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EPSP summary report

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ABSTRACT:

The aim of the DOPAS project was 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) was aimed at the study of developments concerning the design basis, reference designs and strategies including compliance issues.

The EPSP plug was 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 D4.7 “EPSP summary report” provides a summary of the erection of the EPSP experiment, the subsequent conducting of the experiment and associated work.

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1. CONTENTS

2. INTRODUCTION

The aim of the DOPAS project was 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) was aimed at the study of developments concerning the design basis, reference designs and strategies including compliance issues.

The EPSP was designed as a prototype plug for a future Czech Deep Geological Repository (DGR). It is expected, therefore, that a similar plug will function during 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 was 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 EPSP was constructed at the Josef underground laboratory in the crystalline rock environment (granodiorite) of the Mokrsko-West part of the underground facility. Due to the specific geological conditions within the EPSP experimental drift at the Josef underground laboratory, it was necessary to use grouting so as to lower the permeability of the rock mass prior to the commencement of the EPSP experiment.

The performance of the plug was tested by means of injecting air, water, and bentonite suspension into a pressure chamber. The whole testing phase was accompanied by the monitoring of the behaviour of the plug and the surrounding rock mass via the numerous pre-installed sensors.

This report provides a summary of all the phases of the project. The main activities of the project are summarised in Table 1.

Table 1 - Schedule of activities - EPSP experiment

Task	Period	Activity
0	September 2012 – December 2012	Niche selection
	January 2013 – April 2013	Site preparation
	October 2012 and February 2013	Geological mapping
1	May 2013 – September 2013	Tendering for Task 1 work
	November 2013 – July 2014	Drift shape adjustment
	October 2013 and December 2013 – September 2014	Rock improvement (grouting)
	November 2013 – September 2014	Connecting borehole drilling, casting, grouting
	June 2014 – August 2014	Instrumented rock bolts
	January 2015 – May 2015	Contact grouting – inner plug
	July 2015 – August 2015 February 2016	Contact grouting – outer plug
2	January 2014 – October 2014	Tendering for Task 2 work
	October 2014	Pressurisation chamber adjustment
	November 2014	Separation wall installation
	November 2014	Inner plug erection
	December 2014 – May 2015	Inner plug tests
	June 2015	Outer plug erection
	February 2015 – July 2015	Technology installation and testing
3	June 2015	Bentonite emplacement
4	January 2013 – July 2015	Monitoring preparation and installation
5	July 2015 – April 2016	Experimental programme

3. PLUG DESIGN

3.1. BACKROUND AND OBJECTIVES

The EPSP is not a specific DGR plug or seal; rather it was built at a similar scale to a deposition tunnel plug and contributed specifically towards the development of a reference design for such structures. The objective of the EPSP experiment was to test both the materials and technology to be used for implementation, not 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. The experiences for testing the plug components in the Josef Underground Laboratory also give indications on crystalline host rock requirements and may support the site selection programme. The EPSP experiment is the first time that SÚRAO has carried out detailed work on plugs and seals. The complete information on the experiment's design is included in D3.15 (*Svoboda et al., 2015*).

The conceptual design for EPSP (Figure 1) includes the following components:

- Pressure Chamber: The pressure chamber (or the injection chamber) is an open space 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 gas (air), water or bentonite slurry. The chamber was built to be as small as possible to allow the pressure to be readily controlled. The pressure chamber was sealed with a membrane.

- Concrete Walls: The walls, constructed from concrete blocks, were used to facilitate the construction of the EPSP. Three concrete walls were built: one between the pressure chamber and the inner concrete plug, one between the bentonite layer and the filter, and one 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; the mix and pH values were determined during the laboratory testing stage.

- Bentonite Pellets: The bentonite pellet zone is composed of B75 bentonite (a locally extracted material), 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 2m-long bentonite zone is to seal and absorb/adsorb water that flows through the inner concrete plug.

- Filter: The filter collects water that is not absorbed by the bentonite layer. The filter may also be used to reverse the direction of pressurisation of the EPSP.

- Outer Concrete Plug: The outer concrete plug is similar to the inner plug (i.e. constructed using glass-fibre-reinforced low-pH shotcrete) and was designed to hold the other components of EPSP in place.

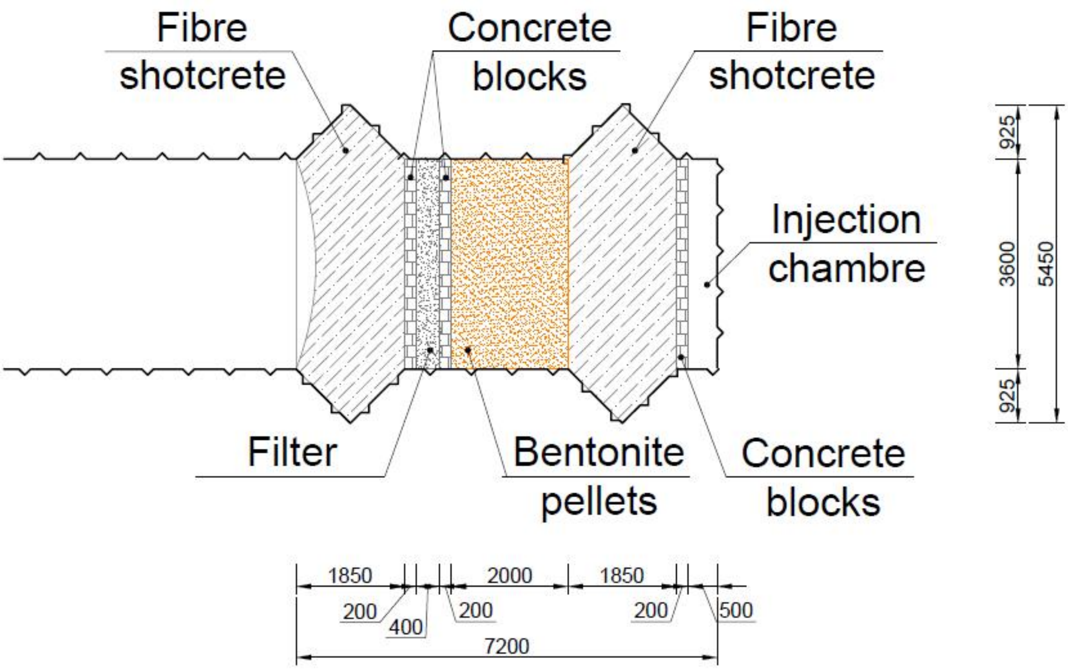


Figure 1 - Scheme of the EPSP

The EPSP experiment was built 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).

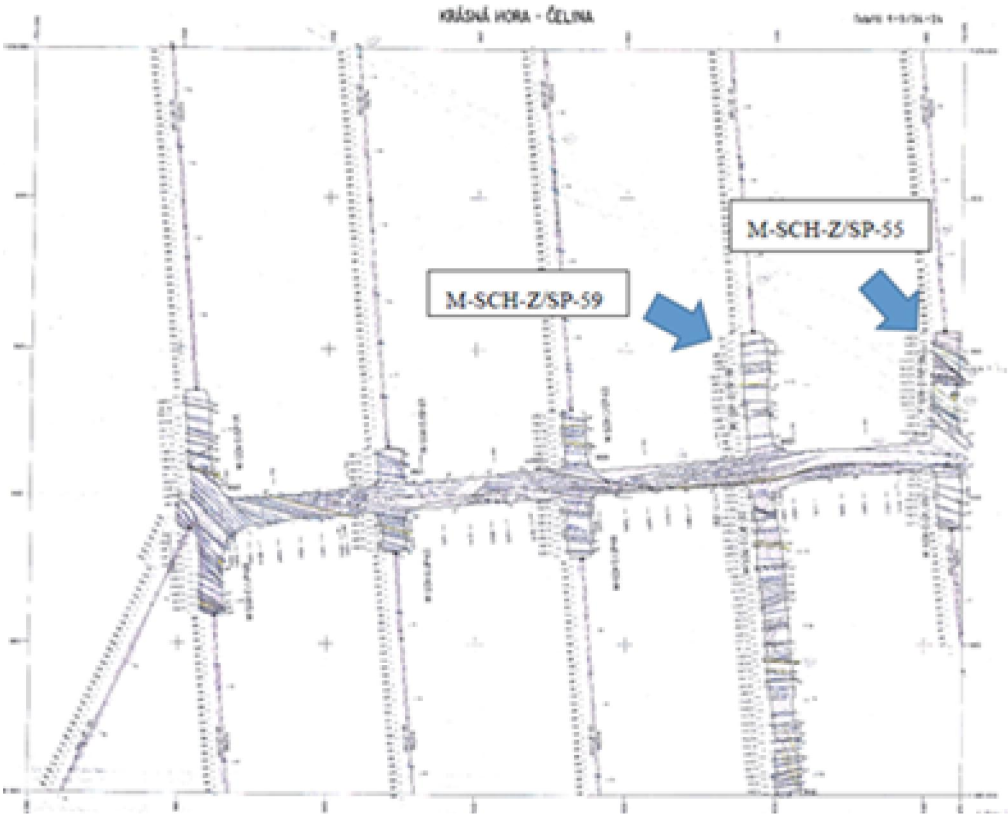


Figure 2 - EPSP location

3.1.1. Siting of EPSP

The Josef Underground Laboratory (URL) is located near the Slapy dam close to the villages of Čelina and Mokrsko in the Příbram district of Central Bohemia, Czech Republic. The total length of the tunnels in the facility is approximately 8km and the length of the main drift is 1,835m, with a cross-section of 14–16m^2. The overlying rock thickness is 90-180m. There are two main geological formations present in the Josef URL, each with different physical and material properties which change in character towards the contact zone and which include many local fracture zones and several intrusions. This provides a high level of flexibility with regard to choosing the appropriate place for conducting experiments depending on the conditions required, for example, fracture systems, rock stability, rock strength and mineralogy (*Svoboda et al., 2015*).

The EPSP experiment is located in a short gallery situated in the granitic area of the Josef URL (the M-SCH-Z/SP-59 experimental gallery niche; Figure 3, Figure 4). The technology required for the experiment is located in the parallel M-SCH-Z/SP-55 niche. The niches are interconnected by means of cased boreholes equipped with tubing for pressurisation media circulation and for monitoring purposes.

Figure 3 – The EPSP experiment niche before construction

The experimental niche was selected according to the following considerations:

- The ground conditions in the niches were considered appropriate for the construction of the EPSP, in particular, the granitic rock did not contain any major fracture zones.
- The operation of the EPSP required the availability of two free adjacent niches which were provided by the M-SCH-Z/SP-59 and M-SCH-Z/SP-55 niches.
- The size of the M-SCH-Z/SP-59 experimental niche (profile and length) was sufficient for the construction of the EPSP without the need for significant additional excavation (other than the shaping of the rock mass).
- The location of M-SCH-Z/SP-59 meant that there would be no significant impacts on other ongoing experiments being conducted at the Josef URL.

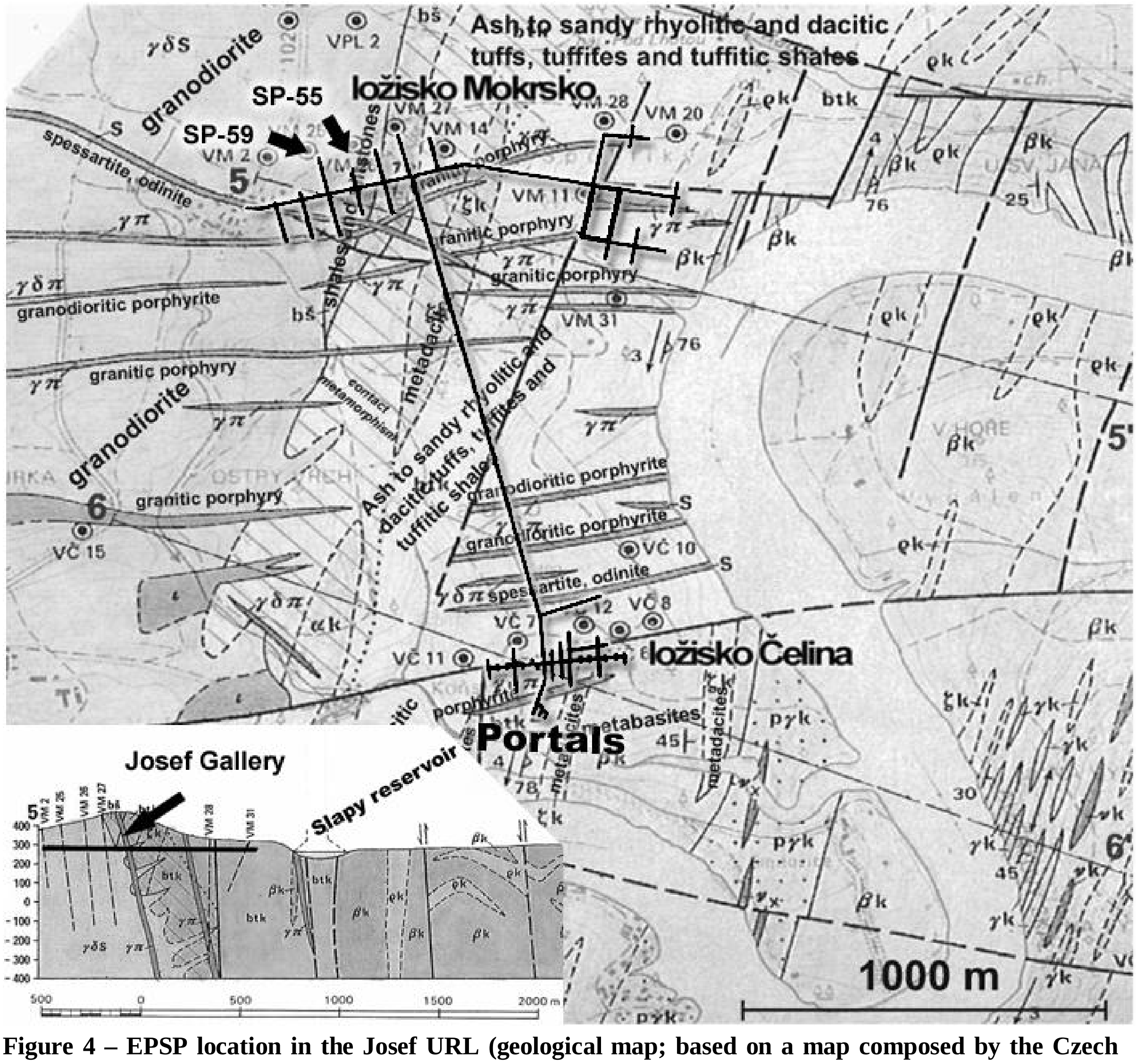


Figure 4 – EPSP location in the Josef URL (geological map; based on a map composed by the Czech Geological Survey 1991)

3.2. MATERIAL TESTING AND DEVELOPMENT

In 2013-2015, a series of laboratory tests focused on the sealing properties of the selected bentonite, and development activities and tests on the proposed concrete mix and bentonite were undertaken. More details on the results of laboratory testing can be found in *Vašíček et al. (2016 - D3.21).*

3.2.1. Selection and testing of the concrete mix

At the outset of the EPSP experiment, it was decided to use glass-fibre-reinforced low-pH shotcrete for the inner and outer concrete plugs. Glass fibres were selected as the EPSP reinforcement material instead of iron-based fibres so as to avoid the potential for the corrosion of the iron-based fibres which might affect the post-closure performance of plugs in the future Czech repository, and also to avoid the introduction of additional iron into the system. These fibres also significantly help to reduce (micro) cracking caused by shrinkage. Moreover, low-pH concrete was required so as to limit potential impacts on the bentonite.

The ÚJV's previous experience with the preparation of low-pH concrete mixes and the experience of a commercial producer of concrete mixtures for building purposes were used in developing initial proposals for the shotcrete mix. The project required that the concrete mixture should be "low-pH concrete", which, in the Czech Republic, is generally interpreted as meaning that the pH value of the pore water (leachate) in equilibrium with the concrete has a value of ~11.5 or less.

Low-pH concrete mixtures with a pH of <11 had been developed by the ÚJV prior to the DOPAS project. Two types of cement were used in these concrete mixtures:

- CEM III/B 32.5 N-SV – Heidelberg.
- CEM II A-S 42.5R – Lafarge.

The concretes were produced by mixing the cement with silica fume (Addiment Silicoll P), fine milled limestone (D8 – Lhoist) and a plasticiser (Addiment FM 935). Although the mixtures developed by the ÚJV exhibited a low-pH leachate, they also exhibited a low compressive strength and therefore were not considered suitable for practical use in construction projects.

It was determined that a reduction in the pH of the leachate of the concrete mixture could be obtained via the partial replacement of the cement by another type of binder or by increasing the ratio of fine SiO_2 (micro silica/silica fume) to the cement content or by the partial replacement of the cement with metakaolin. The addition of metakaolin decreased the leachate pH values from pH~13 to pH~12 after 5 weeks of hardening. However, the addition of metakaolin to the cement mixture led to a decrease in strength. With respect to SiO_2, the decrease in pH values was greater, i.e. a pH of approximately 12 was achieved after one week of curing and a pH~11.5 was achieved subsequently (*Vašíček et al., 2014 – D3.17*).

Following the initial studies based on existing concrete mixes described above, the ÚJV worked with the supplier to develop a concrete mix suitable for EPSP testing. Two mixes were tested and their suitability assessed based on a consideration of pH, compressive strength and rheology, amongst other parameters (Table 2). The two mixes were also subjected to mock-up tests in a testing niche in the Josef URC and underground laboratory.

The selection of the preferred concrete mix was ultimately determined by the chemical performance since one of the concrete mixtures exceeded the pH target (pH = 12.0-12.2), whereas the other met the target (pH = 11.3-11.5) as well as all the other requirements.

Table 2 - Measured strength and pH for the two mixtures considered for the EPSP shotcrete plugs

Parameter	**Mix 1**	**Mix 2**
Compressive strength (mixture)	59.2MPa	51.4MPa
Compressive strength (core drills)	44.4MPa	46.5MPa
Flexural strength	5.8MPa	6.7MPa
pH - filtrate	11.3	12.1

The materials used in the EPSP concrete mixture consisted of:

- Cement: CEM II / B – M (S-LL) 42.5 N.
- Sand and Gravel: 0-4 & 4-8 Dobřín.
- Plasticiser: SIKA 1035CZ.
- Retardant: SIKA VZ1.
- Accelerator: SIKA Sigunit L93 AF.
- Microsilica: SIKA FUME.
- Glass fibres: crack HP (Sklocement Beneš).

The ratio of microsilica to cement was approximately 1:1.

3.2.2. Selection and testing of the sealing materials

One of the main aims of EPSP was to demonstrate the suitability of Czech materials and available technologies for the construction of tunnel plugs. In order to form a basis for the identification and selection of candidate bentonite materials, plug construction requirements (e.g. hydraulic conductivity) were considered alongside a more general set of requirements:

- The bentonite material had to be sourced from the Czech Republic.
- The bentonite material had to be non-activated. This is connected to the previous requirement that the bentonite material had to be sourced from the Czech Republic. There are no sodium bentonite deposits in the Czech Republic and artificial activation would increase costs with no long-term guarantee that the activated materials would not revert to their non-activated state. Therefore, the search focused on non-activated materials.
- The bentonite material had to be capable of fulfilling sealing requirements (*White et al., 2014).*
- The bentonite material used in the experiment had to be homogenous from the chemical and mineralogical points of view.
- The bentonite material had to be available in sufficient quantity.
- The bentonite material had to be available for use during the timeframe of the EPSP experiment.

Following careful consideration of plug construction requirements, factory-produced bentonite (milled, non-activated Ca-Mg bentonite) was selected as the principal material for the bentonite part of the plug. The commercial product “Bentonit 75” (B75) was the only material available at that moment fulfilling all the requirements. B75 is produced by Keramost Plc from the Černý vrch deposit.

The selection of B75 was supported by experience from previous research (*Trpkošová et al., 2013*), where B75 was found to fully comply with the required hydraulic conductivity ($\leq 1 \times 10^{-12}$ m/s) and swelling pressure (≥ 2 MPa) at a dry density of 1.4 g/cm^3. This research was based on material delivered by the producer in 2010. As bentonite deposits are heterogeneous, the B75 used for EPSP, which was delivered in 2013 (and was named B75_2013), was subjected to laboratory testing in order to determine its mineralogical and chemical composition, and to confirm its properties against the requirements set out in *White et al. (2014)*. The mineralogical and chemical compositions of B75_2013 are presented in Figure 5 and Table 3 respectively.

Various laboratory tests were performed on the B75_2013 material so as to verify its properties by the CTU and the ÚJV. The CTU conducted laboratory tests to determine the specific density and Atterberg limits of the bentonite powder. This was followed by the determination of the relationship between the dry density of compacted samples, and hydraulic conductivity and swelling pressure. B75 is produced in powder form which is not ideal for sealing plug purposes due to the low level of compaction. Therefore, the testing of the most appropriate technology for the manufacture of the pellets, in cooperation with potential Czech producers, was also carried out by the CTU. The main conclusion from this work was that B75_2013 bentonite demonstrated sufficient dry density levels and, therefore, could be used to ensure the required geotechnical behaviour of the bentonite seal in the EPSP experiment (*Vašíček et al., 2014 – D4.17*).

The laboratory testing of B75_2013 bentonite by the ÚJV focused on the chemical composition, the measurement of pH in suspensions of bentonite and distilled water at different ratios, and the analysis of leachates (cation concentrations). It was concluded that the main characteristics of B75_2013 bentonite remained constant and fulfilled all the expectations, limits and requirements for the construction of the experimental plug (*Vašíček et al., 2014 – D4.17*).

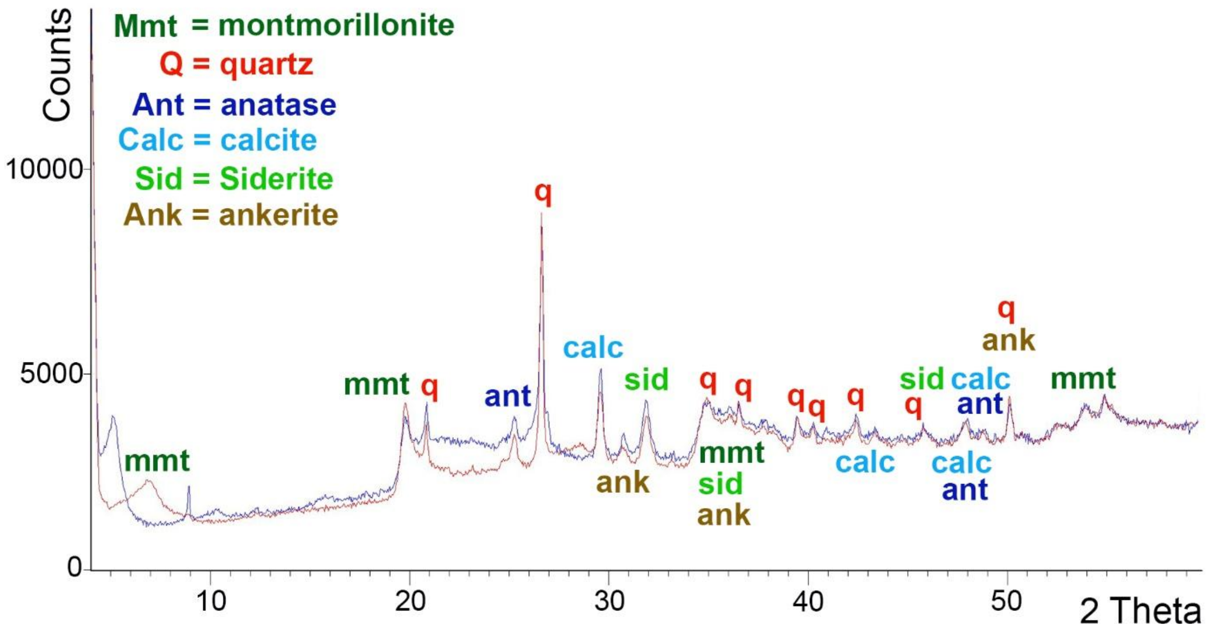


Figure 5 - X-ray diffraction pattern for B75_2013. The red spectrum shows the pattern for untreated B75_2013 and the blue spectrum shows the pattern following glycolation

Table 3 - Chemical composition of B75_2013

Oxide	**Weight%**
SiO_2	49.83
Al_2O_3	15.35
TiO_2	2.82
Fe_2O_3	10.90
FeO	3.74
MnO	0.09
MgO	2.88
CaO	2.01
Na_2O	0.67
K_2O	1.05
P_2O_5	0.63
CO_2	3.66

Two physical model test series were also conducted by the ÚJV at the laboratory scale on the candidate EPSP materials aimed at supporting the design of the EPSP. The objectives of the Physical Hydraulic Model (PHM) tests were to investigate the hydraulic and mechanical processes at work during the saturation of the bentonite and to derive data for the subsequent calibration of numerical models of the saturation of the bentonite material. Two PHM tests were conducted; one with bentonite powder and the other with bentonite pellets, in which the samples were gradually saturated with synthetic granitic water under pressure. The data was used to determine the water retention of the bentonite. The two water retention curves obtained by means of the two tests were comparable and were applied in the numerical modelling of plug performance. The objectives of the Physical Interaction Model (PIM) were to study the interactions between the bentonite and the grouted granite, and between the concrete and the grouted granite interfaces. The PIM incorporated all of the materials that were expected to be used in EPSP including bentonite, concrete and polyurethane materials.

Several different technologies concerning the compaction of powdered bentonite were tested during the course of the research and two were finally selected for further use. The first method involved the production of compacted pellets by means of a roller compaction machine. A number of tests were conducted with respect to the manufacture of the bentonite pellets, the main aim of which was to determine the conditions to be employed in order to achieve bentonite compaction resulting in the best possible dry density parameters. The final product designated as B75 PEL12 consisted of pellets with a diameter of 12mm, a length of up to 40mm and a dry density around 1.8Mg/m^3 (Figure 6). This material was used for the construction of the major part of the sealing layer. The second material finally used for the construction of the sealing layer was prepared via the compaction of powdered bentonite using a roller mill. The final product, B75 REC (Figure 7), featured a good level of compaction and low water content; this material was applied using spray technology.

Figure 6 – B75 PEL12 material

Figure 7 – B75 REC material

3.2.3. Selection of the filter materials

The filter functions as a permeable layer for the collection of any water passing through the sealing part of the experiment. It has no other function. Inert gravel was used in EPSP, with the exact type and grain size determined by the supplier.

3.2.4. Selection of the rock grout

The niche selected for the location of the EPSP experiment is traversed by quartz and quartz-carbonate veins with a maximum thickness of 14cm. The ground conditions had the potential to impact the performance of the EPSP experiment in several ways:

- The low rock strength meant that the pressurisation of the plug components might lead to the reactivation of rock fractures and the failure of the surrounding rock mass.
- The fracture network might lead to excessive water leakage from the experiment.
- The location of the Josef URC and underground laboratory is close to a water reservoir. All the grouting materials used to improve the ground conditions required a

certificate confirming that their use would have no significant impact on groundwater quality.

Therefore, prior to the installation of the EPSP, the surrounding rock had to be grouted so as to improve rock strength and to reduce the permeability of the rock mass. As part of the research and selection of the grouting materials, tests were undertaken in order to ensure that no interactions between the low-pH leachate released from the concrete plugs would significantly impair the performance of the grouted rock mass. Laboratory tests were carried out to test commonly used grouting materials (based on polyurethane). These materials were selected based on their common usage and suitability for rock grouting in the geological conditions of the Josef Underground Laboratory.

The chemical composition and stability, possible interaction, physical properties and applicability of the grouting material were verified. The extent of the interaction of the grouting with the cement and the bentonite leachates served to confirm the stability or otherwise of the grouting. Initial tests indicated that common polyurethane-based grouting materials were not influenced by low-pH solutions and should not be affected by cement leachates in the grouting of the experimental plug; no organic components were found to have leached into the alkaline solutions. A further laboratory test proved that the polyurethane-based grouting material had sufficiently low hydraulic conductivity up to a water pressure of 2.5MPa, thus being suitable for use in the EPSP.

3.3. STRUCTURAL DESIGN

3.3.1. Preliminary design

Some of the initial work on the structural design was performed outside the DOPAS project. A preliminary study performed by the CTU (*Venkrbec*, *2013*) included the basic structural design and numerical modelling of a DGR plug. Pressure and sealing plugs are required to withstand several types of stress which may act upon them during their lifetime. With such types of stress in mind, it was necessary to determine a structural design which was technically feasible and financially viable. A total of three different variants were designed and tested using numerical modelling techniques (Figure 8 - Figure 10). The variants differed in terms of the shape and arrangement of the concrete layers (plugs); each of them allowed differing interactions of the inner concrete plug and the rock mass during the transfer of load from the pressure chamber. Based on the analysis performed, variant C (Figure 10) was finally selected for the EPSP experiment.

