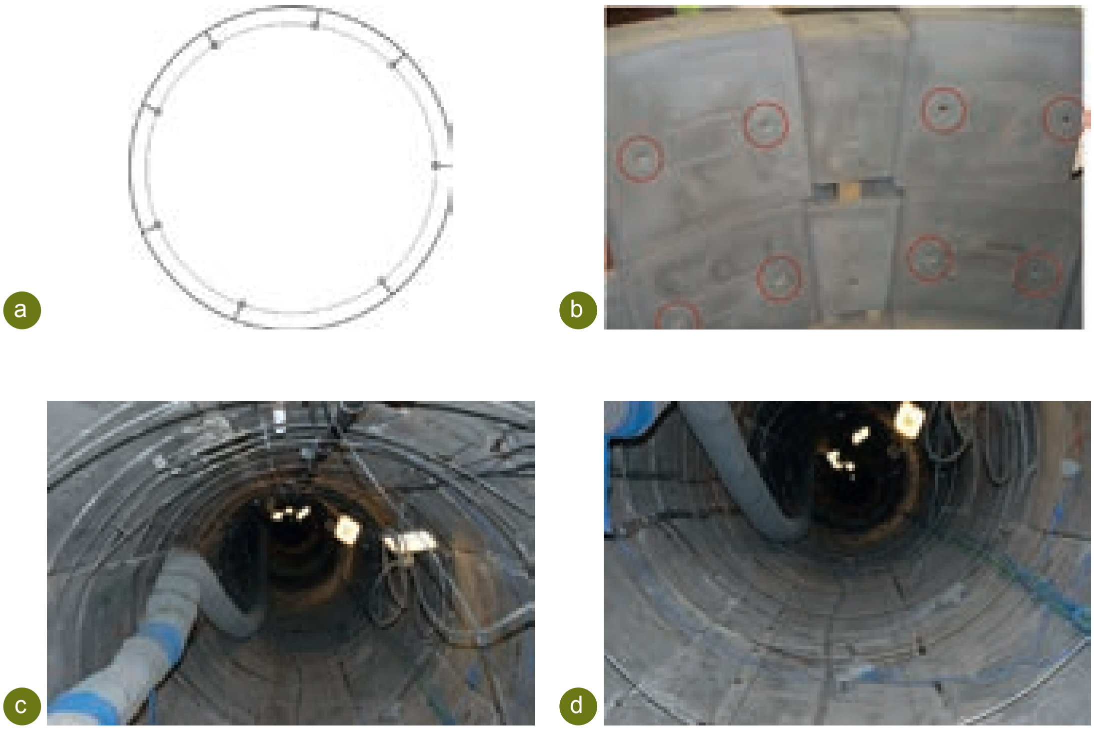


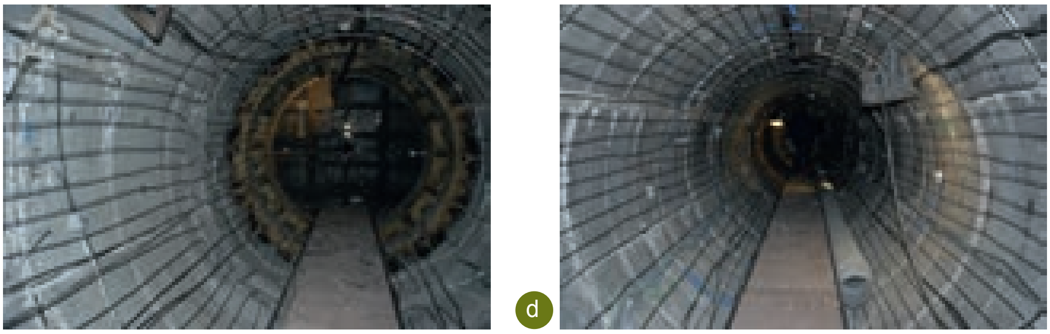
Figure 5-3: Installation of the circular rods to support the primary heater cables: (a) the rods are placed at a distance of 100 mm from the gallery intrados through rings attached to the lining; (b) the rings are attached to the gallery in the M20 openings in the lining segments (marked in red); (c) and (d) view into the PRACLAY gallery after installation of the support rods.

gallery intrados (Figure 5-3). The rings through which these rods are hung are attached to the gallery lining in the M20 openings in the lining segments. Both rods and rings are made of stainless steel. At the intersection between the front-end, middle and far-end sections, two rods are placed to keep the heater cables in the three different sections separated from each other. The diameter of the rod at ring 22 had to be decreased to ca. 1680 mm, and at ring 21 to ca. 1664 mm, to make room for the instrumentation cables.

