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MoDeRn

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1. Introduction

1.1 Background – Modern project

The MoDeRn project (Monitoring Developments for safe Repository operation and staged closure) aimed at providing a reference framework for the development and possible implementation of monitoring activities and associated stakeholder engagement during relevant phases of the radioactive waste disposal process i.e. during site characterisation, construction, operation and staged closure, as well as a post-closure institutional control phase. Monitoring provides operators and other stakeholders with in-situ data on repository evolutions, to contribute to operational safety, to help manage construction, operation and/or closure activities, and may allow for a comparison with prior safety assessments. It thus provides information to inform necessary decisions. If, in addition, monitoring activities respond to stakeholder needs and provide them with understandable results, they will contribute to transparency and possibly to stakeholder confidence in the disposal process.

The project was structured into six work packages (WPs). The first four WPs were respectively dedicated to (i) analyse key objectives and propose viable strategies, based on both technical and stakeholder considerations; to (ii) establish the state of the art and provide technical developments to match specific repository requirements; to (iii) conduct in-situ monitoring demonstration experiments using innovative techniques; and to (iv) conduct a case study of monitoring and its integration into staged disposal, including specific scenario analysis aimed at providing guidance on how to handle and communicate monitoring results, in particular when these provide “unexpected” information. WP5 regroups key dissemination activities and WP6 will provide a reference framework integrating project results and describing feasible monitoring activities, suggesting relevant stakeholder engagement activities, and illustrating possible uses of monitoring results for decision-making.

Work Package 3 consists of the in-situ demonstration of innovative monitoring technologies, conducted to further enhance the experience on which actual disposal monitoring may rely on. The aim of this package is to demonstrate that envisioned monitoring techniques are realistic under conditions present in underground laboratories. These demonstrations rely on a combination of monitoring technologies and they have been carried out in a variety of host rocks. In addition, to contribute to a “best value for money” approach, all of these are built upon either existing infrastructure (TEM in Grimsel, Praclay in Hades) or are attached to infrastructure that are developed and financed by resources outside of this project. This was the case of the disposal drift monitoring system installation and testing demonstrator at Bure, which is the aim of this report. It has also benefited from a mock-up vitrified waste disposal cell to be constructed as part of a larger research program.

1.2 Objectives of the report

Monitoring to provide information on the evolution of geological disposal presents several challenges, as the development of innovative monitoring techniques and the demonstration of the monitoring feasibility. The purpose of this document (Deliverable D.3.5.1 of MoDeRn Project Task 3.5) is to develop an in-situ monitoring demonstration experiments using innovative techniques. This report presents an analysis of a disposal cell (called CAC1601) instrumentation experiment. The aim of this programme was to establish the capacity to conduct integrated monitoring activities in-side the disposal cell, on the cell liner and in the near-field and to assess the capability of the monitoring to withstand construction and liner emplacement procedures.

The excavation, the monitoring implementation and its hydromechanical behaviour over the first 10 months are presented. This experiment realized in Bure Underground Research Laboratory in France comes within the context of Phase 2 of the "High-Level Waste Cells" Program Unit (PU) of Andra experimental program, which also included the excavation test for the Insert HAT1601, the results of which are the subject of the Report [1]. This constitutes the first preliminary monitoring system realisation of a mock-up high-level waste disposal cell, which instrumentation had been specifically embedded into the steel liner and placed in the surrounding rock.

2. General context of monitoring and experimental approach of Andra

After having concluded a feasibility study of deep geological disposal for high-level and long-lived radioactive waste in 2005, Andra was charged by the Planning Act n°2006-739 to design and create an industrial site for geological disposal called Cigéo which must be reversible for at least a century-long period. Within the framework of this geological repository project, the observation and surveillance (or monitoring) must fulfil the knowledge required to run the disposal and its reversible management, structured according to steps of progressive construction, emplacement and closure of disposal cells. This stepwise process also allows progressively updating and optimizing the design for future repository components. It also considers potential retrieval of some or all of the emplaced waste. Observation and surveillance also contribute to the safety analyses in operation and after closure. Monitoring should thus provide required information to confirm the knowledge intervening in the evaluation of the long term safety and precise the models, on the basis of data obtained in situ, within the framework of periodical re-evaluations of the structures. Current understanding and predictions are based on experimental results obtained in surface and underground laboratories, as well as on modelling and simulations. This knowledge will be verified, confirmed and enhanced based on data obtained in-situ, in the repository.

To achieve these objectives and needs, an overall monitoring strategy has been progressed including waste package characterization prior to emplacement, monitoring of disposal structures and the surface environment. In order to develop adapted solutions, several studies and reflections have been led, in particular on (i) the monitoring strategy, i.e. on the global distribution of instrumented structures amongst the repository and on the design of monitoring units, (ii) research and development to adapt, complete and qualify the sensing devices and (iii) specific tests and large scale experiments in underground research laboratory.

This last aspect was the aim of a specific experiment realized to demonstrate feasibility of such a monitoring system, specially designed to survey the hydromechanical behaviour of the experimental disposal cell. As planned at the beginning of the Modern project, the monitoring approach calls for instrumentation of both the nearfield (sensors in boreholes) and the cell liner, according to a monitoring system design intended to provide comprehensive data on the thermo-mechanical evolution of the cell and its near-field. The main goal is twofold, namely to demonstrate:

- The capacity to conduct integrated monitoring activities inside the disposal cell, on the cell liner and in the cell near-field;
- That the designed liner monitoring system is able to withstand construction procedures and to allow for reliable liner monitoring after construction.

Based on the results of preliminary studies to ensure feasibility of each sensor implementation before this experiment, instrumentation of the cell liner and the surrounding rocks had been done as envisaged at the beginning of the Modern project.

3. Objectives and Design of the Test

From a scientific point of view, Phase 2 of the "High-Level Waste Cells" PU has the following main objectives [2]:

1) To instrument the void space between casing and rock to determine the kinetic of the water filling of the annular space and its possible influence on the mechanical behaviour of the casing;
2) To evaluate the potential of robust sensor and wiring by testing the feasibility of using optical fibre instrumentation to monitor the overall thermomechanical behaviour of the casing;

3) To complete the study of the hydromechanical impact of the excavation of a cell (not included in the Modern project);
4) To monitor near field hydraulic pressure evolution through vibrating wire technology
5) To detect and monitor the mechanical behaviour of a 40 m-long casing in relation to the loading applied by the rock.

In order to reach these objectives, the excavation programme provided for the creation of a cell with casing over a length of 40 m (the casing and the annular space at the head of the cell being leaktight), orientated in the direction of the major horizontal stress. The measurement and instrumentation program included the following ([3], [4]):

- Measurements of pore pressure, temperature and displacement around the periphery of the cell in order to determine the hydro-mechanical impact of the excavation;
- The measurement of the hydric conditions (relative humidity and temperature) and of the pressures of any possible water present in the annular space;
- The installation of optical fibres on the internal surface (measurement of deformation and of temperature) and on the external surface (measurement of deformation) of the casing so as to monitor its overall thermo-mechanical behaviour and to detect any possible falls of ground of argillite;
- Measurements of local strain and convergence of the casing so as to determine the way it will be loaded by possible water pressure and/or rock pressure;
- The measurement of the excavation parameters (speed of progress, force of thrust, etc.): on the one hand to estimate the performance and the limits of the method of excavation and, on the other hand, to help to interpret the measurements of the displacement of the rock on the periphery of the cell;
- The measurement of the geometrical characteristics of the cell by a 3D scan.

Phase 2 of the "High-Level Waste Cells" PU was conducted between 22/11/2010 and 18/11/2011:

- Installation of instrumentation (such as hydrogeological devices, extensometers and deflectometer) in surrounding boreholes, from 22 to 29 November 2010;
- Excavation of the Insert HAT1601, from 14 to 16 June 2011 (the results of this test are given in [5]);
- Excavation of the first 6 meters of cell CAC1601 from 27 June to 07 July 2011 (including the extraction of 3 casing elements);
- Excavation of the totality of cell CAC1601, installation of the bottom plate and sealing of the casing from 26 September to 06 October 2011;
- Installation and cabling of the instrumentation of the casing from 06/10/2011 to 18/11/2011.

4. Procedure for excavation of cell CAC1601

4.1 Modifications applied to the equipment in relation after Phase 1

The only modifications applied to the excavating machine and to the casing elements after first tests (phase 1 and phase 1bis), during which a 40 metre-long cell with casing had been constructed (cf. [6]) are as follows:

- On the drilling machine, readjustment and machining of the rectilinear part of the excavation debris disposal device so as to take back the current clearance and ensure the correct alignment of the back-up;
- On the expanders of the cutting wheel, the 3 planes were replaced by 2 planes and 2 pick-hammers so as to obtain a better balance between the clearance of the terrain and the boring of the hole;
- The front casing element was modified so as to be able to receive the closure plate that contributes to the sealing of the casing (insertion of a mounting flange at its end);
- Circumference slots were machined at each end of the casing elements so as to ensure the sealing of the joints by resin injection;
- Four casing elements were machined specifically so as to be instrumented (cf. Figure 8);
- During excavation the wheel was intentionally displaced 12 to 16 mm to the left and 8 to 10 mm upwards so as to compensate for the natural displacement of the device (downwards and

to the right). The result was an excavation which was misaligned with the axis of the casing element (cf. Figure 1).

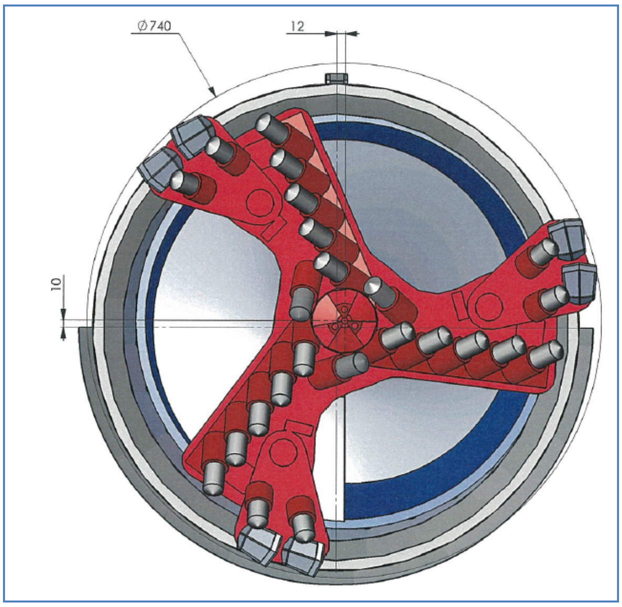

Figure 1: Off-centre position of the cutting wheel in relation to the axis of the casing element during the excavation of cell CAC1601 in June 2011

4.2 June 2011 excavation campaign

The excavation of cell CAC1601 started on 27 June 2011 in the GAN gallery, between arches 99 and 100. It was interrupted after 6 m of excavation (or after installation of 3 casing elements, of which one was instrumented) due to the total dislocation of the 2 front casing elements [7]. This phenomenon is the result of the insertion of the cutting wheel into the ring attached to the end of the front casing element (and intended to receive the bottom plate), which occurred during operations to unblock the auger (by successive manoeuvres alternating left/right and forwards/backwards rotation), made difficult by the presence of large blocks of argillite. In a second step, the front casing elements must then have been displaced a few millimetres during the fixing of the excavation debris disposal pipes when placing each new casing element, the pipes being linked to the drilling machine, itself in stop position in the flange.