Variant C is based on a similar principal to variant B with the difference lying in the shape and dimensions of the inner concrete layer. In the final design both the inner and the outer concrete plugs had the same shape and dimensions. Load transfer from the pressure chamber to the surrounding rock is provided by the inner plug; consequently, the role of the bentonite sealing layer in terms of load transfer was minimised. The function of the outer concrete plug is to prevent the expansion of the bentonite and it also serves as a safety element in case of the failure of the first plug.

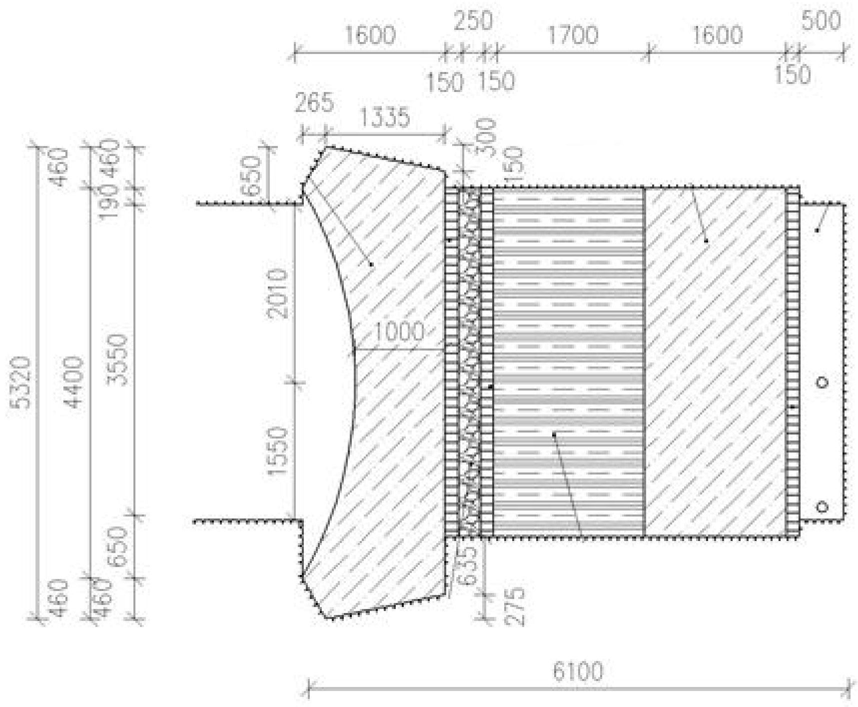


Figure 8 – Design variant A

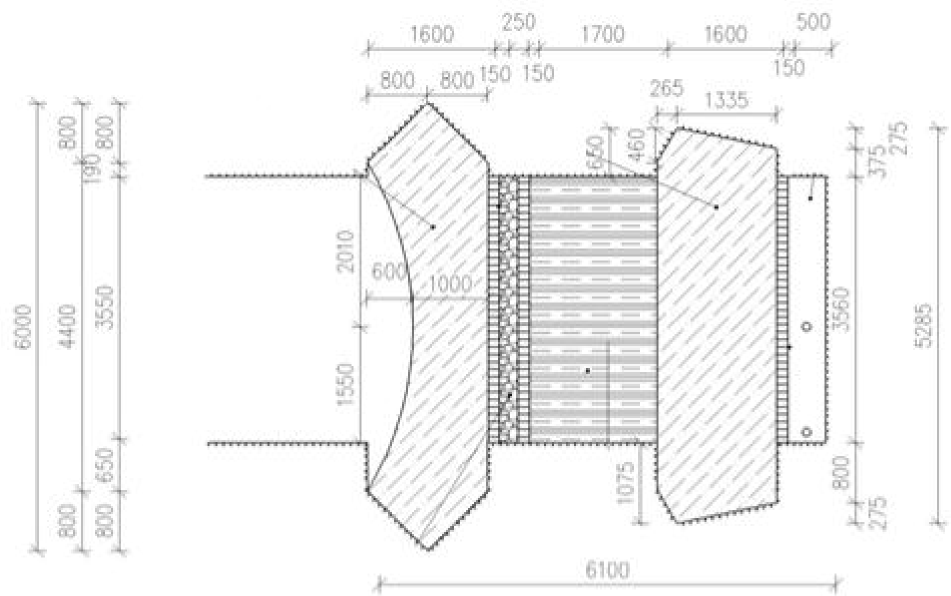


Figure 9 - Design variant B

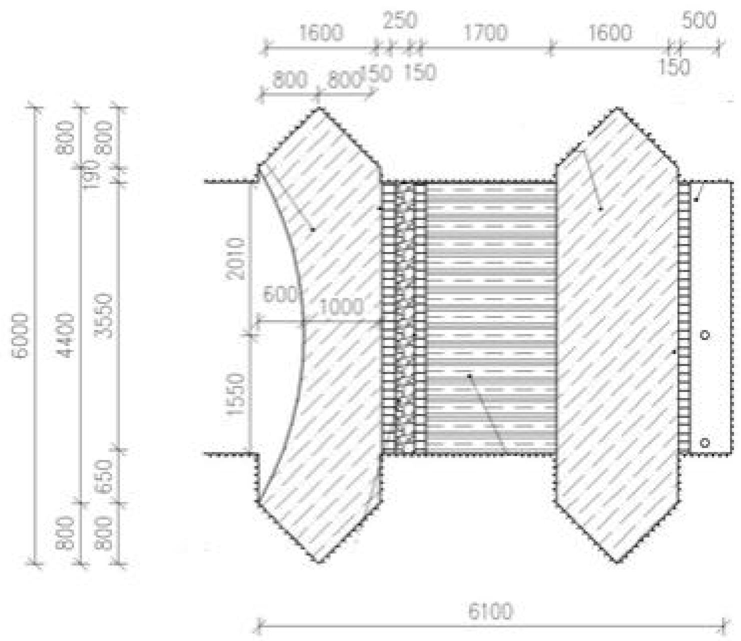


Figure 10 - Design variant C

3.3.2. Final design

Part of the DOPAS project involved the performance of numerical modelling aimed at evaluating the structural performance of the proposed plug design. The aim of the numerical analysis was to verify the design of the concrete plugs, their stability, deformation and changes in stress inside the surrounding rock mass. A basic model was studied which included both plugs, the surrounding rock mass and the pressurisation chamber. A detailed model of one concrete plug in contact with the rock mass was also developed.

The numerical models simulated the construction of the experiment and the subsequent loads experienced by each component. The models did not incorporate stress changes inside the rock mass consequent to the excavation of the niche; since the niche was excavated between 1981 and 1991, it was assumed that any deformation arising from this excavation had already taken place. Groundwater ingress was not considered in the models since the surrounding rock was sealed using grouting within 5m of the original excavation and because water load was simulated by including the overpressure in the injection chamber.

The calculation was conducted according to Czech standard ČSN EN 1997-1 (Eurocode 7) – Design Approach 2, using a finite element package dedicated to the deformation and stability analysis of underground work and geotechnical structures (CESAR-LCPC). The models evaluated the structural response to loads generated by self-weight (compaction), shrinkage, pressure in the chamber and swelling pressure, and a combination of these forces and, moreover, accounted for the impact of fractures on the spatial variability of rock strength.

Once the models and their various load states had been calculated, the maximum stress state in the concrete plugs was compared with the strength of the glass-fibre-reinforced low-pH shotcrete as determined by the laboratory tests. The results of the structural analysis showed that the selected design of the plug and its materials should withstand all the experimental loads without difficulty (*Svoboda et al., 2015*). Figure 11 shows the longitudinal section of the EPSP experiment according to the final design.

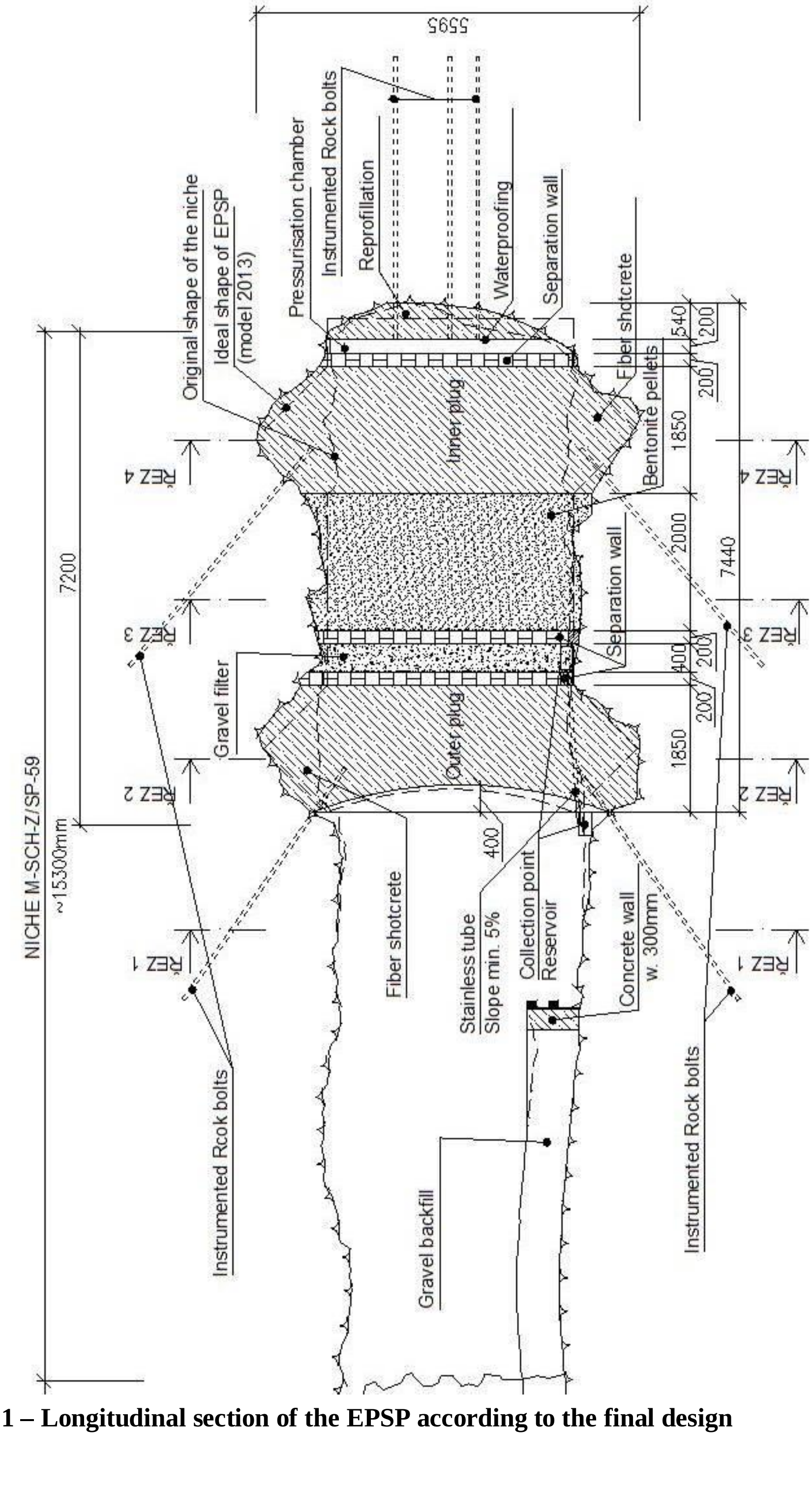


Figure 11 – Longitudinal section of the EPSP according to the final design

3.4. INSTRUMENTATION AND MONITORING SYSTEM

3.4.1. Monitoring goals and strategy

The primary aim of monitoring was 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 were identified and sensors were specially selected in order to capture them. Complete information on the monitoring and instrumentation of the EPSP can be found in D3.18 (*Svoboda et al., 2014*).

Monitoring focused on water movement inside the experiment and the experiment's response to pressurisation (especially the deformation of the plugs). Water movement inside the experiment was monitored in terms of water in/out-flow, water content distribution within the bentonite seal and water (pore) pressure distribution.

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

Temperature distribution was monitored not only during the construction stage (hydration heat) but also during the loading of the experiment as a reference base for sensor compensation.

In order to obtain good and reliable monitoring results from the various sensors, their position within EPSP and the quality of their emplacement was crucial. Key locations were identified and the placement of sensors was focused on those areas. 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.

3.4.2. 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 and Svoboda., 2010).*

The system has two main elements: the data acquisition system (DAQ) and the online monitoring system (Figure 12). The DAQ forms 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.

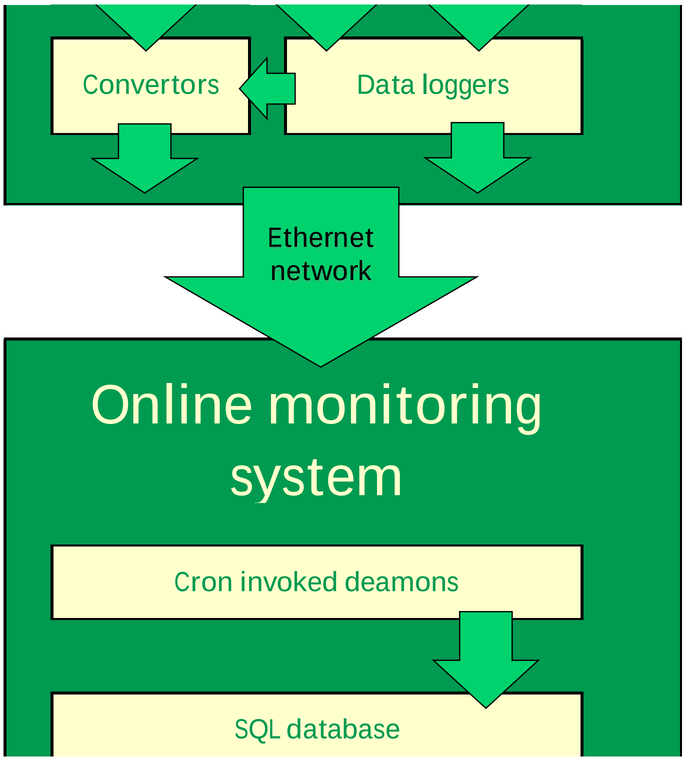


Figure 12 - EPSP measurement system

3.4.3. Data acquisition system

The data acquisition system (DAQ) is responsible for measurement performance and the preparation of data for the monitoring system. There are two key components: the sensors and the data loggers/convertors.

Sensors

The sensors used for DOPAS EPSP were selected so as to capture important processes underway inside the experiment – focused particularly on the monitoring of water distribution, pressure, deformation and temperature. Where possible sensors based on different principles were used to measure the same phenomena in order to enhance reliability.

The following sensors were used:

- Temperature – digital thermometers (DS18B20), analogue (LM35DZ and NTC) resistors
- Water distribution – relative humidity sensors (EE071) and TDR sensors (5TE)
- Pressure – VW pressure cells (4810X-10MPa) and piezometers (4500SHX-10MPa)
- 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 13 - temperature sensor in a protective housing

Figure 14 - RH sensor including cabling protection

Figure 15 - Sensors ready to be fixed into the assembly

Figure 16 - Cable head preparation

The preparation of the sensors was carried out in the Josef URC facility workshop. The sensors were assembled and equipped with protective stainless steel tubing (Figure 13 and Figure 14). Complete assemblies were transported stage by stage to the underground complex in accordance with the plug erection process. The sensors were then installed in their final positions or stored temporarily at the side of the niche until the final location was ready to receive them. The sensors were organised in the form of profiles inside the experiment (Figure 17) so as to allow for easier orientation.

<u>Data loggers/convertors</u>

The DAQ system includes three main types of data loggers:

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

In addition, several media convertors were used to connect the digital sensors directly into the DAQ network.

3.4.4. Online monitoring system

The online monitoring system was designed as part of the CEG's DAQ 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. Mostly open source programs are used within the system.

3.4.5. 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.

3.4.6. 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. 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 a simple data visualisation interface (2D charting and 3D visualisation). For more comprehensive analytical purposes direct data export is available using specialised URLs.

3.4.1. Profiles

The instrumentation is organised in vertical profiles A – G (Figure 17). The profiles are located in key parts of the experiment. A 3D model of the instrumentation is presented in Figure 18. A detailed description of the measurement profiles is included in Table 4.

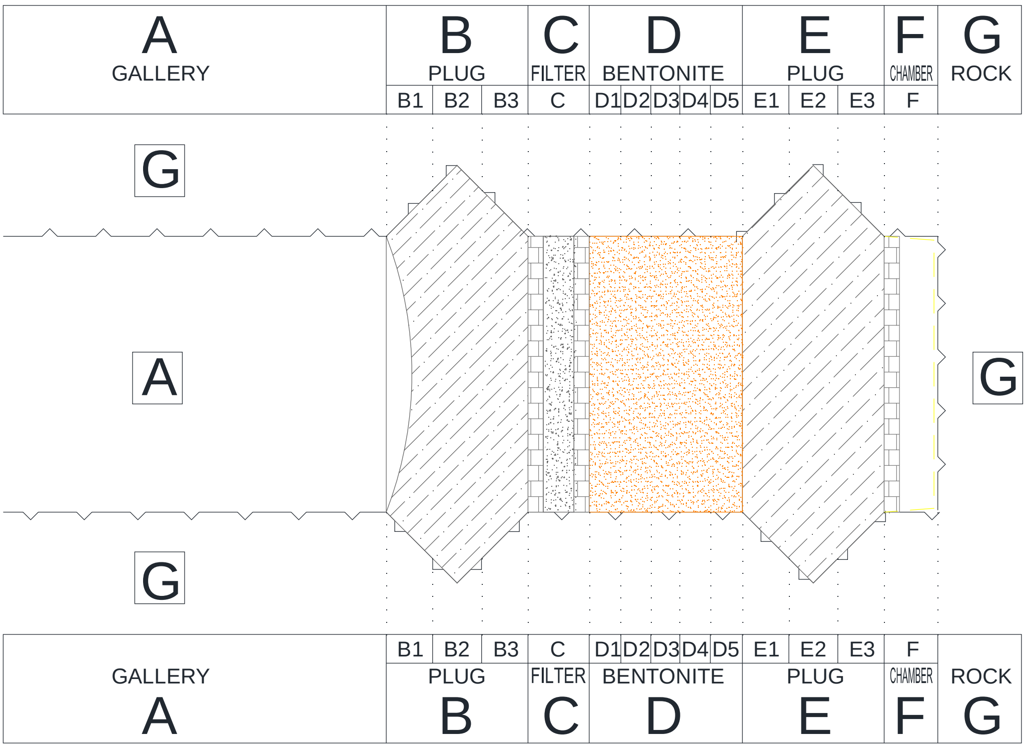


Figure 17 - profiles (A – gallery, B – outer concrete plug, C – filter, D – bentonite, E – inner glass fibre shotcrete plug, F – pressure chamber, G – rock, H – technology)

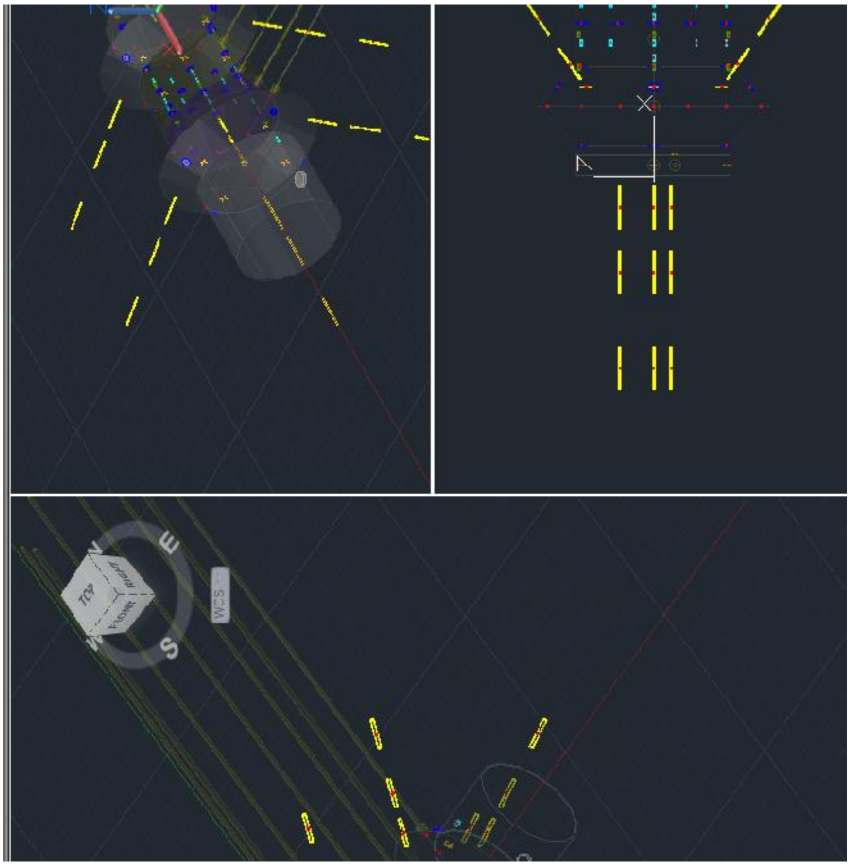
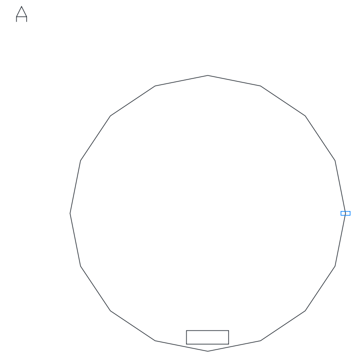
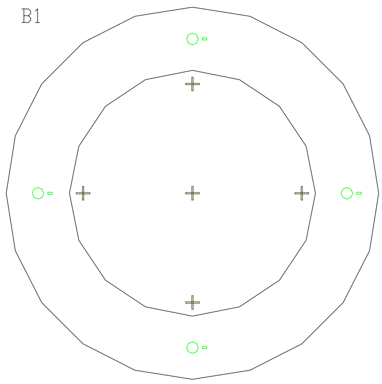
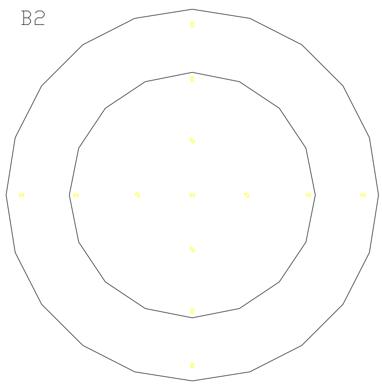
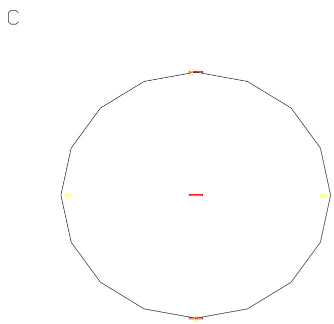
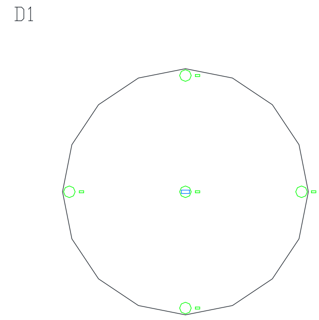
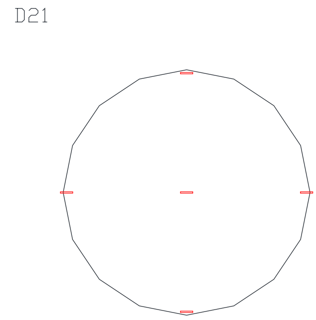
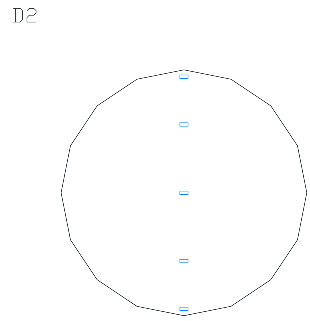
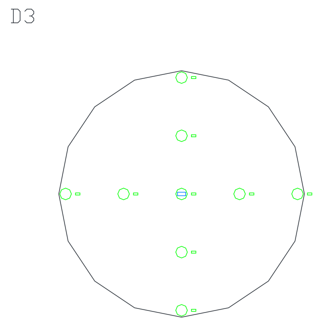
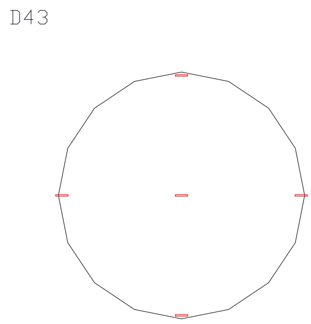
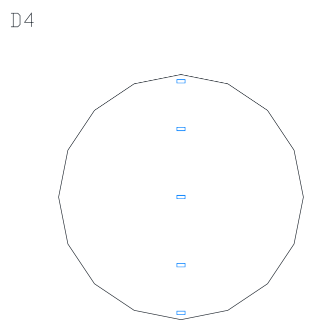
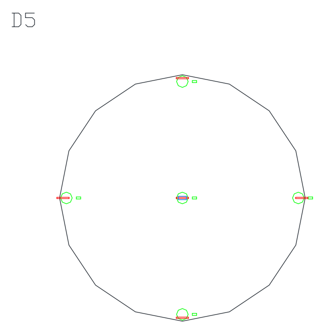
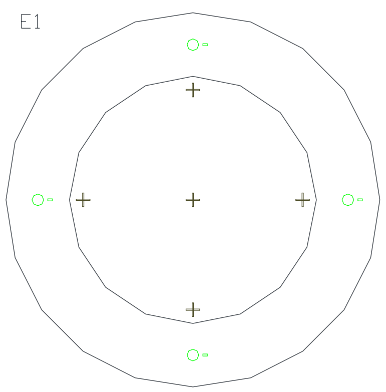
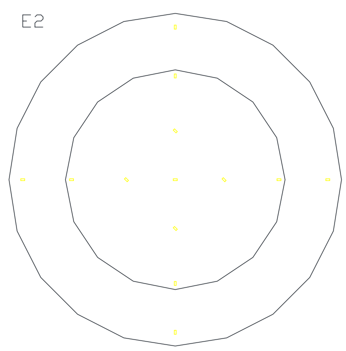


Figure 18 - 3D model of the instrumentation

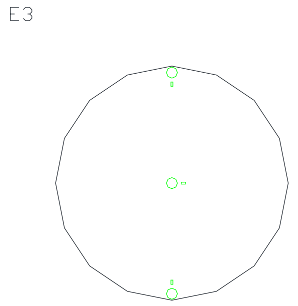
Table 4 – Description of the measurement profiles

<u>Profile A</u> Measurement of: · Amount of water collected by the filter · Relative humidity (ambient) · Temperature (ambient)	
<u>Profile B1</u> Measurement of: · Deformation of the plug (vertical and horizontal) · Contact pressure between the plug and the rock · Temperature of the plug (at locations of deformation and contact stress measurement) Note: Rock bolts start from this profile	
<u>Profile B2</u> Measurement of: · Temperature distribution inside the plug	
<u>Profile C</u> Measurement of: · Pore pressure · Temperature distribution	

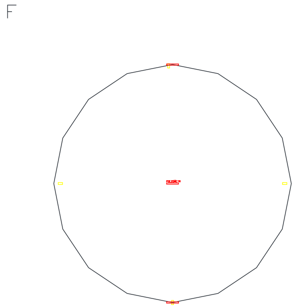
<u>Profile D1</u> Measurement of: · Swelling pressure · Water content · Temperature (at locations of pressure and water content measurement)	
<u>Profile D1/2</u> Measurement of: · Pore pressure · Temperature (at locations of pressure measurement)	
<u>Profile D2</u> Measurement of: · Relative humidity · Water content · Temperature (at locations of water content and relative humidity measurement)	
<u>Profile D3</u> Measurement of: · Swelling pressure · Water content · Temperature (at locations of pressure and water content measurement)	
<u>Profile D3/4</u> Measurement of: · Pore pressure · Temperature (at locations of pressure measurement)	

<u>Profile D4</u> Measurement of: · Relative humidity · Water content – TDR · Temperature (at locations of water content and relative humidity measurement)	
<u>Profile D5</u> Measurement of: · Pore pressure · Swelling pressure · Water content – TDR · Temperature (at locations of pressure and water content measurement)	
<u>Profile E1</u> Measurement of: · Deformation of the plug (vertical and horizontal) · Contact pressure between the plug and the rock · Temperature of the plug (at locations of deformation and contact stress measurement) Note: Rock bolts start from this profile	
<u>Profile E2</u> Measurement of: · Temperature distribution inside the plug	

<table>
<tr>
<td><u>Profile E3</u>

Measurement of:
· Contact pressure between the plug and the separation wall
· Temperature of the plug (at locations of contact stress measurement)</td>
<td>
</td>
</tr>
<tr>
<td><u>Profile F</u>

Measurement of:
· Pressure inside the chamber
· Temperature

Note: Rock bolts start from this profile</td>
<td>
</td>
</tr>
<tr>
<td colspan="2"><u>Profile G</u>
Measurement of:
· Rock deformation
· Temperature (at rock deformation measurement locations)

Rock deformation is measured using rock bolts starting in profiles B1, E1 and F</td>
</tr>
</table>

3.5. TECHNOLOGICAL SETUP

The technological setup allows the injection of water into either the pressurisation chamber or the filter or into both at the same time.

