Assessment of long-term sensor performance based on a large THM experiment in the HADES URL

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Abstract: A monitoring plan is an important part of a disposal programme. Monitoring a deep geological repository for the disposal of radioactive waste faces several challenges. These may arise from the technically demanding environment in which the monitoring equipment must operate or from the potentially long period of time during which they must operate. Over the past decades, a lot of experience has been gained in monitoring experiments in underground research laboratories (URL).

Since the HADES URL became operational in the 1980s, thousands of sensors have been installed. To document the experience gained in this context, ONDRAF/NIRAS launched a research project to evaluate the performance of the monitoring equipment implemented in the HADES URL. This required developing a method to assess the performance of sensors in a consistent way. The methodology is explained in this paper and illustrated for the instruments installed to monitor the THM response of Boom Clay to the large-scale PRACLAY *in situ* experiment.

Monitoring a deep geological repository (DGR) can serve multiple purposes (IAEA 2001; EC 2004; IAEA 2014; NEA 2014). It can be implemented to collect site-relevant information and create an environmental database. It can be used to demonstrate compliance with regulations and licensing conditions, or it can check the performance of the DGR and verify the validity of safety assessment. It may also be aimed at the public to provide assurance that the system is safe.

Monitoring a DGR poses specific challenges. First, the environment in which the monitoring equipment operates can be demanding. The equipment may need to operate under high pressure (both mechanical and hydraulic), elevated temperatures and high levels of radiation. Secondly, the monitoring itself must not negatively affect the performance of the DGR. This means that no monitoring equipment or cables may be used that could create preferential pathways for the release of radionuclides and that the materials used must not chemically interact with the disposal system. Finally, monitoring programmes that are scheduled to last for decades must consider the shelf life of the equipment and power sources.

There is a lot of experience with monitoring equipment in underground environments through its use in experiments conducted in URLs. Considering the preservation of knowledge over the different decades of research (and time towards repository implementation), it is important that information about the long-term performance is well documented. Recent work on this includes deliverables of the EC MoDeRn (EC 2013) and Modern2020 (EC 2019) projects, in addition to more specific work discussing sensor performance in repository-like conditions (e.g. Farhoud *et al.* 2015; García-Siñeriz *et al.* 2019).

Thousands of sensors are installed in the HADES URL. Some sensors used in experiments or research activities that ended years ago still work. However, others have failed, and some even shortly after their installation. This is not surprising, as the sensors used in the HADES URL are often standard industrial or geotechnical sensors modified to meet the specific experimental needs in the URL. For example, some common parts of geotechnical sensors, such as inclinometer casings or sensor wiring, are not designed to withstand the porewater pressures or stresses in the Boom Clay at a depth of 225 m. The long-term impact of these conditions cannot always be estimated or tested in advance.

Recognizing the importance of documenting these lessons learned, ONDRAF/NIRAS started a research project within its Research, Development and Demonstration Plan (ONDRAF/NIRAS 2013) to evaluate the performance of the sensors installed in the HADES URL. First, a methodology was

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developed (Verstricht *et al.* 2022*a*) to assess sensor performance. This paper illustrates how this methodology is put into practice for the instrumentation installed as part of the PRACLAY *in situ* experiment (Fig. 1; Chen *et al.* 2021; Dizier *et al.* 2021). During this experiment, the clay around a 30 m long section of the PRACLAY Gallery is heated for at least ten years. It therefore provides the opportunity to assess the performance of sensors monitoring THM phenomena for at least ten years.

Assessment methodology

The purpose of the assessment is to build a database of sensors used in the HADES URL with information about their installation, the experimental conditions and their performance. This database will be used to inform the instrumentation design for future experiments and the monitoring plan for a future DGR.

The setup of the different experiments is very diverse. Experimental setups may differ in, for example, their scientific objectives, scale (with respect to the dimensions considered for a DGR), date of operation and duration, the conditions under which they are performed, and whether previous experience is available. This also means that there is a wide variety of sensors that are used and that they are often used in different conditions or for different purposes. This indicates the need for a clear methodology that is robust, general and flexible when assessing the performance of all these sensors. The methodology should ensure that the different sensors are described and evaluated in a consistent manner and against the same standards to allow the results of the different assessments being combined into an overall database.

The assessment methodology structures all information about the sensors in five categories:

(1) Installation
(2) Operation
(3) Environment
(4) Measurement quality
(5) Sensor characteristics

In addition, the assessment can only be made properly if sufficient metadata are provided. Therefore, the experimental context is described, thereby documenting as much as possible all relevant project information. This includes the whole design process, from scientific objectives to the technical implementation of the instrumentation design. It includes a discussion of the sensor selection (why a specific sensor type and manufacturer has been selected), sensor calibration and installation.

Regarding the sensor selection – this has been detailed for each sensor set but is not considered a part of the assessment itself, as the latter focuses on the field performance. The selection process, which includes many aspects (technical, commercial, project-related), is, however, a critical step in the design and implementation process of (URL) experimental setups. It is also treated in the discussion of the factual information of the assessment (e.g. failures with time or as a function of the development of other variables, such as the temperature or water pressure). This discussion concludes with an expert judgement on the actual status of the sensor technology (e.g. is it still the best technique for this application), and on the perspective for its use in future monitored demonstrators or in a repository context.

Installation

This category contains information such as sensor location, installation date, and whether an installation procedure for the sensor was available. The latter could be an indication of how routinely these types of sensors are installed. Any problems that arose during installation are also documented in this category.

Knowledge about the sensor location is essential when interpreting their measurements, certainly when comparing them with numerical simulations. Instrumented boreholes are therefore surveyed to determine the sensor positions with sufficient precision.

It is also assessed whether the sensor design is compatible with the environment in which it is used. Boom Clay is a poorly indurated clay, openings made in the clay close relatively fast under the *in situ* stresses. The installation protocols need to take into account that the time window for installing instrumentation can be limited to a few hours.

Operation

This category tracks when the sensor started working and, if applicable, when it stopped (mainly due to failure). Any interruptions in sensor operation and their causes are also documented. Interruptions can be caused by construction works related to the experimental setup, which could obstruct sensor read-out or connection to the data acquisition.

Environment

The environment contains information about the geochemical and hydraulic conditions in which the sensor operates and to what pressures, temperatures and radiation levels it is exposed. Experience shows that increased water pressure, corrosion and mechanical stresses are important factors that have affected the performance of sensors installed in the clay. Also the apparently undemanding environment of the accessible galleries can cause failures to fragile equipment.

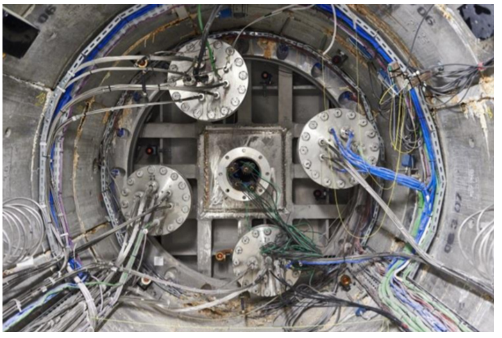

Fig. 1. Photograph of the seal in the PRACLAY Gallery facing the Connecting Gallery, and the many instrumentation and heater cables that are fed through the seal.

Measurement quality

The quality of the measurement data relates to parameters such as signal stability, presence of noise or outliers. It also indicates whether the sensor measurements are in line with what can be expected: do the measurements provide meaningful data and can they be considered representative?

This also includes the concept of conformity. The presence of a sensor should not change the variable that it is supposed to measure. A typical example are total pressure sensors in the Boom Clay. The mere fact that they are installed through an instrumented borehole significantly disturbs the total stress field. In the case of the CLIPEX experiment (Verstricht *et al.* 2022*a*), the measured total stresses were comparable to the measured porewater pressures, which has no physical basis.

Possible causes for poor quality readings in the HADES URL could be related to sensor environment aspects, like water saturated media at high pressures and high temperatures, causing corrosion of metal sensor parts and/or water infiltration. Cabling and cable connections are typically weak points. This can be a slow process, resulting in gradually deteriorating signals for the sensors concerned.

Sensor characteristics

This category discusses the intrinsic parameters of the sensor. This can include information how the sensor converts the physical input to the output signal. This is sometimes referred to as the sensor transfer function (or calibration function).

