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EPSP plug test installation report

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ABSTRACT:

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

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

The D3.20 “EPSP plug test installation report” provides information on the installation of the experiment and the experience gained.

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2. INTRODUCTION

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

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

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

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

The D3.20 “EPSP plug test installation report” provides information on the installation of the experiment and the experience gained.

2.1. **EPSP**

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

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

- Pressure Chamber: The pressure chamber (or injection chamber) consists of an open area that can be used to pressurise the inner concrete plug. The chamber contains an inlet valve and a drain valve that can be used to fill the chamber with air (gas), water or bentonite slurry. The chamber was designed to be as small as possible so as to allow the pressure to be readily controlled. The pressure chamber is sealed with a waterproofing finish.
- Concrete Walls: Concrete walls (made up of blocks) were used so as to facilitate the construction of the EPSP experiment. Three concrete walls were built in total: the first

between the pressure chamber and the inner concrete plug, the second between the bentonite and the filter, and the third between the filter and the outer concrete plug.

- Inner Concrete Plug: The inner concrete plug forms one of the sealing components of EPSP and was constructed using sprayed glass-fibre concrete. The fibre concrete is of relatively low pH.
- Bentonite Pellets: The bentonite pellet zone comprises B75 bentonite, i.e. a natural and high-smectite content Ca-Mg bentonite with notably high iron content in the octahedral layer of the smectite. The purpose of the bentonite is to seal and absorb/adsorb any water that leaks across the inner concrete plug. The bentonite zone is 2m long.
- Filter: It is intended that the filter will collect any water that is not absorbed by the bentonite. This is most likely to occur if the leakage rate across the inner concrete plug is sufficient for the piping and erosion of the bentonite to occur. The filter may also be used to reverse the direction of pressurisation of EPSP.
- Outer Concrete Plug: The outer concrete plug is designed to hold the other components of EPSP in place. However, should the direction of pressurisation of EPSP be reversed, the outer concrete plug will have to perform under the same conditions as the inner concrete plug, and, therefore, the requirements concerning the outer concrete plug are the same as those of the inner concrete plug. The outer plug was built in the same manner as the inner plug and is identical to it.

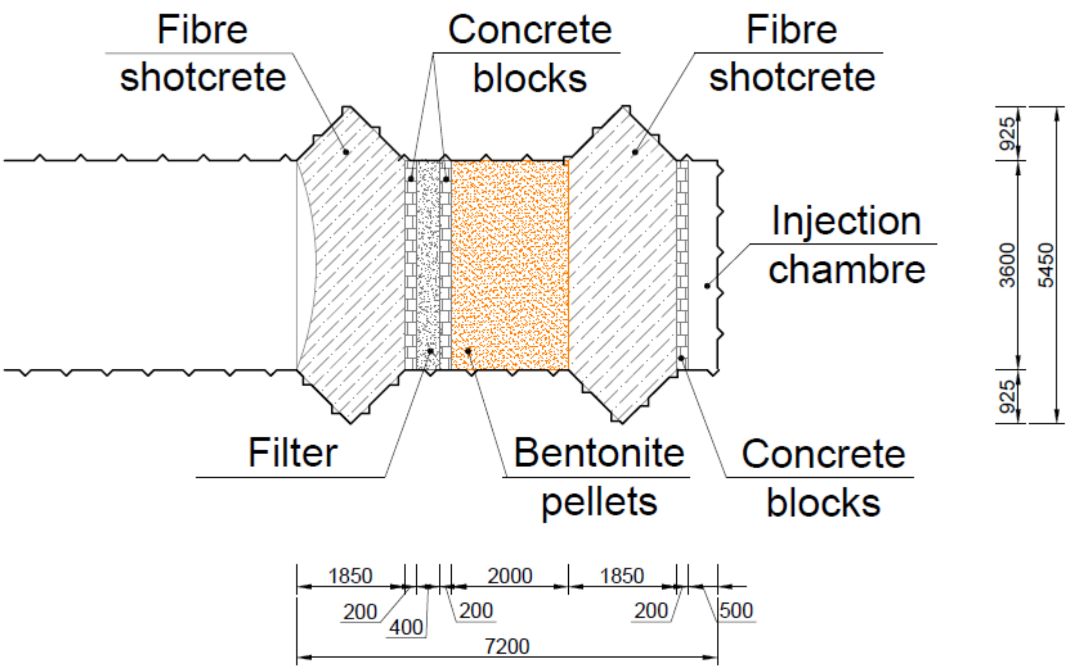


Figure 1 - Scheme of EPSP

2.2. SITING OF EPSP

The Josef 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 Josef galleries is approximately 8km and the length of the main drift is 1,835m, with a cross-section of 14 –16m^2. The thickness of the overlying rock varies between 90 and 180m. Two parallel tunnels lead from the entrance portals, each having a length of 80m and a cross-section of 40m^2.

The Josef URL features two main geological formations, each with different physical and material properties which change in character towards the contact zone and which include a large number of local fracture zones and several intrusions. Such conditions provide a high level of flexibility with regard to selecting the appropriate location for the conducting of 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 2). The technological equipment necessary for the conducting of the experiment is located in parallel niche M-SCH-Z/SP-55 (Figure 2). The niches are interconnected by means of cased boreholes equipped with tubing for both monitoring purposes and for the circulation of the pressurisation media.

These niches were selected based on the following criteria:

- Suitable geological conditions - granitic type rock, good quality rock featuring no major discontinuity zones.
- Space availability at the Josef URL - two free adjacent niches were required.
- Niche profile and length – the dimensions of the experimental niche had to be similar to those of the plug in order to limit excavation work.
- The avoidance of cross interaction with other experiments under way at the Josef URL

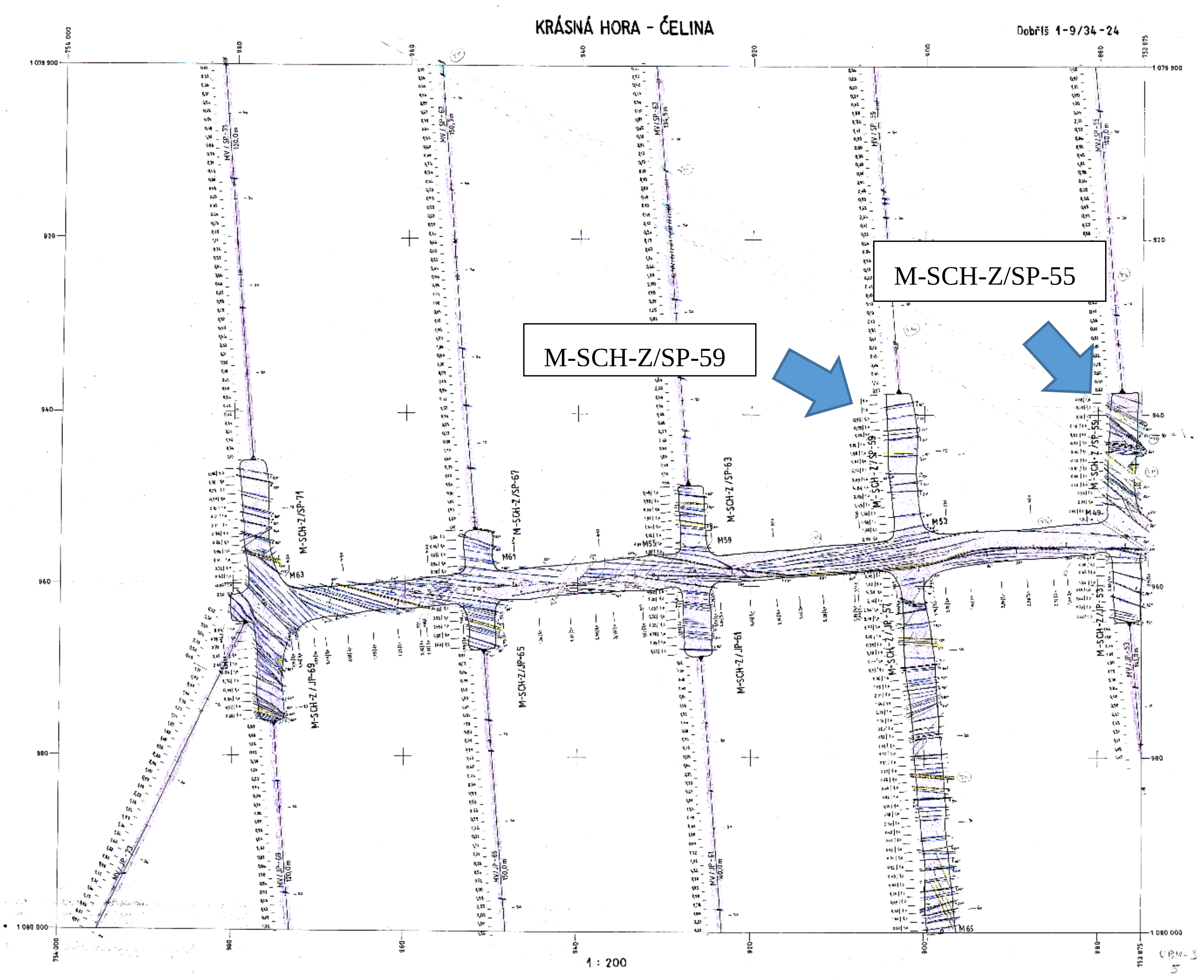


Figure 2 - EPSP location

2.3. DESIGN DEVELOPMENT

The design work undertaken in connection with the EPSP experiment included the use of analytical and numerical calculations for the confirmation of the design concept and the performance of physical model tests under laboratory conditions.

Several numerical models were constructed during the preliminary design stages (outside the remit of the DOPAS project). Two models were created in order to verify the final design concept according to the Eurocode 7 standard (*Svoboda et al., 2015 – D3.15*).

2.3.1. Numerical Modelling and Site-specific Design Issues

Numerical modelling was conducted so as to enable the evaluation of the structural performance of the proposed plug design. The aim of the analysis was to verify the design of the concrete plugs, their stability, deformation and stress changes within the surrounding rock mass. A basic model was constructed which considered both of the plugs as well as the surrounding rock mass and the pressurisation chamber. In addition, a detailed model of a concrete plug in contact with the rock mass was developed.

The numerical models simulated the construction of the experiment and the loads subsequently expected to act upon each component. The models did not, however, incorporate those stress changes inside the rock mass caused by the excavation of the niche; since the niche was excavated between 1981 and 1991, it was assumed that any deformation arising from excavation had already taken place. Moreover, the models did not consider groundwater ingress since the surrounding rock was sealed using grouting up to 5m from the original excavation zone and since water load was simulated by including the overpressure in the injection chamber.

The calculation was performed according to Czech standard ČSN EN 1997-1 (Eurocode 7) – design approach 2 employing CESAR-LCPC code (http://www.itech-soft.com/cesar/). CESAR-LCPC consists of a finite element package dedicated to the deformation and stability analysis of underground constructions and geotechnical structures.

The following loads (and their combinations) were considered in the models: self-weight, shrinkage, pressure in the chamber and swelling pressure.

The results of the laboratory tests indicated that the rock mass contained several discontinuity systems which might lead to anisotropy. Their intensity was classified as small or medium (average 2,000 – 200mm). This phenomenon reduces rock mass strength and was taken into account in the experimental models according to Eurocode 7 practice.

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 low-pH shotcrete as determined by laboratory testing (*Vašíček et al., 2016 – D3.21*). The results of the structural analysis revealed that the selected design of the plug and its materials could be expected to withstand all the experimental loads without any adverse consequences (*Svoboda et al., 2015 – D3.15*).

3. PHASES OF EPSP INSTALLATION

EPSP installation can be divided into 5 tasks:

- Task 0 - Niche preparation and documentation – work performed by the CTU and SÚRAO
- Task 1 - work performed by SÚRAO with 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, etc.)
  - Technology
- Task 3 - Bentonite sealing – work performed by the CTU
- Task 4 - Monitoring – work performed by the CTU

Responsibility for each of the above Tasks was divided between the various partners as follows:

<u>SÚRAO</u>

- Geological mapping, mineralogy
- Rock improvement, boreholes, instrumented rock bolts

E.g. Task 0 + Task 1

<u>CTU</u>

- EPSP design
- Work coordination
- Construction work and technology
- Monitoring
- Conducting of the experiment

E.g. Task 0 + Task 2 + Task 3 + Task 4 + overall coordination

ÚJV Řež was not directly involved in the construction process itself; however, it played an important role in terms of support research with concern to e.g. material suitability verification, concrete recipe development and verification, etc.

3.1. SCHEDULE

<u>Task 0</u>

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

Task 1

Task 1 was performed with the help of a subcontractor. The bidding process for the supplier took longer than anticipated, which was due both to the longer than expected preparation of the tender and to the fact that the winner of the bidding process chose not to proceed with the contract. The second-place contractor was subsequently invited to conclude a contract. The bidding process opened in May 2013 and was concluded by the signing of a contract in September 2013.

Work finally commenced in October 2013 with an expected duration of 6 months. Work began with the reshaping of the niche followed by the grouting of the rock in the upper part of the niche. Once the upper part had been grouted, the lower part was grouted in a similar way. In parallel, the connecting boreholes were drilled and subsequently cased, equipped with cable heads (selected boreholes) and grouted; in addition, the instrumented rock bolts were installed at this time. The work encountered significant delays due to rock grouting taking more time than anticipated and was completed after a period of 12 months in October 2014 further delaying the start of Task 2.

The outstanding work of Task 1 (contact grouting) was completed between the technological stages of and following work on Task 2.

The contact grouting of the inner plug was performed in the period December 2014 – May 2015 (leading to further delays in the Task 2 schedule) and the outer plug was grouted in July-August 2015.

Task 2

Task 2 was also performed with the assistance of a subcontractor. The contractor selection process started in the end of 2013. The negotiations with two possible contractors did not lead to the agreement, and the selection process was relaunched for additional round and the contract was signed in October 2014.

Work began with the installation of piping in the pressurisation chamber and chamber size adjustment in October 2014. The inner plug was constructed in a non-stop run of 23 hours on 12/13 November. During the curing of the inner plug, the piping for the filter was installed and the first part of the filter erected (the lower 1/3) so as to be ready for the emplacement of the bentonite.

Once the plug was considered sufficiently cured, a pressure test was conducted in December 2014, based on the results of which it was decided that contact grouting would have to be performed (part of Task 1).

Grouting was finally completed in May 2015 leaving only a very short time for bentonite emplacement and the erection of the filter and the plug. There was no further time reserve for further delays since the availability of shotcreting machinery could not be extended.

