THE EXTENSION OF THE URF HADES: REALIZATION AND OBSERVATIONS

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ABSTRACT

An important step in the feasibility study of radioactive waste disposal in Boom Clay is the demonstration that we can construct galleries using industrial techniques, keeping the disturbance of the host-rock at an acceptable level for the long term safety of the disposal site. The successful construction of a connecting gallery of 85m in less than 6 weeks demonstrated the feasibility. To limit the disturbance, an expanding lining type was used: the wedge-block system; for the same reason, the lining was installed as soon as possible after excavation and a minimal excavation rate (2m/day) was imposed. The total radial convergence was limited to about 0.09m; the excavation radius was 2.445m.

An extensive instrumentation and observation program accompanied the construction of the connecting gallery. Sensors measuring displacements, total pressure and pore water pressure were installed in the host rock to study the hydro-mechanical behavior of the clay when the gallery was excavated. Sensors in the tunneling shield gave information about the instantaneous convergence and excavation parameters. Strain gauges were placed in three sections of the lining to study the evolution of stresses in the lining with time.

A systematic observation of the face and side-walls provided a useful database of the shape and orientation of encountered fractures. This way, the origin of the fractures can be explained and substantiated. The fractures were induced by differential stresses, about 6m ahead of the excavation face. No evidence of natural induced fractures was found. On the other hand, qualitative evidence of self-healing and self-sealing of the host rock was encountered.

INTRODUCTION

The main objective of the Economic Interest Grouping (EIG) EURIDICE\(^\text{a}\) between the Belgian Nuclear Research Centre (SCKCEN\(^\text{b}\)) and the Belgian Agency for Radioactive Waste and Enriched Fissile Materials (NIRAS/ONDRAF\(^\text{c}\)) is to contribute to the demonstration of the feasibility of the disposal of radioactive waste in clay layers in Belgium. An important instrument in fulfilling this objective is the underground research facility HADES\(^\text{d}\), situated in the Boom Clay layer 223m below surface at the EURIDICE site at Mol (Belgium). In HADES, various experiments on Boom Clay have been conducted during the past 20 years.

An important milestone in the development of a possible repository for radwaste in clay layers is the PRACLAY experiment (PReliminAry demonstration test for CLAY disposal of highly radioactive waste), essentially in the case of vitrified waste. It aims to demonstrate the feasibility of some important elements of such a repository. Firstly, the experiment will demonstrate the technical feasibility of a disposal gallery, taking into account the real and practical nature of the operations. This is attempted by demonstrating the construction, operation and sealing, at an acceptable cost, of a safe disposal system. Secondly, PRACLAY will contribute to the long-term safety and performance of the disposal system through a better understanding of the processes involved in the disposal system and an attempt to validate mathematical models (1).

The PRACLAY experiment requires the construction of a gallery (diameter ~2m; length ~30m) perpendicular to HADES. Therefore, the underground laboratory HADES had to be extended. In a first phase (1997-1999), a new access shaft and two starting chambers were constructed (2). The next phase
(2001-2002) was the excavation of a 85m long connecting gallery between the new shaft and the existing laboratory. Fig. 1 shows the construction history of the URF HADES. The construction of the connecting gallery was an experiment in itself because it was the first time that an industrial excavation technique was used for the construction of a gallery in Boom Clay at a depth of 223m. It also provided us with a unique opportunity to observe hydro-mechanical behavior and geological features in-situ.

The current paper presents the realization of the connecting gallery and the observations made during the construction works. It describes the tunneling technique used, the accompanying instrumentation and observation program and the experiences gained.

![Fig. 1. Construction history of the URF HADES.](image)

**TUNNELING TECHNIQUE**

**Connecting gallery and initial ground conditions**

The gallery is excavated starting from the northern starting chamber, at the bottom of the second shaft, towards the existing underground laboratory (towards the north), its orientation is approximately north-south. The distance between the axis of the second shaft and the front of the existing Test Drift was about 90m. A northern starting chamber is already present, so 85m of gallery has to be excavated and lined. Table I lists some properties of Boom Clay at the Mol site (3,4). The contractor for this project is JV SCM.