First the bottom cables of the primary heater are placed (Figure 5-4). Then a floor platform is built and placed over these heater cables at the bottom [51] (Figure 5-4). The platform is fixed in the lining by 10 mm plugs drilled in the lining. The platform consists of a permanent structure and wooden plates that are temporarily placed on this structure.

Figure 5-4: (a) Placement of the primary heater cables at the bottom of the gallery; (b) and (c) installation of the floor platform over the primary heater cables at the bottom; (d) wooden plates temporarily placed on the platform.

In the next phase the heater cables in the middle and the top sections were placed by attaching them to the support rods (Figure 5-5).



c d

Figure 5-5: Installation of the heater cables in the middle and top sections.

After installation all heater cables were subjected to a Megger test under atmospheric pressure and at an ambient temperature of 16°C. No failures in the heater elements were detected during these tests.

All heater elements were fed through the hydraulic seal and attached to the control system (Figure 5-6).

Figure 5-6: Control system of the PRACLAY heating system.

5.3. Secondary heater and support structure

After the installation of the primary heater cables, the central tube for the secondary heater was installed (Figure 5-7). For this purpose, a secondary platform was built next to the primary platform to enable workers to walk beside the central tube (cf. section 4.3). The secondary platform is attached to the primary platform by means of bolts.

Then the central tube was built in sections of 3 m starting from the end of the PRACLAY gallery. The tube sections were transported through the PRACLAY gallery on a wagon that is rolled over the floor platform. Two steel edges on this platform prevent the tube sections falling off.

Once the tube section was transported to the already built part of the central tube, the section was lifted by chain hoists that are attached to the lining in the M20 openings of the top segments (Figure 5-3b). The lining segments are 0.5 m long. As every 1 metre these openings are already used to attach the rings for the support rods, M20 openings are available for chain hoists every 1 metre. Below the hoisted tube section, the permanent support structure for the tube section was built (cf. section 4.3).

The tube section was then lowered onto this support structure and the upstream end of the section was bolted to the already built part of the central tube. Its downstream end was then moved into the correct position. The correct position of the tube section was determined using a laser.