The technology, located in the SP-55 niche, consists of:

- Heads of the connecting piping
- Pressurisation system
    - o Water reservoir
    - o Low pressure unit
    - o High pressure unit
- Technology control system

The installed pressurisation system was designed to work with water. With respect to tests with air and a bentonite suspension, additional equipment had to be used. This equipment was brought onto the site only when specifically required for such tests.

A scheme of the pressurisation technology is shown in Figure 19. Figure 27 and Figure 28 show photographs of the setup within the technological niche.

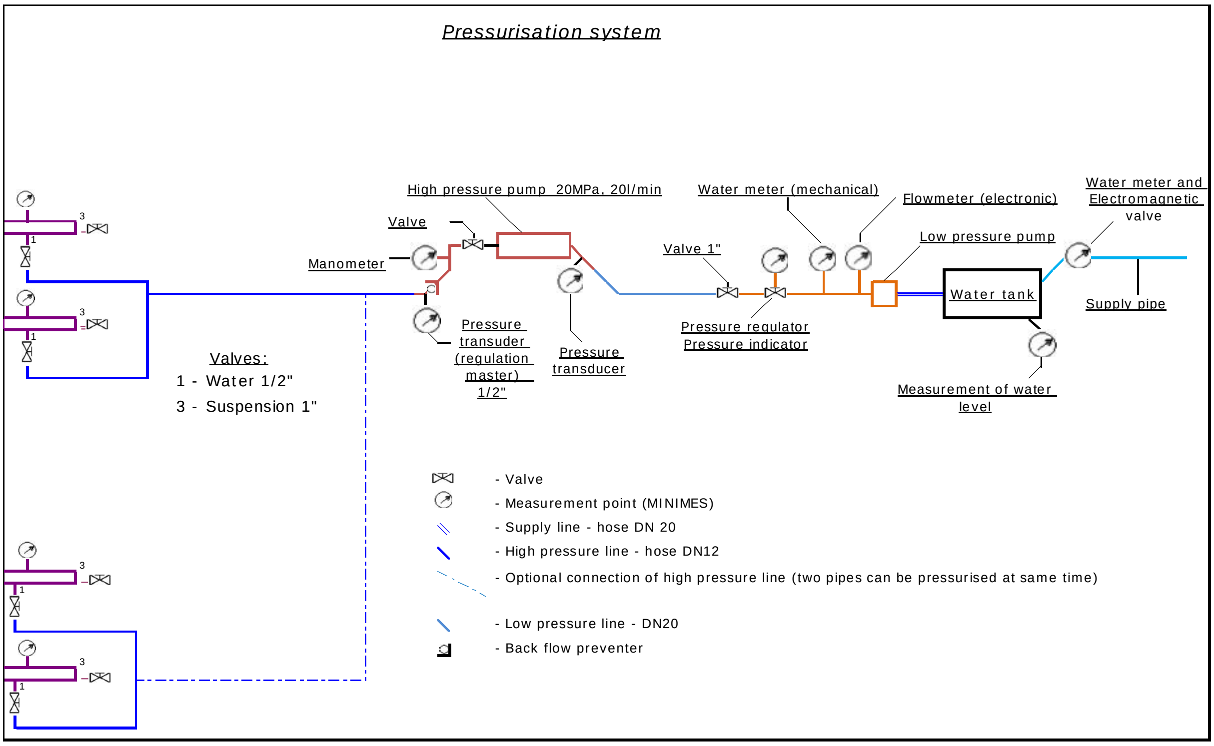


Figure 19 - Pressurisation system (technology)

The pipe heads are fixed to the connecting piping leading into the EPSP experiment (left side of Figure 19). They are installed on all 8 connecting lines – 4 into the pressurisation chamber and 4 into the filter and allow for the easy connection of the water pressurisation system for the use of air or a bentonite suspension (the suspension applies to the pressurisation chamber only). They are also equipped for the monitoring of pressure and temperature.

The pressurisation system has three main components – a water reservoir, a low pressure unit and a high pressure unit. Should lower pressures be required, the high pressure unit is disconnected thus allowing for the direct use of the low pressure unit.

The water reservoir makes up the entry point for the water which is provided from the Josef URL local water supply. The reservoir is equipped with an electromagnetic valve to allow for automatic refilling, the metering of incoming water and water level measurement. The volume of the reservoir is $2m^3$.

Water is supplied from the reservoir to the low pressure unit which consists of a PLURIJET 6/90 pump, valves, a mechanical pressure regulator on output and a flowmeter. The unit is designed to operate at up to 0.5MPa and at 35l/minute. The output from the low pressure unit is either directly connected to the EPSP (via heads and borehole piping) or to the high pressure unit.

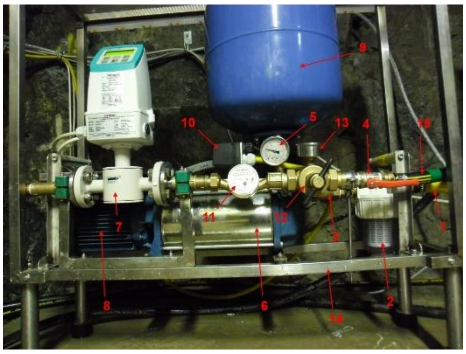


Figure 20 - Low pressure unit

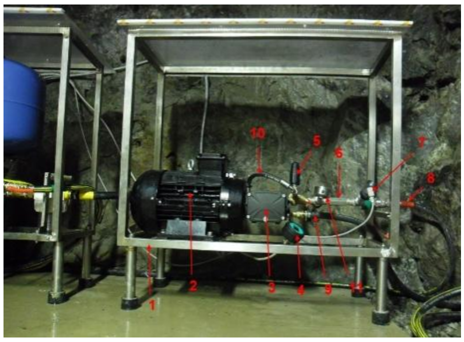


Figure 21 - High pressure unit

The high pressure unit features an Interpump E 21.21/9,2 kW pump capable of attaining up to 20MPa and delivering 20l/minute. The unit allows the electronic measurement of pressure and is equipped with a back flow prevention valve.

The system is controlled electronically. The control system is based on an industrial PLC Allen Bradley Micrologic 1400 with a PanelView Plus 6 Terminal, 600 interface panel.

4. CONSTRUCTION AND INSTALLATION

The different stages involved in the installation of EPSP are described in the chapters below and illustrated in a series of photographs (Figure 43 - Figure 47). Complete information on the installation of the experiment can be found in D3.20 (*Svoboda et al., 2015b*).

The niches for the EPSP experiment were selected as early as in 2012. The selection process was based on the results of a comprehensive geological survey of the various underground spaces available at the Josef URL. Detailed geological mapping was subsequently performed once the niches had been chosen.

In the first part of 2013 the niches were prepared for the construction stage including the removal of excess material and the necessary cleaning up and the installation of the various utility networks (water, electricity, data network, lighting and ventilation).

The first part of construction work commenced in late 2013. The niche was reshaped and the surrounding rock was improved by means of grouting in order to reduce water permeability (in order to allow for the higher pressures applied to the plug).

The installation of the EPSP itself, from the installation of the first concrete separation wall to the installation of the outer concrete plug, took around 3 months; this did not include the time required for grouting and the installation of the monitoring technology. The total time period from chamber adjustment to fully operational experiment was 10 months. A major delay occurred due to the contact grouting of the inner plug which involved a number of campaigns with a long waiting time for curing between each campaign. The shotcreting phase (plug erection) on the other hand was very quick - it took less than 24 hours to erect each plug; the construction of each plug was followed by a 1 month curing period.

Construction work was completed on 20 July 2015 once the outer plug had cured.

The EPSP experiment was installed in the following stages:

1 Preparation of the pressurisation chamber $<2m^3$ (including the installation of the pressurisation tubing).

2 Waterproofing of the pressure chamber.

3 Installation of the first concrete separation wall between the pressurisation chamber and the inner plug.

4 Installation of the inner plug using glass fibre low-pH shotcrete.

5 Installation of the bentonite sealing material, the second concrete separation wall, the filter and the third concrete separation wall which was undertaken concurrently.

6 Installation of the outer plug using the same material and design used for the inner plug.

The monitoring instrumentation was installed as construction progressed.

In terms of the organisation of the EPSP, installation work was divided into 5 tasks:

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

4.1. 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 to allow for other dependent work to begin. The selection process was based on the results of a comprehensive geological survey of the various underground spaces available at the Josef URL.

Having selected the niches, preparations commenced to have them ready for Task 1.

Detailed geological mapping was performed. The detailed mineralogical study of the filling of fissures was carried out in niche SP-59 in 2013; the sampling locations are shown on the map in Figure 22. Six samples were analysed by means of X-ray powder diffraction at the Institute of Chemical Technology, Prague, VŠCHT (X´Pert PRO with Bragg-Brentan geometry, CuK_{α}, 40kV, 30mA, High Score Plus) and SEM at the Faculty of Sciences, Charles University in Prague.

In the first part of 2013 the niches were prepared for construction work. This preparatory stage included the removal of excess material, general clearing-up and the installation of the utility networks (water, electricity, data network, lighting, ventilation).

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

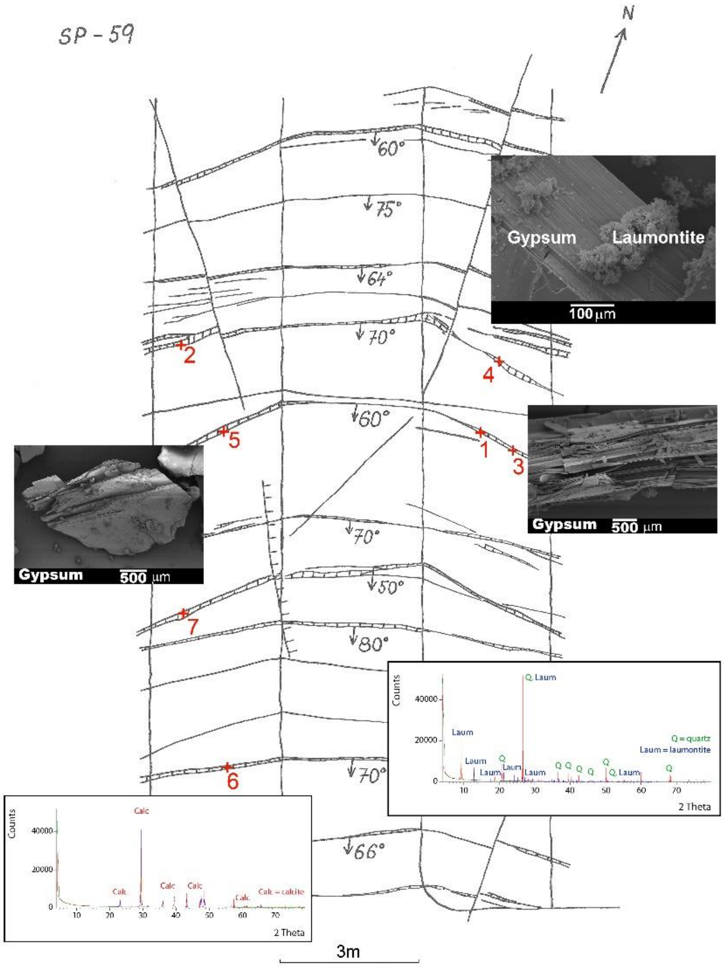


Figure 22 – SP-59 tectonics and mineralogy

4.2. 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.

4.2.1. Excavation of the EPSP Tunnel: Reshaping and Ground Improvement

The EPSP was constructed in an existing niche that was excavated between 1981 and 1991 (Figure 3). Prior to the commencement of the construction of the EPSP experiment, it was necessary to reshape the experimental gallery niche and to improve the ground conditions. The reshaping and ground improvement activities commenced in October 2013 with the 3D scanning of the existing niche profile. Based on the scanning results the precise location of the EPSP experiment was determined. The location selected was the one that would minimise the need for additional ground work.

Once the position of EPSP was fixed, excavation work began with the excavation of the slots in which the shotcrete plugs would be emplaced. Excavation was carried out gradually, in two stages. Firstly, the rough excavation of the rock was carried out in the upper half of both plugs, working from a platform built in the existing experimental niche. Subsequently, the platform was disassembled and the excavation of the lower half of both plugs was conducted. Following the completion of the rough work, the rock surfaces were smoothed by means of diamond sawing and chiselling.

The selection of the rough excavation method was constrained by the requirement that excavation must be conducted without blasting. This requirement was introduced so as to minimise the potential for EDZ development. Initially, the hydraulic wedge splitting technique was employed; however, this technique was found to be somewhat problematic in terms of the excavation of the EPSP shotcrete plug slots, i.e.:

- The application of the technique did not result in a smooth excavation profile.
- The splitting of the rock required high pressures; the unconfined compression strength reached a maximum of 120MPa. This made the use of this technique both slow and physically demanding for the workers involved.
- The use of the hydraulic splitting technique left unbroken ends with respect to the 45mm-diameter boreholes with variable depths.

In response to the identification of these issues and in order to test the use of an alternative approach, a second technique was used for the construction of part of the outer plug consisting of the pressure disintegration technique using Green Break Technology (GBT) cartridges (non-detonating gas expansion cartridges). The GBT technology significantly accelerated the pace of work on the excavation for the plugs; moreover, the excavated opening contour was more precise and smoother than the results of using the hydraulic splitter technique. During the course of excavation, the dimensions of the plugs were checked against the set requirements using a triangular measurement tool. Whenever the shape of the space excavated for the plug was found not to be in compliance with requirements, fine enlargement work was carried out using a diamond saw; and the incised rock was removed by hand using chisels.

Following the construction of the slots, the rock mass was injected with polyurethane resin at high pressure so as to improve the quality of the host rock. The required hydraulic conductivity value of the massif following injection was a maximum of 1 x 10^{-8} m/s. The requirement was to improve the quality of the massif surrounding the experiment up to a radius of 5m. The injection mixture, consisting of WEBAC 1401 polyurethane resin, was injected into a total of 72 injection boreholes which were fitted with mechanical packers. The resin was injected into the boreholes by means of a WEBAC IP 2 high-pressure grouting set. Injection was terminated once a pressure level of approximately 35MPa had been attained. A total of 760.45kg of WEBAC 1660, WEBAC 1410,WEBAC 4170T, WEBAC 150 and WEBAC 1403 PU resins were used so as to achieve the required hydraulic parameters within the rock mass in the required area.

Borehole hydraulic tests were conducted which confirmed that the modified hydraulic conductivity of the rock mass in the space for the plug met the set requirements. Once testing was completed, the boreholes were filled by means of the injection of 32 litres of WEBAC 1660 resin.

Thirteen 23m-long connecting boreholes were drilled between the SP-59 experimental niche and the SP-55 technological niche for the purpose of pressurising the experiment and for instrumentation requirements. Eight of the boreholes were used for pressurisation and five for the cabling (Figure 23) for the experiment monitoring system.

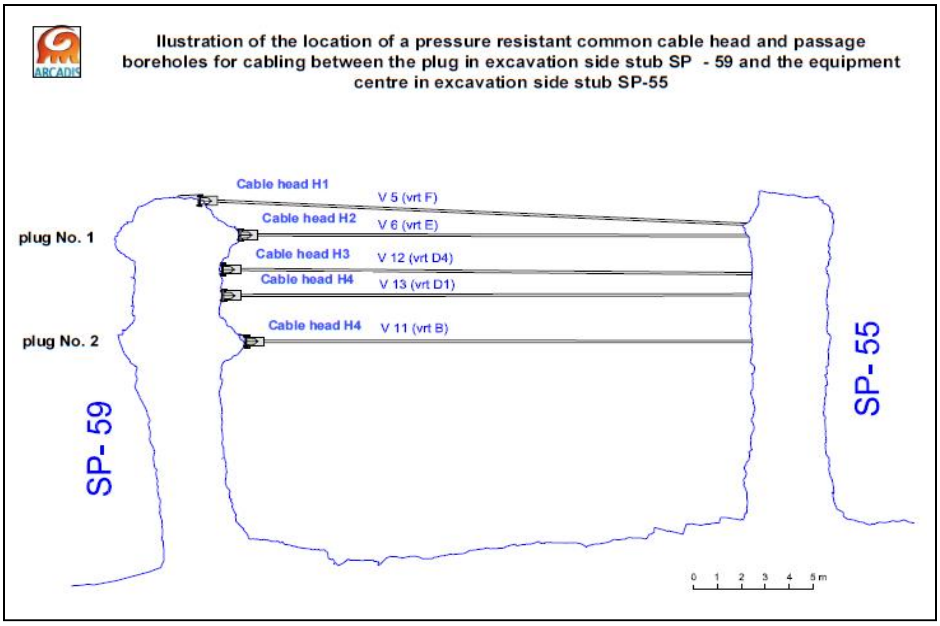


Figure 23 – Boreholes for the cabling connecting the experimental and technology niches

4.2.2. Instrumented rock bolts

The boreholes intended for the measurement bolts were drilled in compliance with D3.18. The boreholes, 12 in total, were drilled into the excavation face in the plug slots.

Holes S1 (4.75m long, 47mm dia), S2 (5.18m long, 47mm dia), S3 (5.18m long, 47mm dia) and S4 (5.06m long, 47mm dia) were drilled into the excavation face and then fitted with measurement bolts. The S1 borehole was 5.1m long and was drilled on the axis of the plug. The S2, S3 and S4 boreholes were drilled at intervals of 120°, at a distance of 0.9m from the axis and with an incline of 30° from the centre line.

A total of eight boreholes were drilled in the space intended for the inner and outer plugs and subsequently fitted with measurement bolts. Four boreholes were drilled in each plug space, two in the upper half and two in the lower half of the space. They were drilled at an angle of 45° to the plug's centre line, at the mid-point of the conically excavated plug space and inclining towards the south, i.e. towards the Mokrsko West cross tunnel. The following boreholes were drilled in the space intended for the inner plug: S5 (5.16m long, 47mm dia), S6 (5.19m long, 47mm dia), S7 (5.05m long, 47mm dia), S8 (5.19m long, 47mm dia); outer plug: S9 (5.12m long, 47mm dia), S10 (5.16m long, 47mm dia), S11 (5.19m long, 47mm dia) and S12 (5.16m long, 47mm dia).

Each borehole was fitted with a total of three 4911A-type GEOKON vibrating wire strain gauges which were fixed at distances of 0.7m, 2.15m and 3.5m from the borehole mouths using plastic spacers. Individual cables (with a total length of 171m) were pulled through 8mm-diameter SCHWER steel pressure-resistant tubes designed for a pressure of 160bar, which were coupled with screwed pipe couplings.

Following assembly, whole sets of three bolts were positioned in the boreholes, the mouths of the boreholes were sealed and, subsequently, the boreholes containing the bolts were filled with WEBAC 4170T epoxy resin.

Figure 24 - Rock bolt assembly prior to installation

4.2.3. Grouting

Inner plug

Grout was injected under high pressure around the circumference of the shotcrete inner plug with the aim of sealing the interface between the rock mass surface and the shotcrete forming the inner plug. In the first phase of grouting the holes were drilled at regular intervals of 0.7m around the circumference to a depth of around 0.40 – 0.45m.

The holes were drilled in such a way that guaranteed that the contact interface was encountered. A total of 17 non-cored holes were drilled, provided with mechanical packers and filled by means of the injection of WEBAC 1660 resin. The consumption of the grouting mixture amounted to 8.05 litres. A total of 26 full-profile boreholes was drilled. Subsequent pressure testing, however, revealed that attempts to seal the interface had failed.

In the second phase of additional sealing grouting, the spacing of the boreholes was reduced in the lower half of the space intended for the plug, initially in locations with the greatest extent of water outflow. A total of 21 non-cored boreholes were drilled and provided with mechanical packers. WEBAC 1660 resin consumption amounted to 38.0 litres.

Hydraulic testing, conducted after a period of 7 days proved that this round of grouting had not prevented the seepage of water. The third phase of additional sealing grouting for the inner plug involved the drilling of 22mm-diameter full profile boreholes in a staggered pattern with a spacing of around 0.2m alternately from the concrete and the rock mass so as to ensure that the contact interface was encountered. In this phase a total of 24 boreholes was drilled and provided with packers.

The concrete protruding from the plug face in the concrete-rock contact zone in the lower half of the plug was removed prior to the injection of the grout. The concrete on the interface was cleaned and porous concrete was rendered impermeable using WEBAC 4525 epoxy resin with the intention that it would form a barrier against grouting resin leakage through the porous concrete in the lower part of the plug and create the support required for higher injection pressures into the interface. Up to this time, it had been possible to apply a pressure of 5bar.

WEBAC 4170T resin and WEBAC 1660 resin were subsequently injected into the interface with a consumption of 8 litres and 2.5 litres respectively.

The hydraulic testing of the third phase of grouting, carried out after a 6-day curing period, once again revealed that the attempt to prevent seepage had failed.

In the fourth phase of the injection of additional sealing grouting into the contact interface of the inner plug, the concrete along the concrete-rock interface was penetrated. A total of 35 22mm-diameter non-core boreholes was drilled with regular spacing initially in locations of most intense water inflow. The boreholes were 0.4 – 0.45m long. Following cleaning, WEBAC 4180N epoxy resin with the consistency of water and the capability to penetrate into the pores of the material was injected into the boreholes without the exertion of pressure. The grout material was injected into 24 boreholes in total. The boreholes were completely saturated with resin.

Hydraulic testing was carried out after 5 days of resin curing and, again, it was revealed that the attempt to prevent seepage and the leakage of water had failed.

By this time a total of 106 30 - 45cm long non-cored holes had been drilled with the aim of sealing the contact interface between the rock mass and the concrete of the inner plug. The total consumption of WEBAC 1660, WEBAC 4170T and 4180N resins used for grouting purposes amounted to 62 litres. A WEBAC IP2 high-pressure grouting pump set was used for the injection of grout and the boreholes subjected to grouting were provided with mechanical packers at their mouths.

Finally, the sealing of the contact zone between the inner plug and the rock mass was accomplished by a new subcontractor. Sealing was aimed at preventing concentrated discharges of water at 20 bar pressure within the pressurisation chamber. The concentrated discharge flow amounted to no more than 1 litre per minute at one location. It was essential that grouting work did not affect the smooth functioning of the pressurisation chamber. In the first stage the boreholes intended for injection work were drilled around the circumference of the plug at a distance of 300mm from the edge (see Figure 25 green dots). In the second stage boreholes were added on the right and left sides of the plug (see Figure 25 blue dots). In the third stage boreholes were added at the bottom of the plug (see Figure 25 pink dots). The old packers were removed following the conclusion of the process.

CarboPur WF/WFA/WX was used as the injection medium and electrical hand drilling hammer screws with a diameter of 14mm were sunk to a depth of 250 to 800mm.

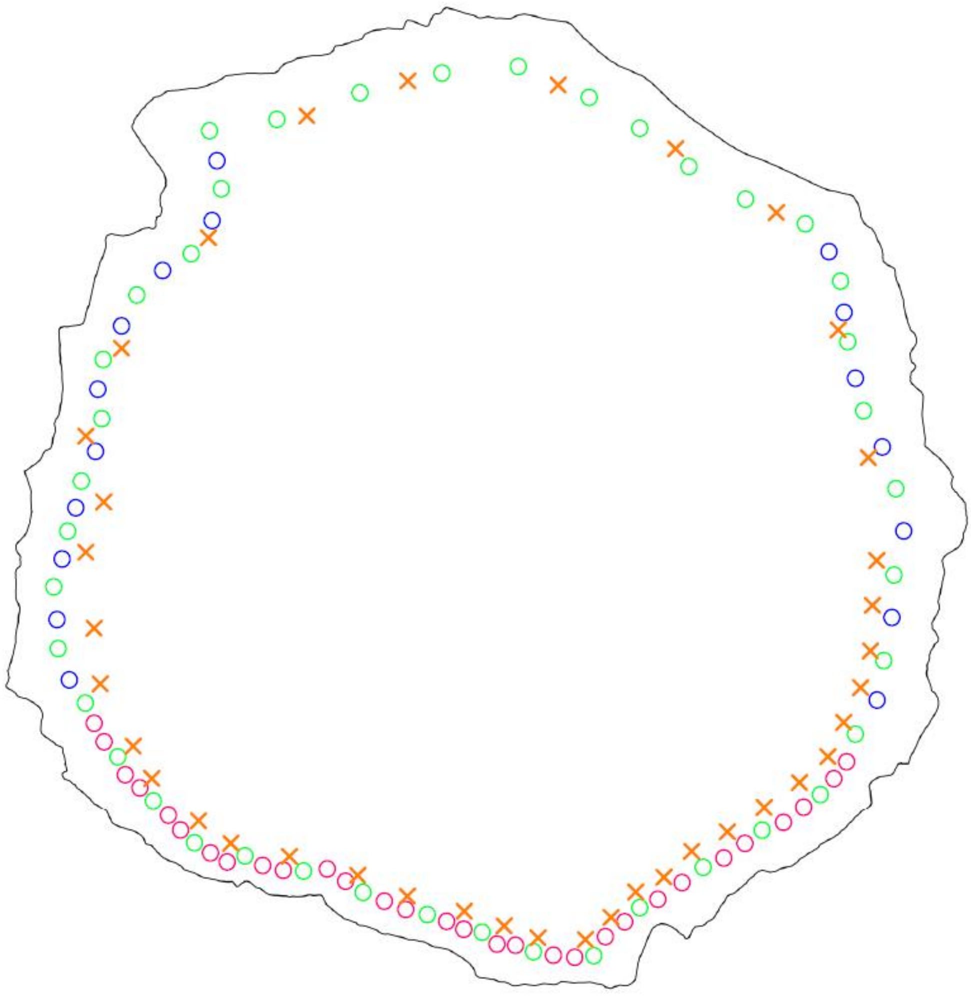


Figure 25 – Drilling pattern for injection work on the inner plug

Outer plug

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. Furthermore, the space in front of the outer plug was sealed to a distance of 2m in front of the plug.

Purinjekt, polyurethane and Sika were used as the injection media and electrical hand drilling hammer screws with a diameter of 18mm were sunk to a depth of 450 to 1000mm.