Once the grouting was finished, the filter was gradually erected according to the Task 3 schedule (bentonite emplacement).

Immediately following the completion of the construction 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 to the construction work. The technological equipment was prepared at the premises of the supplier and subsequently installed in the Josef underground complex in February 2015 where upon it was tested, with a full pilot run following in July 2015.

Task 3

Work in Task 3 was primarily conducted by the CTU instead of the planned subcontractor, which allowed for working on further project preparations in parallel with work on Task 2.

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

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

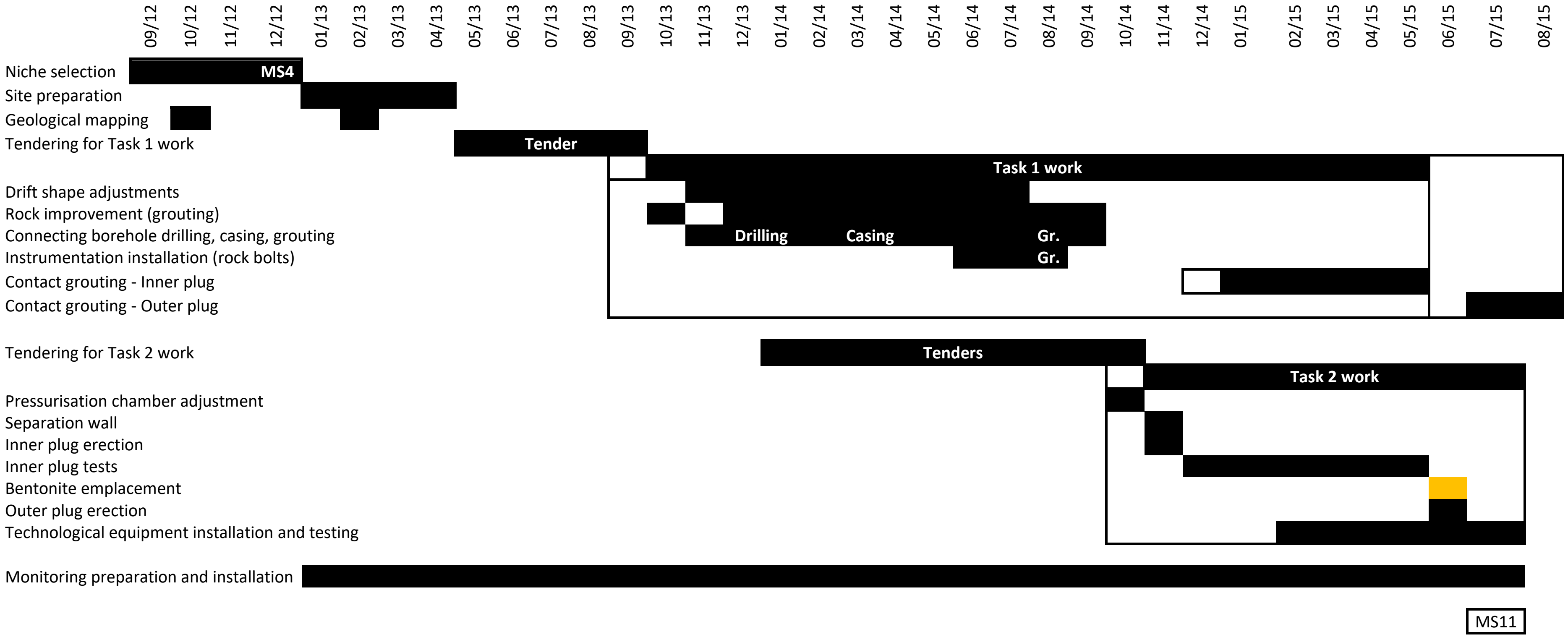
Emplacement was conducted in the period 9 to 15 June 2015 by the CTU.

Task 4

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

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

Work was concluded by the integration of all the parts of the system (including the technological equipment) into the Josef underground laboratory's measurement system once the construction work was completed and following the successful conclusion of pilot operation.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Niche selection
MS4
Site preparation
Geological mapping
Tendering for Task 1 work
Tender
Task 1 work
Drift shape adjustments
Rock improvement (grouting)
Connecting borehole drilling, casing, grouting
Drilling
Casing
Gr.
Instrumentation installation (rock bolts)
Gr.
Contact grouting - Inner plug
Contact grouting - Outer plug
Tendering for Task 2 work
Tenders
Task 2 work
Pressurisation chamber adjustment
Separation wall
Inner plug erection
Inner plug tests
Bentonite emplacement
Outer plug erection
Technological equipment installation and testing
Monitoring preparation and installation
MS11

4. TASK 0 - NICHE PREPARATION

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).

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 technological equipment.

5. TASK 1 – ROCK MASS

Work on Task 1 commenced in October 2013 with an expected duration of 6 months. 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 Task lasted a total of 12 months, reaching its conclusion in October 2014.

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

5.1. ROCK RESHAPING

5.1.1. Preparation of the SP-59 niche for excavation

The excavation niche (SP-59) was completely inundated with mine water prior to the commencement of work on enlarging the excavated profile in the section between the excavation face and the concrete barrier. Work commenced on 7 October 2013 with the gradual pumping out of the water from a side stub. Once pumping was completed, the initial 3D scanning of niches SP–59 and SP–55 was carried out by a surveying subcontractor who, subsequently, set the centre line of the future plugs (both inner and outer). The centre line was stabilised by means of a point in the cross tunnel and a point on the niche excavation face so that it was possible to follow it during the course of ongoing excavation work. The so-called "contractual zero" was determined so as to allow for the setting of the layout of the plugs and walls in the space determined for the plug. The contractual zero was marked on the surface of the rock on the right-hand side exactly 100mm from the V2 borehole in the direction of the cross tunnel.

Subsequently, work commenced on the construction of a working platform in the space between the concrete barrier and the excavation face of the SP–59 niche intended for the plug.

The working platform was constructed from pressure-impregnated round mining timber 180mm in diameter. The round timber formed cross beams anchored by a steel rod embedded (by means of drilling) in the rock mass in the niche. The resulting grid supported 60mm-thick impregnated planks which were secured against displacement.

5.1.2. Enlargement of the excavation niche profile for the SP-59 plug

Work on the alteration of the niche so as to achieve the required dimensions commenced with the enlarging of the niche profile and the creation of a planar excavation face. A Darda EP hydraulic splitting set with a Darda C9N hydraulic wedge was used for enlargement purposes. A HILTI TE MD 20 drill with a TE MW 100 hydraulic leg was used for the drilling of the 45mm-diameter holes. The excavation face was then treated to form a plane with a rough diameter of 3.6m.

Subsequently, work on the enlargement of the SP–59 niche profile began in the section determined for the start of the plug in the direction away from the excavation face towards the cross tunnel with a length of around 8m. A Darda EP hydraulic splitting set with a Darda C9N hydraulic wedge was used for enlargement operations. A HILTI TE MD 20 drill with a TE MW

100 hydraulic leg was used for the drilling of the 45mm-diameter holes. The shape was thus modified so as to form an approximately circular profile 3.6m in diameter.

5.1.3. Excavation of slots for the plugs

The precise direction of the plugs was set out following the completion of the enlargement of the side stub profile. The plugs had the shape of a wedge ring 1850mm wide and 920mm deep.

With concern to the requirement for excavating the rock without using blasting in order to minimise the occurrence of small failures in the rock mass surrounding the experiment, the Darda hydraulic splitting technique was employed.

The excavation work concerning the inner plug (at a distance of 0.7m from the excavation face) was conducted practically using this technique only, whilst with respect to the outer plug only partially; with a view to both accelerating the pace of excavation work and to facilitating the excavation for the remaining parts of the plugs, the pressure disintegration technique, using GBT (Green Break Technology) cartridges, was tested and, based on the results, subsequently applied in combination with the hydraulic splitting technique.

Excavation was carried out in two stages; firstly, the rough excavation of the rock was performed in the area destined for the upper half of both plugs using the working platform built within the space for the plug. Subsequently, the platform was disassembled and excavation proceeded in the space allocated to the lower half of both plugs. GBT technology supplemented by the Darda hydraulic splitter technique were used for the breaking of the rock in the lower part of the plug spaces. The use of GBT technology significantly accelerated plug space excavation work and, moreover, it resulted in practically no evidence of the original boreholes remaining following the completion of the excavation process. In addition, the excavated opening contour was found to be both more precise and smoother than the results obtained via the use of the Darda hydraulic splitter technique, the use of which, subsequently, was limited to the rough excavation work required.

A loose block of rock located in the crown of the space between the plugs was secured using one 4m-long rock bolt with a faceplate. The rock bolt was stabilised via the injection of WEBAC 1660 PU resin along the whole length of the bolt.

3D laser scanning was conducted following the completion of the excavation work for both plugs.

The total volumes of unbulked rock excavated for both plugs was calculated by comparing the scanning carried out before the commencement of excavation work and the final 3D scan. The total volumes of unbulked rock excavated for the installation of the two plugs amounted to 19.1m^3 and 18.0m^3 respectively. The volume of unbulked rock excavated due to the adjustment of the side stub amounted to 5.1m^3. The total volume of unbulked rock amounted to 42.2m^3 while the total volume of excavated material amounted to 59.08m^3.

5.2. CONNECTING BOREHOLES AND TUBING

5.2.1. Borehole drilling

Interconnecting boreholes were drilled between the SP-59 plug niche and the SP-55 technological equipment niche. Two times set of four of the boreholes were intended for pressurisation purposes, with a further five boreholes for the cables for the instrumentation transducers and sensors installed in the plug space.

A Lumesa – SIG Monty 2000 with an electrohydraulic drive, a driving engine (drilling head) on a 3m-long drilling tower and a Craelius T2 double core drill bit on a WL-NQ tight-assembly drilling shaft provided with narrow-edge bits with cutting diameters of 76mm and 102mm were used for drilling purposes.

The directions of the boreholes were set by the surveyors prior to the commencement of drilling. The accuracy of the mouths of the boreholes of the SP-59 niche in the space intended for the plug was conditioned by the maximum accuracy of the directions of the boreholes. A total of 13 cored boreholes were drilled uphill with a gradient of 1.8% to 4.6%.

The following boreholes were drilled into the pressure chamber: **V1** (76mm dia, 22.50m long), **V2** (76mm dia, 22.86m long), **V3** (76mm dia, 22.69m long), **V4** (76mm dia, 22.71m long) and **V5** (102mm dia, 22.83m long). The **V6** hole (102mm dia, 16m long) was drilled into the crown of the opening excavated for the inner plug; boreholes **V12** (102mm dia, 22.21m long) and **V13** (102mm dia, 22.19m long) were drilled into the bentonite sealing space. Boreholes **V7** (102mm dia, 22.03m long), **V8** (102mm dia, 22.16m long), **V9** (102mm dia, 22.33m long), **V10** (102mm dia, 22.59m long) were drilled into the gravel filter space. Borehole **V11** (102mm dia, 21.34m long) was drilled into the crown of the space intended for the outer plug. The drill cores obtained from all the boreholes were then stored in a storage facility in front of the entrance to the Josef underground complex. The boreholes leading to the pressure chamber encountered a significant geological disturbance with a thickness of around 10m.

5.2.2. Casing of the connecting boreholes between the space for the plug and the technological equipment centre

All of the above-mentioned boreholes were provided with casing using stainless steel pressure-resistant tubes consisting of 42/3mm tubes produced by SCHWER FITTINGS (of a total length of 184m, tested with pressurised water up to an internal pressure of 200bar) for the cable lines, and 38/3mm tubes (of a total length of 115m, tested with pressurised water up to an internal pressure of 160bar) for the filling and pressurising of the pressure chamber in front of the plug.

The tubes were connected using union nuts with a cutting ring. Each individual joint was pressure tested before being placed in the respective connecting borehole between the equipment centre in the SP-55 niche and the pressure chamber in the SP-59 niche. The whole length was further subjected to pressure testing following placement within the borehole. Each of the assembled lengths of pressure tubing was tested using water at a pressure of 160bar. No pressure drops were detected during the hydraulic testing of the pressure resistant tubes.

Both the pressurisation and cable tubes were terminated using SCHWER-system packing washers and nuts – straight ring coupling - heavy product range 38 S 50538S (13- 2839 pl.) and light product range 42L 50542L (13-2914 pl.)

Following the installation of the tubes, all the boreholes fitted with pressure tubing were filled with grout injected from both sides up to a depth of around 1m from the rock surface using WEBAC 1660 resin. The plugs required for the injection of cement grout into the boreholes were created in this way. A perforated grouting tube was pulled through the boreholes prior to the injection of the grout and concurrently with the installation of the tubing so that sealing grouting could be carried out following the filling of the boreholes with cement grout. Breather tubes were installed on the cable heads and on the sleeves for the passing of the tubes into the space intended for the plug. The space between the tubes and the rock mass was subsequently filled with activated cement grout.

The total weight of the 325-grade cement used amounted to 1400kg. The consumption of cement was significantly higher than that calculated for the annulus between the rock mass and the tubes. It is probable that high-pressure grouting forced grout into the geological disturbance passing between the two niches (SP-55 and SP-59) with a total thickness of around 10m. The additional sealing of the interconnecting boreholes involved the injection of WEBAC 1610 resin once the cement had hardened. The total consumption of this mixture amounted to 40 litres. Following this final grouting stage the interconnecting boreholes were completely sealed.

5.2.3. Steel pressure-resistant common cable head and interconnecting pressure resistant tubing

Five steel pressure-resistant common cable heads with pressure-resistant sleeves embedded in the rock mass were installed for the passage of the cables from the measurement sensors located in the space intended for the plug. The number of sleeves on individual cable heads amounted to 32 and 34 respectively. Three stainless steel pressure-resistant common cable heads for 32 sleeves designed to withstand an external operating pressure of 150bar were supplied together with an additional 2 stainless steel pressure-resistant common heads for 24 sleeves designed to withstand an external operating pressure of 150bar. A total of 114 pressure-resistant 8mm-diameter cable sleeves designed to withstand a pressure of 160bar were installed for the pressure-resistant common cable heads. Steel pressure-resistant common cable heads were installed in boreholes V5, V6, V12, V13 and V11 (Figure 3).