The actual parameters depend on the sensor type. Typical parameters include sensitivity (change of output relative to unit input variation) and zero reading (signal when input is zero), but these are not always applicable. An important indicator is the accuracy, which gives an indication of the reliability of the conversion performed by the sensor. To quantify the accuracy, a calibration needs to be performed. This is normally performed by the manufacturer and, where possible, before sensor installation. Once the sensor is installed and cannot be accessed, the calibration is no longer possible. In that case indirect techniques are applied to verify the longer term accuracy and sensor integrity. This can be done through measuring the electrical impedance or isolation resistance measurements (and in particular their evolution with time), analysing the sensor signal (e.g. sudden appearance of noise) and comparing the sensor measurements to those of adjacent sensors or numerical simulations. The pressure transmitters of the piezometers, however, do remain accessible. This makes it possible to regularly perform calibrations to verify the accuracy and detect possible deviations from the calibration parameters.

A final indicator is the resolution, i.e. the smallest variation that can be detected. As explained further, this often depends on the readout equipment.

Expert judgement

Based on the outcome of the assessment, conclusive remarks are drawn in an ‘expert judgement’ format, in which both the performance of the current state of the sensor technology in the actual setup conditions, as well as the perspective of the technology for future demonstrators and in the context of a DGR are considered. As these are not yet defined (e.g. which monitoring approach will be used in a DGR? what are the measurement objectives?), the nature of the judgement is mainly qualitative and indicative. As a typical example, the good performance of the twin-tube piezometer can be mentioned, but its invasive character could question its applicability in a DGR context, depending on the monitoring approach chosen).

Instrumentation details

The PRACLAY Heater Test is installed in the PRACLAY Gallery (PG): a 45 m long gallery built perpendicular to the Connecting Gallery (CG) (Fig. 2). The purpose of the heating test is to investigate the impact of a thermal load on the Boom Clay. During the heating test, the clay around a 30 m long section of the PRACLAY Gallery is heated to 80°C for at least 10 years and the THM response of the clay is monitored. In order to create undrained hydraulic boundary conditions, a bentonite seal was installed to close the water-saturated and heated part of the PRACLAY Gallery.

The construction of the gallery and the installation of the seal are tests in themselves: the Gallery and Crossing Test and the Seal Test. Together with

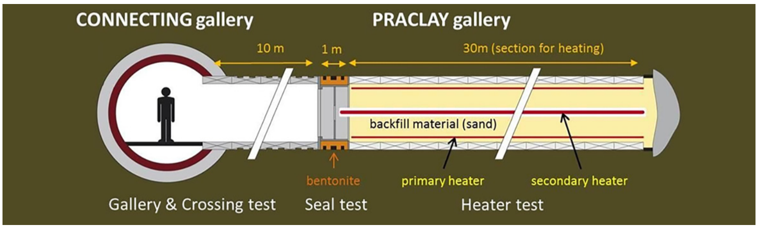

Fig. 2. The PRACLAY *in situ* experiment includes three tests: the Gallery and Crossing Test, the Seal Test and the Heater Test.

the Heater Test, they form the so-called PRACLAY *in situ* experiment (Van Marcke *et al.* 2013).

Scoping calculations were performed to support the design of the experimental set-up. These calculations allowed to define or optimize key experimental parameters such as the target temperature, length of the heated part and required boundary conditions. They also provided input for the instrumentation plan. It made it possible to define the locations where sensors could best be installed and what the measurement ranges and accuracy should be.

In total, approximately 1300 sensors were installed as part of the PRACLAY *in situ* experiment. They measure a wide range of parameters such as porewater pressures, stresses, temperatures, and displacements. They are installed in the following experiment components:

- the Boom Clay
- the PRACLAY Gallery lining
- the PRACLAY seal
- the sand backfill in the heated part of the PRACLAY Gallery

To structure the assessment, the 1300+ sensors were categorized into 30 ‘sensor sets’: groups of sensors with comparable properties (mainly considering the sensor type and the specific environment in which they are installed). For example, one sensor set contains all the vibrating wire strain gauges installed in the gallery lining to monitor the stresses in the lining, while another set contains all the thermocouples mounted in the piezometer casings that were installed from the Connecting Gallery.

A general overview of the sensors is shown in Table 1.

Instrumentation in the Boom Clay

Measurements in the Boom Clay are performed through instrumented boreholes (Fig. 3). From the Connecting Gallery, nine boreholes were instrumented. After completion of the PRACLAY Gallery, 13 more boreholes were drilled and instrumented. Most boreholes are horizontal, but there are also vertical and inclined boreholes that allow assessing the anisotropic response of the clay.

Most of the boreholes are instrumented with multi-filter piezometers (Fig. 4a). These consist of a 100 mm (or 76 mm for the installations from the PG) wide steel casing with integrated filters. One borehole can contain up to 16 filters used to measure porewater pressure. Each filter is connected, through a pair of capillary tubes, with a pressure transmitter located in the access gallery, near the accessible end of the instrumented borehole. At the inside of the casing, next to each filter, temperature sensors have been installed (Fig. 4b). They consist of thermocouples type T (this type has an accuracy of 0.5°C, which is better than the other thermocouple types) spot-welded at the inside of the filters. Three boreholes also have long filters (500 mm) for geochemical characterization through on-line measurements and sampling. At the deep end of several boreholes, total pressure cells (flatjacks (Fig. 4c) and/or biaxial stressmeters) were installed.

For the instrumented boreholes installed from the PRACLAY Gallery, the instrumented casings are no longer accessible because the PRACLAY Gallery has been backfilled and saturated (to a pressure of approximately 2.8 MPa) and is currently heated to 80°C at the interface between the gallery lining and the Boom Clay. Such conditions are quite demanding for the signal cables and capillary tubes, especially their connections.

Inclinometers and extensometers are used to measure displacements in the clay. The inclinometer is installed in an inclined borehole from the CG next to the gallery crossing. It consists of a chain of 15 segments, each equipped with an electro-level (which is basically a bubble level giving an electrical output signal). Each level along this chain provides a measurement for the slope. By integrating the subsequent slopes, a vertical profile can be constructed. Changes with time then allow to determine the vertical displacements along the borehole.

The extensometers are installed in three boreholes from, and perpendicular to, the PRACLAY Gallery, but in different directions. Each extensometer has a chain of 3 fibre optic gauges (interferometric type) fixed at anchor points 5, 10 and 20 m deep in the borehole.

Table 1. *Overview of the main sensor types according to measurement variable*

Sensor type	Brand	Material type (probe)	Measurement range	Accuracy	Calibration curve	Selection process*	No. installed
Temperature							
Thermocouple (type T)	Thermo Electric	Stainless steel sheath (AISI 316)	0–200°C	±0.5°C	IEC 60584	a, f	380
Thermistor	(VW supplier)	(integrated)	0–100 ± °C	±0.2°C	Steinhart–Hart	h	246
Distributed optical fibre (Brillouin scattering)	SmarTec – DiTeSt	Single-mode optical fibre		±1°C	Integrated in read-out	g	2
Total pressure							
Flatjack w/VW sensor	Geokon	Stainless steel (AISI 316L)	0–7.5 MPa(g)	±0.5% FS	Individual calibration by manufacturer	a, b, c	61
Miniature piezoresistive sensor	Kulite		0–7 MPa bar(g)	±0.5% FS	Individual calibration by manufacturer	b, d	10
Porewater pressure							
Twin-tube piezometer	Druck, Keller	Stainless steel (AISI 316L)	0–8 bar(abs) … 0–40 bar(abs)	±0.25% FS	Linear (best straight line)	a	326
Relative humidity							
Capacitive RH sensor	Rotronic HC2-C04	Stainless steel	0–100% RH	±1.5% RH	Manufacturer (linear)	b, d	11
Load							
Flatjack w/VW sensor	Geokon 4850-1X	Stainless steel (AISI 316L)	0–50 MPa(g)	±0.5% FS	Individual calibration by manufacturer	a, b, c	9
Strain							
VW strain gauge	Gage Technique	Stainless steel	−3000 + 3000 μstrain	±1% FS	Bulk gauge factor	a, c	176
Resistive strain gauge	Vishay CEA-06-250UT-350		−5000 + 5000 μstrain		Bulk gauge factor	d	24
Displacement							
Inclinometer	Boart-Longyear (Interfels)	Stainless steel	−3 + 3°	±1% FS	Individual calibration by manufacturer	a	15
Fibre optic interferometer	SmarTec – SOFO	Optical fibre in nylon tubing	−0.5 + 1.0%	±5 μm	Not applicable	e, g	12
Potentiometer	SolExperts SFX		0–100 mm	±0.02 mm	Individual calibration by manufacturer	b, c, e	20

*Main criteria for selection: a, previous experience in HADES; b, references from setups in other locations; c, manufacturer interaction/assistance; d, (small) sensor size; e, environmental conditions; f, robustness; g, (test of) prototype; h, integrated (auxiliary sensor).

