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Monitoring data from the EPSP plug test summary report

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ABSTRACT:

The aim of the DOPAS project is to address the design basis of, and reference designs and strategies for, plugs and seals to be used in geological disposal facilities. The Czech experiment "Experimental Pressure and Sealing Plug" (EPSP) is aimed at the study of developments concerning the design basis, reference designs and strategies including compliance issues.

The EPSP plug has been designed as a prototype plug for a future Czech deep geological repository. It is expected, therefore, that similar plugs will be required to function throughout the whole of the operational phase of the repository, i.e. 150 years with an expected over-pressure of up to 7MPa.

The D4.6 "Monitoring data from the EPSP plug test summary report" provides information on the monitoring data gathered during the erection and subsequent conducting of the experiment.

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2. INTRODUCTION

The aim of the DOPAS project is to address the design basis of, and reference designs and strategies for, plugs and seals to be used in geological disposal facilities. The Czech experiment "Experimental Pressure and Sealing Plug" (EPSP) is aimed at the study of developments concerning the design basis, reference designs and strategies including compliance issues.

The EPSP plug has been designed as a prototype plug for a future Czech deep geological repository. It is expected, therefore, that similar plugs will be required to function throughout the whole of the operational phase of the repository, i.e. 150 years with an expected over-pressure of up to 7MPa.

Furthermore, the plug has been designed as a multilayer system consisting of two main structural elements which ensure the overall stability of the system, i.e. concrete blocks and a sealing element - a bentonite section positioned between the concrete blocks. Fibre shotcrete was used in the construction of the various elements of the EPSP; the bentonite sealing section was constructed by means of compaction and spray technology.

The plug will be tested by means of injecting air/water/a suspension into a pressurizing chamber followed by the monitoring of the performance of the plug. As a result of the geological conditions within the EPSP experimental drift at the Josef underground laboratory, it was necessary to employ grouting so as to reduce the permeability of the rock mass prior to the commencement of the EPSP plug experiment.

The primary aim of the monitoring of EPSP is to investigate the various processes underway inside each plug component, to verify component behaviour and to assist in assessing their performance in order to build a knowledge base for the construction of a future repository plug.

The key processes and locations inside EPSP have been identified and sensors have been specially selected in order to capture them. The monitoring of EPSP focuses on water movement within the experiment and the response of the experiment to pressurisation.

One of the integral elements of the monitoring process consisted of the presentation of measurement data for further analysis; therefore, the data was made instantly available online to end-users via a simple web interface.

The D4.6 "Monitoring data taken from the EPSP plug test summary report" provides information on the monitoring data gathered during the erection and subsequent conducting of the experiment.

2.1. EPSP

It was not intended that EPSP would take the form of a specific DGR plug or seal; rather it was built at a similar scale to a disposal tunnel plug and will contribute specifically towards the development of a reference design for such structures. The objective of the EPSP experiment is to test both the materials and technology to be used for implementation, rather than to test the design and performance of the reference disposal tunnel plug. At this early stage in the Czech geological disposal programme (SÚRAO 2011), more than 50 years prior to the scheduled commencement of operation, it is considered by those involved more important to build knowledge and experience rather than to refine implementation designs for an, as yet, unidentified site with unknown mechanical, hydrogeological and chemical characteristics.

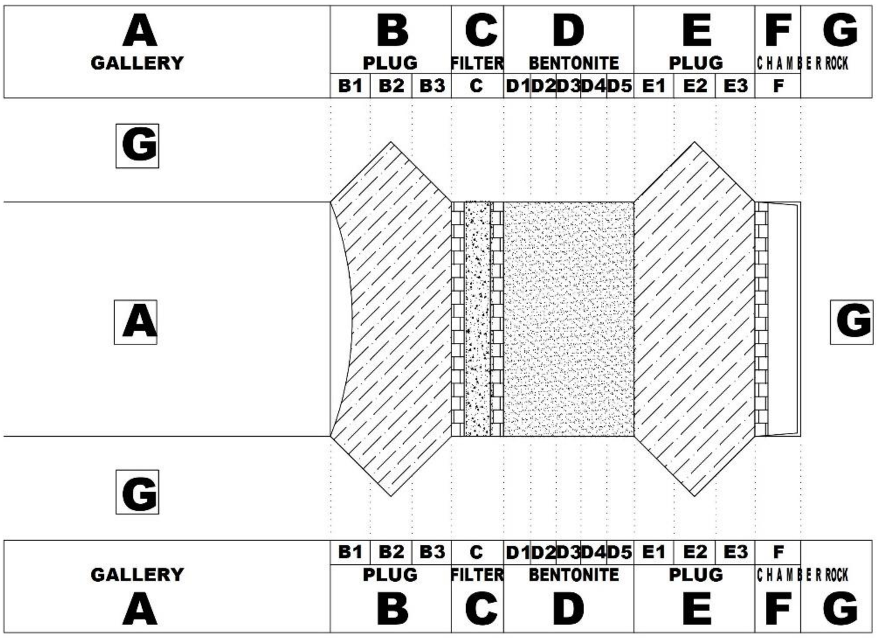


Figure 1 - Scheme of EPSP

The EPSP experiment represents the first occasion on which SÚRAO has carried out detailed work on plugs and seals. The conceptual design for the EPSP experiment includes the following components (see DOPAS deliverable D2.1):

- Pressure Chamber: The pressure chamber (or injection chamber) consists of an open area that can be used to pressurise the inner concrete plug. The chamber contains an inlet valve and a drain valve that can be used to fill the chamber with air (gas), water or bentonite slurry. The chamber was designed to be as small as possible so as to allow the pressure to be readily controlled. The pressure chamber is sealed with a waterproofing finish.

- Concrete Walls: Concrete walls (made up of blocks) were used so as to facilitate the construction of the EPSP experiment. Three concrete walls were built in total: the first between the pressure chamber and the inner concrete plug, the second between the bentonite and the filter, and the third between the filter and the outer concrete plug.

- Inner Concrete Plug: The inner concrete plug forms one of the sealing components of EPSP and was constructed using sprayed glass-fibre concrete. The fibre concrete is of relatively low pH.

- Bentonite Pellets: The bentonite pellet zone comprises B75 bentonite, i.e. a natural and high-smectite content Ca-Mg bentonite with notably high iron content in the octahedral layer of the smectite. The purpose of the bentonite is to seal and absorb/adsorb any water that leaks across the inner concrete plug. The bentonite zone is 2m long.

- Filter: It is intended that the filter will collect any water that is not absorbed by the bentonite. This is most likely to occur if the leakage rate across the inner concrete plug is sufficient for the piping and erosion of the bentonite to occur. The filter may also be used to reverse the direction of pressurisation of EPSP.

- Outer Concrete Plug: The outer concrete plug is designed to hold the other components of EPSP in place. However, should the direction of pressurisation of EPSP be reversed, the outer concrete plug will have to perform under the same conditions as the inner concrete plug, and, therefore, the requirements concerning the outer concrete plug are the same as those of the inner concrete plug. The outer plug was built in the same manner as the inner plug and is identical to it.

2.2. LOCATION OF EPSP

The EPSP experiment was constructed at the Josef underground laboratory. The EPSP experimental plug itself is located in the M-SCH-Z/SP-59 niche. The measurement system technology and the data loggers are located in the nearby M-SCH-Z/SP-55 niche.

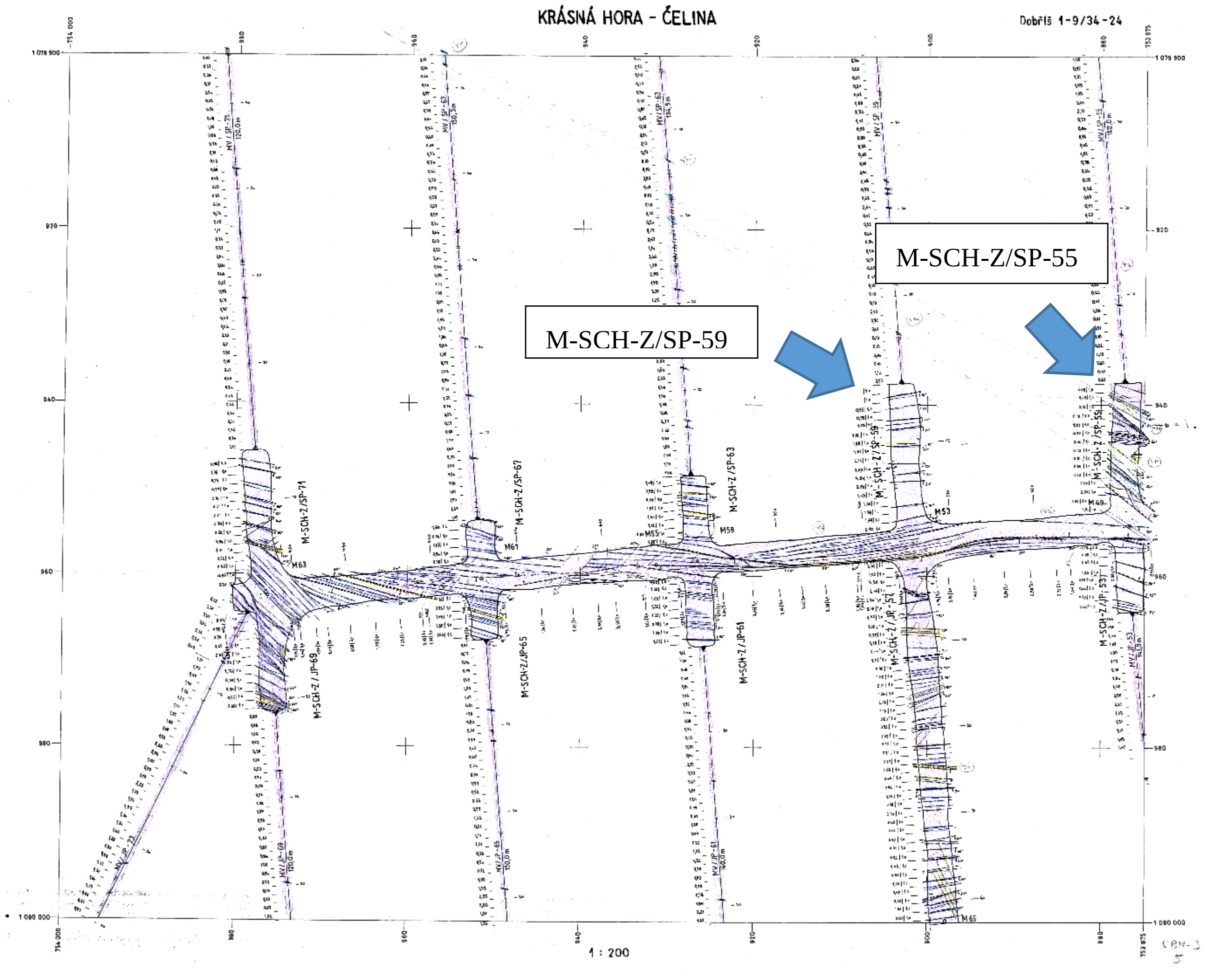


Figure 2 - EPSP location

2.3. **MONITORING OF EPSP**

The primary aim of the monitoring of EPSP is to investigate the various processes underway inside each plug component, to verify component behaviour and to assist in forming an assessment of the performance of the various components in order to build a knowledge base for the construction of a future repository plug.

The key processes and locations within EPSP were identified and sensors specially selected in order to capture those processes. The monitoring of EPSP is focused on water movement inside the experiment and the response of the experiment to pressurisation.

Water movement within the experiment is monitored in terms of water inflow, water content distribution within the bentonite seal and water (pore) pressure distribution.

The mechanical response of the plug is monitored by means of strain gauges installed at key locations in the concrete plugs and instrumented rock bolts positioned within the rock mass. Moreover, contact stress measurement is deployed between the rock and the plug.

Temperature distribution is monitored since it is important not only to form an understanding of the hydration heat generated through curing, but it is also used as a reference base for sensor compensation during the loading of the experiment.

An integral element of the monitoring process consisted of the presentation of the measured data for further analysis; therefore, the data was made instantly available online to end-users via a simple web interface.

2.4. **MEASUREMENT SYSTEM**

The data acquisition and monitoring systems are based on components previously developed and used at the Czech Technical University in Prague (CTU), Centre of Experimental Geotechnics (CEG) (Pacovský et al. 2006, 2010; Levorová & Vašíček 2012, Vašíček & Svoboda 2011).

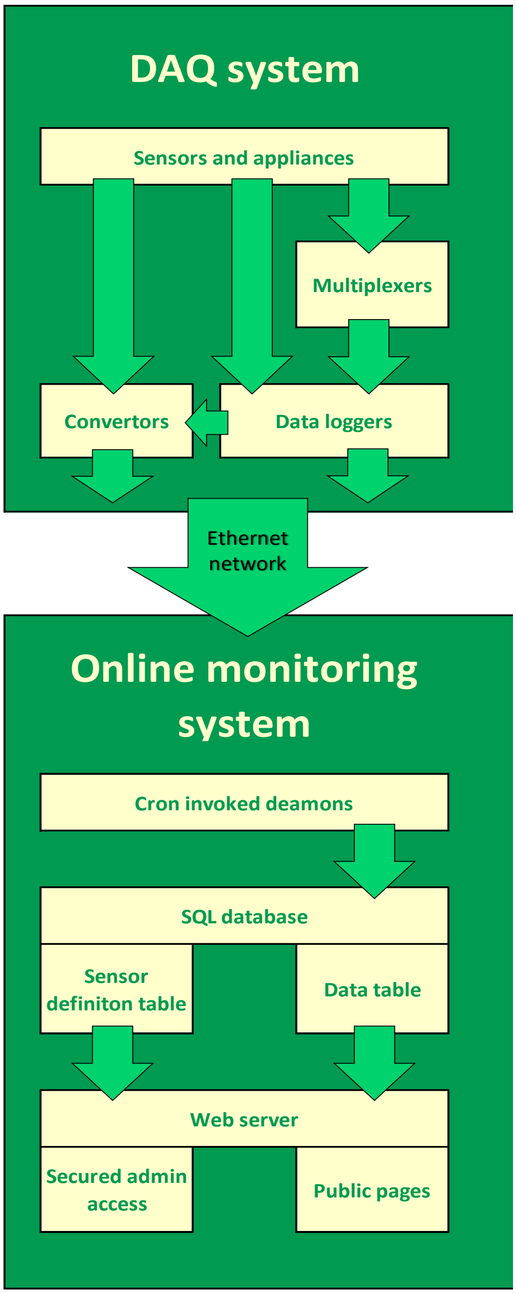


Figure 3 - EPSP measurement system

The system has two main elements: the data acquisition system (DAQ) and the online monitoring system (Figure 3). The DAQ makes up the main hardware element and is responsible for the actual taking of measurements. The online monitoring system is responsible for data collection, storage and presentation to end-users.

2.4.1. Data acquisition system

The data acquisition system (DAQ) is responsible for measurement performance and the preparation of data for the monitoring system.

The DAQ has two key components: sensors and data loggers/convertors.

Sensors

The sensors used for DOPAS EPSP were selected in order to capture important processes at work within the experiment – focusing on the monitoring of water distribution, pressure, deformation and temperature. Wherever possible, sensors based on different principles were used to measure the same phenomena in order to enhance overall data reliability.

The following sensors were employed:

- Temperature –DS18B20 digital thermometers, analogue LM35DZ and NTC resistors
- Water distribution – EE071 relative humidity sensors and 5TE TDR sensors
- Pressure – 4810X-10MPa VW pressure cells and 4500SHX-10MPa piezometers
- Deformation – VW strain gauges (4200A-2) and instrumented rock bolts (4911-4X)

Moreover, the pressurisation technology was monitored including water inflow into the experiment.

Figure 4 - temperature sensor in a protective housing

Figure 5 - RH sensor including cabling protection

Figure 6 - Sensors ready to be fixed into the assembly

Figure 7 - Cable head preparation

The preparation of the sensors was carried out in the workshop of the Josef URC facility and, following assembly, were equipped with protective stainless steel tubing (Figure 4 and Figure 5). The complete assemblies were then transferred to the underground complex once the plug had been constructed. The sensors were either installed in their final positions underground or temporarily stored on the side of the experimental niche until their final locations were ready for installation.

The sensors were positioned within the experiment in the form of profiles (Figure 1) so as to enhance future orientation.

Data loggers/convertors

Three main types of data loggers are employed in the DAQ system:

- The Campbell Scientific CR1000-based system
- GeoKon LC2x16
- CTU in-house built data loggers for the digital thermometers

Moreover, several media convertors were used to connect the digital sensors directly to the DAQ network.

2.4.2. Online monitoring system

The online monitoring system was designed as part of the CEG's overall DAQ and monitoring system. From the point of view of hardware, it consists of a heterogeneous collection of various sensors, data loggers, network infrastructure and servers on top of which is located the software stack which features two main components: the backend and frontend. Mainly open source programs are used within the system.

Backend

The backend is responsible for data collection and storage. Data collection is handled by a set of daemons each of which is custom built to fit a specific data logger or digital sensors/equipment.

These daemons are responsible for data collection, data format transformation and storage in the open source MariaDB SQL database. They typically run at 10-minute intervals (using Cron) so as to ensure the collection of the very latest data.

Frontend

The frontend is the most visible part of the system since it is the part with which the user interacts. The frontend is web based and runs on an nginx (http://nginx.org/) web server; it consists of a specialised web site written in the php programming language and JavaScript.

The system pulls all the necessary data from the backend database and presents it to the user and, moreover, the system rapidly calculates results for the user from the raw data. The results of calculations are cached and held in a separate database in order to speed up the system and to reduce system processing power requirements; this significantly reduces system overheads.

The website provides online information on the status of the experiment and the simple data visualisation interface (2D charting and 3D visualisation). For more comprehensive analytical purposes direct data export is available using specialised URLs.

2.5. **EPSP ERECTION**

EPSP installation can be divided into 5 tasks:

- Task 0 - Niche preparation and documentation – work performed by the CTU and SÚRAO
- Task 1 - work performed by SÚRAO with assistance from a subcontractor
  - Rock reshaping and improvement
  - Instrumented rock bolts
  - Connecting boreholes
  - Plug contact grouting
- Task 2 - work performed by the CTU with assistance from a subcontractor
  - Construction work (shotcrete, support structures, filter, etc.)
  - Technology
- Task 3 - Bentonite sealing – work performed by the CTU
- Task 4 - Monitoring – work performed by the CTU

Task 0

Task 0 work commenced at the very beginning of the project in order that the niches (MS4 – end of 2012) be selected as soon as possible and so as to allow the commencement of related work. Once the niches had been selected, work began to prepare them for Task 1.

Detailed geological mapping was performed and in the first part of 2013 the niches were prepared for preparatory construction which included the removal of excess material, cleaning and the installation of utility networks (water, electricity, the data network, lighting and ventilation).

Subsequently, (i.e. prior to the installation of the technological equipment) part of the floor of the technology niche was concreted so as to provide for the easier and safer installation of the technological equipment.

Task 1

Work on Task 1 commenced in October 2013. Work began with the reshaping of the experimental niche followed by rock grouting in the upper part of the niche. Once the upper part had been grouted, the lower part was treated in a similar way. In parallel, the interconnecting boreholes were drilled, cased, equipped with cable heads (selected boreholes) and grouted; instrumented rock bolts were then installed. This phase encountered significant delays and lasted a total of 12 months, reaching its conclusion in October 2014, further delaying the start of the work planned for Task 2.

The remaining parts of Task 1 work (contact grouting) were carried out between the various technology installation stages of Task 2 and following the completion of Task 2 work.

The contact grouting of the inner plug took place in the period December 2014 to May 2015 and of the outer plug in July-August 2015.

Task 2

Work on phase 2 commenced with the installation of piping in the pressurisation chamber and chamber size adjustment in October 2014 (reshaping via the use of shotcrete).

The inner plug was erected in a non-stop run of 23 hours on 12/13 November. During the curing period of the inner plug, the filter piping was installed and the first part of the filter was erected (the lower 1/3) so as to be ready for bentonite emplacement.

Once the plug had sufficiently cured, pressure testing was performed in December 2014. Based on the results of testing, it was decided that contact grouting would have to be applied. Work on Task 2 was therefore suspended and the site handed back to the Task 1 supplier for grouting.

Grouting was completed in May 2015 thus leaving a very short time for bentonite emplacement and the erection of the filter and plug. Once the grouting work was concluded, the filter was erected stage-by-stage according to the progress of Task 3 work (bentonite emplacement).

Immediately following the completion of the filter, preparations for the erection of the outer plug commenced including the installation of the grouting ring. The outer glass fibre shotcrete plug was erected in a non-stop run of 24 hours on 19/20 June 2015.

Work on the technological equipment was conducted in parallel with ongoing construction work. The technological equipment was first prepared at the supplier's premises and installed in the Josef underground facility in February 2015; it was then tested and subjected to a full pilot run in July 2015.

Task 3

Task 3 work was performed primarily by the CTU which allowed for work on the preparations for this task to be conducted in parallel with work on Task 2.

The properties of the materials were verified, the pellet production system was selected and the emplacement technology was tested and fine-tuned by means of laboratory research work *(Vašíček et al., 2016 – D3.21).*

Collaboration with bentonite pellet producers was established and, subsequently, the production of the selected material commenced.

Emplacement was conducted in the period 9 to 15 June 2015 by the CTU.

Task 4

Work on monitoring began soon after the launch of the project with the design of the monitoring equipment. Subsequently, the monitoring system was constructed stage-by-stage principally by the CTU instead of a subcontractor as originally planned. Again, this allowed for working on the monitoring system in parallel to other work under way.

The various components of the monitoring system were first prepared and assembled at the Josef facility's own workshop. Subsequently, as construction work progressed, the system was gradually installed in-situ.

Work was concluded by the integration of all the parts of the system (including the technological equipment) into the Josef underground laboratory's measurement system once the construction work was completed and following the successful conclusion of pilot operation.

2.6. EXPERIMENTAL RUN

The conducting of the experiment proper commenced on 21 July 2015. The original experiment loading plan consisted of the injection of water into the pressurisation chamber with a gradual increase in pressure (accompanied by the possibility to inject water into the filter and reverse the direction of flow if necessary). The injection of a bentonite slurry was also planned.

However, on the basis of the results obtained during the initial part of the experimental phase, the plan had to be altered. The updated conducting of the experiment was divided into 5 phases based on the character of the loading of the experiment:

- Phase 1 – water injection into the pressurisation chamber
- Phase 2 – saturation of the bentonite core (water injection into both the filter and the chamber)
- Phase 3 – water injection into the pressurisation chamber
- Phase 4 – bentonite slurry injection into the chamber
- Phase 5 – water injection into the pressurisation chamber

Phase 1

The conducting of the experiment proper commenced with water injection tests at lower pressure levels, which was followed by higher pressure level testing. One of the higher pressure tests led to the flushing out of traces of bentonite at one stage; the origin of the bentonite could not be accurately determined although two potential sources were considered: the filter, which may have become contaminated with bentonite during the emplacement of the bentonite seal (especially during the shotclaying process); or the erosion of the bentonite seal during the pressurisation of the experiment.

The character of the flow and the bentonite content indicated that water probably travelled for some time along a fracture (opened by the high level of pressure) in the rock mass before entering the filter structure. The greater part of the bentonite detected was therefore most likely to have proceeded from the filter (contamination flushed out by water).

However, as a precaution testing was interrupted and it was decided that the bentonite core at least should be saturated using the filter and the chamber, thus resulting in the alteration of the experimental plan.

Phase 2

Phase two focused on the saturation of the bentonite core; water was simultaneously injected into the filter and the pressurisation chamber.

In addition to the saturation of the bentonite, it also allowed for the testing of the outer concrete plug. The plug was unilaterally loaded from the inner side by means of the pressure within the filter with no support from the opposite side (higher extreme load state than the inner plug).

Phase 3

Phase 3 was performed with the intention of checking the state of EPSP, i.e. the influence/success of saturation phase 2. Moreover, it served as a baseline prior to the injection of the bentonite slurry.

Phase 3 consisted of the injection of water into the pressurisation chamber and fully drained filter.

Phase 4

Phase 4 was designed to test the effect of slurry injection; slurry was injected into the pressurisation chamber at various (increasing) pressure levels.

At the end of phase 4 the slurry was removed from the chamber and the chamber was cleaned (residues were flushed out using clean water).

Phase 5

Phase 5 in a sense consisted of the continuation of phase 1 – i.e. the original experimental plan. Water was injected into the pressurisation chamber only, the filter was fully drained and water leakage was measured. Pressure was increased in a step by step manner.

Table 1 - Experimental phases

Phase	**Start**	**End**
Phase 1 – Water injection into the chamber	21-07-2015	13-08-2015
Phase 2 - Saturation phase (water injection into the chamber and filter)	25-08-2015	29-02-2016
Phase 3 - Water injection into the chamber	07-03-2016	12-03-2016
Phase 4 - Injection of bentonite slurry into the chamber	15-03-2016	17-03-2016
Phase 5 - Water injection into the chamber	22-03-2016	Still underway

3. MONITORING DATA FROM EPSP INSTALLATION

The demonstration of EPSP construction forms one of the key outcomes of the project; therefore, the close monitoring of the erection process itself was essential.

Monitoring commenced prior to construction work via sensors placed inside the rock mass. The remaining sensors were gradually installed according to the progress of the construction of the experiment, i.e. sensors were connected to the system prior to each stage of construction and installed in their final positions either at the same time or later as conditions allowed (the sensors inside the various EPSP components).

The schedule of the various installation phases is provided in Table 2. The table also shows which data is considered important in any particular phase and which is presented in the following chapters.

Note: Data was taken from all the installed sensors (typically in 10-minute intervals) and is available for further use.

Details of the testing of the tightness of the inner plug – pressure and inflow (using a temporary pressurisation system for the first tests) are provided in Table 3 and Figure 8.

The dates of the grouting of the inner and outer plugs are provided in Table 4.

Table 2 EPSP installation - monitoring

Phase	**Start**	**End**	**Duration of phase (days)**	**Focus on**
Pressurisation chamber adjustment	27.10.2014	27.10.2014	1	Temperature evolution
Inner plug erection	12.11.2014 19:50	13.11.2014 18:30	1	Temperature evolution Deformation (shrinkage) Contact stress
Bentonite sealing and filter erection	5.6.2015	14.6.2015	9	Water content Pore pressure Total pressure
Outer plug erection	2015-06-19 12:00	20.6.2015 12:00	1	Temperature evolution Deformation (shrinkage) Contact stress

Table 3 - Leakage tests of the inner plug (injection into the chamber)

Date	Test media	Pressure
3.12.2014	water	<1 bar
7.1.2015	water	4
19.1.2015	water	<1 bar
20.1.2015	water	<1 bar
21.1.2015	water	<1 bar
26.1.2015	water	<1 bar
9.2.2015	water	<1 bar
16.2.2015	water	4
18.2.2015	water, air	<1 bar (water)
9.3.2015	water, air	<1 bar (water)
14.5.2015	water	<1 bar
18.5.2015	water	5
21.5.2015	water	5
28.5.2015	water	5

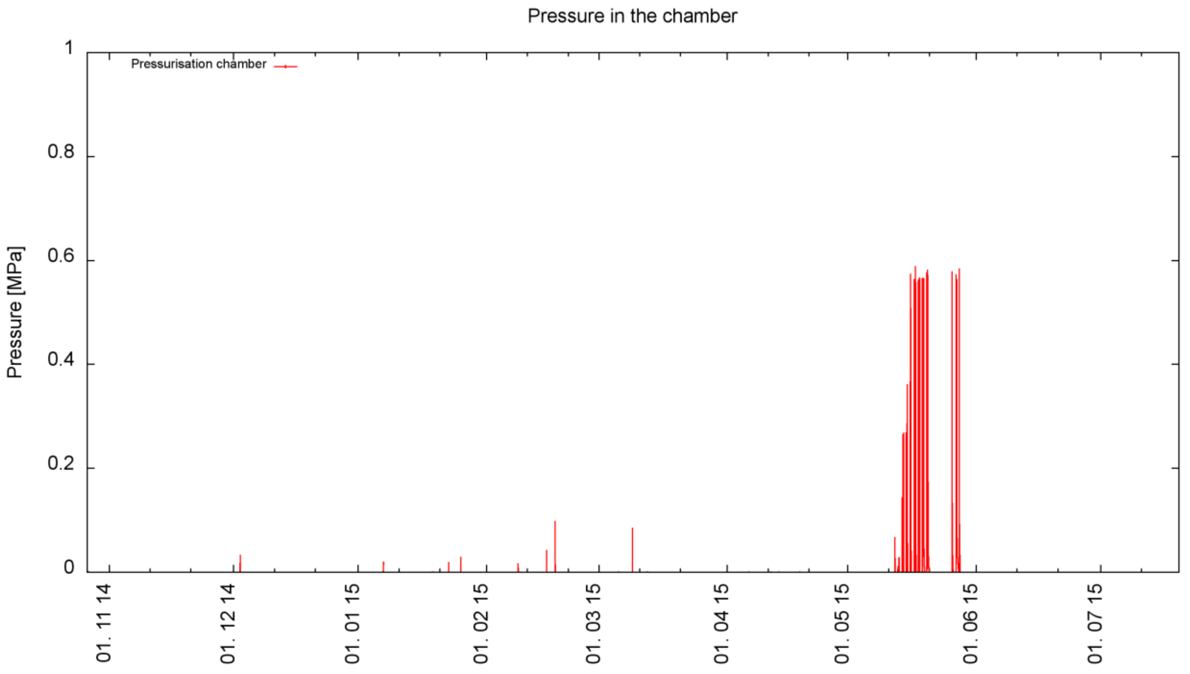


Figure 8 - Water tightness tests (pressure in the chamber)

Table 4 – Grouting of the plugs

Date	**Grouting**
16.12-17.12.2014	Contact grouting of the inner plug
12.1.2015	Contact grouting of the inner plug
6.2.2015	Contact grouting of the inner plug
10.2.2015	Contact grouting of the inner plug
25.2.2015	Contact grouting of the inner plug
14.5.-20.5.2015	Contact grouting of the inner plug
27.5.2015	Contact grouting of the inner plug
7.7. – 8.7.2015	Grouting of the outer plug using preinstalled system
9.7.2015	Contact grouting of the outer plug
10.7.2015	Contact grouting of the outer plug
13.7.2015	Contact grouting of the outer plug
2.9.2015	Contact grouting of the outer plug
4.9.2015	Contact grouting of the outer plug
11.2.2016	Contact grouting of the outer plug
12.2.2016	Contact grouting of the outer plug
15.2.2016	Contact grouting of the outer plug
16.2.2016	Contact grouting of the outer plug
17.2.2016	Contact grouting of the outer plug
19.-22.4.2016	Grouting of the connecting pipeline

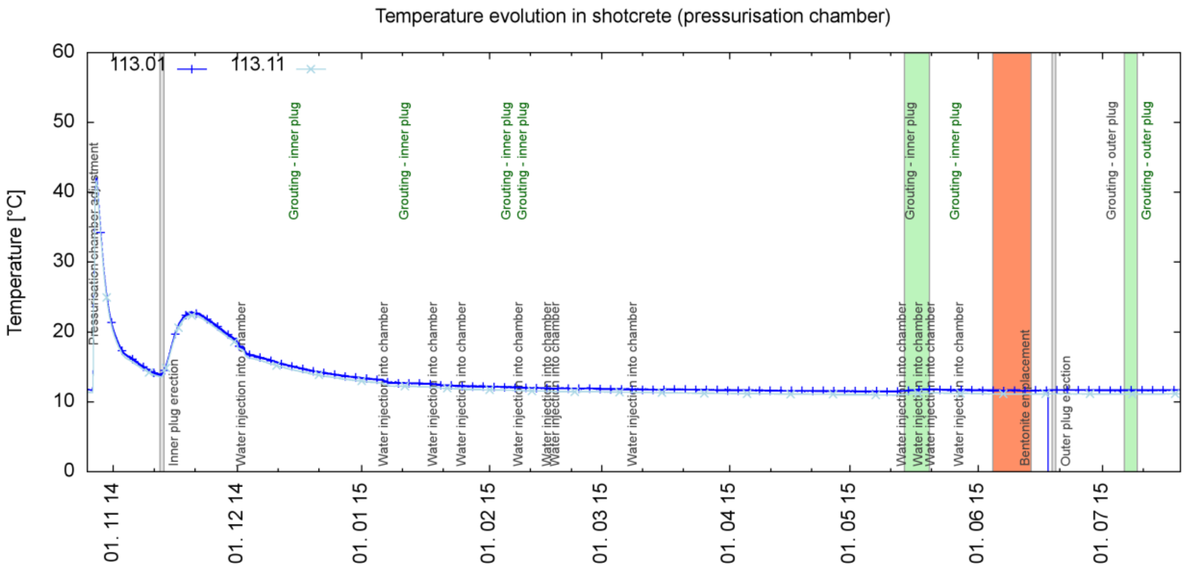
3.1. PRESSURISATION CHAMBER

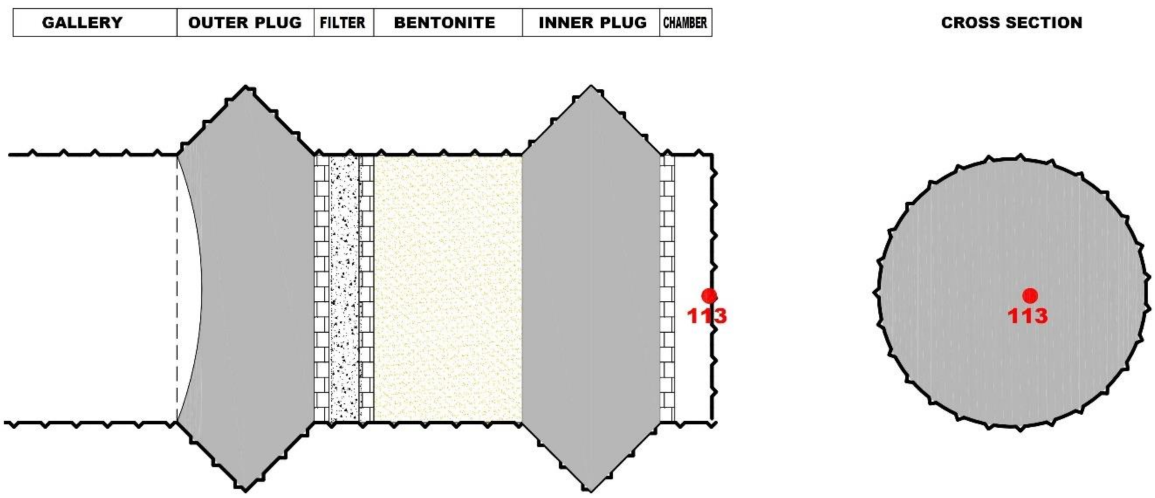
Work on plug construction commenced with the installation of piping leading into the pressurisation chamber and chamber size adjustment on 27 October 2014 (reshaping using shotcrete).