A pocket of rock was removed in the location of interconnecting borehole V5 in the direction of the excavation face so as to allow for the embedding of steel pressure-resistant cable head H1 and its connection to the steel pressure-resistant piping. In addition, a space surrounding the borehole (550mm minimum) was treated for the potential anchoring of the drill set stand using a diamond saw followed by the removal of the incised rock by hand using chisels. The large-profile boreholes required for the moving of the pressure-resistant cable heads to the rock massif were drilled to the required depth from the surface of the side of the treated niche excavation. Cable head H was left partially protruding (15 – 20cm) from the borehole in the pressure chamber. The other cable heads, H2 and H5, were fully embedded in the rock massif leaving only the protruding bolt heads visible. The H3 and H4 common cable heads in the space between the plugs were completely embedded in the rock mass (including the bolts).

The bolts were welded onto the head before being embedded in the rock pocket. The diameters of the boreholes drilled for the installation of the cable heads were 400mm and 500mm with depths ranging from 600mm to 700mm. The holes were drilled parallel to the previously drilled interconnecting boreholes containing the steel pressure-resistant tubes.

Contingent deviations from the direction of the pressure-resistant tubes inside the boreholes were removed by hand in a similar way to those relating to the annulus of the core following the completion of drilling (by hand, using chisels).

Following the completion of the drilling work concerning the rock pockets and the removal of the rock, the steel pressure-resistant cable heads were installed.

Hydraulic sealing testing was conducted following the connection of the cable heads to the steel pressure-resistant pipes in the borehole using bolts. Pressurisation was applied by means of a URACA grouting pump up to a minimum pressure of 180bar. Following the completion of the testing of the sealing capacity of the cable heads and their connection to the pipe, the complete cable head – pipe assemblies were carefully shifted into the rock pocket. The cable heads were supported and centred using silicon wedges and were set in the required direction in a way that prevented stress acting upon the joint between the cable heads and the pipe. All of the cable heads (H2, H3, H4 and H5) were fully embedded into the rock mass, with the exception of the H1 cable head, i.e. the cable head inside the pressure chamber, which partially protruded into the space.

The cable heads embedded in the rock pockets were encapsulated by means of WEBAC 1660 resin injected around them up to a distance of around 1m from the cable head flanges. The pipe was sealed at a distance of around 1m from the beginning of the interconnecting borehole by means of a plastic ring.

A slot was cut into the rock mass in the upper part of the pocket before the cable heads were completely shifted into the pocket, the design of which included a loop to support the cover of the cable head during dismantling and subsequent repeated assembly.

Each pressure-resistant cable head and pressure pipe assembly was subjected to hydraulic testing up to a maximum pressure of 180bar. No loss of pressure was recorded during pressure testing.

The confirmation hydraulic testing of 2 boreholes lasting for 1/2 and 2 hours was conducted following the completion of the assembly of the pipes and their connection to the cable heads; pressure was maintained in one of the boreholes for a total of 19 hours. The boreholes for the equipment with blank flanges were also tested under a test pressure of 200bar; the boreholes were selected at random. No perceptible drop in pressure was recorded in the pipes tested after being subjected to pressure levels of up to 200bar.

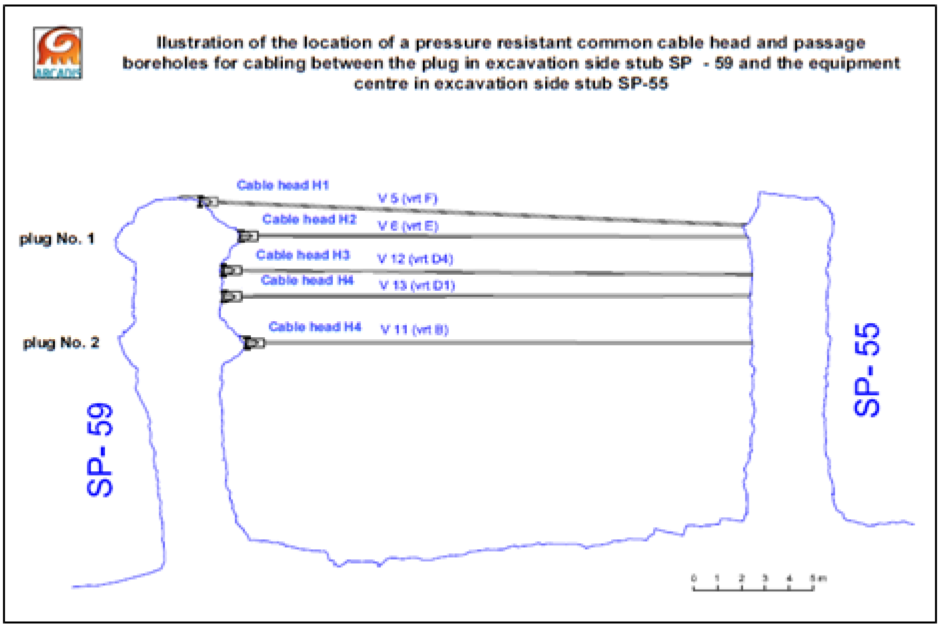


Figure 3 – Cable heads and connecting boreholes

5.3. **GROUTING**

5.3.1. Impregnation of the rock mass in the space for the plug using high-pressure grouting with polyurethane resins

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. The spacing between the transverse profiles was 1.5 metres. The spacing between the boreholes in the grouting profile drilled in the spaces intended for the plugs was 2.3m, with a borehole length of 3.8m and diameter of 36mm. Holes were drilled with a spacing of 1.3m, a length of 4.7m and a hole diameter of 36mm in the niche profile. In the space in front of the concrete barrier, from which deposits from the bottom were not removed, 5.25m-long grouting boreholes were drilled so as to form a fan inclining under the barrier at an angle of 64° thus completing the grouting of profile no. 1. The spacing between the grouting boreholes was reduced in some of the profiles with respect to local conditions, i.e. taking into consideration the faulting of the rock mass and water inflows. The total number of grouting boreholes amounted to 72. 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 WEBAC IP 2 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 completely 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 required to verify the effectiveness of grouting operations. Hydraulic testing subsequently confirmed that the level of impermeability following grouting met all the requirements concerning the permeability of the rock mass.

5.3.2. Grout injection to seal groundwater inflow and the increasing of the height of the barrier in SP-59 and its sealing

The significant inflow of groundwater through fissures exposed at the bottom of the niche was encountered during excavation work for the collars of both inner and outer plugs. The inflow rate was locally estimated at 8 – 10 litres per minute.

In addition, the drainage system in the cross tunnel was found to be permanently overflowing with water. Therefore, high-pressure grouting using WEBAC 150 polyurethane resin was performed with the aim of preventing the inflow.

Due to the pressure exerted by the groundwater, the grouting mix was forced out of the fissures and it was deemed necessary to use a resin with a shorter reaction time, i.e. WEBAC 151. The inflow along water carrying fissures was gradually sealed until it was eventually completely stemmed. It was necessary to drill a total of 4 cored boreholes 0.8 – 1.0m long, 8 non-cored boreholes to a maximum depth of 1.5m, and 10 boreholes into the barrier and the contact between the barrier and the rock mass. The total consumption of grouting material amounted to 16 litres of WEBAC 150 resin and 20 litres of WEBAC 151 resin.

An area of approximately 26m^2 was sealed against groundwater inflow in the space intended for the plug. Once the sealing of the water inflow and seepage around the barrier was completed, mine water which had collected in front of the barrier began to overflow. Due to the water subsequently inundating the space intended for the plug, it was deemed necessary to increase the height of the barrier using rapid-hardening RedRock concrete which was poured directly behind the prepared formwork. The sides of the rock massif and the surface of the existing concrete barrier were cleaned prior to the casting of the concrete. Once the concrete hardening process was completed, only small leaks of water along the barrier-massif contact surface were detected which were subsequently sealed using WEBAC 1403 resin. The consumption of resin amounted to 32 litres. The height was increased by 0.25m at a width of 0.35m.

5.3.3. Borehole hydraulic tests

Borehole hydraulic tests were conducted for the checking of the impermeability of the rock mass in the space intended for the plug, which had been treated to a depth of 5m. A total of six boreholes 76mm in diameter and 3.1m long were drilled for the verification of the sealing capacity of the rock mass up to the same depth of 5m. An additional four boreholes 14mm in diameter and 0.3m long were then drilled for the verification of the sealing capacity of the near-surface layer of the rock massif in the space intended for plug 1. Hydraulic testing borehole VTZ – 1 was located on the axis of plug 2; the borehole was drilled at the exact location of the future borehole interconnecting this space with the SP-55 niche. Testing was conducted prior to the injection of grout aimed at rendering the rock mass surrounding the space for the plug impermeable.

The VTZ – 2 borehole was drilled in the location of the testing of the impermeability of the grouting in front of the space intended for the plug in RZ-59. The VTZ – 3 borehole was drilled along the axis of plug 1, vertically to the sub-grade. The VTZ – 4 borehole was drilled along the axis of plug 1, uphill and to the left-hand side of the plug. The VTZ – 5 borehole was drilled along the axis of plug 1, approximately along the longitudinal axis of the space intended for the plug, perpendicular to the excavation crown. The VTZ – 6 borehole was drilled along the axis of plug 1, on the right-hand side, obliquely upwards to the excavation crown. VTZM testing boreholes were drilled along the axis of plug 1. Once testing was concluded, the boreholes were filled by means of the injection of WEBAC 1660 resin; the total consumption amounted to 32 litres.

5.3.4. Sealing of the interface between the concrete body of the inner plug and the rock mass

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 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 to ensure that the contact interface was encountered. In this phase a total of 24 boreholes were 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 were 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 pressurising chamber. The concentrated discharge flow amounted to 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 Fig.4 green dots). In the second stage boreholes were added on the right and left sides of the plug (see Fig.4 blue dots). In the third stage boreholes were added at the bottom of the plug (see Fig. 4 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.

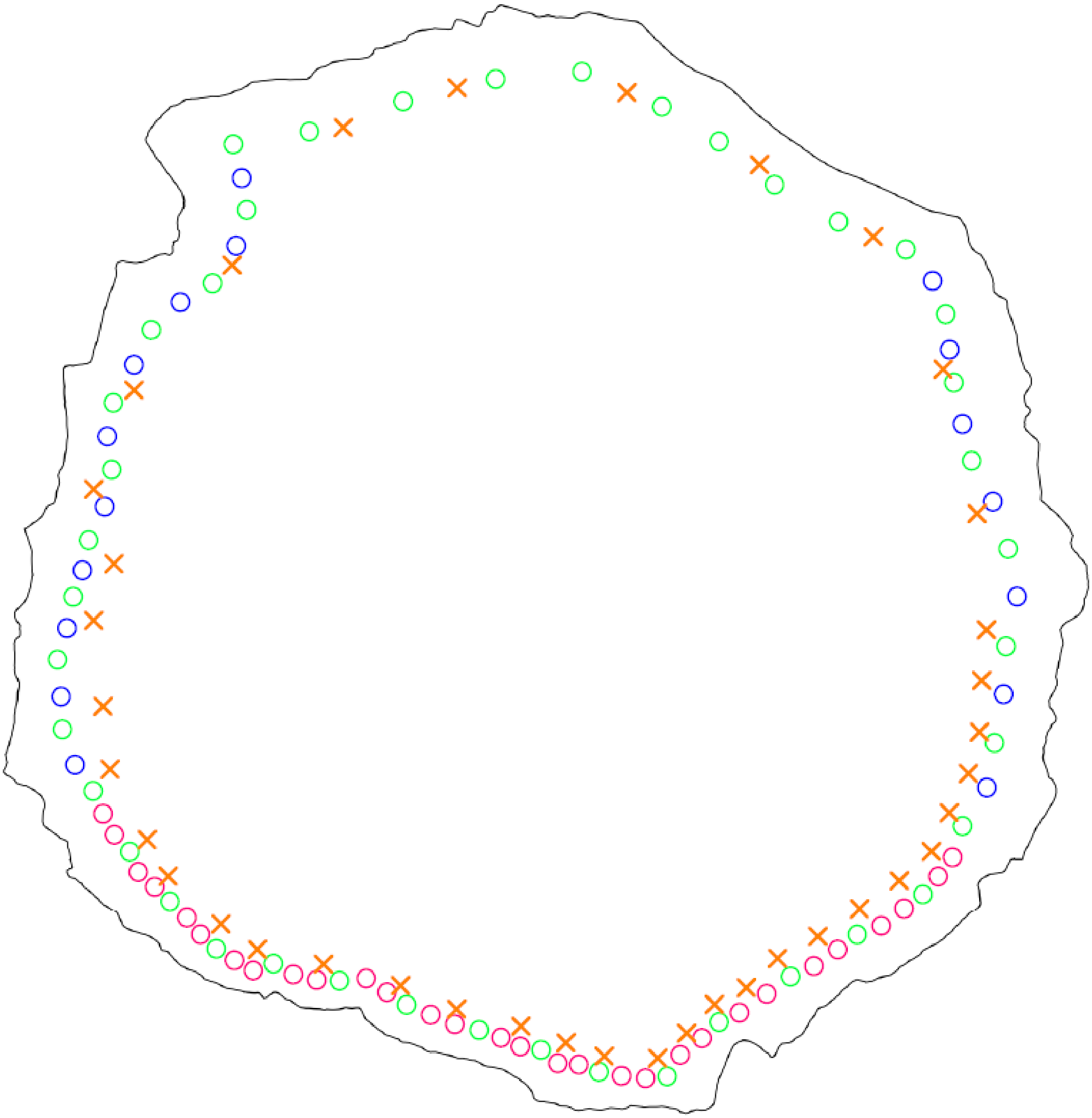


Figure 4 – Drilling pattern for injection work on the inner plug

5.3.5. Sealing of the interface between the concrete body of the outer plug and the rock mass

The sealing of the contact zone between the outer plug and the rock mass was carried out so as to prevent concentrated discharges of water at 5-10 bar pressure. A concentrated discharge flow of more than 1 litre per minute from one location was considered too excessive. 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.