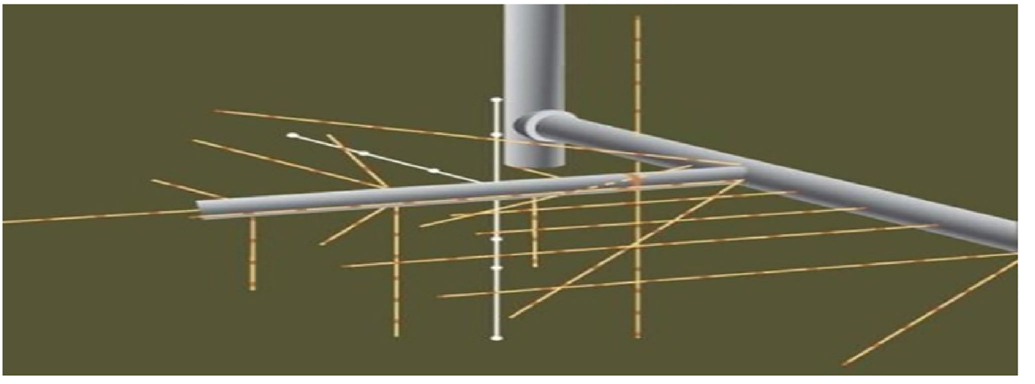

Fig. 3. Instrumentation placed in boreholes drilled in the Boom Clay near the PRACLAY Gallery.

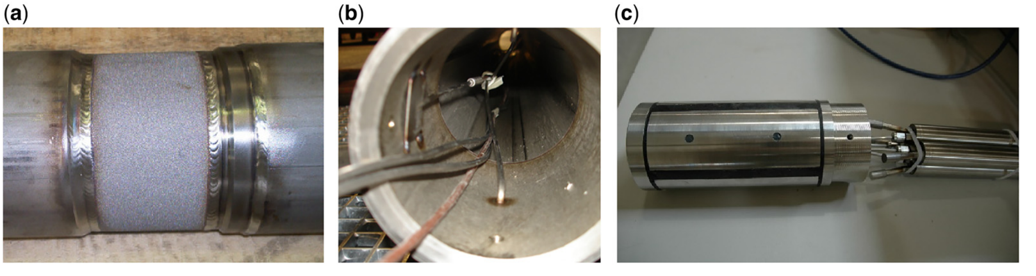

Fig. 4. (**a**) Multi-filter piezometer with a filter for measuring porewater pressures or extracting water samples. (**b**) Thermocouple spotwelded onto the piezometer casing. (**c**) Total pressure cell to be integrated at the end of the piezometer casing.

Finally, micro-seismic sensors (transmitters and receivers) were placed in some boreholes. These sensors were also placed against the clay through holes drilled in the lining of the PRACLAY Gallery (Fig. 5). Transmitters create seismic waves that propagate through a part of the clay near the PRACLAY Gallery to receivers. The velocity, damping and frequency of these waves provide information about the elastoplastic behaviour of the clay. In addition, acoustic (elastic) waves are also generated in the host clay as it undergoes irreversible changes due to the temperature gradient or mechanical forces. This phenomenon is known as 'acoustic emission' and the receivers also detect these waves.

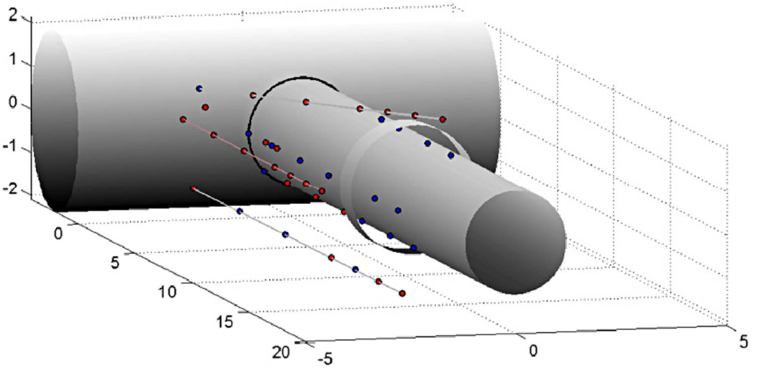

Fig. 5. Layout of the network of micro-seismic sensors placed in the clay close to the PRACLAY Gallery (red dots, transmitters; blue dots, receivers).

Instrumentation in the PRACLAY Gallery lining

The PRACLAY Gallery lining is constructed ring by ring which were erected as the excavation of the gallery progressed. Each lining ring is made up of several concrete segments. In several of these segments, a range of sensors were installed (Fig. 6), including:

- thermocouples
- vibrating wire strain gauges
- pressure and load cells
- displacement sensors
- piezometers

In 10 lining rings, thermocouples are inserted into 4 of their segments (Fig. 7). These measure the temperature at the intrados (inner surface), centre and extrados (outer surface) of the lining.

Four lining rings were instrumented with vibrating wire strain gauges (Fig. 8). Two types of strain gauges were used: vibrating wires and optical fibres. The vibrating wires were installed all around the intrados and the extrados. The optical fibres are placed in the longitudinal direction. These strain gauges are mounted on a support cage and placed in the mould for casting the concrete segments. The strain gauges measure the deformations that can be converted into stresses in the lining. Because this requires a thermal correction, the strain gauges are equipped with thermistors.

Load cells are placed in an opening in the segment extrados to measure the radial pressure exerted onto the gallery lining (Fig. 9). In addition, load cells are embedded in shorter segments (10 cm thick) to measure the circumferential stresses in the lining. These load cells are installed in three lining rings.

In the heated part of the PRACLAY Gallery, compressible materials are inserted between some segments of the lining rings. These materials should limit the stresses in the lining during the heating test. To measure the compression of these materials, potentiometer displacement sensors are placed over these materials in five rings (Fig. 10).

Finally, micro-seismic sensors and piezometers are placed against the clay through holes in the lining. The piezometers measure the porewater

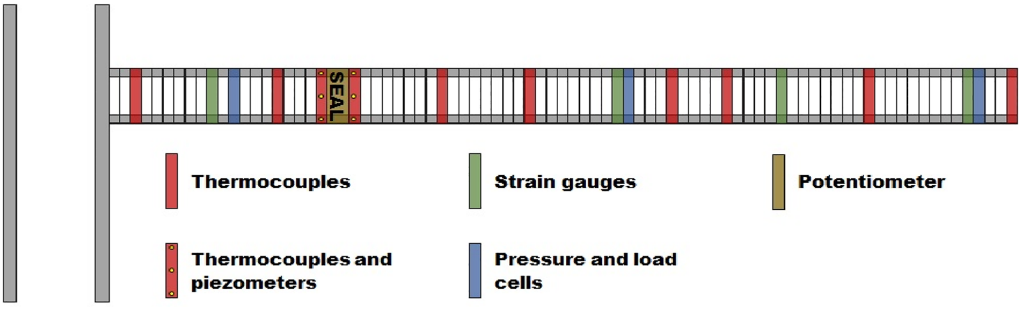

Fig. 6. Lining rings of the PRACLAY Gallery with sensors embedded in their lining segments.

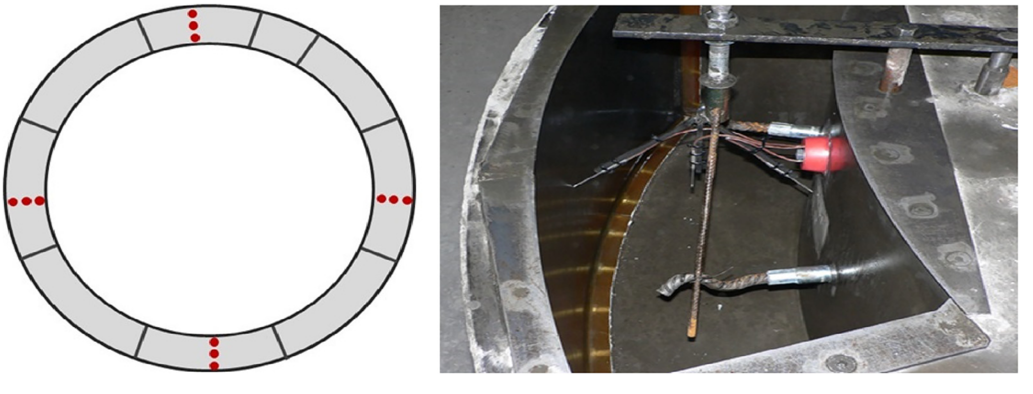

Fig. 7. Thermocouples are inserted at the intrados, centre and extrados of four segments in ten lining rings of the PRACLAY Gallery.