3.1.1. Temperature evolution in the shotcrete (pressurisation chamber)

A twin temperature sensor (analogue and digital) was placed in the shotcrete that was used in the construction of the pressurisation chamber. The location of the sensor is shown in the scheme presented below. The evolution of hydration heat within the shotcrete is shown in the graph. The temperature reached a maximum of 42°C 34 hours following the commencement of shotcreting.

The erection of the chamber served as the ultimate test of the plug erection setup and technology, subsequently proving that the technology worked and there was no excessive heat production.





3.2. INNER PLUG ERECTION AND CURING

The inner plug was erected in a nonstop run lasting 23 hours on 12/13 November 2014. During the curing of the inner plug, the filter piping was installed and the first part of the filter was erected (the lower 1/3) so as to be ready for bentonite emplacement.

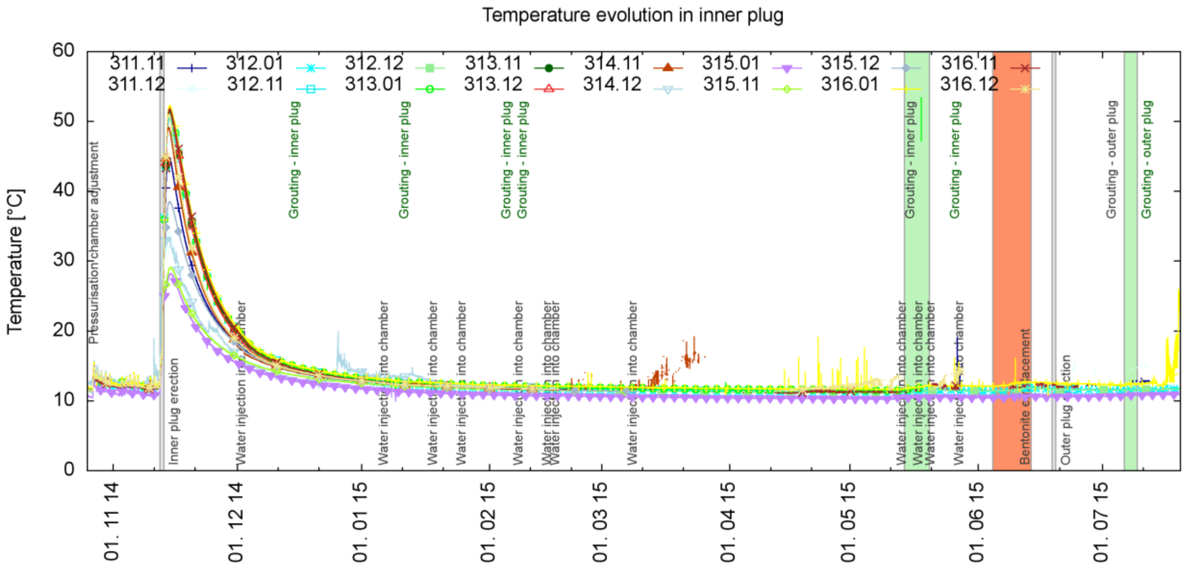
Once the plug had sufficiently cured, a pressure test was performed (see Table 3 and Figure 8). Based on the results of this test, it was decided that contact grouting would have to be applied (the grouting schedule is shown in Table 4). Grouting was completed in May 2015.

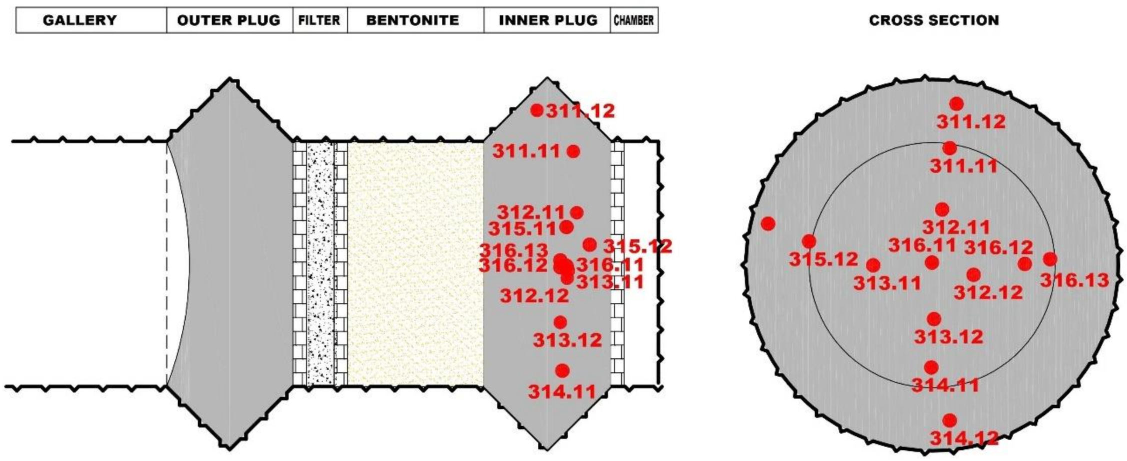
The following data is reported in this chapter:

- Temperature evolution inside the plug
- Deformation (shrinkage) of the plug
- Contact stress
    - Between the plug and the rock mass
    - Between the plug and the separation wall

3.2.1. Temperature evolution in the shotcrete (inner plug)

A total of 16 independent temperature sensors were placed in the shotcrete during the construction of the inner plug (the other temperature sensors make up part of the strain gauges and other sensors). The location of the sensors is shown in the scheme below. The evolution of hydration heat in the shotcrete is shown in the graph. The temperature reached a maximum of 52°C 34 hours following shotcreting taking one month to cool. The maximum temperature attained was within the safe limit determined for the shotcrete plug.



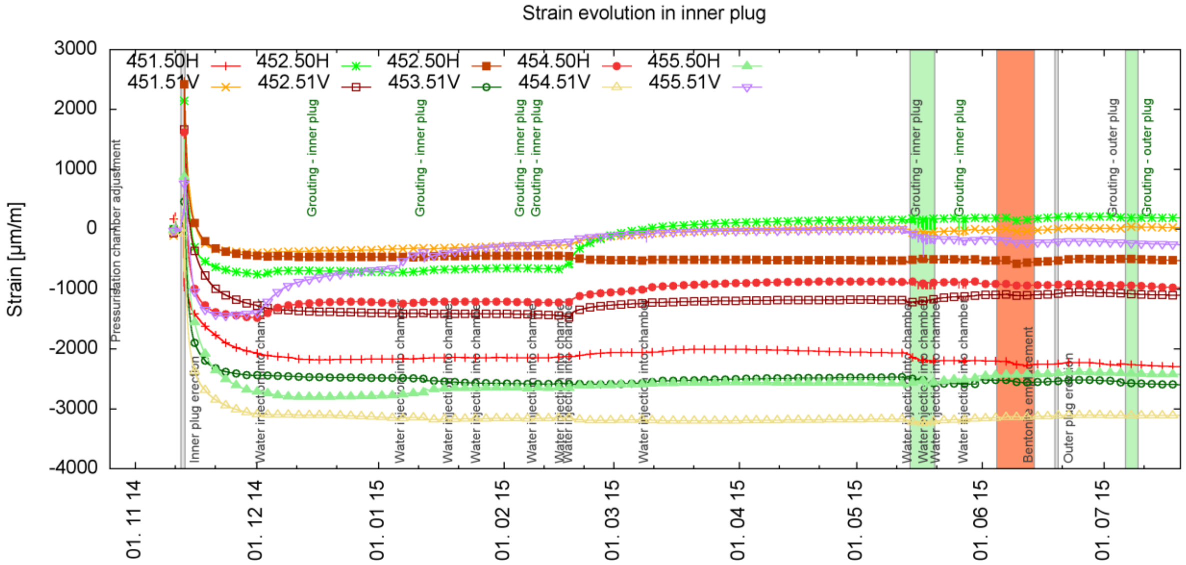


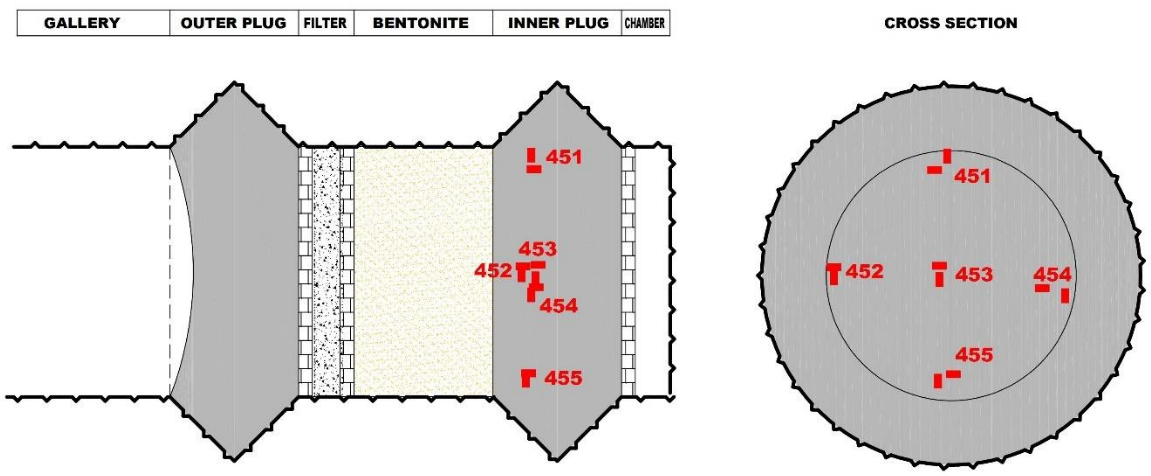
3.2.2. Deformation of the shotcrete (inner plug)

Ten vibrating wire strain gauges were placed in the shotcrete during the construction of the inner plug. In each location two sensors were installed perpendicular to each other in order to monitor both horizontal and vertical strain. The location of the sensors is shown in the scheme below. The evolution of strain within the shotcrete is shown in the graph below.

Shrinkage in the range of 2200 - 3600µm/m was observed (the initial peak was due to installation). The evolution of strain closely followed the cooling of the plug.

It can be seen that the water tightness tests (pressurisation from the chamber) and contact grouting had a significant impact.





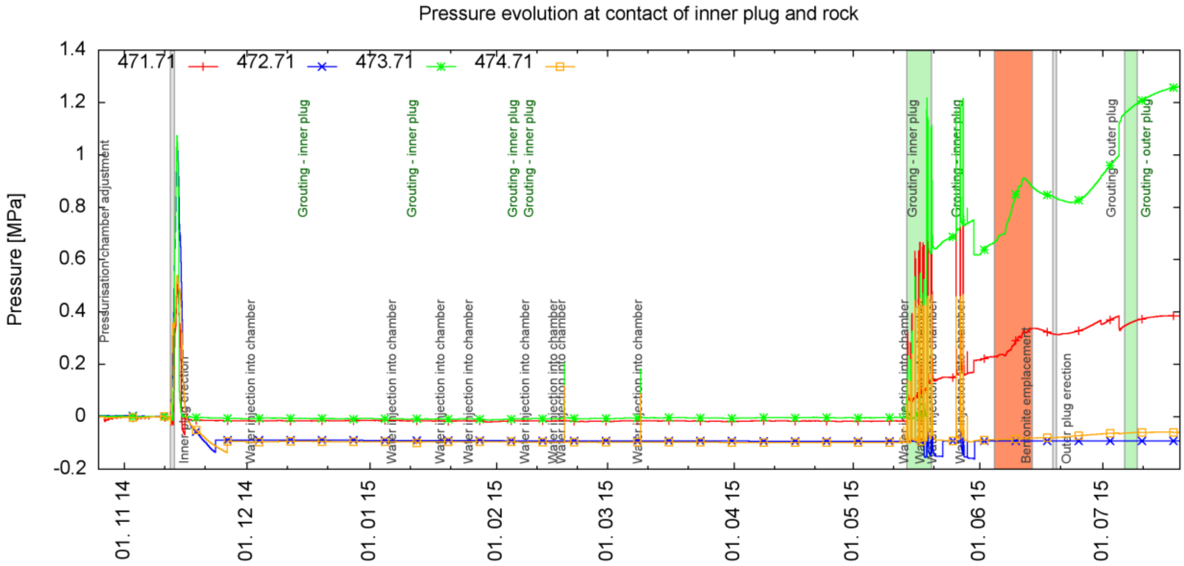
3.2.3. Contact stress evolution in the contact zone between the inner plug and the rock mass

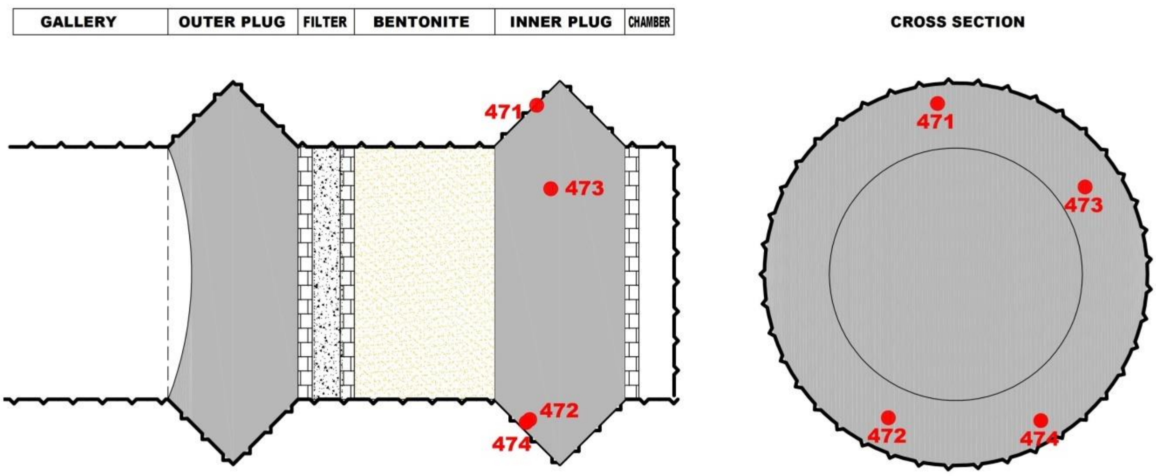
Four total pressure cells were installed on the plug-rock interface in the wedge.

The location of the sensors is shown in the scheme below and the evolution of stress is shown in the graph below.

The highest peak was observed 17 hours following shotcreting – half-way before reaching the hydration heat temperature peak. The bottom sensors (472 and 474) measured negative values at certain points which was most probably due to the pulling of the cells by the shrinking body of the concrete plug. The abrupt return towards a zero value points to the cells having separated from the plug or the rock.

The substantial increase reported by the upper cells in May indicates that grouting was successful in the upper parts (i.e. it penetrated into the area monitored by the cell).





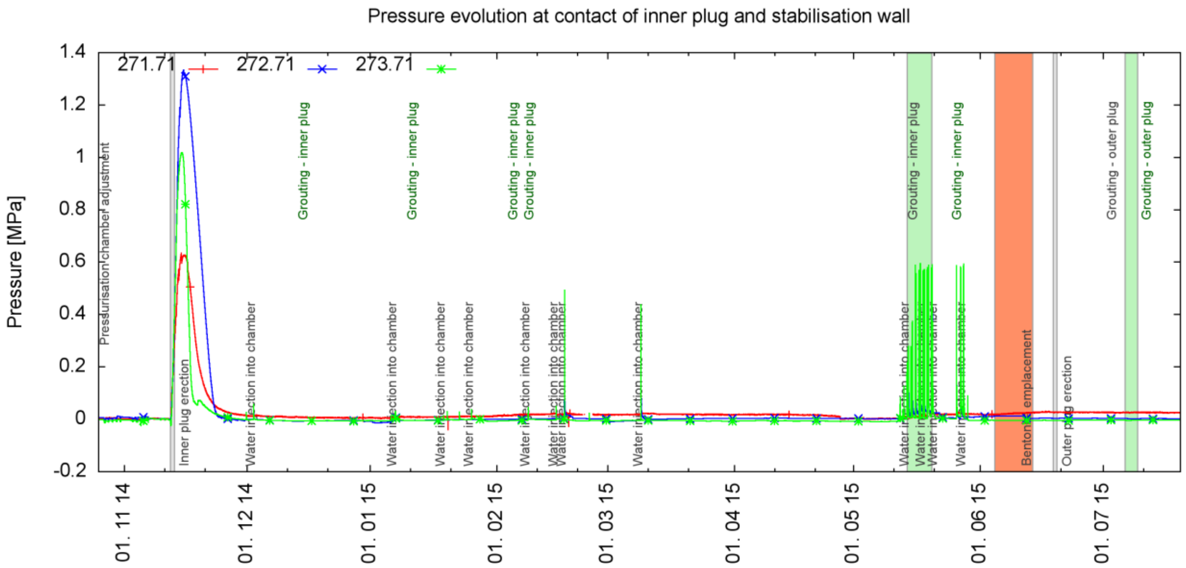
3.2.4. Contact stress evolution on the contact between the inner plug and the stabilisation wall

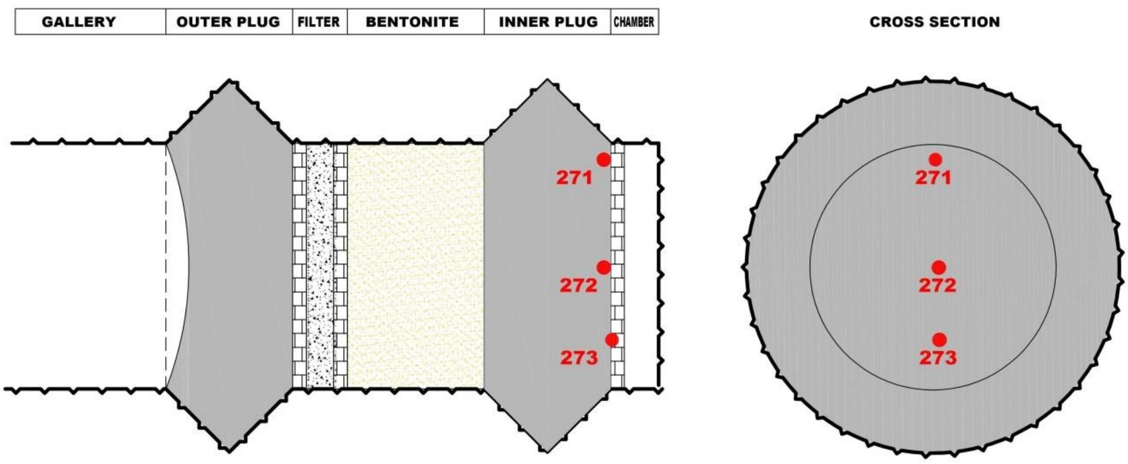
Three total pressure cells were installed on the plug-stabilisation wall interface.

The location of the sensors is shown in the scheme below and the evolution of stress is shown in the graph below.

A maximum peak of 1.3MPa was observed 49 hours following shotcreting. The sensors responded according to the behaviour of the shotcrete – expansion, shrinkage and reaction to water injection into the chamber. The response however was "slower" than that of the cells in contact with the rock mass.

The unchanged value following grouting indicates that there was no leakage of the grout behind the plug. The changes observed during grouting were due to water back pressure – indicating that the separation wall does not obstruct water flow and therefore functions as intended.





3.3. OUTER PLUG ERECTION AND CURING

The outer glass fibre shotcrete plug was erected in a non-stop run of 24 hours on 19/20 June 2015.

The outer concrete plug was constructed in exactly the same manner as the inner plug with the exception that grouting tubes were positioned around the circumference of the outer plug prior to shotcreting.

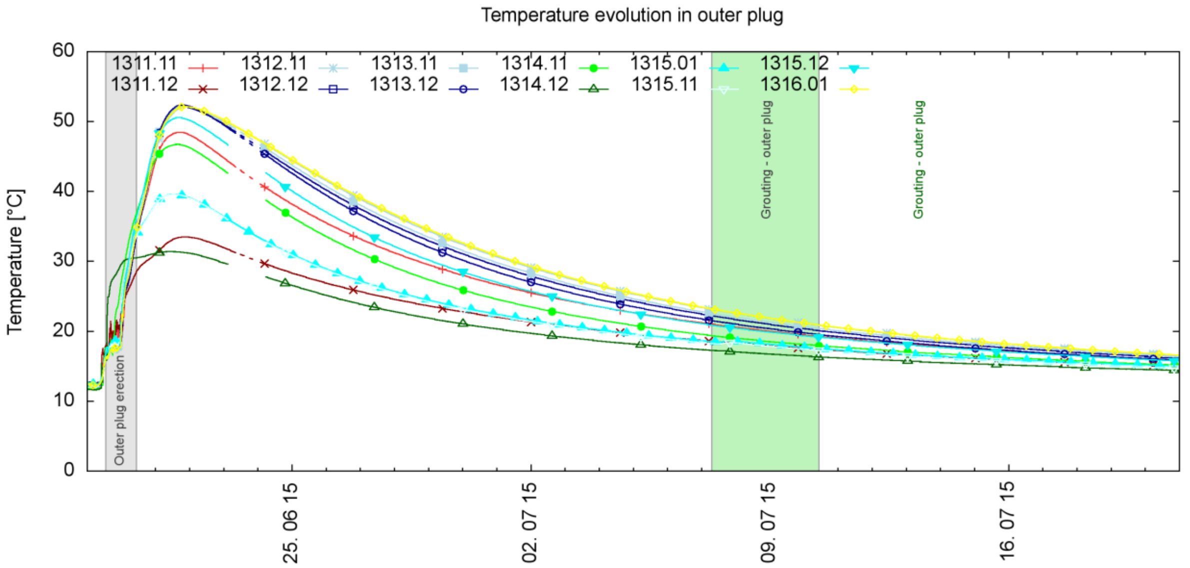
Once the plug had cured, grouting was undertaken using the preinstalled tubes. The initial pressure testing of the EPSP demonstrated that this grouting was insufficient and additional grouting was employed in a similar way as with the inner plug (see schedule of the grouting in Table 4).

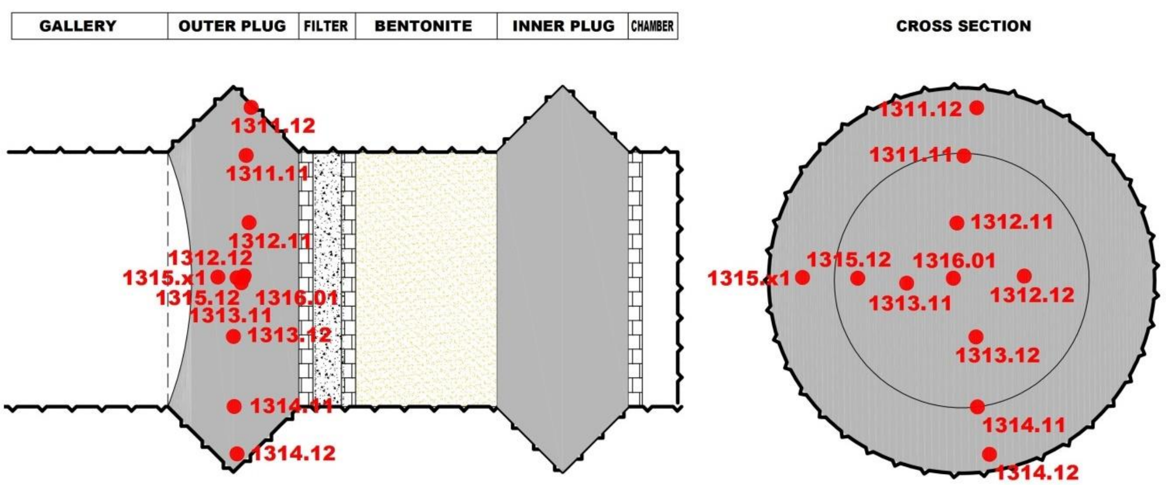
The following data is reported in this chapter:

- Temperature evolution inside the plug
- Deformation (shrinkage) of the plug
- Contact stress between the plug and the rock mass

3.3.1. Temperature evolution in the shotcrete (outer plug)

A total of 12 independent temperature sensors were placed in the shotcrete during the construction of the outer plug (the other temperature sensors formed part of the strain gauges and other sensors). The location of the sensors is shown in the scheme below and the evolution of hydration heat in the shotcrete is shown in the graph. The maximum temperature reached 52°C 30 hours following shotcreting and took over one month to cool. The maximum temperature was within the safe limit determined for the shotcrete plug.

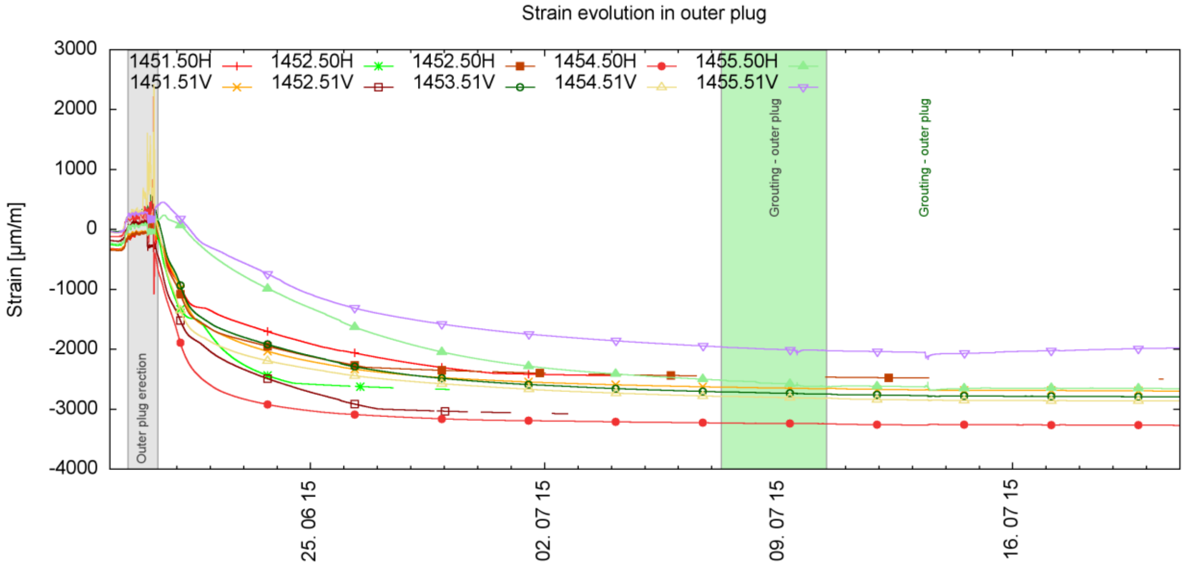


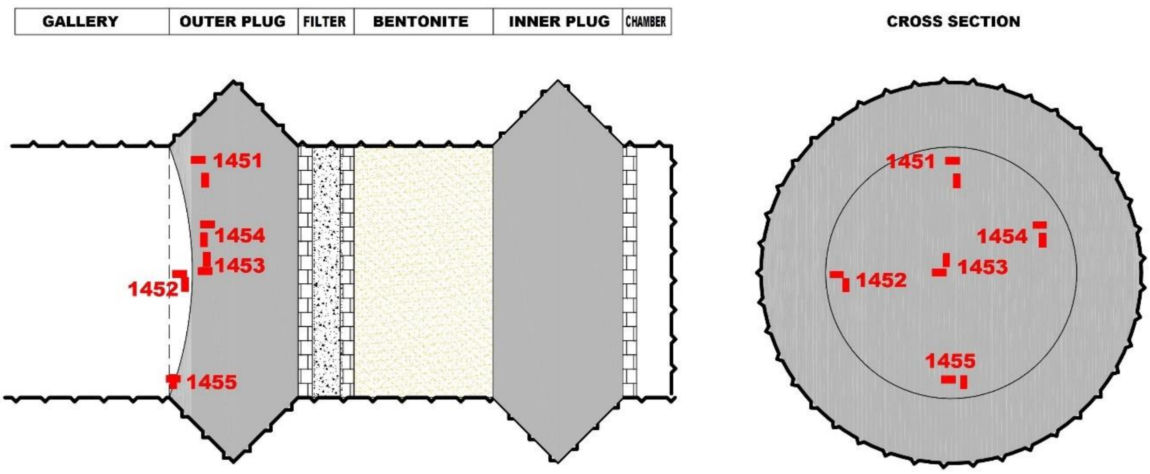


3.3.1. Deformation of the shotcrete (outer plug)

Ten vibrating wire strain gauges were placed in the shotcrete during the construction of the outer plug. In each location two sensors were installed perpendicular to each other in order to monitor both horizontal and vertical strain. The location of the sensors is shown in the scheme below. The evolution of strain within the shotcrete is shown in the graph.

Shrinkage in the range of 2200 - 4000µm/m was observed (the initial peak was due to installation) closely following the cooling of the plug.



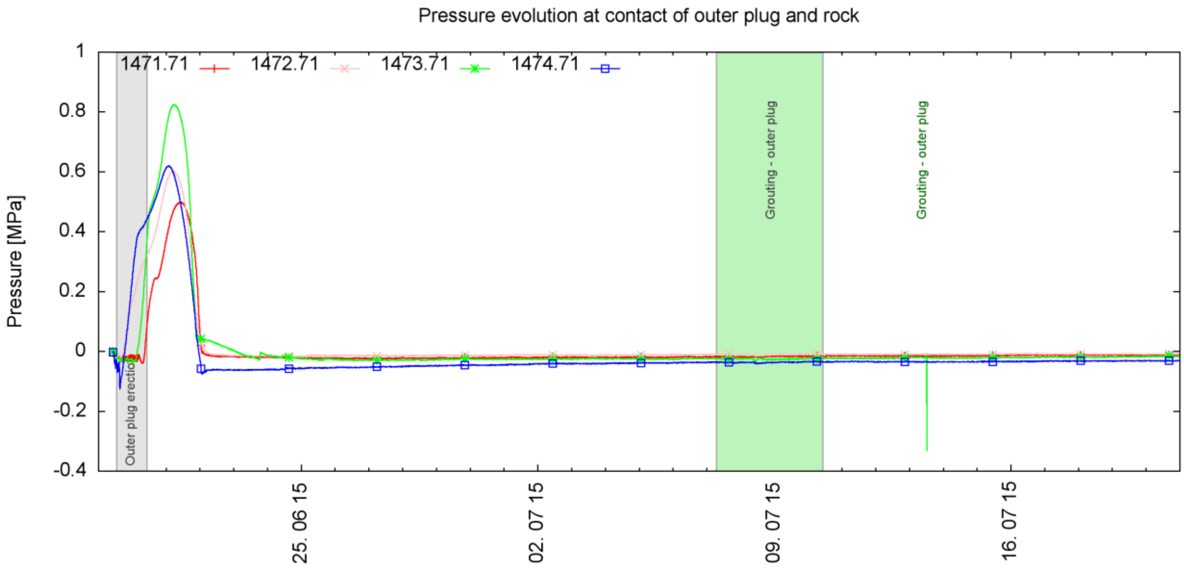


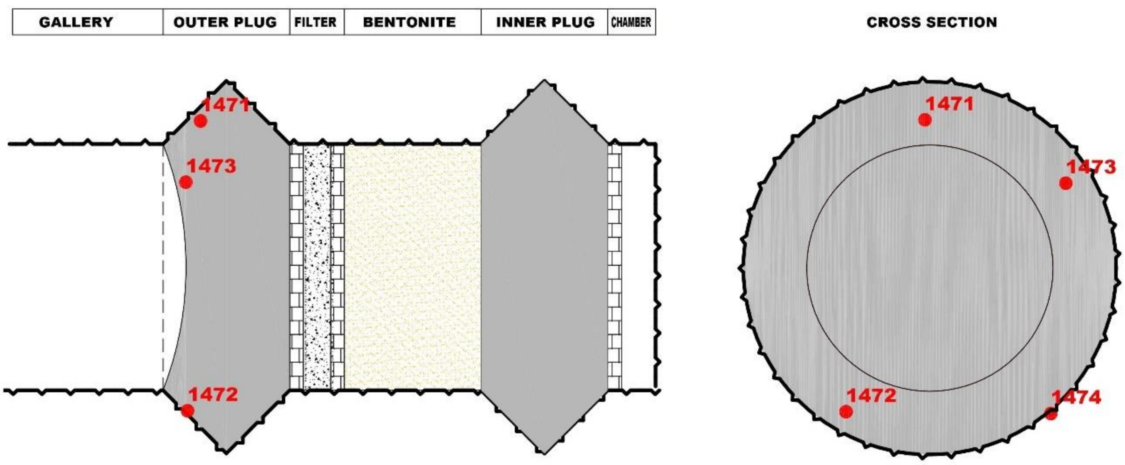
3.3.2. Contact stress evolution between the plug and the rock (outer plug)

Four total pressure cells were installed on the plug-rock interface in the wedge.

The location of the sensors is shown in the scheme below and the evolution of stress is shown in the graph below.

A maximum peak of 0.8MPa was observed 18 hours following shotcreting. The sensors responded according to the behaviour of the shotcrete – expansion, shrinkage and reaction to grouting.





4. MONITORING DATA FROM THE CONDUCTING OF THE EXPERIMENT

The experiment proper commenced on 21 July 2015. The original plan for the loading of the experiment consisted of the injection of water into the pressurisation chamber with a gradual increase in pressure (with the possibility of injecting water into the filter and reversing the flow if necessary). The injection of a bentonite slurry was also planned.