**General design**

The tunneling shield has a rear diameter of 4.82m and the clay face is excavated by means of a roadheader. The shield is pushed into the clay by hydraulic jacks; this way a cutting head at the front of the shield ensures a smooth excavation profile. A bird-wing erector (fixed to the shield) places the lining; the wedge-block system is applied: 12 segments are used to build a lining ring, which has a nominal external diameter...
of 4m80, a wall thickness of 0.4m and a length of 1m. 83 rings are installed; in the last few meters of the connecting gallery the tunneling shield itself acts as lining.

Fig. 2 shows the general design of the excavation technique: Fig. 2a is a schematic view of the tunneling equipment and its different parts. Fig. 2b shows the same equipment in reality, Fig. 2c explains the wedge-block principle, Fig. 2d presents details of the bird-wing erector (with wedge block) and hydraulic jacks and Fig. 2e finally shows the rotating roadheader and the cutting head at the front of the shield.

Table I. Hydro-mechanical properties of Boom Clay at the Mol site.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial total stress</td>
<td>4.5 MPa</td>
</tr>
<tr>
<td>Initial pore pressure</td>
<td>2.25 MPa</td>
</tr>
<tr>
<td>Young's modulus E'</td>
<td>300 MPa</td>
</tr>
<tr>
<td>Poisson's coefficient v'</td>
<td>0.125</td>
</tr>
<tr>
<td>Cohesion c'</td>
<td>300 kPa</td>
</tr>
<tr>
<td>Friction angle φ</td>
<td>18°</td>
</tr>
<tr>
<td>Dilatation angle ψ</td>
<td>0°-10°</td>
</tr>
<tr>
<td>Porosity n</td>
<td>0.39</td>
</tr>
<tr>
<td>Water bulk modulus K_water</td>
<td>0.2 - 2 GPa</td>
</tr>
<tr>
<td>Hydraulic conductivity k</td>
<td>$2 \times 10^{-12} \text{m/s} - 4 \times 10^{-12} \text{m/s}$</td>
</tr>
</tbody>
</table>

Limiting convergence

Throughout the entire connecting gallery project, limiting the convergence of the host rock has been one of the main priorities: the less convergence one allows, the smaller the extent of the EDZ will be. In our case, this is important because we use the laboratory to study the properties of the clay layer and ideally this is done in "undisturbed" conditions. Moreover, the Boom Clay has an important barrier function in the current repository design; limiting the damage to the host rock around a future repository makes sure the barrier function is optimized. It is therefore important to demonstrate that it is possible to limit the convergence and EDZ to an acceptable level for the long term safety of the repository.

A parameter study based upon an elastoplastic-viscoplastic model showed that at excavation rates of 2m/day and more, no delayed convergence of the host rock ahead of the face occurs. This conclusion brings on one of the basic requirements for this project: a minimal excavation rate of at least 2m/day at all time; 24 hours a day and 7 days a week.

Another parameter that has an influence on the total convergence is the overcut (difference between the excavation diameter and the final lining diameter). From convergence perspective, the overcut should be kept as low as possible but on the other hand, if it is too small, the shield could get blocked due to friction with the converging clay. To cope with this friction, a TEFLOON coating is painted on the shield extrados, a large thrust force is available (40000kN) and the shield is slightly conical. Based upon modeling results, an overcut of 90mm is used.

The distance between the face and the placement of the lining is to be kept small as well. This implies using a short tunneling shield and a short unsupported zone behind the shield. The stiffness of the lining is high, to avoid additional convergence after placement.

Shield and roadheader

The face is excavated under the protection of a tunneling shield. The shield is slightly conical: front diameter 4.83m and rear diameter 4.82m; its length is 2.3m. The shield ensures a smooth excavation profile as it is equipped with a cutting head; the excavated diameter that is milled off by the roadheader is slightly smaller than the diameter of the cutting head, so the cutting head scrapes of the last few decimeters as the shield is pushed forward. The amount of overcut provided by the cutting head can be
adjusted between 0 and 30mm (on radius) and is called *oversize*. Despite the oversize and conical shape, there is contact between the (converging) clay and the rear of the shield. This way the shield also contributes to keeping the convergence as low as possible.

The design of the shield required a good knowledge of the response of the host rock. Indeed it was important to assess the instantaneous convergence accurately in order to avoid the blocking of the tunneling machine. A contact at the rear of the shield is required to centralize it but the contact length between the host rock and the shield may not be too important in order to allow the steering of the machine. The software FLAC® was used to model the contact-length and additional convergence in the unsupported zone as a function of the oversize. A Mohr-Coulomb model was used with the parameters of Table I; Table II lists some calculation results. Based upon these values and the fact that decreasing the oversize is much easier than increasing it, a starting oversize of 30mm was decided upon.