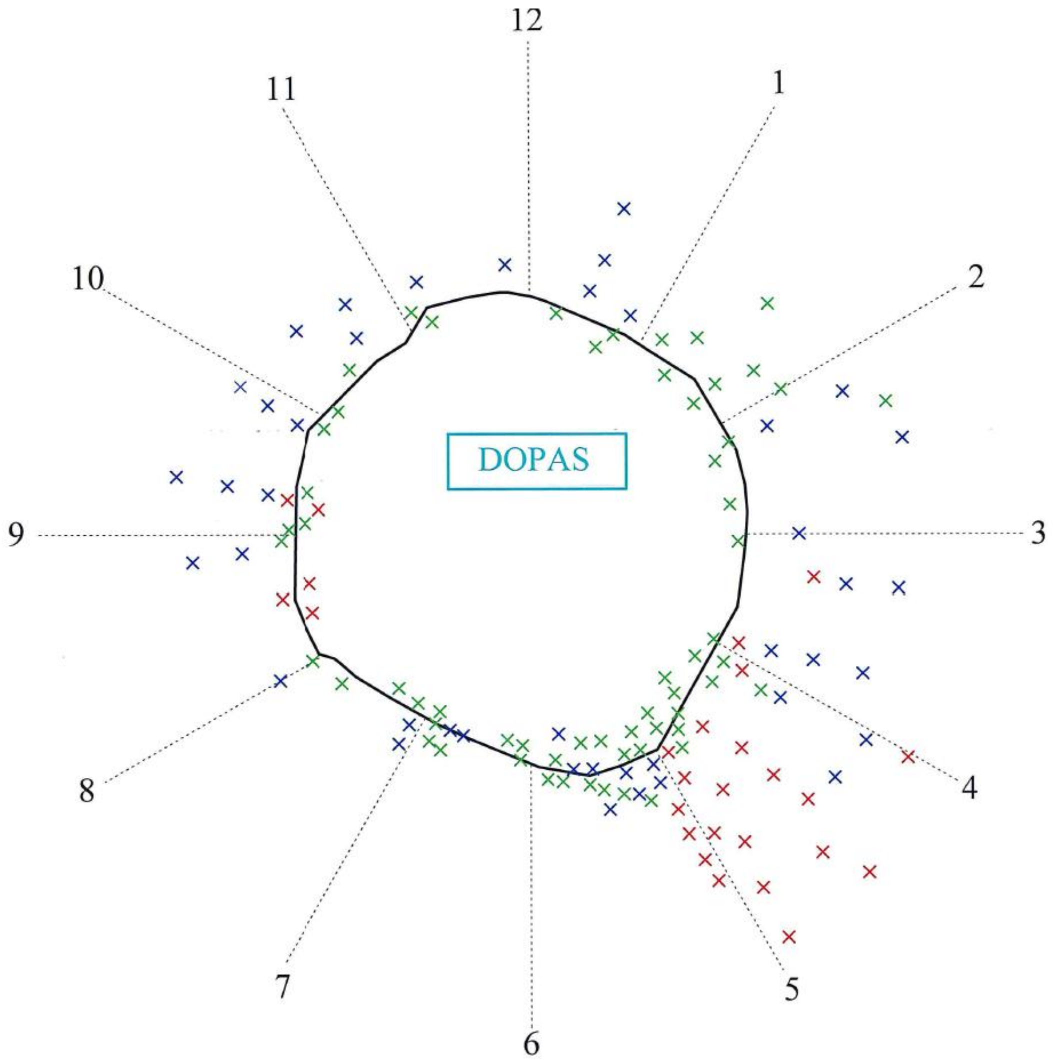


Figure 26 – Drilling pattern for injection work on the outer plug

In total 42 boreholes were sealed using 68kg of Sika material (see Figure 26 blue marks). 26 boreholes were sealed using Purinjekt polyurethane on the right and left sides of the plug (see Figure 26 brown marks). 62 boreholes were sealed using Purinjekt polyurethane around the whole of the plug's circumference (see Figure 26 green marks).

The total consumption of polyurethane amounted to 140kg.

4.3. TASK 2

Work on Task 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.

4.3.1. Installation Work Connected with the Pressurisation Chamber

The walls and floor of the pressurisation chamber were prepared using shotcrete and SikaTop-122SP (www.sika.com). The thickness of the profiling was such that there was a gap of 100mm between the remodelled chamber surface and the next structure (the first concrete separation wall). The surface of the remodelled chamber was treated with a 3mm thick waterproofing finish: SikaTop Seal 107. The pressurisation chamber was closed by means of the installation of the first concrete separation wall. The shotcreting of the pressure chamber also served for the testing of the technology used for the shotcreting of the inner plug.

4.3.2. Inner Concrete Plug

The inner plug was constructed using glass-fibre-reinforced low-pH shotcrete employing the wet mix shotcreting procedure. The thickness of the inner plug is 1850mm. Shotcreting was performed by means of the application of approximately 100mm-thick layers in a non-stop run of 23 hours. Measurements and observations taken during the experiment demonstrated that contact grouting would be necessary between the plug and the rock mass so as to ensure water tightness.

The most significant influence on the speed of the shotcreting work consisted of the logistics of the process. The concrete mix was produced at a concrete plant in Prague and transported by road to the Josef URL. At the entrance to the facility, the mixture was reloaded into small trucks (each capable of transferring 1m^3 of concrete), since the small profile of the Josef tunnels limited the size of the trucks that could access the location of the experiment.

Within the Josef facility, there is only one location at which the trucks supplying the concrete could pass and, therefore, the turnaround time for each truck (40 minutes) represented the rate-limiting factor in the shotcreting process. That meant that every 20 minutes a new batch of concrete was available for shotcreting. The shotcreting process itself was much quicker, therefore, the time between the arrivals of each batch of concrete was used to clean up the rebound from the area around the shotcrete plug and to install monitoring equipment.

Following the construction of the inner concrete plug, a series of water pressure tests (pressurisation of the chamber using water and air) was performed focusing on the verification of plug tightness using a temporary pressurisation system. Measurements and observations of water flow across the plug during the test demonstrated that contact grouting between the plug and the rock would be necessary in order to ensure water tightness.

The rock-plug interfaces, which contained preferential pathways for water flow, were sealed by means of grouting through a series of boreholes sunk at leakage locations. Grouting was conducted as part of Task 1 (see chapter 4.2.3).

4.3.3. Filter

The gap between the second and third separation walls was used for the installation of the gravel filter which was manually emplaced in a number of stages. Initially, the lower part of the walls (approximately one-third to half of the overall height) was erected and the gravel filter was emplaced in the resulting gap. Subsequently, the emplacement of the bentonite commenced. Once the bentonite level reached the level of the walls (and the filter) a new layer of concrete blocks was constructed and the filter set in position. The final layer of the separation walls and the gravel was emplaced immediately following the conclusion of shotclaying.

4.3.4. Outer Concrete Plug

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 using boreholes was subsequently conducted. The tightness of the outer plug was verified following the commencement of water pressure testing (experimental run – phase 2).

Grouting was conducted as part of Task 1 (see chapter 4.2.3).

4.3.5. Technology

The partial testing of the technological equipment began at the beginning of 2015 initially at the supplier's premises and, subsequently, at the Josef facility.

The main parts of the technological equipment were delivered in February 2015 and were tested following installation for basic functionality (only the inner plug had been erected at that time).

Testing with the equipment fully connected to the experiment was performed later once the construction work was completed – i.e. once the outer plug had been erected and allowed to cure.

The full pilot testing of the experiment was performed in July 2015. A series of (stress) tests were performed and the results were used for the verification both of the functioning of the equipment and the overall experiment. The pilot run of the experiment was concluded in July 2015.

Figure 27 - Technology installation

Figure 28 - Technology installation

4.4. **TASK 3**

Work on Task 3 was performed primarily by the CTU which allowed preparation work to take place in parallel with work on Task 2.

The material was verified, the pellet production system selected and the emplacement technology tested and fine-tuned as part of the laboratory agenda (*Vašíček et al., 2016 – D3.21*).

Contact was established with pellet producers and the production of the material commenced.

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

4.4.1. Pellets

Several different technologies concerning the compaction of powdered bentonite were tested during the research at the CEG and two were finally selected for further experimentation purposes. The first method involved the production of compacted pellets by means of a roller compaction machine. This product was named B75 PEL 12 (Vašíček et al., 2016). The second product was named B75 REC 0,8-5mm (Vašíček et al., 2016) and consisted of material produced by the roller mill which was subsequently crushed and sieved into specific grain size fractions.

<u>B75 PEL 12</u>

The pilot testing process commenced with a material water content of around 28% with a resulting dry density value of around 1.40Mg/m^3. The water content of the material was gradually reduced to a value of 16% which proved to represent the limit of the technological ability of the roller machine employed in the research. The final product (B75 PEL12) with a maximum dry density value of around 1.80Mg/m^3 was selected for the compacted part of the EPSP. The pellets have a diameter of 12mm, a length of up to 40mm and a dry density of 1.82Mg/m^3. A total of 36 tonnes of B75 PEL 12 was produced prior to the construction of the EPSP (Figure 30 - Figure 34). A quality control audit subsequently revealed a good distribution of water content and dry density in the B75 PEL 12 (Figure 29).

<u>B75 REC 0,8-5</u>

This material (Figure 35) originated as the result of negotiations with a Czech bentonite production company. The pellets (fragments of highly-compacted bentonite plate) are not available commercially but they do represent an intermediate stage of the industrial process employed by the company. Laboratory testing revealed a good level of compaction (dry density 1.70-1.98g.cm^{-3}) with a relatively low water content value. The advantage of this technology consists of the production of pellet fragments of various sizes, i.e. it allows for the mixing of various grain sizes in order to achieve the best grain distribution curve which helps in terms of achieving a sufficient level of dry density within the emplaced material. The resulting material was code-named B75 REC. Following pilot testing, B 75 REC 0,8-5 was selected for spraying application (Vašíček et al., 2016).

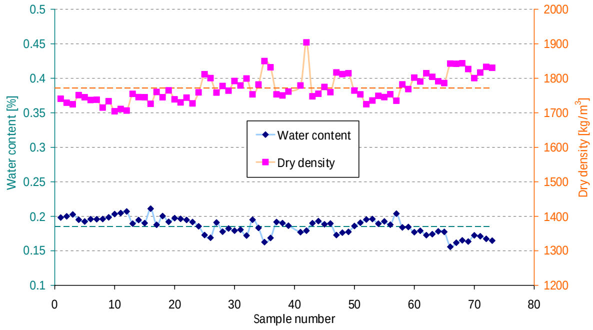


Figure 29 - Results of sampling during the production process

Figure 30 - Mixing machine for adjusting water content in the dry bentonite

Figure 31 - Roller compaction machine

Figure 32 - Transport of the pellets from the roller compaction machine

Figure 33 - First stage of packing

Figure 34 - Final product in bags

Figure 35 - B75 REC

4.4.2. Emplacement

The bentonite was emplaced between the inner shotcrete plug and the second separation wall. Over ninety-five percent of the bentonite seal was composed of bentonite pellets that were vibration-compacted. The crown space of the seal could not be accessed using the vibrator and was therefore emplaced using spray technology. The filter separation walls served as support for the emplaced bentonite, and were constructed in parallel with bentonite emplacement.

Originally, consideration was given to using a mixture of bentonite and ice for spraying, which might potentially have provided high densities for the emplaced bentonite. However, it was found that ice spraying technology has limited throughput and, owing to the time constraints governing the installation of the bentonite seal, it was decided not to use this technology. Nonetheless, following the fine tuning of the machinery, it was possible to achieve the same density of deposited material using sprayed bentonite pellets only (at a much higher application rate).

The bentonite (B75) was used in the form of pellets. Two types of pellets were used; the first type (compacted by a roller - B75 PEL 12) was used for the lower parts. The second type (compacted by rollers and subsequently crushed and sieved - B75 REC) was used for shot clay application in the upper parts of the experiment. Based on the project requirement for a minimum swelling pressure of 2MPa and a maximum hydraulic conductivity of $10^{-12}ms^{-1}$ in the bentonite sealing, a minimum dry density of $1.4Mgm^{-3}$ was required following bentonite application.

The construction of the EPSP bentonite pellet layer was completed in just 9 days. The total amount of emplaced material was 39.9 tonnes placed in a total volume of $23.7m^3$. Two methods of density verification were employed – sampling and total mass balance. Both methods revealed a dry density value higher than the required level (1.40Mg/m^3).

Emplacement using vibration compaction

Based on a pilot test (*Vašíček et al., 2015*), which demonstrated good compaction of the pellets, two vibration-desk machines (the NTC compaction plate and the Masalta vibration plate) were selected for the bulk work. The bentonite pellets were emplaced in horizontal layers, each with a maximum height of 3cm, and were vibration compacted. Electric hammer drills (HILTI TE 3000-AVR and HILTI TE 1500-AVR) with a plate were used for the compaction of the bentonite pellets around the measurement sensors, along the drift wall and in the upper part of the drift where the space available for utilising the vibration-desk machines was limited.

Figure 36 - Vibration compaction

Figure 37 - Emplaced pellets

Shot clay technology

Sprayed clay technology was used for the backfilling of the upper part of the drift. Approximately 5% (1.5m^3) was backfilled using sprayed B75 REC 0.8-5. The spraying machine selected consisted of an SSB 14 DUO (Filamos Ltd.) machine with an Atlas Copco electric air compressor (working pressure 10 bar, air capacity 350m^3/h). Both machines were pilot tested before the construction phase commenced.

Figure 38 - Upper part of the drift – space to be filled by spraying

Figure 39 - Spraying of the bentonite


Figure 40 - Sprayed bentonite


Figure 41 - Spraying machine

4.5. TASK 4

Work on the monitoring system began at the very beginning of the project with the design of the monitoring setup - see chapter 3.4 and D3.18 *(Svoboda et al.,2014)*. Subsequently, the monitoring system was gradually constructed primarily by the CTU instead of a subcontractor as originally planned. This allowed preparations to continue in parallel to other ongoing work.

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

The work was concluded by means of the integration of all the parts of the system (including the technology) into the measurement system of the Josef underground laboratory once the construction work and the pilot run had been completed.

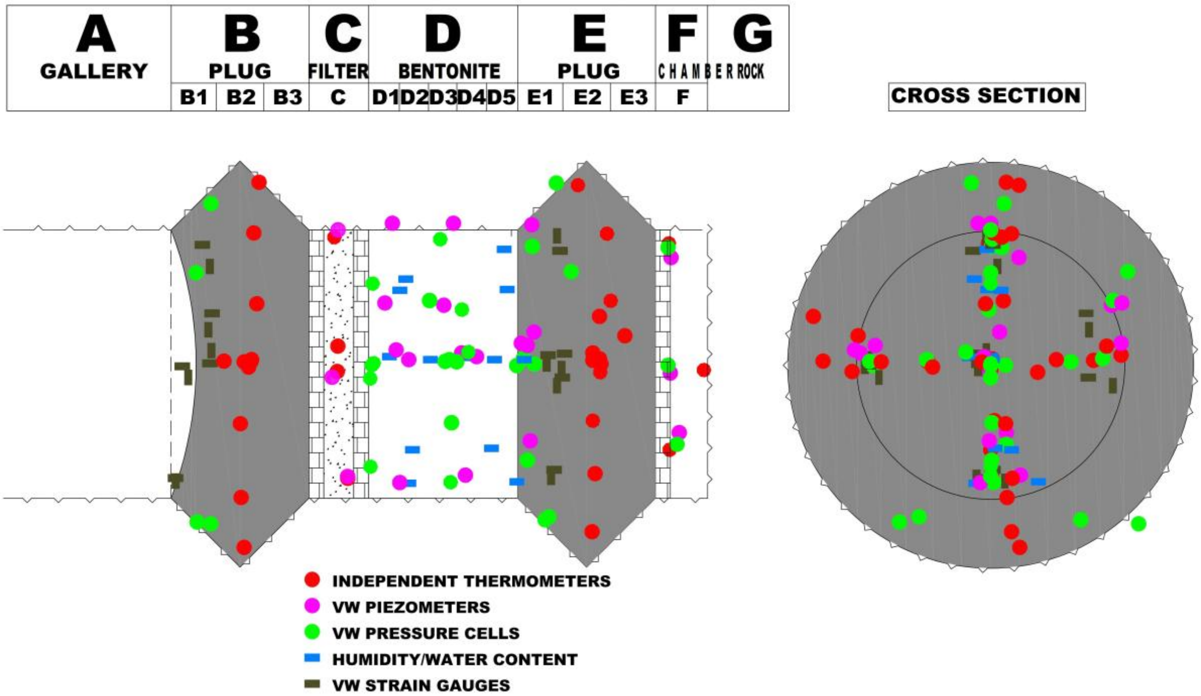


Figure 42 – Sensors installed in the EPSP

4.5.1. Sensor probe preparation

The preparation of the sensors took place in the workshop of the Josef URC facility (except for the instrument rock bolts which were prepared and installed by another party as part of Task 1).

The sensors were supplied with very different levels of readiness from bare sensing components up to fully-assembled sensors equipped with protective tubing.

The general procedure consisted of connecting the sensing element to the cable, the placing of a protective cap on the sensing element and protective tubing on the cable and the attaching of the assembled sensor to the cable head plate.

Sensor functionality was checked following every stage of assembly. The measurement system with the connected sensors was subjected to a dry run performed in the laboratory in order to verify system functionality.

The sensor probes were grouped into sensor assemblies according to their assigned cabling boreholes. The assemblies were put together by means of the cables of the probes being pulled through the cable head plate and by the subsequent fixing of the protective tubing into the cutting ring fitting on the cable head plate. Each sensor assembly contained up to 32 probes.

The completed assemblies were then packed and transported into the underground complex where they were fitted to the corresponding cable head at the end of the borehole. In total 5 assemblies were installed in the EPSP experiment.

4.5.2. In-situ installation

The instrumentation was pre-assembled at the surface facility from where it was transported to the underground complex. The sensor assemblies were installed gradually as erection work progressed.

In general, the installation of the sensors in-situ can be divided into the following stages:

1. Sensor assembly
   a. the assembly was transported to the underground complex and positioned against the borehole cable head
   b. the pre-installed sensors (rock bolts) were connected to the cable head plate
   c. the cables were bound together and pulled through the borehole
   d. the cable head plate was fixed to the cable head of the borehole and sealed
2. The sensors were connected to the data loggers
3. Sensors with their locations prepared:
   a. the sensor was installed in its final position
   b. the position of the sensor was recorded and documented
   c. the cabling of the sensor was fixed (to the walls or on “ladders”)
4. Sensors without a prepared location were temporarily stored on the side wall or ceiling
5. During construction work the temporarily stored sensors were processed thus:
   a. the sensors were gradually installed in their final positions once the location had been prepared
   b. the position of each sensor was recorded and documented (immediately following the installation of the sensor)
   c. the sensor cabling was fixed (immediately following the installation of the sensor)

Note: The sensor assemblies were installed gradually as erection work progressed.

The positions of all the sensors installed in the EPSP plug are depicted in Figure 42.

<u>Instrumented rock bolts (profile G)</u>

The instrumented rock bolts were installed as part of Task 1 work. Due to their nature (fixed in the rock) it was not possible to include them in the sensor assemblies prepared in advance in the laboratory. Therefore, they were connected to the cable head plate once the corresponding assembly had been transported in-situ.

In total 12 rock bolts were installed. 4 rock bolts starting from the face, 4 from the inner plug slot and 4 from the outer plug slot. Each rock bolt contains 3 strain gages (type 4911-4X).

<u>Pressurisation chamber and separation wall (profile F)</u>

The pressurisation chamber houses one of the connecting boreholes for the cabling. The cable head F assembly was installed at the end of September/beginning of October 2014. This cable head also provided space for the cabling of four instrumented rock bolts (part of profile G) which were attached during the installation of the cable head assembly.

The sensors attached to the cable head were installed and connected to the system prior to chamber size adjustment by means of shotcreting. Some of the sensors were installed in their final positions but most of them were stored at the side of the chamber and fixed in their final positions later, i.e. before and during the construction of the separation wall (some of the thermometers, pressure cells and piezometers).

Profile F contains 6 thermometers (analogue or digital) emplaced in the pressurisation chamber or along the separation wall, 3 piezometers emplaced in the pressurisation chamber and 3 pressure cells installed along the separation wall. Each vibrating wire sensor (piezometer, pressure cell) also contained an internal temperature sensor.

Inner plug (E)

The inner plug houses the second connecting cabling borehole. The cable head E assembly was installed in October 2014. This cable head also provides space for the cabling of four of the instrumented rock bolts (part of profile G) which were attached during the installation of the cable head assembly.

The first step involved the installation of four pressure cells in their final positions on the contact zone between the rock mass and the shotcrete (applied later). Subsequently, the protective tubing of the sensor cabling (of the pressure cells and rock bolts) was attached to supporting rods. The cabling was widely spaced in order not to create obstacles to the shotcreting process. The rest of the sensors were temporarily attached to the side of the chamber. These sensors were installed one-by-one during the shotcreting process in the intervals between the delivery of individual batches of shotcrete.

The inner plug contains a total of 20 temperature sensors (analogue or digital); some of the measurement points consist of two thermometers (analogue and digital). Deformation of the plug was measured by means of strain gauges installed at 5 measurement points; each point contains one vertically and one horizontally positioned strain gauge.

Bentonite (D)

The bentonite sealing section of the EPSP experiment houses two cable connecting boreholes. Cable head assemblies D4 and D1 were installed in November and December 2015. The sensors were not installed immediately (they were stored temporarily on the side of the chamber) in order to allow for the testing of the inner plug and grouting. Once grouting was completed and the concrete plug successfully tested, the sensors stored on the rock face along with other structural elements were installed in their final positions. The remaining sensors were stored on the side of the chamber and installed once the level of bentonite emplacement reached just above their planned installation positions.

Special precautions were in place so as to avoid damage to the sensors during the compaction process. Bentonite pellets were compacted above the level of the sensor to be installed. A hole was then excavated, the sensors positioned in the hole and the space surrounding the sensor was finally backfilled using crushed material.

D profile contains 19 hydraulic pressure cells for the measurement of contact stress between the bentonite section and the surrounding rock, the inner plug or the filter separation wall, or to measure evolution of swelling pressure inside the bentonite section. 5 pressure cells were installed on the surface of the inner plug, 5 on the filter separation wall, and 9 cells were distributed inside the bentonite matrix.

Furthermore, the bentonite section contains 13 sensors for the measurement of changes in water saturation (7 TDR sensors and 6 relative humidity probes) and 15 piezometers for the measurement of pore pressure. All of the sensors also contain internal temperature sensors.

Filter (C)

The filter houses no connecting cabling borehole; the associated cabling uses borehole and cable head D1 which is located at the end of the bentonite section. The relevant sensors were therefore installed at the same time and in the same manner as the sensors in the bentonite. Moreover, the filter structure served as support for the bentonite; therefore, it was raised gradually as bentonite emplacement progressed.

A total of 4 temperature sensors and 3 piezometers were positioned in the filter.

Outer plug (B)

The installation of the outer plug sensors was performed in exactly the same manner as for the inner plug. The outer plug houses a second connecting cabling borehole. The cable head B assembly was installed in June 2015. This cable head also provides space for the cabling of four of the instrumented rock bolts (part of profile G) which were attached during the installation of the cable head assembly.

The first step involved the installation of four pressure cells in their final positions on the contact zone between the rock mass and the shotcrete (applied later). Subsequently, the protective tubing of the sensor cabling (of the pressure cells and rock bolts) was attached to supporting rods. The cabling was widely spaced in order not to create obstacles to the shotcreting process. The rest of the sensors were temporarily attached to the side of the chamber. These sensors were installed one-by-one during the shotcreting process in the intervals between the delivery of individual batches of shotcrete.

Profile B contains the same instrumentation as Profile E.

Technology (A)

The experimental technology is controlled and monitored electronically. The control system is based on an industrial PLC Allen Bradley Micrologic 1400 with a PanelView Plus 6 Terminal, 600 interface panel. The control system communicates with the CTU measurement system over an Ethernet network via a MODBUS protocol. Moreover, backup data is stored directly in the control panel of the technology. The control system was integrated into the measurement system following delivery and installation in-situ in February 2015.

4.6. CONSTRUCTION IN PICTURES

Experimental niche prior to reshaping and ground improvement (2.11.2012)

Excavation of the plug slots

Grouting work

Excavated plug slots

Shotcreting of the chamber (27.10.2014)

Comp 2014)

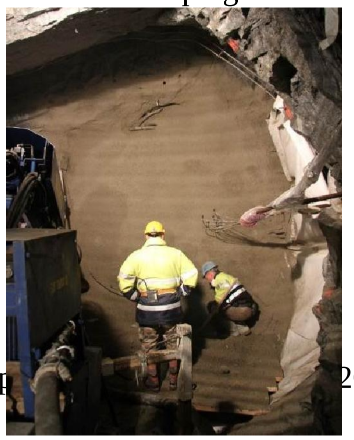
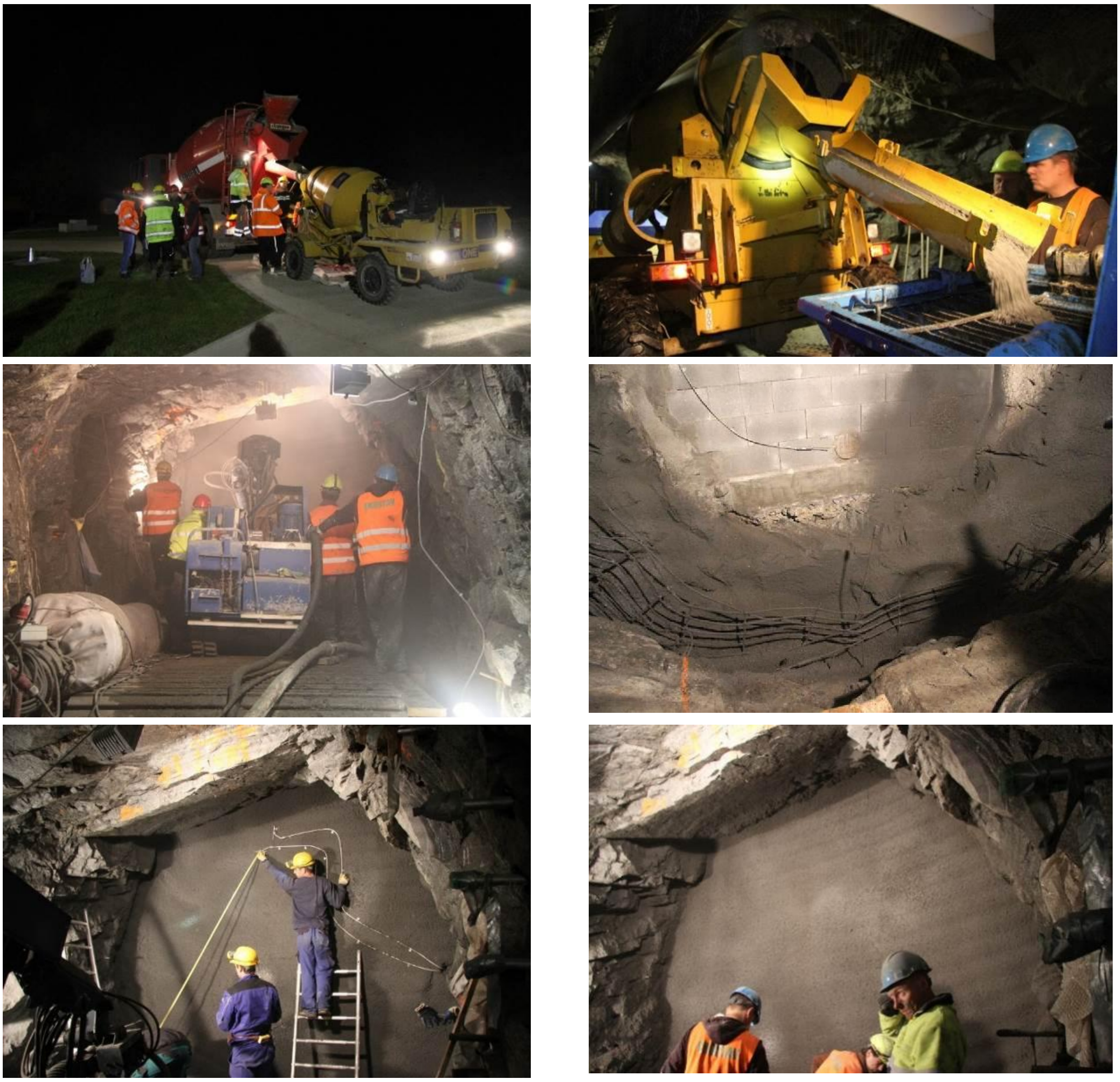


Figure 43 - EPSP installation

Separation wall erection (4.11.2014) Completed separation wall (5.11.2014)



Inner plug erection and sensor installation (12-13.12.2014)

Figure 44 - EPSP installation

Sensor assembly within the inner plug before bentonite emplacement (5.6.2015)

First part of the filter erected (photo taken at the start of bentonite installation, 5.6.2015)

Pellet emplacement (compaction)

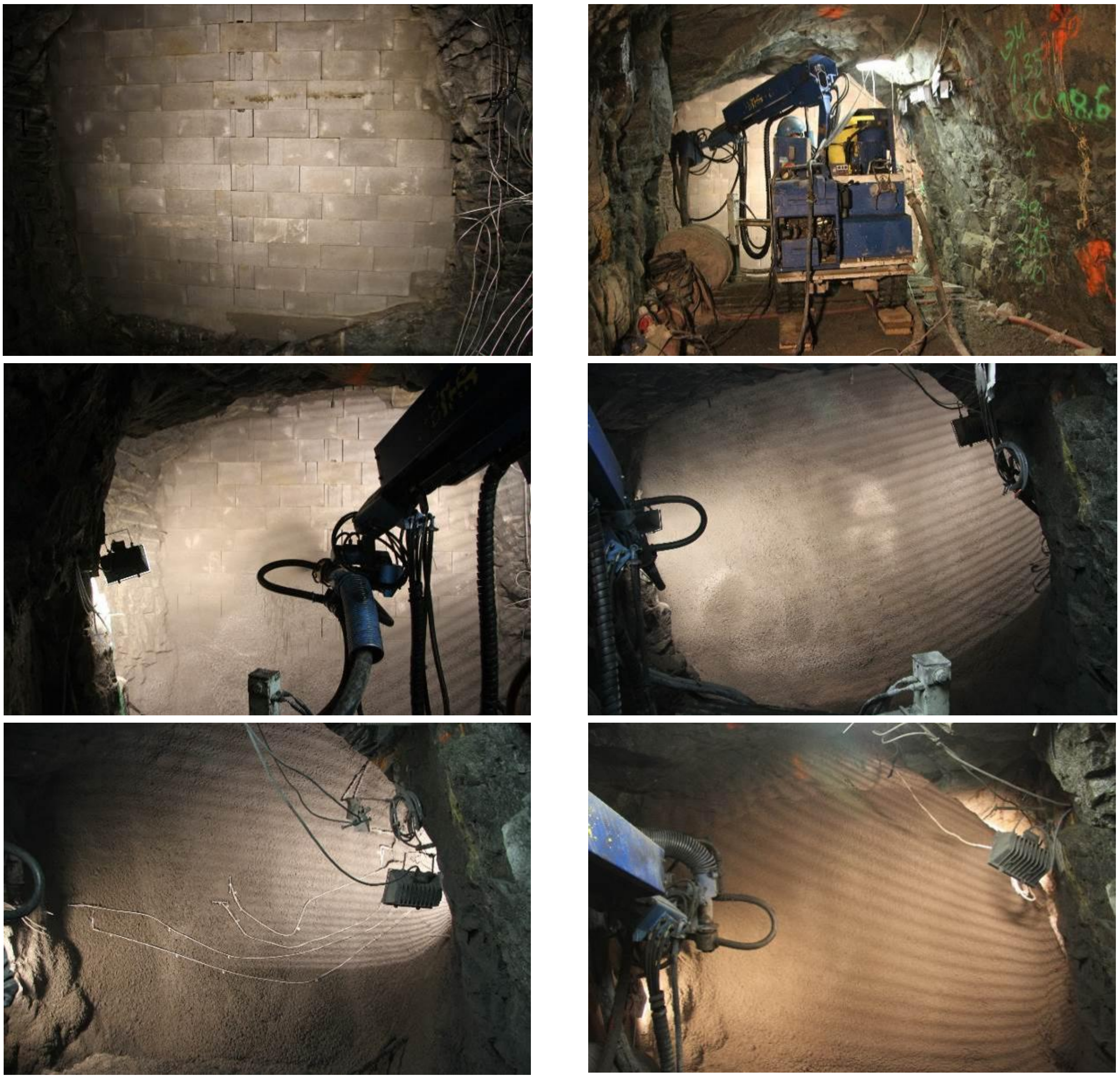
Upper part of the drift – space for spraying

Shotclaying

Figure 45 - EPSP installation

Technology installation in the niche (24.2.2015)

Technology installation in the niche (24.2.2015)



Outer plug erection (19-20.6.2015)

Figure 46 - EPSP installation

Completed outer plug

Start of the experimental programme (21.7.2015)

Start of the experimental programme (21.7.2015)

Figure 47 - EPSP installation

5. MONITORING OF CONSTRUCTION

EPSP installation itself made up one of the key outcomes of the project. Therefore, the monitoring of the erection process itself was extremely important. Monitoring commenced prior to construction work via sensors positioned inside the rock mass. The remaining sensors were gradually installed following the erection process. The scheduling of the most important monitoring installation periods is provided in Table 5.