It was not possible to re-insert the two front casing elements, therefore it was decided to withdraw all 3 casing elements. While casing elements 2 and 3 were withdrawn without problems, the extraction of the front element required the use of three 100-tons jacks (cf. Figure 2 and Figure 3). The maximum tensile load required for the extraction of the casing element was 185 tons.

Figure 2: Front casing element blocked in the ground (Casing elements 2 and 3 have already been withdrawn)

Figure 3: Equipment put in place for the withdrawal of the front casing element

4.3 September 2011 excavation campaign

The excavation of cell CAC1601 was resumed on 26 September 2011. The main technical modifications made since the July 2011 campaign are the following:

On the front casing element:

- Removal of the semi-circular runner attached to the bottom of the casing element and the passage of the same thickness as the supporting runners (20 to 10 mm);
- Removal of the internal flange (and consequent change in the method of attachment of the bottom plate);

On all casing elements:

- Insertion of 3 lugs at an angle of 120º into the attachment slot between the casing elements in order to avoid any risk of dislocation.

The 40 m mark was attained on 29 September, representing an average speed of progress of 0.53 m per hour [8].

The following operations were undertaken after the excavation in order to seal the casing and the annular space at the front of the cell:

- Insertion of the flange, of the gasket and of the bottom plate at the end of casing element no.1;
- Injection of sealing resin (type HIT 500 Re, made by Hilti) in the circumferential grooves between casing elements[1];
- The construction of a transverse facing block (through the injection of fibred mortar into the annular space over an area 1 m in length followed by the fixing of a metal plate fitting into the casing so as to hold the mortar in place while hardening, cf. Figure 4).

Figure 4: Transversal facing block for cell CAC1601 to ensure the watertight sealing of the annular space at the front

[1] A STABILCEM backfill, which had been demonstrated by CSM Bessac to remain effective at an external pressure of 5 MPa [10], was used first (for the seals of casing elements 1/2, 2/3 and 19/20). Since the viscosity of this product does not allow for the filling of the entire sealing surface, it was decided to change to a resin for the other seals.

4.4 Evolution of the excavation parameters

Figure 5 shows the evolution of the thrust applied to the casing elements and to the cutting wheel and also the wheel torque. A significant increase in the thrust applied to the casing is observed after approx. 25 m of excavation, rising to 120 t at 40 m. This phenomenon was also observed during the excavation of cells ALC1601 and HAT1602 (cf. Figure 6).

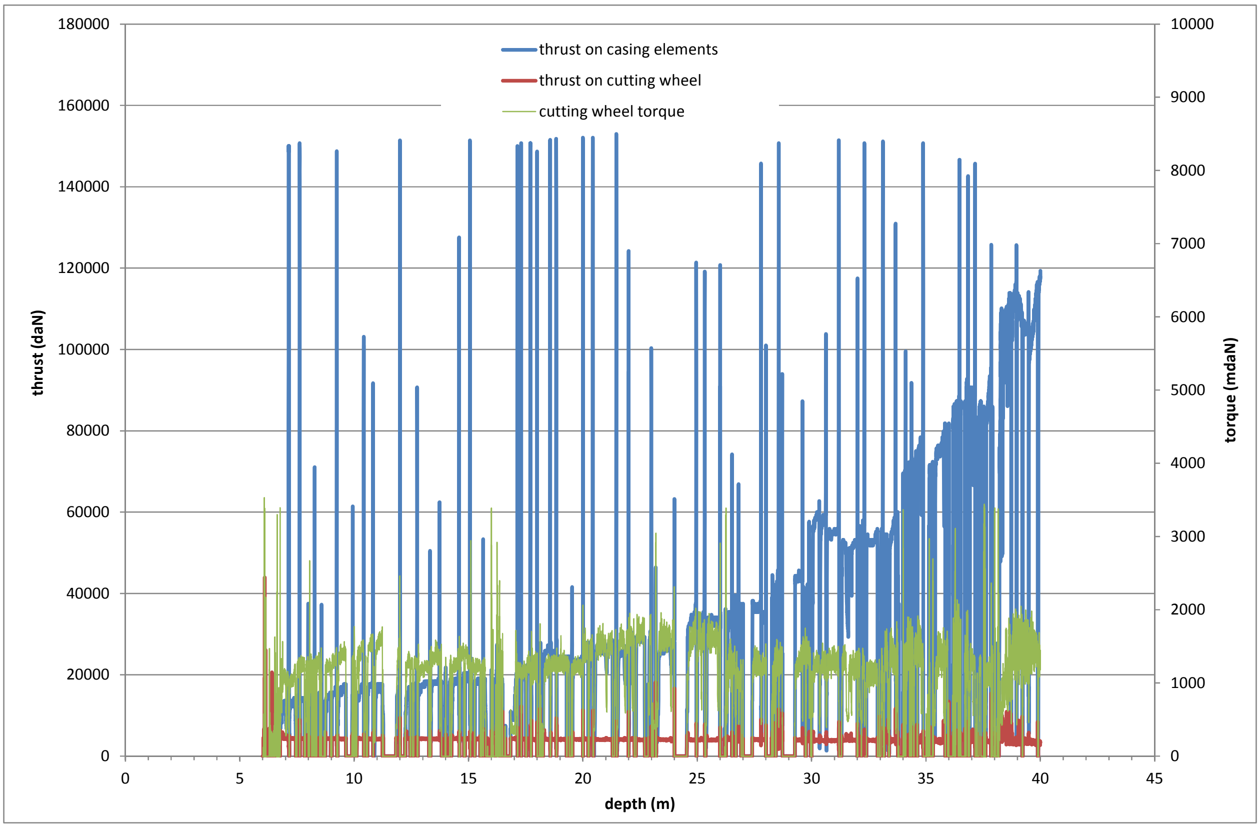

Figure 5: Evolution of the excavation parameters as the operation progresses

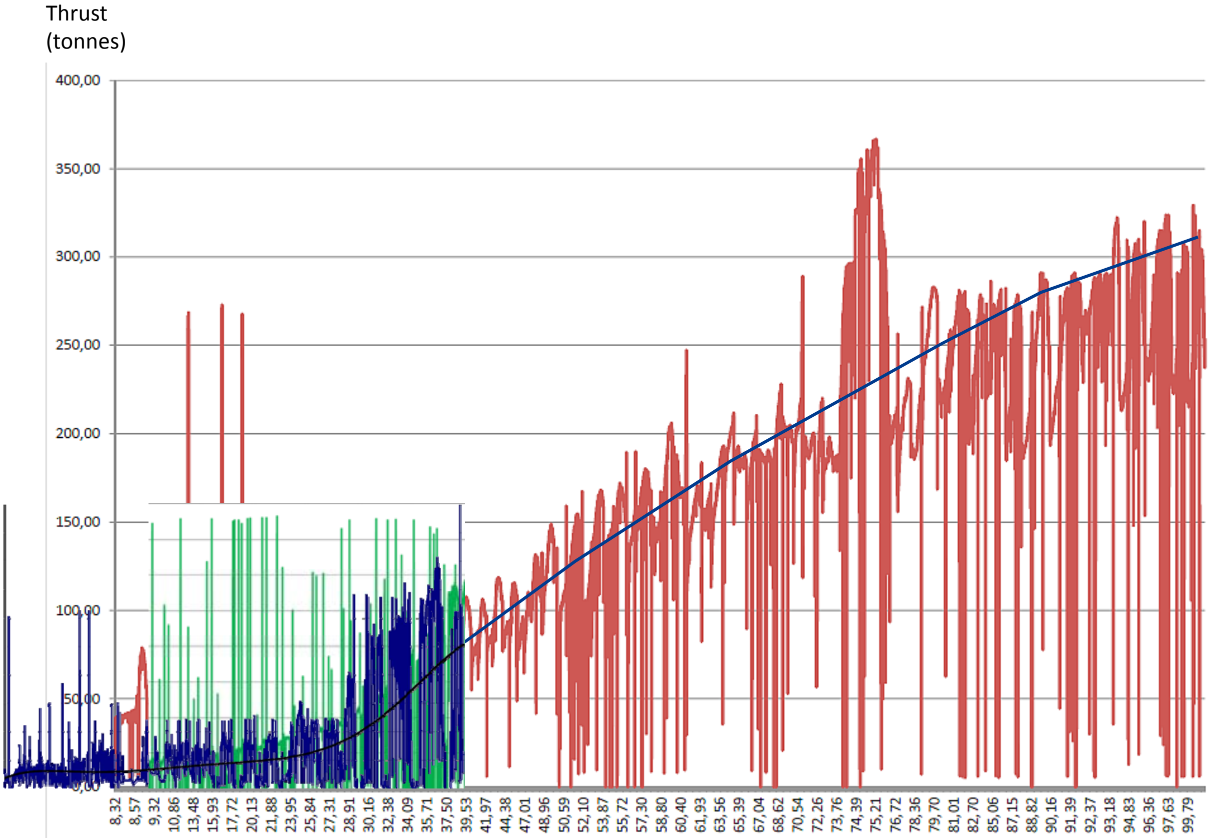

Figure 6: Evolution of the thrust applied to the casing during the excavation of cells CAC1601 (green), ALC1601 (blue) and HAT1602 (red)

4.5 Trajectory of the cell

The 3D scan carried out after the excavation work showed the following [9]:

- There is an overall displacement of the cell (i.e. the difference between its theoretical finishing point and real finishing point) of 8 cm towards the right and 7 cm upwards (cf. Figure 7);
- There is a maximum displacement of the casing elements of 3 cm in the horizontal plane and 5 cm in the vertical plane (cf. Figure 7).