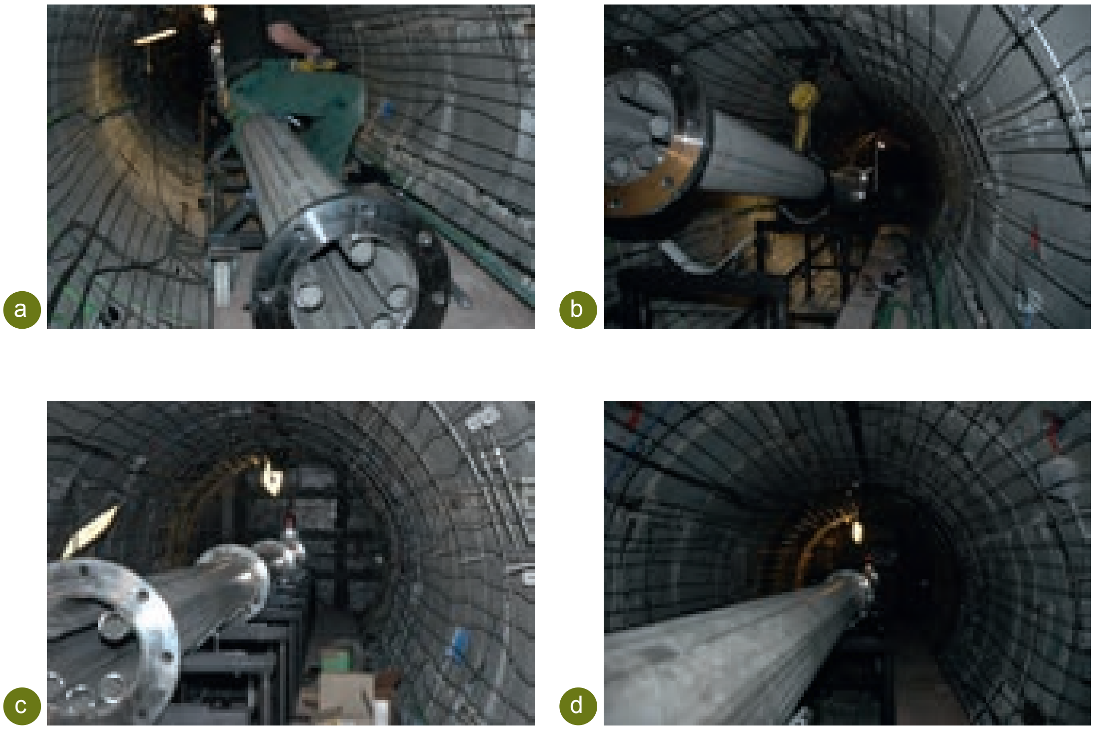


Figure 5-7: Assembly of the central tube sections (a) the tube section is transported through the gallery on a wagon to its assembly position; (b) the tube section is hoisted and a support structure is built below the hoisted tube section; (c) the tube section is lowered onto the support structure and its upstream end is bolted to the previously installed tube section; (d) the downstream end of the tube section is positioned using a laser.

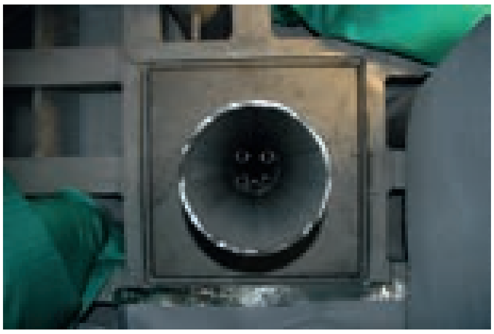
The central tube came to just before the hydraulic seal so that the heated part of the PRACLAY gallery remained accessible for backfilling (cf. section 5.4) (Figure 5-8). The leaktightness of the central tube was then tested by filling it with a mixture of air and nitrogen at a pressure of 30 bar. No decrease in gas pressure was observed over the next 7 days, indicating that the central tube was leaktight.

Once the gallery had been backfilled, the last tube section was installed (Figure 5-8). Again the tube was filled with air at a pressure of 30 bar to test its leaktightness. No gas pressure decrease was observed and thus the central tube could be assumed to be leaktight.

The end flange was subsequently cut to allow the placement and welding of the central tube over the manhole in the hydraulic seal. After the central plate was assembled onto the hydraulic seal, the flange at the last section of the central tube was again welded onto this tube and the heater cables of the secondary heater were placed in the central tube. However, at the moment of publication of this report, the design of the secondary heater is revised. Full installation is planned for early 2014.

a

b

c

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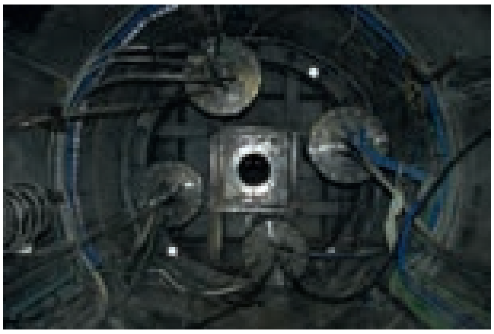


Figure 5-8: (a) Before backfilling, the central tube could only come to just before the hydraulic seal; (b) once backfilling was complete, the last tube section was assembled; (c) the flange on the last section of the central tube was cut to allow the assembly of the central plate onto the hydraulic seal; (d) after assembly of the central plate, this flange was again welded onto the end of the central tube.

5.4. The saturated backfill sand

Finally the heated part of the PRACLAY gallery was filled with Mol M34 sand (Figure 5-9). The sand was delivered by SIBELCO in big bags of 0.9 t (0.6 m³). Three containers were used to transport the sand

a

b


Figure 5-9: (a) Storage of 170 tonnes of Mol M34 sand; (b) the sand was loaded into containers and transported to the underground laboratory; (c) and (d) the sand was blown into the gallery using a shotcreting machine, which blew the sand through a tube placed at the top of the gallery; (e) and (f) sand front in the gallery.

from the surface to the underground laboratory. There it was brought into the gallery by dry blowing it through a 3” tube placed on top of the gallery. The sand was blown using a shotcreting machine. The gallery was filled from the dead-end towards the hydraulic seal by pulling back the blowing tube. The injection was regularly stopped to check the sand front.