Based on the results obtained during the initial part of the experimental phase, the plan had to be altered. The conducting of the experiment (based on the updated plan) was divided into 5 phases based on the character of the loading of the experiment:

- Phase 1 – water injection into the pressurisation chamber
- Phase 2 – saturation of the bentonite core (water injection into both the filter and the chamber)
- Phase 3 – water injection into the pressurisation chamber
- Phase 4 – bentonite slurry injection into the pressurisation chamber
- Phase 5 – water injection into the pressurisation chamber

Table 5 Experimental programme schedule

Phase	**Sub phase**	**Start**	**End**	**Duration of phase [days]**	**Pressure [MPa]**
Phase 1 – Water injection into the chamber		21-07-2015	13-08-2015	23	0.5 - 1
Phase 2 - Saturation phase (water injection into the chamber and the filter)		25-08-2015	29-02-2016	188	
	2.1 Constant injection	25-08-2015	08-10-2015		0.2
	2.2 Pulse tests, Constant Pressure tests	13-10-2015	02-11-2015		0.2
	2.3 Constant injection long-term test 2 bar	03-11-2015	14-01-2016		0.2
	2.4 Constant injection (several pressure levels)	14-01-2016	29-02-2016		0.2 – 1.2
Phase 3 - Water injection into the chamber		07-03-2016	12-03-2016	5	0.1 - 0.4
Phase 4 - Injection of bentonite slurry into the chamber		15-03-2016	17-03-2016	3	1.5 - 3
Phase 5 - Water injection into the chamber		22-03-2016	Still underway; in report to 31-05-2016	39+	0.15 - 1.2

4.1. PHASE 1 - WATER INJECTION

Start: 2015-07-21 07:51:00 (UTC) Start of the first water injection into the chamber

End: 2015-08-13 12:15:00 End of the injection phase

Test phase 1 commenced approximately 1 month after the end of the construction of the second shotcrete layer and consisted of pulse tests in the first half of the testing phase and short Constant Pressure tests in the second part. During this period, the output pipe leading from the filter was kept open and water outflow was measured. Leakages of water from the injection chamber (the water leaked through the interface between the boreholes and injection pipes leading to the injection chamber) were registered during the injection periods; this outflow rate was also measured in selected time intervals.

The graph below shows the evolution of pressure in the chamber (pressure sensor 191 – situated in the upper part of the chamber).

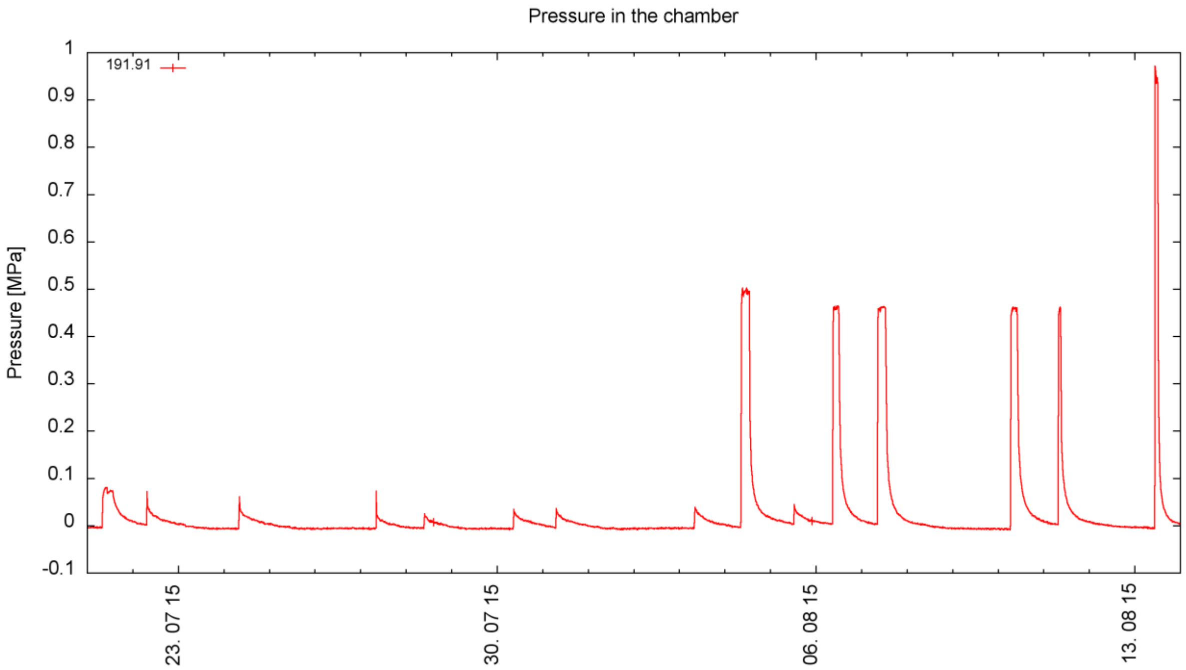
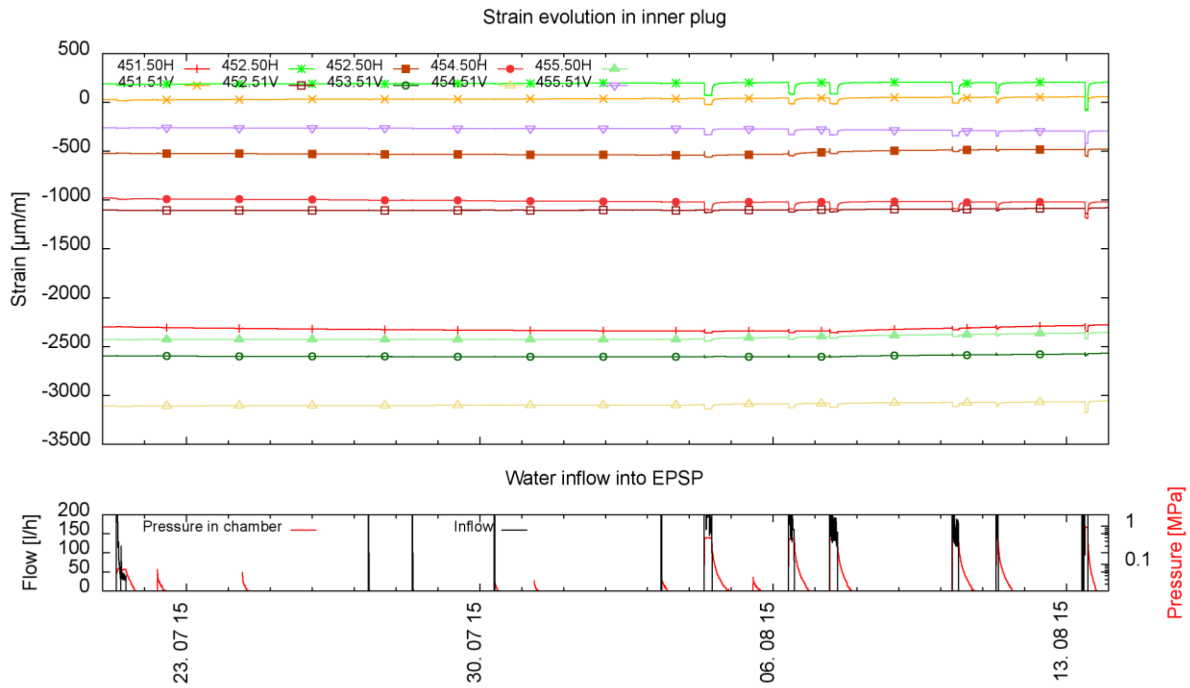


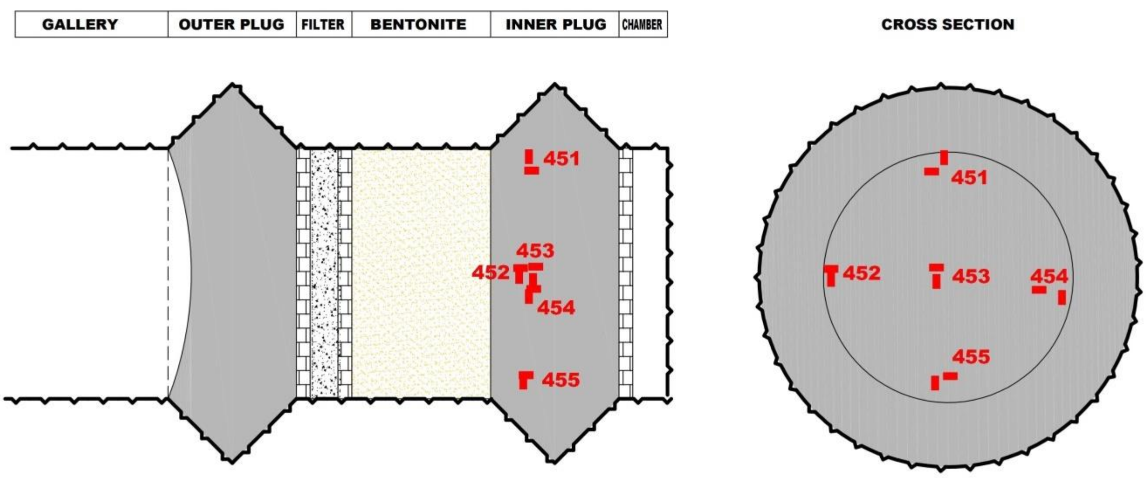
Figure 9 – Pressure in the pressurisation chamber during Phase 1

4.1.1. Deformation of the shotcrete (inner plug)

A total of 10 strain gauges were placed in the shotcrete during the construction of the inner plug. In each location two sensors were installed in order to control horizontal and vertical strain. The location of the sensors is shown in the scheme below and the evolution of strain in the shotcrete is shown in the graph.

Only a small response up to 120μm/m for the 0.5MPa pressure test and 280μm/m for the 1MPa pressure test were recorded.



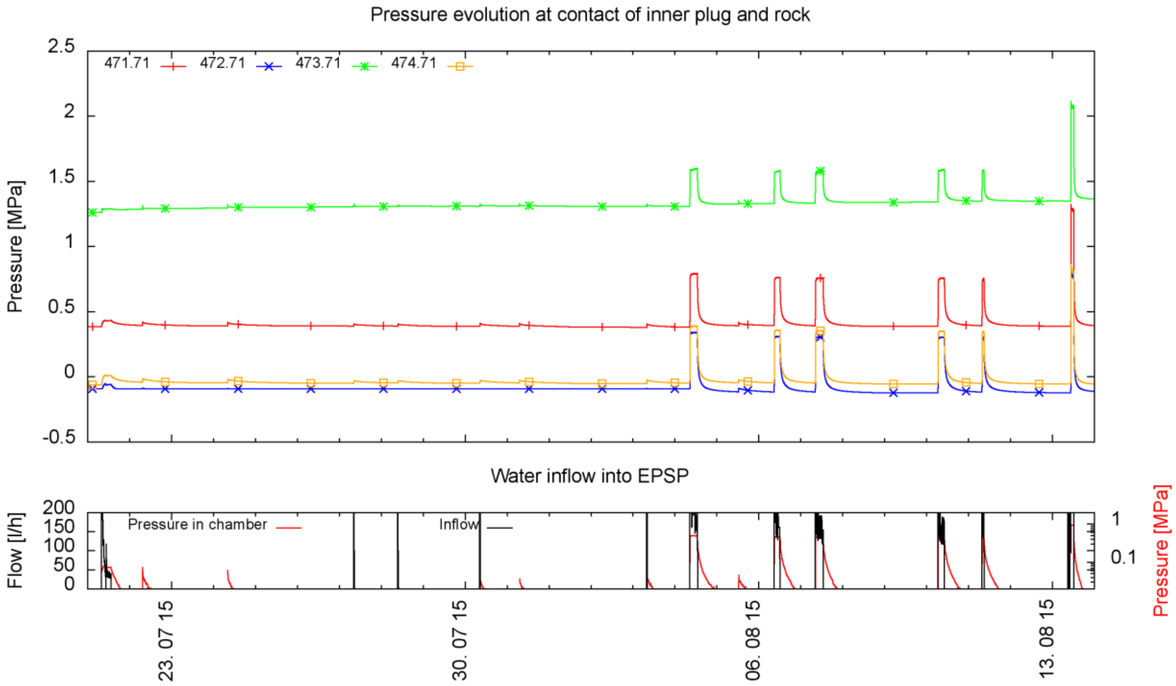


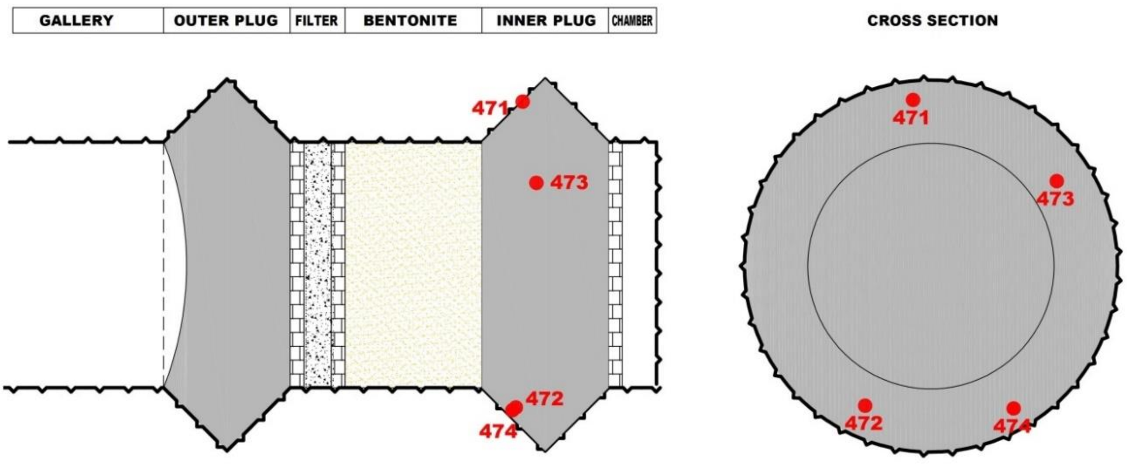
4.1.2. Contact stress evolution on the contact between the inner plug and the rock mass

Four total pressure cells were installed in the plug-rock interface in the wedge.

The location of the sensors is shown in the scheme below and the evolution of stress is shown in the graph below.

Absolute values were influenced by grouting and only relative changes are important in terms of evaluation. Pressure increased according to the rate of injection of water into the chamber. Pressure increase values follow chamber pressure with only relatively small differences. This would tend to indicate either good hydraulic connection to the chamber or that the plug wedged into the rock or both.



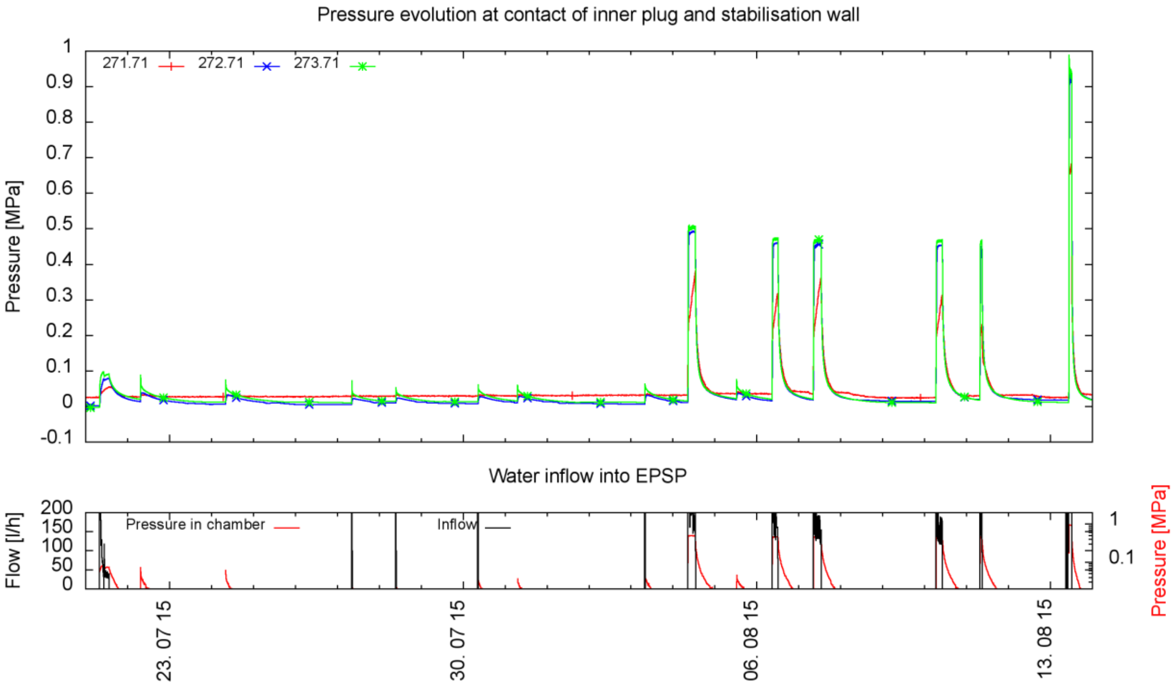


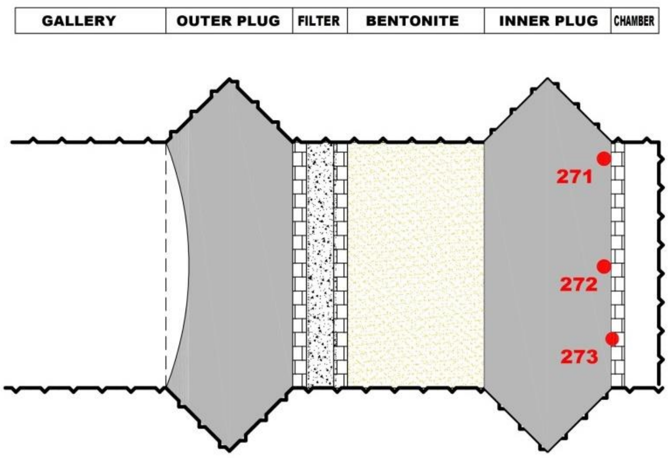
4.1.3. Contact stress evolution on the contact between the inner plug and the stabilisation wall

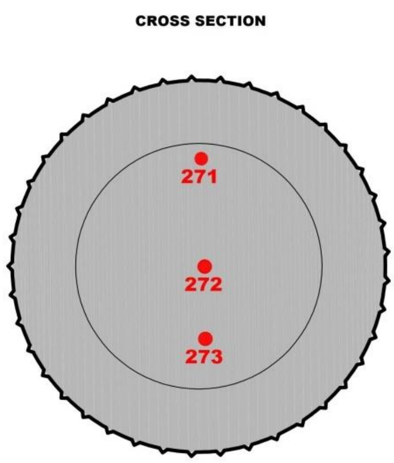
Three total pressure cells were installed in the plug-stabilisation wall interface.

The location of the sensors is shown in the scheme below and the evolution of stress is shown in the graph below.

Pressure levels can be seen to follow the pressure in the chamber which would appear to indicate that the interaction between the separation wall and plug is minimal and that the wall does not obstruct water flow i.e. it works as intended.







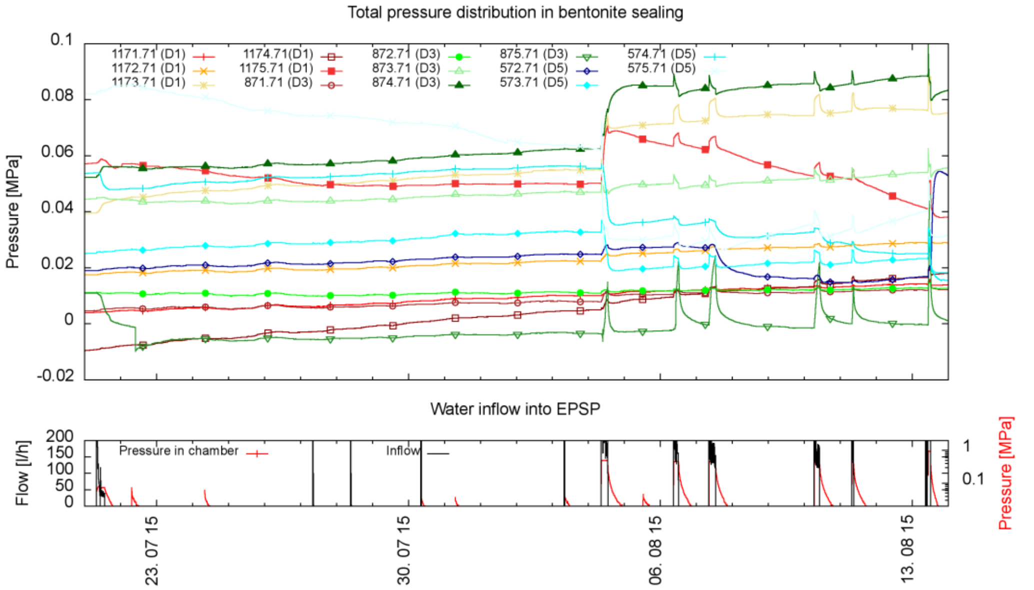
4.1.4. Total pressure evolution in the bentonite sealing

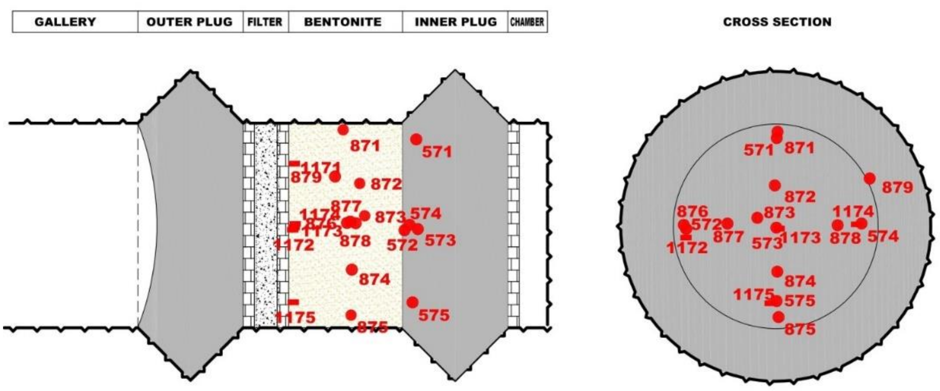
20 total pressure cells were installed in the bentonite sealing. The location of the sensors is shown in the scheme below and the evolution of stress is shown in the graph below.

Caution: The values and their changes (especially in the first part of the period) are very small; therefore, the conclusions have to be treated with care.

It is evident that in the first part of the period, changes in stress were minimal. The amount of water was very limited (short water pulse tests). The initial reaction was probably due to the release of residuals resulting from vibration compaction due to the softening of the pellets on coming into contact with water (the hard pellets were pre-stressed/compressed via vibration compaction).

The second part of the period featuring longer injection times and higher pressure levels exhibits changes in total stress distribution. The values measured are quite low compared to the injection pressure which (together with the pore pressure values) indicates that pressure was transferred mechanically through the bentonite due to water pushing against the bentonite along the interface. No significant swelling pressure was recorded (total pressure values follow injection pressure without any significant continuous rise following the end of a pulse).

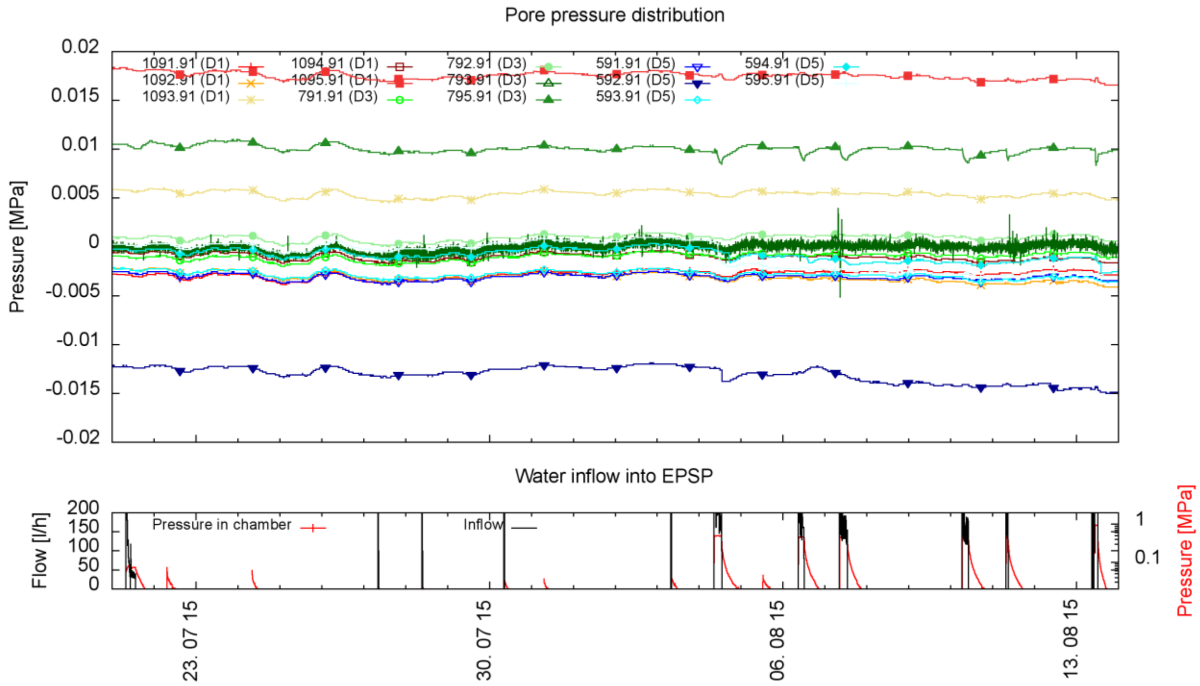


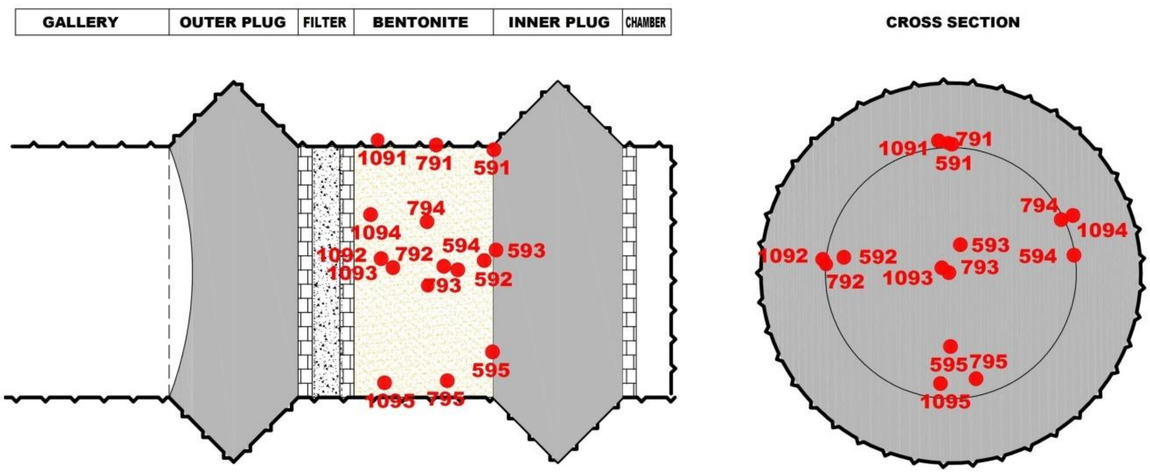


4.1.5. Pore pressure evolution in the bentonite sealing

A total of 14 piezometers were positioned in the bentonite sealing. The location of these sensors is shown in the scheme below and the evolution of pore pressure within the bentonite is shown in the graph.

No changes in pore pressures were recorded in the first part of the period and only very limited changes in the second part, which appears to indicate that no water reached any of the sensors and that the changes were probably due to changes in air pressure.

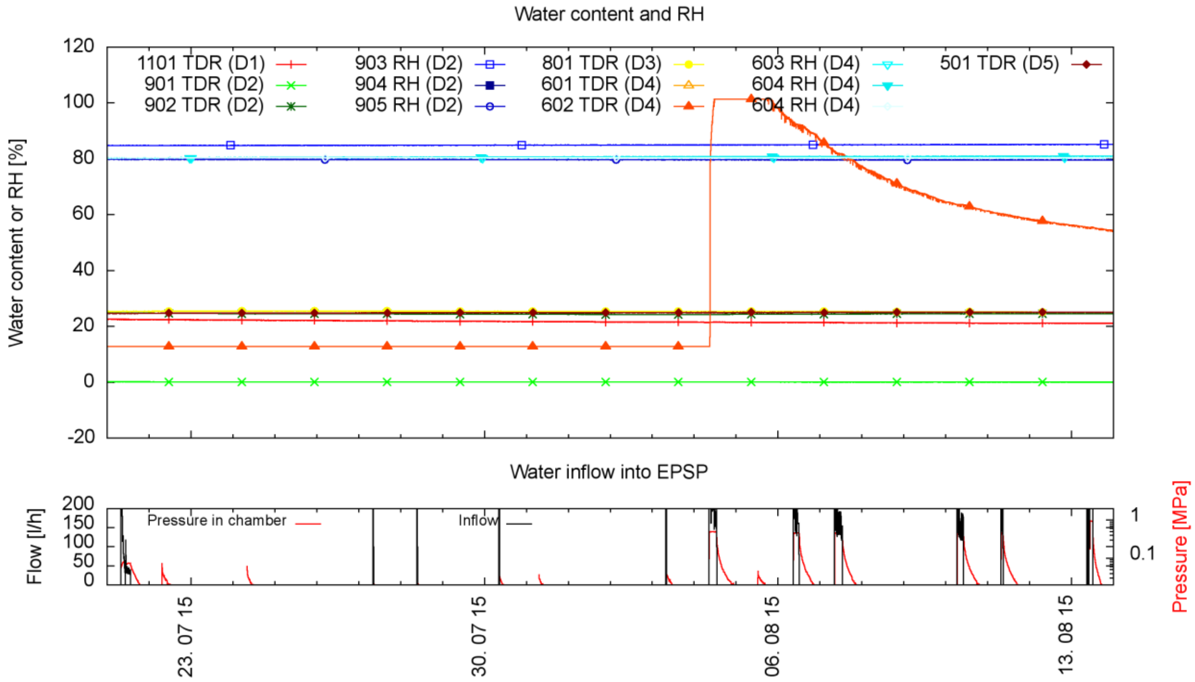


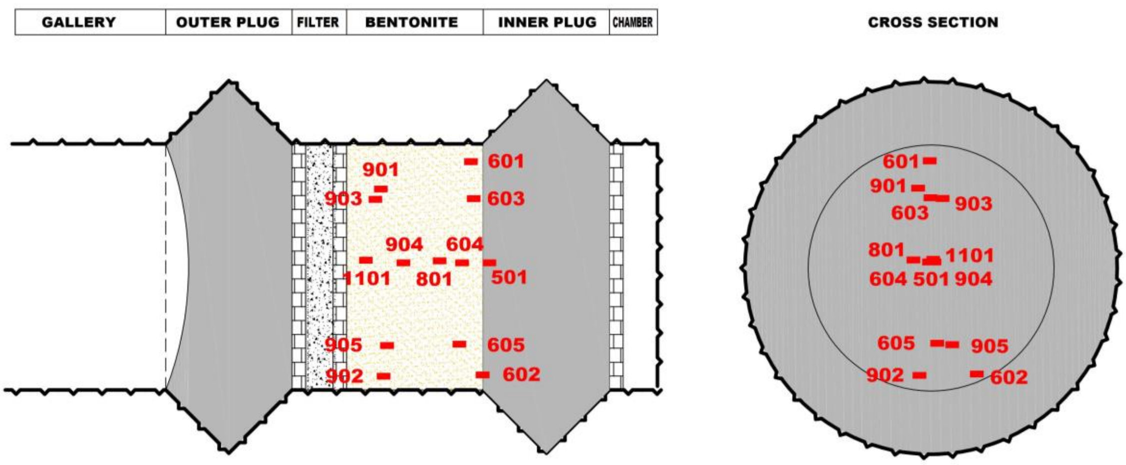


4.1.6. Water content evolution in the bentonite sealing

A total of 13 TDR and RH sensors were positioned within the bentonite sealing. The location of the sensors is shown in the scheme below and the evolution of water content in the bentonite sealing is shown in the graph.

No reaction was recorded by the sensors (except in the case of sensor 602), i.e. the RH sensors located at the bottom of the plug face probably became flooded during the course of the initial longer test. After several days, sensor recovery is evident followed by a steady decline in RH values. This indicates that a water flow path was closed and that water no longer had direct access to the sensors, thus demonstrating the sealing and self-healing abilities of bentonite.