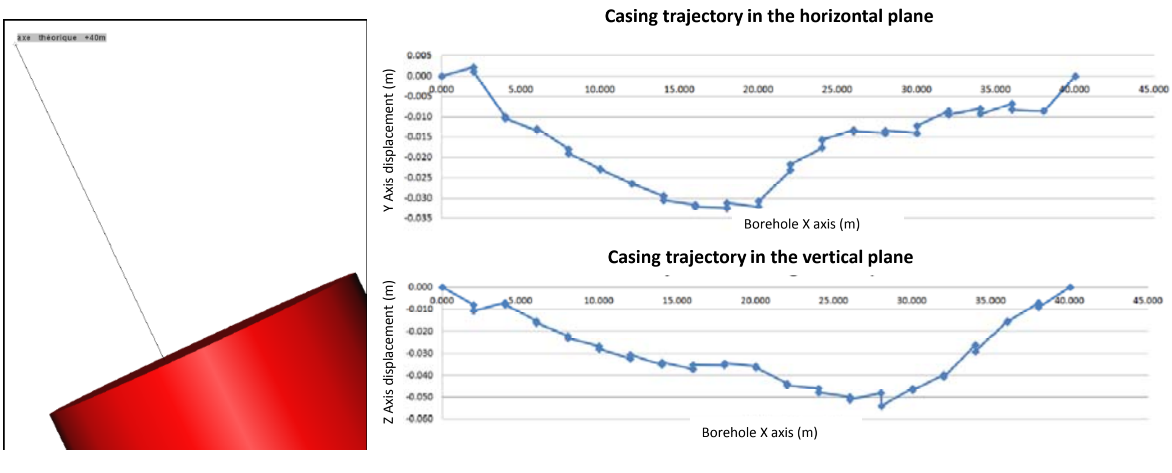

Figure 7: Distance between the theoretical axis of cell CAC1601 and the deepest casing element (left, seen from above) and the maximum displacement in the horizontal and vertical planes (right)

5. Instrumentation of the casing of cell CAC1601

The instrumentation of the casing was carried out by Egis Géotechnique in October/November 2011. Casing elements no. 3, 8, 13 and 17 were instrumented (cf. Figure 8 and Figure 9).

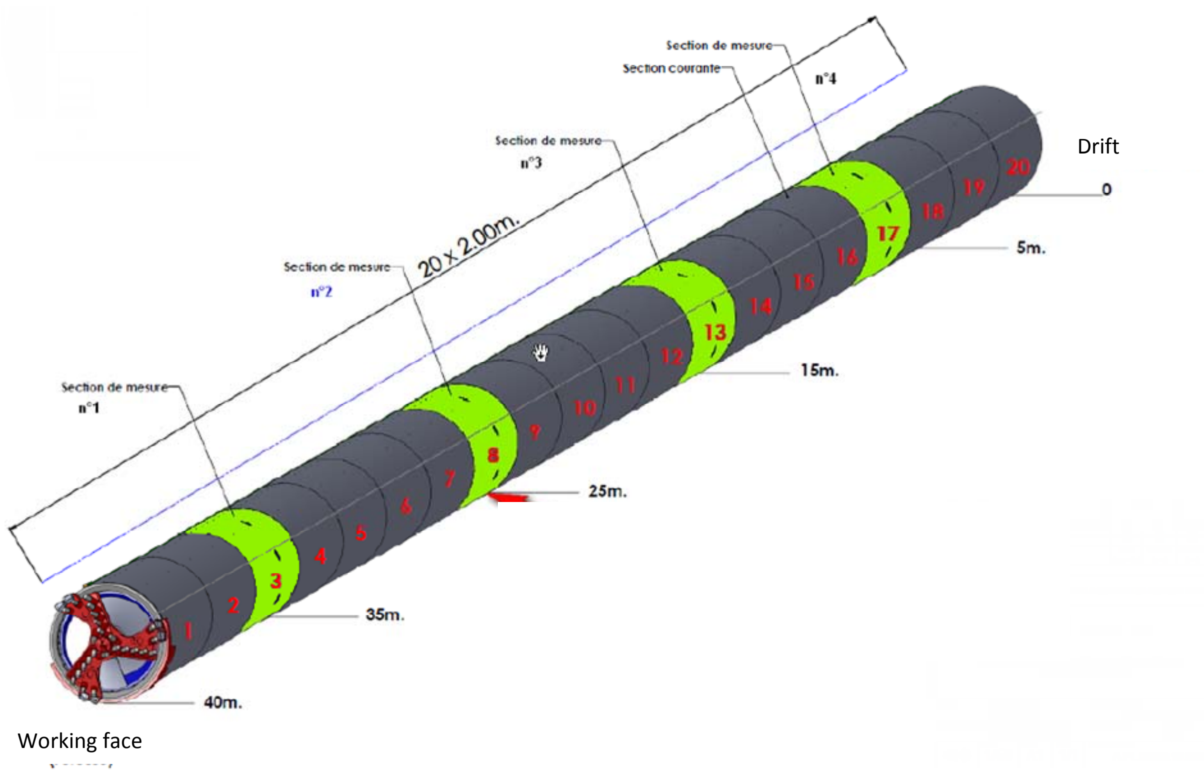

Figure 8: Location of the 4 instrumented casing elements (in green) of the casing of the cell CAC1601

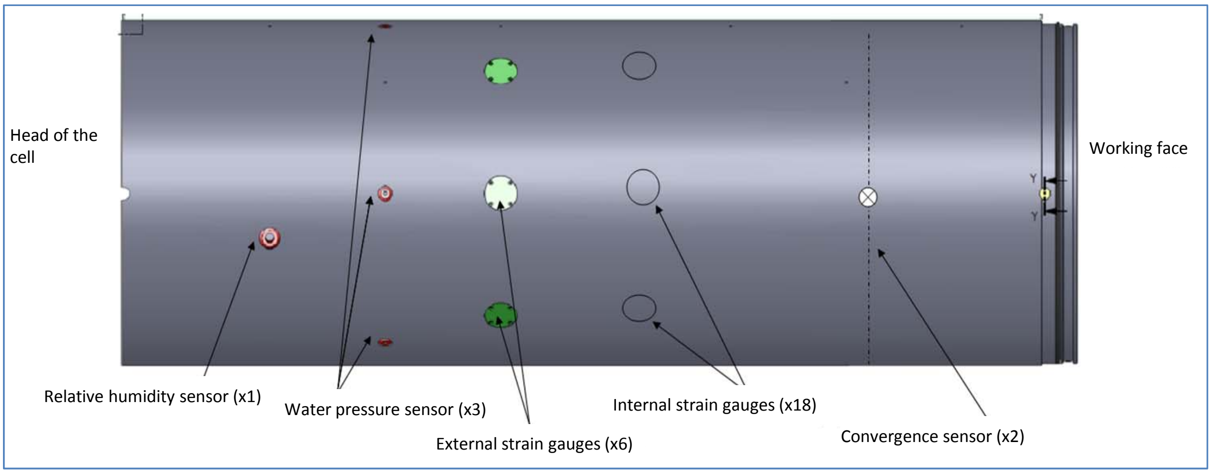

Figure 9: Location of the sensors on an instrumented casing element

Each of the 4 instrumented casing elements was equipped with the following sensors:

- 18 strain gauges on the internal surface and 6 on the external surface, so as to measure:
  - The local internal deformation of the casing element in 6 corner positions and in 3 directions (longitudinal, circumferential and at an angle of 45º);

- The local external deformation of the casing element in 6 corner positions and in an ortho-radial direction;

- 2 displacement sensors in order to measure the convergence of the casing in the horizontal and vertical directions;
- 1 relative humidity and temperature sensor so as to measure these two values in the casing/rock annular space.

Casing elements no. 3 and 17 were also equipped with 3 pressure sensors in order to measure the pressure of any possible water found in the annular space from 3 corner positions.

The casing was equipped throughout its length with 4 optical fibres:

- An external fibre to measure possible falls of break-outs after excavation;
- Two internal fibres to measure the temperature profile throughout the length of the casing;
- One internal fibre to measure the deformation profile throughout the length of the casing.

Only the stress gauges were placed on the casing elements before excavation. All the other sensors were put in place either during (for the external optical fibre) or after excavation by human intervention inside the cell. Figure 10 shows the sensors place inside casing element n°8.

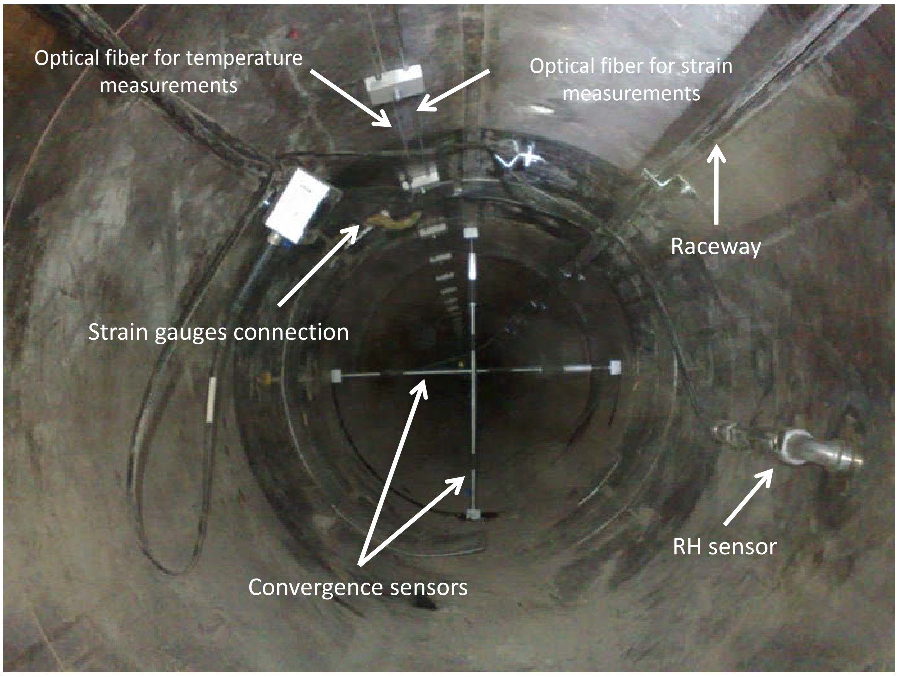

Figure 10: Instrumentation placed on casing element no.8

6. Instrumentation of zones near the cell CAC1601 (vibrating wire test for pore pressure cells)

6.1 Aims

After the study and the conception phase, this experimental approach enabled us to establish for the first time a device to measure pore pressure through vibrating wire technology in relation to the argillites of the Callovo-Oxfordian formation. Testing took place in the ANDRA underground research laboratory. This system was selected with a view to being suitable for use in a context of geological disposal, as a result of the potential durability it shows. Two parameters were borne in mind for the study:

- To test its use in an environment of very low permeability
- To evaluate the compatibility of this type of sensor with a disposal environment

6.2 Implementation

The installation work took place between 24/11/2010 and 26/11/2010 in the GAN gallery, in the ANDRA Meuse/Haute Marne Underground Laboratory.

The equipment installed consists of an aneroid pore pressure cell equipped with a vibrating wire sensor operating in maintained mode. The cell was placed at the bottom of the borehole at 5 cm from the end so as to form a measurement chamber. This chamber was then filled with 1.5 litres of water from the site and blocked off with quick-setting backfill of a very low permeability. The rest of the borehole was blocked off with the same backfill without a fast-setting agent. The following figures show the system for enclosing the equipment put in place in borehole CAC1611.