After backfilling the end section of the gallery (i.e. the abandoned tunnelling shield) and ca. 10 m of gallery lining, the cabling of a thermocouple got damaged and had to be repaired (Figure 5-10).

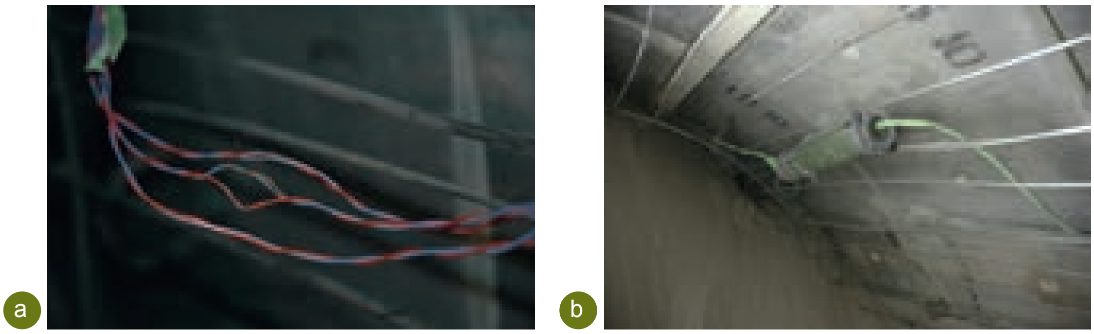
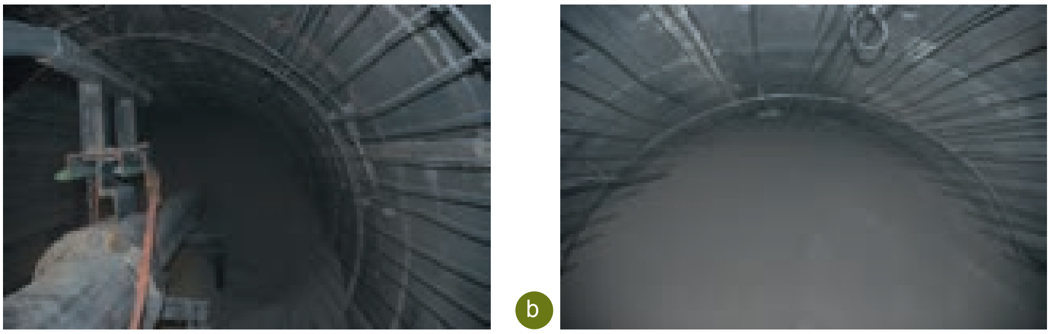


Figure 5-10: (a) Cable of thermocouple damaged by the sand backfilling; (b) damaged cable repaired by placing a tube over the damaged cable section.

The backfilling method was subsequently adjusted, as the placement of the backfill tube near the top of the gallery was deemed to pose too much risk of damaging the cables at the top of the gallery. Therefore the tube was placed on top of the central tube, which is more to the centre of the gallery (Figure 5-11). In this way the injected sand was blown onto the already installed sand away from the cables that are placed along the gallery lining. Regular checks in the gallery showed that no more cables were damaged and that the gallery was still filling well (no voids at the top).



a b

Figure 5-11: (a) The injection tube was placed on top of the central tube to avoid damaging the cables along the gallery lining; (b) the gallery backfilling was still going well in the adjusted configuration.

During backfilling a box was placed in the gallery to determine the density of the backfill sand (Figure 5-12). The measured density was 1.6 t/m³. The hydraulic conductivity of the sand for this dry density was again calculated and was $5.2 \cdot 10^{-4}$ m/s, which is sufficiently high (cf. section 2.2).

Figure 5-12: Box capturing the backfill sand to determine its density.

Before backfilling the last part behind the hydraulic seal, the last section of the central tube was assembled (cf. section 5.3). Then the last part was backfilled, except for the top section just behind the hydraulic seal (Figure 5-13). This could not be filled before closing the hydraulic seal by welding the central plate onto the hydraulic seal (cf. part II of the report on the installation of the PRACLAY In-Situ Experiment – The hydraulic seal). Once the hydraulic seal was closed, this top section was also backfilled (Figure 5-13).