Fig. 2. General design of the excavation technique; a) schematic view of the tunneling equipment, b) the same equipment during a test assembly on surface, c) the wedge-block principle, d) hydraulic jacks and bird-wing erector, e) adjustable cutting head and roadheader.
Table II. Modeling results: Contact-length and convergence in unsupported zone as a function of the oversize.

<table>
<thead>
<tr>
<th>Oversize [mm, on radius]</th>
<th>Contact-length [m]</th>
<th>Convergence in unsupported zone [mm, on radius]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.50 - 1.75</td>
<td>23</td>
</tr>
<tr>
<td>20</td>
<td>1.00 – 1.25</td>
<td>19</td>
</tr>
<tr>
<td>30</td>
<td>~0.75</td>
<td>17</td>
</tr>
</tbody>
</table>

The shield is pushed forward by 20 hydraulic jacks (grouped in 10 pairs, Fig. 2d) with a thrust force of 2000kN each. The force is applied to the last installed lining ring and each ram pair can be controlled separately so course corrections can be made.

Lining

Twelve unreinforced poured concrete segments make up one lining ring: 2 conical key segments (wedges), 4 counter-key segments and 6 normal segments (Fig. 2c). First the bird-wing erector places the bottom segments, the keys are inserted in two pockets in the shield and then the erector places the top segments which are temporarily fixed by the corresponding ram pairs. To complete the ring, the keys are pushed out of the pockets and into the ring by two small hydraulic jacks, expanding the lining against the sidewalls.

The diameter of the unsupported zone between the shield and the previous installed lining ring is determined by many parameters (sometimes unknown or impossible to control). The wedge-block system should therefore allow a range of possible lining diameters. The conical key segments are shorter than the other segments, so their axial position within the ring is variable: pushing them in further means increasing the diameter. This mechanism ensures that diameters between 4.79m and 4.81m are achievable. If this range should be insufficient, smaller and larger key segments are present and special shims can be placed between segments or annular plates can be applied to the lining exterior. All these measures result in a possible diameter range between 4.77m and 4.89m.

Very strict tolerances are imposed on the dimensions of the segments, this way no spoiling should occur during placing and manipulating the segments or when the shield is pushed forward against the previous installed ring. In order to facilitate the expansion of the ring, soap is applied on the sidewalls. The lining is dimensioned in such a way that an opening with a diameter up to 15cm can be drilled in it without jeopardizing stability. This permits the installation of future experiments in the Boom Clay. Larger openings are possible as well, but then reinforcement is needed.

Mounting chamber

Before the actual excavation works can start, a mounting chamber (diameter: 6m; length: 3.75m) is constructed from the northern starting chamber. The mounting chamber provides the necessary space to assemble the 10 segments of which the tunneling shield is made up from. After reinforcing the face of the starting chamber with fiber anchors, the mounting chamber is excavated by means of a pneumatic hammer and lined with steel sliding ribs and shotcrete. Shotcrete is also applied on the face of the mounting chamber to prevent dehydration of the clay. When the excavation of the connecting gallery itself starts, wedge-block lining is installed within the former mounting chamber and the annular space between this secondary lining and the primary lining is filled with grout.

INSTRUMENTATION PROGRAM

The construction of the connecting gallery provides a unique opportunity to characterize geological and hydro-mechanical features. To take full advantage of this opportunity, the project was accompanied by an
extensive instrumentation and observation program. Fig. 3 shows an overview of the four instrumented and observed locations: host rock (Clipex project), tunneling shield, gallery lining and clay face and sidewalls.

**Clipex**

The instrumentation of the CLIPEX project (CLay Instrumentation Program for the E Xtension of an underground research laboratory) includes essentially total stress, pore water pressure and displacement measurements (5). It is located in two zones around the connecting gallery (Fig. 3): eight instrumented boreholes (30m deep) from the Test Drift and two instrumented boreholes (21m and 30m deep) from the second shaft. From the Test Drift, four sub zones are instrumented: the axis of the future connecting gallery (sub zone A), the upper interface between the future gallery lining and host rock (B), around the gallery in a vertical plane (C) and in a horizontal plane (D). Each sub zone is instrumented by means of two boreholes: one for measuring deformation and another for total pressure and pore water pressure measurements, totalizing eight boreholes.