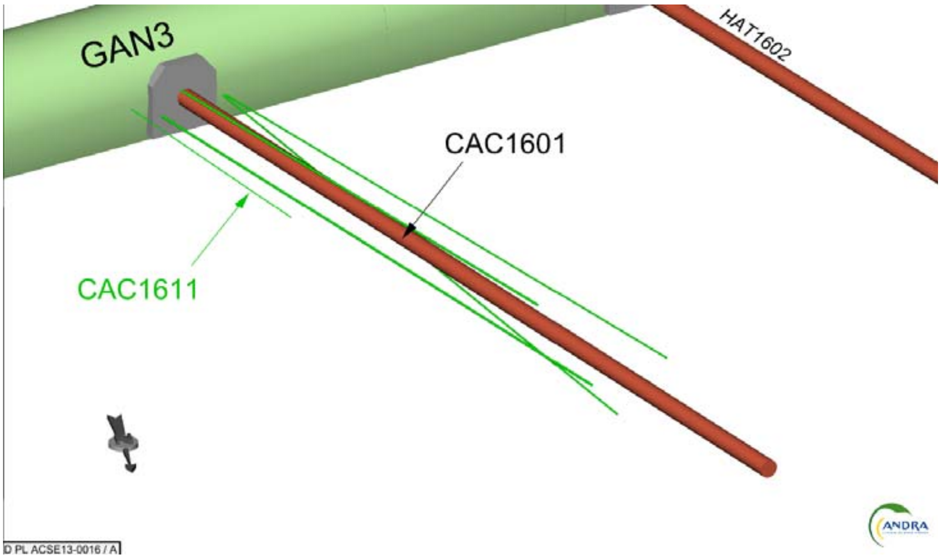

Figure 11: CAC1611 borehole surrounding the CAC1611 HL test cells

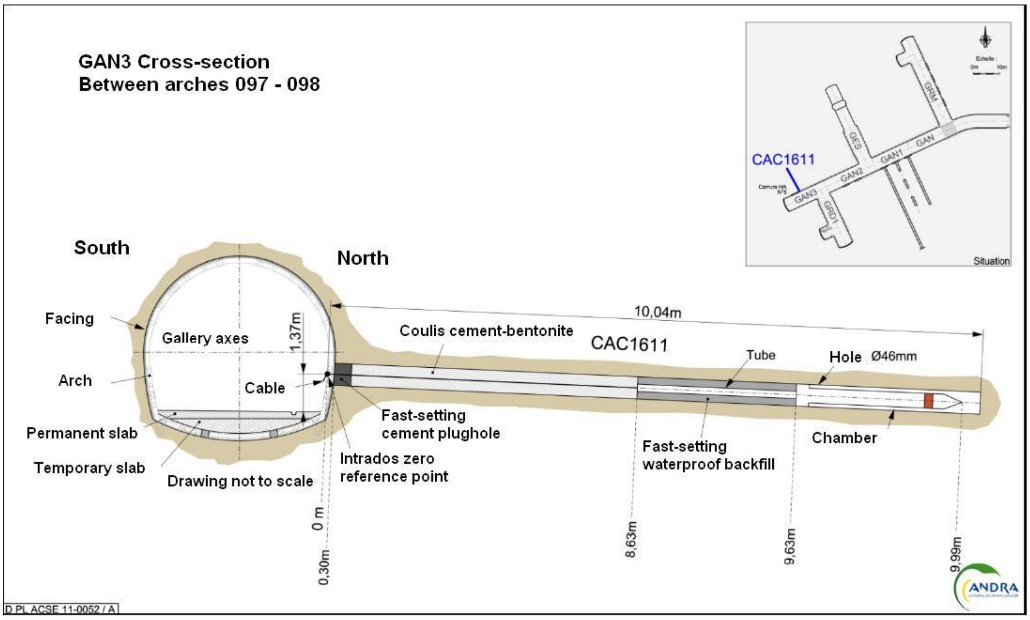

Figure 12: System for blocking off borehole CAC1611 equipped with a pore pressure sensor

7.Experimental results

7.1 Evolution of the hydric conditions in the annular space

7.1.1 Relative humidity and temperature

Figure 13 shows the location of the relative humidity and temperature sensor inside each instrumented casing element. The sensor is screwed into a projecting thread which is made watertight by use of a flat seal.

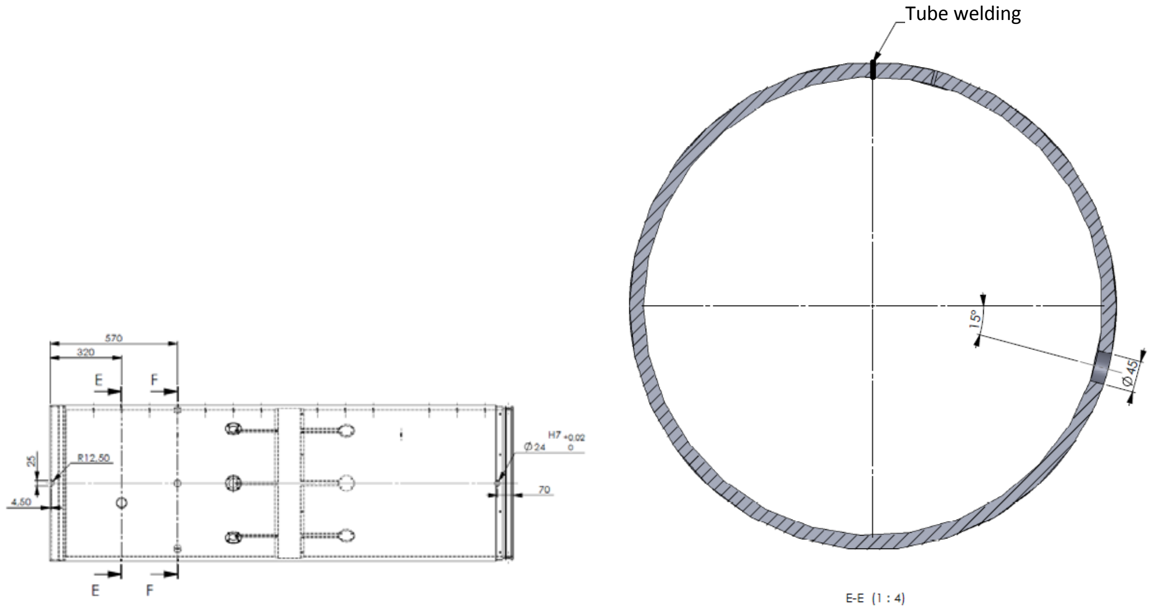

Figure 13: Location of the relative humidity and temperature sensor (casing elements no.3, 8, 13 and 17)

Figure 14 shows the evolution of the relative humidity in the annular space for each measurement section. A progressive saturation of the annular space can be observed in the 3 deepest sections (between 15 and 35 m.), with relative humidity reaching 98% after 300 days. In the case of the section nearest the gallery (at a distance of 7 m), the relative humidity started to fall after 150 to 200 days. This behaviour can be linked to the evolution of the temperature in the annulus, which, at a depth of 7 m, continues to be influenced by the evolution of the temperature in the gallery (cf. Figure 15). It was noted, however, that the range of daily temperature variations in this section decreases over time, an indication of an improvement in the watertight sealing of the annular space through the convergence of the surrounding rock.

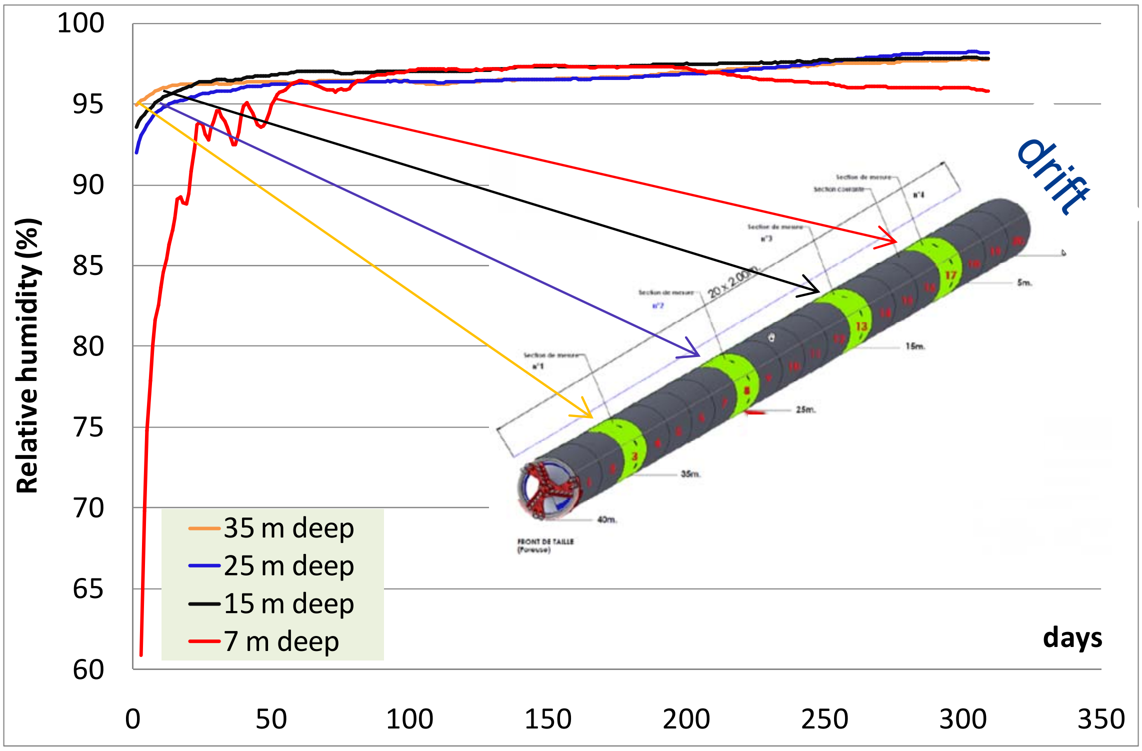

Figure 14: Evolution of the relative humidity in the annular space at different depths