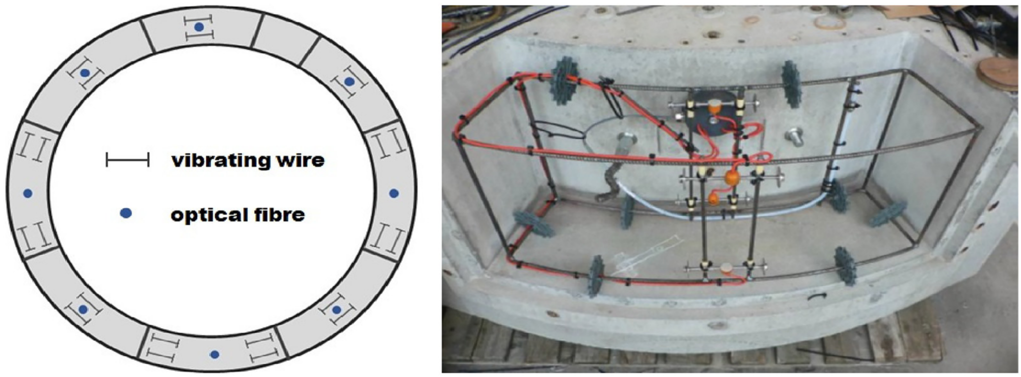

Fig. 8. Strain gauges (vibrating wire and optical fibre) have been fitted in the segments of four lining rings.

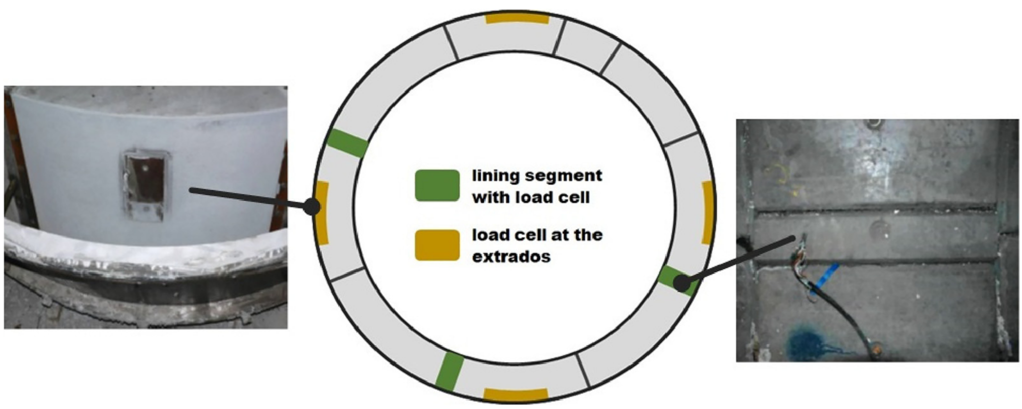

Fig. 9. Load cells have been placed at the extrados and between the segments of three lining rings.

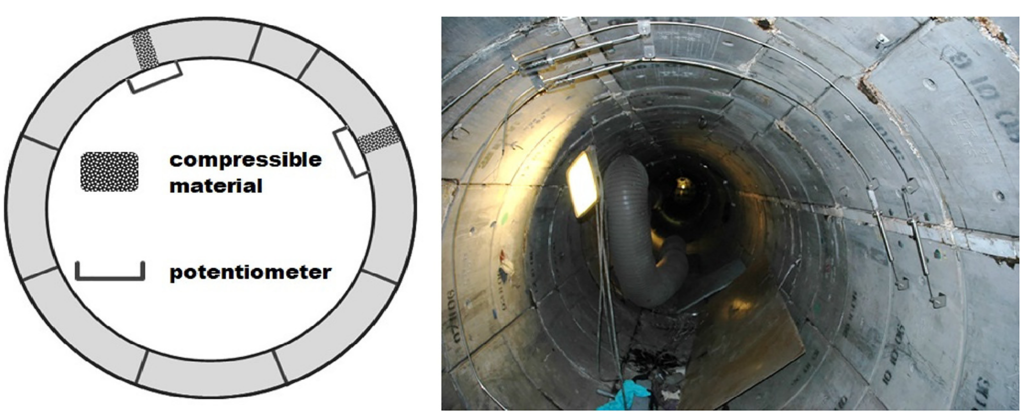

Fig. 10. Potentiometers have been placed over the compressible materials of five lining rings.

pressure on each side of the seal to verify seal performance.

Similar to the conditions of the PG instrumented boreholes, the elevated water pressure and temperature inside the closed part of the PG result in harsh conditions for the sensors installed in that part of the PG.

Instrumentation in the PRACLAY Seal

In order to monitor the behaviour of the bentonite in the PRACLAY seal, sensors were placed in the bentonite (Fig. 11). These sensors are all concentrated in three sections of the bentonite ring. The following sensors were installed:

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

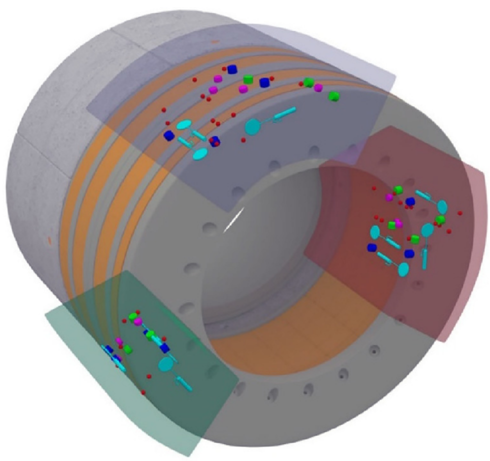

Fig. 11. The sensors in the bentonite seal are grouped into three sections of the bentonite ring.

These sensors were placed in some of the bentonite blocks that make up the bentonite ring. This was done by manually milling a recess in the bentonite where the sensor had to be placed (Fig. 12).

Instrumentation in the sand backfill

The heated part of the PRACLAY Gallery was backfilled with sand. The sand is saturated with water and switching on the heater was only done after the water pressure in the gallery is in equilibrium with the porewater pressure in the surrounding clay. Six filters are placed at the bottom of the gallery to artificially saturate the gallery (Fig. 13). Also, five vent filters have been installed at the top of the gallery to allow venting the air inside the gallery during the saturation of the backfill. Once the heating test was started, the saturation filters were used to measure the water pressure in the backfill and to take water samples for chemical characterization.

In addition, the heater cables were also equipped with thermocouples to watch over the thermal state of these cables. Finally, three fibre optic gauges, each 10 m long, were installed along the wall at the inside to check for possible overall elongation of the PG.

Instrumentation performance

The assessment methodology described above provided a basis for systematically assessing the performance of the many sensors used in the PRACLAY *in situ* experiment. The first instrumented boreholes for this experiment were installed in 2006. The heater was switched on in 2014, and the thermal regime reached its steady state (80°C at outside of PG lining) mid-2015, which is planned to last for 10 years. With the heating phase now halfway through, some conclusions can be drawn on the sensor performance with regard to the measurement of several variables.