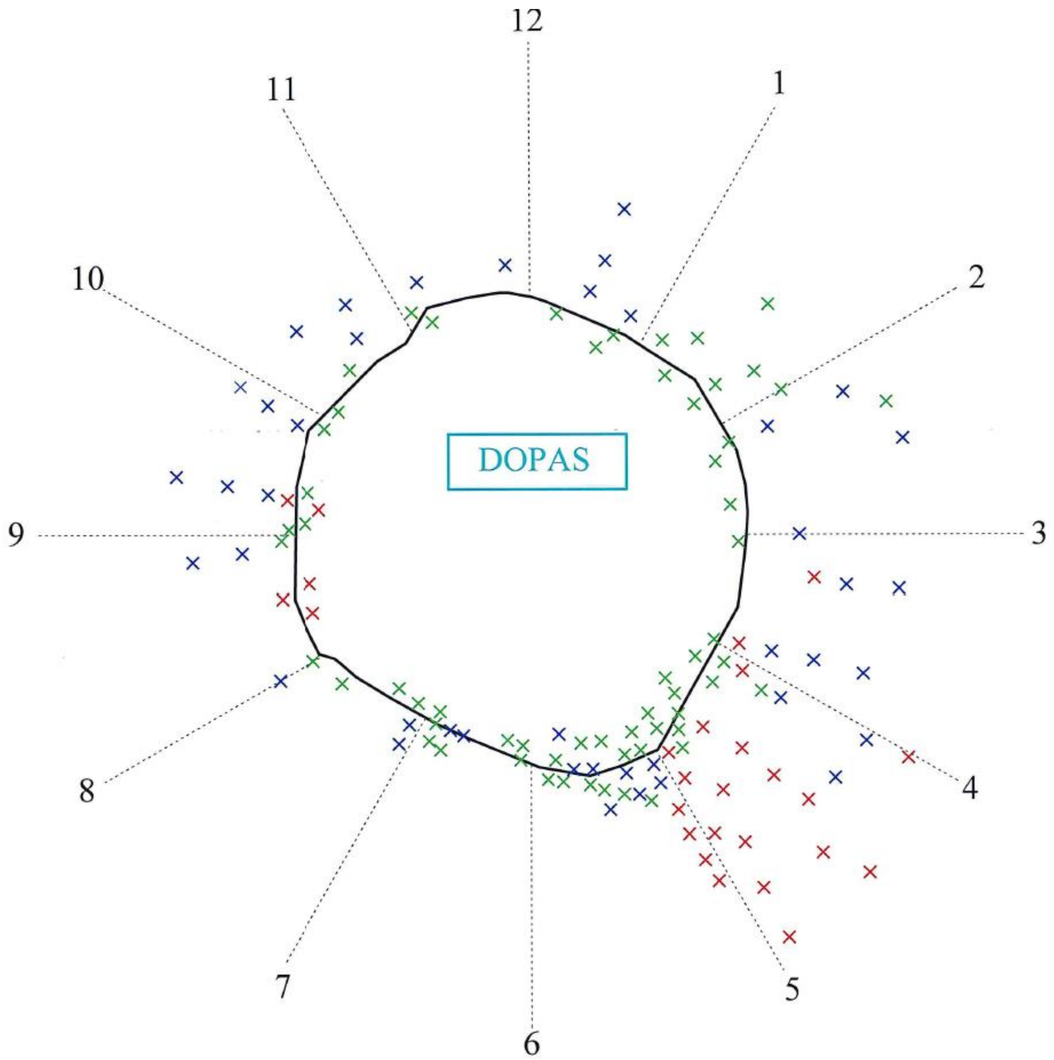


Figure 5 – Drilling pattern for injection works outer plug

In total 42 boreholes were sealed using 68kg of Sika material (see Fig.5 blue marks). 26 boreholes were sealed using Purinjekt, polyurethane on the right and left sides of the plug (see Fig.5 brown marks). 62 boreholes were sealed using Purinjekt, polyurethane around the whole of the plug’s circumference (see Fig.5 green marks).

The total consumption of polyurethane amounted to 140kg.

5.4. INSTALLATION OF MEASUREMENT BOLTS FOR MEASURING STRESS IN THE ROCK MASS

Boreholes intended for the measurement bolts were drilled in compliance with the design set out in the bidding documentation. The boreholes, 12 in total, were drilled into the excavation face and in the spaces intended for the plugs. 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 holes were drilled in the space intended for plugs 1 and 2 and then 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 plug 1: S5 (5.16m long, 47mm dia), S6 (5.19m long, 47mm dia), S7 (5.05m long, 47mm dia), S8 (5.19m long, 47mm dia), 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.

5.5. FIELD AND LABORATORY TESTS OF THE ROCK MASS

Laboratory tests were conducted for the determination of unconfined compression strength, tensile splitting strength, modulus of deformation Edef (MPa) and density. The tests were carried out on specimens of the rock mass (quartziferous tonalite) taken from the space intended for the plug in niche SP-59. Six 50mm-diameter specimens with a slenderness ratio of 1:2 were analysed in total. The tests were carried out at the ARCADIS CZ a.s. accredited laboratory. Further tests were conducted directly inside the space intended for the plug in niche SP-59. The static plate test for determining the modulus of deformation was carried out on the axis of plug 1, at the bottom of the excavation. The resultant modulus of deformation was determined at 5-10GPa.

A total of 8 tests using a uniaxial press was carried out in the boreholes with the aim of determining the modulus of deformation Edef (MPa) in situ. The resultant values of the moduli of deformation were determined at 6.2-12.1GPa and 34.5-43.1GPa; the difference between the two moduli was due to the presence of fissures. The tests were carried out at the ARCADIS CZ a.s. accredited laboratory.

6. TASK 2 – EPSP ERECTION

Work on Task 2 commenced with the installation of piping in the pressurisation chamber and chamber size adjustment in October 2014. 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 pilot run in July 2015.

Work on Task 2 was conducted according to *Svoboda et al., 2015 – D3.15 Detailed design of the EPSP plug* and *Svoboda et al., 2014 - D3.18 Testing plan for EPSP instrumentation and monitoring.*

6.1. PRESSURISATION CHAMBER

The first step involved the installation of a cable head plate with the attached instrumentation (sensor assembly) in the pressurisation chamber. The cable head plate was preassembled in the Josef URC's own laboratories including the attachment of the various sensors and the associated cables. The whole assembly was then transported to the underground facility.

The installation of the sensor assembly commenced with the leading of all the cables through the 23m-long interconnection cased borehole. Once this was completed, the cable head plate was attached to the borehole head. The whole assembly was then secured by bolts which connected both parts of the head.

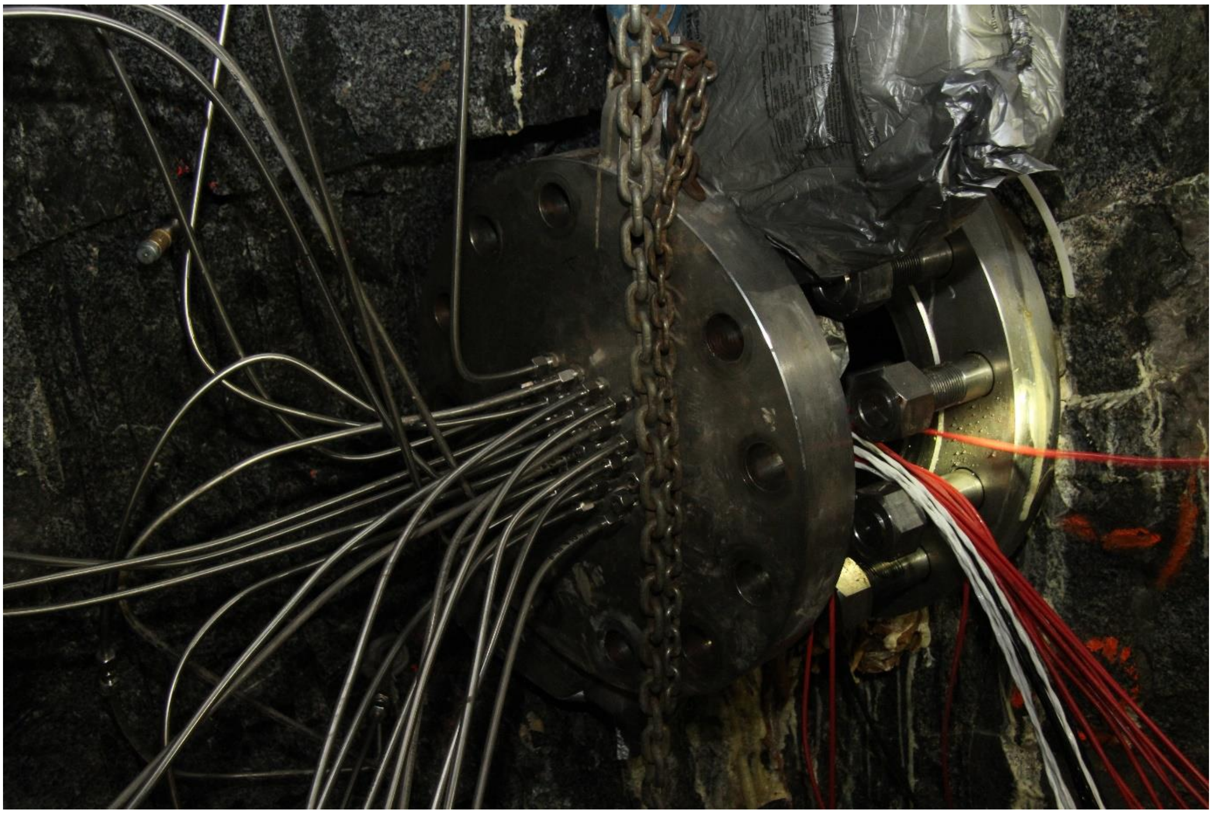


Figure 5 - Cable head before leading the cables through the borehole (29 August 2014)

Figure 6 - Preparation for the leading of the cables

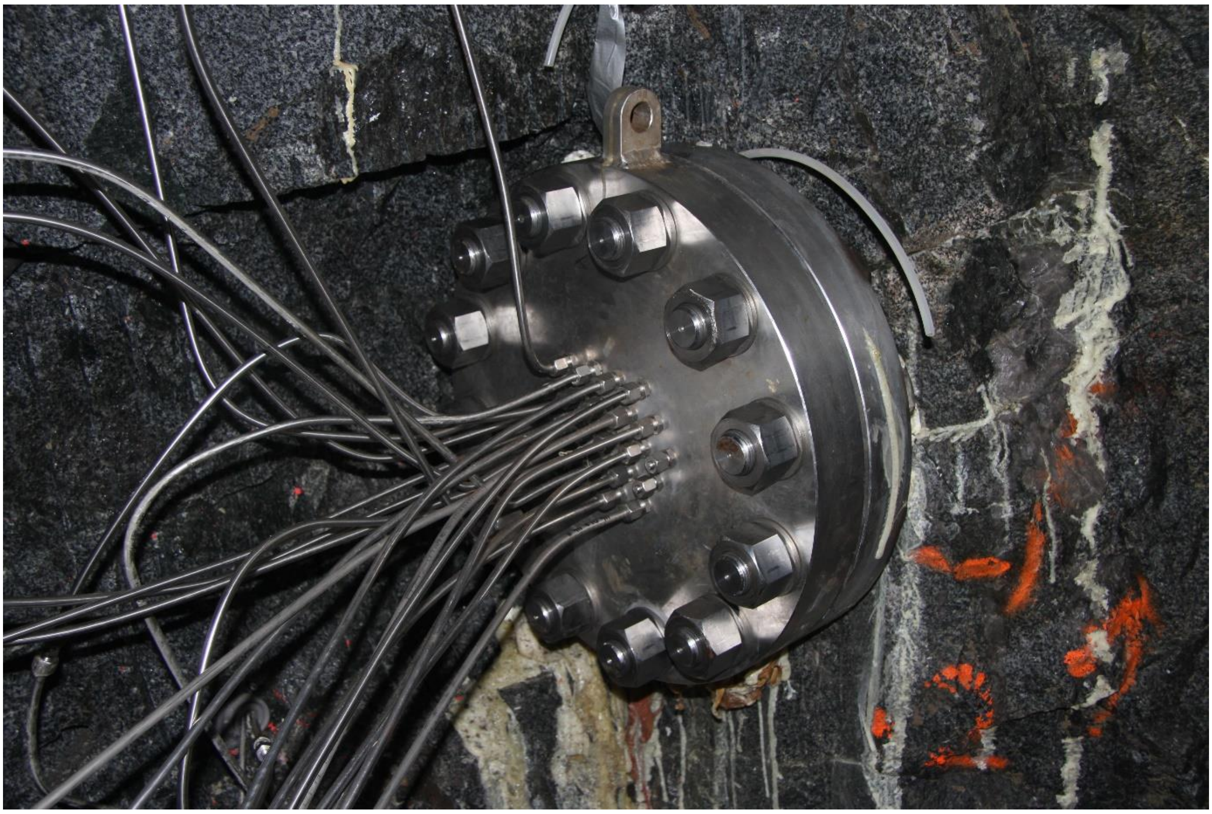


Figure 7 - Installed cable head with attached sensors (1 September 2014)

Following the installation of the cable head plate, the various sensors were fixed either to their final positions or temporarily to the side of the niche (those sensors intended for the shotcrete filling or separation wall).

The pressurisation chamber was then equipped with piping which would connect to the pressurising media in/outlets (via connecting boreholes from the technological niche). The piping consisted of four welded stainless steel (DIN 1.4571) tubes of a diameter of 38mm. One end of every tube was then fixed to the head of the piping leading to the technological niche; the other ends were left open into the chamber. Two of the pipes ended at the top of the chamber and two at the bottom (Figure 8). The tubes were fixed in place by clamps on stainless steel rods.

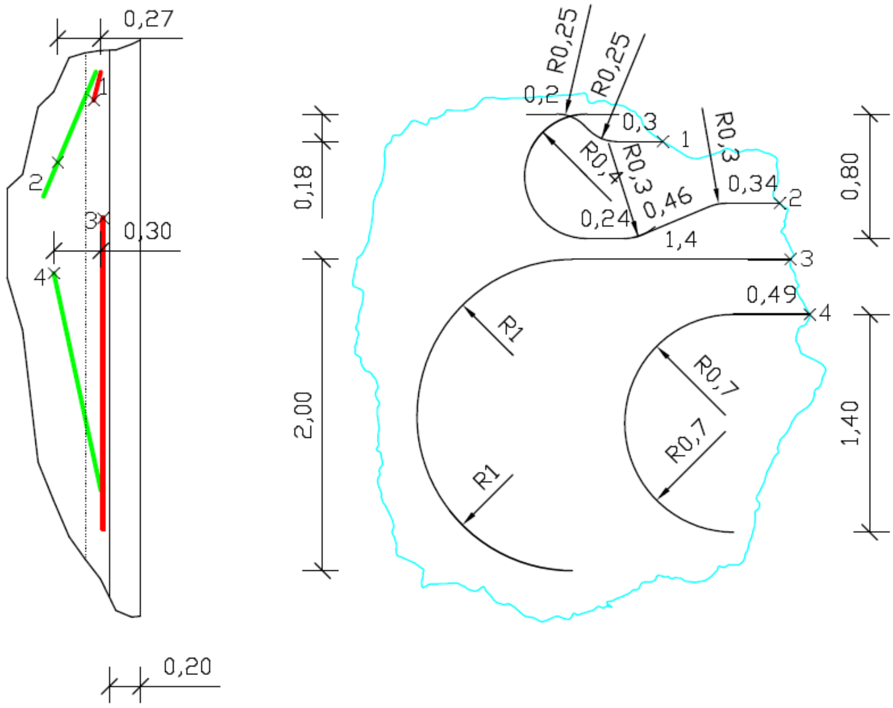


Figure 8 - Piping in the pressurisation chamber

The walls and floor of the pressurisation chamber were treated 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 of SikaTop Seal 107 (www.sika.com). The instrumentation for the monitoring of the shotcrete filling (temporarily stored at the side of the plug space) was installed between the application of individual batches of shotcrete and once shotcreting was completed.