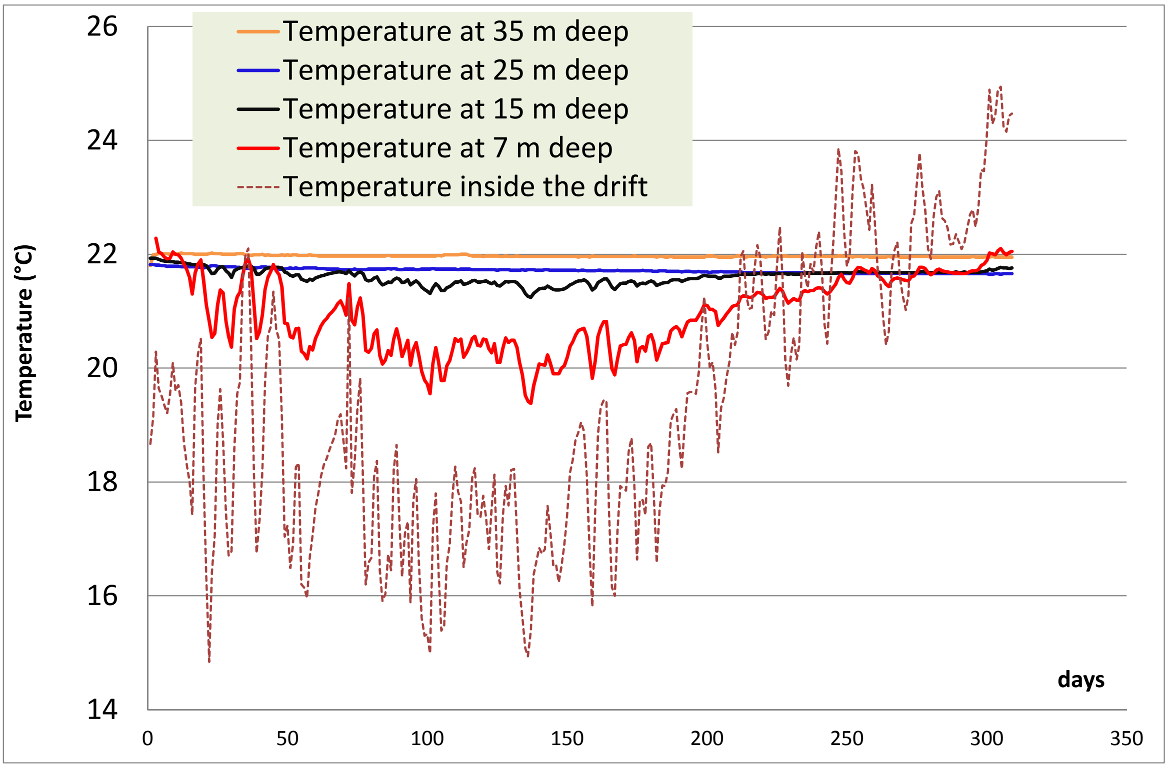

Figure 15: Evolution of the temperature in the annular space at different depths and in the GAN gallery (sensor OHZ1690_TEM01 located between arches 83 and 84)

7.1.2 Water pressure

Figure 16 show the location of the water pressure sensors inside casing elements no.3 and 17. The sensor is screwed into a pre-tapped hole, the watertightness of which is ensured by a flat seal.

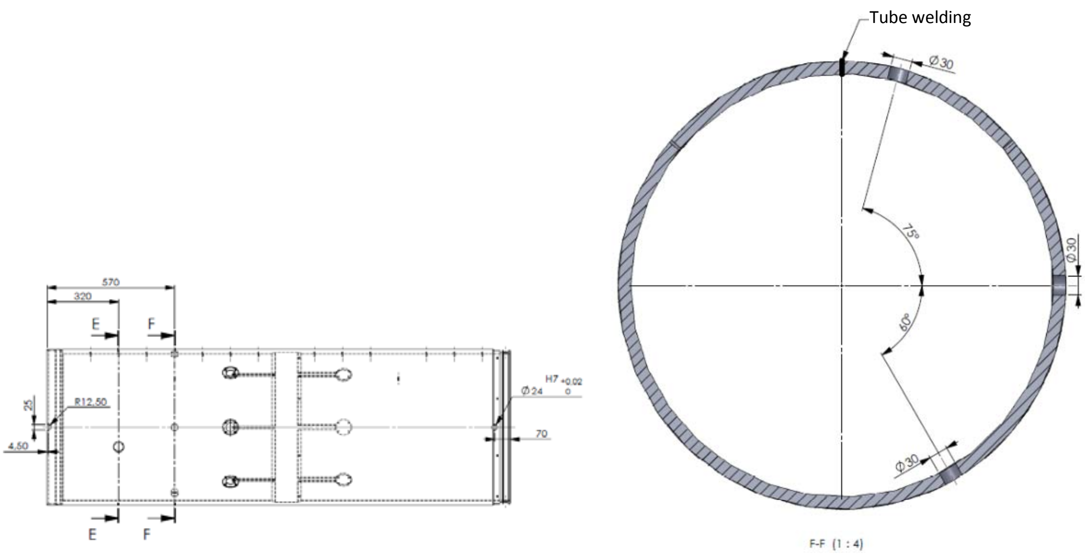

Figure 16: Location of the water pressure sensors on casing elements no.3 and 17

Since the annular space is not yet saturated, no water pressure has been measured to date.

7.2 Deformation of the casing

7.2.1 Convergence

Figure 16 shows the variation in the diameter of the casing in the horizontal and vertical directions as measured on each of the 4 instrumented casing elements. In all the cases we observe a convergence in the horizontal direction and a divergence in the vertical direction. This behaviour is consistent with the measurements of convergence taken during phases 1 and 1bis on non-cased cells with the same orientation [6].

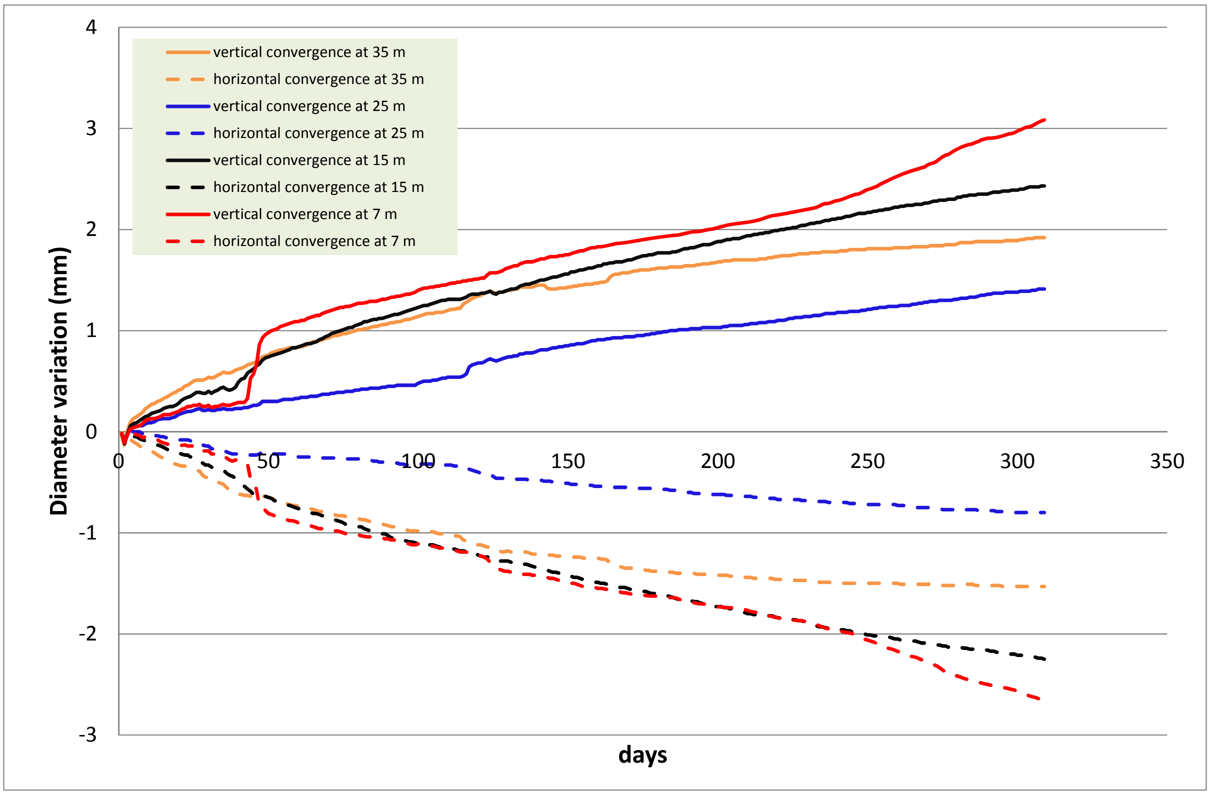

Figure 17: Variation of the internal diameter of the casing at different depths (negative values indicate convergence)

Figure 17 also shows that the casing has been undergoing deformation ever since measurements started, i.e. at the very latest 1 month after excavation (the time required to install instrumentation). The initial annular space (40 mm over the diameter) has thus been taken up again in less than a month, in the horizontal direction. Since the casing continues to be more and more out-of-round (oval-shaped), the clearance in the vertical direction has not yet been taken up again after over 300 days.

7.2.2 Local strain

Local strain is measured on the internal surface and on the external surface on each instrumented casing element, and is monitored from 6 corner positions (cf. Figure 18). The gauges were glued to sheets of 0.3 mm-thick steel, themselves welded at the bottom of spot facings onto the casing. The internal and external sheets are spread out on either side of an internal circumference slot designed to receive the cables for the gauges (cf. Figure 9 and Figure 16). Their respective depths are 7 mm (internally) and 10 mm (externally), and their role is to protect the gauges and their electronic systems during excavation work. Figure 19 shows a view of an instrumented sheet, welded to the bottom of a spot facing on the internal surface.

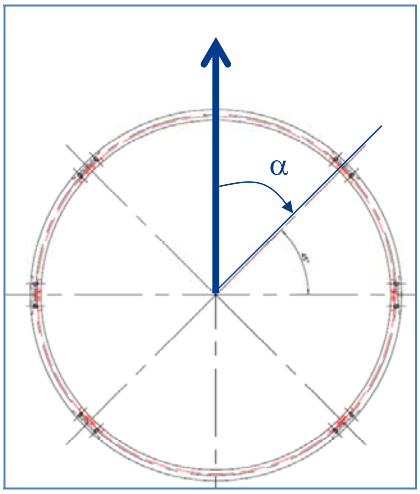

Figure 18: Angles for the measurements of local strain on the internal and external surface (α = 45, 90, 135, 225, 270 and 315°)

Figure 19: Instrumented sheet welded to the bottom of an internal spot facing and to which stress gauges have been attached (with 3 directions of measurement) together with their electronic components

All the gauges were set up as a full bridge circuit, with 2 active gauges and 2 bridge circuit complementary gauges not subject to mechanical stress for the purpose of offsetting temperatures. The conversion factors for the gauges were determined through a radial isotropic loading test on casing element n°8 [11].

Figure 20 represents the evolution of the circumferential strains (in the direction of greatest stress) on the internal and external surfaces of the casing, and at different depths. All measurement signals were disrupted in an identical manner. The precise origin of this disruption has not been identified. The missing signals correspond to gauges that were damaged during excavation.