Table 5 - EPSP monitoring installation (important periods)

Phase	Start	End	Duration of phase (days)
Pressurisation chamber adjustment	27.10.2014	27.10.2014	1
Inner plug erection	12.11.2014 19:50	13.11.2014 18:30	1
Bentonite sealing and filter erection	5.6.2015	14.6.2015	9
Outer plug erection	19.6.2015 12:00	20.6.2015 12:00	1

The processes monitored during the construction phase are summarised in this report; the complete list of the results of monitoring can be found in D4.6 (*Svoboda et al. 2016*).

5.1. TEMPERATURE

The evolution of hydration heat was monitored using 16 independent temperature sensors placed in each of the shotcrete plugs (Figure 48 and Figure 49). The temperature in both plugs peaked at 52°C approximately 30 hours following the completion of the shotcreting process. The maximum registered temperatures were within the defined safe limit. The curing of each plug lasted around 1 month, following which the temperatures dropped to the level of the surrounding rock.

5.1.1. Inner plug

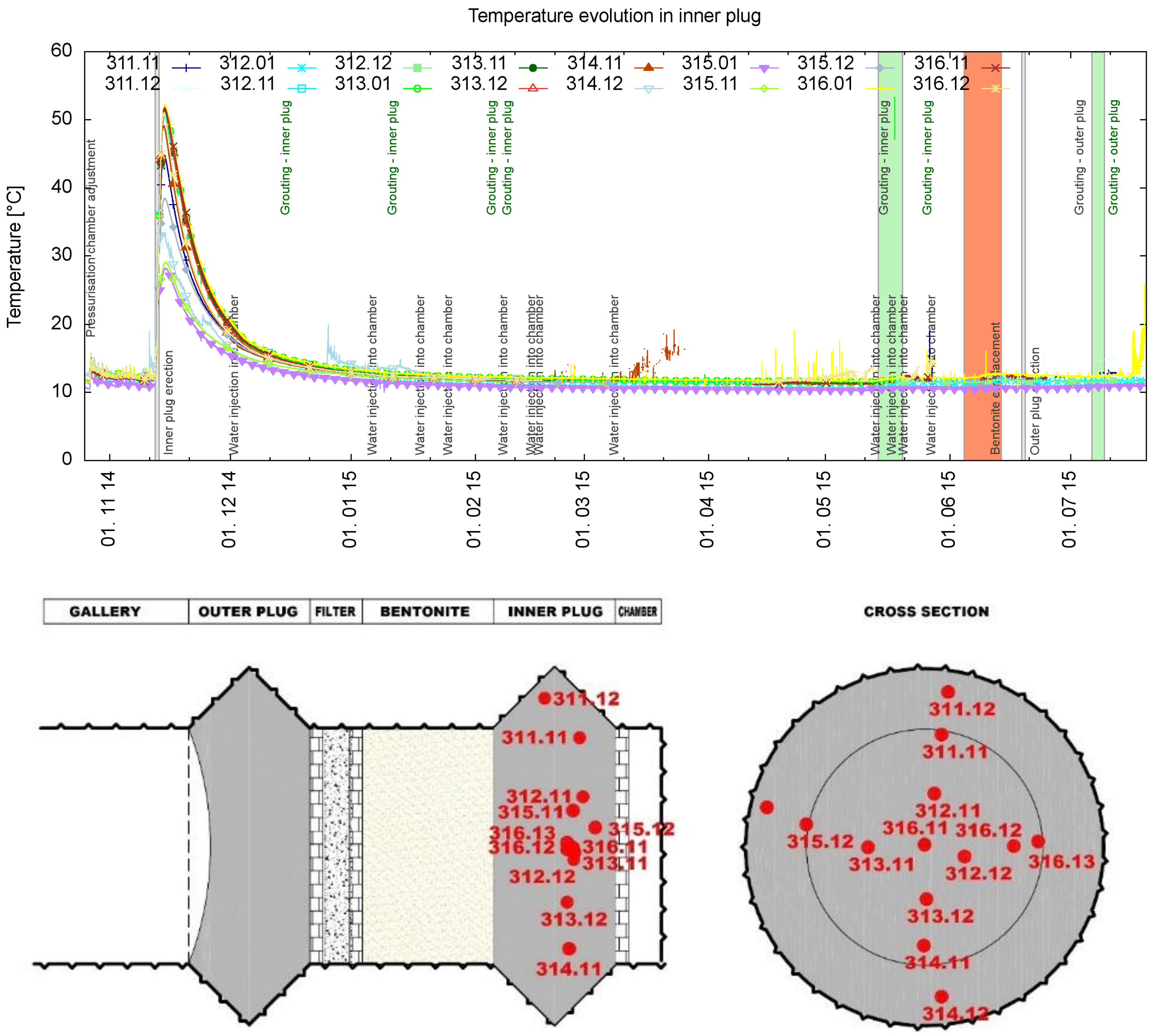


Figure 48 – Temperature in the inner shotcrete plug

5.1.2. Outer plug

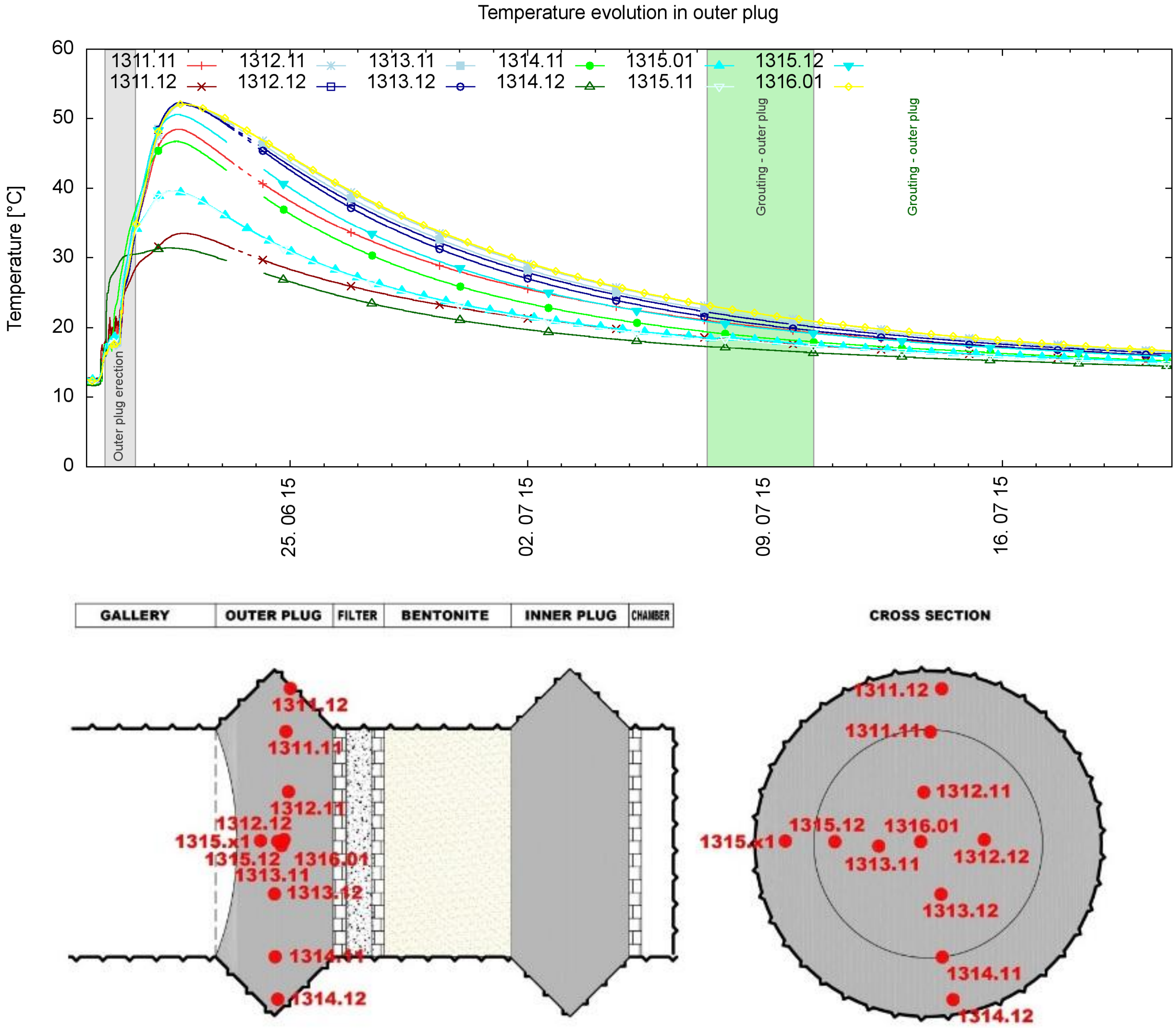


Figure 49 – Temperature in the outer shotcrete plug

5.2. DEFORMATION

Deformations within the shotcrete plugs were monitored using vibrating wire strain gauges (10 in each of the plugs). In each location two sensors were installed perpendicular to each other in order to monitor both horizontal and vertical strain. The locations of the sensors are shown in Figure 42. The evolution of strain in both plugs is shown in Figure 50 and Figure 51.

5.2.1. Inner plug

Shrinkage in the range of 2200 - 3600µm/m was observed for the inner plug. The evolution of strain closely followed the cooling of the plug. It was observed that the water tightness tests (pressurisation from the chamber) and the contact grouting had a significant influence.

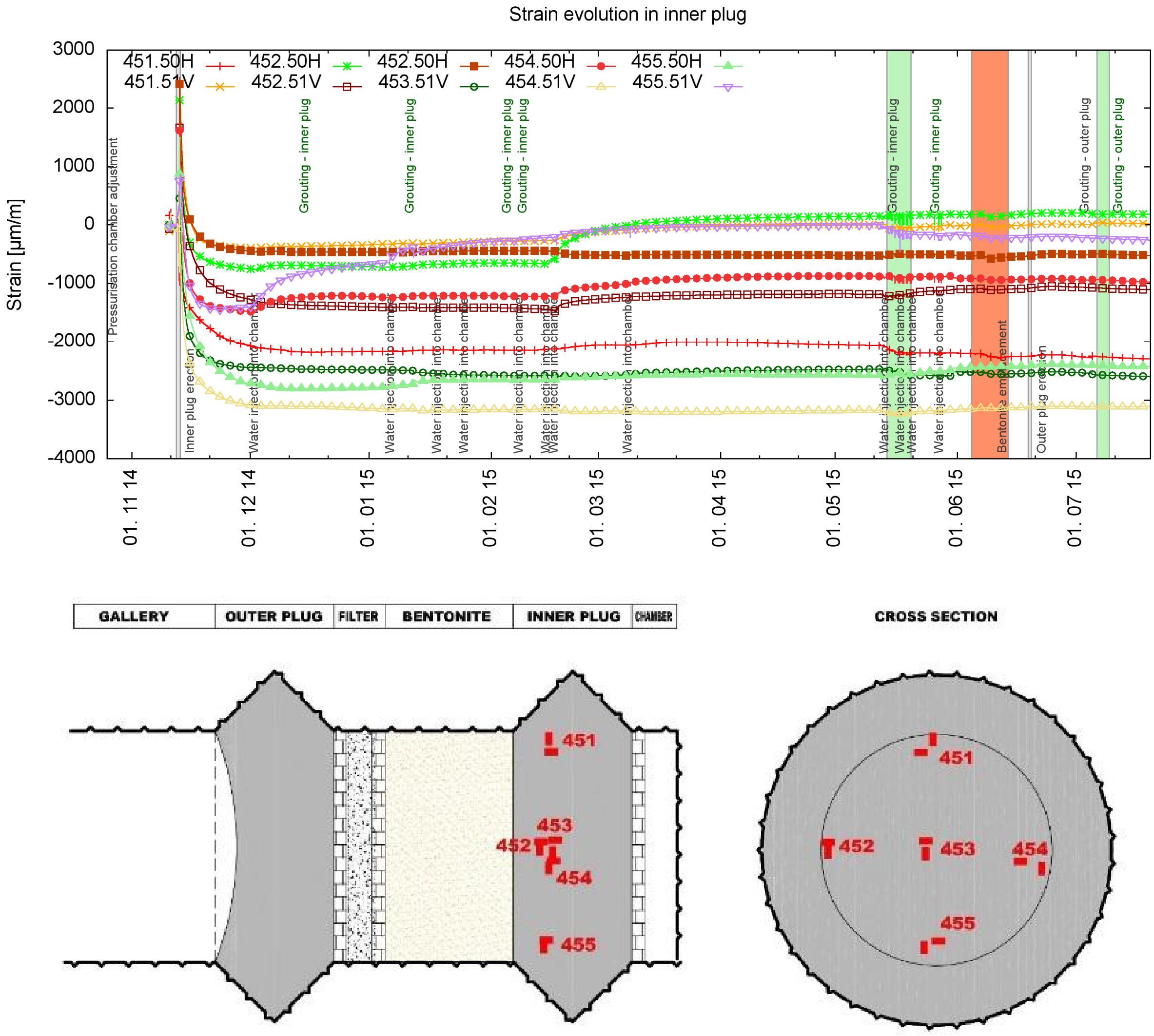


Figure 50

5.2.2. Outer plug

Shrinkage in the range of 2200 - 4000µm/m was observed for the outer plug. The evolution of strain closely followed the cooling of the plug.

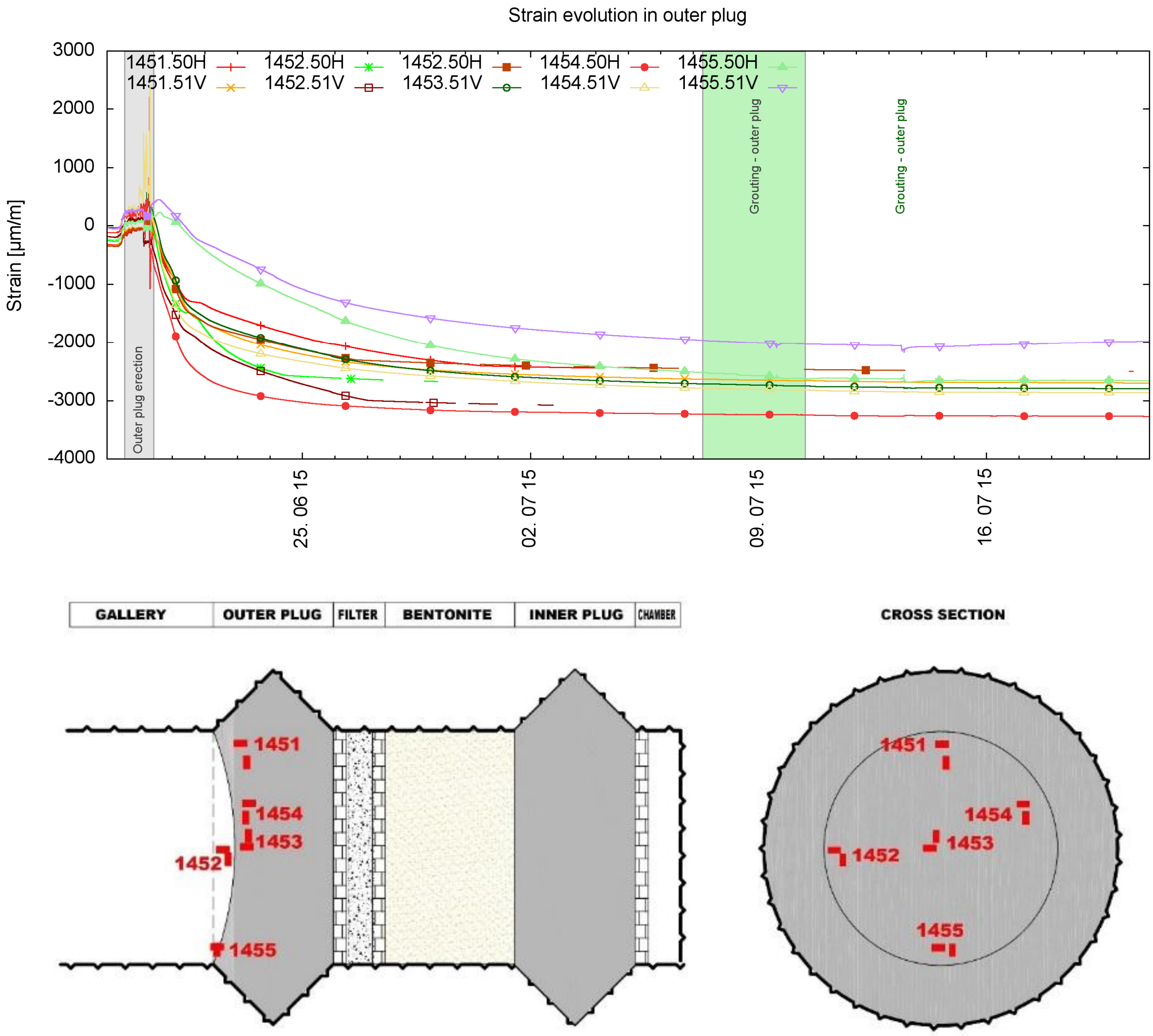


Figure 51

5.3. CONTACT STRESS EVOLUTION ON THE CONTACT BETWEEN THE PLUGS AND THE ROCK MASS

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

5.3.1. Inner plug

The highest peak was observed 17 hours following shotcreting – in the middle of the heating phase. The bottom sensors (472 and 474) probably became unstuck from the plug (or rock) as the shotcrete shrank during the cooling phase which explains the negative values when cooling occurred and the almost zero response following water injection into the chamber.

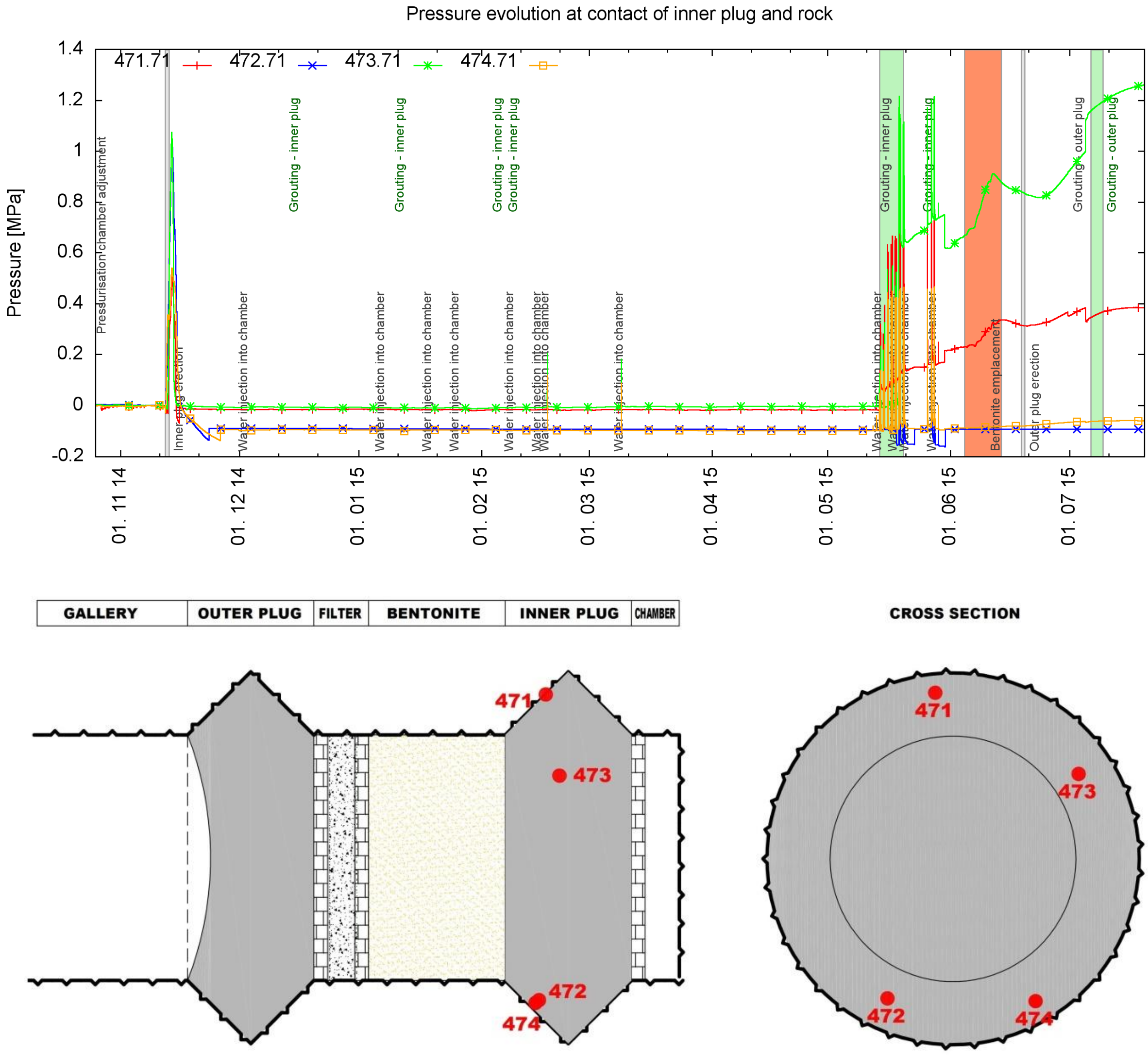


Figure 52 - Pressure evolution at on the contact between the inner plug and the rock mass

5.3.2. Outer plug

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

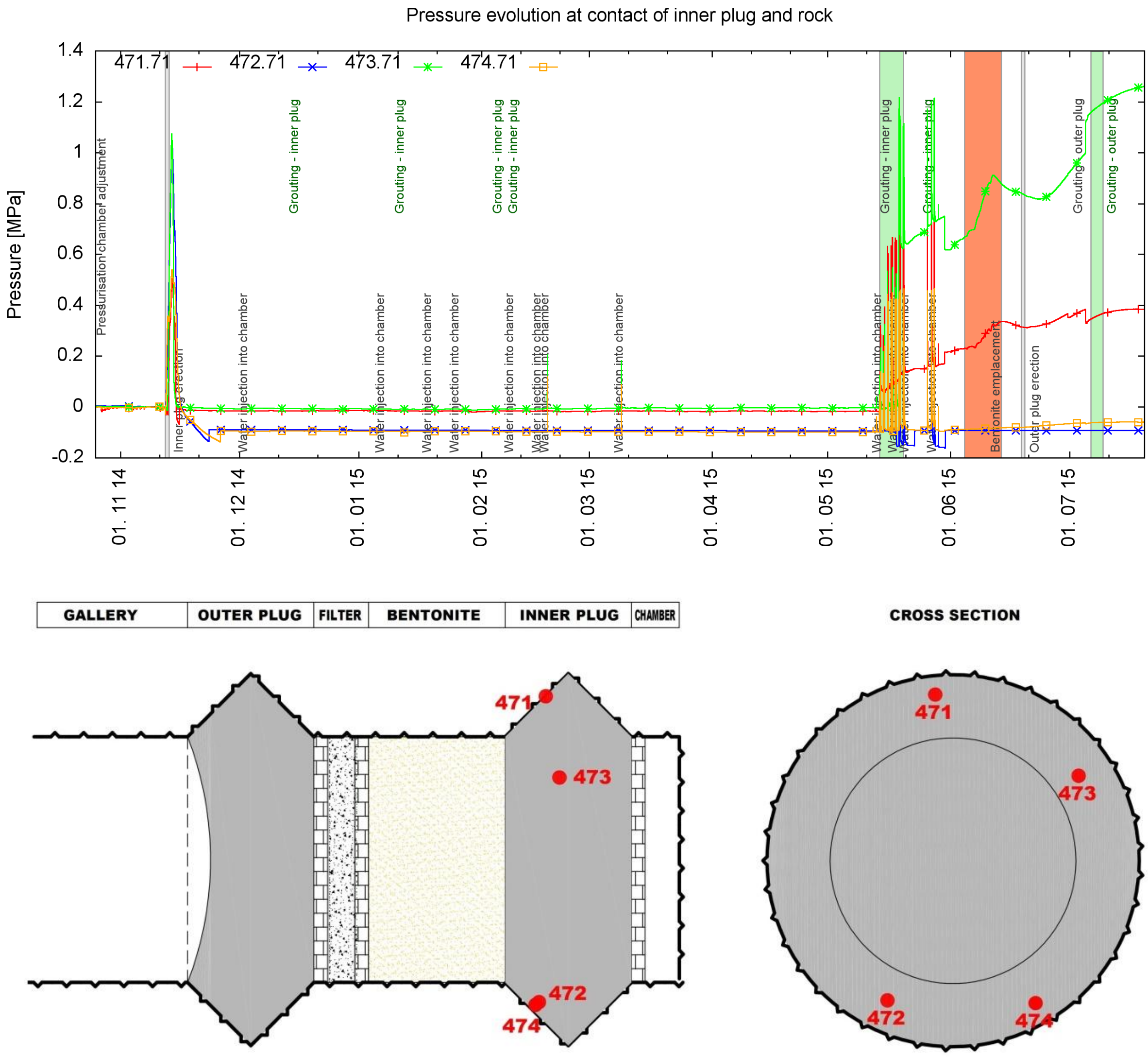


Figure 53 - Pressure evolution at on the contact between the outer plug and the rock mass

5.3.3. Contact stress evolution at the contact between the inner plug and the stabilisation wall

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

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 did not obstruct water flow and therefore functioned as intended.