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Fig. 3. Instrumentation and observation program during the construction of the connecting gallery. Four locations were instrumented and observed. Host rock (Clipex project): sensors and sensor tubes as seen on the excavated face and the face of the Test Drift. Tunneling shield: convergence measurements through holes and data overview. Gallery lining: cable carrying box and first measurements after installation. Clay face and sidewalls: fracture characterization and clay sampling.
Sub zones A and B are located in the future clearance of the gallery and will be encountered and removed during the excavation. The other sub zones are located around the future gallery and therefore piezometers C and D can be reconnected after the excavation has crossed their respective boreholes. From the shaft, two boreholes (E) monitor the pore water pressure and the vertical displacements -by means of an inclinometer probe- above the future connecting gallery. An important part of the CLIPEX project is devoted to blind predictions of the hydro-mechanical behavior of the clay massif during the construction of the connecting gallery and comparison these predictions with in-situ measurements. Five different modeling teams using four different codes were involved in this project.

**Tunneling shield**

The tunneling shield is equipped with different types of sensors. They monitor the pressure on all the hydraulic ram pairs and the two key rams, the length of 4 hydraulic ram pairs and strain at 20 places on the shield. Every 30 seconds, the readings are stored on a PC by a data acquisition system. Besides these automated measurements, the position and orientation of the shield, the excavated diameter and the convergence are regularly measured manually. The convergence is obtained by measuring the distance between the host rock and the exterior of the shield, for this purpose 10 small holes were made through the shield (Fig. 3).

**Instrumented lining**

32 lining segments are equipped with vibrating wire embedment strain gauges, 6 or 12 gauges were placed per segment. The gauges are placed in the molds and are kept at there correct position by a cable carrying box, a sort of support structure (Fig. 3), then the segment can be cast. Three entire rings (except the two key segments) can be built using instrumented segments.

**Fractures and stratigraphy**

As the excavation progresses, the face and sidewalls of the gallery are observed, drawn and photographed; fractures are characterized by measuring their dip and dip direction when this is possible in a safe way. The result is a detailed database describing fracture type and orientation over the whole tunnel length. This information allows us to determine whether and how the excavation process induces fractures or whether they are naturally induced (pre-existing).

Systematic sampling of clay is carried out in relation with the fractures (6). Two types of samples are taken. The first kind consists of larger or smaller blocks (2 to 25 kg), sampled as function of fault distance, near or at the occurrence of specific faults, in the vicinity of boreholes, at undisturbed zones, … The second kind of samples consists of cylinders (3cm diameter, between 3 and 10 cm long) removed in-situ by dry drilling with a simple cylindrical drill head (Fig. 3). The stratigraphy is also observed along the excavation. The Boom Clay formation has a distinct layered structure and the general dip of the formation is examined by tracing the position of thin layers of pyrite (FeS₂) and septaria (carbonate rich concretions) along the gallery.

**PERFORMANCE OF THE TUNNELING TECHNIQUE**

In general, the tunneling technique performed adequately and the successful construction of the connecting gallery using this industrial technique is an important step in demonstrating the feasibility of an underground nuclear repository in Boom Clay. As the construction of the connecting gallery was an experiment in itself, this is a first and important result.
The gallery was excavated in less than 6 weeks. Except for the first and last few meters of the gallery, the minimal excavation rate $2\text{m/day}$ was always respected and sometimes even doubled. The actual connection between the existing and new laboratory is well aligned: the distance between the axes of the Test Drift and the connecting gallery is only a few centimeters.

A feature that caused some problems was the presence of pyrite concretions. Lumps of up to $30\text{cm}$ diameter were encountered and damaged the teeth of the roadheader since the head was designed to excavate soft rock only. The teeth had to be replaced several times.

Contrary to design specifications, the concrete-concrete contact between adjacent lining rings led to spoiling when the shield was pushed forward. Construction tolerances of the segments were met, but the damage was probably due to small misalignments during placing. The spoiling was immediately observed and from that point onward, high density PE plates ($3\text{mm}$ thickness) were inserted between rings and it no longer occurred.