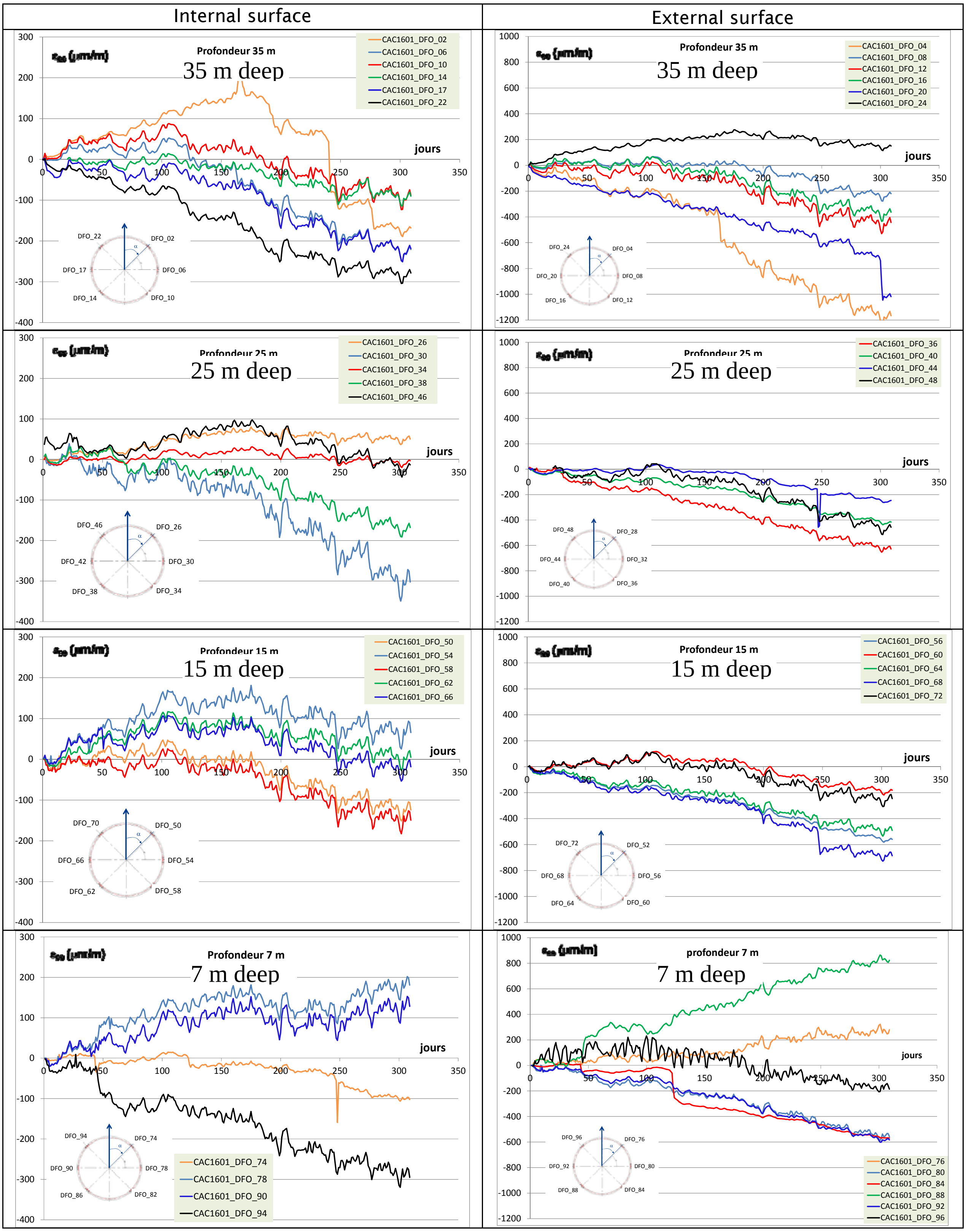

Figure 20: Evolution of internal and external circumferential strains at different depths and positioned at different angles

The maximum values attained on the internal surface did not exceed 300 µm/m as absolute values, despite local weakening of the casing by the spot facings. On the external surface, the maximum values attained are perceptibly higher, partly because of deeper spot facings (10 mm, or half the thickness of the structure). After 300 days, the casing is weakly loaded ($\sigma_{\theta\theta}$ < 100 MPa on the internal surface and at the bottom of the spot facing). Under isotropic loading, the increase in stress linked to the presence of the spot facing has been estimated as 40% **Erreur ! Source du renvoi introuvable.**, the maximum circumferential stress to which the casing is subjected after 300 days can thus be estimated at 70 MPa.

The mechanical signatures of the casing for each instrumented section are presented in Figure 21. These constitute the polar display of the evolution of circumferential strain.

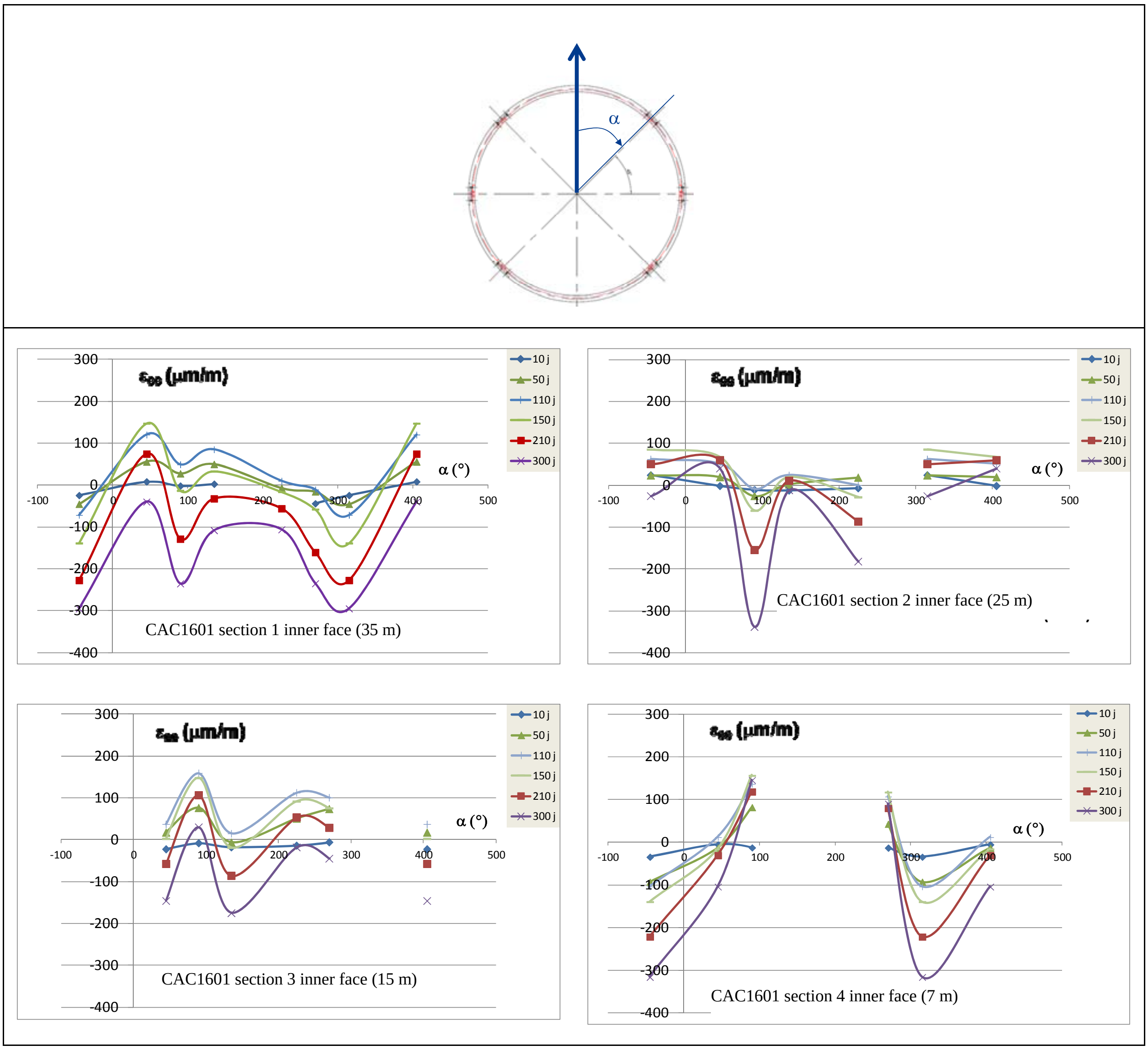

Figure 21: Evolution over time of the mechanical signatures of the casing (on the internal surface) and at different depths

Figure 22 represents a superposition of the mechanical signatures of the casing (identified on the internal surface) for each depth and a theoretical signature corresponding to a localised loading in the horizontal direction. The amplitude of this theoretical signal was fixed arbitrarily, in reality it depends on the size of the rock/casing contact zone and the intensity of the load. Local strain measurements do not at this stage make it possible to trace them back to typical loading examples, such as those studied in [12]. A number of reasons can be put forward to explain this difficulty:

- the signals are incomplete due to the fact that some gauges are damaged;

- the level of strain is still low compared with that observed during small scale experiments (cf. Figure 23);
- the mechanical loading applied to the casing is not yet stabilised.

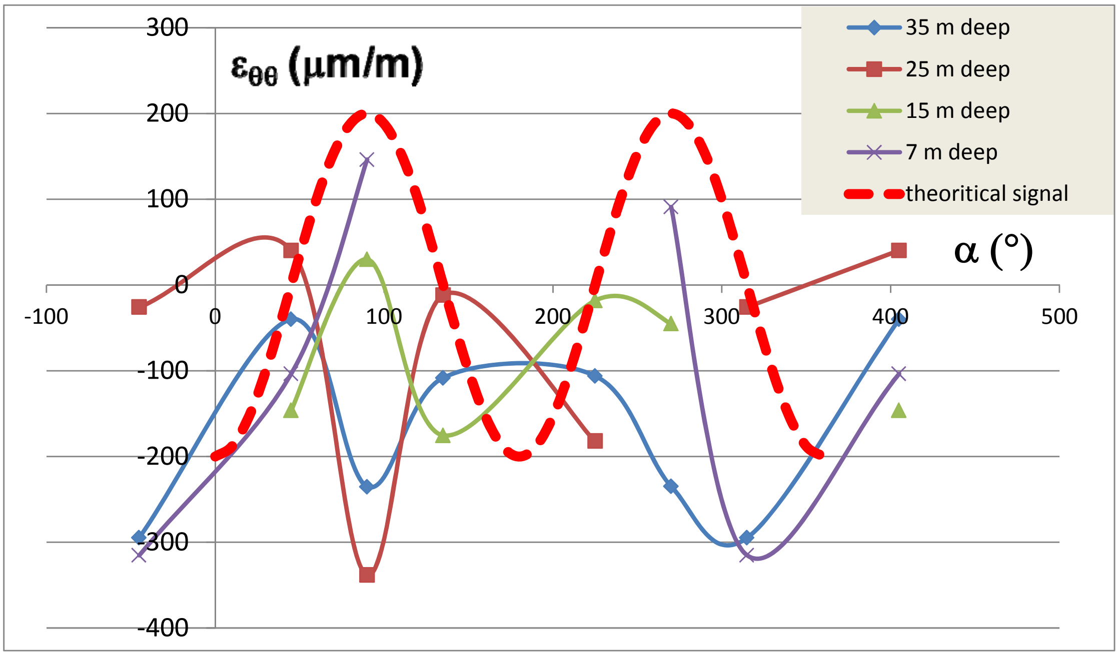

Figure 22: Mechanical signatures of the casing at different depths after 300 days and the theoretical mechanical signature of a loading localised in the horizontal direction