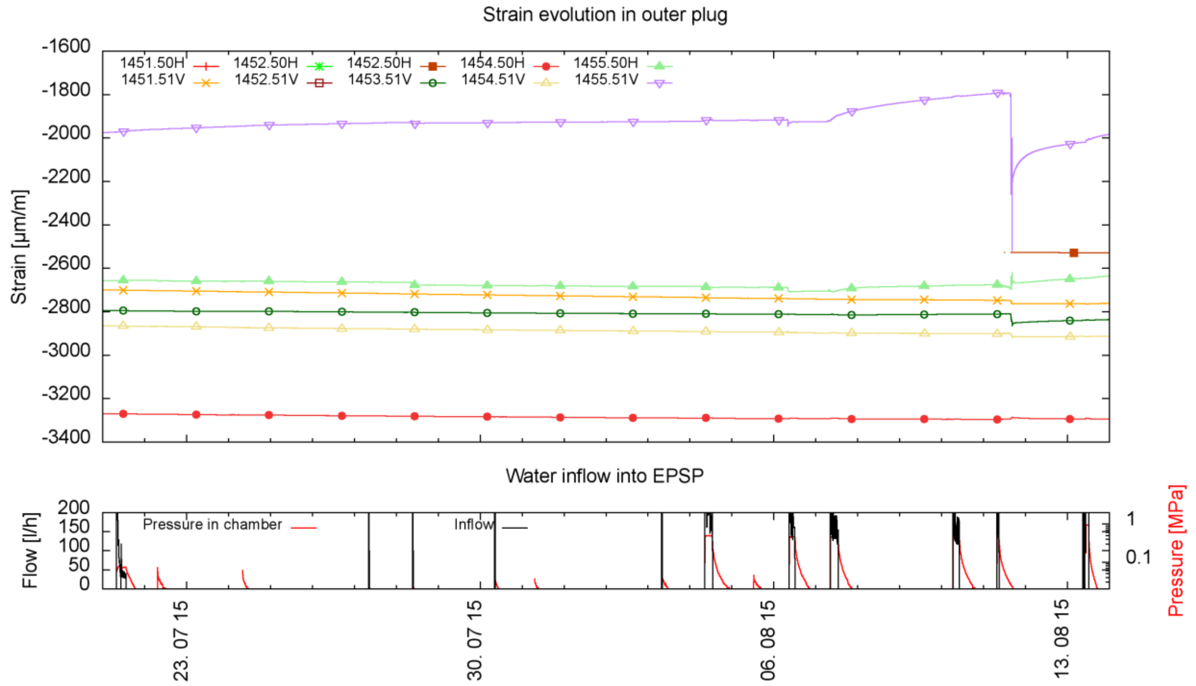


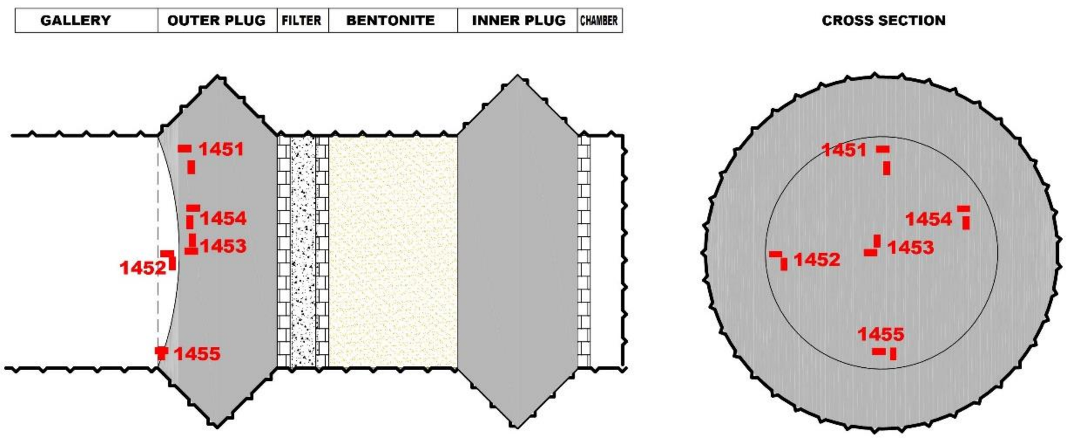


4.1.7. Deformation of the shotcrete (outer plug)

Ten strain gauges were positioned in the shotcrete during the construction of the inner plug. In each location two sensors were installed so as to record both horizontal and vertical strain. The location of the sensors is shown in the scheme below and the evolution of strain within the shotcrete is shown in the graph.

No response was registered in the first half of the period. However, an unidentified process initiated by the second longer injection test (6.8.15) and accelerated by the third test (7.8.15) led to significant deformation which ended with an event on 11.8.15. Subsequently, deformation returned to its pre-event course. The afore-mentioned event coincided with a change in pressure levels as recorded by the contact cells (see the next chapter) which could indicate the "movement" of the plug.



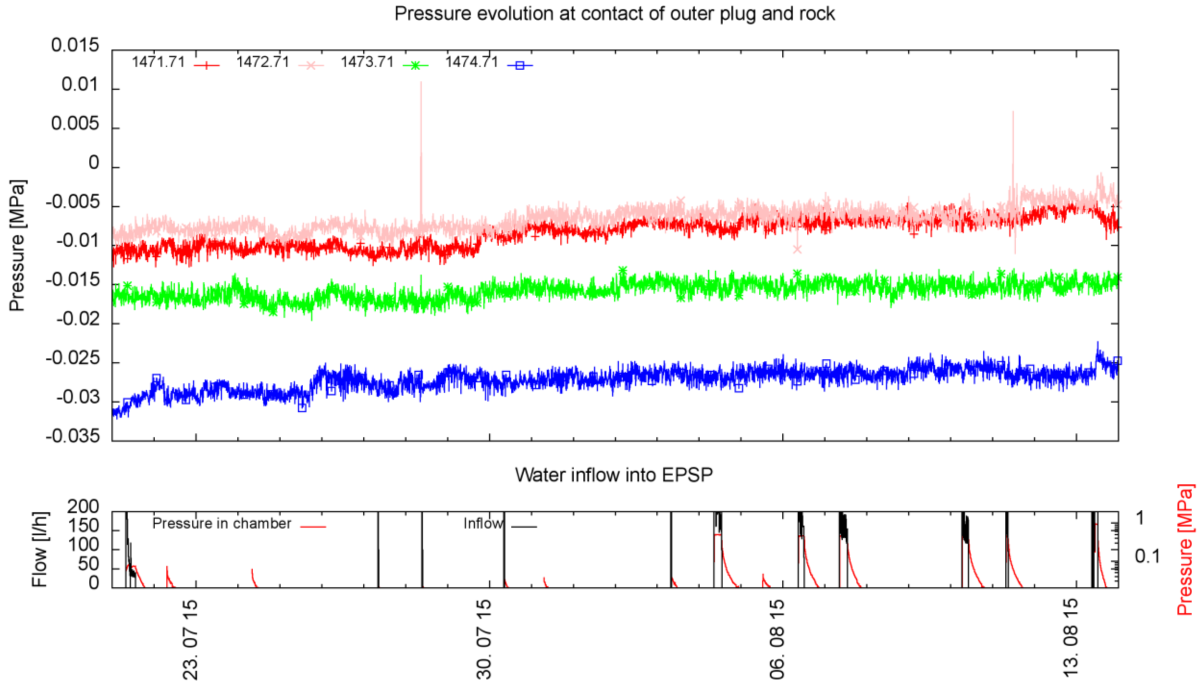


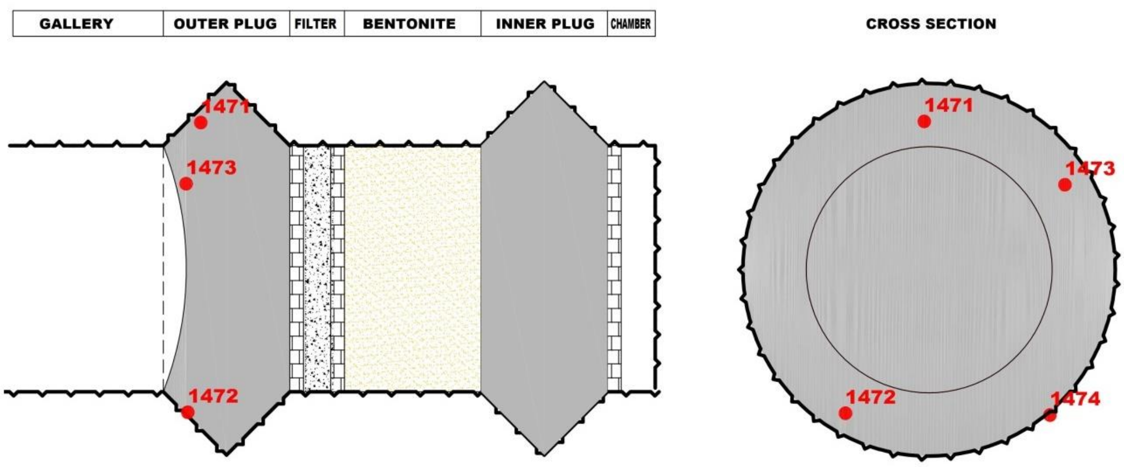
4.1.8. Contact stress evolution between the plug and the rock (outer plug)

Four total pressure cells were installed in the plug-rock interface in the wedge.

The location of the sensors is shown in the scheme below and the evolution of stress is shown in the graph below.

The cells were positioned behind the drained filter; therefore, it was expected that there would be a reaction from these cells during this phase, which turned out, on the whole, to be the case. However, two peaks appeared during the tests followed by a small reaction at the end of the period which could indicate the presence of a hydraulic connection bypassing the filter. However the values recorded and their changes are so small (close to background levels) that no firm conclusions can be drawn.





4.2. PHASE 2 SATURATION PHASE (WATER INJECTION INTO THE CHAMBER AND THE FILTER)

Start: 2015-08-25

End: 2016-02-29

A possible piping effect was detected during Phase 1 and it was decided to temporarily change the course of the experiment. The filter was sealed, filled with water and connected to the pressurisation system in the same way as the chamber. Thus, the bentonite was saturated from both sides (the filter and the plug) and much more rapidly than previously. The primary objective of this phase consisted of activating the bentonite and the sealing of potential piping pathways.

Phase 2 therefore consisted of several stages of simultaneous water injection into the chamber and the filter.

The side-effect of this phase consisted of the testing of the outer load with hydrostatic pressure of up to 1.2MPa.

Phase	**Sub phase**	**Start**	**End**	**Duration of phase [days]**	**Pressure [MPa]**
Phase 2 - Saturation phase (water injection into the chamber and the filter)		25-08-2015	29-02-2016	188	
	2.1 Constant injection	25-08-2015	08-10-2015		0.2
	2.2 Pulse tests, Constant Pressure tests	13-10-2015	02-11-2015		0.2
	2.3 Constant injection long-term test 2 bar	03-11-2015	14-01-2016		0.2
	2.4 Constant injection (several pressure levels)	14-01-2016	29-02-2016		0.2 – 1.2

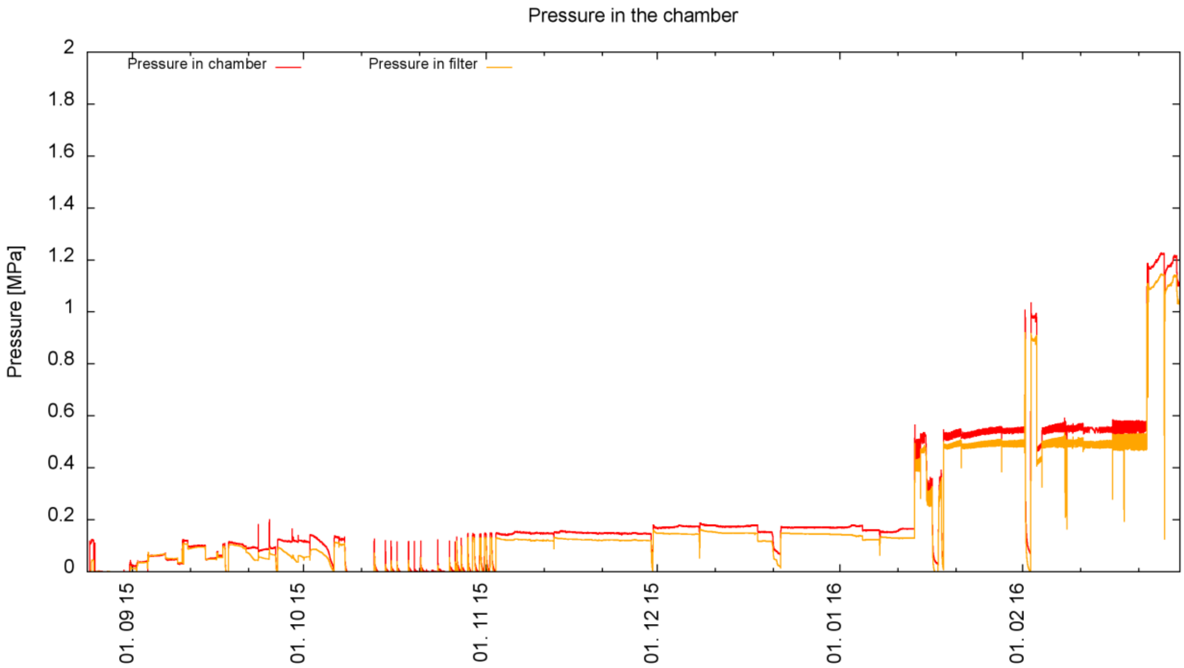
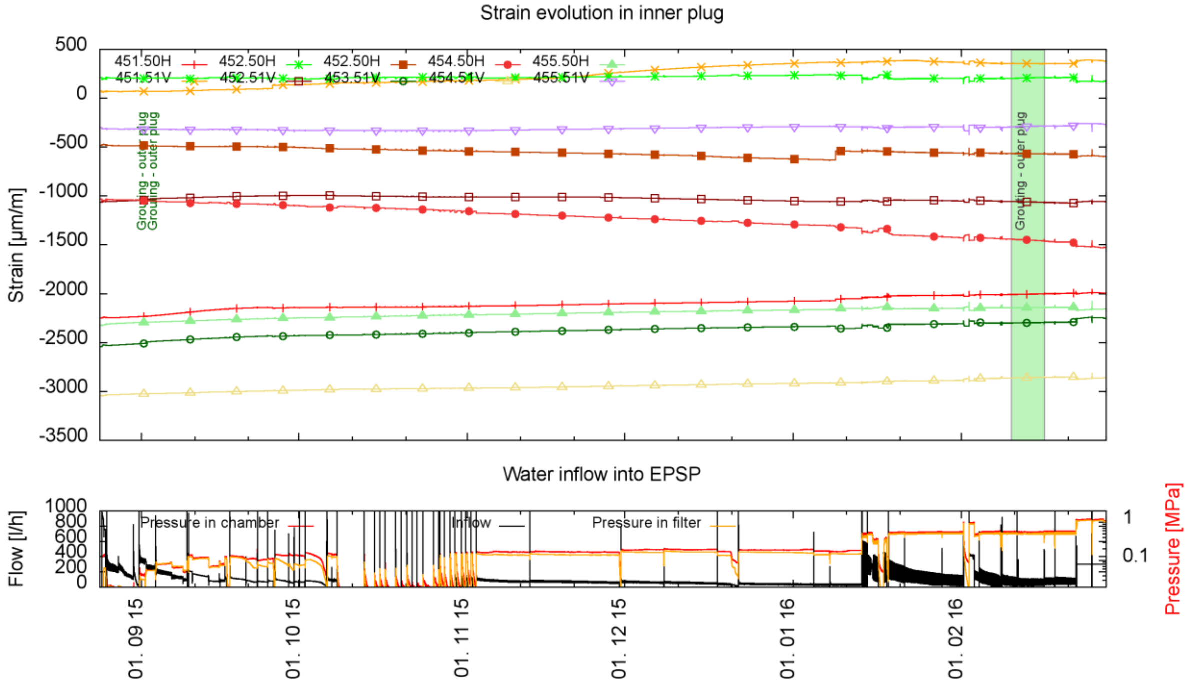


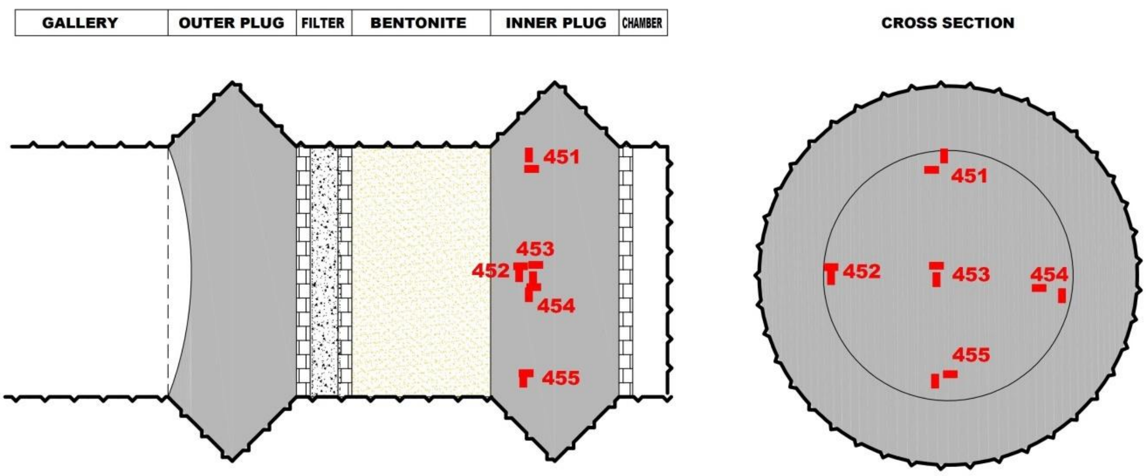
Figure 10 - Pressure in the pressurisation chamber during Phase 2

4.2.1. Deformation of the shotcrete (inner plug)

Ten vibrating wire strain gauges were placed in the shotcrete during the construction of the inner plug. In each location two sensors were installed perpendicular to each other in order to monitor both horizontal and vertical strain. The location of the sensors is shown in the scheme below and the evolution of strain in the shotcrete is shown in the graph below.

Only a very slight mechanical response to pressure loading was observed. Most of the deformation developed very steadily and can be attributed to processes at work inside the concrete saturated by water or to pressure developing inside the bentonite section.



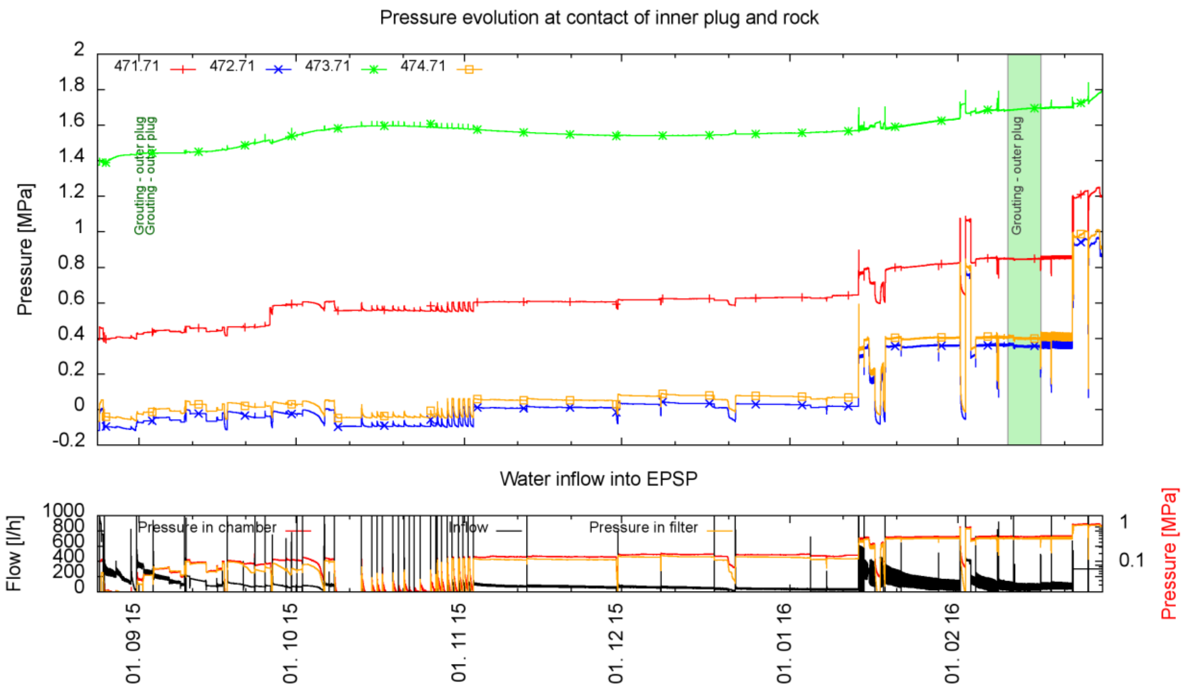


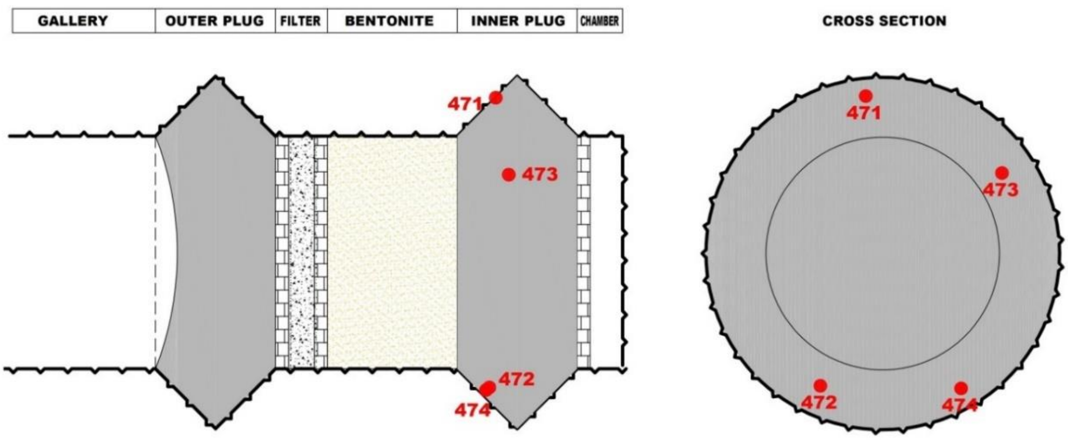
4.2.2. Contact stress evolution on the contact between the inner plug and the rock mass

Four total pressure cells were installed in the plug-rock interface in the wedge.

The location of the sensors is shown in the scheme below and the evolution of stress is shown in the graph below.

Since the absolute values were influenced by grouting, only the relative changes are important in terms of evaluation. Pressure increased according to the injection of water into the chamber. The pressure increase values followed chamber pressure with only relatively small differences recorded by cells 472 and 474. Those cells influenced by grouting exhibit the same pattern but with a smaller change depending on their “starting point”. The most significant change concerned cell 473 which, in the previous phase, closely followed the evolution of pressure inside the chamber, whereas in this phase the reaction was slow, smoothed out and much less intense.



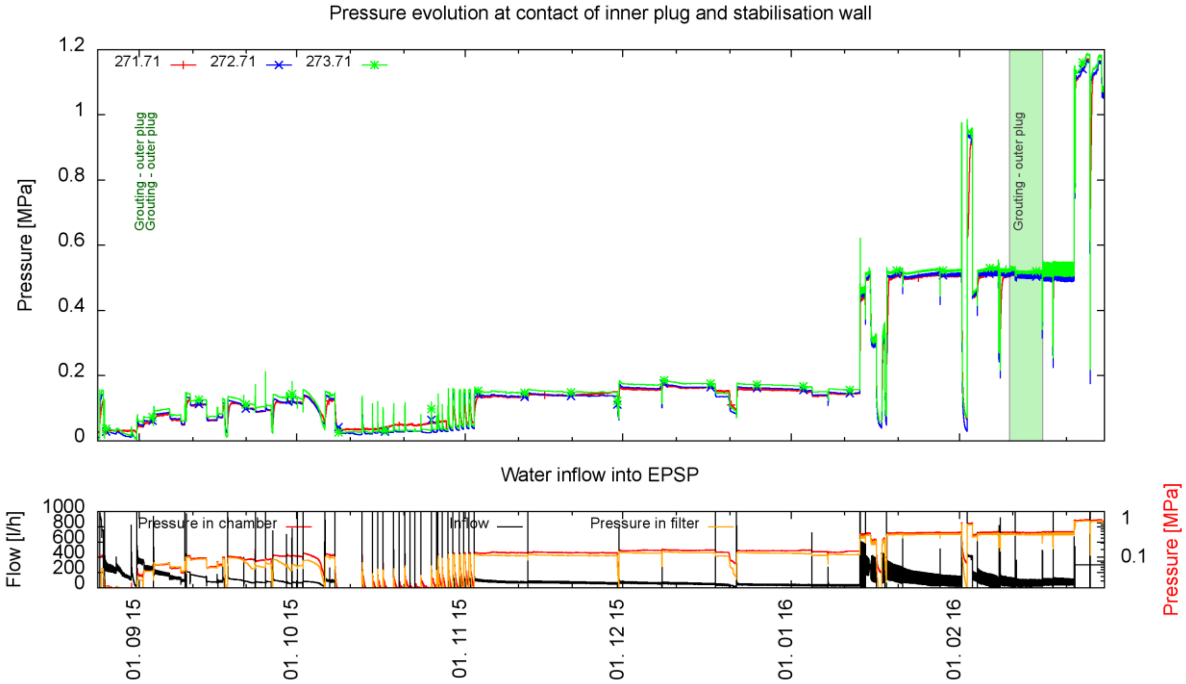


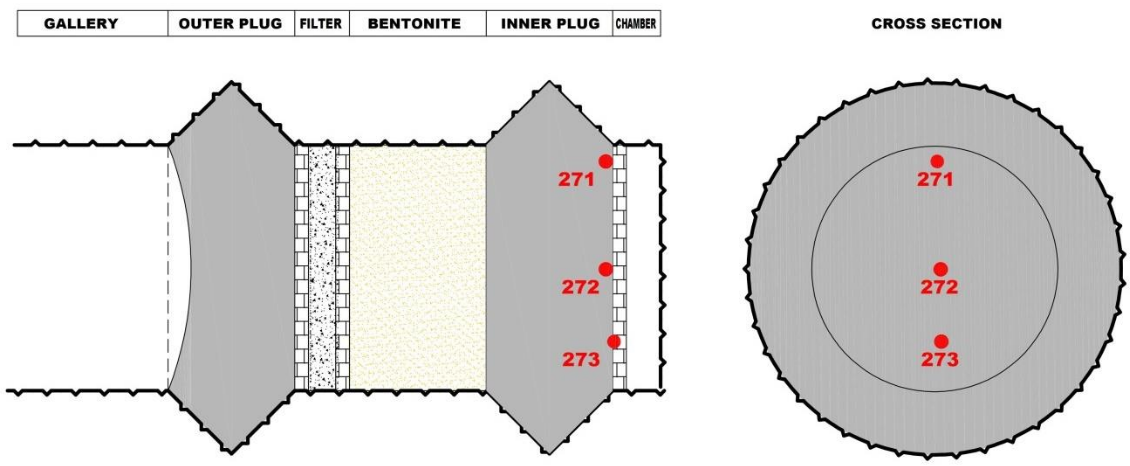
4.2.3. Contact stress evolution between the inner plug and the stabilisation wall

Three total pressure cells were installed in the plug-stabilisation wall interface.

The location of the sensors is shown in the scheme below and the evolution of stress is shown in the graph below.

Pressure was found to follow the pressure in the chamber which indicates that the interaction between the separation wall and the plug is minimal and that the wall does not obstruct water flow i.e. it works as intended. No change in behaviour was discovered compared to the previous phase.





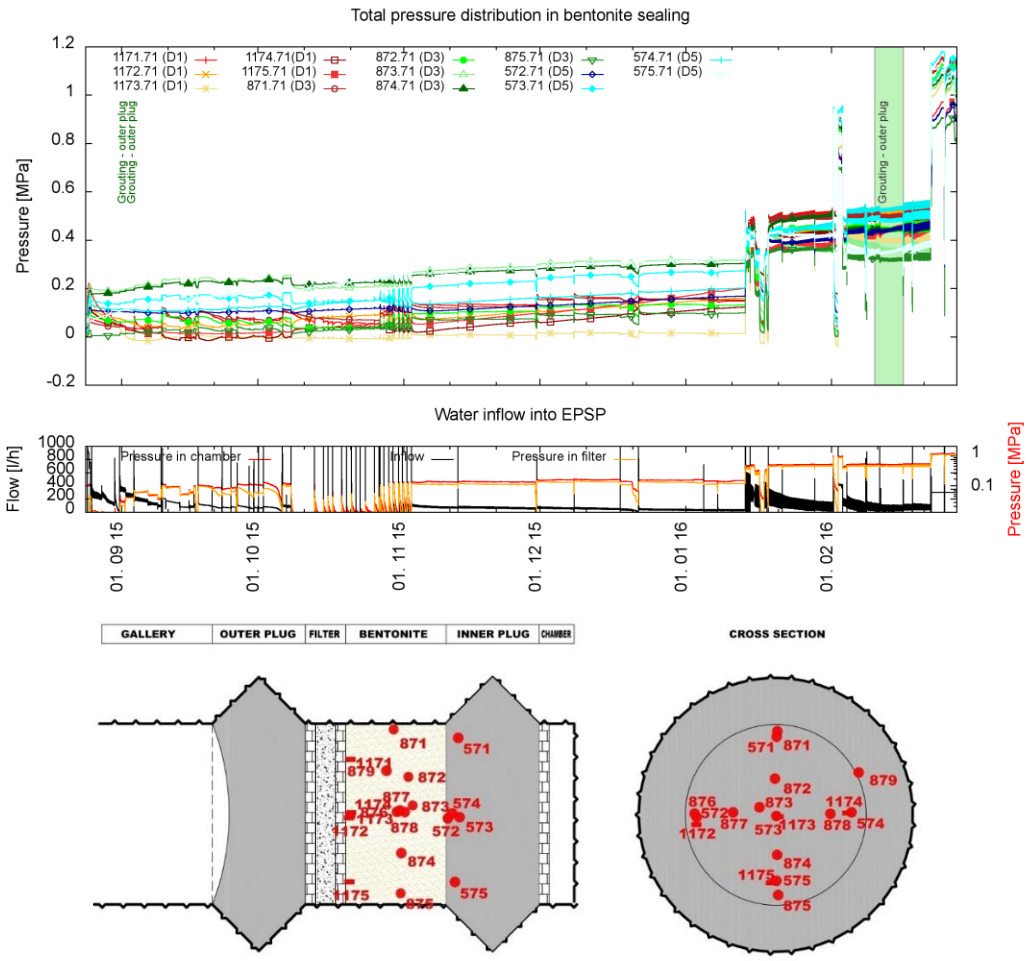
4.2.4. Total pressure evolution in the bentonite sealing

20 total pressure cells were installed in the bentonite sealing. The location of the sensors is shown in the scheme below and the evolution of stress is shown in the graph below.

The behaviour of total pressure can be divided into two periods within phase two – low pressure and high pressure (of the injected water).

During the low pressure period, total pressure was principally influenced by the pressure of the water applied and swelling pressure; swelling pressure gradually took over as the principal force acting, which is demonstrated by the fact that total pressure did not fall to zero when the injection pressure dropped. This does not, however, mean that the full volume of the bentonite swelled. Most probably only the surface layer (increasingly thick) swelled and the rest was mechanically transferred.

This was demonstrated following the application of higher pressures at which point water penetrated into the swollen layer (mechanically – water pressure was higher than swelling pressure) and a similar effect as at the beginning of phase 1 was observed. The rapid introduction of water to the "dry" bentonite pellets led to their sagging; thus, when the water pressure was removed, total pressure dropped dramatically (the sagging pellets were not able to resist/support the swelling pellets). The situation gradually improved as more water penetrated and the wet layer became thicker.

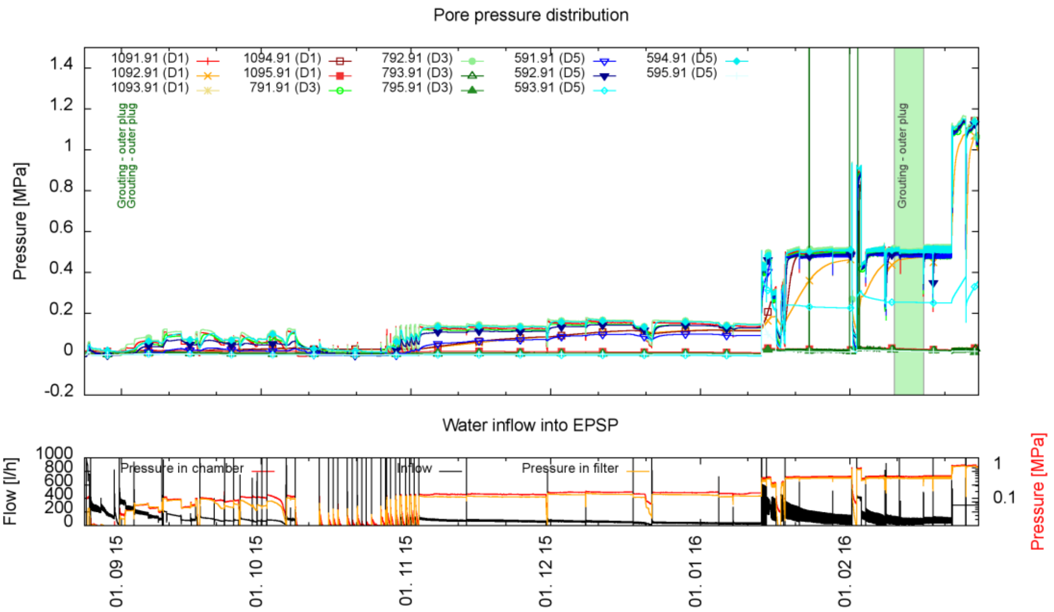


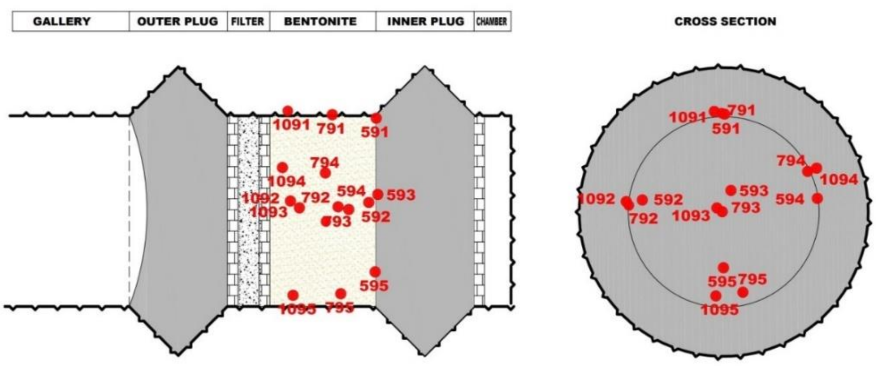
4.2.5. Pore pressure evolution in the bentonite sealing

14 piezometers were placed in the bentonite sealing. The location of the sensors is shown in the scheme below and the evolution of pore pressure in the bentonite is shown in the graph.

Three groups of sensors could be distinguished in terms of the areas inside the experiment in which they were placed. The core group exhibited almost zero reaction; this group consists of sensors along the experimental axis and, interestingly, sensors in the bottom part of the experiment (the sensors were not directly in contact with the rock mass but buried within the bentonite). The only exception consists of the sensor on the experimental axis located upon the plug, which reacted to higher pressures (in excess of 0.5MPa).

The other two groups follow the pressure of the water applied - one group immediately at full value and the other following slowly (i.e. with a delay) and with lower values. Both groups merge at higher pressures. This behaviour indicates that there is a wet transition zone on the surface of the bentonite which prevents direct water flow from forming a gradient. At higher pressures the water pressure is probably higher than the swelling pressure of the transition zone thus allowing the water to penetrate further. There is a parallel here with Phase 1 during which water quickly penetrated through the dry part before a sufficient layer of bentonite pellets was wetted and consequently swelled.