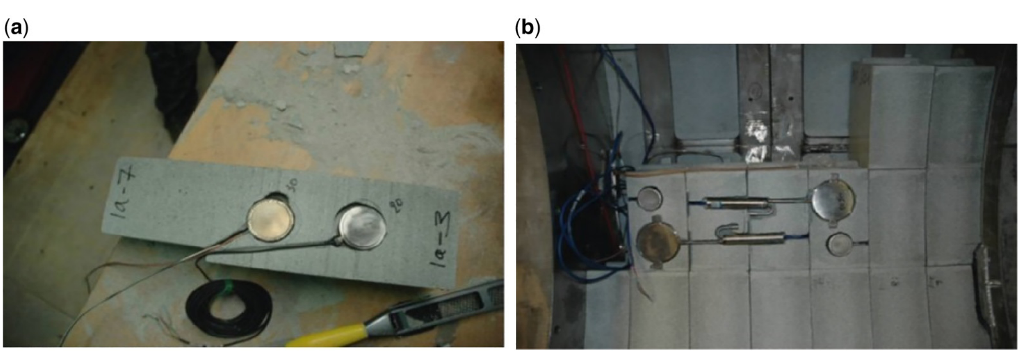

Fig. 12. (**a**) Seal bentonite block prepared with a filter (with integrated relative humidity sensor) and miniature pressure sensor. (**b**) Flatjack total pressure cells and filters inserted in the bentonite blocks.

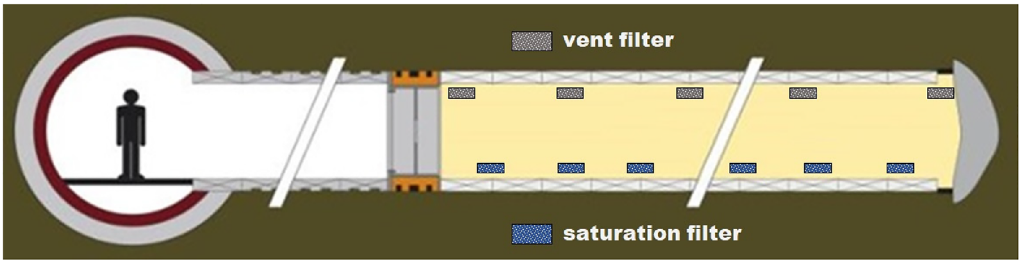

Fig. 13. Saturation filters placed at the bottom of the heated part of the gallery are used during the Heater Test for measuring the porewater pressure and extracting water samples.

In this paper, we give the principal results for the five categories for the main measurement variables (porewater pressure, total pressure, strain, temperature and displacement). All detailed results are reported by Verstricht *et al.* (2022*b*).

Porewater pressure

Four sensor sets measuring porewater pressures have been defined representing a total of 326 sensors. The actual pressure transmitters are in a different location than the measurement locations (this is where the filters are installed) and the complete measurement setup consists of the filters, the pressure transmitters and the capillary tubes connecting both components. The pressure transmitters remain accessible and are recalibrated annually, as explained further in the section on sensor characteristics. This results in a large dataset that makes it possible to verify the actual measurement characteristics, as well as their evolution over time.

Installation. A lot of experience is available with installing and using these types of sensors around the HADES URL. Problems were encountered for some upward boreholes that crossed a water-bearing layer (about 10 m above the level of the HADES URL). Because of the large water inflow and the resulting instability of the borehole, the casing with the instrumentation could not be installed in these boreholes. Apart from this issue, all other sensors could be installed at the planned locations, even for the longest instrumented borehole, which is 46 m long.

Installing instrumentation and determining the position of the sensors, however, becomes more difficult with increasing borehole length. The borehole is measured using a total station and a retro-reflector that is moved inside the borehole. This method requires an optical line of sight between both elements and can therefore only be applied to the borehole section where its deviation is smaller than the borehole diameter. The position of points beyond that depth needs to be determined by extrapolation, which creates larger uncertainties that could reach a few decimetres in the case of curved boreholes (in particular for the vertical position in horizontal boreholes). This can become an issue when assessing the measurements through model predictions as these assume a sensor with an exactly known position.

A few days to a few weeks after installing the piezometers, the filters were connected to the pressure transmitters. It was important to verify that the filter tubes were completely filled with water to avoid that entrapped gas would compromise the pressure readings. Sometimes the filter tubes were manually filled with water until the clay had converged around the filter. In other cases, the pressure transmitters were only connected after water outflow was observed from the capillary tubes.

Operation. All pressure sensors installed around the PRACLAY Gallery are still functioning and most sensors provide continuous and reliable measurements. Nevertheless, a few have been replaced with a sensor with an adapted measurement range. One reason was to cope with thermally induced pressure increases, while this range was decreased for some filters near the accessible gallery so that more accurate measurements are obtained (as accuracy typically depends on the measurement range).

Environment. All borehole piezometers are located in saturated Boom Clay, which is affected by the plastic deformation around the borehole (no packers or grouting are used for the installation). Due to its mechanical properties, this has no relevant influence on the hydraulic properties. Indeed, the properties can be characterized during the whole lifetime through permeability testing for instance. One sensor set has been installed in precompacted bentonite, where particular attention needs to be paid to some installation details, such as the saturation of the filter prior to installation.

Measurement quality. Based on an initial review of these measurements and numerical simulations of the porewater pressures, they are considered to give a representative picture of the actual conditions (i.e. porewater pressure field disturbed by gallery excavation, drainage and heating) in the Boom Clay.

Some, however, show pressure readings that seem unreliable. This could be caused by water leakage into the filter or capillary tubes. These components are in the PRACLAY Gallery and Boom Clay where there are higher porewater pressures due to the Heater Test. During the initial heating phase, the porewater pressures are higher inside the PRACLAY Gallery than in the surrounding clay. It cannot be ruled out that water from the gallery is pushed into the borehole casing and leaks into the filters, for example through glued connections, which were established between the separate casing segments during the installation of the instrumented casing into its borehole. This is a clear example that instrumentation designed with an open and accessible environment in mind, such as the Connecting Gallery, cannot be implemented in conditions imposed by the PRACLAY *in situ* experiment. The experience gained with PRACLAY has provided some suggestions for improvement, such as sealing the inside of borehole casings. After all, an open (water-filled) volume should be avoided as much as possible as it can cause water circulation, thereby influencing temperature measurements and worsen the consequences of possible leaks in the casing (e.g. due to a non-hermetic assembly between two casing segments).

Another problem occurred for the sensors installed in the seal. These porewater pressure sensors are also equipped with a relative humidity probe. It appeared that the humidity probe was not designed for hermetically sealed environments, as water leakage occurred along the signal cable. Because of this setup, no hermetically closed system was obtained showing irregular porewater pressure measurements.

The complete setup – filter, capillary tubes and pressure transmitter – is sensitive to temperature variations. This can be seen in the porewater pressure readings of sensors whose tubes are close to the heater cables. Every few days these heater cables are alternately turned on and off. This affects the porewater pressure measurements of the sensors whose capillary tubes are next to the heater cables (Fig. 14).

Sensor characteristics. The transmitters are regularly calibrated by applying a pressure cycle (pressure increasing from atmospheric pressure to maximum range, followed by pressure decrease). A pressure calibrator is used to perform this calibration at high accuracy. The transmitter outputs are recorded at 11 points in each direction. This results in a set of (signal output, pressure) measurements, on which a linear regression is applied, which can be considered as the ideal line for each sensor. Each calibration then allows us to determine how the actual sensor output deviates from this ideal line, showing some hysteresis and non-linearity (Fig. 15). The overall

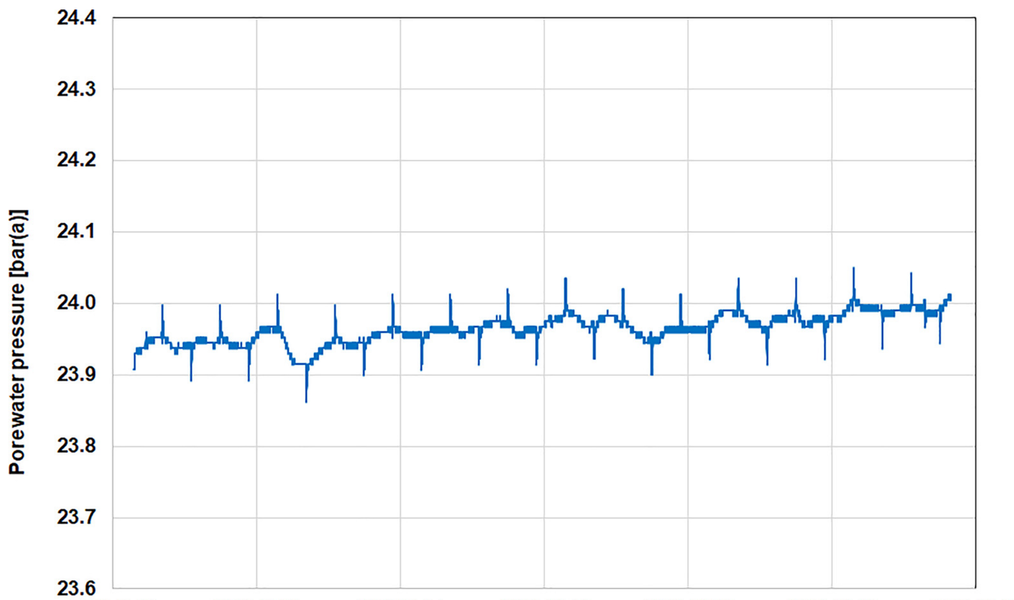

Fig. 14. Variations in porewater pressure readings coincide with the periodic on and off switching of the primary heater cables.