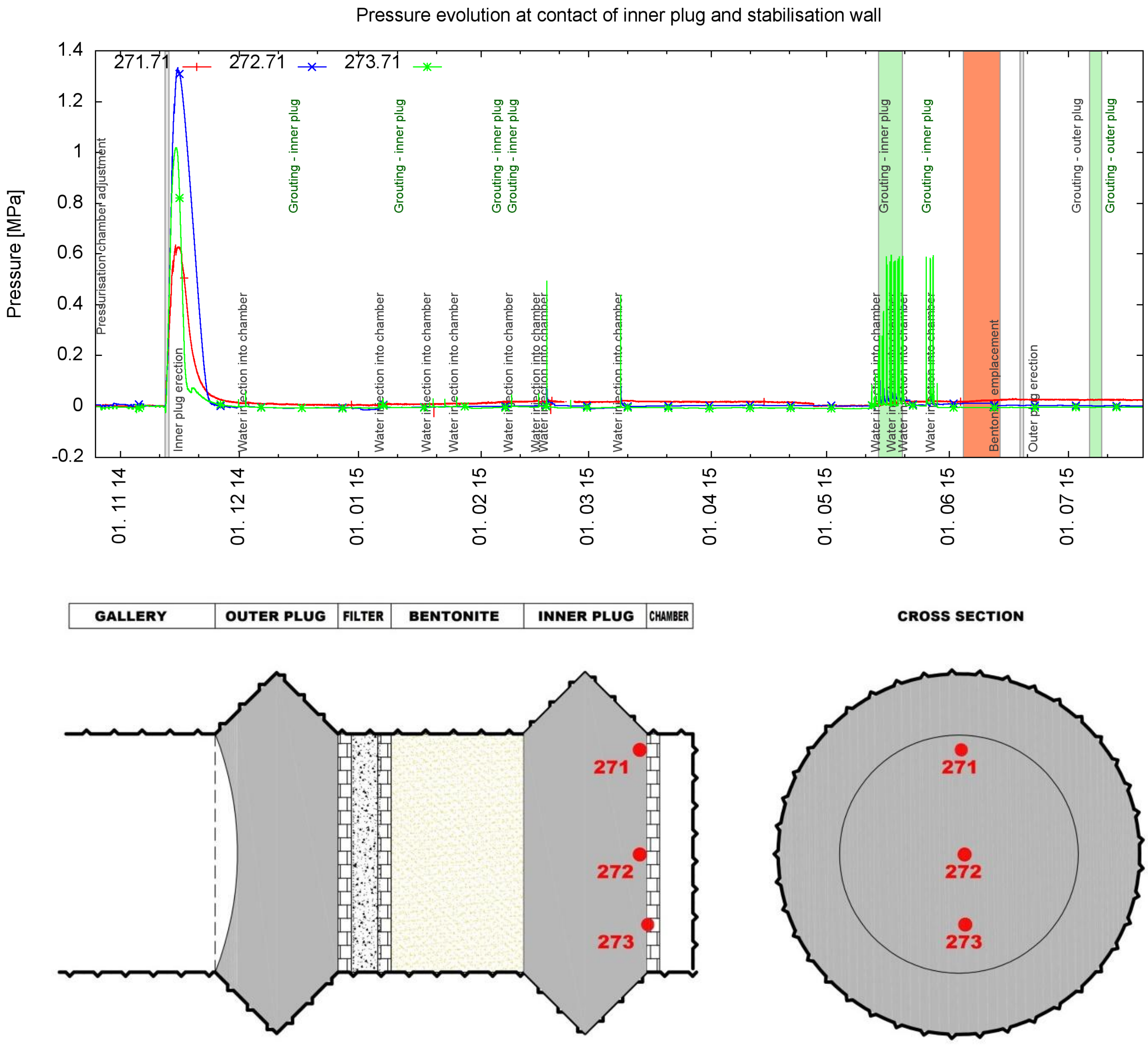


Figure 54 - Contact stress evolution at the contact between the inner plug and the stabilisation wall

6. EXPERIMENTAL RUN

The experimental run commenced on 21 July 2015. The original plan for the loading of the experiment consisted of the injection of water into the pressure chamber with a gradual increase in pressure (with the potential to inject water into the filter and reverse the flow if necessary). The injection of a bentonite slurry was also planned.

However, it was found necessary to alter the plan based on the results obtained during the initial part of the experimental phase. The experimental run (based on the updated plan) was divided into 5 phases based on the character of the loading of the experiment (Table 5).

Complete information on the experimental phase of the EPSP can be found in D4.6 (*Svoboda et. al, 2016*).

Table 6 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 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	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	Ongoing; in report up to 31-05-2016	39+	0.15 - 1.2

<u>Phase 1</u>

Experimental phase 1 commenced approximately 1 month following the end of the construction of the second shotcrete layer.

During this period the output pipe leading from the filter was kept open and water outflow was measured.

The experimental run commenced with the performance of water injection tests at a lower pressure level followed by higher pressure tests. One of the higher pressure tests led to the flushing out of traces of bentonite at one point during the test. The origin of the bentonite however could not be fully determined. Two origins for the bentonite were considered possible: the filter, which may have become contaminated by bentonite during the emplacement of the bentonite seal (especially during shotclaying), 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 most of the time along a fracture (opened by the high level of pressure) in the rock mass before entering the filter structure. The major part of the bentonite detected was therefore most likely to have flowed from the filter (contamination flushed out by water).

However, as a precaution the tests were interrupted and it was decided to at least partly saturate the bentonite core using the filter and the chamber, i.e. the experimental plan was modified.

Pressure levels along the interface of the inner plug and the separation walls (total pressure measured by the pressure cells) could be seen to follow the pressure in the chamber, which would appear to indicate that the interaction between the separation wall and the plug was minimal and that the wall did not obstruct water flow, i.e. it performed as intended. This was observed not only in phase 1 but in all the phases.

Contact pressure between the inner plug and the rock mass (total pressure measured by the pressure cells) increased according to the rate of injection of water into the chamber. The pressure increase values can be seen to follow chamber pressure with only relatively small differences. This would tend to indicate either good hydraulic connection to the chamber (bad – permeable interface on the chamber side of the plug; grouting not successful in penetrating into that area) or that the plug wedged into the rock or both (most probable). The only exception concerned cell 473 which exhibited a steady increase.

The inner plug itself exhibited only a small response (compared to shrinkage) - up to 120μm/m for the 0.5MPa pressure test and 280μm/m for the 1MPa pressure test were recorded in the inner plug. This response is totally reversible.

The effect of water injection was somewhat limited in the bentonite core which was most probably due to the low amount of water injected during the short tests (especially the initial tests). No changes in pore pressure 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. A very similar situation was observed with regard to total pressures. It is evident that in the first part of the period, changes in stress were minimal; 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). The water content and RH measured exhibits no reaction except in the case of sensor 602. This RH sensor, located at the bottom of the plug face, probably became temporarily 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.

No response was registered within the outer plug in the first half of the period. However, an unidentified process initiated by the second longer injection test (6.8.2015) and accelerated by the third test (7.8.2015) led to significant deformation which ended with an event on 11.8.2015. 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, which could indicate the “movement” of the plug. 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 were so small (close to background levels) that no firm conclusions can be drawn.

Phase 2

A possible piping effect was detected during Phase 1 and it was decided to temporarily change the course of the experiment leading to the commencement of phase 2. 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.

In addition to bentonite saturation, this phase allowed the testing of the outer concrete plug. The plug was unilaterally loaded from the inner side by the pressure in the filter with no support from the other side (more extreme load state than the inner plug). The outer plug was loaded with hydrostatic pressure of up to 1.2MPa.

The inner plug exhibited only a very slight mechanical response to pressure loading. Most of the deformation developed very steadily and can be attributed to processes at work inside the concrete saturated with water or to pressure developing inside the bentonite section.

The pressure on the contact of the inner plug followed chamber pressure with only relatively small differences recorded by cells 472 and 474. Those cells, influenced by grouting, exhibited 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, followed the evolution of pressure inside the chamber, whereas in this phase the reaction was slow, smoothed out and much less intense.

The bentonite core became gradually saturated from its surface which can be observed with respect to total pressure, pore pressure and water content + RH distribution changes.

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 exhibited a slow increase in water content. The rest of the sensors exhibited 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 to such an extent so as to seal off a rapid/preferential path for the water.

With respect to pore pressure, three groups of sensors could be distinguished in terms of the areas inside the experiment in which they were placed. The core group exhibited an almost zero reaction; this group consisted 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 consisted of the sensor on the experimental axis located on the plug, which reacted to higher pressures (in excess of 0.5MPa).

The other two groups followed 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 was a wet transition zone on the surface of the bentonite which prevented 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, consequently swelled and sealed off fast flow.

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 temporarily unable to resist/support the swelling pellets). The situation gradually improved as more water penetrated and the wet swelling layer became thicker.

In the outer plug 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.

The evolution of contact pressure between the outer plug and the rock mass followed the pressure in the filter (with reduced values). Leakage on this interface was detected (especially at higher pressures); therefore, additional grouting was applied close to the end of phase 2.

Phase 3

Phase 3 was performed with the intention of checking the state of the EPSP – the influence/success of saturation phase 2, and 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 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.

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

The transition from the saturation phase to single direction flow could be observed in the evolution of total pressure and pore pressure. 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 difficult to accurately attribute the development of different pressures as relevant processes acting against each other (the release of leftover pressure from the previous phase, pressurisation and swelling). Notwithstanding, only very low pore pressure (<0.1MPa) and total pressure (0.2MPa) were evident.

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 was unrealistic and most probably indicated sensor error (it showed measurement in air).

The outer plug exhibited no reaction to the pressurisation of the EPSP, as was expected for this unloaded part of the experiment, except for a slight but steady decrease monitored by sensor 1473 (probably trapped pressure from the previous phase being slowly released).

Phase 4

Phase 4 was designed to test the effect of the injection of a bentonite slurry. The slurry was injected into the pressurisation chamber at various (increasing) pressure levels up to 3MPa. A total of three campaigns was 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.

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

The injection of slurry at 3MPa represented the highest load placed on the EPSP to date. The inner plug exhibited deformation of up to ~950μm/m (in most places less). The 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 corresponded to both load and structure types.

The pressure on the rock-plug contact increased according to the rate of injection of water into the chamber. The increase in the pressure value followed chamber pressure with only a relatively slight difference, which indicated either a good hydraulic connection to the chamber or that the plug had wedged into the rock mass or both. It seems that the high pressure to which the slurry was exposed easily overcame the various processes and progressed with relative ease.

Pore pressure inside the bentonite followed the injection of the slurry suspension but at much lower values, which indicated that the inner plug worked 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 swelling pressure was estimated at around 0.1-0.2MPa. Moreover, the even part in the middle probably indicated the opening of a new pathway (probably hydraulically connected to the filter).

Note: the “core” was not influenced.

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.

Total pressure evolution supports the conclusions arrived at from pore pressure changes. 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.

The water content and RH evolution is in accordance with the proposal that only the skin of the bentonite becomes saturated and the inside remains relatively stable. 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.

There was a very minor temporary response from the outer plug which was totally in line with pressure changes inside the filter. Similarly, the pressures on the contact between the outer plug and the rock mass 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.

Phase 5

Phase 5 is, in a sense, a continuation of phase 1 (e.g. the original plan) 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.

The deformation of the inner plug follows the pressure applied in the chamber. The deformation appears to be reversible; returning to former levels when pressurisation is interrupted. Moreover, there still appear to be a number of minor long-term processes underway. The rock-plug interface pressure increased according to the injection of water into the chamber. The pressure value increase followed 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. It seems that the high pressure of slurry injection cleared/(re)opened pathways into the interface.

The effects of phase 4 were still visible in the bentonite sealing section at the start of phase 5. Subsequently, total and pore pressure reacted 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.

The last 1/3 of phase 5 is important. Pore pressure has begun 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 now 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.

This is further supported by water content and RH measurements. 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.

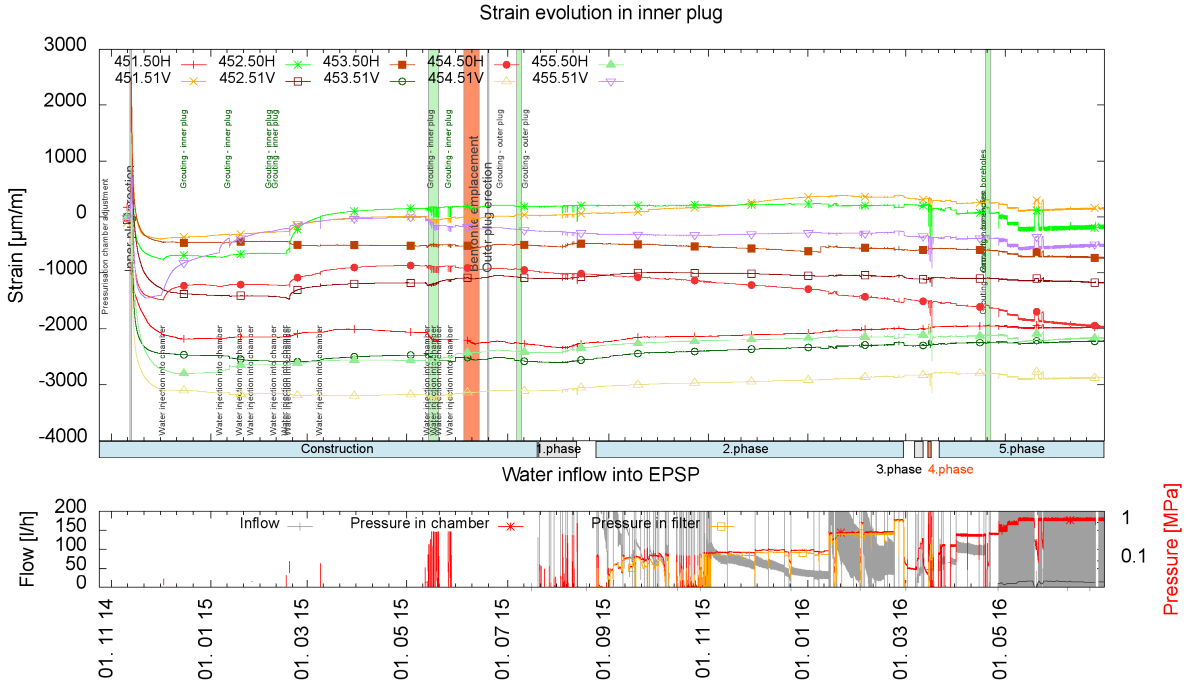
There was one exception; in the area around sensor 601 (upper part close to the inner plug) a significat increase in water content was recorded. It seems in this case that the slurry created a pathway (probably along the rock – plug – shotclay interface) which was (re)opened by high pressure levels. This pathway is not stable and has been sealed several times by the bentonite – the water content fluctuates (and decreases) over time.

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

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.

6.1. 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.



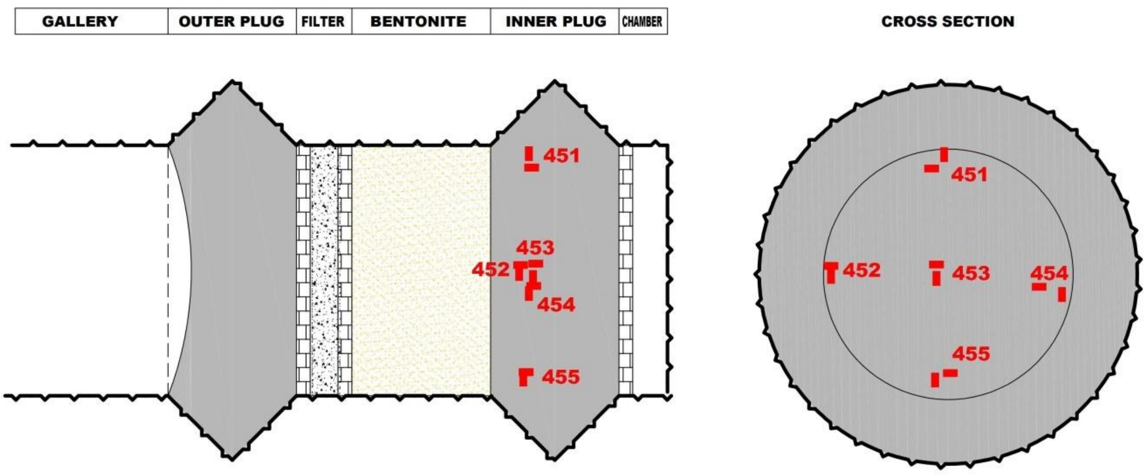


Figure 55 - Deformation of inner plug

6.2. 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.

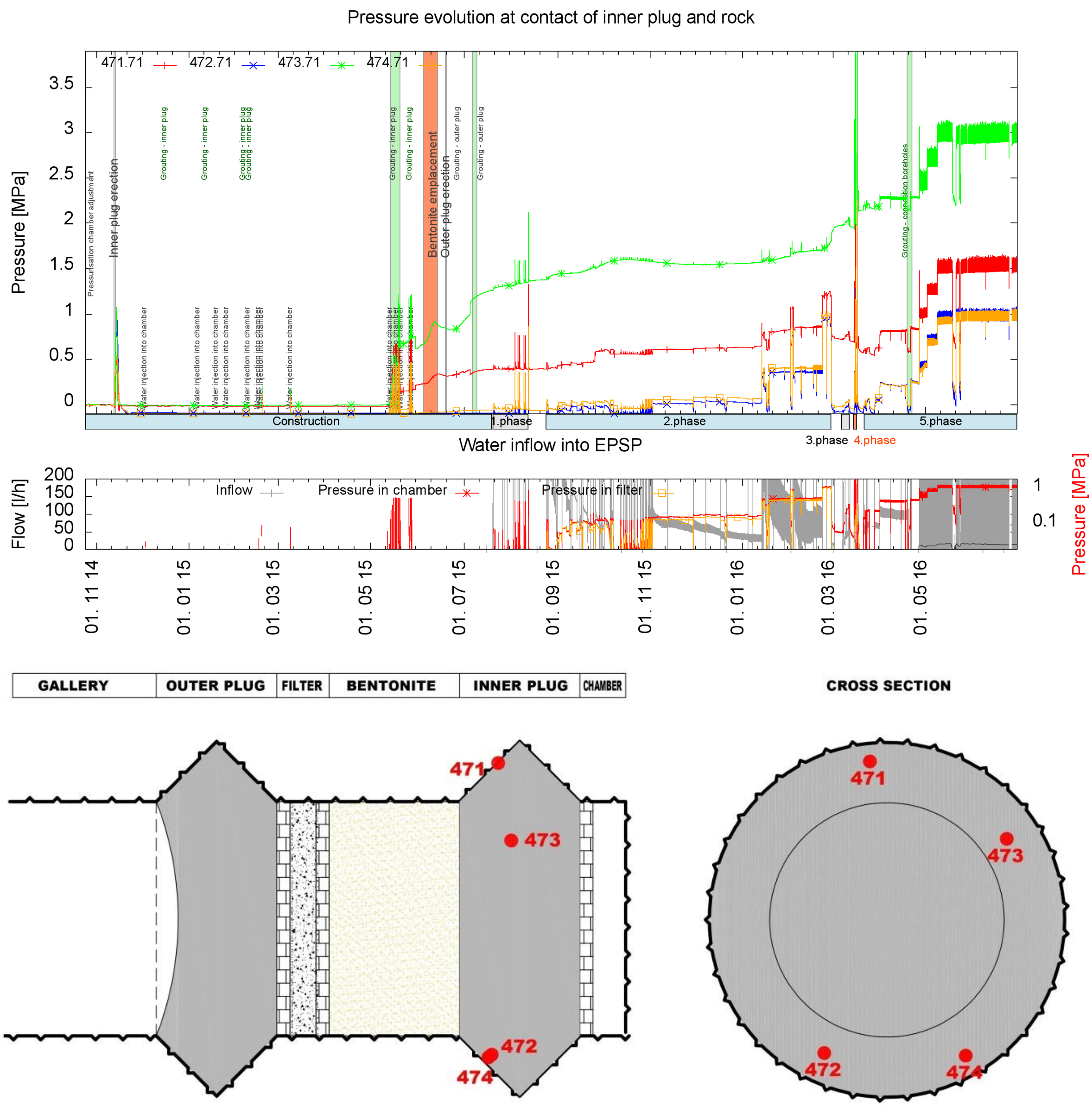


Figure 56 - Deformation of outer plug

6.3. CONTACT STRESS EVOLUTION AT THE CONTACT BETWEEN THE INNER PLUG AND THE STABILISATION WALL

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

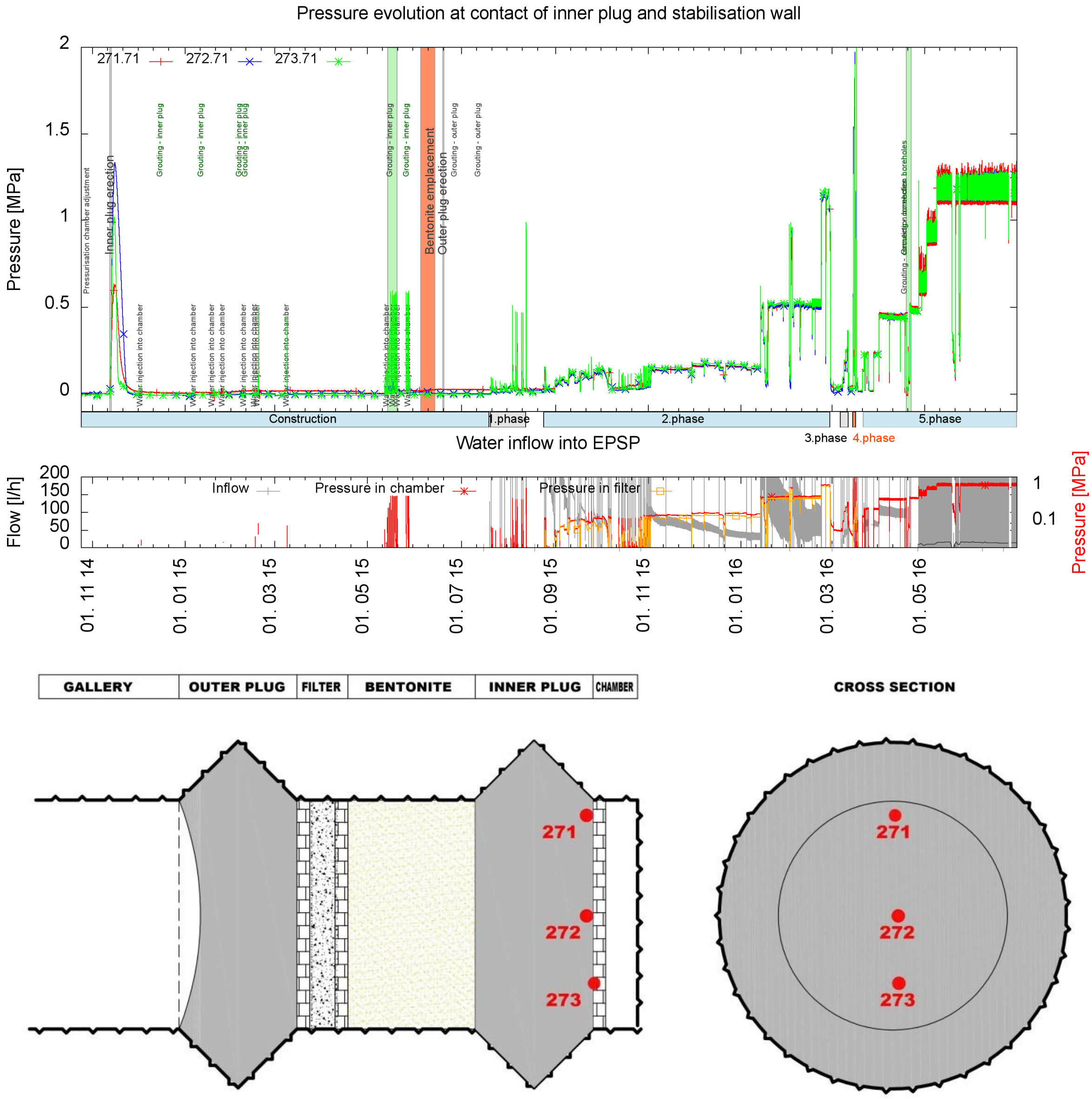


Figure 57 - Contact stress at the contact of inner plug and the stabilisation wall

6.4. 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.

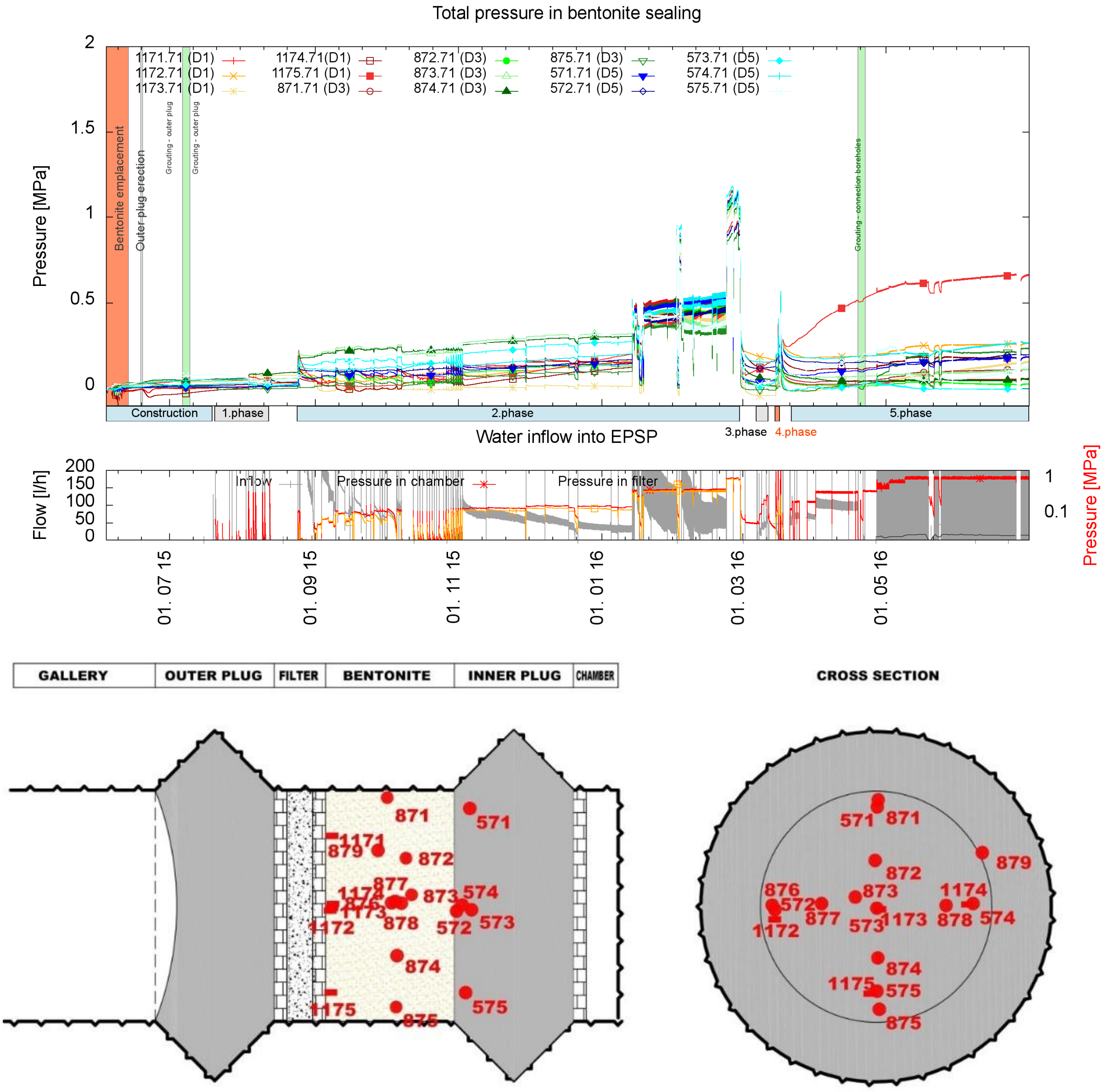
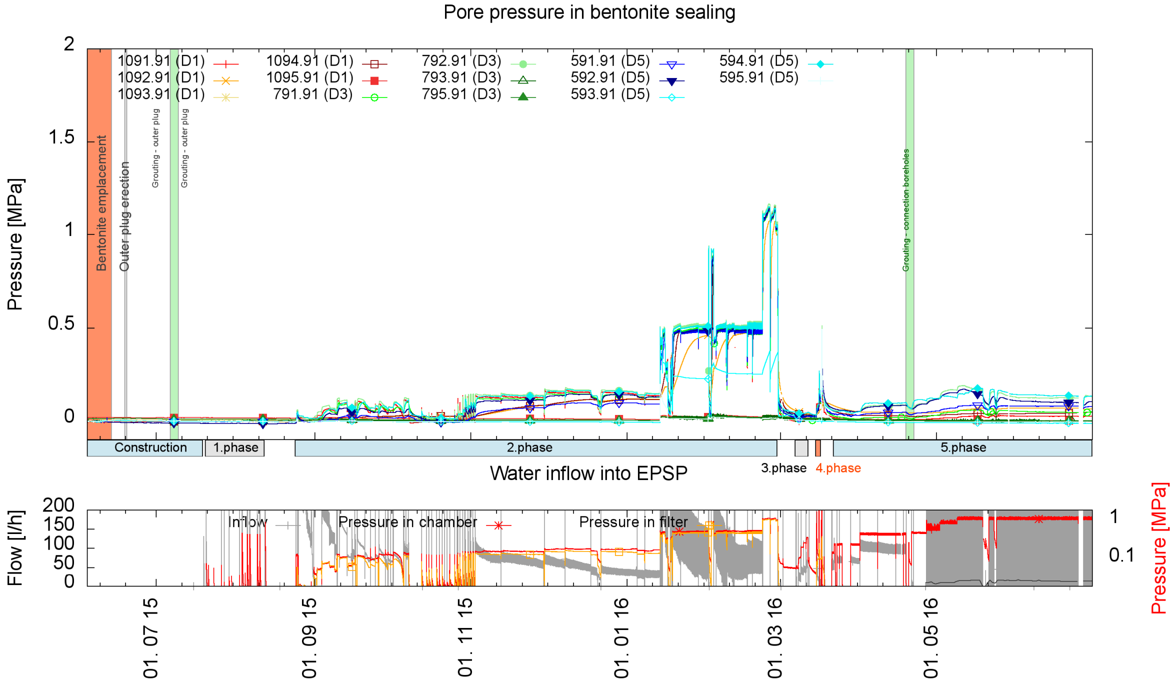


Figure 58 - Total pressure evolution in the bentonite sealing

6.5. PORE PRESSURE EVOLUTION IN THE BENTONITE SEALING

A total of 14 piezometers were positioned in the bentonite sealing.