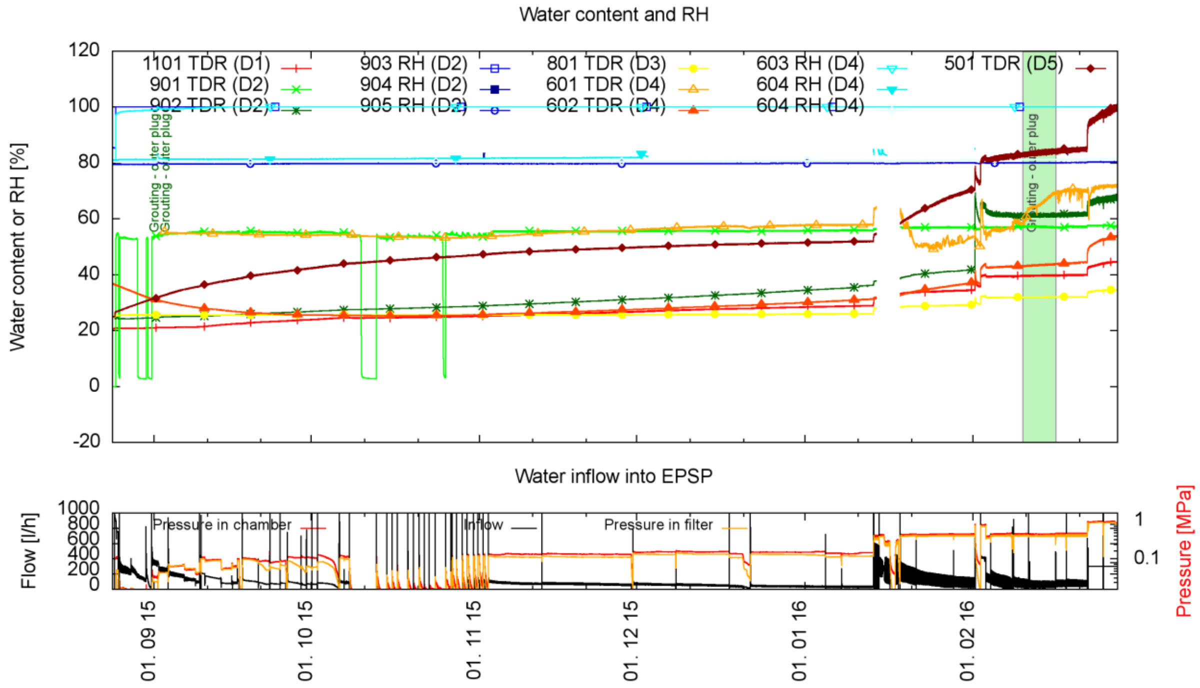


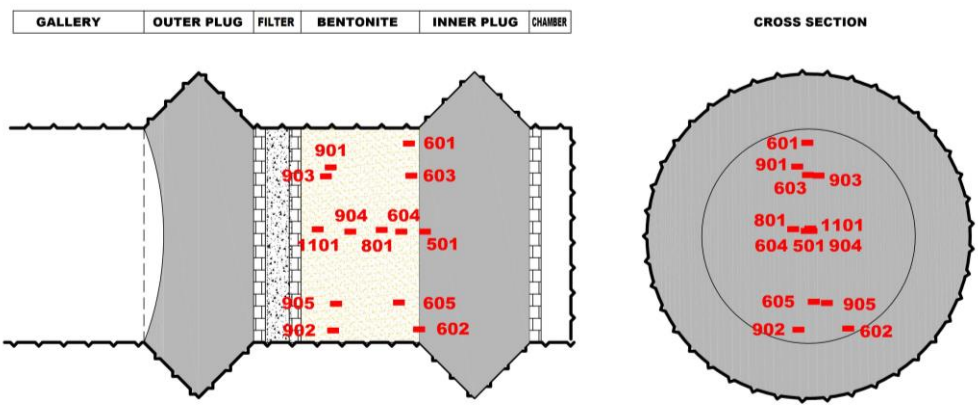


4.2.6. Water content evolution in the bentonite sealing

13 TDR and RH sensors were placed in the bentonite sealing. The location of the sensors is shown in the scheme below and the evolution of water content in the bentonite sealing is shown in the graph.

Water content and humidity evolution support the idea of a bentonite core skin being gradually wetted; indeed, it is possible to see an immediate reaction from those sensors close to the interfaces with the rock and the filter such as RH 603,903 and TDR 601,901. The sensor (501) located on contact with the concrete on the plug axis exhibits a slow increase in water content. The rest of the sensors exhibit only very slow and small changes as wetting progresses. The pace changed however once high pressures (over 0.5MPa) were introduced. A rapid increase in water content was recorded by several sensors following each increase in pressure. Interestingly, sensor 901 which reacted immediately to the first injection was steady in the high pressure injection area. This, together with a temporary decrease in the value measured by sensor 601, indicates that a part close to the filter was saturated enough so as to seal off a rapid/preferential path for the water.

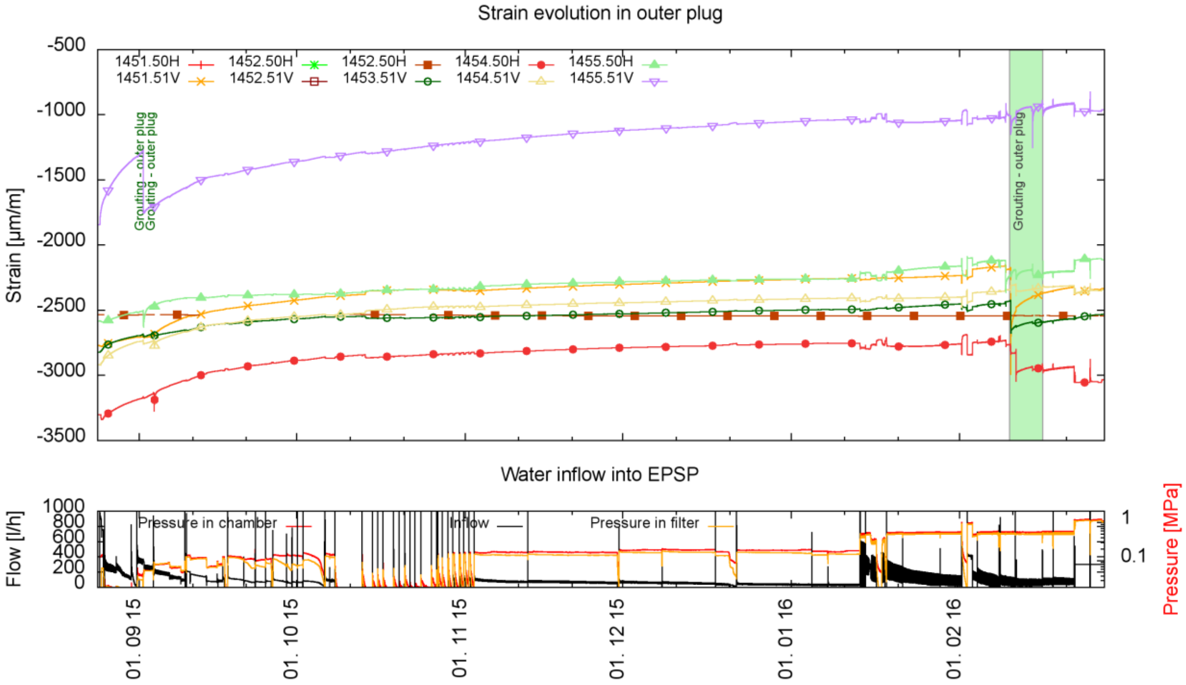


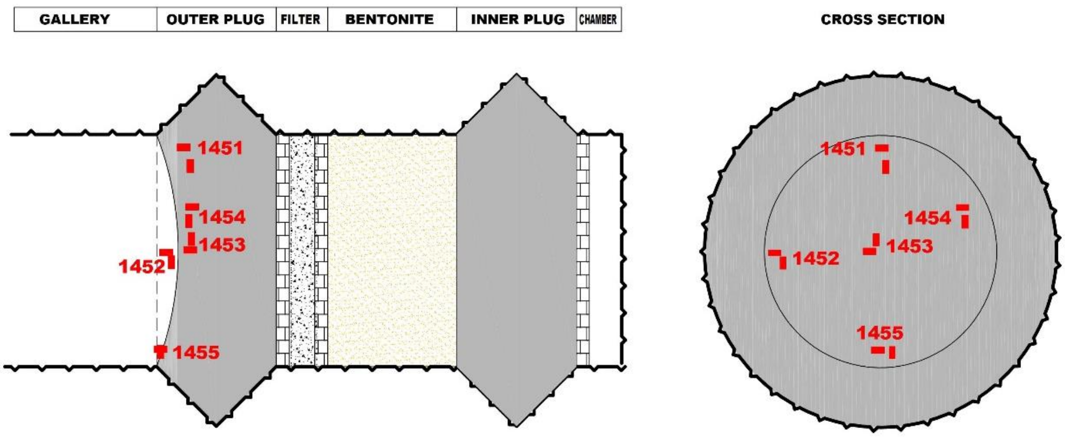


4.2.7. Deformation of the shotcrete (outer plug)

10 strain gauges were placed in the shotcrete during the construction of the inner plug. In each location two sensors were installed so as to monitor horizontal and vertical strain. The location of the sensors is shown in the scheme below and the evolution of strain within the shotcrete is shown in the graph.

There was only a very small mechanical response to pressure loading. Most of the deformation developed steadily and can be attributed to the processes at work within the concrete saturated by water. A mechanical response on the grouting was also observed which, interestingly, was much higher than the response to pressurisation.



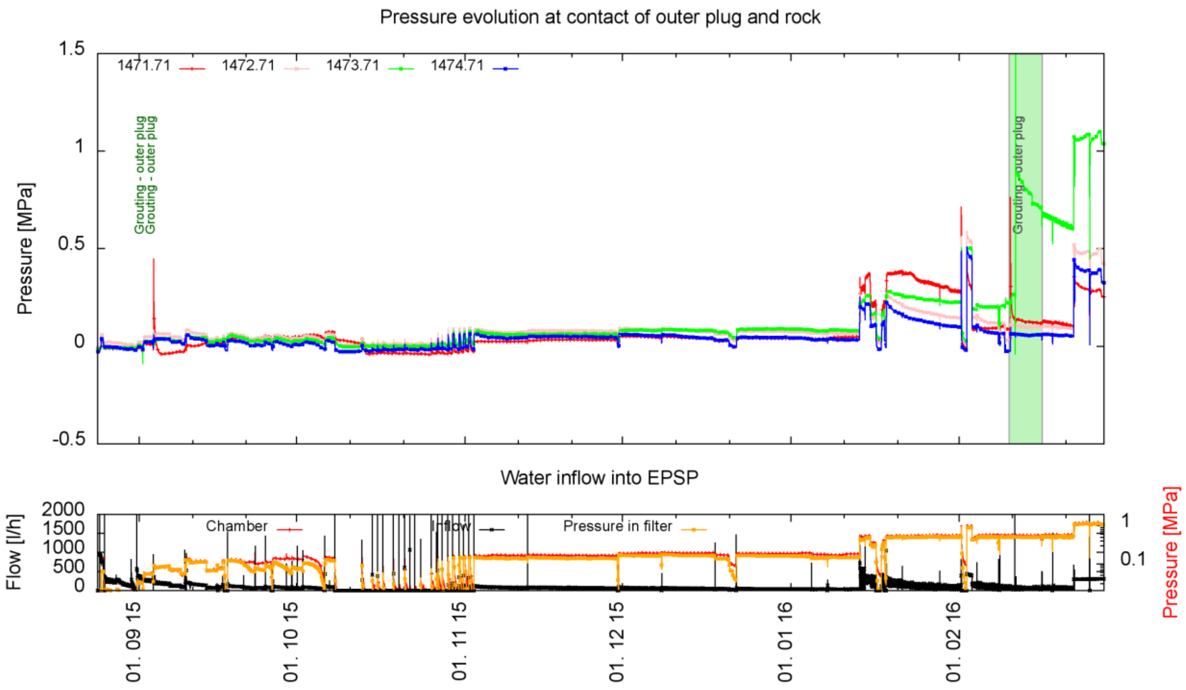


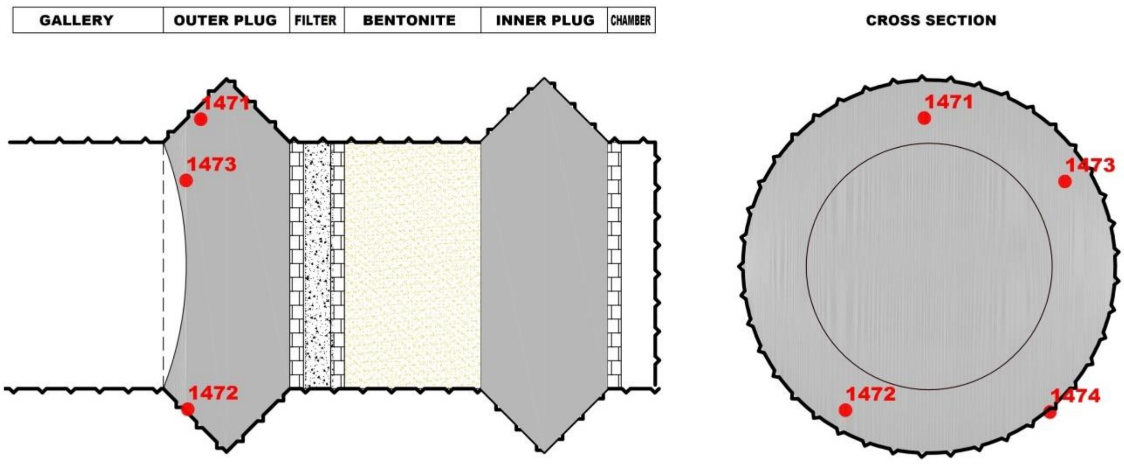
4.2.8. Contact stress evolution between the plug and the rock mass (outer plug)

Four total pressure cells were installed in the plug-rock interface in the wedge.

The location of the sensors is shown in the scheme below and the evolution of stress is shown in the graph below.

Evolution follows the pressure in the filter (with reduced values). Leakage was detected (especially at higher pressures), therefore, additional grouting was applied close to the end of phase 2.





4.3. PHASE 3 - WATER INJECTION INTO THE CHAMBER

Start: 2016-03-07

End: 2016-03-12

Phase 3 was intended as a preparation stage for the eventual injection of a bentonite suspension; in other words, it was a transitional period during which flow was readjusted from overall saturation to a single direction flow. The influence of the previous period was clearly visible especially inside the bentonite.

The main aim was to quickly assess the success of the saturation phase and to obtain a baseline prior to the injection of the bentonite suspension if possible.

This phase consisted of water injection into the chamber only (the filter was drained). Pressure was increased step-by-step up to 0.4MPa.

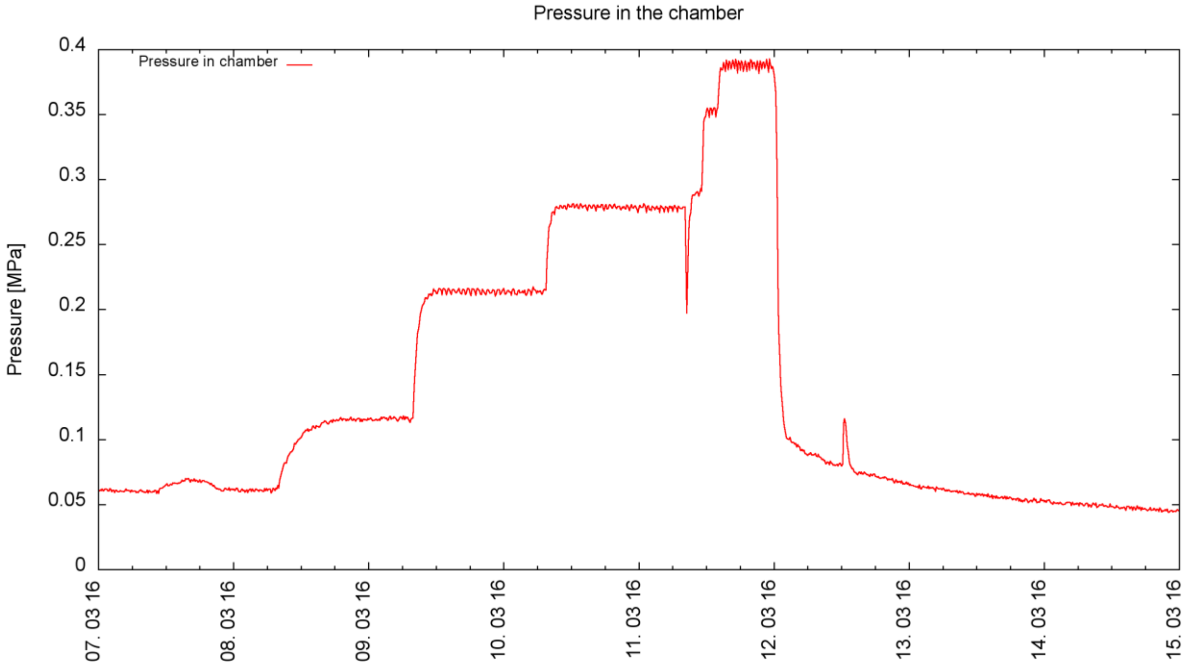
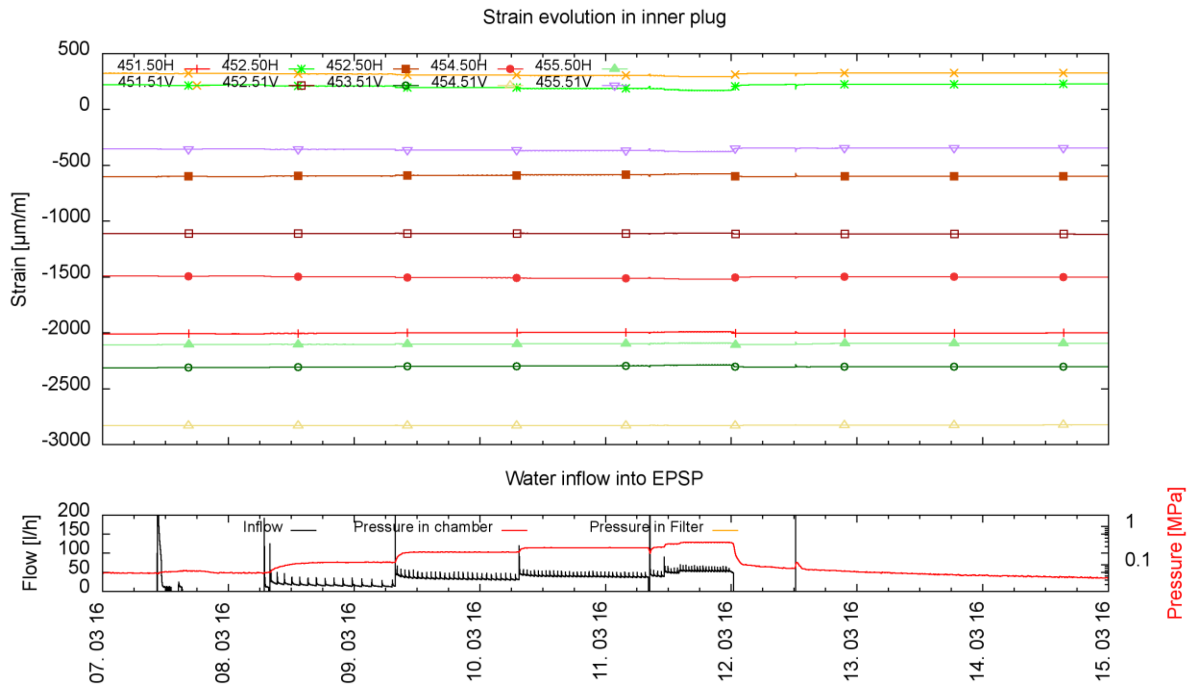


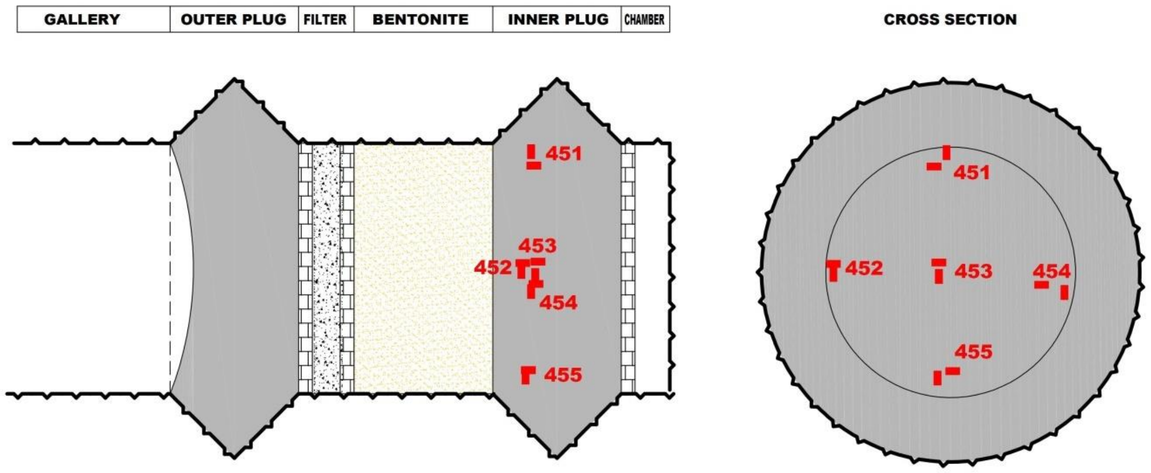
Figure 11 - Pressure in the pressurisation chamber during Phase 3

4.3.1. Deformation of the shotcrete (inner plug)

Ten strain gauges were placed in the shotcrete during the construction of the inner plug. In each location two sensors were installed so as to monitor horizontal and vertical strain. The location of the sensors is shown in the scheme below and the evolution of strain within the shotcrete is shown in the graph.

The response within the concrete plug was negligible – practically no deformation was detected.



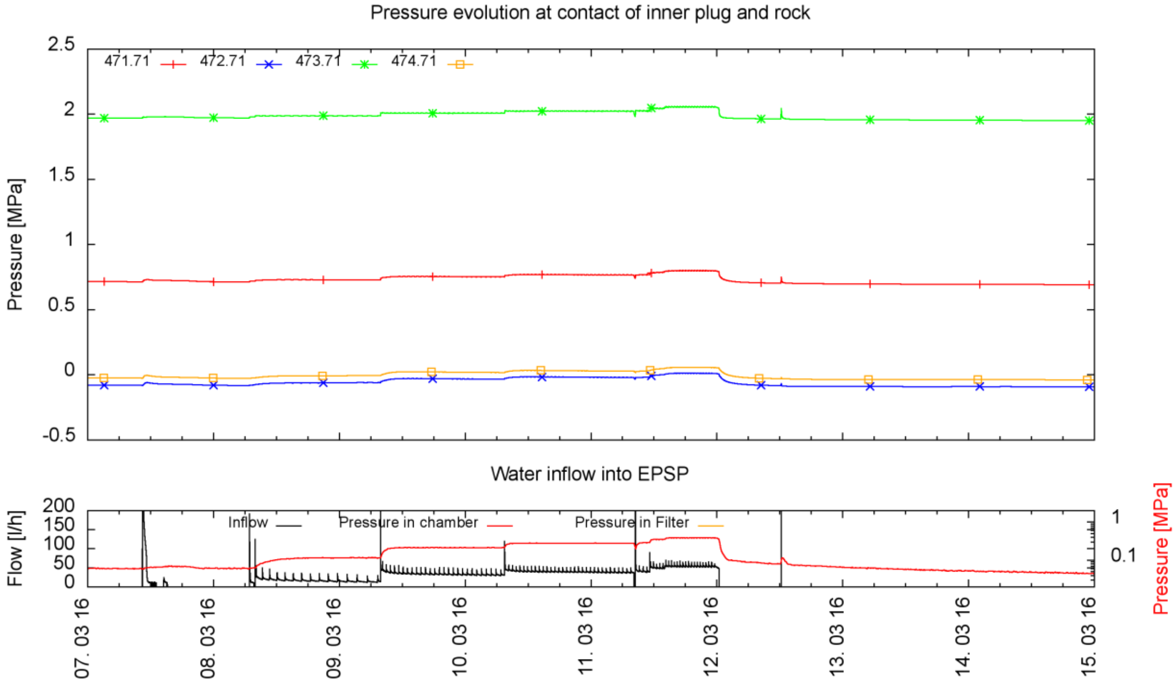


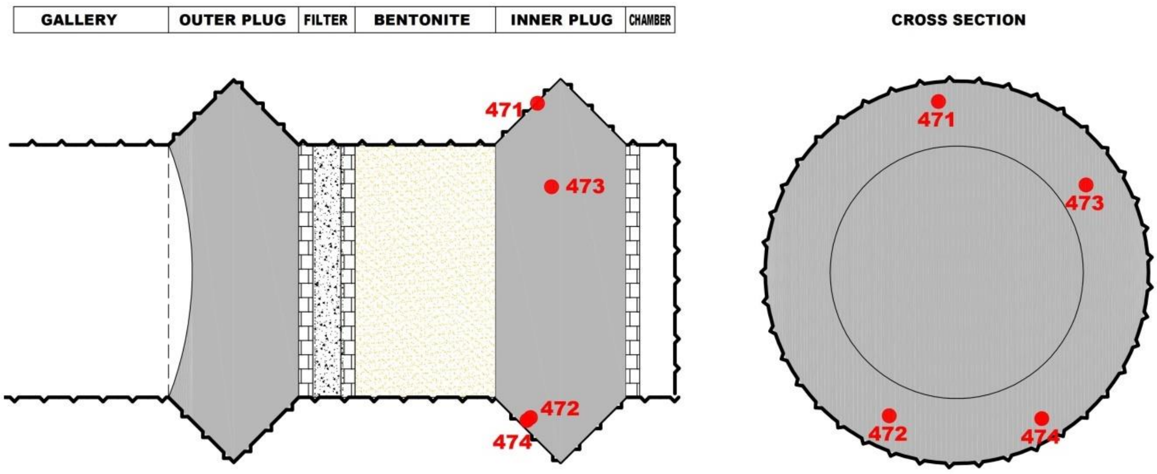
4.3.2. Contact stress evolution on the contact between the inner plug and the rock mass

Four total pressure cells were installed in the plug-rock interface in the wedge.

The location of the sensors is shown in the scheme below and the evolution of stress is shown in the graph below.

Interestingly, the response of the pressure cells was very small (<0.15MPa for 0.4MPa) and the reaction of all the cells was the same. There was no continuation of the "independent" operation of sensor 473 from the previous phase. It seems that the plug nicely wedged itself into the rock due to water pressure.



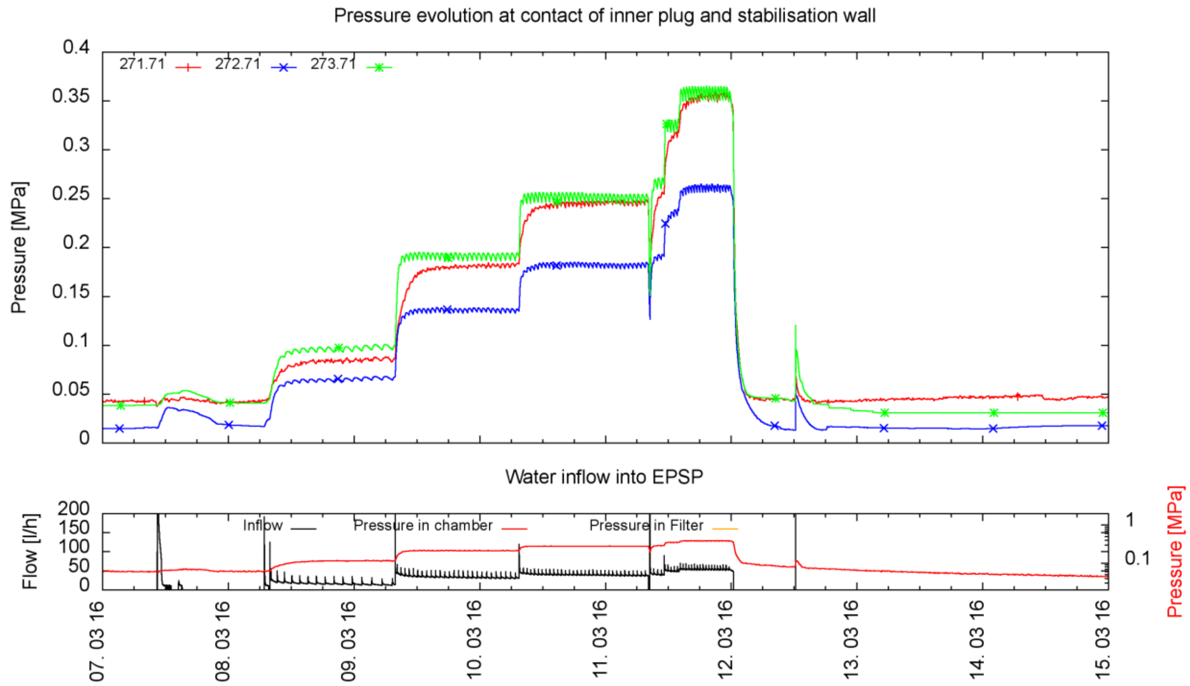


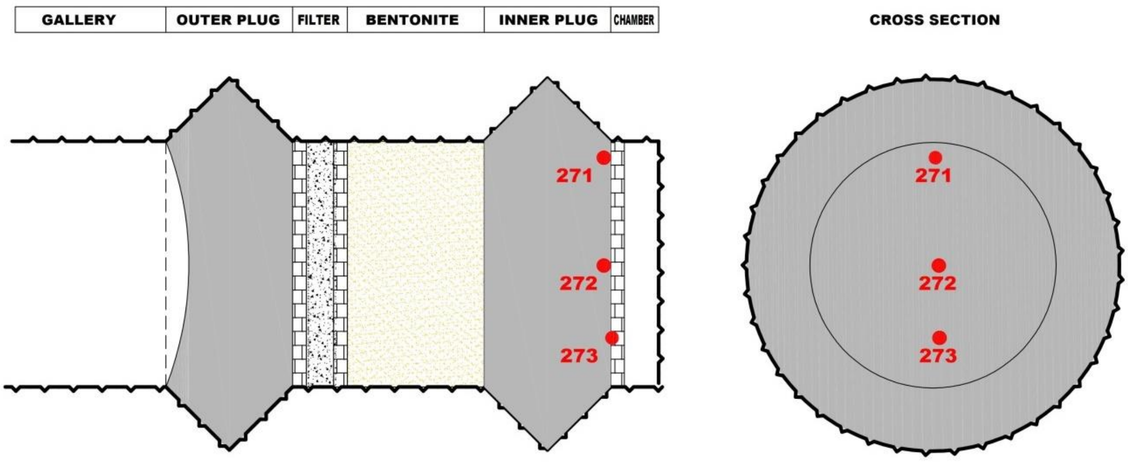
4.3.3. Contact stress evolution between the inner plug and the stabilisation wall

Three total pressure cells were installed in the plug-stabilisation wall interface.

The location of the sensors is shown in the scheme below and the evolution of stress is shown in the graph below.

Pressure follows the pressure in the chamber which indicates that the interaction between the separation wall and plug is minimal and that the wall does not obstruct water flow i.e. it works as intended. No change in behaviour was recorded compared to the previous phases.

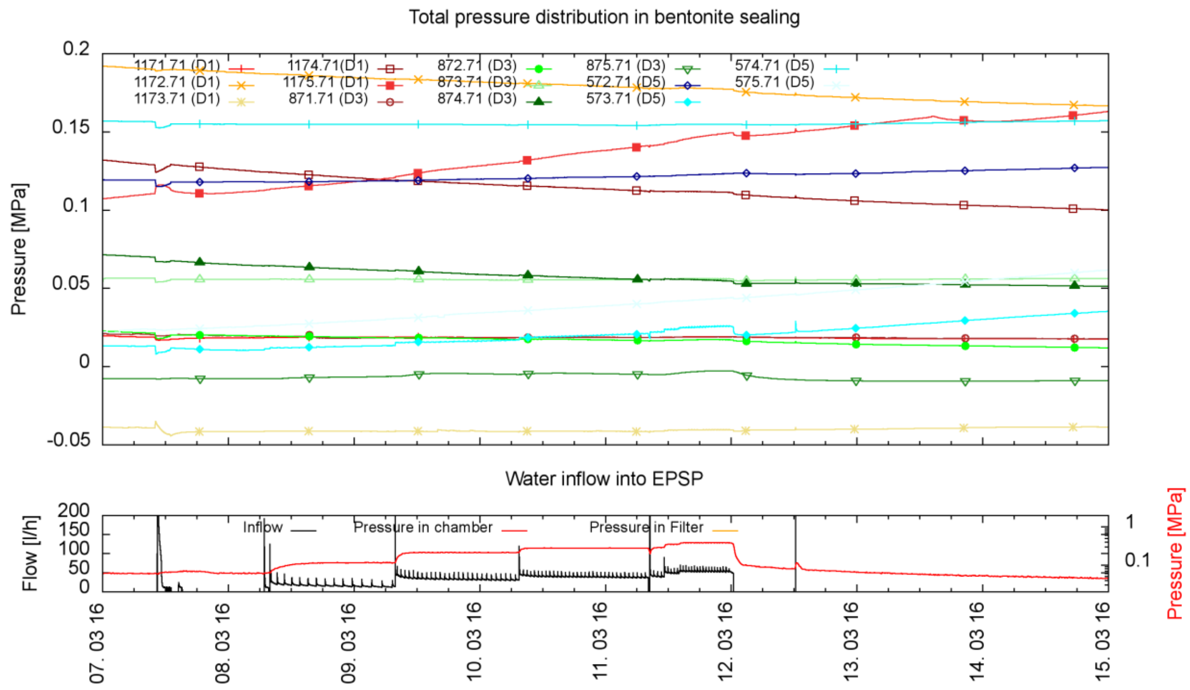


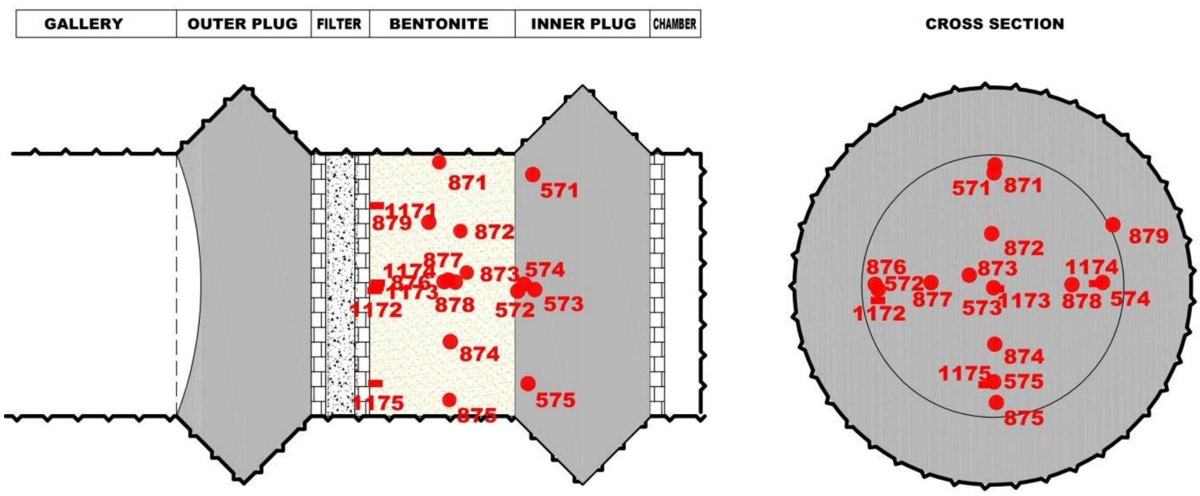


4.3.4. Total pressure evolution in the bentonite sealing

20 total pressure cells were installed in the bentonite sealing. The location of the sensors is shown in the scheme below and the evolution of stress is shown in the graph below.