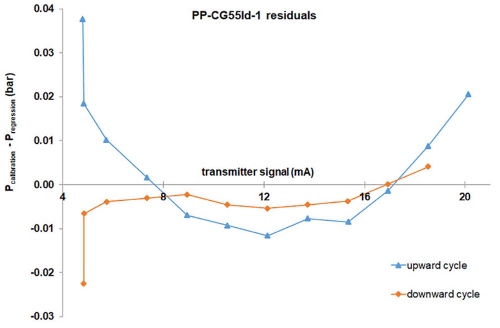

Fig. 15. Calibration allows us to determine the residuals (difference between actual pressure and pressure calculated through the linear formula) both at increasing and decreasing pressure within the calibration cycle.

deviations are generally well within the accuracy limits (in this case 0.006 MPa). Detailed analysis allows us to identify quality differences between different brands, and even production lots (based on the serial number). The calibration formula that needed to be applied (to convert the transmitter output into a pressure) remained fairly stable over the years, as no clear trend or drift could be observed.

Expert judgement. While in general the good performance of previous implementations of the piezometer boreholes was confirmed, its application in a thermal field showed some particular effects on the pressure measurements. The most important issue for application in a DGR context is, however, its invasive nature.

Total pressure

A large difference was observed in the performance of the different sensor types measuring total pressures. Six sets of sensors have been defined.

Installation. The installation of the total pressure devices went smoothly, as they were integrated mostly in general devices (e.g. flatjack based total pressure devices integrated at the deep end of the piezometer borehole casing). Recesses in the bentonite allowed flatjacks and miniature pressure sensors to measure the swelling pressure inside the seal.

Operation. Table 2 shows the number of sensors that failed for each sensor set, demonstrating the differences in performance between the different sensor types. For the sensors installed in the gallery lining, the environment clearly affects their performance too as only the sensors installed in the lining of the heated gallery section have failed. Most probably, the saturated environment and high water pressure (almost 3 MPa) in addition to the elevated temperature have caused these failures through water ingress at the cable connections. A design improvement would therefore be avoiding such connections in a saturated environment.

The impact of the temperatures and pressures also appears from the timing of failure. Most sensor failures occurred during the first three years of the PRACLAY Heater Test (Fig. 16).

Environment. Depending on the sensor set, the sensors were subjected to different conditions. While the measuring surface was usually in contact with the saturated clay, some sensors had their cabling submerged in the pressurized and heated environment of the PRACLAY Gallery.

Measurement quality. Valuable measurements were obtained in the seal, where the swelling pressure (due to the bentonite hydration) could be monitored rather well.

Despite the high failure rate of the sensors in the lining of the heated section, some important observations could be made. These sensors showed that the orthoradial stresses in the lining segments decreased during the Heater Test. This contradicted what was

Table 2. *Failures of the total pressure sensors*

	Number of sensors		Number of sensors failed		Failure percentage	
	total	heated part	total	heated part	total	heated part
Flatjacks CG boreholes	16	–	0	–	0	–
Flatjacks PG boreholes	20	–	10	–	50	–
Load cells lining PG	12	8	8	8	66	100
Flatjacks lining PG	9	6	6	6	66	100
Flatjacks seal	13	–	4	–	31	–
Kulite® seal	10	–	10	–	100	–
Total	**80**	–	**38**	–	**48**	–

CG, Connecting Gallery; PG, PRACLAY Gallery.

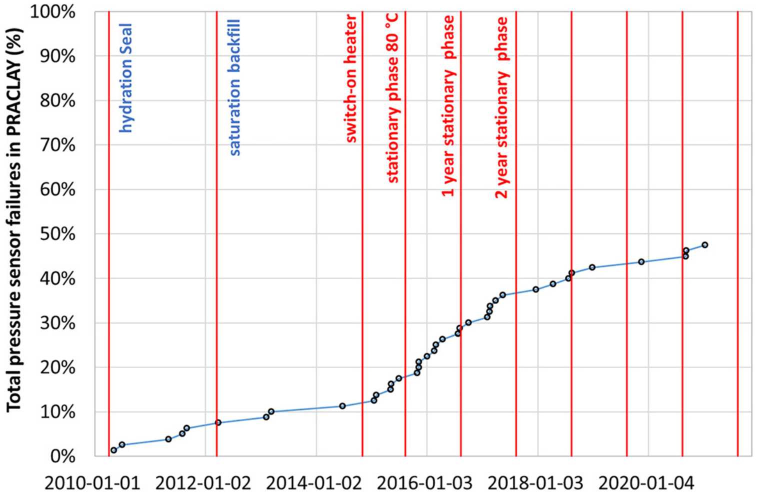

Fig. 16. Most total pressure sensor failures occurred during the first three years after the start of the PRACLAY Heater Test.

earlier assumed, namely that these stresses would increase with increasing temperature.

Measurement of total pressure in the host rock through instrumented borehole casings remains an issue, as the drilling operation needed for the installation significantly alters the stress field, which, in contrast with the porewater pressure field, recovers much less with time to the original values.

Sensor characteristics. The intrinsic accuracy of the sensors is mostly better than 1% of the full scale, which is more than sufficient considering the measurement uncertainty due to the installation.

Expert judgement. While total pressure monitoring in the host rock still needs to be improved, useful applications are currently mainly situated at interfaces and in engineered barrier system environments.

Strain

Two sensor sets cover the strain sensors: vibrating wire strain gauges embedded in the lining, and resistive strain gauges installed on a steel support structure at the outside of the gallery.

Installation. Installation of both sensor sets went rather smoothly. For the embedded vibrating wire gauges, experience from a previous application allowed for a near-perfect installation, while resistive gauges were installed using established practices.

Operation. The vibrating wire strain gauges that had been installed in the lining of the Connecting Gallery had been performing very well (Dizier *et al.* 2023). Only two out of 270 gauges failed over a period of 20 years. This excellent performance could unfortunately not be reproduced by the strain gauges installed in the lining of the PRACLAY Gallery. By the end of the heating up phase the first strain gauges in the heated gallery section started to fail. Five months later, all gauges had failed (Fig. 17). On the other hand, however, almost all strain gauges in the accessible (non-heated) part of the PRACLAY Gallery are still functioning. Although no exact explanation could be given up to now, the failures are more than likely related to the sustained, elevated temperature.

The resistive gauges could be read using a dedicated setup for this type of sensors. Monitoring indicated the lack of mechanical stress build-up, which could be confirmed by visual observations.

Environment. The heated and saturated environment of the PRACLAY Gallery exposed the vibrating wire gauges to harsh conditions, of which the elevated temperature may have caused the sensor failures. In addition, cable connections in this environment could not be avoided and might have contributed to the failures. This (as for many other sensors located in this environment) is to be confirmed during the dismantling of the setup.

Measurement quality. Mixed results were obtained for the strain gauges. For the vibrating wire gauges, the harsh environment in the heated part of the PRACLAY Gallery caused some deteriorating signals prior to failure, while clear signals and, hence, measurements are obtained in the accessible part of the gallery. Resistive gauges evolved from clear monitoring results to deteriorating values after several years.