The shotcreting process also served as the ultimate test of the technological setup for plug erection (the same machine setup was used).

Figure 9 - Pressurisation chamber prepared for shotcreting (24 October 2014)

Figure 10 - Shotcreting of the chamber (27 October 2014)

Figure 11 - Sensor installation within the shotcrete (27 October 2014)

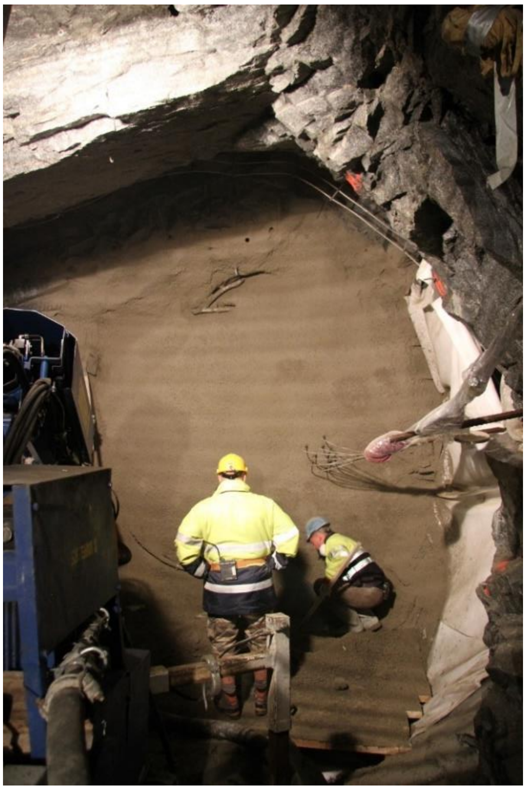


Figure 12 - Completed shotcreting (27 October 2014)

6.1. **SEPARATION WALL**

The pressurisation chamber was closed off by means of the installation of the first concrete separation wall, i.e. an auxiliary structure serving as a base for the shotcreting of the inner plug and for the instrumentation.

The separation wall was made of prefabricated hollow blocks (in the form of a lost formwork) which were filled with concrete. The spacing of the blocks was intentionally "loose" so as to allow for free water flow through the wall.

Figure 13 - Separation wall erection (4 November 2014)

Figure 14 - Completed separation wall (5 November 2014)

6.2. **INNER AND OUTER PLUG**

Both plugs were erected following an almost identical procedure. The only difference was that the outer plug featured pre-installed grouting pipes.

Generally, the plug erection sequence was as follows:

1. Installation of the grouting pipes (outer plug only)
2. Installation of the cable head with the attached instrumentation
3. Instrumentation and cabling fixed into their final or temporary positions
4. Machinery setup
5. Spraying of the plug in layers, gradual installation of the instrumentation
6. Curing of the plug
7. Grouting and pressure tests (repeated)

6.2.1. Instrumentation installation

The instrumentation was pre-assembled at a surface facility, i.e. an assembly consisting of the sensors attached to the cable head was prepared in advance and then transferred to the underground facility.

The first step involved the positioning of the cable head in front of the corresponding borehole head. Then the cables from the sensors already installed in the rock mass (instrumented rock bolts) were attached to the head.

The second step involved the tight bundling of the cables to form one assembly which was then pulled through the borehole. Once the cabling was pulled through the borehole, work commenced on connection to the data loggers.

The third step consisted of the attachment of the cable head plate to the rest of the borehole head and the tightening of the connector bolts.

The fourth step involved the fixing of the cabling (in protective tubing) to either the rock mass or to so-called “ladders”. The cabling was arranged in such a way as to minimise its impact on the shotcreting, i.e. to avoid the creation of shadows by the spreading of the cables.

The instrumentation destined to be positioned in the shotcrete plug itself was temporarily stored at the sides of the plug space. It was positioned later as the shotcreting of the plug progressed.

Figure 15 - Cable head preparation (outer plug, 17 June 2015)

Figure 16 - Cable head and instrumentation before shotcreting (outer plug, 19 June 2015)

6.2.2. Technological setup

The technological setup used for plug erection consisted of the following main components:

- Electric compressor - Atlas Copco GA55
- Concrete pump - MEYCO Suprema
- Spraying machine with remote controlled nozzle - MEYCO Oruga

All the electrical setup was chosen so as to prevent ventilation problems within the Josef underground complex. It was determined some years ago that the natural ventilation of the main gallery at the Josef facility might not be adequate under certain climatic conditions. Therefore, a limit was set on the use of combustion engines, which ruled out the use of a diesel powered compressor to supply the electrical power for the experiment. Since the electrical setup, however, stretched the power lines at the Josef facility to the maximum, strict limits were place on power usage during shotcreting.

The electric compressor was positioned at the main Mokrsko crossing so as to save space at the EPSP site. Compressed air was transported via temporary piping fixed to the side of the gallery spanning several hundred meters.

The concrete pump was positioned at the entry point to the EPSP niche so that materials could be offloaded directly from the delivery vehicles.

The spraying machine was positioned within the EPSP niche itself on a specially built temporary floor. The nozzle was operated via a cable remote device with the cable operator able to move along the sides of the machine so as to be able to visually monitor the spraying process.

6.2.3. Material

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). 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 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 from shrinkage. Moreover, low-pH concrete is required so as to limit possible impacts on the bentonite.

The exact requirements were derived from D3.15: Detailed design of the EPSP plug (Svoboda, et. al., 2015). The inner plug was constructed using glass-fibre low pH shotcrete which was required to fulfil the following requirements:

- pH of the leached water below 11.7 (in less than 60 days)
- hydraulic conductivity $K < 10^{-8}$m/s
- uniaxial strength (cylindrical) minimum 30MPa, recommended 40MPa
- Flexural strength (first peak – at crack creation) minimum 3MPa, recommended 5MPa
- crack size <0.2mm; no pass through the cracks
- recommended micro silica/cement ratio: 50/50
- minimum amount of fibres 3kg/m^3

The outer plug was constructed from shotcrete employing the same procedure as that used for the inner plug; the use of fibres was not obligatory. The same concrete composition was recommended and subsequently used (including fibres).

Two mixes were tested and their suitability assessed based on a consideration of pH, compressive strength, rheology and other parameters (Table 1). The two mixtures were also subjected to mock-up tests in a testing niche in the Josef URC underground laboratory (Figure 17).

Figure 17 - Core sampling in-situ (material qualification test)

The selection of the preferred concrete mix was ultimately determined by chemical analysis since one of the concrete mixtures exceeded the pH limit (pH = 12.0-12.2), with the second mixture meeting the target (pH = 11.3-11.5) and all the other requirements.

Table 1 - Measured strength and pH of 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 Strengths	5.8MPa	6.7MPa
pH - filtrate	11.3	12.1

The mixture selected for EPSP use was as follows:

- 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. The workability of the mixture was 12 hours.

6.2.4. Material transport

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.

The start of shotcreting was timed to avoid the Prague rush hour in order to assure the time delivery of a mix as possible.

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.

6.2.5. Ventilation

Ventilation makes up one of the key safety elements when working underground. Two major issues arise when performing construction work:

- Pollution from combustion engines and the associated reduction in the oxygen level
- Dust production

The Josef underground complex uses a combination of natural and forced ventilation which, to some degree, limits the amount of fresh air delivered to the work areas and galleries. Therefore, strict controls and regulations are in place.

With respect to the first point (pollution) an all-electric setup was chosen for the machinery (except for the delivery trucks). 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 issue (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.

6.2.6. Plug erection

Inner plug

The inner glass fibre shotcrete plug was erected in a non-stop run of 23 hours on 12/13 November 2014. The wet mix shotcreting procedure was used for the construction of the plug; the mixture consisted of glass-fibre low-pH shotcrete.

The thickness of the inner plug is 1850mm. The shotcreting was performed via the application of approximately 100mm-thick layers starting at the bottom and the separation wall. The short breaks between the delivery of batches of sprayed concrete were used for sensor installation inside the plug.

Once the plug had cured, a pressure test was undertaken using water and air. Measurements and observations taken during the test demonstrated that contact grouting would be necessary between the plug and the rock mass so as to ensure water tightness.




Figure 18 - Inner plug erection and sensor installation (12/13 December 2014) – reloading of the concrete mix, offloading the mix into the pump, shotcreting machine, first batches sprayed, instrumentation installation, finished plug

Outer 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 was employed in a similar way as with the inner plug.

Figure 19 - Outer plug erection (19/20 June 2015)

Figure 20 - Finished outer plug

<u>Plugs overall</u>

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.

Shotcreting behaviour was good 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.

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 performance overall during emplacement was very good with a very good (low) level of dust evolution. The main advantages and disadvantages generally stem from the shotcrete technology in general: the method is fast, it is flexible, no formwork is needed, there are no uneven surfaces etc.; however, the quality of application depends to a great extent on nozzle operator skills. The disadvantages consist of “shadows”, rebound and dust.

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 (outside of the plug) 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.

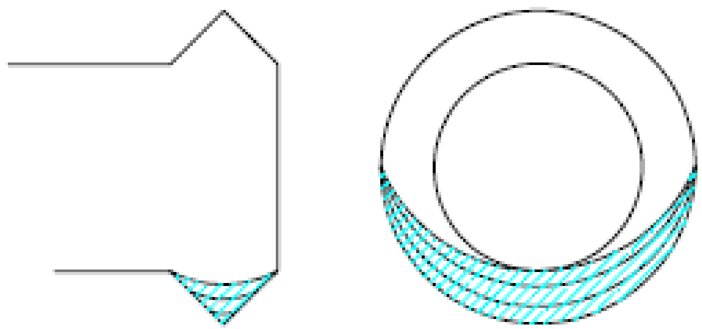
6.2.7. Spraying sequence

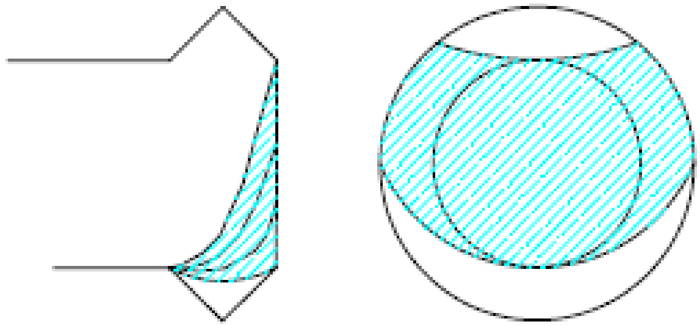
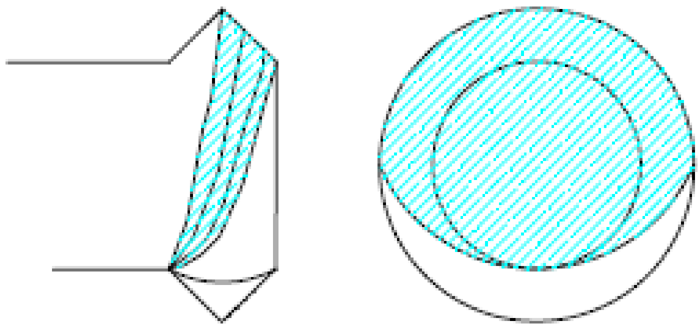
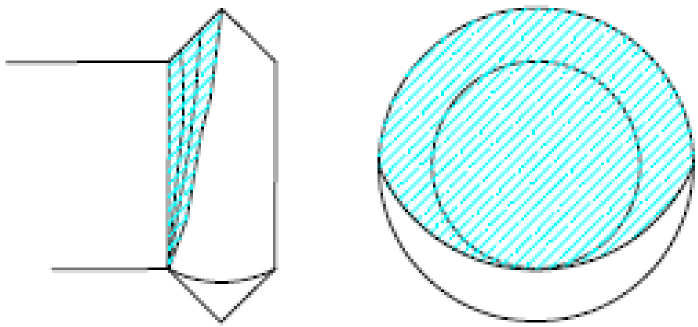
The spraying sequence used for both plugs generally followed the sequence described in Table 2 as proposed in D3.15 Detailed design of the EPSP plug (Svoboda et al., 2015).

The only difference was that the bottom part and the face phase (first and second rows in the table) were, to some extent, interconnected so as to attain more even progress and a better overall bond. The thickness of the sprayed layers was generally 50mm in all parts.

The shotcreting process was also influenced by the monitoring equipment. Special care had to be taken around the cable head where the concentration of cabling might have led to the creation of “shadows”. The instrumentation inside the plugs did not pose a significant problem – it was stored at the side of the niche and gradually installed within the plugs between individual spraying applications.

Table 2 - Shotcreting sequence

Bottom part spreading into the sides Thickness of the layers 50mm	

Face Thickness of the layers max. 100mm.	
Face and upper vault Thickness of the layers max. 100mm.	
Upper vault and filling up of structure Thickness of the layers max. 100mm.	

6.2.8. Quality control and verification testing

In order to ensure the successful erection of the EPSP, a quality control system was designed. The system relied on two tiers:

- The prescribed work procedures and their supervision
- Verification testing

The procedures were presented in advance by the contractor and reviewed by CTU. The supplier was required to have a certified quality management system in place.

At critical moments of the construction process, the presence of specialists was required on site (such as the concrete mixture designer/engineer at the time of shotcreting). The non-stop supervision of the critical work was performed by the CTU.

Verification testing

A verification testing plan was designed in advance and agreed by both the contractor and the investor. The plan specified which tests had to be conducted and their timing.

During plug erection the slump/flow table test was performed on a sample of concrete taken from each truck arriving at the Josef facility. In addition, samples were taken at the construction site itself at pre-set stages of the erection process and placed in sampling boxes. Once the concrete had cured, core samples were taken (drilled) from the sampling boxes and subjected to testing at an accredited laboratory. Moreover, independent sampling was conducted by the CTU for cross-verification purposes.