The transition from the saturation phase to single direction flow can be observed in the graph. Most of the changes are of a long-term nature and most probably driven by swelling pressure slightly influenced by pressurisation.

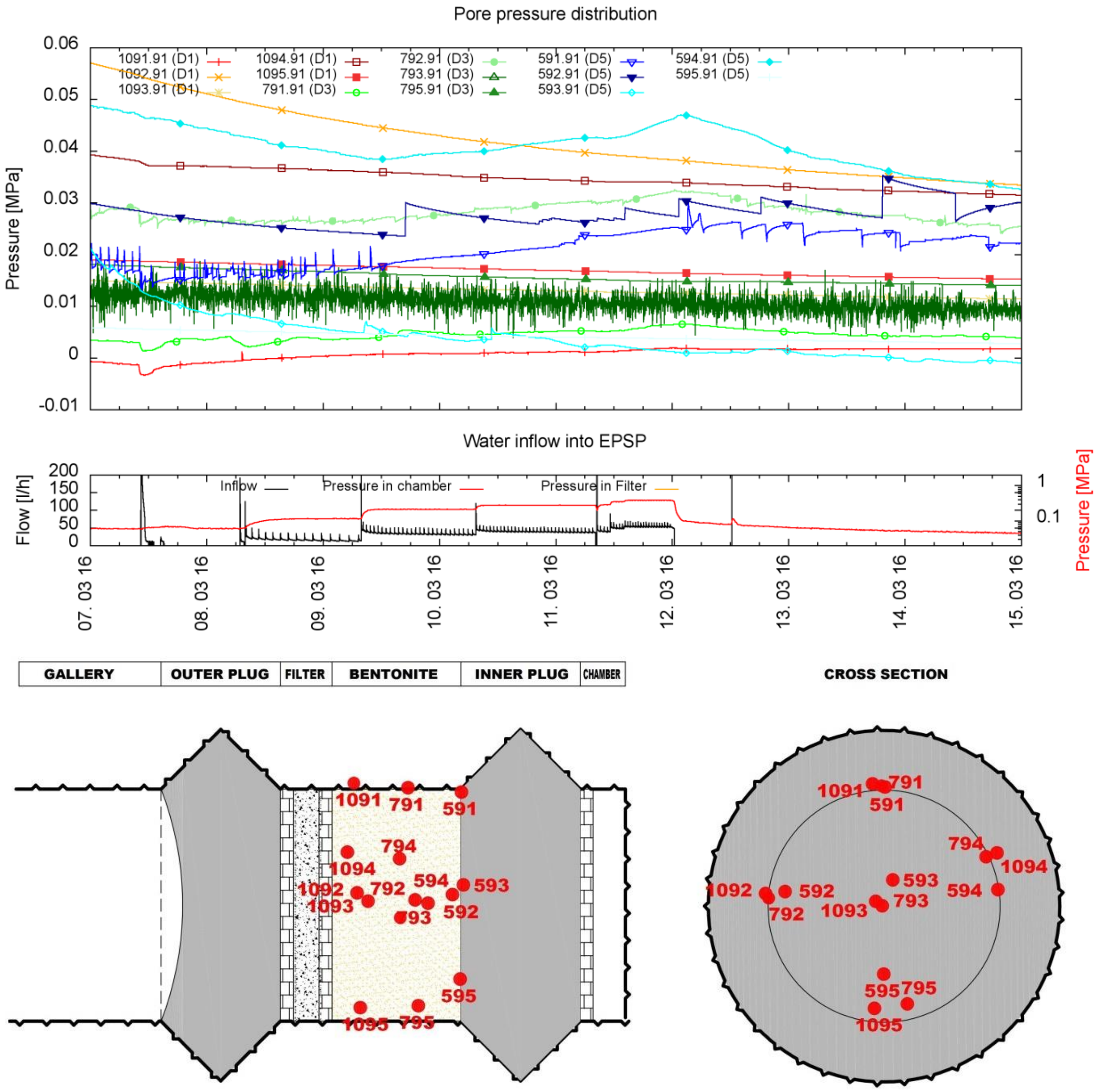




4.3.5. Pore pressure evolution in the bentonite sealing

14 piezometers were placed in the bentonite sealing. The location of the sensors is shown in the scheme below and the evolution of pore pressure within the bentonite is shown in the graph.

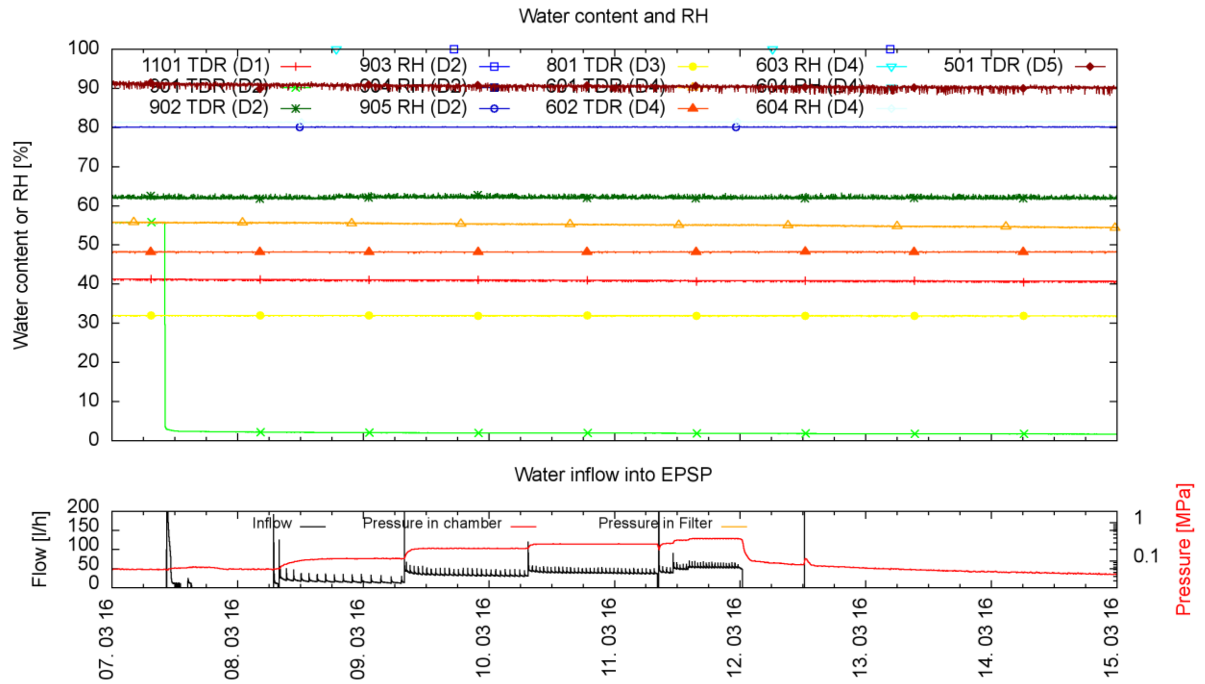
The transition from the saturation phase to single direction flow can be observed in the graph. Most of the changes were of a long-term nature showing that pressure redistribution following the end of the saturation phase had not yet completely finished. It is therefore quite hard to properly attribute the development of pore pressures (processes acting against each other).

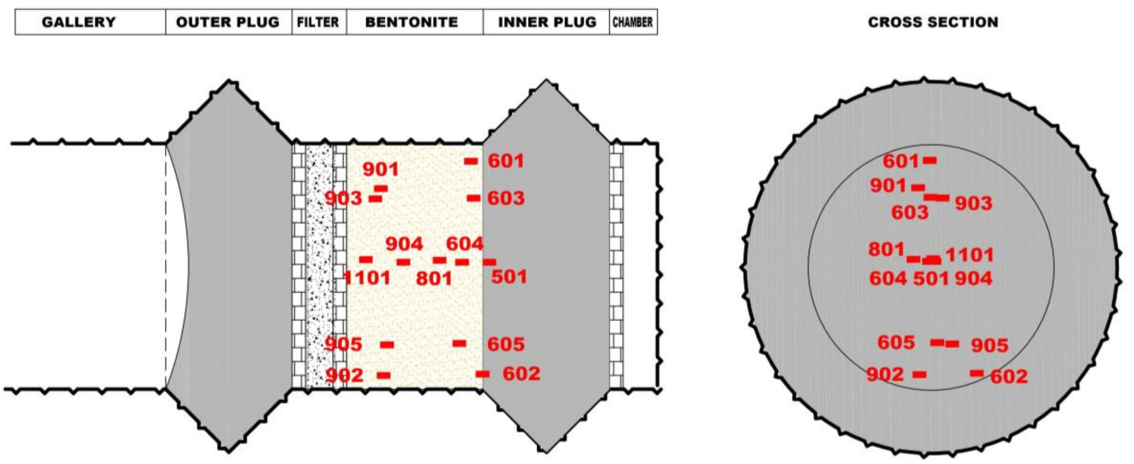


4.3.6. Water content evolution in the bentonite sealing

13 TDR and RH sensors were placed in the bentonite sealing. The location of the sensors is shown in the scheme below and the evolution of water content in the bentonite sealing is shown in the graph.

Although there were changes in pore pressure within the bentonite, there were no changes in water content distribution. The sudden change recorded by sensor 901 is unrealistic and most probably indicates sensor error (it shows measurement in air).

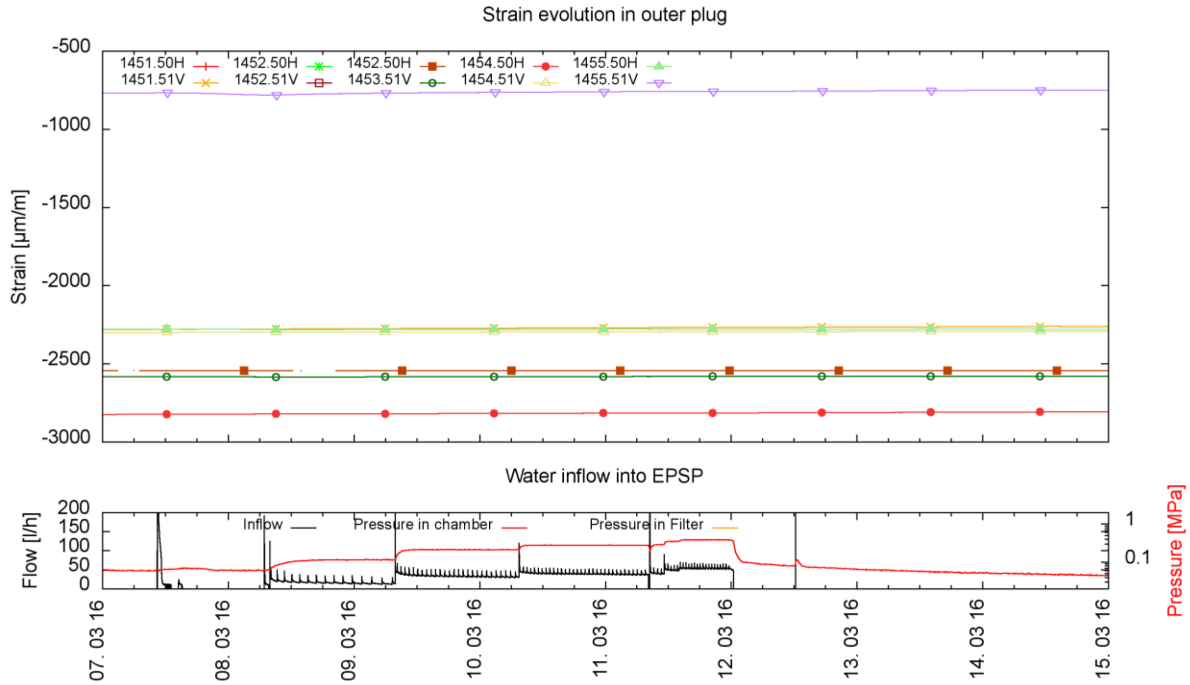


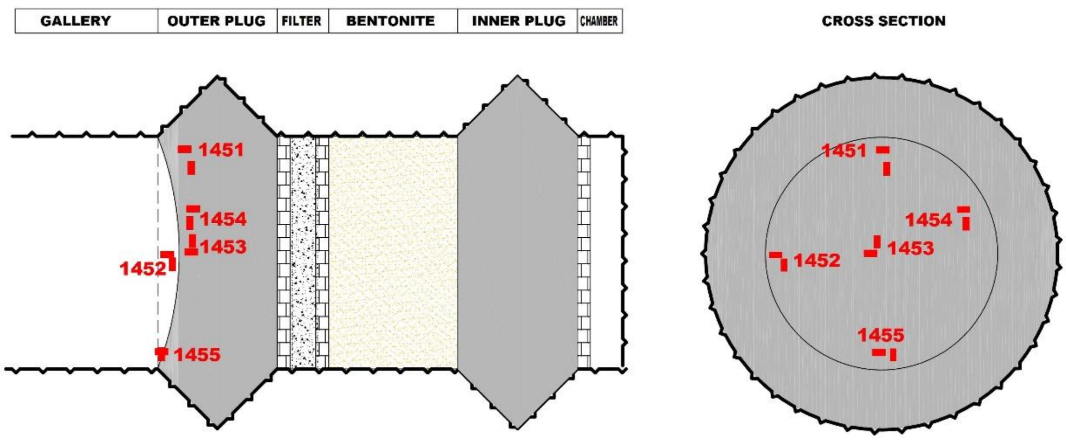


4.3.7. Deformation of the shotcrete (outer plug)

10 strain gauges were placed in the shotcrete during the construction of the inner plug. In each location two sensors were installed so as to monitor horizontal and vertical strain. The location of the sensors is shown in the scheme below and the evolution of strain in the shotcrete is shown in the graph.

As was to be expected, there was no reaction with respect to the unloaded plug.



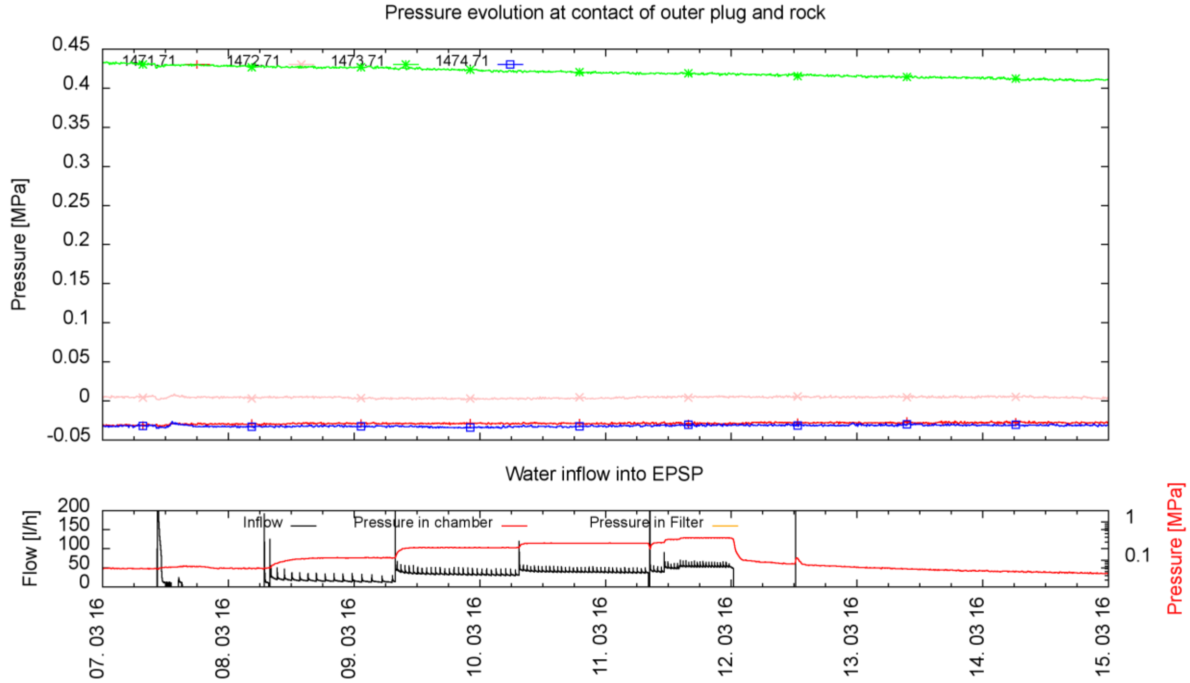


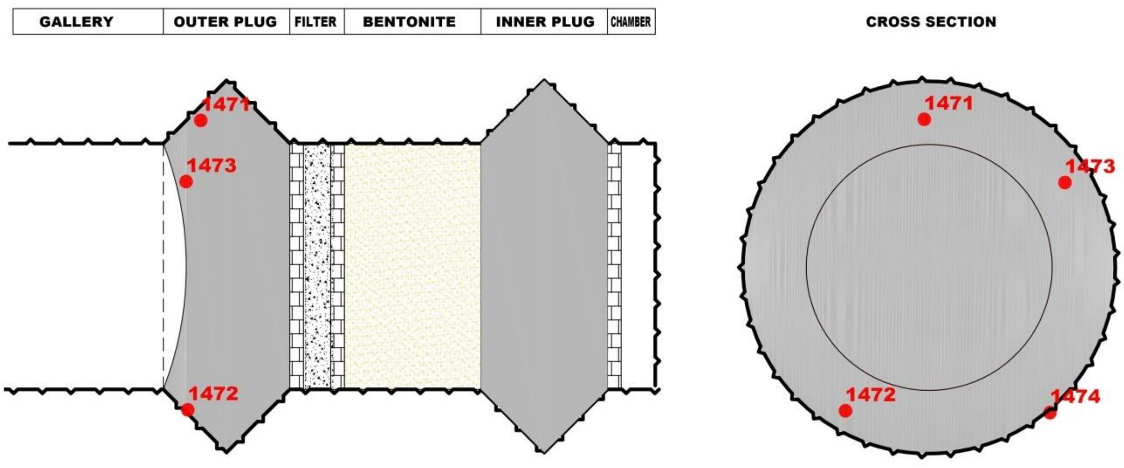
4.3.8. Contact stress evolution between the plug and the rock mass (outer plug)

Four total pressure cells were installed in the plug-rock interface in the wedge.

The location of the sensors is shown in the scheme below and the evolution of stress is shown in the graph below.

As was to be expected, there was no reaction with respect to the unloaded plug except for a slight but steady decrease monitored by sensor 1473.





4.4. PHASE 4 - INJECTION OF BENTONITE SLURRY INTO THE CHAMBER

Start: 2016-03-15 Commencement of the first bentonite slurry injection into the chamber

End: 2016-03-17 End of injection

Phase 4 focused on the injection of bentonite slurry into the pressurisation chamber. A total of three campaigns were performed at different pressure levels. The filter was filled with water and back pressure was maintained so as to prevent the slurry from contaminating the filter.

Following the conclusion of the final campaign, any remaining slurry was extracted from the chamber and the chamber was flushed clean using water.

Phase	Start	End	Injection period [min]	Pressure [MPa]
4.1	2016-03-15 09:15:00	2016-03-15 14:15:00	300	1-1.5
4.2	2016-03-16 07:40:00	2016-03-16 13:00:00	320	2
4.3	2016-03-17 08:00:00	2016-03-17 13:40:00	340	3

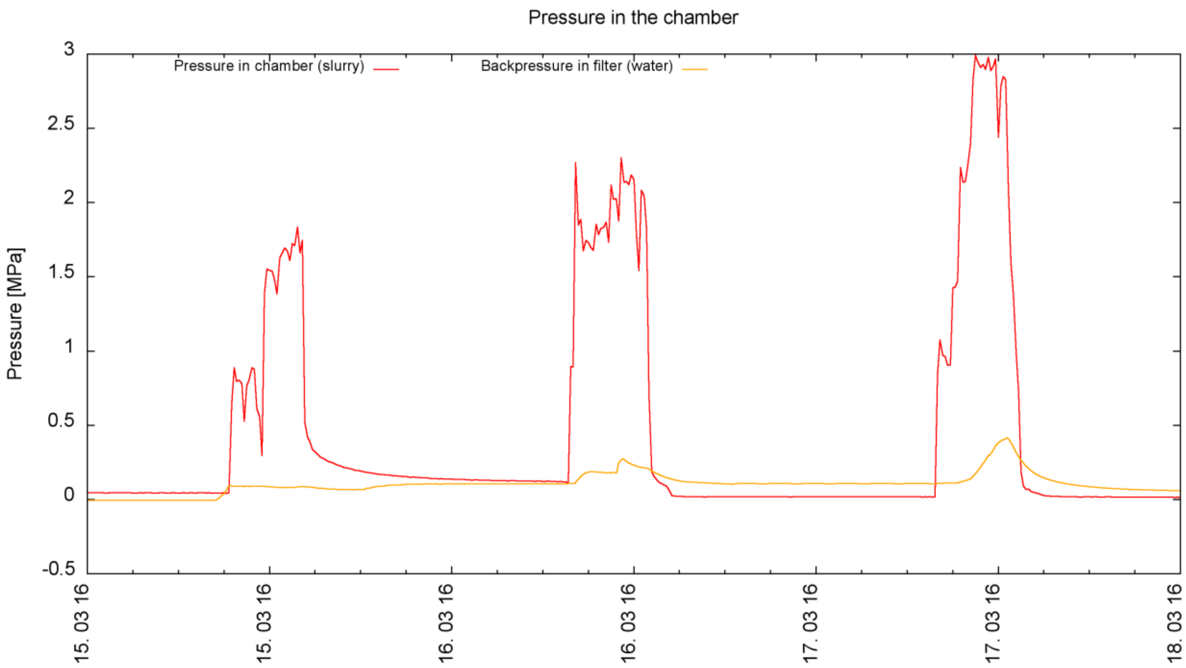
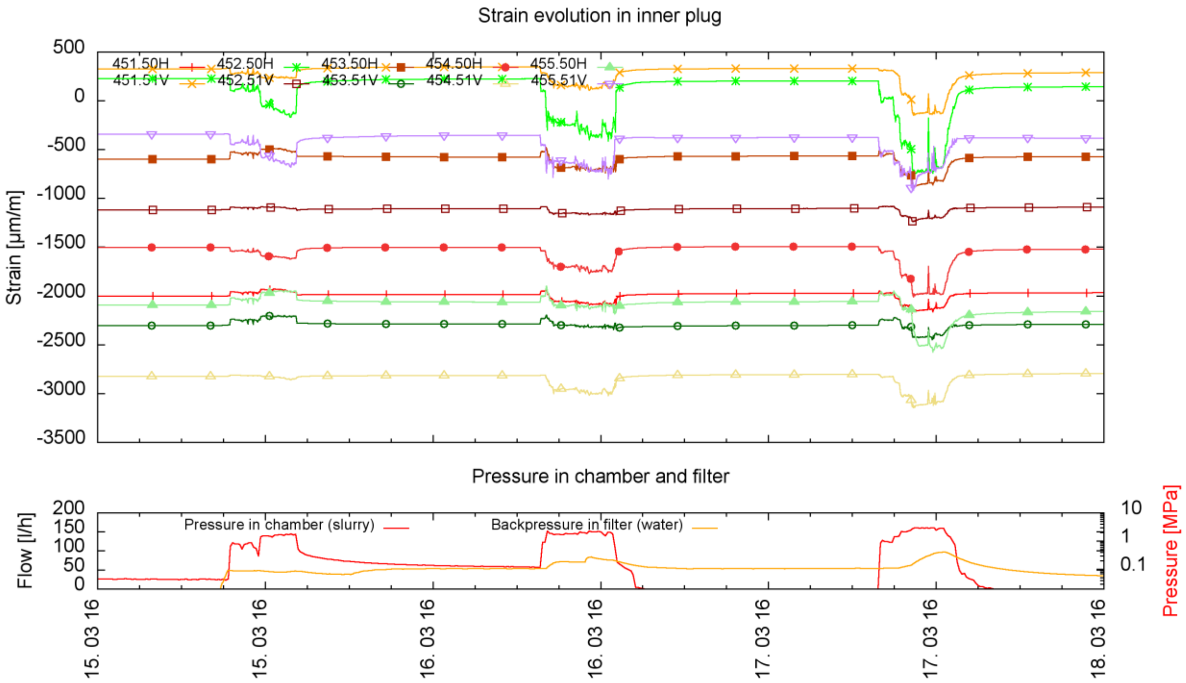


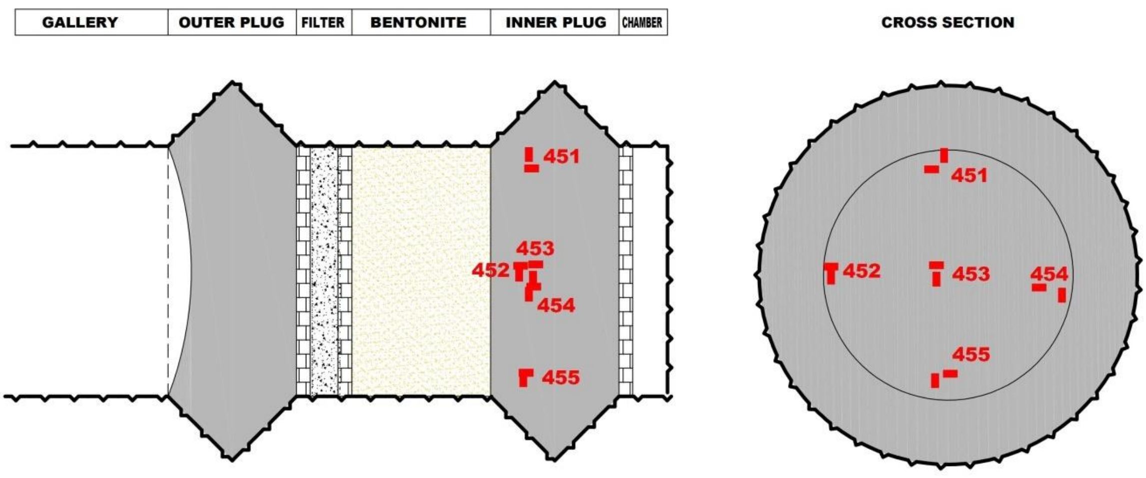
Figure 12 - Pressure in the chamber and the filter

4.4.1. Deformation of the shotcrete (inner plug)

Ten strain gauges were placed in the shotcrete during the construction of the inner plug. In each location two sensors were installed so as to monitor horizontal and vertical strain. The location of the sensors is shown in the scheme below and the evolution of strain in the shotcrete is shown in the graph.

Measured deformation was not completely evenly distributed which was most probably caused by the uneven surface of the excavated slot which led to higher loads in certain areas. Notwithstanding, deformation corresponds to both load and structure types.



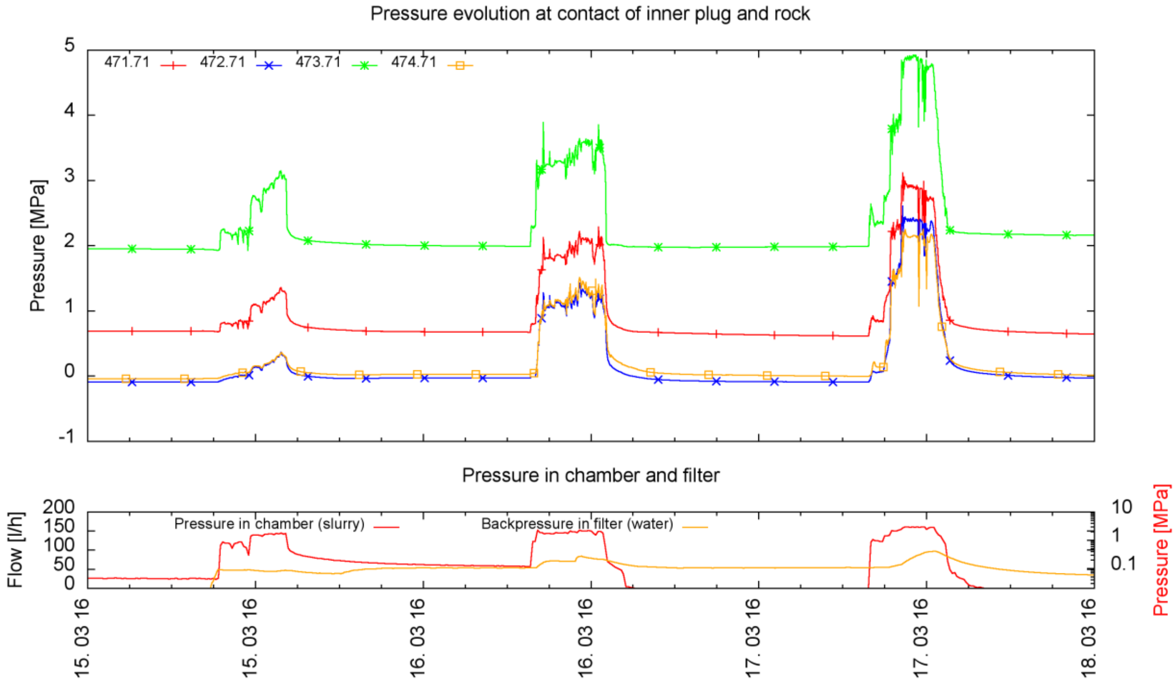


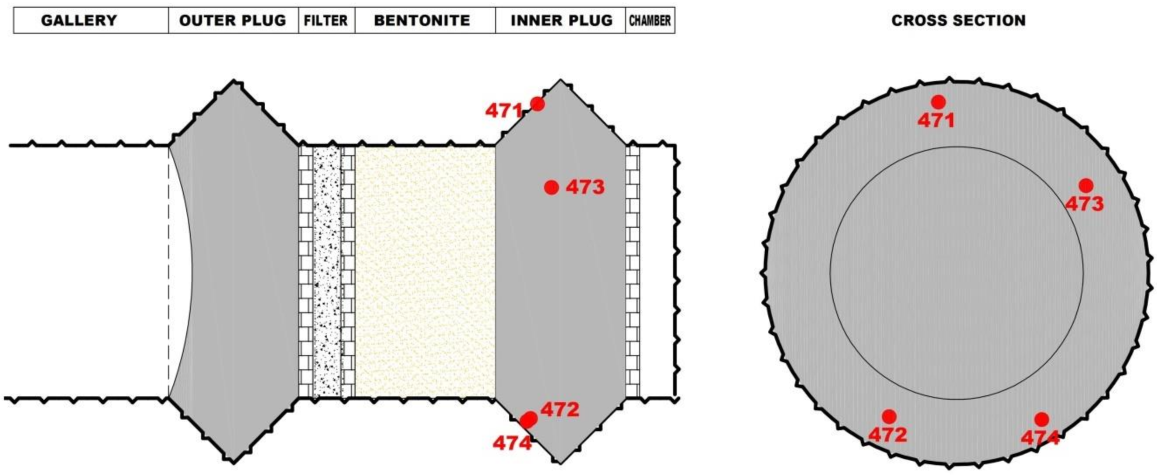
4.4.2. Contact stress evolution on the contact between the inner plug and the rock mass

Four total pressure cells were installed in the plug-rock interface in the wedge.

The location of the sensors is shown in the scheme below and the evolution of stress is shown in the graph below.

The absolute values were influenced by grouting; therefore, only the relative changes are important for evaluation purposes. Pressure increased according to the rate of injection of water into the chamber. The increase in the pressure value follows chamber pressure with only a relatively slight difference, which indicates either a good hydraulic connection to the chamber or that the plug wedges into the rock or both.