Sensor characteristics. Strain gauges are typically characterized by a bulk calibration factor instead of

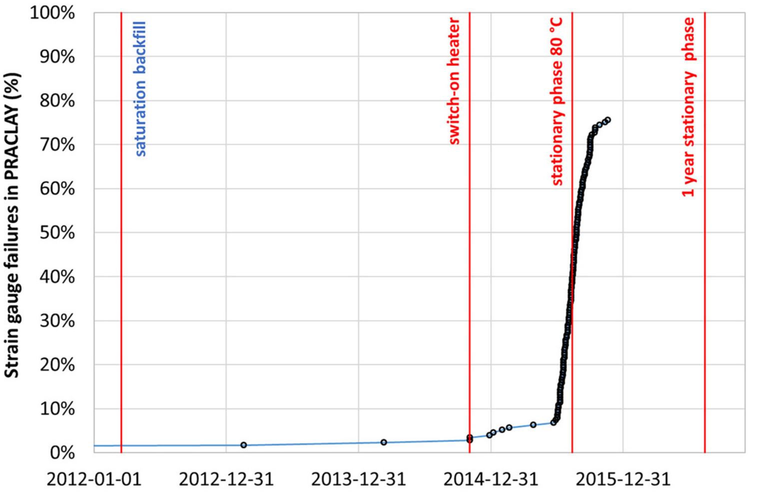

Fig. 17. The strain gauges in the heated part of the PRACLAY Gallery lining started to fail towards the end of the heating up phase.

an individual calibration. Comparing the measurement amongst each other (in particular where redundant installations exist) and with model predictions, it appears that the accuracy is sufficient to obtain a reliable picture of the strain evolution.

Expert judgement. Vibrating wire gauges can deliver reliable results for several decades. For elevated temperatures (in this case around 80°C), special designs are needed to guarantee longer-term performance. Resistive gauges on the other hand, are, even according to their manufacturers, not suited for measurement campaigns exceeding a few years.

Novel techniques for strain monitoring have popped up, most notably techniques based on fibre optics. These have not been applied in PRACLAY, but should definitively be considered for long-term monitoring in DGR conditions.

Temperature

The temperatures in the Boom Clay, the gallery lining, the seal and the backfilled gallery are measured using different types of temperature sensors.

The majority of the temperature measurements come from thermocouples. The rest of the temperature sensors are integrated in sensors measuring other parameters:

- thermistors in all vibrating wire sensors (strain gauges in the gallery lining, flatjack pressure sensors in the piezometer casings and in the seal);
- integrated circuit temperature sensors in the inclinometer electro-levels in the Boom Clay (above the PRACLAY Gallery);
- temperature-dependent resistances in the relative humidity (RH) sensors in the seal.

Two piezometer boreholes are equipped with an optical fibre for distributed sensing. The idea was to obtain a continuous temperature profile based on the Brillouin scattering; this measurement principle is based on the temperature dependency of this particular type of light scattering in an optical fibre.

Installation. Due to the small size of most sensors (of which many were also integrated in other sensors), the installation proceeded overall in a smooth way without relevant issues.

Operation. A total of 379 thermocouples were installed. These can be grouped into five sets whose performance is summarized in Table 3. Similar to the total pressure cells, the failure rate strongly depends on the location. The thermocouples with wiring inside the heated section of the PRACLAY Gallery were most affected, with elevated failure rates of up to 77% for the thermocouples installed inside PG piezometer casing. The failure rate started to increase after the temperature reached the stationary level of 80°C (Fig. 18).

The performance of the thermistors is closely linked to that of the strain gauge sensors and flatjack sensors in which they are integrated. As a result, most sensors with wiring running inside the heated section of the PRACLAY Gallery eventually failed. This confirms that cabling and cable connections are the most vulnerable part in saturated and pressurized conditions. Furthermore, the RH sensors cannot cope with saturated conditions and failed when their seal became saturated. When these sensors

Table 3. *Failures of the temperature sensors*

	Number of sensors		Number of sensors failed		Failure percentage	
	total	heated part	total	heated part	total	heated part
Piezometer CG boreholes	109	–	0	–	0	–
Piezometer PG boreholes	83	–	64	–	77	–
Thermocouples lining PG	120	84	44	44	37	52
Thermocouples heater	24	–	11	–	46	–
Thermocouples seal	43	–	2	–	5	–
Total	**379**	–	**121**	–	**32**	–

CG, Connecting Gallery; PG, PRACLAY Gallery.

failed, also the temperature sensors integrated in them stopped working. The inclinometer temperature sensors are still all functional.

The device used to read out the optical fibres (Brillouin optical time domain reflectometer) did not produce reliable temperature data. It required a more advanced interpretation of the reflected optical signal. Other applications of this measurement technique abroad (Vogt *et al.* 2012) indicate that an on-line calibration of the fibre (i.e. a section of the fibre is kept in two temperature-controlled baths) is needed to obtain meaningful and reliable temperature data. This complex set-up was not anticipated, nor specified by the instrument supplier, and hence was not further developed in PRACLAY.

Environment. The different sensor sets are subjected to the variety of environmental conditions present in PRACLAY. Thermocouples inside the piezometer borehole casings installed from the main access gallery (Connecting Gallery) are subjected to dry conditions, while thermocouples integrated in the lining segments have their signal cable running through the heated and saturated PRACLAY Gallery.

Measurement quality. To illustrate the complexity of defining the measurement quality and the exact failure date, the signals of the thermocouples installed in the piezometer casing PG50S (which is the horizontal piezometer installed from the PG in the middle of this gallery) are illustrated in Figure 19. Signals can start drifting from the expected value, noise can appear, or sudden changes to a new (more or less stable) value can be detected. Sensor readings that do not give representative measurements could, however, still be valuable, as they could give an indication of the failure cause, such a failing sensor cable connection. Such a failing connection could result in readings that do not give the temperature at the location of the thermocouple, but at the location of the failing connection. In this case, the

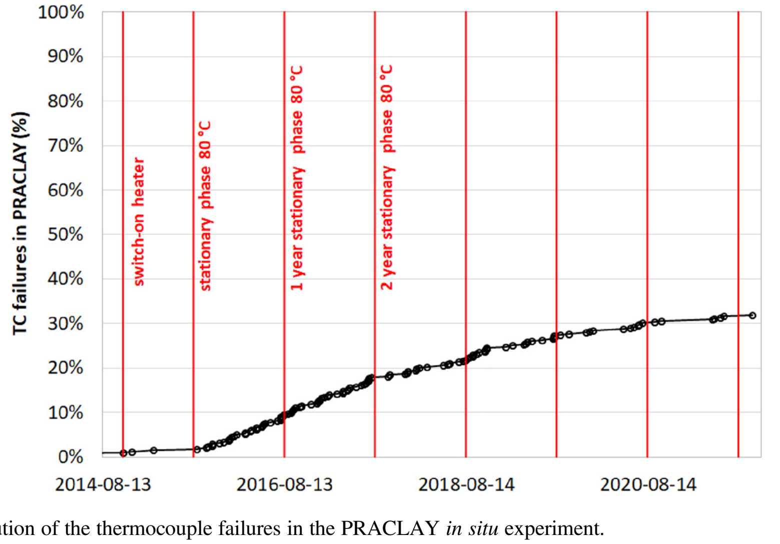

Fig. 18. Evolution of the thermocouple failures in the PRACLAY *in situ* experiment.

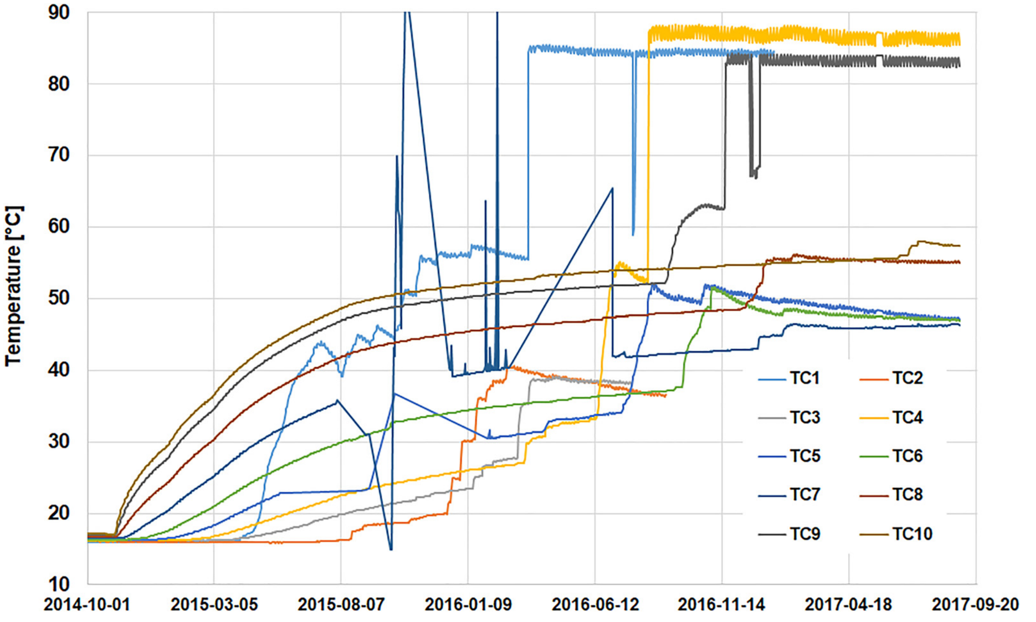

Fig. 19. Example of thermocouple (TC) data showing the complexity of defining measurement quality and the failure date. Some thermocouples show a new semi-stable reading around 85°C, which is the temperature at the inside lining of the PRACLAY Gallery.