A summary of the verification testing is presented below. For detailed results of the verification tests see D3.21 Final results of EPSP laboratory testing (Vašíček et al. 2016)

Slump/flow table test

The concrete samples from each of 6 concrete mixing transport trucks were tested at the time of truck arrival to the Josef URL. Settlement results varied between 180 - 260mm and flow values between 350 - 590mm. All the results were deemed acceptable and the concrete was subsequently used for plug construction purposes.

The installation of the outer plug took place on 19/20 June 2015 at which time concrete samples from each of 6 concrete mixing transport trucks were tested. Settlement results varied between 250 - 285mm and flow values between 540 - 600mm. All the results were deemed acceptable and the concrete was subsequently used for plug construction purposes.

Uniaxial strength of the samples

The requirements of the uniaxial strength of the inner plug were at least 30MPa with a recommendation of 40MPa. The average cylindrical value was determined at 50.7MPa and the minimum value revealed by testing 46.9MPa. Thus, all the samples fulfilled and exceeded the recommendation of 40MPa.

The requirements of the uniaxial strength of the outer plug were also at least 30MPa with a recommendation of 40MPa. The average cylindrical value was determined at 48.0MPa and the minimum value revealed by testing 45.8MPa. Thus, all the samples fulfilled and exceeded the recommendation of 40MPa.

Flexural strengths (first peak and ultimate)

Six beam samples were tested after 28 days of curing (10 December 2014) on samples taken during installation of inner plug (12/13 November 2014).

The requirement of the tender with regard to flexural strength (first peak – at crack creation) was a minimum of 3MPa with a recommendation of 5MPa. The average first peak value was determined at 5.7MPa and the minimum value from the test at 5.2MPa. Thus, all the samples exceeded the recommended 5MPa.

As with the inner plug, six samples were taken following the installation of the outer concrete plug (19 June 2015) and tested on 17 July 2015 (i.e. after 28 days).

The requirement of the tender with regard to flexural strength (first peak) was a minimum of 3MPa with a recommendation of 5MPa. The average first peak value was determined at 5.2MPa and the minimum value from the test at 4.5MPa. Thus, all the samples fulfilled the requirement of 3MPa and exceeded or approximated to the recommended 5MPa.

Hydraulic conductivity

Hydraulic conductivity tests on hardened shotconcrete samples were carried out at the Institute of Geology of the Czech Academy of Science. The results are taken from Petružálek & Nemejovský (2015).

Three samples taken during the installation of the inner concrete plug (12/13 November 2014) were tested on 29 December 2014.

Hydraulic conductivity (at 10°C) values were found to be in the range k_{10} = 3.6 – 7.5E-12m/s which indicated the same order of magnitude as the required and real values with regard to the bentonite pellet sealing section.

The rock surrounding the EPSP experiment was sealed using grouting to a distance of 5m from the original excavation and the resulting hydraulic conductivity of the rock mass was subsequently tested ($<10^{-10}$m/s). All the values with concern to the concrete plugs were found to be approximately one order of magnitude better, i.e. less permeable.

The requirement of the tender with concern to the concrete was $k = 10^{-8}$m/s and better; therefore, it could be concluded that the concrete exhibited the required behaviour.

pH leachate

The testing of pH leachates was performed at ÚJV Řež a. s. and commissioned by the subcontractor Metrostav a. s. Three samples taken during the installation of the inner concrete plug (12/13 November 2014) were tested on 29 December 2014.

The tender documentation set out the requirement with regard to the pH of concrete leachates of 11.7 and lower. The average values were 11.3 and maximum values 11.4; none of the tests exceeded the limit, thus the concrete fulfilled the given requirements.

6.2.9. Pressurisation tests and grouting

Inner plug

The inner plug was tested on 3 December. Water was injected into the pressurisation chamber and leakages were monitored. Contact grouting was employed (part of Task 1) based on the results of this test.

No grouting piping was installed prior to the erection of the inner plug. Therefore, grouting was performed by means of drilling boreholes into the contact zone followed by the injection of grout. The boreholes were then backfilled with WEBAC 1660 resin.

CarboPurWF and CarboPurWFA resin were used as the grout material. The success of the grouting process was tested using pressure testing techniques following each application of grouting material (using water and/or air).

Several grouting "campaigns" were performed until leakage was reduced (a certain amount of leakage was allowed to continue in order to facilitate the testing of the bentonite sealing).

Contact grouting was performed as part of Task 1 (see 5.3.4).

Outer plug

The experience gained from the erection of the inner plug resulted in the installation of grout piping in advance of outer plug erection in the contact zone of the outer plug. The outer plug was then grouted using this piping. Additional grouting was subsequently performed based on the results of the "pressure testing" (a side effect of bentonite sealing activation by means of water issuing from the filter structure) of the outer plug in places in which leaks were detected. Grouting was performed in a similar way as for the inner plug, i.e. by drilling grouting boreholes into the contact zone where deemed necessary.

The grouting materials consisted of PU Purinjekt and AP SIKA Injection 304.

6.3. **FILTER (INCLUDING THE SEPARATION WALLS)**

The gap between the second and third separation walls was used for the emplacement of the gravel filter, which was installed manually in a number of stages. Firstly, the lower parts of the walls (approximately one-third to half of the overall height) were erected and the gravel filter emplaced in the resulting gap. Subsequently, bentonite emplacement 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 emplaced. The final layers of the separation walls and gravel were emplaced immediately once the shot clay process was completed.

The filter was equipped with a bottom drain for water collection and pressurisation piping similar to the piping in the pressurisation chamber, thus allowing for the use of the filter as a secondary pressurisation chamber if necessary.

The bottom drain formed a part of the base of the separation walls, therefore it formed the first part of the filter structure to be erected. It was fitted with a stainless steel outlet tube at its lowest point leading through the outer plug and ending with an outlet valve. A water collection device can be fitted below the valve thus allowing for the measurement of outflow water if required.

Pressurisation tubing similar to the tubing in the pressurisation chamber was installed in advance prior to the erection of the filter. The piping, which is able to serve as pressurising media in/outlets is connected via boreholes to the technological niche. The piping consists of four welded stainless steel (DIN 1.4571) tubes of a diameter of 38mm. One end of each tube was fixed to the head of the piping leading to the technological niche. The other end was left open into the filter. Two of the pipes ended at the top of the chamber and two at the bottom (Figure 22). The tubes were fixed in place by clamps on stainless steel rods.

The instrumentation on the walls and in the filter lead from the cable head at the end of the bentonite sealing. The cable head was installed prior to the commencement of filter erection as part of the preparation of the instrumentation of the bentonite sealing section. The instrumentation was then gradually fixed to the separation walls and to the filter following the erection of the filter.

Figure 21 – Bottom drain of the filter (pressurisation tubes with temporary protection overlying the drain)

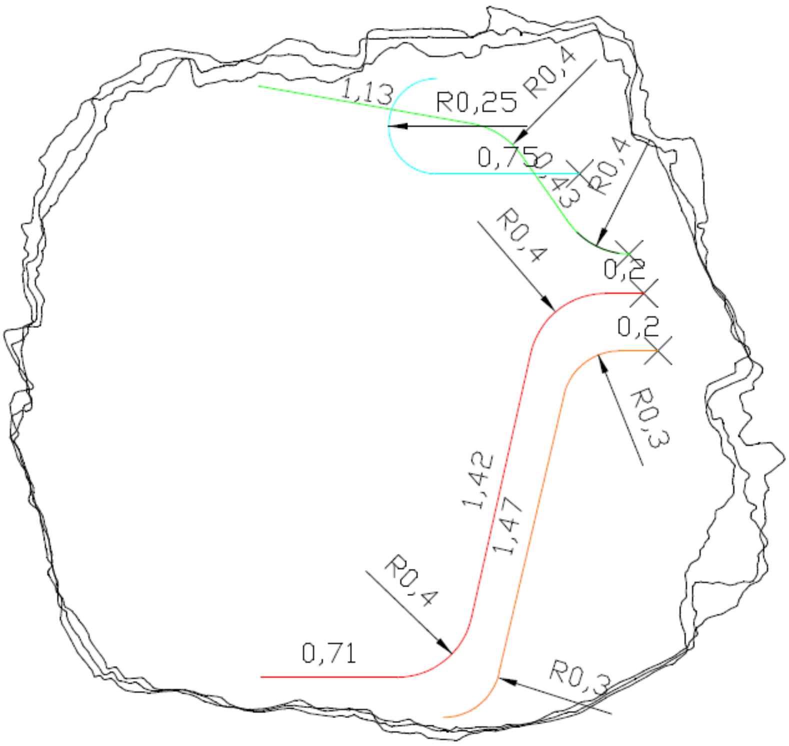


Figure 22 - Piping in the filter

Figure 23 - Lower part of separation wall erection with the installed pressurisation piping (5 December 2014)

Figure 24 - First part of the filter erected (photo taken at the time of the start of bentonite installation, 5 June 2015)

6.4. TECHNOLOGICAL EQUIPMENT

The technological support equipment is located in the SP-55 niche and consists of:

- Connecting piping heads
- The pressurisation system
- The technological equipment control system

The technological equipment allows the injection of water into either the pressurisation chamber or the filter or both. The installed pressurisation system is designed to work with water only; should testing with air and a bentonite suspension be required, additional equipment will have to be employed and will be brought on site only during such testing.

6.4.1. Technological setup

The technological setup of EPSP features the following main elements:

- Connecting borehole pipe heads
- Pressurisation system
  - Water reservoir
  - Low pressure unit
  - High pressure unit
- Control system

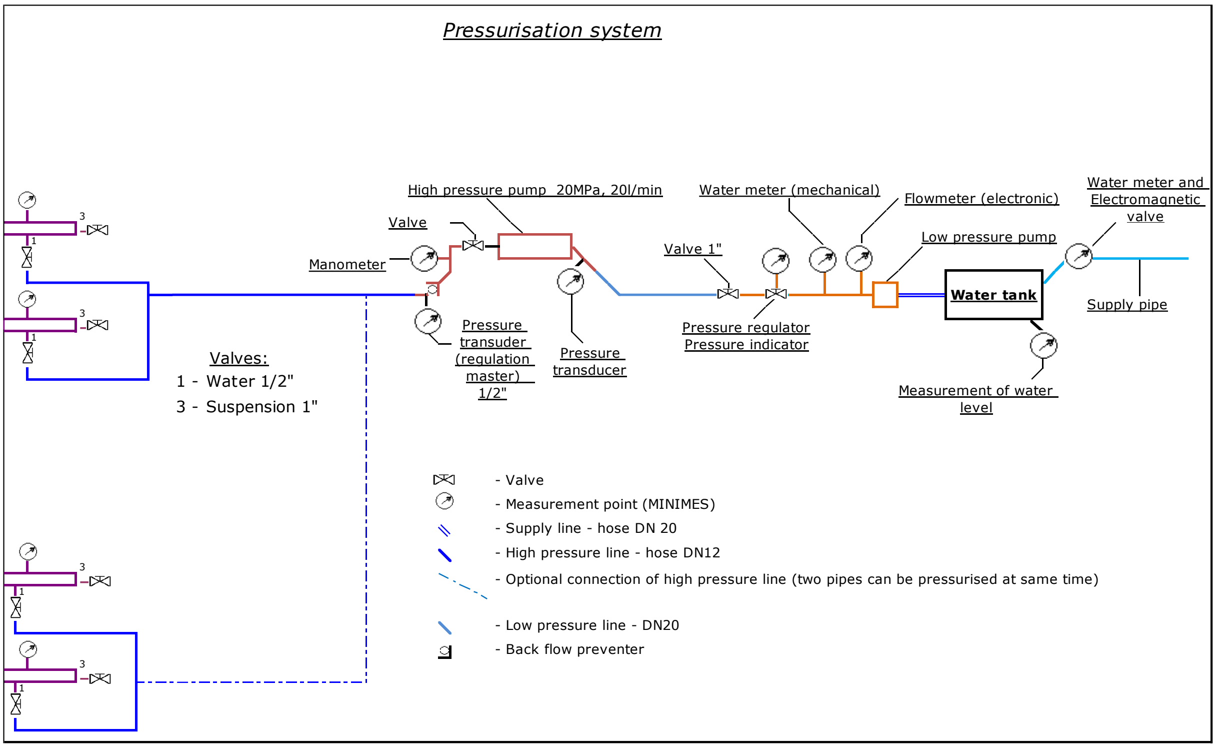


Figure 25 - Pressurisation system (technological setup)

The pipe heads are fixed to the connecting piping leading into the EPSP experiment (left side of Figure 25). 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.

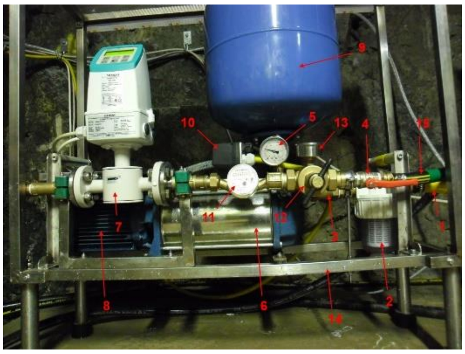


Figure 26 - Low pressure unit

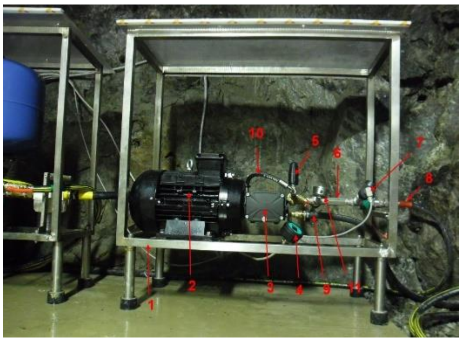


Figure 27 - High pressure unit

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.

6.4.2. Installation and testing

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.

The experimental programme commenced on 21 July 2015, after finishing the fieldwork

Figure 28 – Technological equipment installation in the niche (24 February 2015)

Figure 29 - Technological equipment installation in the niche (24 February 2015)

Figure 30 - Experimental programme commencement (21 July 2015)

Figure 31 - Experimental programme commencement (21 July 2015)

7. TASK 3 - BENTONITE EMPLACEMENT

Czech raw Bentonite 75 in powder form was selected as the material to be employed for compaction into pellet form (the powder material was marked as B75 2013). Laboratory geotechnical testing successfully demonstrated that B75 2013 could be used as the basic material for the bentonite pellet layer of the EPSP (Vašíček et al., 2016).