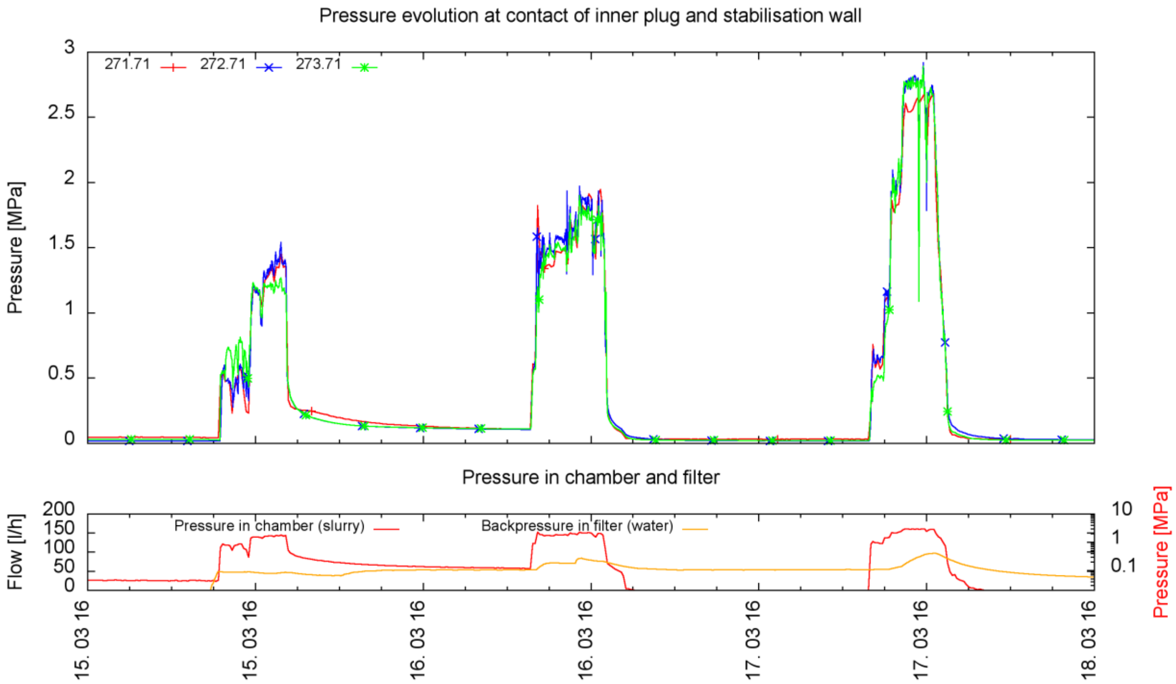


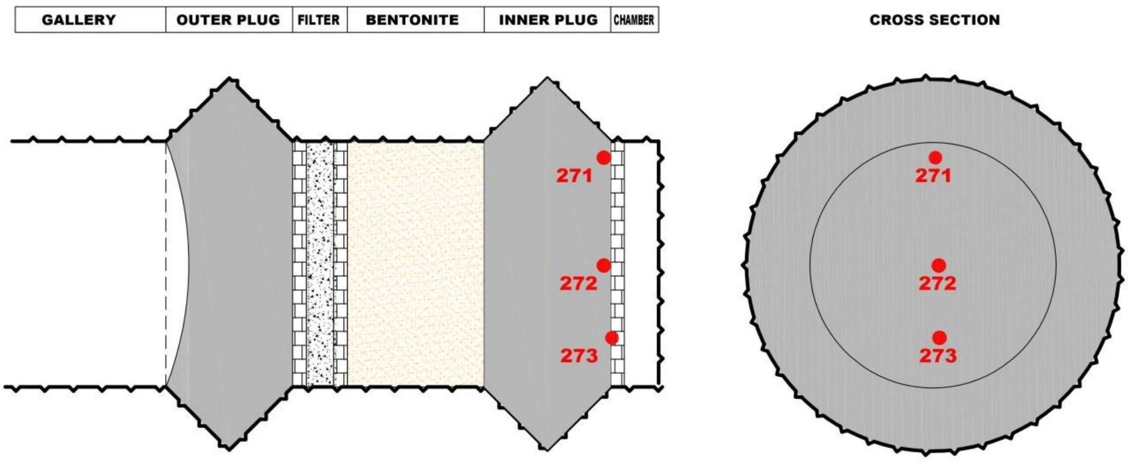
4.4.3. Contact stress evolution between the inner plug and the stabilisation wall

Three total pressure cells were installed in the plug-stabilisation wall interface.

The location of the sensors is shown in the scheme below and the evolution of stress is shown in the graph below.

Pressure follows the pressure in the chamber which indicates that interaction between the separation wall and the plug was minimal and that the wall does not obstruct water flow i.e. it works as intended. No change in behaviour was recorded compared to the previous phase.



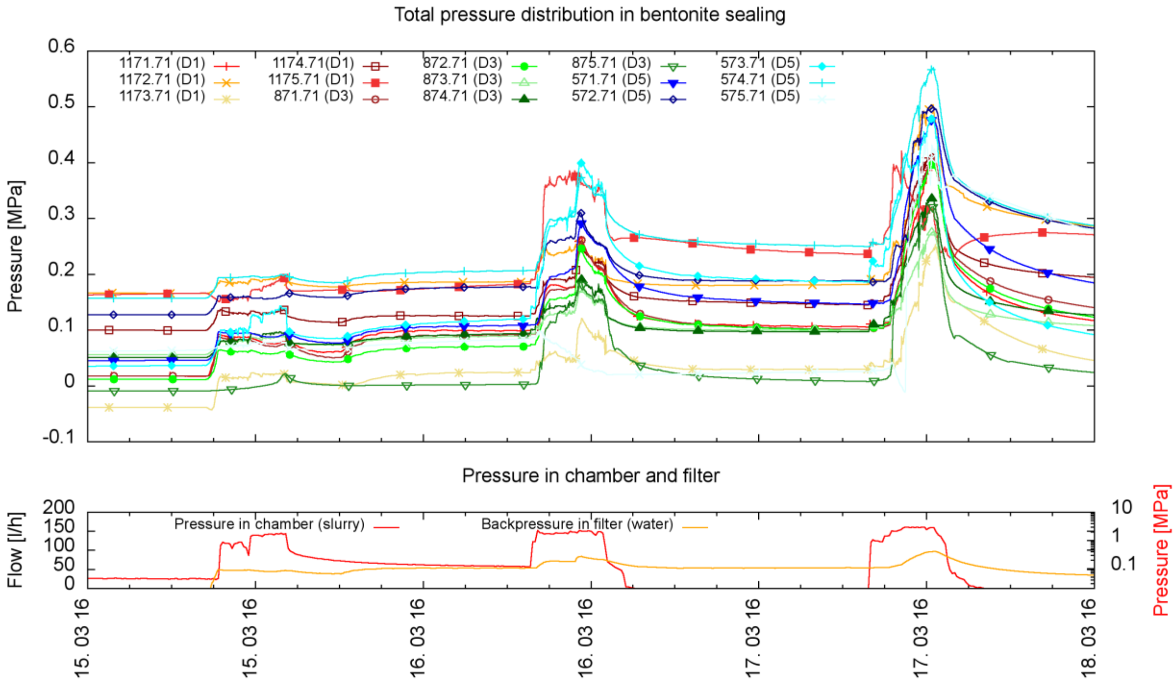


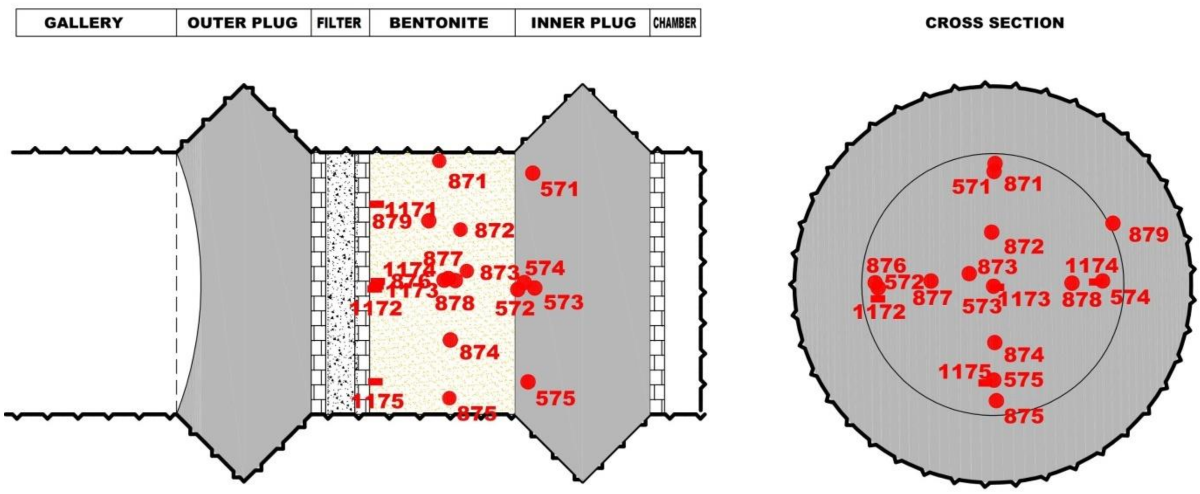
4.4.4. Total pressure evolution in the bentonite sealing

20 total pressure cells were installed in the bentonite sealing. The location of the sensors is shown in the scheme below and the evolution of stress is shown in the graph below.

The reaction in the first campaign (rather mute) indicates that swelling pressure inside the EPSP reached 0.1-0.2MPa. This is further supported by a similar difference between total and pore pressure during the campaigns.

It was discovered that the high pressure of the slurry was able to mechanically breach and push against the bentonite. This was demonstrated in the second and third campaigns in which an increase in pore pressure raised total pressure. During the second campaign, during which initially the reaction was reduced, an important event occurred (in the middle of the campaign) most probably involving the opening of a new pathway which led to a pore pressure (and total pressure) surge.





4.4.5. Pore pressure evolution in the bentonite sealing

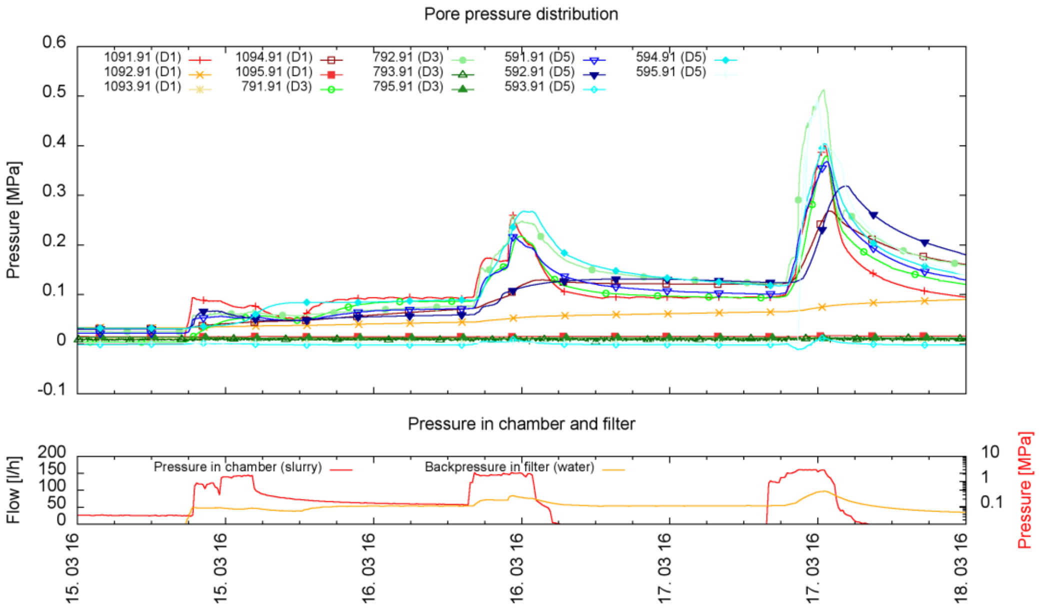
14 piezometers were placed in the bentonite sealing. The location of the sensors is shown in the scheme below and the evolution of pore pressure within the bentonite is shown in the graph.

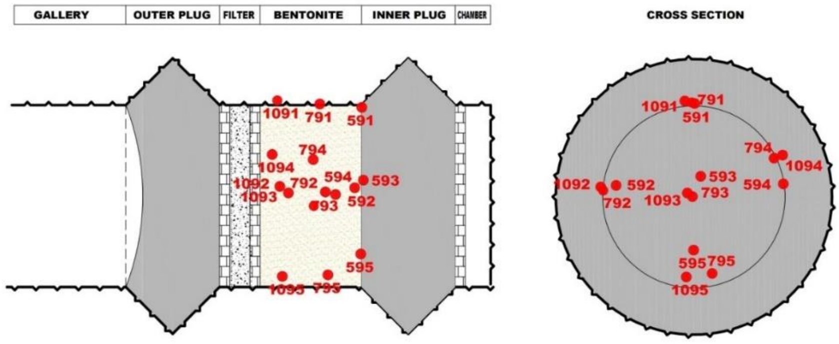
Pore pressure follows the injection of the suspension but at much lower values, which indicates that the inner plug works as intended, i.e. as the first hydraulic barrier (demonstrated by the final campaign in which slurry pressure was significantly above the maximum swelling pressure of the bentonite).

An important development occurred in the second campaign involving certain sensors showing only a gradual increase to 0.1MPa and others exhibiting saddles of around 0.15MPa. This would tend to indicate that the bentonite started to work more and more as a sealing medium and estimates swelling pressure around 0.1-0.2MPa. Moreover, the even part in the middle probably indicates the opening of a new pathway (probably hydraulically connected to the filter).

Development between the campaigns could be attributed to back pressure which was maintained at around 0.1MPa without interruption between the campaigns and to the ability of the swollen parts to “trap” pore pressure up to a certain level.

Note: the “core” was not influenced (see chapter 4.2.5)



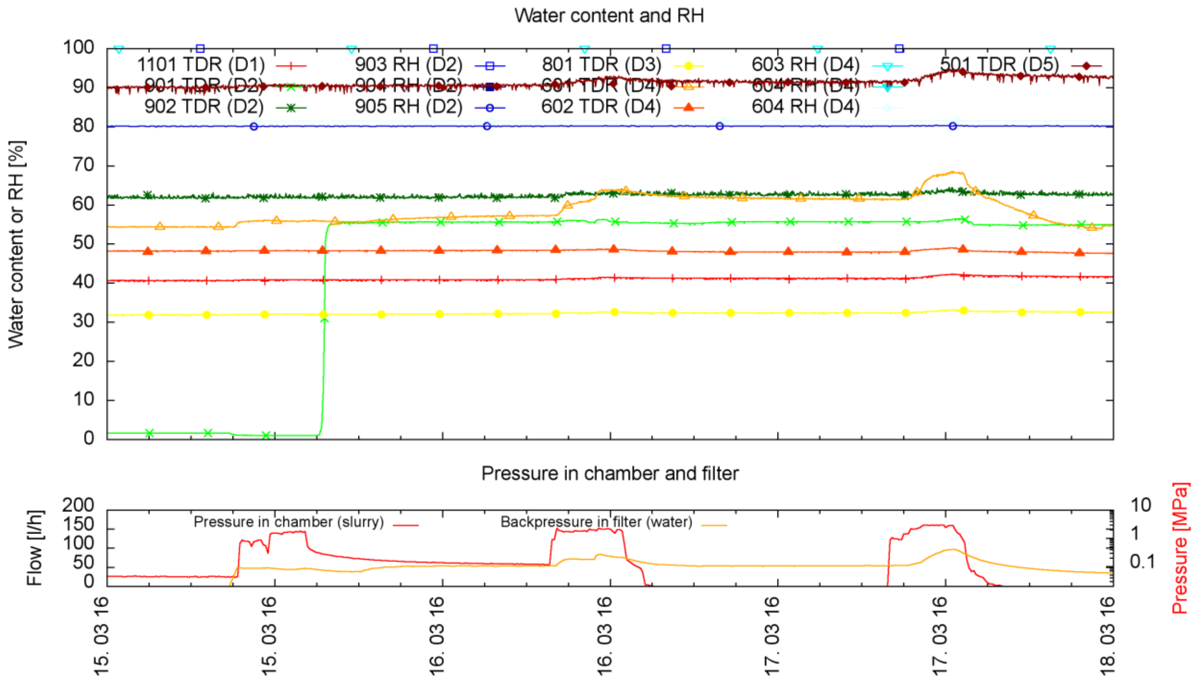


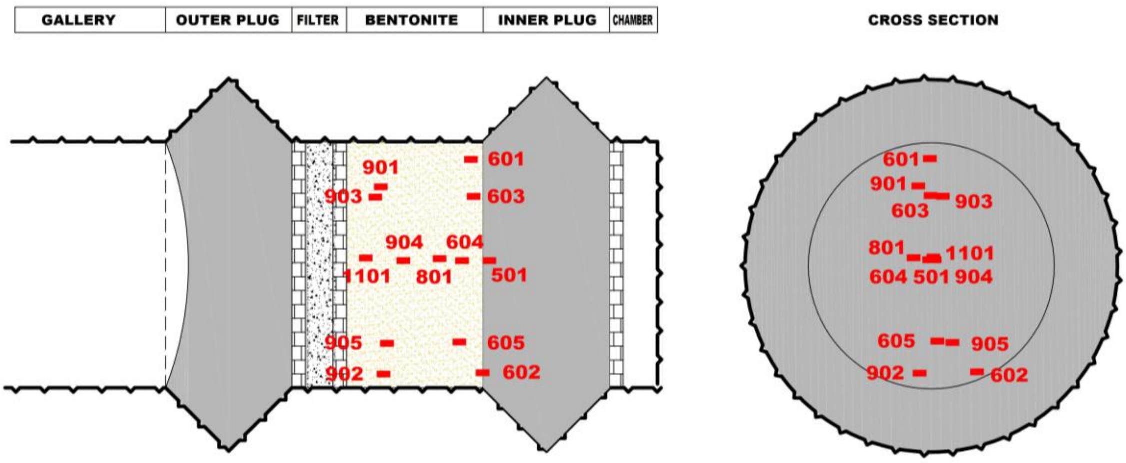
4.4.6. Water content evolution in the bentonite sealing

13 TDR and RH sensors were placed in the bentonite sealing. The location of the sensors is shown in the scheme below and the evolution of water content in the bentonite sealing is shown in the graph.

In most places no sudden change in water distribution was evident in the experiment which indicates that although there were certain changes in pore pressure, very little water moved inside the experiment.

However, there was one exception; with concern to the area in which sensor 601 is located (the upper part close to the inner plug) it seems that there was a significant temporary increase in water content during the campaigns. However, following the final test the value returned to normal. It appears that the slurry found a temporary path (probably along the rock – plug – shot clay interface) which quickly healed once the high pressures were shut off. A similar event but on a much smaller scale was witnessed on the face of the inner plug.

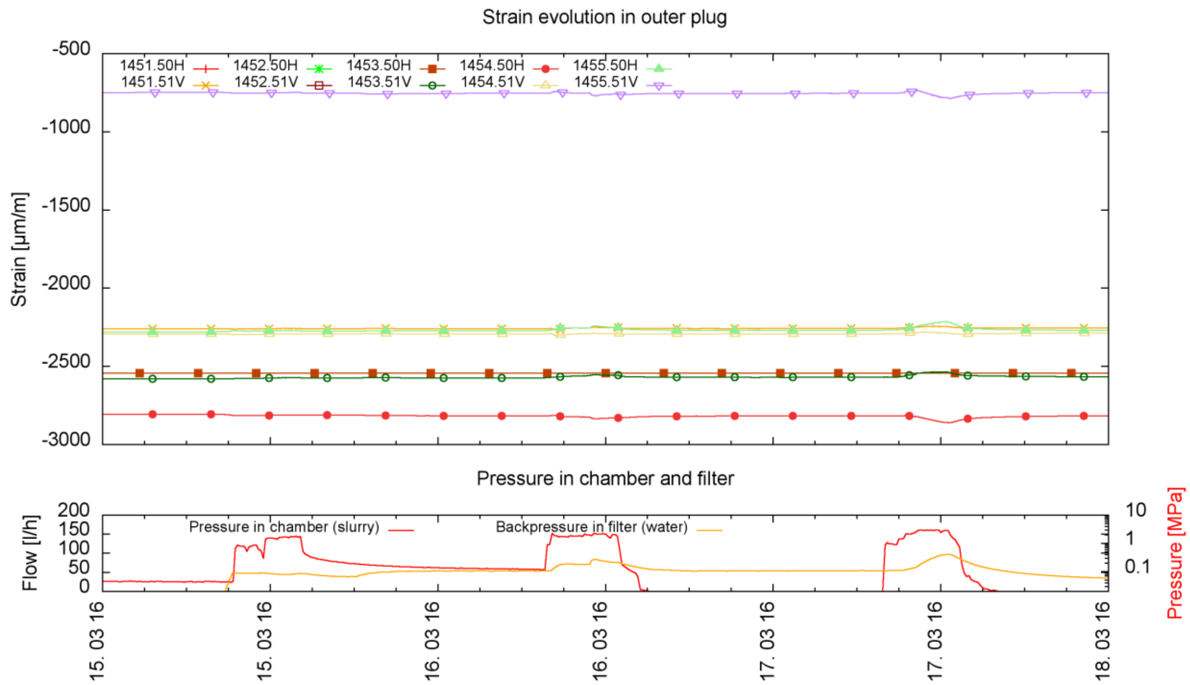


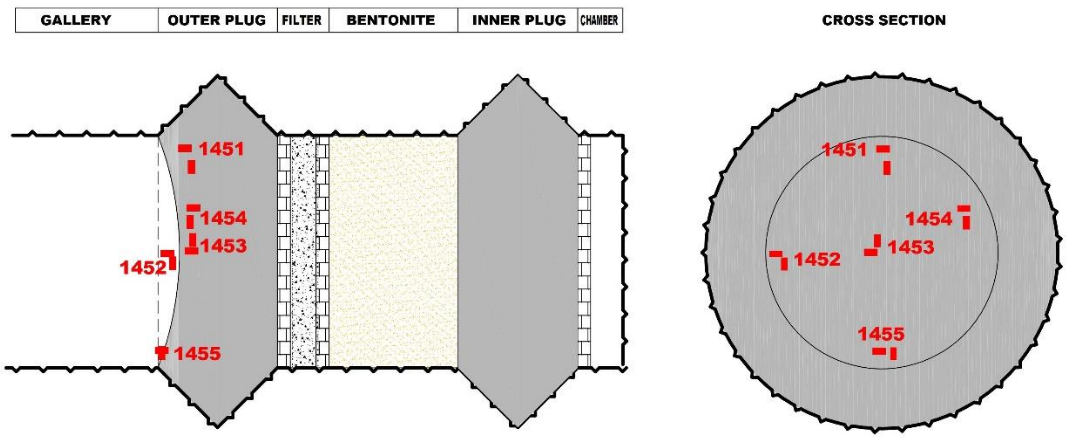


4.4.7. Deformation of the shotcrete (outer plug)

10 strain gauges were placed in the shotcrete during the construction of the inner plug. In each location two sensors were installed so as to monitor horizontal and vertical strain. The location of the sensors is shown in the scheme below and the evolution of strain in the shotcrete is shown in the graph.

There was a very minor temporary response from the outer plug which was totally in line with pressure changes inside the filter.



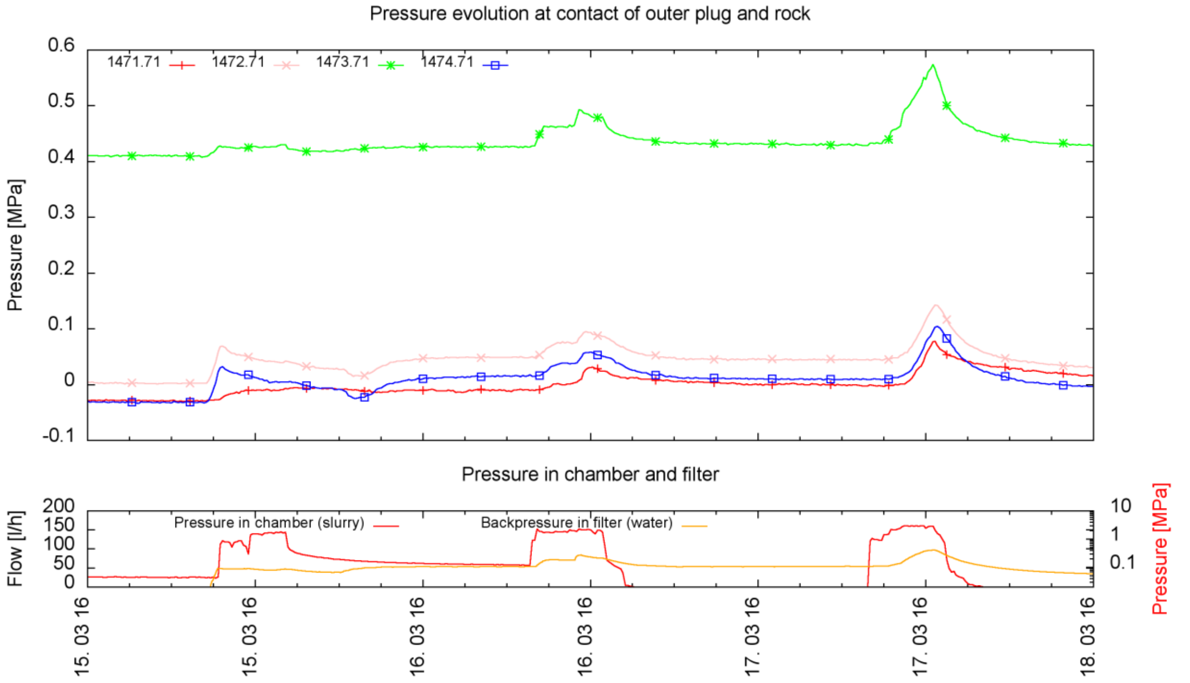


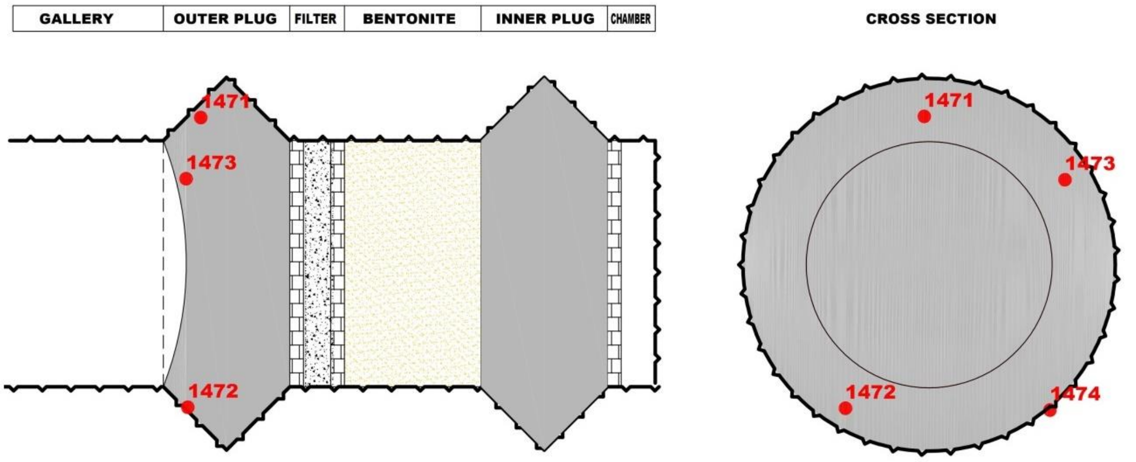
4.4.8. Contact stress evolution between the plug and the rock mass (outer plug)

Four total pressure cells were installed in the plug-rock interface in the wedge.

The location of the sensors is shown in the scheme below and the evolution of stress is shown in the graph below.

The absolute values were influenced by grouting and only the relative changes are important for evaluation purposes. Pressure followed filter pressure but at a reduced scale which indicates either hydraulic connection to the chamber or that the plug wedged into the rock or both.





4.5. PHASE 5 - WATER INJECTION INTO THE CHAMBER

Start: 2016-03-22

End: still running

Phase 5 is, in a sense, a continuation of phase 1 which was interrupted by the discovery of potential piping.

Water is continuously being injected into the chamber and pressure is being increased step-by-step.

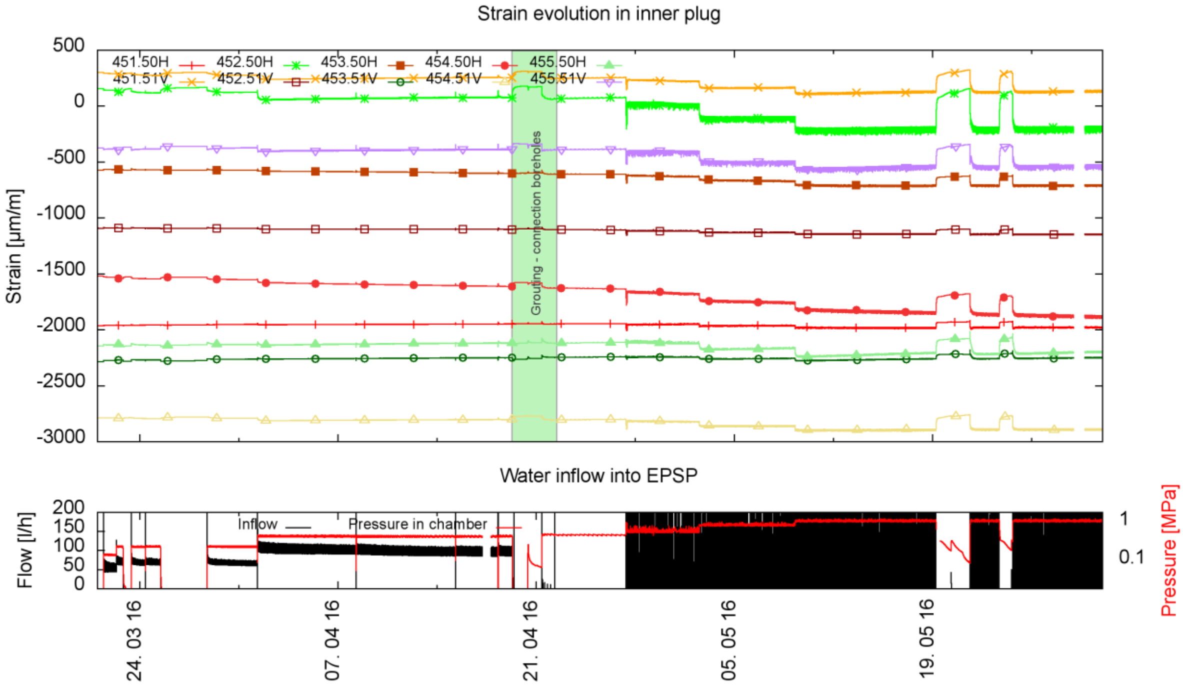
The filter is open continuously and outflow is being monitored.

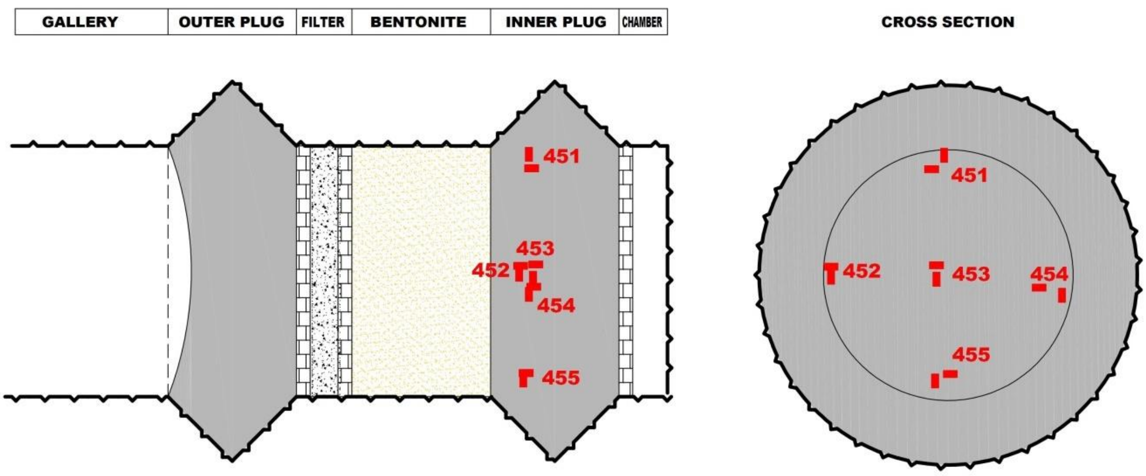
Note: The bentonite slurry test in phase 4 led to an increase in water leakage from the pressurisation chamber along the connecting pipe. Therefore, additional grouting was applied to the pipe.

4.5.1. Deformation of the shotcrete (inner plug)

Ten strain gauges were placed in the shotcrete during the construction of the inner plug. In each location two sensors were installed to monitor horizontal and vertical strain. The location of the sensors is shown in the scheme below and the evolution of strain in the shotcrete is shown in the graph.

The deformation of the plug follows the pressure applied in the chamber. The deformation appears to be reversible; returning to former levels when pressurisation is interrupted.