thermocouples are installed inside the piezometer casing, but with extension wiring that runs along the inside of the heated part of the PRACLAY Gallery. When this thermocouple does not show values that can be expected inside the clay, but rather resembles the temperature inside the gallery of around 85°C (in Fig. 19, three thermocouples show this behaviour), this can indicate that a connection inside the gallery has failed. Such a failure could have created a shortcut at this connection (e.g. due to water ingress) and a new hot (or measurement) junction replacing the original (deeper) junction. It indicates the usefulness of maintaining the recording of the raw signals, even if they are at first sight not representative anymore.

Sensor characteristics. Within PRACLAY, different resolutions were also obtained for the thermocouple measurements, depending on the data acquisition system. For the thermocouples in PRACLAY, type T was selected. This type has a rather limited temperature range (safe upper limit of 300°C, but usually limited to lower temperatures depending on the cable type) compared to other types, but which is still largely sufficient for the experimental conditions of the PRACLAY setup. On the other hand, its accuracy of 0.5°C is the best of all thermocouple types. With this accuracy, it was considered sufficient to have temperature values read with a resolution of 0.1°C (according to the specifications of the selected data-acquisition system, the MX100 from Yokogawa). However, it has been observed that for slowly evolving temperatures, this can result in a stepped graphical representation. When data acquisition equipment with a better resolution is used (in this case, a Campbell Scientific CR1000X with a 24-bit analogue-to-digital conversion), smoother graphs are obtained. It indicates that the notion of ‘accuracy’ encompasses several factors, such as a systematic component (which typically remains constant over a limited range) and repeatability, which is much smaller and is not or hardly noticeable in the measurements. For type T, the repeatability has been shown to be less than 0.1°C (Wang 1989), and a resolution better than 0.1°C is therefore recommended.

Expert judgement. Point measurements based on sensors such as thermocouples, platinum resistance sensors or thermistors offer reliable measurements if their installation (including extension cabling and cable connections) is compatible with the environment. Novel techniques based on fibre optic technology (in particular distributed sensing) offer promising perspectives as they offer a large number of measurement points with a minimal invasive effect. Their measurement performance needs, however, to be improved to allow hassle-free measurements over a long term.

Displacement

Two main sensing techniques to measure displacements have been applied in the Boom Clay around the PRACLAY Gallery: interferometric long-gauge fibre optic sensing (SOFO®) and in-place inclinometer (chain based on electro-levels as explained above). For the fibre optic sensors, 5 m long and 10 m long gauges were used. Although being rather a novel instrument, monitoring the radial displacement of the clay around the heated gallery could not performed by most conventional instruments, as it would imply the positioning of an (electronics filled) measurement head inside the heated (up to 90°C) and saturated (at a pressure up to 3 MPa) gallery.

Installation. Based on experience from the CLIPEX project, the inclinometer was installed using an additional casing to avoid the inclinometer casing from collapsing. This helped to install the inclinometer without any problems. For the SOFO gauges, an installation protocol was developed because no such protocol for installing these gauges in boreholes was defined by the manufacturer. This protocol consisted in embedding the gauges inside a flexible hose filled with a modified silicone polymer kit. This not only provided sufficient rigidity to install the setup, but also additional protection to the gauges. Nevertheless, one gauge failed during the installation.

Operation. The SOFO sensors suffered from a fragile construction. The connectors and the read-out devices that were located near construction activity, such as seal installation or gallery backfilling, had to be repaired or serviced frequently. Repairs consisted of fibre optic splicing, e.g. due to damaged connectors, while the read-out device (SOFO V from SmarTec) was sent back several times for repair. This resulted in an incomplete data series, which is more difficult to interpret. Some periods with more frequent readings are available (up to a few readings per day, when the read-out device functioned autonomously), while manual readings were taken at more irregular times, depending on the availability of the instrument or operators. Finally, these sensors failed when the water pressures exceeded 1.5 MPa.

Environment. Both the inclinometer and the SOFO sensors were installed inside the saturated clay. The inclinometer casing was, however, protected additionally by a steel casing for both mechanical and water-proofing reasons.

Measurement quality. The SOFO sensors provided measurements with a high resolution (1 µm over the complete gauge length of 5–10 m) and a high repeatability (differences between repeated measurements were limited to 2–3 µm).

Sensor characteristics. The SOFO sensors provided measurements with a high resolution (1 µm over the complete gauge length of 5–10 m) and a high repeatability (differences between repeated measurements were limited to 2–3 µm).

When interpreting the inclinometer sensor readings, it was noticed that the calibration of some sensors showed a low accuracy. As the inclinometer interpretation is based on an integration of individual level sensors, errors in previous sensors will accumulate when determining the vertical position or displacement at a certain location. This makes it difficult to obtain an accurate picture of the movement of the clay due to the excavation and heating.

Expert judgement. Displacement measurements in a poorly indurated clay such as the Boom Clay require specific attention, in particular when moving parts are involved. The fibre optic interferometric measurement principle proved to show readings with a high resolution and precision, showing its promising potential; its implementation, however, needs further improvement to make it a reliable long-term measurement technique for DGR conditions. Current inclinometer versions are now based on micro-electro-mechanical systems sensors, which have better measurement characteristics than the now outdated electro-levels. Traditional inclinometer designs require, however, invasive boreholes, limiting their use in a DGR rather to the edges of the monitored zones.

Conclusions

Thousands of sensors have been installed in the HADES URL. The PRACLAY *in situ* experiment alone accounts for about 1300 sensors. In addition to the measurements these sensors provide, this also generates a wealth of information about the performance of these sensors in conditions representative of those in a possible DGR.

ONDRAF/NIRAS recognized the importance of documenting these lessons learned and started a research project to evaluate the performance of the sensors installed in the HADES URL. This required developing a methodology to assess the performance of sensors in a consistent manner. The methodology identified a number of performance indicators that are grouped into five categories. The sensors themselves were grouped into 30 sensor sets. The assessment methodology was applied to the sensors installed in the PRACLAY *in situ* experiment.

The performance of the sensors was found depend on several factors. Some are intrinsic to the sensor, such as a fragile construction, but others are linked to the environment in which the sensor operates. The temperatures and pressures created by the PRACLAY Heater Test led to failure of some sensors. Particularly signal cable connections have proven to be sensitive to failure.

An extensive analysis of the calibration data from the pressure transmitters of the piezometers showed that sensor drift was minimal. Others factors affecting the sensor performance are linked to the demanding environment. For several sensors, such as the thermocouples, the measurement resolution depends on the data acquisition.

It has also become clear that instrumentation that functions well in an open and accessible environment such as the Connecting Gallery, does not automatically perform similarly under the conditions imposed by the PRACLAY *in situ* experiment. The experience gained with PRACLAY has provided some suggestions for improvement, such as sealing the inside of borehole casings.

The methodology to assess sensor performance can be used to build a database of sensors used in the HADES URL. The database will contain information about how the sensors are installed and used, the experimental conditions in which they operate and their performance. This will provide valuable input to the monitoring plans for future experiments and a possible future DGR.

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Author contributions **JV**: conceptualization (equal), data curation (lead), investigation (lead), methodology (equal), project administration (supporting), visualization (lead), writing – original draft (lead), writing – review & editing (equal); **DN**: data curation (supporting), investigation (supporting), visualization (supporting); **XLL**: resources (lead), supervision (supporting), writing – review & editing (equal); **DL**: project administration (lead), supervision (equal), writing – review & editing (supporting); **SL**: project administration (supporting), supervision (equal), writing – review & editing (equal); **MVG**: conceptualization (equal), funding acquisition (lead), methodology (equal), writing – original draft (supporting), writing – review & editing (supporting).

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