The oversize was kept at $30\text{mm}$ at all times, only two rings were built with special measures to adapt the diameter: normal key stones and no annular plates or shims. Short key stones were used in the other two rings because the excavated diameter at that time was thought to be too small to expand the ring; afterwards it appeared this was incorrect and no problems would have occurred using normal segments. The biggest problems were caused by fracturing of the host rock and the subsequent falling of blocks out of the face. This phenomenon is dealt with later on, after the description of the fracture pattern.

**RESULTS & OBSERVATIONS OF THE INSTRUMENTATION PROGRAM**

Fig. 4 shows some results of the instrumentation program: pore pressure readings from CLIPEX sensors at sub zone C, displacements readings from CLIPEX sensors at sub zone E, convergence measurements of the sidewall and strain values in an instrumented segment.

![Fig. 4](image)

**Fig. 4.** Some results of the instrumentation program: a) pore water pressure readings (CLIPEX, sub zone C), b) displacements (CLIPEX, sub zone E), c) convergence of the sidewall: distance between host rock and shield extrados, d) strain in an instrumented segment.
Clipex, results & observations (7)

The CLIPLEX instrumentation program has allowed us to obtain a very valuable databank for the hydro-mechanical behavior of Boom Clay. The pore water pressure and displacement evolutions have been followed in three dimensions before, during and after the construction of a gallery. The sensor readings of the CLIPLEX instrumentation installed from the front of the Test-Drift permitted to characterize the hydro-mechanical behavior ahead of the excavated gallery.

Fig. 4a presents the pore water pressure readings of the piezometer in sub zone C (inclined piezometer in a vertical plane), the depths of the individual filters are indicated. The excavation of the connecting gallery began on 1 February 2002 with the removal of the temporary shotcrete face of the mounting chamber. The measurements show that the pore pressures before the excavation started are different for each sensor: the pressure in WC1 is quite different from that in WC8, there is about 5.5 bar difference. This is the consequence of the Test Drift excavation (drop down due to the decompression).

As the connecting gallery face approaches, all filters record the same evolution: progressive pressure increase until a maximum and then a pressure drop down when the front is very close. After the gallery has passed underneath a filter, the pore pressure climbs again. Piezometer C2 was installed in an inclined borehole from the Test Drift. When the intersection of this borehole and the gallery is met, the tubings of the piezometer have to be cut and the pore pressure suddenly drops to the atmospheric value.

The increase of the pore pressure corresponds to the undrained contractant plastic behavior of the material. The drop phenomenon is linked to decompression of the massif and fracturing around the front. When the convergence of the gallery wall comes into equilibrium with the lining support, this can induce recompression of the clay and pore pressure rises again.

It is remarkable to see that the consecutive construction steps (1step= excavate 1m + place 1m of lining) are visible in the pressure graph: small undulations with a period of a few hours. This illustrates the sensitivity of the pressure readings.

One of the most interesting results is the large hydraulic influenced zone around the excavation: all sensors react almost immediately after the start of the excavation. The nearest sensor at that moment is at ~60m distance; whereas elasto-plastic models (e.g. Mohr Coulomb) predict an influenced zone of about 6m along the gallery axis. This phenomenon was already noticed during the construction of the second shaft and in a first effort to explain it, the influence of fracturing and skeleton viscosity were studied (4).

Fig. 4b shows the result of the inclinometer which was installed from the second shaft ~5m above the axis of the connecting gallery. As a reference, the value at 0m (shaft wall) on 1 January 2002 is set to zero. The deepest sensor (30 m deep from the shaft) recorded a vertical displacement as high as 60 mm. This value seems to be realistic taking into account that the total radial displacement on the excavated wall was about 90 mm. The displacement generation tends to slow down after the excavation front passes underneath the sensors. The rapid lining installation largely limited the short-term disturbance of the massif. The horizontal distance between the shaft wall and the face of the mounting chamber is about 7m, this causes the smaller response in the first few meters. If the displacements are plotted against time, again the construction steps are visible.

The other CLIPLEX piezometers and displacement sensors show similar results. The total pressure measurements did not perform properly.

Tunneling shield, results & observations

Fig. 4c shows the distance between the shield exterior and the clay side-wall as measured through the holes in the shield on 3 March 2002 and compares it with modeling results (cf. Table II). There is a good agreement between the two curves. The higher value at 170cm is probably caused by a void in the clay sidewall due to the detachment of a clay block.