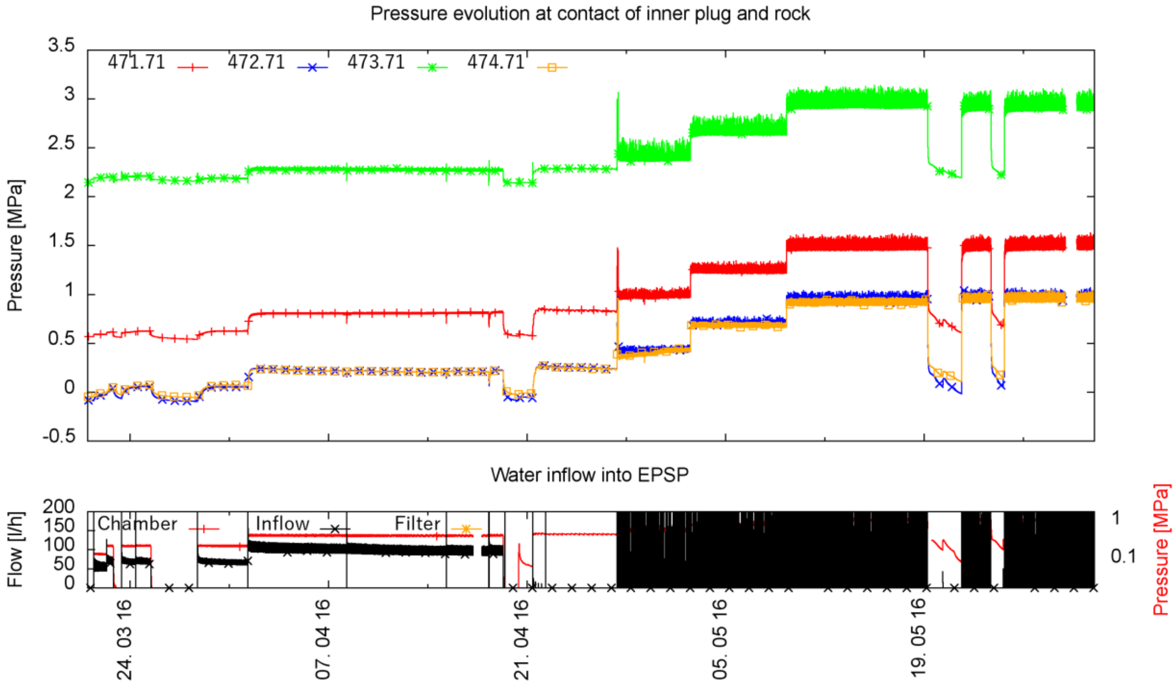


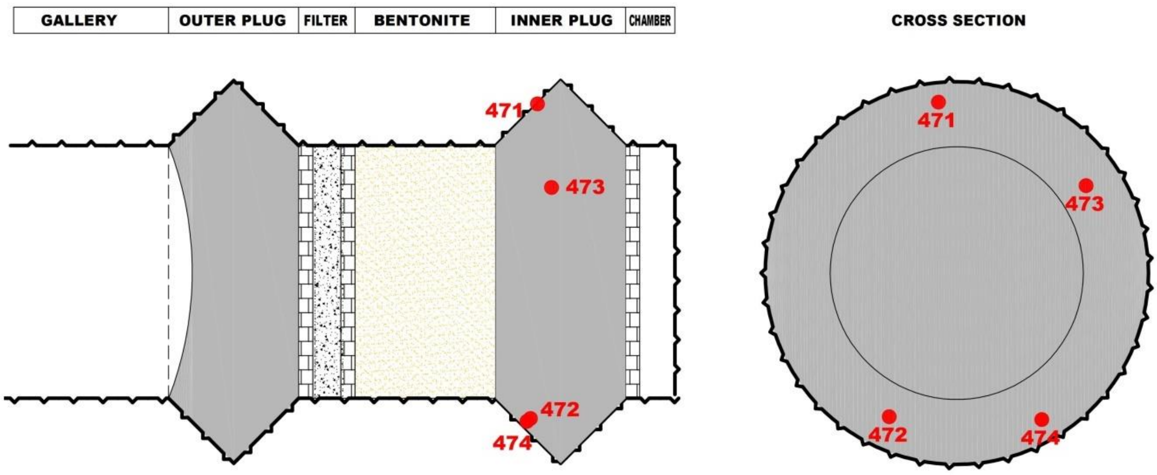
4.5.2. Contact stress evolution at the contact between the inner plug and the rock mass

Four total pressure cells were installed in the plug-rock interface in the wedge.

The location of the sensors is shown in the scheme below and the evolution of stress is shown in the graph below.

The absolute values were influenced by grouting; thus, only relative changes are important for evaluation purposes. Pressure increased according to the injection of water into the chamber. The pressure value increase follows chamber pressure with only a relatively slight difference, which indicates either good hydraulic connection to the chamber or that the plug wedged into the rock or both.



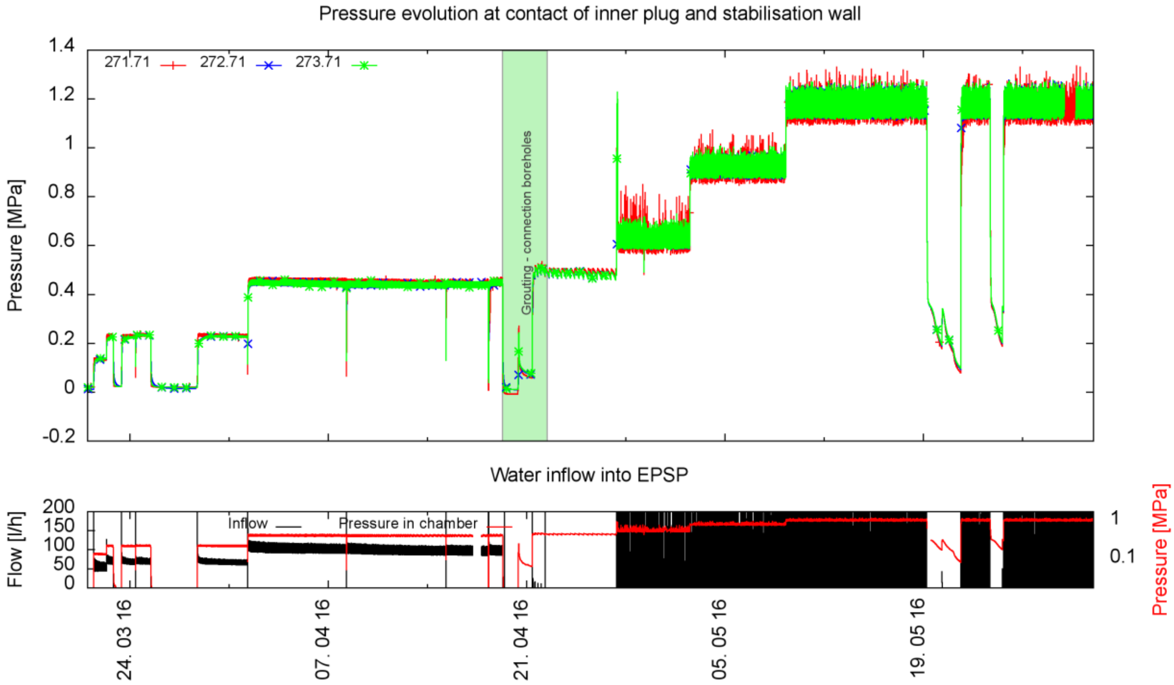


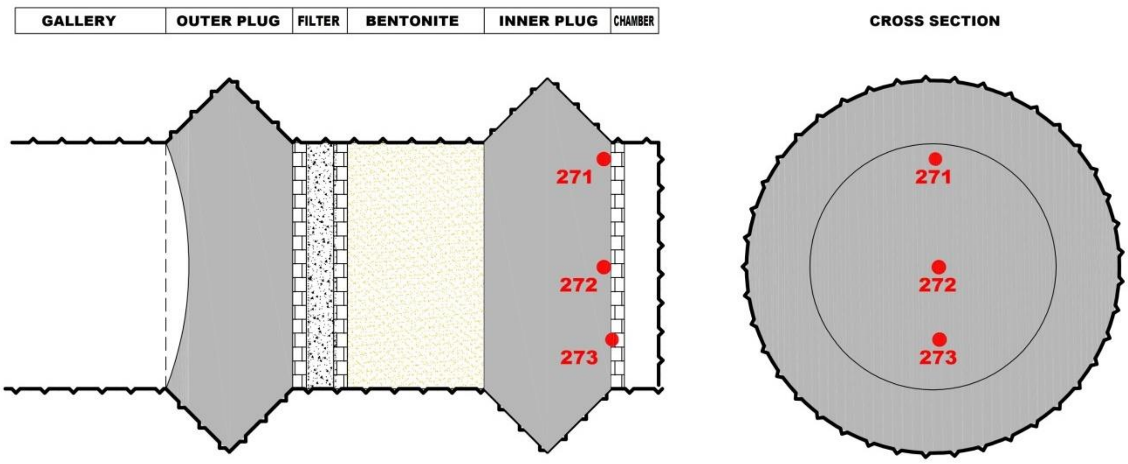
4.5.3. Contact stress evolution between the inner plug and the stabilisation wall

Three total pressure cells were installed in the plug-stabilisation wall interface.

The location of the sensors is shown in the scheme below and the evolution of stress is shown in the graph below.

Pressure follows the pressure in the chamber which indicates that the interaction between the separation wall and the plug is minimal and that the wall does not obstruct water flow i.e. it works as intended. No change in behaviour was recorded compared to the previous phase.



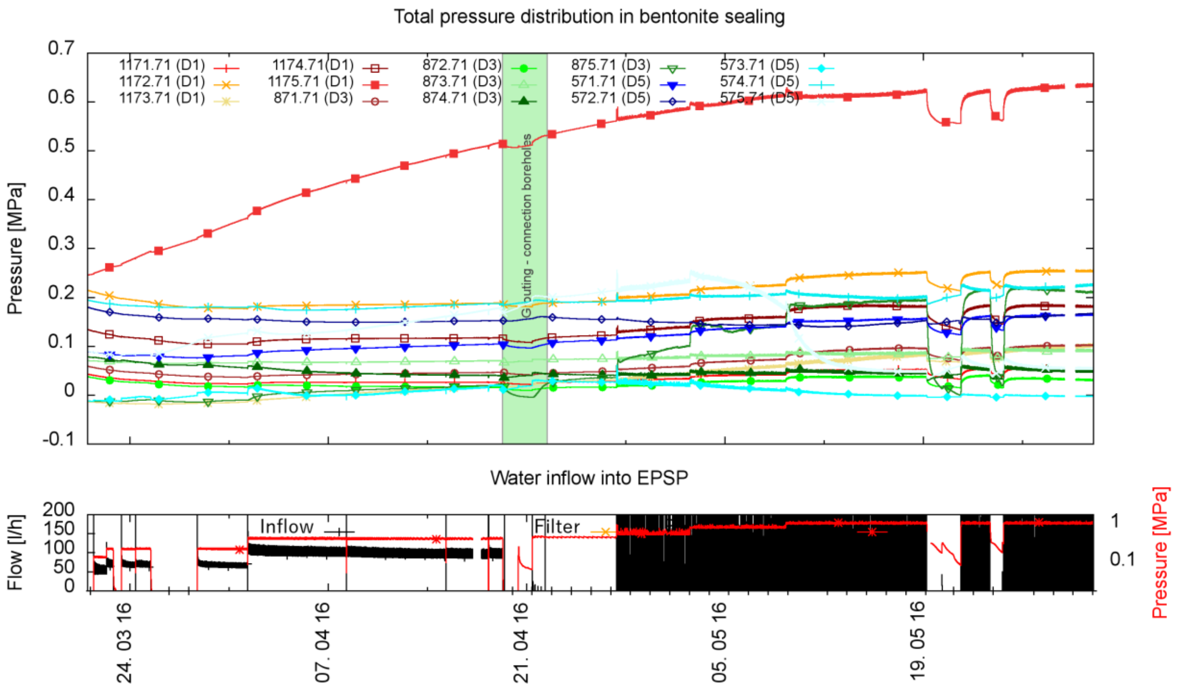


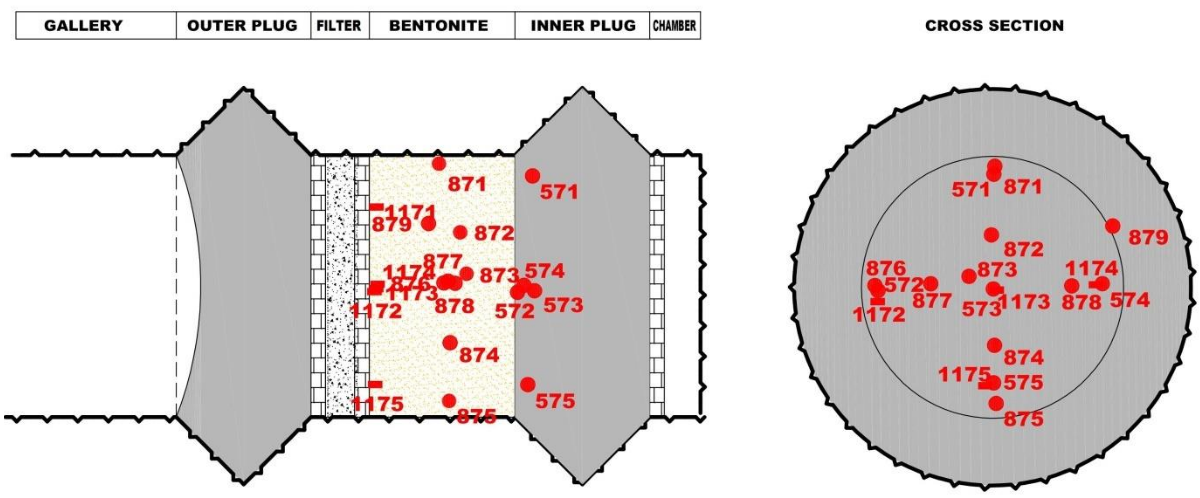
4.5.4. Total pressure evolution in the bentonite sealing

20 total pressure cells were installed in the bentonite sealing. The location of the sensors is shown in the scheme below and the evolution of stress is shown in the graph below.

At the start of phase 5 the effect of phase 4 was still visible. Subsequently, total pressure reacts in a similar way as in the previous phases - following injection pressure but at very mild levels. This, together with the non-zero values recorded during injection outages, indicates that swelling is present.

Moreover, this is further demonstrated by sensor 1175 which indicates that pressure levels reached as high as 0.6MPa.



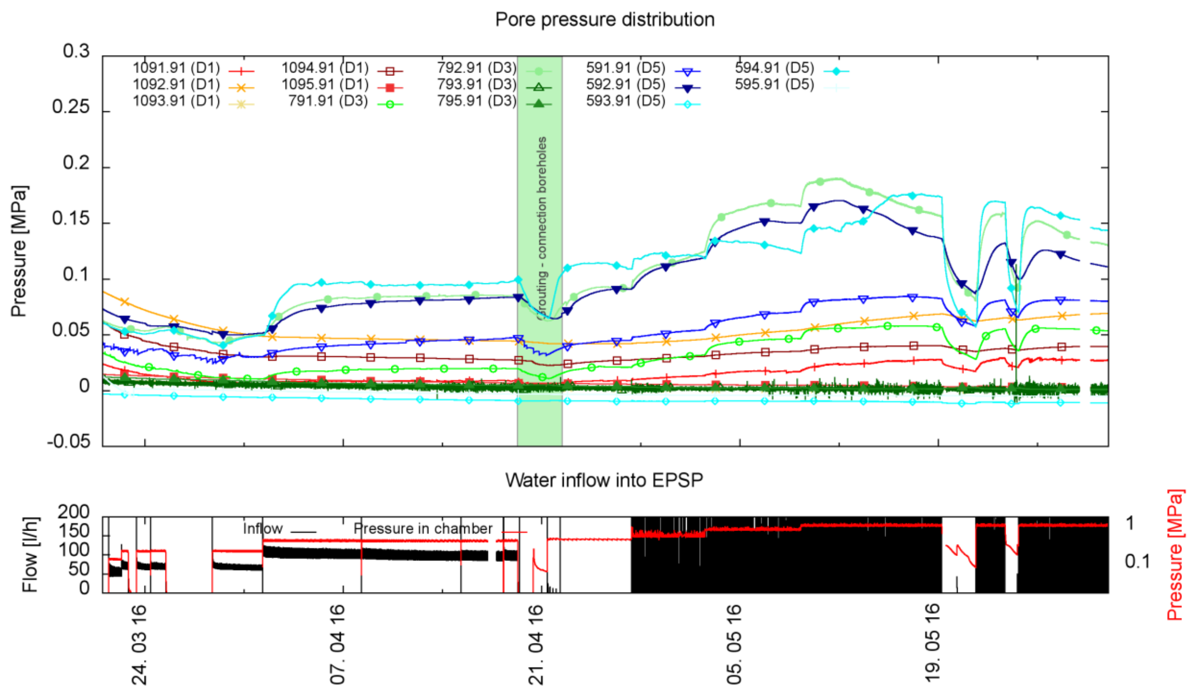


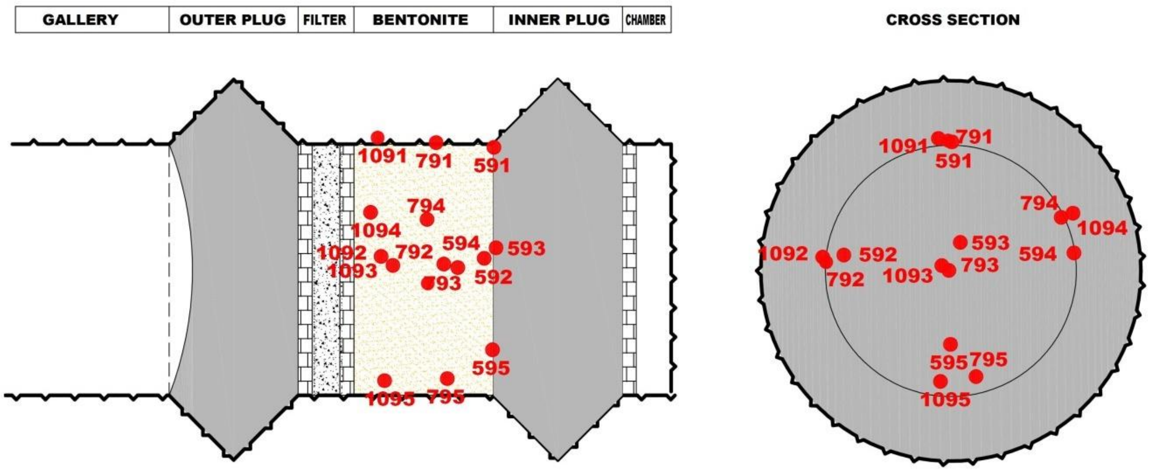
4.5.5. Pore pressure evolution in the bentonite sealing

14 piezometers were placed in the bentonite sealing. The location of the sensors is shown in the scheme below and the evolution of pore pressure in the bentonite is shown in the graph.

At the start of phase 5 the effect of phase 4 was still visible. Subsequently, pore pressure reacts in a similar way as in the previous phases - following injection pressure but at lower levels.

The last 1/3 of phase 5 is important. Pore pressure begins to fall despite the steady injection pressure, which indicates that the bentonite probably seals off any inside pathways on a continuous basis. Most probably the equilibrium between the pore pressure induced by injection and swelling pressure has reached its limit and flow is governed by the relatively low permeability of the bentonite instead of mechanical push through. This appears to indicate that the bentonite core functions as anticipated.



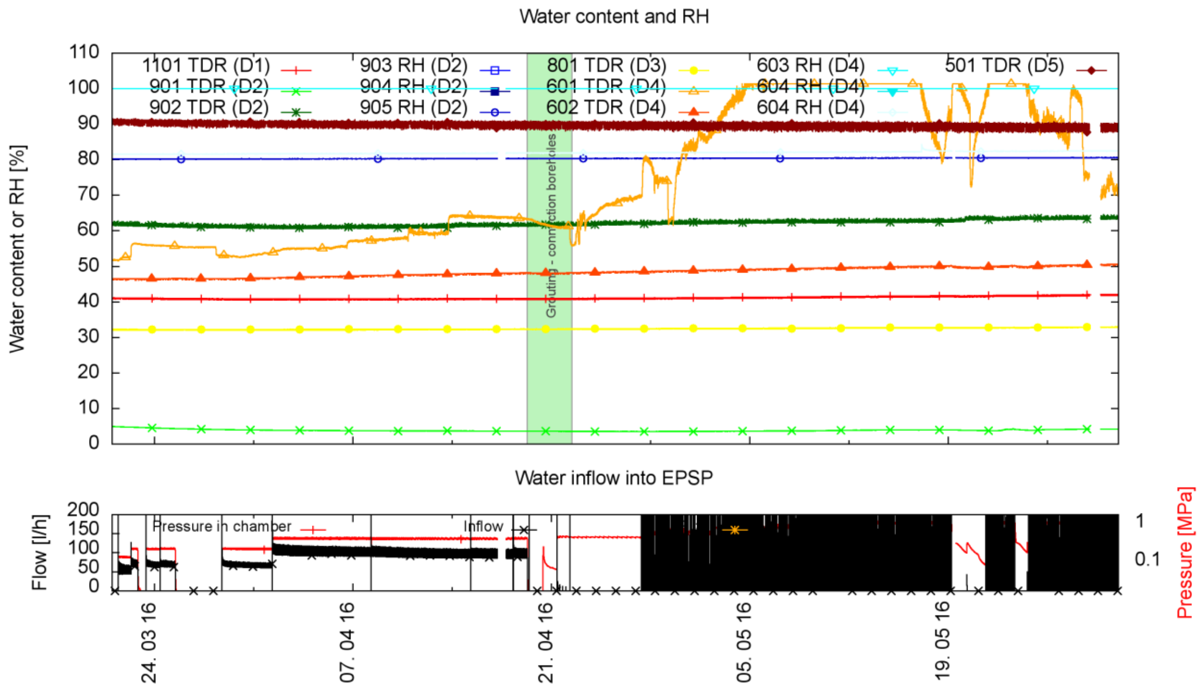


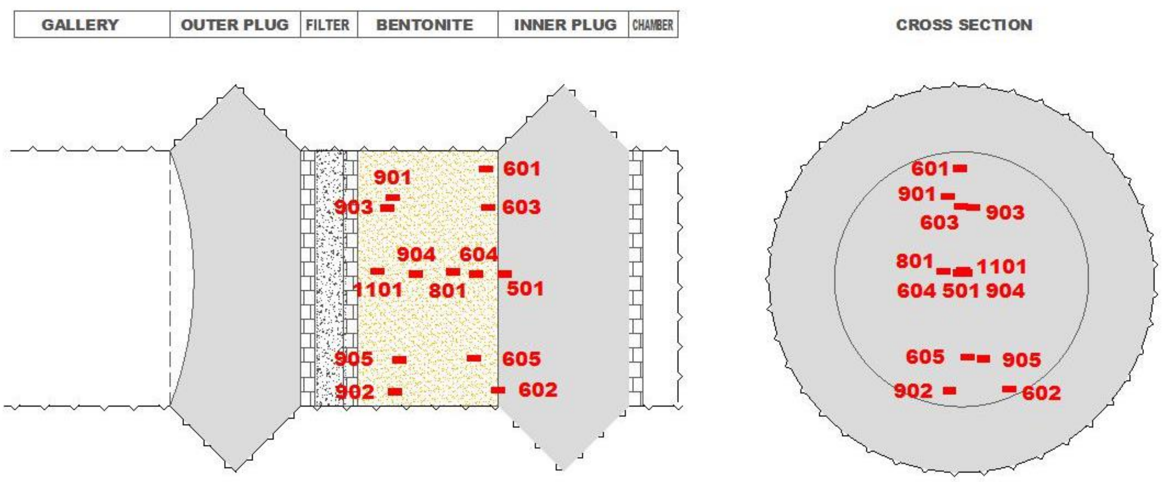
4.5.6. Water content evolution in the bentonite sealing

13 TDR and RH sensors were placed in the bentonite sealing. The location of the sensors is shown in the scheme below and the evolution of water content in the bentonite sealing is shown in the graph.

No change or only a very slight increase was recorded in water distribution through the experiment in most places, which indicates that although there were changes in pore pressure, there was not very much water movement inside the experiment.

There was one exception; in the area around sensor 601 (upper part close to the inner plug) a significant increase in water content was recorded. It seems in this case that the slurry created a pathway (probably along the rock – plug – shotclay interface) which was reopened by high pressure levels.

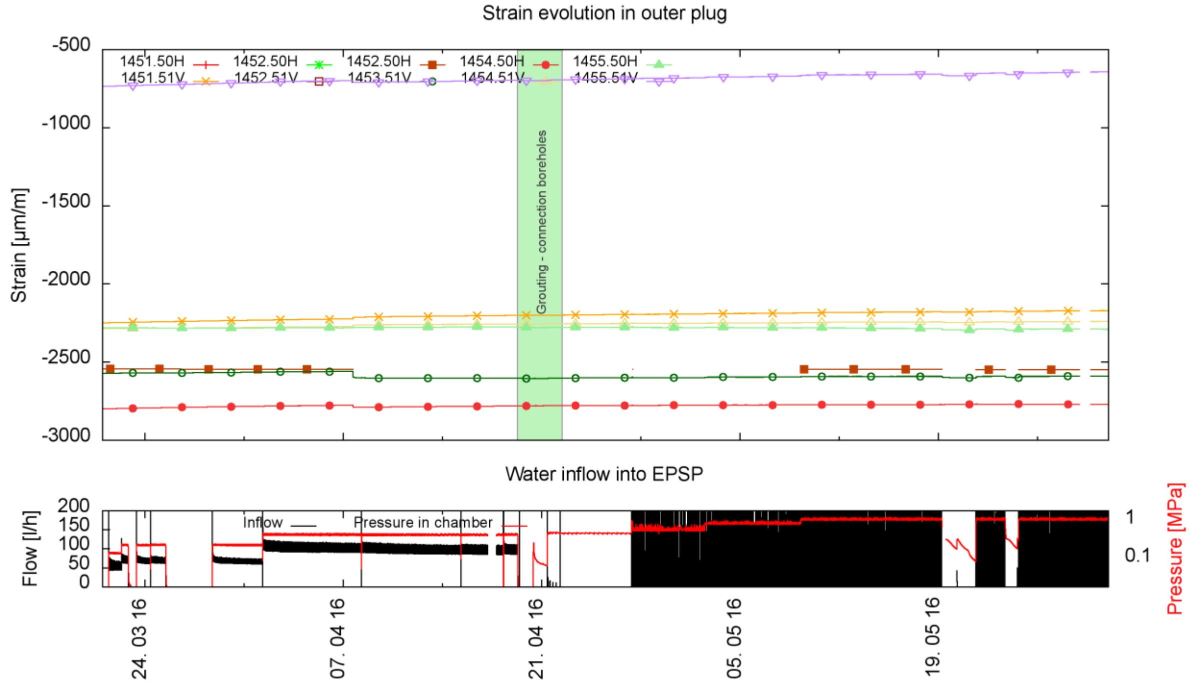


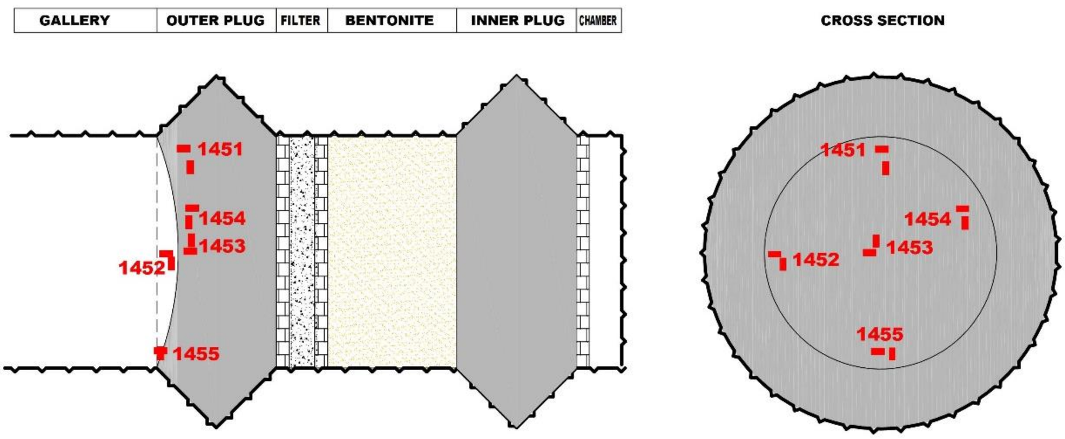


4.5.7. Deformation of the shotcrete (outer plug)

10 strain gauges were placed in the shotcrete during the construction of the inner plug. In each location two sensors were installed so as to monitor horizontal and vertical strain. The location of the sensors is shown in the scheme below and the evolution of strain in the shotcrete is shown in the graph.

Only very small long-term changes were recorded with regard to the outer plug, probably due to the drying of the concrete.



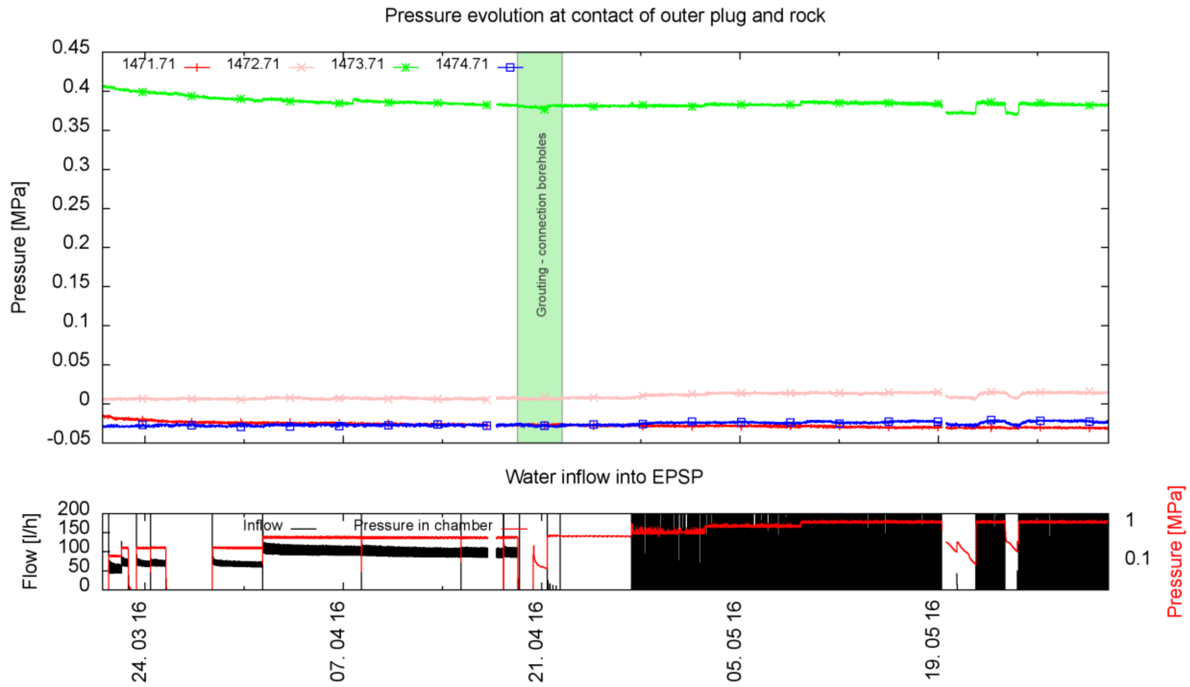


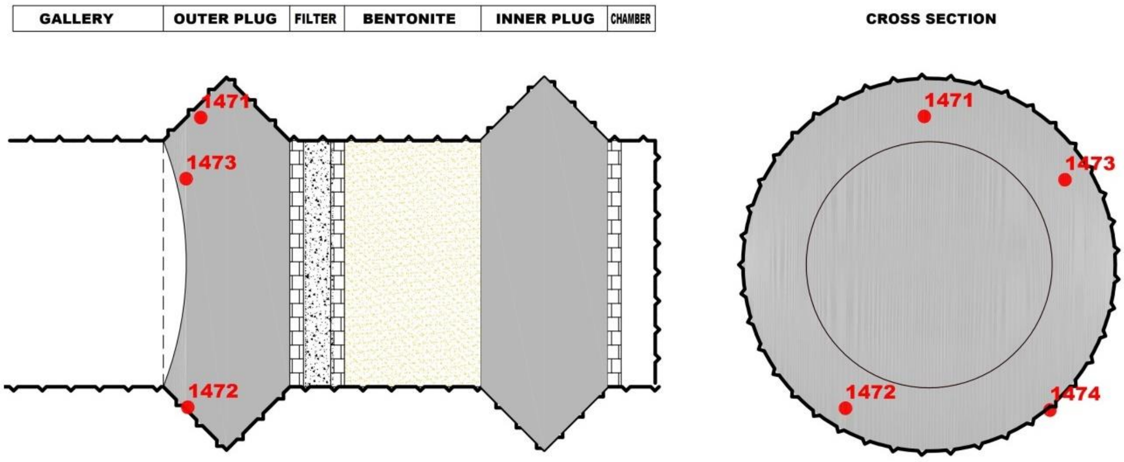
4.5.8. Contact stress evolution between the plug and the rock mass (outer plug)

Four total pressure cells were installed in the plug-rock interface in the wedge.

The location of the sensors is shown in the scheme below and the evolution of stress is shown in the graph below.

Although there should have been almost no change in contact stress (the outer plug is not loaded), small changes were recorded during pressurisation outages at the end of phase 5. This could mean that a hydraulic connection exists which bypasses the filter.





5. CONCLUSION

The EPSP has been successfully installed and the experimental phase is under way. The initial objective of EPSP – the demonstration of technologies suitable for plug erection has been achieved and the relevant experimental data has been collected.

The experimental phase of EPSP has commenced and important information concerning plug system behaviour is currently being gathered.

Data from both the construction phase and the conducting of the experiment proper is available and will serve as the basis for the further analysis of EPSP plug behaviour. The data will allow for the evaluation of the performance of each component individually and the system as a whole. Moreover, it will serve as input information for both subsequent mathematical modelling and the decision-making process with respect to the design of the plugs for the future DGR.

The unintended change to the pressurisation sequence (required due to potential piping) proved to be most beneficial in terms of the data gathered and the investigation of system behaviour; the various modes of EPSP operation provided very interesting and important data on a number of processes which otherwise would not have been gathered by implementing merely the originally intended one direction of flow.

Although the primary objective of this report is to provide data rather than analysis, a number of preliminary conclusions concerning EPSP behaviour can be drawn.

The data from the construction phase helps to confirm the suitability of the construction technologies and materials used. The results of hydration heat evolution prove that a plug with such dimensions made from lower pH glass fibre shotcrete can be erected in one stage without the need for artificial cooling. Moreover, although shrinkage was measured, no cracks were detected on the bodies of the concrete plugs.

The EPSP experimental run has provided some very important insight into concrete – bentonite stack behaviour. It has been proved that a concrete plug is able to limit flow into bentonite and therefore reduce the threat of piping (or mechanical breakthrough). This was demonstrated in the final part of the experimental run at which time constant pressure over 1MPa was maintained, the bentonite core was loaded with significantly less pressure (reduced by the concrete plug) and sealing took place. On the other hand, at the time of the "dry" bentonite sealing a possible piping occurred. At the beginning of the experimental phase it was necessary to alter the course of the experiment and saturate the sealing core at least to a limited extent to mitigate it.

The results of the experiment suggest that at least the outer "skin" needs to be saturated (the inside of the EPSP sealing appears to be relatively dry) in order to function properly and to resist the above-mentioned effects. Once this has been achieved, the complete EPSP stack performs as designed.

The various components of the concrete plug are performing as expected; they provide mechanical stability for the system. The data gathered to date proves that they are functioning well with no significant problems, although a certain amount of uneven deformation has been detected (within limits) probably due to the uneven surface of the slots.

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