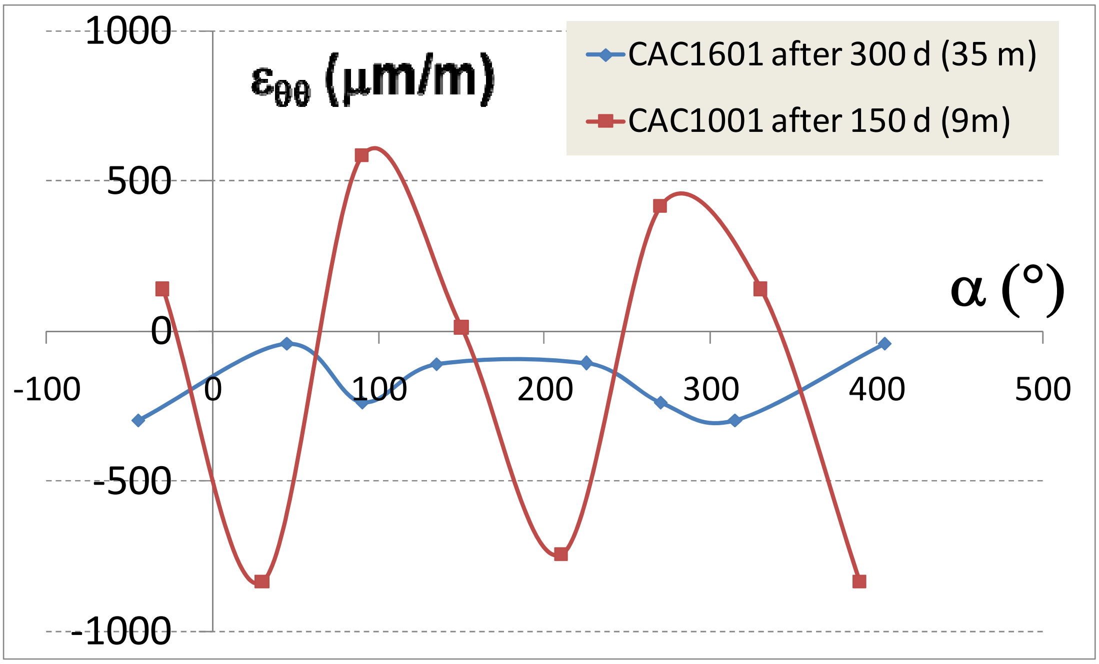

Figure 23: Comparison of the mechanical signatures of the casing of cell CAC1601 and of a steel tube inserted in the borehole CAC1001 of the same orientation with a reduced initial annular space (5 mm in diameter) – the diameter/thickness ratios are similar in both cases

7.3 Instrumentation by optical fibres sensors (OFS)

The measurement technique used for this instrumentation is the BOTDA (Brillouin based Optical Time Domain Analysis) measurement system, which has the advantage of a good signal/noise ratio but the disadvantage of operating within an enclosed system [11].

7.3.1 External optical fibre

The purpose of this instrumentation is to detect possible falls of blocks of argillite through scaling after excavations. A length of reinforced optical fibre was attached to the interior of a u-profile, welded onto the longitudinal edge all along the casing (cf. Figure 24). The installation was put in place at the same time as the excavation.

The measurement was conducted by backscattering and required the looping of the fibre connected to the analyser. Two monomodal fibres therefore needed to be welded together at the front of the cell to allow the signal to be returned. The welded zone (located in a watertight unit) was inserted at the front of casing element n°1, fitting into a specially-designed inset covered by a cap (cf. Figure 25). Despite this protection, the welding did not withstand the stress generated during excavation work (mainly in the form of vibrations). This fibre is not currently taking measurements. An interrogation system better adapted to this optical fibre is currently being purchased in order to be able to carry out the measurements required.

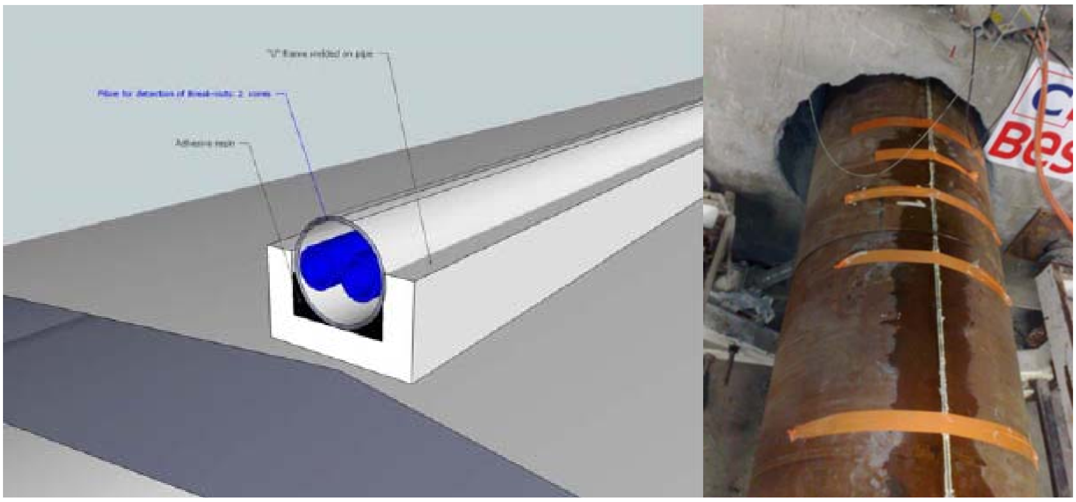

Figure 24: Diagram showing the method of attachment for external optical fibre (left) – view of fibre on two casing elements in the process of being excavated (right)

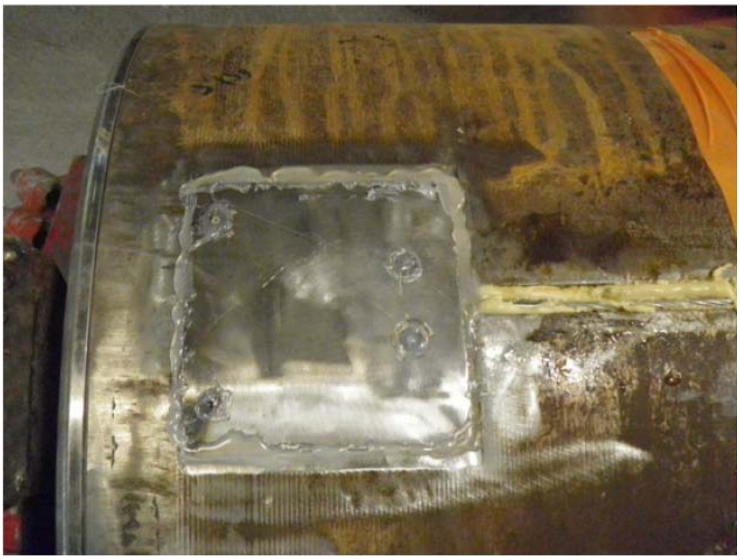

Figure 25: Capped inset holding the welded link between 2 optical fibres for measuring falls of blocks (front of casing element n°1)

7.3.2 Internal optical fibres

Three of optical fibres were installed inside the casing after excavation (cf. Figure 26):

- 1 fibre for Brillouin temperature measurement;
- 1 fibre for Brillouin deformation measurement and 1 fibre for Raman temperature measurement, inserted in the same sheath.

Since the measurements were conducted in a looped system, the OFS at the bottom of the cell needed to be welded together. Since this was not possible in the case of the Brillouin temperature-measurement fibre (due to the fracture of the welded connection during the operation to attach the fibre to the casing, despite the protective watertight case), it was therefore decided to double the length of the fibre so as to undertake the welding outside the cell, after positioning the fibre [14].

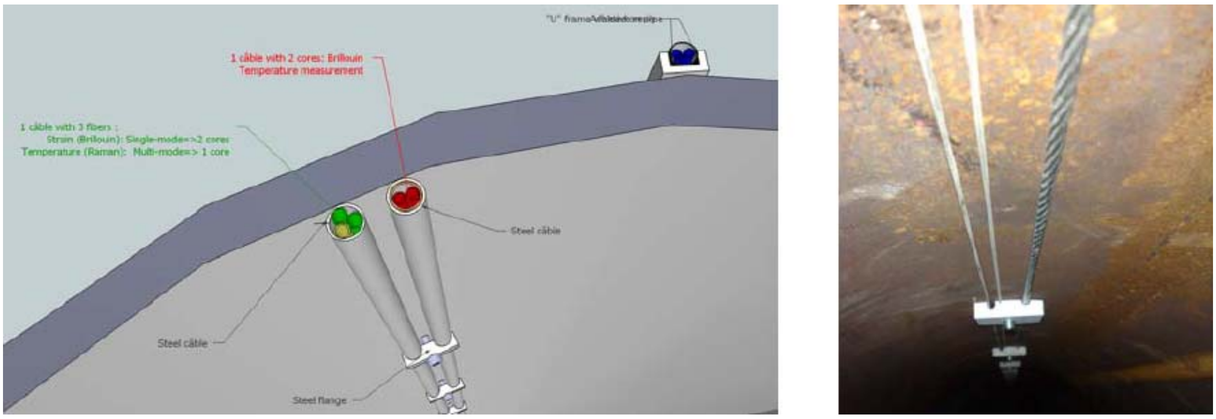

Figure 26: Instrumentation in OFS inside the casing – theoretical diagram (left) and photograph of the installed fibres (right: doubled fibre for temperature on the left; and deformation fibre on the right)

The cables containing the optical fibres were attached to the casing through flanges screwed on every 50 cm (cf. Figure 26). The spacing and attachment of the flanges were determined on the basis of surface laboratory tests, in such a way as to ensure a cable/casing contact strong enough to reproduce faithfully the deformation of the casing element while not disrupting the signal [11].

The measurements acquisition started in February 2012. Figure 27 shows the evolution of the temperature of the casing at different depths, and Figure 28 shows the evolution of the axial deformation of the casing at the same depths.