The bentonite B75 was used in the form of pellets. Two types of pellets were used. The first type (roller compacted - B75 PEL 12) was used in the lower parts of the experiment and the second type (roller compacted and subsequently crushed and sieved - B75 REC) was used for shot clay application in the upper parts of the experiment.

Based on project requirements for a minimum swelling pressure of 2MPa and a maximum hydraulic conductivity of $10^{-12}ms^{-1}$ with respect to the bentonite sealing, a minimum dry density of $1.4Mgm^{-3}$ was required following bentonite deposition.

The construction of the EPSP bentonite pellet layer was carried out in 9 days between 5 June and 15 June 2015. The total amount of emplaced material consisted of 39.9 tonnes emplaced in a volume of $23.7m^3$.

Two density verification methods were employed – sampling and total mass balance. Both methods revealed a dry density of more than the required level ($1.40Mg/m^3$).

The instrumentation was prepared in advance and sensors were gradually installed as bentonite emplacement progressed.

7.1. 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 0,8-5 mm (Vašíček et al., 2016) and consisted of material produced by the roller mill which was subsequently crushed and sieved into specific grain size fractions.

7.1.1. B75 PEL 12

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. A quality control audit subsequently revealed a good distribution of water content and dry density in the B75 PEL 12 (figure).

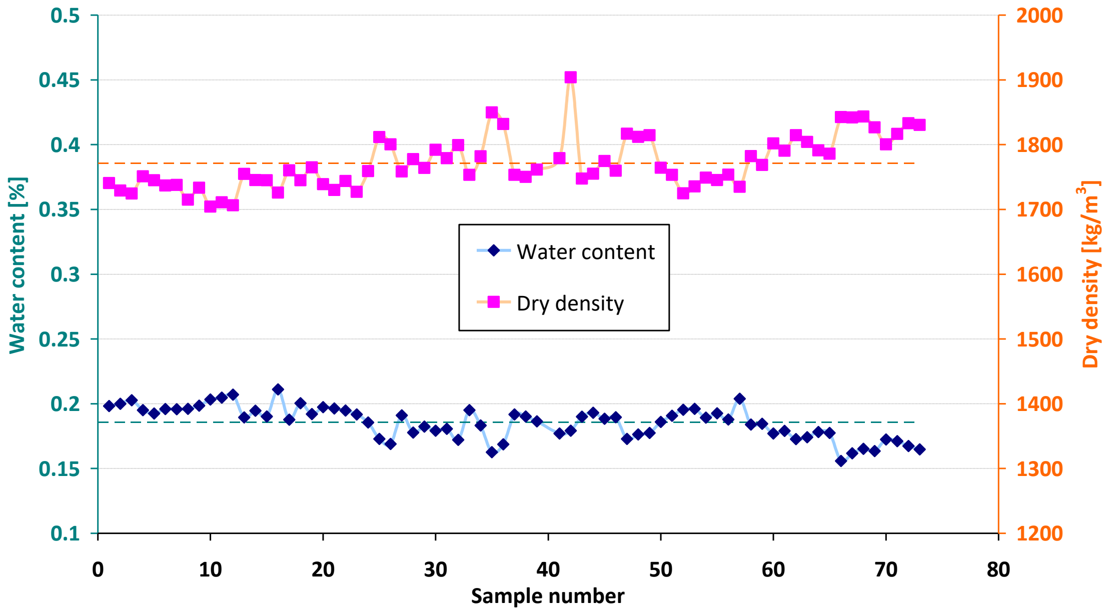


Figure 32 - Results of sampling during the production process

Figure 33 - Mixing machine for adjusting water content in the dry bentonite (from w=8% to approx. 19%)

Figure 34 - Roller compaction machine

Figure 35 - Transport of the pellets from the roller compaction machine

Figure 36 - First stage of packing

Figure 37 - Final product in bags

7.1.2. B75 REC 0,8-5

This material 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 38 - B75 REC

7.2. EMPLACEMENT USING VIBRATION COMPACTION

Based on pilot testing (Vašíček et al., 2016) which revealed a good pellet compaction level, two vibration-desk type machines were selected for the bulk work (NTC compaction plate, Masalta vibration plate). The bentonite was emplaced in horizontal layers with a maximum height of 3cm and subsequently vibration compacted.

Electric hammer drills (HILTI TE 3000-AVR and HILTI TE 1500-AVR) fitted with plates were used for compaction purposes around the measurement sensors, in the vicinity of the drift wall and in the upper part of the drift.

Figure 39 - Vibration compaction

Figure 40 - Emplaced pellets

7.3. 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 41 - Upper part of the drift – space to be filled by spraying

Figure 42 - Spraying of the bentonite

Figure 43 - Sprayed bentonite

Figure 44 - Spraying machine

7.4. SAMPLING AND QUALITY CONTROL

The quality control of the bentonite sealing was based on two main principles:

- Monitoring of the emplaced material
- Sampling

7.4.1. Monitoring of the emplaced material

The emplaced material was weighed and its water content checked during the emplacement process thus determining the total amount of emplaced material. Armed with a knowledge of the total volume of the sealing section (from laser scanning), average density and dry density values were calculated.

Table 3 – Progress of emplacement

Technology	Date	Level	Emplaced material		Average density	
			m^3	kg	ρ - kg/m^3	ρ_d - kg/m^3
vibration	05.06.2015 9:30	-1.5	0.97	1667	1719	1456
vibration	07.06.2015 10:40	-1.33	1.94	3433	1770	1500
vibration	07.06.2015 12:30	-1.22	2.61	4596	1761	1492
vibration	07.06.2015 18:44	-0.9	4.66	8321	1786	1513
vibration	08.06.2015 10:40	-0.81	5.27	9508	1804	1529
vibration	08.06.2015 23:51	-0.5	7.47	13200	1767	1498
vibration	09.06.2015 2:05	-0.32	8.82	15626	1772	1501
vibration	09.06.2015 21:05	0	11.29	19791	1753	1486
vibration	10.06.2015 12:40	15	12.48	21791	1746	1480
vibration	11.06.2015 16:58	0.45	14.98	26074	1741	1475
vibration	12.06.2015 2:45	slope	22.5	38833	1726	1463
shot clay	12.06.2015 15:00	slope	23.15	39100	1689	1431
shot clay	13.06.2015 15:00	slope	23.55	39700	1686	1429
shot clay	14.06.2015 12:00	slope	23.7	39900	1684	1427
Total			**23.7**	**39900**	**1684**	**1427**

7.4.2. Sampling

The sampling plan was prepared in advance and included the sampling both of the vibration compacted and shot clay parts.

With respect to the vibration compacted part, sampling was conducted using the cylinder penetration method according to the sampling plan; however, this method eventually proved to be unsuitable. The pellets tended both to block the advance of the cone into the layer and to disturb the sample. Moreover, it was very difficult to “cut” the tops and bottoms of the samples in order to obtain the required flat ends, which both reduced the precision of this method and increased the sampling time significantly. Moreover, the emplaced material experienced more disturbance than expected. Therefore, cone sampling was restricted to just two layers – one in the bottom part and one in the middle part of the experiment.

With respect to the shot clay part, pieces were manually cut out of the emplaced material and their density was estimated using the weighing under water method (the paraffin method).

Table 4 – Sampling using the cone method

	Mass water content	Dry density ρ_d - kg/m^3
Bottom profile	18.7%	1399
	17.8%	1416
	17.6%	1205
	17.6%	1346
Middle profile	17.2%	1518
	16.6%	1517
	18.4%	1471
	19.0%	1346

Figure 45 – Sampling

Figure 46 - Sampling

7.5. INSTRUMENTATION

The instrumentation installation sequence followed a previously determined pattern.

The instrumentation was pre-assembled at the Josef surface facility and an assembly of sensors attached to the cable head, which was prepared in advance, was then transferred to the underground complex.

The first stage of the process involved the positioning of the cable head in front of the corresponding borehole head.

The second stage consisted of the bundling of the cables into a single assembly and pulling them through the borehole. Once the cabling was through, work started connecting the cables to the data loggers.

The third step involved matching the cable head plate with the borehole head and final fixing.

The fourth step involved fixing the sensors with the respective cabling contained in protective tubing either to the rock/separation walls or temporarily to the side or ceiling of the plug space.

This sequence was used for both the sensor assemblies in the sealing section.

Those sensors that were fixed temporarily were installed later during the bentonite emplacement stage.

Figure 47 - RH sensor installation (7 June 2015)

Figure 48 - Pressure cell (8 June 2015)

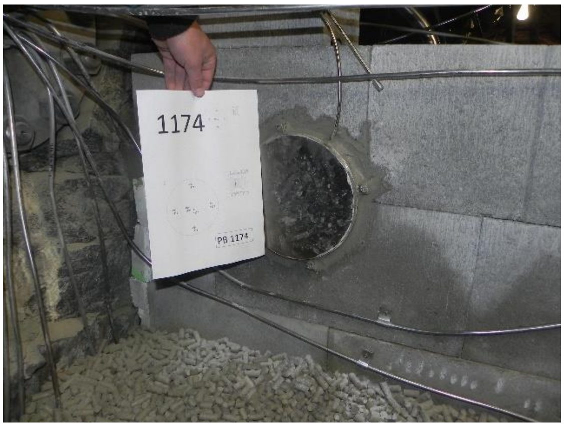


Figure 49 - Pressure cell fixed to the separation wall (9 June 2015)

Initially the bentonite sealing was compacted above the level intended for the sensors and subsequently a pocket was excavated for sensor emplacement. The sensor was then installed and covered with a fine or coarse (depending on the type of sensor) layer of crushed pellets removed during the excavation of the pocket; the filling material was carefully hand compacted. Thus, the sensors were protected and machine compaction could be used for the next layer.

8. TASK 4 - MONITORING INSTALLATION

The primary aim of the monitoring of EPSP is to investigate the various processes under way 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 the sensors specially selected in order to capture the various processes. The monitoring of EPSP focuses on water movement inside the experiment and the response of the experiment to pressurisation.

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

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

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

Several measures were taken in order to ensure the provision of reliable data such as cross-validation (sensors working on different principles are used to measure similar phenomena) and redundancy. Only pretested/calibrated/verified sensors were used in the experiment.

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

For details of the monitoring plan see D3.18 Testing plan for EPSP instrumentation (Svoboda et al., 2014)

Monitoring equipment installation can be divided into three main parts:

- Sensor preparation
- Installation of the sensors
- System setup and integration

8.1. PROFILES AND COORDINATE SYSTEM

8.1.1. Profiles

The instrumentation is organised in a number of vertical profiles termed A – G (Figure 50). All the profiles are located in key parts of the experiment.

An overall description of the instrumentation installed in each profile is presented later in this chapter.

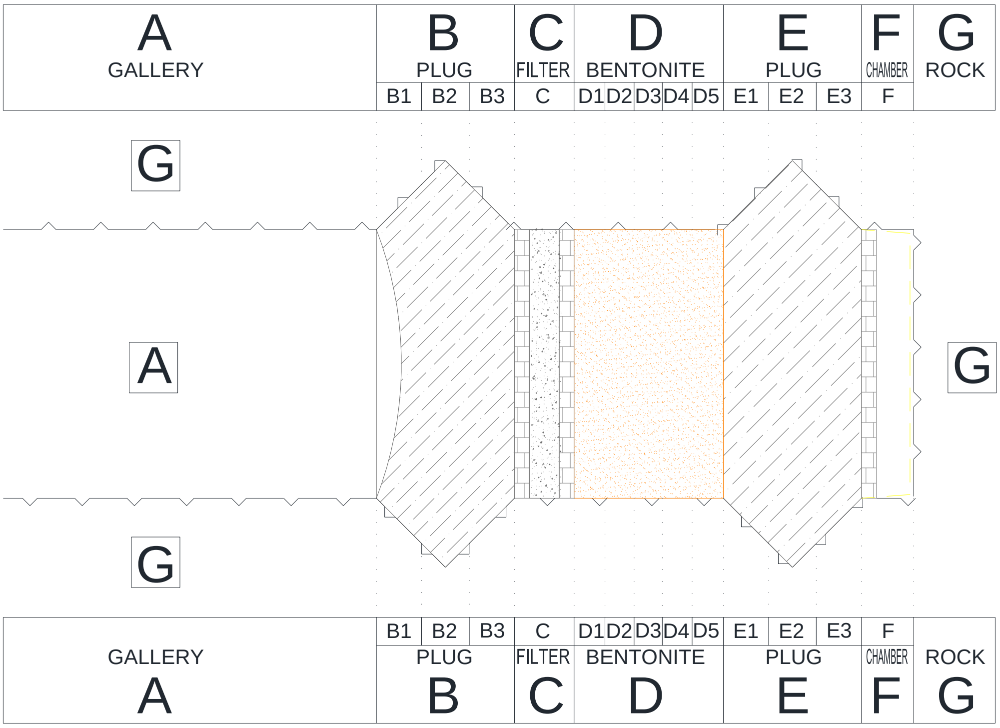


Figure 50 - profiles (A – gallery, B – outer shotcrete plug, C – filter, D – bentonite, E – inner shotcrete plug, F – pressure chamber, G – rock, H – technological equipment)

8.1.2. EPSP coordinate system

The EPSP experiment uses principally a local positive (right-handed) Cartesian coordinate system with a supplemental cylindrical system.

Cartesian system:

- The X axis is the longitudinal axis of symmetry of the experiment.
- The Y axis is horizontal
- The Z axis is vertical

Cylindrical system:

- The X axis is shared with the Cartesian system
- The angle (alpha) is clockwise with 0 going up
- The radius is measured from the X axis

The “0” is for both systems at the rock face.

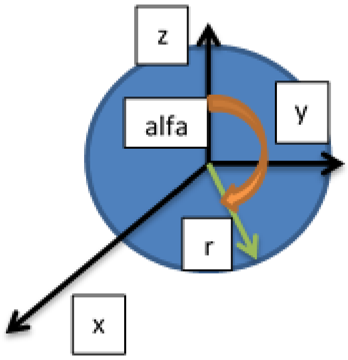


Figure 51 - Coordinate system

8.2. 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.

8.2.1. Sensors

<u>Standalone thermometers</u>

Standalone thermometers (both digital DS18B20 and analogue LM35DZ) were acquired in a standard TO 90/92 package – i.e. the bare component with no protection (Figure 52).

The thermometers were connected to the cabling and subsequently the stainless steel protective cap was fitted. The sensors were fixed in the cap using resin (DENTACRYL). The cap was equipped with a cutting ring fitting for the connection of the protective stainless steel tube (Figure 52 - Temperature sensors (analogue and digital)). Generally, both an analogue and digital sensor were installed into the same cap in case of the malfunctioning of one of the sensors (redundancy).