The diameters of the unsupported zone (and also the internal diameters of the lining) show an anisotropic behavior: the horizontal convergence was larger than the vertical convergence. Occasionally, the sidewalls at the left and right of the unsupported zone had to be trimmed manually in order to be able to
install the lining. Also, course correction to the west or east were harder to make than up or down. This phenomenon is dealt with after the discussion of the encountered fractures. The tunneling shield could be improved by adding a support system to the upper part, this system should prevent clay blocks from detaching in the unsupported zone.

Online measurement of the pressure and stroke of the hydraulic jacks performed adequately and were very useful during the construction works. The thrust force needed to push the shield forward was always significantly lower than the available 40000kN; a maximum of 7500kN was recorded. However, no long delays or excavation stops were experienced but if this should be the case, the needed forces would have been higher, but probably still lower than 40000kN.

Strain measurements on the shield were difficult to interpret due to the complex structure of the shield.

**Instrumented lining, results & observations**

Fig. 4d shows the results of the strain gauges in a lining segment of ring 50. The three upper curves are gauges near the intrados of the lining, the lower three near the extrados. Lab tests were performed on 4 cored concrete samples to determine Young's modulus (E) and failure stress (σc). E ranged between 48.4MPa and 50.3MPa and σc between 104.5MPa and 113.5MPa. When E=50MPa is used, a maximum stress of 28MPa is obtained from Fig. 4d.

Tests to characterize the creep behavior of the lining segments are being conducted at the moment. These results will be used to interpret the strains in more detail.

**Fractures and stratigraphy, results & observations**

The front and sidewalls were systematically observed and fractures were characterized and mapped. Based upon this database and upon photographs of the sidewalls, a fracture map of the complete gallery was drawn. Fig. 5a and 5b show photos of the excavation face and the (eastern) sidewall. The orientation of the encountered fractures is consistent along most of the excavation, other orientations were encountered in the first and last meters of the gallery, respectively due to the influence of the second shaft and the existing laboratory. The average dip direction is parallel to the gallery axis.

The pattern consists out of two fractures: one in the upper part, dipping towards the excavation direction (north) and one in the lower part, dipping towards the opposite direction (south). The two fracture planes meet at half height of the gallery; there, their dip is up to 60°-70° (N or S) but further away from the axis in a vertical plane (higher or lower), the dip becomes lower (values as low as 30° have been measured): the planes are curved. The fracture planes are also curved in the other dimension (horizontal plane): the dip direction is parallel to the gallery axis (~N-S) near the center of the face but towards the east and west sidewalls it changes. The curved shape is much more pronounced in a vertical plane than in an horizontal one. The distance between subsequent fractures is a few decimeters. To assess the radial extent of the fractures into the host rock, two cored borings were performed shortly after the realization of the connecting gallery. Fractures were identified up to approximately 1m (8). A vertical section through the gallery is given in Fig. 5c, it is a sketch of the fracture pattern: partial finished gallery, tunneling shield and fractures are shown.

It is important to mention that the main focus was on shear fracture planes. These can be recognized by their shiny surface; slickensides are present). Other features were encountered as well but they were not systematically studied. For instance, in the lower part of the front, horizontal decompression fissures were observed and large vertical tension fissures were also seen on the face, as a consequence of detachment of large blocks.

If the fracture pattern is simplified to two flat fracture planes (one dipping 50°N, the other 50°S) with a trend perpendicular to the gallery axis, the theoretical trace on the gallery sidewalls in the unsupported zone can be calculated as the intersection of the planes and a cylinder. The calculated trace is shown at the right hand side of Fig. 5e: it shows an unfolded cylinder (gallery sidewalls) and one band corresponds to 1 meter. The observed fracture traces in the unsupported zone (detail of the fracture map, Fig. 5c) are quite
similar (the red curves have the same shape as the calculated trace). The complete fracture map covers the entire gallery, fractures are divided into categories and pyrite and septaria traces are also shown. All the information on the map is digitized as well, this way average trace orientations can be calculated to determine the shape of the fracture pattern quantitatively (in progress).

Similar fracturing has been observed during the construction of the Test Drift and the second shaft (9,10). Near the connection with the Test Drift, fractures due to its excavation 15 years ago were encountered. Their orientation was consistent with that of the fractures induced by the connecting gallery: two fracture planes, dipping towards the south in the upper part and towards the north in the lower part.