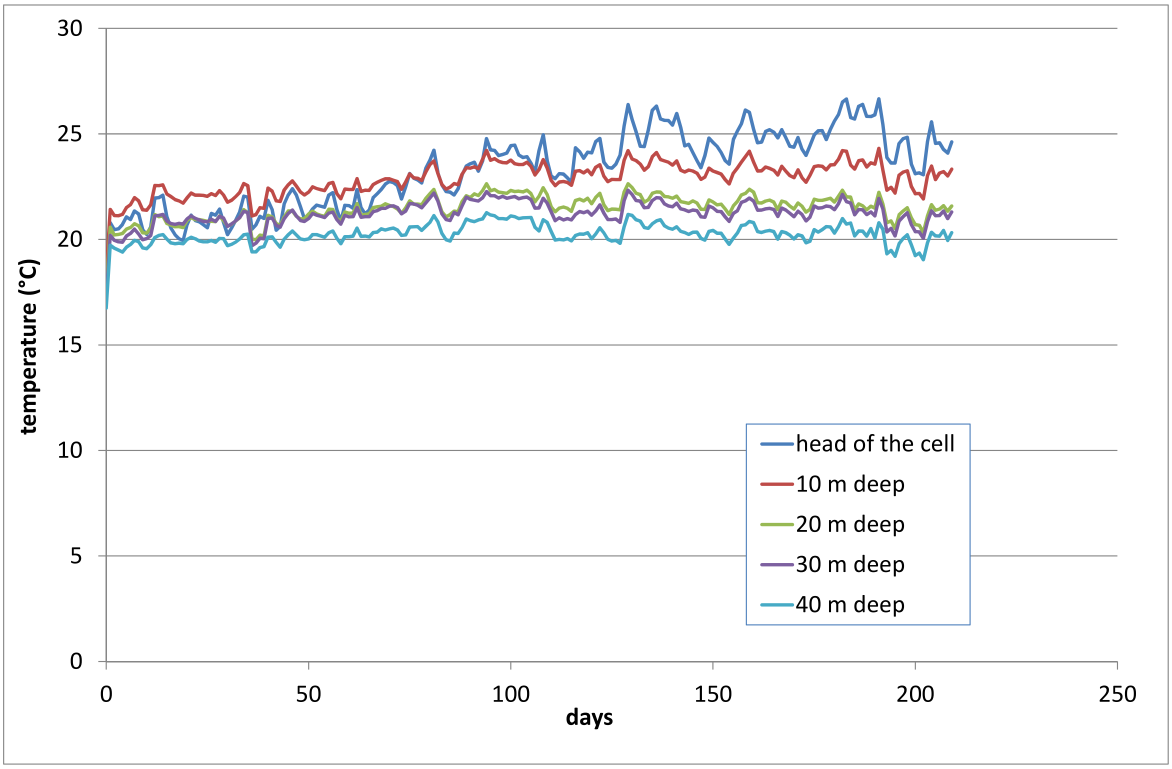

Figure 27: Evolution of the temperature of the casing measured by optical fibre at different depths

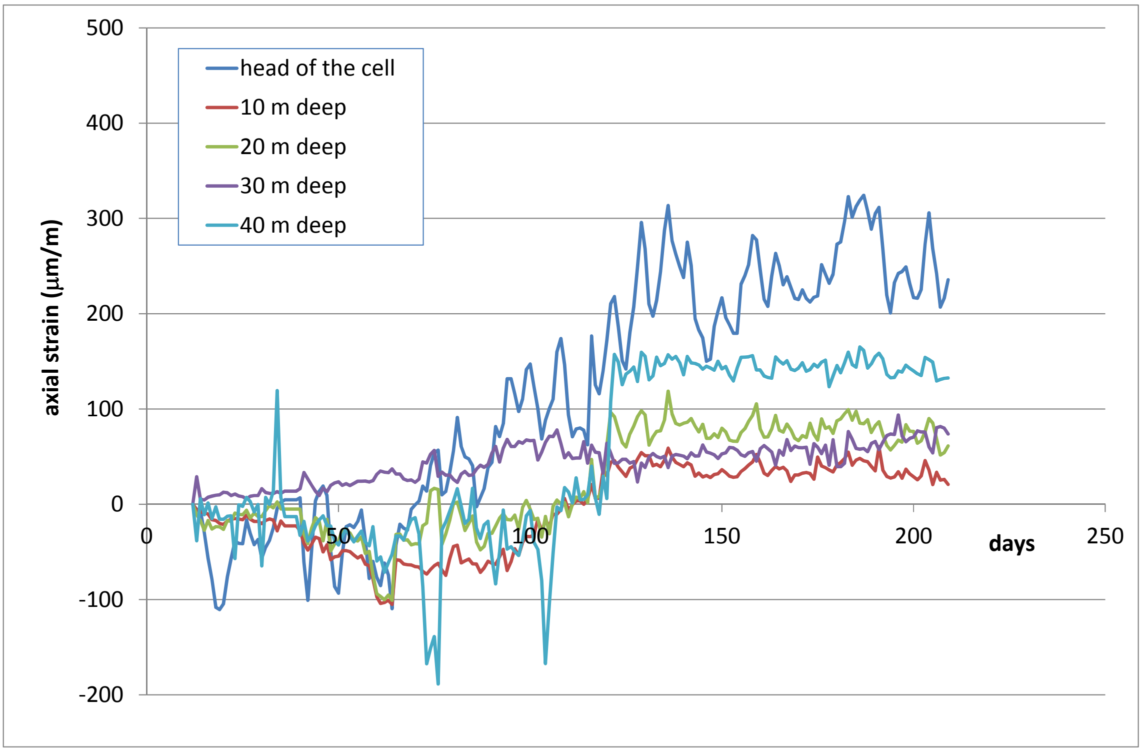

Figure 28: Evolution of the longitudinal deformation of the casing in the crown, measured by optical fibre (the first 10 days of measurements were disrupted by power-cuts in the underground laboratory)

7.4 Pore pressure in zones near the cell

The first results obtained (cf. figure below) show a slow and quasi-constant increase in pressure since the installation.

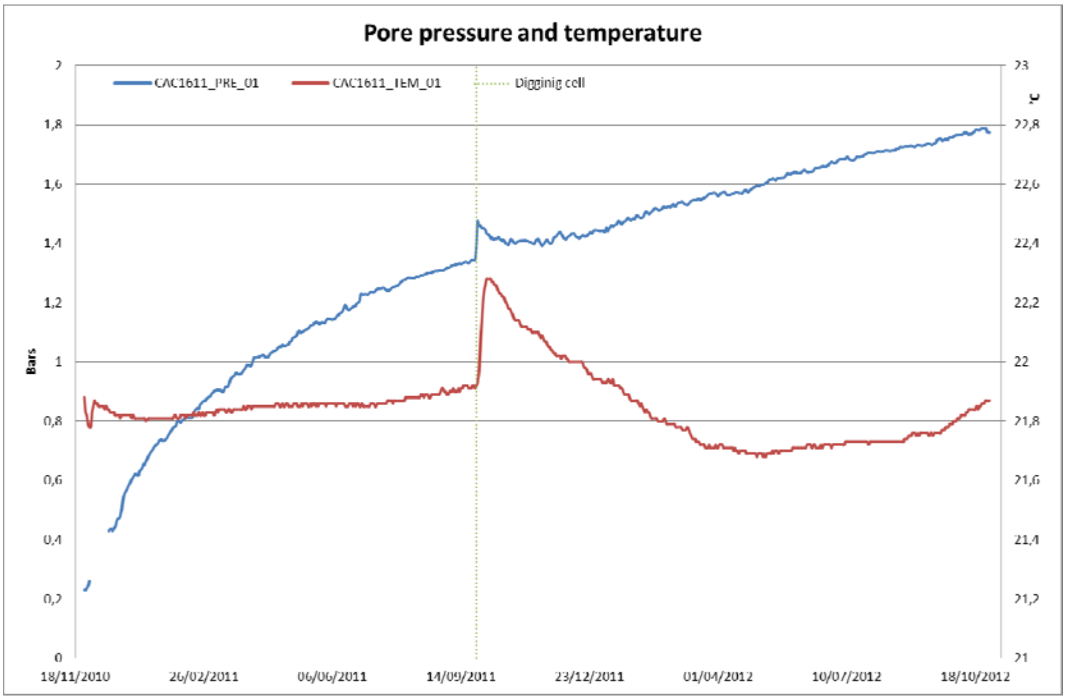

Figure 29: Evolution of pore pressure and temperature (in red) in borehole CAC1611.

This increase of pressure is very low because of the very low permeability of the host rock and the kinetic of the water flow in the chamber. In addition, a suction phenomenon occurs after installation due to the sealing material, made by cement – bentonite mixture. Finally, the permeability of such a sealing has to be measured in order to assess if it makes a hydraulic drain in the borehole CAC1611 (surrounding the CAC1601 cell).

An overpressure was observed on about 26 September 2011, corresponding to the passing of the cell excavation machinery near the cell. The rise in pressure returned to the same levels of increase after the dissipation of the overpressure resulting from the excavation.

8. Main assessment

From a technical point of view, the "High-Level Waste Cell", phase 2 experiment confirmed the feasibility of excavating a cased cell 40 m in length with a low overall deflection (less than 10 cm in the horizontal and vertical planes) and will continue to be assessed over a longer period than the Modern project.

The experimental campaign also demonstrated the feasibility of the complex instrumentation of casing with the aim of determining both its mechanical behaviour and the evolution of the hydromechanical conditions in the annular space. This instrumentation can only be installed after excavation. The feasibility of post-excavation optical fibre instrumentation was also demonstrated.

The evolution of the hydric conditions in the annular space shows that after approx. 300 days the arrival of water has not been observed, despite the watertightness of the casing (in the form of sealing between casing elements and bottom) and of the annular space at the front of the cell. On the other hand, measurement of convergence and local strains in the casing show that it was subjected to mechanical load as soon as it had been installed in the ground. This load was localised in the horizontal direction, in accordance with what is observed during experiments on small-scale casing of similar orientation (TEC / CAC [15]). These results show that the configuration of the casing of a High-Level Waste Cell undergoing stress exclusively from the pressure of water on its extrados (or external surface) is highly unlikely, especially since the casing / rock clearance initially foreseen in the 2009 design (25 mm in diameter) is less than that defined for the experiments (40 mm in diameter).

While the mechanical loading of the casing occurred very soon after its installation, it is nevertheless of a low intensity in relation to what was observed in small-scale casing over a comparable time-scale. This scale effect can be explained by the initial annular space, which, proportionally to its diameter, was larger in the case of cell CAC1601 (approx. 0.05 ∅ for the scale 1 cell, compared with approx. 0.03 ∅ for the casing).

This first test made it possible to validate the feasibility of the implementation of a pore pressure cell in such a geological environment, and with this type of equipment, the pore pressure cell test shows an increase in pressure that does not enable us to reach any conclusion concerning the suitability of this sensor for the future monitoring of Cigéo. Additional tests have been conducted since this first test so as to be in a more realistic situation in terms of the measuring environment and so as to improve the arrangements in relation to 2 parallel aspects:

- To conceive a backfill for sealing off the borehole with satisfactory hydro-mechanical efficiency in the medium and long term;

- To test the cell with an effective "short-term" sealing system so as to validate the sensor's performance.

9. References

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