The backfilling of the gallery lasted in total ca. 18 days. At the end of the gallery backfilling, just before closing the hydraulic seal, the heater cables were subjected to a final Megger test on 12.09.2011. All cables passed the test, except for one (in the bottom quarter of the middle section), for which a resistance of ca. 15 MΩ was measured. On 26.09.2011 TYCO replaced the connections at the end of the cold lead of this cable, but no improvement (i.e. a higher resistance) was obtained. On 28.11.2011 the backfill saturation started. Ordinary tap water was injected through 6 filters placed at the bottom of the gallery

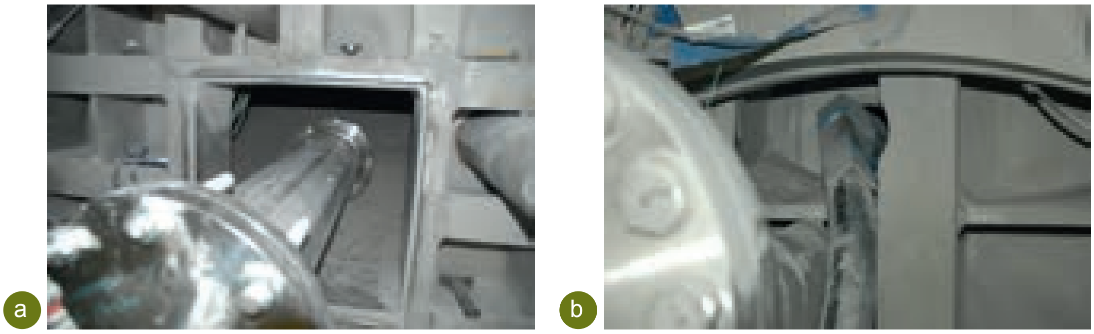


Figure 5-13: The top section just behind the hydraulic seal could only be backfilled after closing the hydraulic seal: (a) before closure of the hydraulic seal; (b) backfilling of the top section after closure of the hydraulic seal.

(Figure 5-14a). The water injection was performed 24h/day and ca. 2.5 m³ water was injected per day. Flow indicators were used to ensure that an equal water volume was injected through each filter (Figure 5-14b). After 12 days, on 9.12.2011, 29 m³ water had been injected and the injection was stopped for the weekend, as it was considered possible that the backfill sand would become completely saturated during the weekend and the purpose of the water injection was to completely saturate the backfill sand without pressurizing the backfilled gallery. The injection was restarted on Monday 12.12.2011. On 15.12.2011 water came out of the venting filters indicating that the backfill sand was completely saturated. 38 m³ water had been injected. The water injection was then stopped.