Fig. 5. Fractures observed during construction works in the Mol underground: a) excavation face, b) clay sidewall, unsupported zone, c) sketch of the fractures around the gallery deduced from the observations and modeling, d) modeled stresses (radial and axial) along the gallery axis, ahead of the face, e) theoretical trace on the sidewall of a (slightly simplified) fracture pattern and a part of the fracture map that was drawn during the project. The theoretical and observed trace are similar and pyrite (purple) and septaria (yellow) layers are visible as well.
The shape and orientation of the fracture planes described above is understood theoretically, it can be explained by the elevated stress and differential stresses present ahead of the gallery face. The fractures originate about 6m ahead of the face: Fig. 5d shows modeled stresses (axial and radial) along the gallery axis, ahead of the excavation front. The modeled plastic zone has a more or less spherical shape around the face, which corresponds with the curved fracture planes observed in reality. The horizontal intersection of the two conjugated fracture planes is explained by the in-situ stress conditions: in the undisturbed host rock, the primary stress is vertical and the horizontal stresses are slightly lower. An important issue is that from the description above, it can be concluded that all observed fractures at the Mol site were excavation induced. Pre-existing fractures were not observed but on the other hand it is impossible to prove their absence. Such natural fractures do occur in outcrops - where the clay burial history is completely different than that at Mol (11).

As the fractures originate ahead of the face, they are present in the excavation face and can cause large blocks to fall down which poses a safety risk. Presence of workers near the front should be avoided and precise fracture characterization at the front is too dangerous as well. Furthermore, falling blocks can cause overexcavations at the face and blocks can also fall down from the sidewalls in the unsupported zone. If this is the case, a smooth excavation profile (needed for the wedge block system) is no longer present: voids have to be filled with hard wood or cement bags.

The shape of the fracture pattern can be used to explain the anisotropic convergence (cf. supra). As the dip directions are more or less parallel to the gallery axis, vertical de-stressing is partly ensured by fracturing and further convergence (top and bottom of the gallery) will be limited; the host rock east and west of the gallery converges as if no fracturing occurred which results in larger convergence in this sense.

The fractures will however not jeopardize the long term performance of a future disposal site as a self healing mechanism exists. Qualitative evidence of self healing is already available. Before the construction of the connecting gallery a cored boring from the northern starting chamber parallel to the gallery axis was performed; no casing was used. While excavating the first meters of the gallery, it was impossible to locate the borehole visually: self healing had occurred. Other proof was found near the connection with the Test Drift. Although fractures induced by the Test Drift were encountered about 6 meters before the Test Drift itself and although these fractures were there during 15 years, only the last part (<1m) showed signs of oxidation. Further away from the Test Drift front, the fractures had been sealed. Sealing effects can also be observed around instrumentation tubes in the host rock. Since December 2001, an international research project in the European Commission 5th framework program called SELFRACh studies this phenomenon in detail.

CONCLUSION

The construction of the connecting gallery was a success. For the first time at this depth, an industrial technique was used to construct a gallery in a plastic clay layer. The radial convergence was limited to 0.09m thanks to all the precautions to limit the disturbance of the host rock. The entire instrumentation and observation program, except total pressure measurements in the host rock and strain measurements on the shield, provided very valuable and useful in-situ data.

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FOOTNOTES

a. European Underground Research Infrastructure for Disposal of radioactive waste In Clay Environment, Boeretang 200, 2400 Mol, Belgium; formerly known as EIG PRACLAY.
b. StudieCentrum voor Kernenergie / Centre d'Etude de l'énergie Nucléaire, Boeretang 200, 2400 Mol, Belgium.
d. High-Activity Disposal Experimental Site
e. Joint Venture "Schacht Combinatie Mol"; a joint venture between Smet-Tunnelling, Wayss & Freytag AG and Deilmann-Haniel GmbH.
f. Excavation Damaged (or Disturbed) Zone.
g. Fast Lagrangian Analysis of Continua (version 4.00.307), 2D explicit finite difference program from Itasca Consulting Group, Inc.

h. EC contract FIKW-CT2001-00182; coordinator: EIG EURIDICE; partners: NAGRA, SOLEXPERT, G3S, UJF, KUL, UPFL.