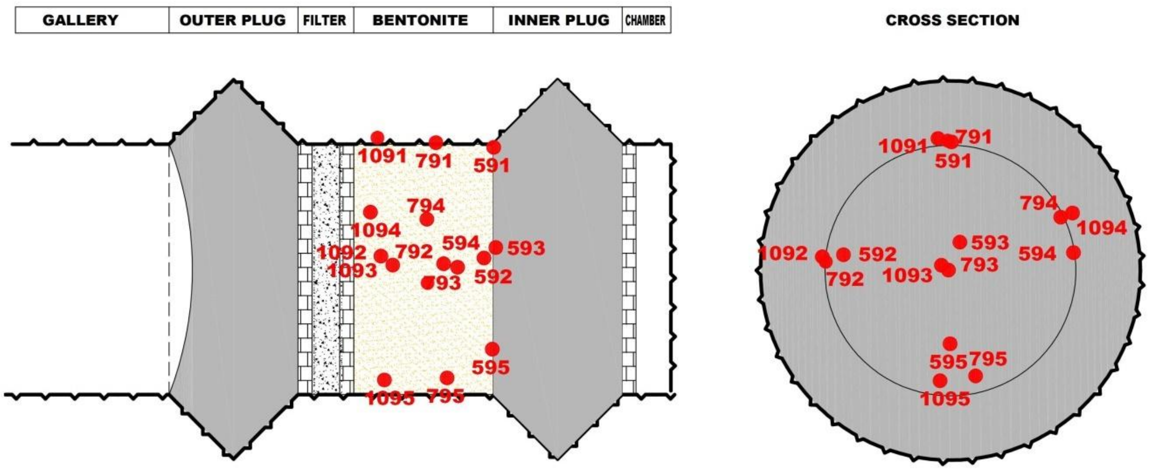


Figure 59 - Pore pressure evolution in the bentonite sealing

6.6. WATER CONTENT EVOLUTION IN THE BENTONITE SEALING

A total of 13 TDR and RH sensors were positioned within the bentonite sealing.

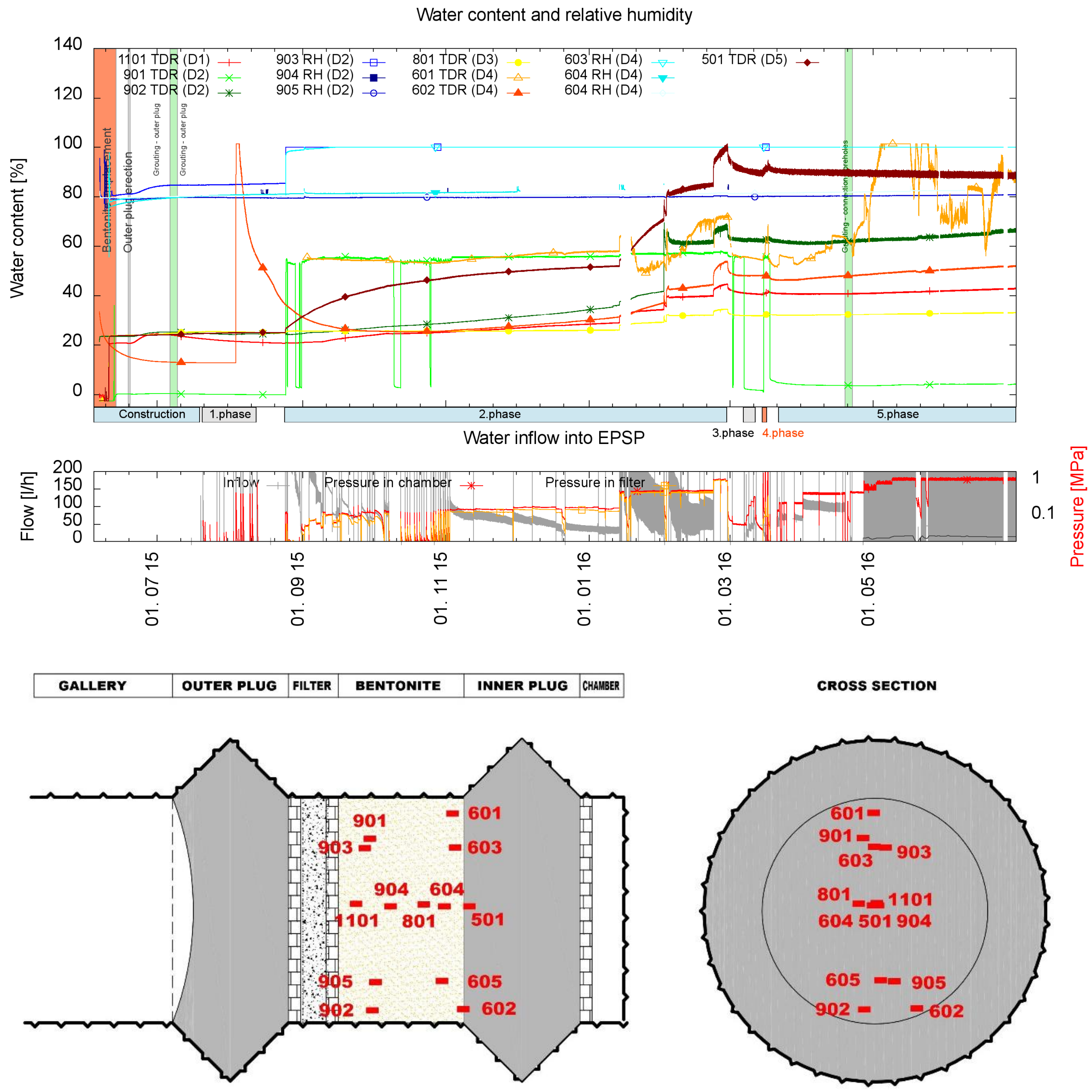


Figure 60 - Water content evolution in the bentonite sealing

6.7. 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

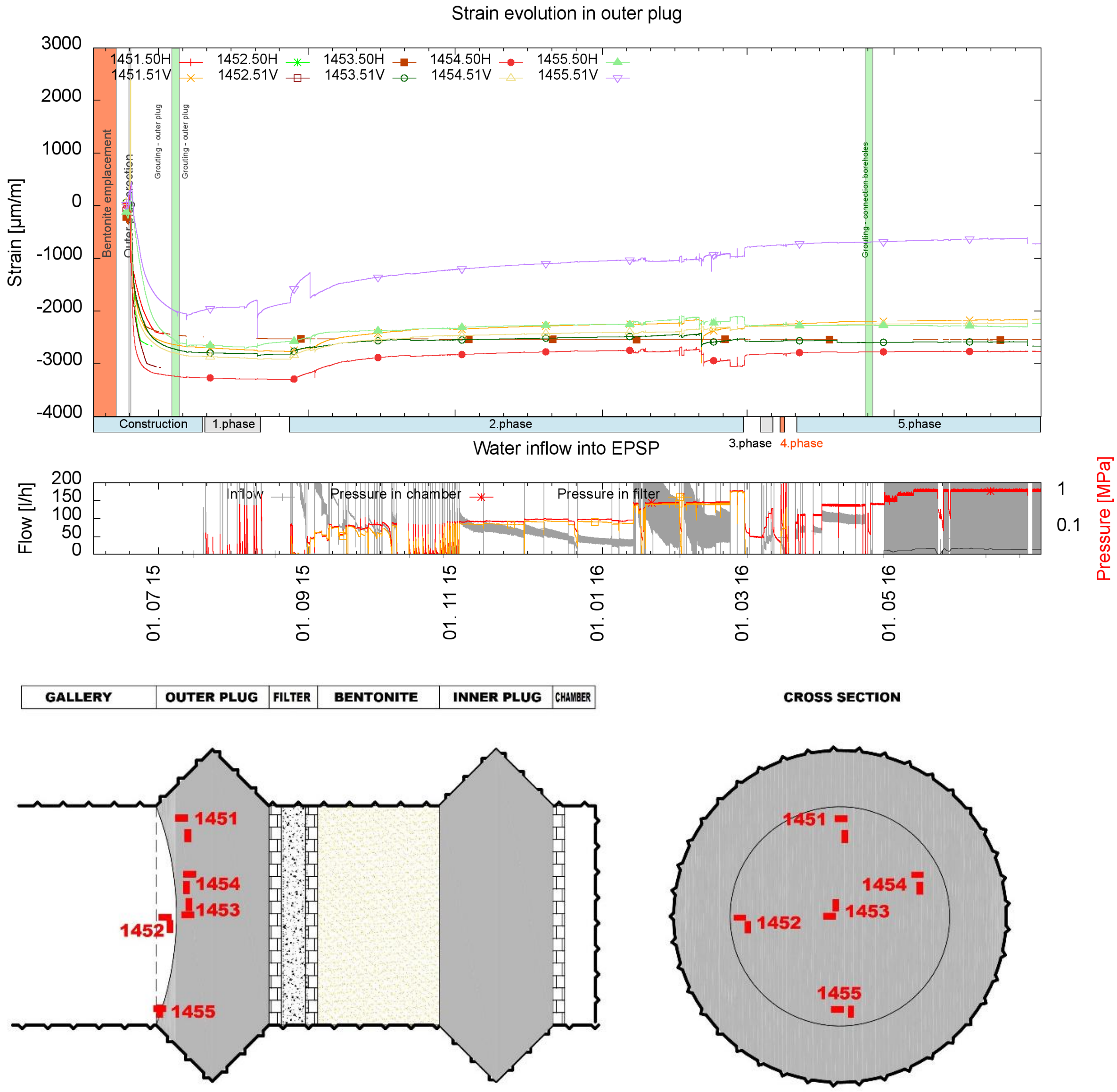


Figure 61 - Deformation of the outer plug

6.8. 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.

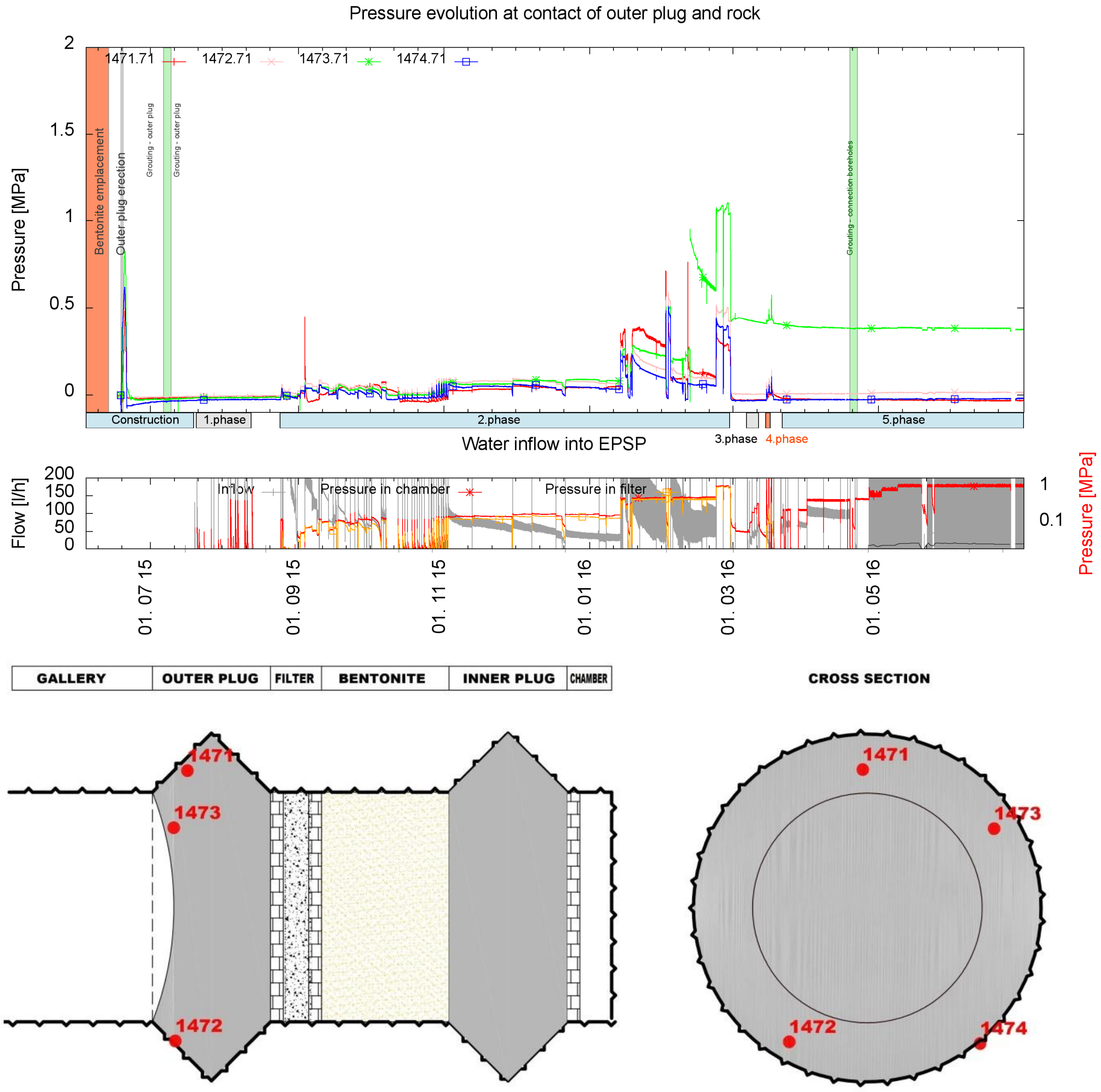


Figure 62 - Contact stress evolution between the plug and the rock mass (outer plug)

6.9. DEFORMATION OF THE ROCK

Four instrumented rock bolts were installed behind the pressurisation chamber each containing three vibrating wire strain gauges.

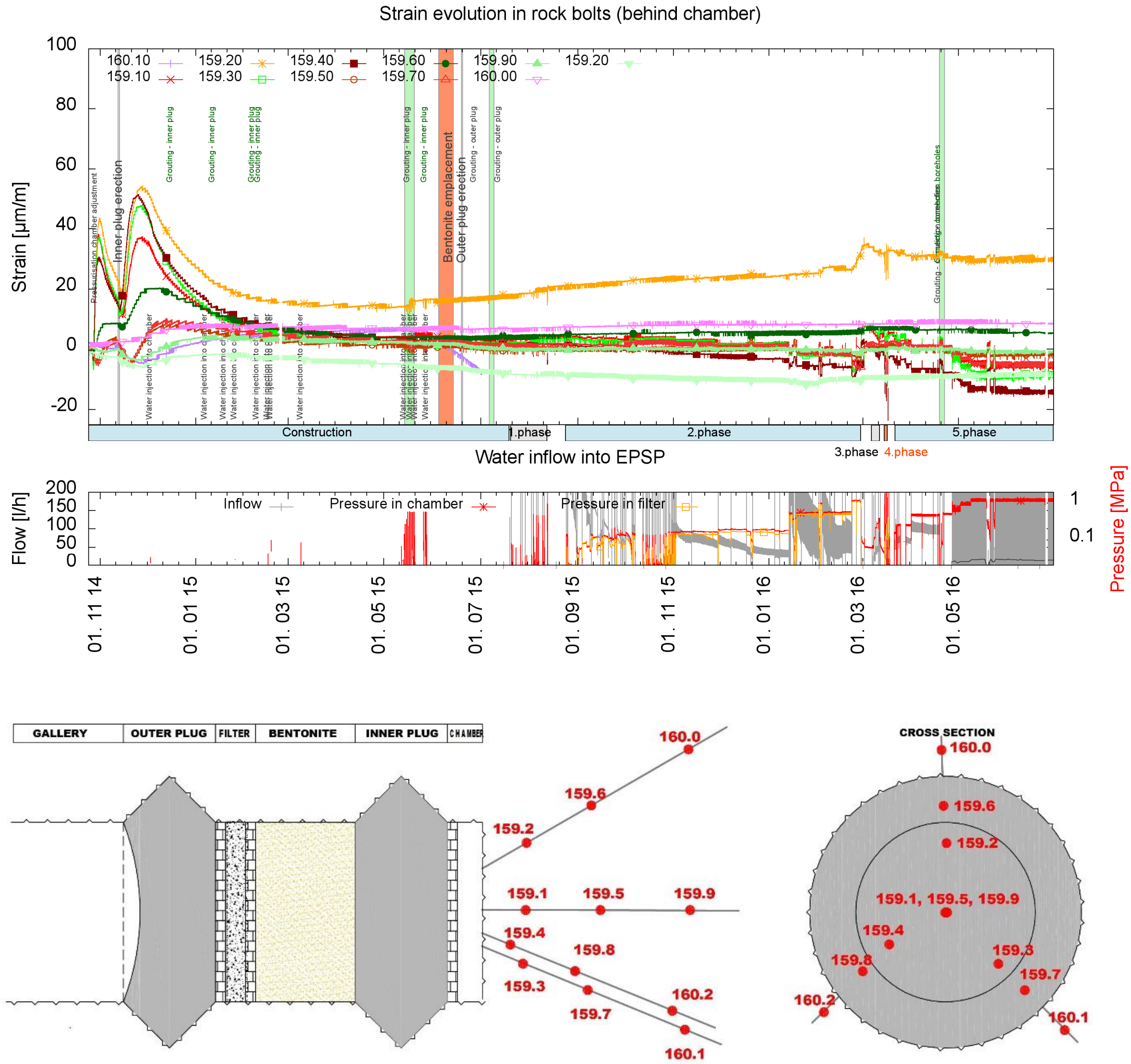


Figure 63 - Deformation of the rock

Four instrumented rock bolts were installed in the rock mass from the slot of the inner plug each containing three vibrating wire strain gauges.

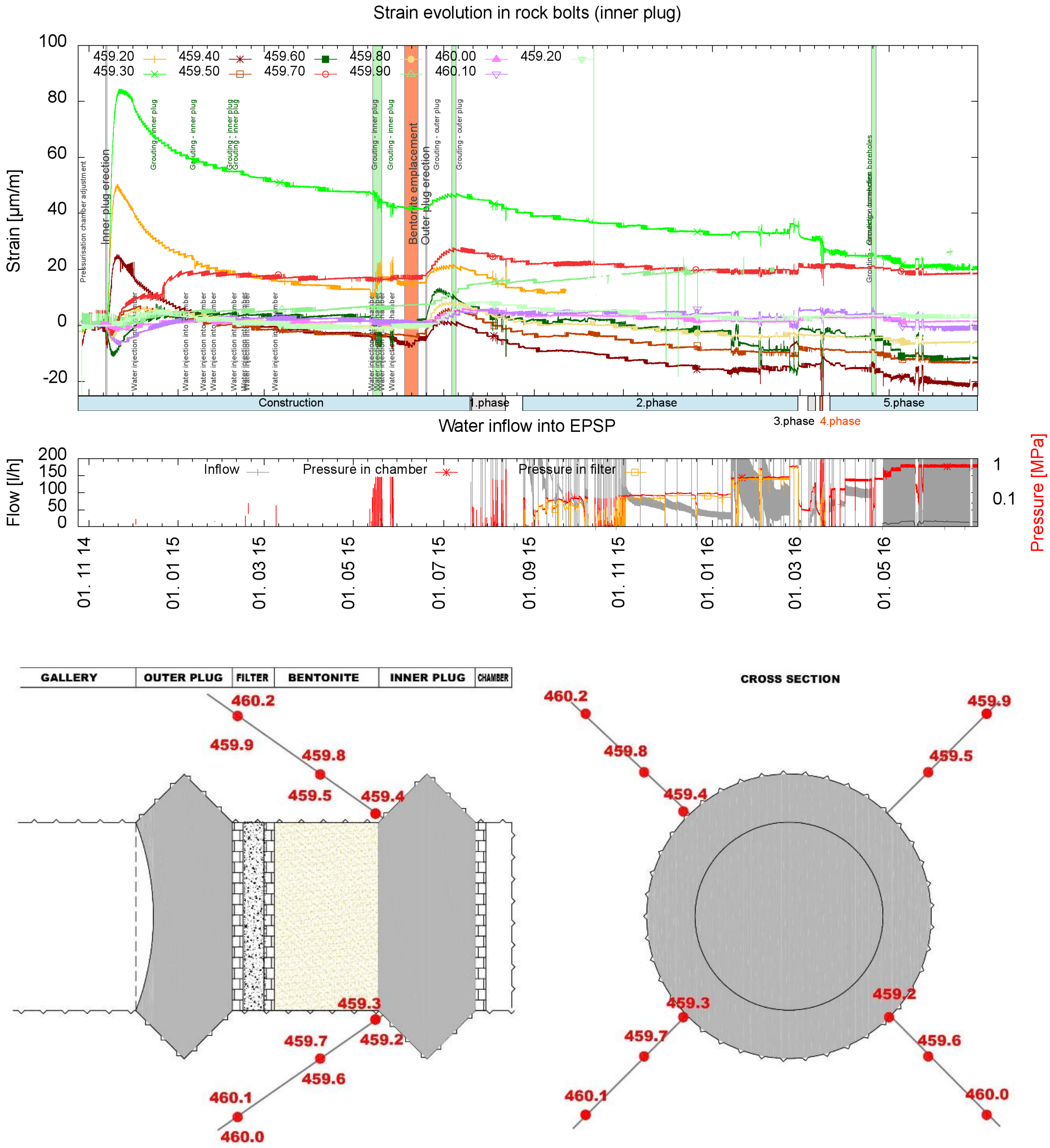


Figure 64 - Deformation of the rock

Four instrumented rock bolts were installed in the rock mass from the slot of the outer plug each containing three vibrating wire strain gauges.

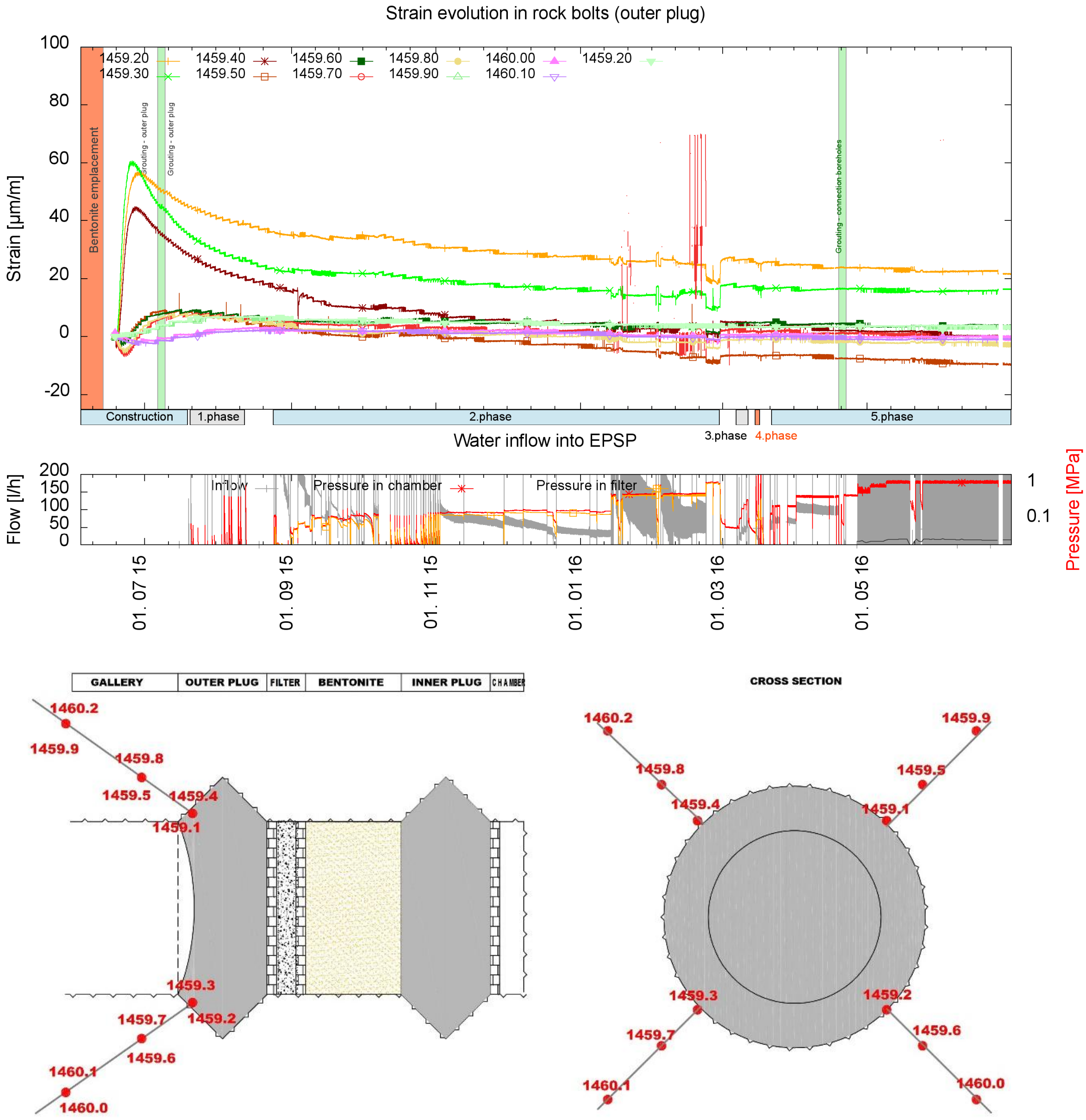


Figure 65 - Deformation of the rock

7. MAIN OUTCOMES

The EPSP has been successfully installed and the experimental phase is underway. 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 allows 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 main outcomes of EPSP can be divided into two categories:

- Construction-related
- Results of the experimental testing of the plug

The first category provides input for future practical use while the second represents the actual performance of the EPSP plug system.

7.1. CONSTRUCTION

One of the primary objectives of the EPSP experiment was to test both the materials and technology to be used for the construction of a future DGR in the Czech Republic.

The selection of the various technologies and materials was based on previous experience gained from underground structures such as underground tunnels, caverns and the Háje gas storage pressure plugs *(Hilar and Pruška, 2011)*. Where possible off-the-shelf technologies and materials were used or adapted for EPSP requirements.

The materials selected were further tested prior to use in the experiment as reported in EPSP D3.21: Final Results of EPSP Laboratory Testing *(Vašíček, et. al., 2015)* provided they met the design requirements set out in D3.15: Detailed Design of the EPSP Plug *(Svoboda, et. al., 2015)*.