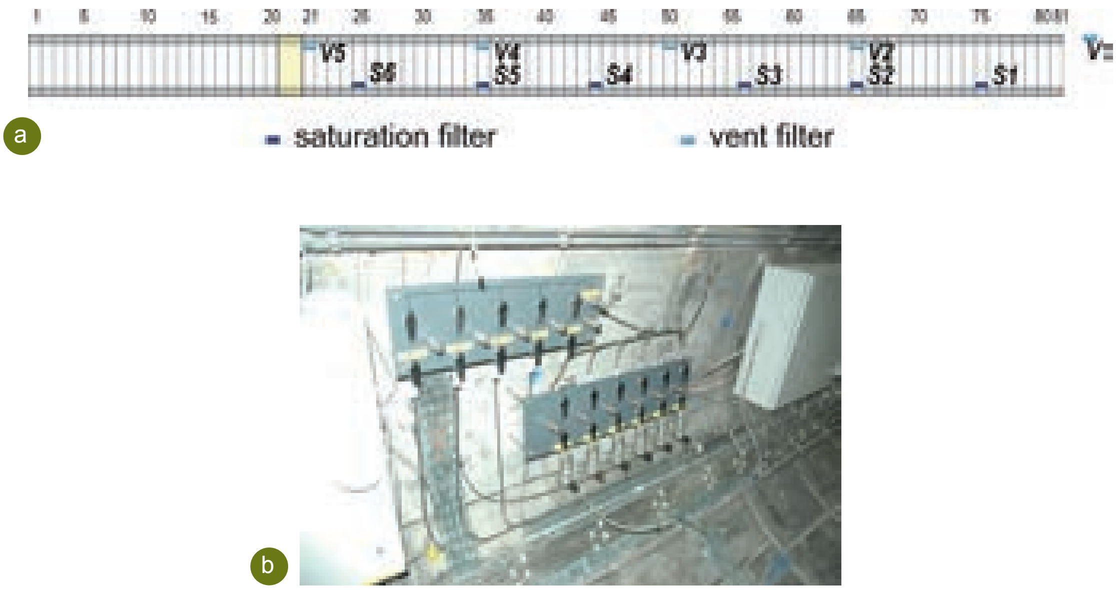


Figure 5-14: (a) Saturation system consisting of 6 saturation filters S1 to S6 and 5 vent filters V1 to V5; (b) injected volume indicator.

6. Conclusions

The last phase in the installation of the PRACLAY In-Situ Experiment was successfully completed in 2011 with the installation of the heating system and backfill material. The heating system has to heat the clay at the gallery extrados from its in-situ temperature of 16°C to a temperature of 80°C and maintain the gallery–Boom Clay interface at this temperature for ca. 10 years. The saturated backfill material ensures quasi-undrained hydraulic boundary conditions at the interface between the Boom Clay and the gallery lining.

The heating system consists of a primary heater close to the gallery intrados and a secondary heater inside a central tube. Both of these are electrical heaters. The primary heater is inaccessible during the Heater Test and is therefore installed in a redundant manner. The secondary heater is a backup and remains accessible and replaceable at all times during the test. Besides these heating elements, a control system regulating the heating power is also part of the heating system. Each heating system has its own control system. The temperatures measured by thermocouples at the intrados and extrados of 7 lining rings serve as input for the control system.

A constant temperature along the extrados of the gallery can only be achieved when a higher power per metre is applied at the two ends, compensating for the larger heat dissipation at these two ends. Therefore the heating system is divided into three sections along the length of the heated part of the PRACLAY gallery – the front-end section behind the hydraulic seal, the middle section and the far-end section at the dead-end of the gallery.

The secondary heater is placed in a central tube, which rests on a support structure. The support structure is made up of prefabricated components that are assembled in-situ. No welding is allowed to avoid damaging the instrumentation and heater cables. At the moment of publication of this report, the design of the secondary heater is revised. The full installation of the secondary heater is planned for early 2014.

During the start-up phase the temperature is increased step-wise and very slowly. The rate of the temperature increase is limited by the maximum allowable thermal gradient in the concrete lining. The maximum allowed difference between the intrados and extrados temperature of the lining during the start-up phase is 15°C. The temperature increase rate is nevertheless larger than around an actual disposal gallery for heat-emitting waste.

The saturated backfill material has a thermal conductivity higher than the thermal conductivity of the lining and Boom Clay to efficiently transfer the heat generated by the heating system. It also has sufficiently high hydraulic conductivity, allowing rapid homogenisation of the water pressures in the backfill material. Furthermore it has a narrow grain size distribution, limiting the density differences between the top and bottom due to segregation. Mol sand was selected as backfill material, with ca. 145 tonnes being required to fill the gallery. The sand was installed by blowing it in a dry state into the gallery. In a later phase the backfill sand was saturated by injecting 38 m^3 water through 6 saturation filters placed at the bottom of the heated part of the PRACLAY gallery.

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ANNEXE

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Annexe:
List of documents related to the PRACLAY In-Situ Experiment

The following list comprises all documents relating to the design and installation of the PRACLAY In-Situ Experiment. The aim is to ensure traceability and justification of all design and other choices made over the years since the initiation of the PRACLAY experiment through to completion of the process of setting up the experiment. These documents are referred to by placing the number of the document in the list between square brackets (e.g. [x]).

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EIG EURIDICE is an Economic Interest Grouping involving the Belgian Nuclear Research Centre SCK•CEN and the Belgian Agency for Radioactive Waste and Enriched Fissile Materials (ONDRAF/NIRAS). It manages the HADES underground research facility and carries out safety and feasibility studies for the disposal of high-level and/or long-lived radioactive waste in a clay host rock.

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