The wide range of technologies and materials tested during the construction of the EPSP can be divided into the following main categories with respect to the construction process:

- Careful excavation techniques (niche adjustment and slot excavation)
    - Hydraulic splitting
    - Non-detonating cartridges
- Concrete plug erection
    - Low pH glass-fibre shotcrete
    - Shotcreting
- Bentonite sealing erection
    - Pellet production
    - Emplacement technologies
- Grouting
    - Rock improvement
    - Contact grouting

The data gathered from the construction phase has helped to confirm the suitability of the construction technologies and materials used.

7.1.1. Excavation techniques

The selection of the rough excavation method was constrained by the requirement that excavation be conducted without blasting. This requirement was introduced so as to minimise the potential for EDZ development.

Niche enlargement work was aimed at achieving the required dimensions of the niche profile and the creation of a planar excavation face, which was followed by the excavation of the slots for the concrete plugs.

Initially, the hydraulic wedge splitting technique was applied (Darda EP hydraulic splitting set with Darda C9N hydraulic wedge), but this technique was found to be particularly challenging with respect to the excavation of the EPSP shotcrete plug slots; progress was slow and resulted in leftover borehole ends. Therefore, the pressure disintegration technique using Green Break Technology (GBT) cartridges (non-detonating gas expansion cartridges) was used for the construction of part of the outer plug. The GBT technology significantly accelerated the plug excavation work; in addition, the excavated opening contour was more precise and smoother than was achievable employing the hydraulic splitter technique.

Indeed, the hydraulic wedge splitting technology was only partly successful, most probably due to the type of machinery used by the contractor (see the POPLU experiment for comparison, D4.5 POPLU Experimental Summary Report). Conversely, the GBT technology (non-detonating gas emitting cartridges) was found to work particularly well. This technique is similar to blasting but without most of the negative effects thereof.

7.1.2. Concrete plugs

<u>Low pH glass-fibre shotcrete</u>

At the outset of the EPSP experiment, it was decided to use glass-fibre-reinforced low-pH shotcrete for the inner and outer concrete plugs. The decision was based on previous experience with iron-fibre shotcrete gathered from the production of the Háje gas storage pressure plugs (*Hilar and Pruška, 2011)* and other underground structures. With respect to EPSP, glass fibres were selected for reinforcement purposes instead of iron-based fibres so as to avoid the potential for the corrosion of the iron-based fibres to affect the post-closure performance of the plugs in the Czech repository, and also to avoid the introduction of additional iron into the system. These fibres also significantly help to reduce (micro) cracking caused by shrinkage. Moreover, it was decided to use low-pH concrete so as to limit any possible impacts on the bentonite.

The ÚJV's previous experience with the preparation of low-pH concrete mixes and the experience of a commercial producer of concrete mixtures for building purposes were used in developing the shotcrete mix.

The final mixture used in the EPSP had pH <=11.4 with a ratio of microsilica to cement of approximately 1:1 (for the composition see chapter 3.2.1**Virhe. Viitteen lähdettä ei löytynyt.**). The concrete mixture was produced at a concrete mixing plant in Prague and then transported to the Josef facility for emplacement.

The concrete mixture behaved very well both in terms of workability, emplacement and, subsequently, during the curing process. The 12-hour workability period proved to be very useful in that it provided enough buffer time for transport to the Josef facility, reloading into smaller trucks, transportation to the emplacement location and final emplacement. No segregation was detected during transport.

The glass fibres were added during the mixing process at the concrete plant and created no problems with respect to emplacement. No glass fibre accumulation or clogging was detected.

The behaviour of the shotcrete was considered satisfactory and was identical to "ordinary" shotcrete mixtures. The sprayed shotcrete adhered well to the surface with a rebound rate equal to or even less than that of "ordinary" shotcrete mixtures. Moreover, dust evolution was noticeably lower than that of "ordinary" shotcrete mixtures.

<u>Shotcreting and curing</u>

The shotcreting technique was used for the inner and outer concrete plugs; shotcreting was mandatory with respect to the inner plug. The choice of whether to use shotcrete or SCC for the outer plug was left to the supplier who subsequently decided to also use shotcreting for the outer plug. The decision was based on the use of a simpler erection process (no formwork was required) and the fact that the process had already been validated and the equipment was available on site.

The main advantages and disadvantages generally stemmed from shotcrete technology in general: the method is fast and flexible, no formwork is needed, there are no problems with uneven surfaces etc.; however, the quality of the application depends to a great extent on nozzle operator skills. The disadvantages consist of possible "shadows" (created behind structures which obstruct the spraying process), rebound and dust.

Plug emplacement itself was rapid (one day non-stop for each plug) and the only limiting factor consisted of the transport of the concrete mixture in the Josef URL. In the end, the biggest challenge turned out not to be the shotcreting itself but the associated logistics, ventilation and worker safety.

The shotcrete plugs behaved very well during the curing period. The maximum temperature reached inside the plug was approximately 55°C, thus presenting no danger to the concrete. No shrinkage (or other) cracks were detected on the bodies of the plugs. The only cracks detected were located between the shotcrete sprayed on the sides of the niche and the bodies of the plugs which would tend to indicate that the body of each plug shrank in one piece while probably separating to some extent from the rock surface.

One of the minor tasks of the experiment was to check if shotcrete plugs can be used without contact grouting. The inner plug was tested for air- and water-tightness following curing by means of gradually increasing the pressure to 0.6 MPa. An excessive leak, defined as a steady flow of water, was detected in the contact zone between the plug and the rock, therefore it was decided to grout this interface. The following main factors causing the leak were identified as:

- Separation of the body of the plug from the rock mass due to shrinkage.
- Failure to fully seal the EDZ (especially close to the plug-rock interface).
- Weaker concrete on contact with the rock, possibly including leftover uncleaned rebound or "shadows".

The above factors are listed in order of the most significant to the least significant according to practical observations and expert judgement. However, no exact quantification can be made without dismantling the experiment.

Testing also revealed that certain rock fractures which were believed to have been closed and sealed by means of previous grouting were reopened by pressure testing as evidenced by the observation of leakages from these fractures.

No grouting pipes were installed in the inner plug prior to erection. Therefore, grouting was performed by drilling boreholes into the contact zone which were then injected with grout. Several campaigns were performed until the leakage was reduced to a few drips (a certain amount of leakage was allowed to remain so as to allow the testing of the bentonite sealing).

The escape of grouting media from the rock in the vicinity of the plug was observed, thus providing support for the above suggestion that the EDZ was not fully sealed.

The experience gained from the inner plug resulted in the installation of grouting pipes in the contact zone of the outer plug prior to the erection phase. The outer plug was then grouted primarily through the use of this piping. Additional grouting was performed later based on the results of the pressure testing (a side effect of bentonite sealing activation by water from the filter structure) of the outer plug in locations at which leaks had been detected. This was conducted in a similar way as for the inner plug, i.e. by drilling grouting boreholes into the contact zone where necessary.

It was considered that the weakest point of the fibre shotcrete plug structures consisted of the wider contact zone between the plug body and the rock mass. It was determined that the effect of this weak point could be mitigated via the grouting of the interface. It is strongly recommended that preparations are made in advance, e.g. through the pre-installation of grouting pipes in the plug/rock contact zone.

7.1.3. Bentonite sealing

Bentonite

One of the main aims of EPSP was to demonstrate the suitability of Czech materials and already available technologies for the construction of tunnel plugs. Following the careful consideration of plug construction requirements, factory-produced bentonite (milled, non-activated Ca-Mg bentonite) was selected as the principal material for the bentonite part of the plug. Commercially produced “Bentonit 75” (B75) was the only material available at the time that fulfilled all the various requirements. B75 is produced by the Keramost company and originates in the Černý vrch deposit. Various laboratory tests were performed on the B75 material in order to verify its properties – D3.21 (*Vašíček et al., 2016*).

B75 is produced in powder form which is not ideal for sealing plug purposes due to the low level of compaction. Therefore, the testing of the most appropriate technology for the manufacture of pellets, in cooperation with potential Czech producers, was also carried out by the CTU.

Several different technologies concerning the compaction of powdered bentonite were tested during the course of the research and two were finally selected for further use. The first method involved the production of compacted pellets by means of a roller compaction machine. A number of tests were conducted with respect to the manufacture of the bentonite pellets. The final product designated as B75 PEL12 consisted of pellets with a diameter of 12mm, a length of up to 40mm and a dry density of around 1.8Mg/m^3. This material was used for the construction of the major part of the sealing layer. The second material, used for the construction of the sealing layer, was prepared via the compaction of powdered bentonite using a roller mill. The final product, named B75 REC was used for spray technology application purposes.

The main conclusion of this stage of the research was that B75 bentonite demonstrated sufficient dry density levels and, therefore, that it would ensure the required geotechnical behaviour of the bentonite seal in the EPSP experiment (*Vašíček et al., 2016 – D3.21*).

Emplacement

The construction of the EPSP bentonite pellet sealing section was completed in a period of nine days in June 2015. The total amount of emplaced material was 39.9 tonnes emplaced in a volume of 23.7m^3. The average density achieved was 1684kg/m^3 and the dry density was determined at 1427kg/m^3.

Bentonite emplacement was performed using two techniques.

The largest part (over 95% of the sealing) of the clay material was emplaced in layers which were vibration compacted. Each layer was vibration-compacted using a compaction plate (NTC compaction plate, Masalta vibration plate) or electric hammers. This emplacement technique proved to be quick and could be easily scaled to an industrial level. Dust generation was low. The only drawback consisted of the machinery being too large to fit into the upper parts of the niche; therefore, shotclay technology was employed for the emplacement of the upper parts of the bentonite seal.

The upper parts were emplaced using shotclay technology. Due to the limited space available (and the volume of the bentonite core) it was possible to use small-scale machinery only. The SSB 14 DUO (Filamos Ltd.) spraying machine was selected with an Atlas Copco electric air compressor (working pressure 10 bar, air capacity 350m^3/h). These machines were fully tested prior to use in the EPSP experiment.

The shotclay technology functioned successfully. The main advantage of this method consists of the ability to fill confined and irregular spaces. However, there are a number of drawbacks: throughput is lower than that of other methods, it is operator-dependent, the rebound has to be removed and there is a relatively high level of dust generation.

Generally, due to size constraints, only small machines were used for bentonite emplacement in the EPSP experiment. It is expected that full-sized machinery with higher throughput will be used in the future repository. Bentonite emplacement will need further development in terms of up-scaling in order to reach an industrial application level.

7.1.4. Grouting

Grouting did not originally make up a primary scientific objective with respect to the EPSP experiment; it was employed principally in order to improve the rock conditions of the Josef URL so as to better represent the conditions within the future repository. The secondary use of grouting was planned as an alternative with respect to the plug-rock interface should there be an occurrence of excessive leakage (experience from similar structures constructed in the past indicated that this was likely).

Thus, the selection of the grouting materials and techniques was based primarily on the conditions and requirements of the Josef URL since it was not intended that grouting would make up part of the EPSP plug. Nevertheless, the grouting materials were selected and tested with the future DGR in mind.

Grouting was employed in two main areas:

- Rock improvement
- Interface between the plugs and the rock mass

In addition, grouting was used to seal leaks along the connecting boreholes.

In general, grouting was successful although a number of problems were identified and more grouting was necessary than originally anticipated.

<u>Rock improvement</u>

The rock mass around the space for the plug in niche SP-59 was rendered impermeable by means of high-pressure grouting to a depth of 5m from the surface of the opening excavated for the plug. The total length of the grouted section was around 10m. The grout was injected along nine grouting profiles in the sides of the niche, and a fan of grouting holes was drilled into the excavation face.

WEBAC 1401 polyurethane resin was used for grouting purposes. The boreholes were fitted with mechanical packers and the resin was applied in the boreholes by means of a high-pressure grouting set. The injection of grout into the rock mass was terminated upon attaining a pressure level of around 35MPa. A total of 760.45kg of WEBAC 1660, WEBAC 1410, WEBAC 4170T, WEBAC 150, WEBAC 1403 PU resins was consumed so as to render the rock mass in the required area impermeable.

It was necessary, during the application of the polyurethane resins, to ensure that the high-pressure grouting adhered to the curing times prescribed for mining environments in which the temperature varies from 10°C to 12°C and, moreover, the curing time was even extended to between 3 and 4 weeks. Only once the curing process was completed was it possible to conduct the hydraulic testing (using test boreholes) required to verify the effectiveness of grouting operations.

The testing of the boreholes confirmed the required tightness of the rock mass. However, subsequently, during the testing of the plug, it was found that this type of (deep) grouting had had only limited success in the rock surface area, i.e. a number of fractures visible on the rock surface continued to produce water which had to be remedied during later grouting campaigns. Moreover, when high pressure was applied (especially above the virgin stress level) even the sealed fractures reopened, which, to a certain extent, limited the maximum pressure which could be used for injection.

<u>Interface between the concrete plugs and the rock mass</u>

One of the minor tasks of the experiment was to check if the shotcrete plug could be used without contact grouting. Unfortunately, both of the plugs had to be grouted (see chapter 4.2.3 and 7.1.2).

The inner plug was constructed with no pre-installed grouting system. Grouting was therefore conducted via new boreholes drilled around the circumference of the plug into the plug-rock interface. It was necessary to install the grouting very carefully in order not to jam the pressurisation chamber with any leaking grout. In total, it was necessary to apply five rounds of grouting not only into the interface but also to mitigate a number of water bearing fractures in the rock (identified during plug tightness testing).

The knowledge gained from the inner plug was subsequently applied to the treatment of the outer concrete plug in which grouting tubes were installed prior to the emplacement of the shotcrete.

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. Furthermore, the space in front of the outer plug was additionally sealed to a distance of 2m in front of the plug.

7.1.5. Worker Safety

Worker safety made up one of the main concerns with respect to the construction of the EPSP experiment and the work conducted in the underground complex. Working in such an environment is particularly demanding due to the limited space available, limited access routes, ventilation problems and other issues. Therefore, strict regulations were enforced.

With respect to the EPSP it was necessary to address two major concerns ventilation related:

- Air quality (various gases including O2 and NOx)

- Dust evolution

The first issue was addressed by the introduction of strict limits on the use of combustion engines in the Josef URL. The machinery setup was exclusively electrically powered (somewhat exceptional especially with regard to compressors) and the only non-electrically-driven equipment consisted of the concrete delivery trucks which were allowed into the facility only during the actual erection of the plugs. This greatly reduced the demand for a fresh air supply and pollutant extraction. On the other hand, it stretched the electrical system of the Josef facility to the maximum. Therefore, power consumption was strictly limited during construction work so as to prevent system overload.

The second problem (dust) was minimised via the installation of an additional (temporary) ventilation system which consisted of an extraction fan positioned in the experimental niche, the necessary piping and a sedimentation/filtration chamber.

The air containing dust was extracted as close as possible to the working face so as to prevent dust transport into the other galleries. The polluted air was then transferred via the connecting piping into a sedimentation chamber in a nearby niche. The sedimentation (filtration) chamber consisted of a niche closed off by a number of curtains made of a geotextile material which acted as a filter.

The general quality of the air was checked using handheld devices according to the established safety procedures in place at the Josef facility.

Other concerns with respect to the EPSP experiment consisted of the logistics and the movement of personnel. Plug erection required a lot of equipment in a very restricted space with the presence of personnel; therefore, regulations concerning the working environment and the movement of personnel had to be introduced. In addition, even though the transport of the concrete required the almost exclusive use of the main galleries of the Josef URL, it still represented a limiting factor in terms of the speed of the shotcreting. This was solved by the complete closure of the Josef URL during the erection of the plugs. This, however, will not be an option for the future DGR and this issue will have to be addressed in advance in the design of the layout of the DGR and the various operational procedures.

7.1.6. Monitoring

The monitoring equipment performed well during construction work and the emplacement of the bentonite. The monitoring system was able to reliably monitor both hydration heat evolution and the shrinkage of the concrete plugs.

The influence of the monitoring system on the erection process was however mostly negative (but within manageable limits). The fixed cabling created obstacles for the sprayed concrete which led to the potential creation of “shadows”, i.e. weaker sections behind the respective obstacles. It was however possible to mitigate this problem to a large extent by the skilled operation of the shotcrete nozzle by the operator; nevertheless, locations around such objects were considered weak spots. On the other hand, the protective steel tubing acted as reinforcement for the plug (although very minor).

7.1.7. Conclusion

The initial objective of EPSP – the demonstration of technologies suitable for plug erection has been achieved. The knowledge and experience gained will serve as important input material for the Czech deep geological repository development programme.

The experience gained will have an impact on the design and construction phases of the future repository as well as on operational safety. The separation of the construction of parts of the repository proper with that of ongoing construction work on other parts of the facility will be necessary not only due to radiation safety considerations, but also so as to prevent the spread of pollution such as dust and exhaust gases into “clean” spaces. In order to achieve this aim, the design and operational procedures of the repository will have to be carefully adapted as construction work continues during most of the repository’s operational lifetime.

From the point of view of the EPSP experiment, the above considerations resulted in the introduction of additional ventilation in the working space equipped with a filtering system, the limiting of the amount of dust created and a strict limit being imposed on the use of combustion engines.

A further major issue is that of logistics. Underground spaces are, by their nature, very confined and feature only a small number of access routes which, in addition to the related safety issues, imposes limits on the movement of personnel, materials and machinery. At the same time, however, the construction process requires the extensive movement of materials and machinery. Thus, both the speed of operation and the choice of machinery used are severely limited by the space and access routes available. Moreover, in terms of the future repository, such factors must not hinder the normal operation of the repository which itself adds to requirements relating to space and access routes.

With respect to the EPSP experiment, the space constraints had a significant influence on the speed of plug construction. Only very small trucks could be used to transport materials to the experimental site along a single access route (with only one passing place), which proved to be a major limiting factor.

Several technologies were tested during the construction of the EPSP including rock excavation techniques, the shotcreting of the plug and shotclay technology.

The adjustment of the shape of the niche and slot excavation was performed using both hydraulic wedge and GBT technologies in order to limit rock damage. However, the hydraulic wedge splitting technology was only partly successful, most probably due to the type of machinery used by the contractor; progress was slow and resulted in leftover borehole ends. On the other hand, the GBT technology (non-detonating gas emitting cartridges) was found to work very well. This technique is similar to blasting without most of the negative effects thereof.

The shotcreting technique was used for the lower pH glass-fibre concrete parts of EPSP construction. Shotcreting enjoys the advantages of rapid application, no need for a front formwork and shape flexibility. The disadvantages consist of the production of dust (although the recipe used in the EPSP experiment led to dust production lower than that of ordinary shotcrete), the necessity to consider rebound and dependence on operator skills.

The data from the construction phase helped 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 impact of instrumentation cabling on the experiment was limited by the careful selection of cable paths with the main direction perpendicular to the experiment and the paths leading via sealed cased boreholes into the adjacent parallel niche. The same approach was also chosen with respect to the technological equipment positioned in the parallel niche and its connection into the pressurisation chamber (and filter) via sealed cased boreholes.

One of the minor tasks of the experiment was to check if the shotcrete plug could be used without the need for contact grouting; however, the initial testing of the inner concrete plug of the EPSP experiment demonstrated that contact grouting was necessary in order to ensure that the concrete seals performed appropriately. This knowledge was subsequently applied to the treatment of the outer concrete plug in which grouting tubes were installed prior to the emplacement of the shotcrete.

Bentonite emplacement was performed using two techniques, both employing bentonite pellets. The largest part of the clay material was emplaced in layers which were vibration compacted. The upper parts were emplaced using shotclay technology. Due to the limited space available (and the volume of the bentonite core) it was possible to use small-scale machinery only. Bentonite emplacement will need further development in terms of up-scaling in order to reach an industrial level of application.

A further objective of the EPSP experiment, i.e. to test materials suitable for plug construction, has also been achieved.

In short, the EPSP experiment was performed as an integrated project which included the extensive development and testing of a wide range of materials and which has led to significant advances regarding the level of knowledge of concrete and bentonite materials in the Czech deep geological repository development programme. The enhanced understanding of local bentonite materials (e.g. B75) will be of considerable benefit in terms of the design of plugs and seals as well as with respect to the design of buffers and backfill techniques.

EPSP has also benefitted from the transfer of knowledge from other industries, most notably with respect to fibre-reinforced shotcrete as previously used in the plugs and seals of Czech underground gas storage facilities. This illustrates therefore how industrial analogues can be successfully incorporated into nuclear waste disposal programmes.

7.2. EXPERIMENTAL RUN

The experimental testing of the EPSP commenced as early as during the construction process. The inner plug was pressurised via the injection of water and air into the chamber up to 0.5MPa in order to confirm the water tightness of the concrete and to determine whether grouting would be necessary.

Once the outer plug had cured, the main experimental programme started with a series of short water injection tests followed by long-term tests at various pressure levels (starting at 0.1 MPa and gradually increasing to 1MPa). At 1MPa the potential channelling of the bentonite seal was detected; at this time, the swelling pressure in the bentonite had not yet fully developed.

In order to avoid the erosion of the bentonite, the testing sequence was interrupted and the sealing section was saturated via the injection of water into both the filter and the pressurisation chamber in order to allow swelling pressure to develop. Saturation commenced with low pressure and was gradually increased to just over 1MPa.

Following the saturation of the bentonite, a short pressure test was undertaken involving the injection of bentonite slurry into the pressurisation chamber at pressures up to 3MPa. The pressurisation chamber was then cleaned and the pressurisation of the experiment using water pumped into the pressurisation chamber resumed with gradually increasing pressure of up to 1.2MPa.

Since the EPSP experiment focused on the development of knowledge and experience, no performance criteria have been identified for the plug to date in the Czech disposal programme; rather, parameters have been monitored in order to develop an understanding of the performance of plugs under pressurisation.

7.2.1. Concrete plugs

The sprayed fibre concrete plugs performed well during all of the pressure tests undertaken. 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. No structural damage has been recorded. The plugs exhibited limited strain in response to all of the pressure loads, including the loads exerted from the pressure chamber and from the filter. The strain measured in response to pressurisation to date has been significantly lower than the strain resulting from shrinkage during curing. From the mechanical point of view, the concrete plugs are performing as expected, i.e. they provide the system with mechanical stability.

The data indicates that no direct leakage is taking place through the body of the inner concrete plug into the bentonite seal and no leakage through the body of the outer plug has been detected. However, the contact zone between the plug and the rock represented a weak spot where leakage had to be treated by means of grouting. The weak contact zone to some extent limited the usefulness of the concrete plug in terms of reducing flow into the bentonite sealing layer. Nevertheless, a significant decrease in pressure (to 1/5) has been detected in the inner plug which shows that the inner plug is fulfilling its role as the first hydraulic barrier limiting flow into the bentonite.

7.2.2. Bentonite sealing

The testing of the bentonite sealing section commenced with the pilot run of the experiment at low pressure followed by tests at higher pressures.

One of the higher pressure tests on the non-swollen (“dry”) sealing led to the flushing out of traces of bentonite at one point in the test. The origin of the bentonite could not be fully determined; however, two possible origins of the bentonite were considered: the filter, which may have become contaminated with bentonite during the emplacement of the bentonite seal (especially during shotclaying) and the erosion of the bentonite seal during the pressurisation of the experiment.

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

As a precaution the experimental plan was changed – artificial saturation was employed (water injection from both the filter and the chamber at the same time). This change to the pressurisation sequence proved to be most beneficial in terms of the investigation of system behaviour, i.e. it allowed the investigation of a number of processes which otherwise would not have been observed by implementing merely the originally intended one direction of flow.

Initially the processes inside the bentonite sealing section were driven by the intrusion of water (via the rock interface and filter) into the dry bentonite. At first the water enjoyed relatively easy access through the spaces between the pellets. Once the pellets had swollen sufficiently, the speed gradually slowed down as a thick wet skin developed. Nevertheless, the injection pressure applied through the filter in phase 2 was higher than the swelling pressure, thus the water was able to penetrate into the seal at least with respect to the surface parts. However, a pressure gradient/equilibrium was established through the skin while the core remained dry. This could be observed through pore pressure and water content/RH changes with respect to which the inner parts were influenced at a much smaller scale or not at all.

This behaviour corresponds to the self-sealing ability of the bentonite which was detected indirectly by the monitoring system at several locations where water quickly accessed sensors along the cabling which subsequently "disappeared", thus indicating that the water flow path had been closed and the water absorbed by the bentonite.

From this point of view, the bentonite sealing section behaved very well during the saturation phase and although only the surface part of the bentonite core was saturated, the saturation phase can be regarded as successful based on the results of the final phase.

In the final phase the EPSP was tested as originally intended, i.e. water was injected into the chamber, the filter was kept open and leakage was monitored. At this point the water pressure applied to the bentonite was significantly reduced by the concrete plug (as intended in the design).

Following an initial rise, pore pressure within the bentonite sealing decreased while total pressure continued to increase. This indicated that swelling pressure was sufficiently high and that the bentonite sealing worked as intended, i.e. water flow is driven by gradient and very low permeability and not by mechanical push through à very slow water movement.

This, together with other measurement results, indicates that the bentonite sealing has been activated and is functioning as intended.

During the course of the experimental run, a bentonite suspension was injected through the chamber into the experiment; several pressure levels were exerted up to 3MPa. The objectives of this test were to study the effect of the injection of slurry and to determine whether the slurry could be used to seal up pathways; the results however were inconclusive. No significant difference in EPSP behaviour was detected although the slurry seemed to be a little "gentler" than water and should be considered in the future for saturation purposes since it poses a lower risk of erosion. The most significant effects were caused by the high pressures employed which led to the (re)opening of preferential pathways. Leakage along the connecting borehole increased following the injection of the slurry (again clearly the effect of high pressure) and, moreover, the slurry was unable to seal this leakage probably due to the high flow velocity.

7.2.3. Monitoring

During pilot testing and the subsequent experimental run, the instrumentation also performed well. It managed to reliably track developments inside the experiment, especially in the sealing section.

Positioning the cabling perpendicular to the axis of the experiment helped to reduce the negative influence of potential flow along the cabling.

There were a number of problems regarding water leakage into the sensors during high pressure testing and one of the sensors even caused the back flooding of several others. The leak has however been resealed and the affected sensors disconnected. Fortunately, the sensors affected consisted of temperature sensors which had already fulfilled their primary purpose (hydration heat monitoring); therefore, the impact on the system as a whole was minimal. The compartmentalisation and redundancy built into the system helped greatly to reduce the impact of this incident.

7.2.4. Conclusion

The EPSP experimental run has provided some very important insight into concrete – bentonite stack behaviour.

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.

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, possible piping occurred at the time of “dry” bentonite sealing; therefore, at the beginning of the experimental phase it was deemed necessary to alter the course of the experiment and to saturate the sealing core at least to a limited extent in order to mitigate this effect.

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. This suggests the consideration of the employment of measures to have bentonite with higher water content and with less initially available pore space in the vicinity of the plug in the future DGR. These measures could include artificial saturation or layer of shot clay deposited bentonite.

The self-sealing ability of bentonite was confirmed several times by the sensors and was supported by the development of pressure during the final phase of testing

From the mechanical point of view, the concrete plugs 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.

8. CONCLUSION

The EPSP plug was designed as a model plug for a future Czech deep geological repository. It is expected therefore that similar plugs will function during 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 was 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. Glass-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 selection of technologies and materials was based on previous experience from underground structures such as underground tunnels, caverns and the Háje gas storage pressure plugs *(Hilar and Pruška, 2011)*. The design itself was optimised with respect to the requirement for minimal intrusion into the rock mass while retaining its function and with respect to the chosen construction technology – shotcreting.

The selection of the materials was performed with respect to the testing of materials which will potentially be used in the future Czech DGR particularly with respect to the main materials employed in the experiment, i.e. glass-fibre shotcrete with a lower level of pH and bentonite of Czech origin.

The EPSP has been successfully installed and the materials and technologies have been field tested. The initial objective of EPSP – the demonstration of technologies suitable (careful excavation, shot clay technology, etc.) for plug erection has been successfully achieved and the relevant experimental data has been collected.

The experimental phase of EPSP has commenced and important information concerning plug system behaviour has been and continues to be collected. The unintended change to the pressurisation sequence (required due to potential piping) proved to be 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.

The EPSP experiment has provided some very important insight into concrete – bentonite stack behaviour and the latest data proves that the stack functions as intended.

Although the EPSP is not intended to be a specific plug as such, it will serve as important input for the Czech repository design development concept, especially with respect to DGR plugs. The EPSP experiment, conducted under real-scale in-situ conditions, represents an important step in the transition from laboratory testing to the final construction of the future Czech DGR.

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