Intermediate digital sensors were installed on the cabling of a number of the probes following the shared bus principle according to which a number of sensors coexist on the same cable. These intermediate sensors were installed in a similar way to that of the end sensors except that the protective caps were fitted with cutting ring fittings on both sides so as to allow the connection of the protective tubing in two directions.

The digital sensors (DS18B20) were factory calibrated and their calibration was verified by means of a dry run of the measurement system in the laboratory. The analogue sensors (LM35DZ) were calibrated by the CTU.

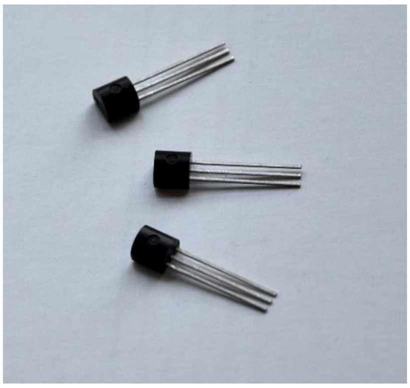


Figure 52 - Temperature sensors (analogue and digital)

Figure 53 - Temperature probe

<u>TDR water content sensors</u>

TDR-type water content sensors (5TE) manufactured by DECAGON were acquired in the form of a fully-sealed package including the cabling. The sensors were, however, equipped with protective tubing in the Josef workshop consisting of a number of parts, including HDPE plastic tubing serving for the mechanical protection of the cable while allowing a certain degree of flexibility and, subsequently, a cable gland for sealing the entry of the cable within the stainless steel protective tubing assembly. The complete assembly consisted of the cable gland, a cutting ring fitting and protective stainless steel tubing.

The TDR sensors were factory calibrated. The correlation between permittivity measured by means of the sensors and water content was measured by the CTU for B75 bentonite as part of the laboratory experimental programme.

Figure 54 – TDR water content probe

Relative humidity sensors

EE071 sensors manufactured by E+E elektronik were chosen for the measurement of relative humidity. These sensors were supplied in the form of a stainless steel body with a protective permeable cap. The sensors were fitted with an M12 O ring sealed connector on the body by the manufacturer.

The sensor cabling fitted with protective tubing, manufactured by the Josef workshop, consists of an M12 sealed connector, fittings with a cutting ring and protective stainless steel tubing.

The advantage of the M12 connector consisted of the ability to first position the cabling and subsequently install the sensors themselves which considerably reduced the potential for sensor damage during the erection of the experiment (only the cabling was in place most of the time).

The sensors were factory calibrated.

Figure 55 – Relative humidity probe

Pressure cells

4810X-10MPa vibrating wire pressure cells manufactured by GeoKon were chosen for the measurement of absolute pressure and contact pressure between the rock mass and the plug (http://www.geokon.com/fat-back-pressure); the experiment uses a special version of the cell featuring protective tubing attached by the manufacturer. No adjustments to the cells were made on site.

The sensors were factory calibrated.

Figure 56 - Pressure cell

Pore pressure

It was decided that pore pressure would be measured using 4500SHX-10MPa vibrating wire piezometers manufactured by GeoKon (http://www.geokon.com/standard-piezometers); the experiment uses a special version of the sensor featuring protective tubing attached by the manufacturer. No adjustments were made on site.

The sensors were factory calibrated.

Figure 57 - Piezometer (VW)

Strain gauges

Deformation within the concrete plugs is measured using 4200A-2 vibrating wire strain gauges manufactured by GeoKon (http://www.geokon.com/4200-Series) which were acquired in the form of a fully-sealed package including the cabling. The sensors were, however, equipped with protective tubing in the Josef workshop consisting of a number of parts, including HDPE plastic tubing serving for the mechanical protection of the cable while allowing a certain degree of flexibility and, subsequently, a cable gland for sealing the entry of the cable within the stainless steel protective tubing assembly. The complete assembly consisted of the cable gland, a cutting ring fitting and protective stainless steel tubing.

The sensors were factory calibrated.

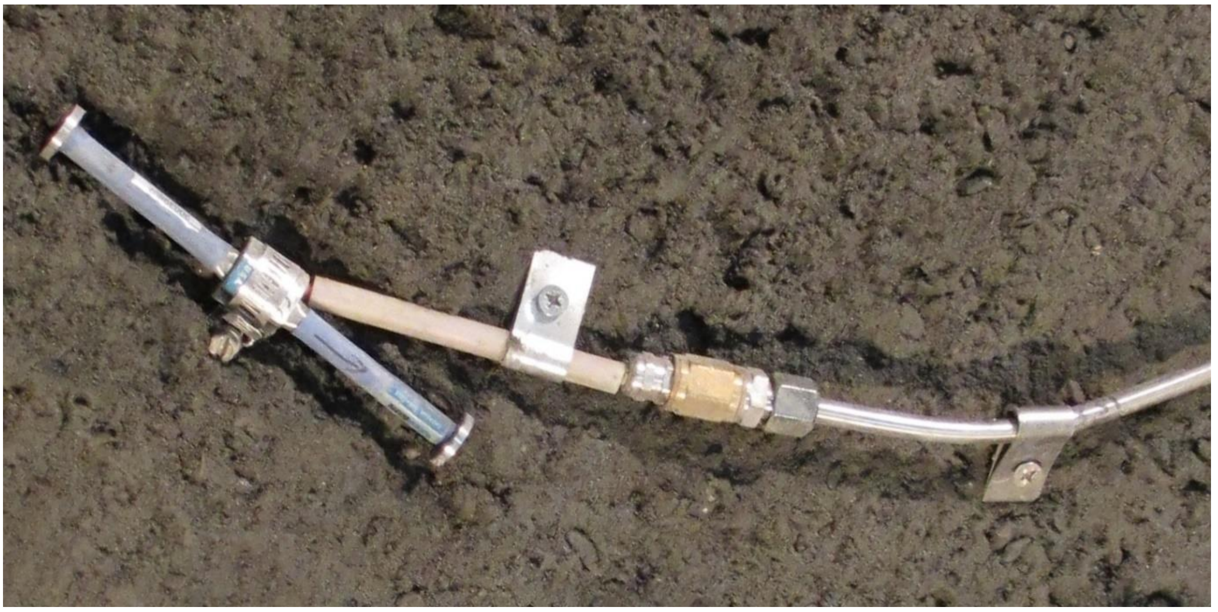


Figure 58 - Strain gauge

Rock bolts

The aim of the instrumented rock bolts is to monitor the response of the surrounding rock mass. The rock bolts have been fitted with GeoKon 4911-4X vibrating wire strain sensors (http://www.geokon.com/4911-4911A) which were equipped in-situ with protective tubing.

The sensors were factory calibrated.

Note: the rock bolts were installed by ARCADIS as part of Task 1 subcontractor work.

Figure 59 - Rock bolt assembly prior to installation

8.2.2. Cable protection

Cable protection is based on the use of stainless steel (1.4751) tubing with an external diameter of 8mm and a wall thickness of 1mm. The tubes are connected to housings or the cable head plate via cutting ring fittings.

The type of tubing was selected based on the following criteria:

- high mechanical protection
- high pressure protection
- corrosion resistance
- easy manipulation (shape change by hand possible)
- enough internal space for the cable.

8.2.3. Sensor assembly

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.

Figure 60 - Sensor assembly preparation

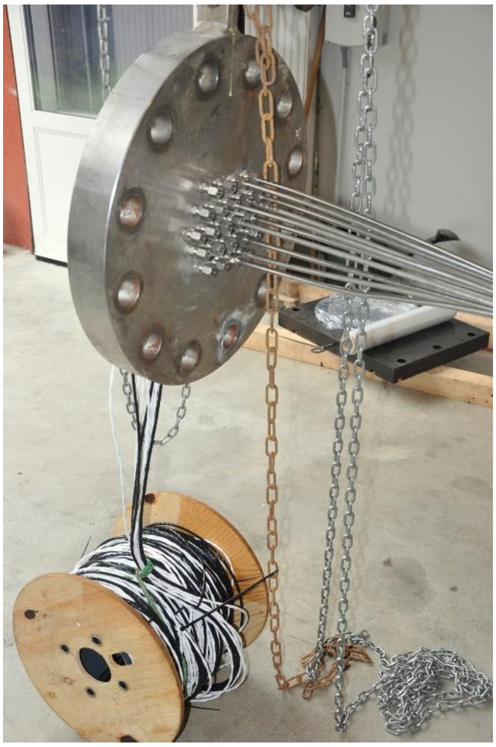


Figure 61 - Sensor assembly

8.2.4. Documentation

Each sensor had its own "passport" which was partly pre-filled according to the plan in D3.18 and which was updated during the probe production process.

The sensor manufacturing passport keeps track of:

- Sensor ID
- Sensor type
- Sensor serial number
- Cable length
- Protective tube length
- Production date
- Data logger to which it is connected

- Input of the data logger to which it will be connected
- Photo documentation (reference)
- Calibration (optional)

Those sensors which required (re)calibration were assigned a calibration protocol which was attached to the passport.

Formulář ČIDLA - výroba

ČIDLO

Číslo čidla		Profil Typ Číslo ID/typ	Číslo čidla dle číslování EPSP
Typ čidla			Např.: teploměr analogový, vlhkoměr RH/ABS, strunový tenzometr, …
Výrobní číslo čidla			Výrobní (sériové) číslo/adresa nebo jiná **jednoznačná** identifikace od výrobce.
Datum a čas výroby			podpis
Parametry	Délka kabelu		[m]
	Délka trubičky		[m]
Navazuje na čidlo		Profil Typ Číslo ID/typ	Číslo čidla dle číslování EPSP
Datum a čas zalití			podpis
Fotografie	první		Číslo (název) první fotografie ve fotoaparátu
	poslední		Číslo (název) poslední fotografie ve fotoaparátu
Ústředna	Číslo ústředny IP adresa ústředny	192.168.168.__________	Vyplnit jak číslo ústředny, tak IP adresu
	Kanál a vstup na ústředně		
Poznámka:			
Postup:	1. Vyplnit výrobní číslo, číslo čidla, typ čidla, datum výroby, podpis 2. Připravit čidlo (vyrobit) a otestovat (připojit na ústřednu) 3. Doplnit číslo ústředny a vstup, kam je čidlo připojeno (+popsat kabel) 4. Vyfotit čidlo + zapsat číslo první/poslední fotografie 5. Zalít čidlo, vyplnit datum a čas, podpis 6. Instalovat šroubení a trubičku (nutno těsnit závit!), zkontrolovat těsnost 7. Připojit zpět na ústřednu (a zkontrolovat funkčnost) **Všechny fotografie musí obsahovat číselník s číslem čidla!**		

ČVUT FSV – CEG, Thákurova 7, 166 29 Praha 6,

Figure 62 - Sensor manufacturing passport

8.3. INSTALLATION OF THE SENSORS IN-SITU

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.

8.3.1. Instrumented rock bolts (profile G)

The instrumented rock bolts were installed as part of Task 1 work (see chapter 5.4). 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.

Table 5 - Instrumented rock bolts

no.	description	x	y	z	r	alfa
159.10	Rock bolt - strain gauge (VW)	-0,87	-0,09	0,04	0,10	-66
159.20	Rock bolt - strain gauge (VW)	-0,89	-0,10	1,39	1,39	-4
159.30	Rock bolt - strain gauge (VW)	-0,82	1,03	-1,03	1,46	135
159.40	Rock bolt - strain gauge (VW)	-0,56	-1,16	-0,64	1,33	-119
159.50	Rock bolt - strain gauge (VW)	-2,37	-0,09	0,04	0,10	-66
159.60	Rock bolt - strain gauge (VW)	-2,19	-0,07	2,14	2,14	-2
159.70	Rock bolt - strain gauge (VW)	-2,12	1,56	-1,56	2,21	135
159.80	Rock bolt - strain gauge (VW)	-1,86	-1,69	-1,18	2,06	-125
159.90	Rock bolt - strain gauge (VW)	-4,62	-0,09	0,04	0,10	-66
160.00	Rock bolt - strain gauge (VW)	-4,14	-0,11	3,26	3,27	-2
160.10	Rock bolt - strain gauge (VW)	-4,06	2,36	-2,36	3,34	135
160.20	Rock bolt - strain gauge (VW)	-3,81	-2,47	-2,00	3,17	-129
459.20	Rock bolt - strain gauge (VW)	2,61	1,97	-1,97	2,79	135
459.30	Rock bolt - strain gauge (VW)	2,61	-1,97	-1,97	2,79	-135
459.40	Rock bolt - strain gauge (VW)	2,61	-1,97	1,97	2,79	-45
459.50	Rock bolt - strain gauge (VW)	3,67	2,72	2,72	3,85	45
459.60	Rock bolt - strain gauge (VW)	3,67	2,72	-2,72	3,85	135
459.70	Rock bolt - strain gauge (VW)	3,67	-2,72	-2,72	3,85	-135
459.80	Rock bolt - strain gauge (VW)	3,67	-2,72	2,72	3,85	-45
459.90	Rock bolt - strain gauge (VW)	5,25	3,84	3,84	5,43	45
460.00	Rock bolt - strain gauge (VW)	5,25	3,84	-3,84	5,43	135
460.10	Rock bolt - strain gauge (VW)	5,25	-3,84	-3,84	5,43	-135
460.20	Rock bolt - strain gauge (VW)	5,25	-3,84	3,84	5,43	-45
1459.10	Rock bolt - strain gauge (VW)	6,90	1,97	1,97	2,79	45
1459.20	Rock bolt - strain gauge (VW)	6,90	1,97	-1,97	2,79	135
1459.30	Rock bolt - strain gauge (VW)	6,90	-1,97	-1,97	2,79	-135
1459.40	Rock bolt - strain gauge (VW)	6,90	-1,97	1,97	2,79	-45
1459.50	Rock bolt - strain gauge (VW)	7,96	2,72	2,72	3,85	45
1459.60	Rock bolt - strain gauge (VW)	7,96	2,72	-2,72	3,85	135
1459.70	Rock bolt - strain gauge (VW)	7,96	-2,72	-2,72	3,85	-135
1459.80	Rock bolt - strain gauge (VW)	7,96	-2,72	2,72	3,85	-45

8.3.2. Pressurisation chamber and separation wall (profile F)

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 in October 2014. 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).

Table 6 - Sensors in profile F

no.	description	x	y	z	r	alfa
111.01	Analogue thermometer	0.52	-0.03	1.62	1.62	-1
111.11	Digital thermometer	0.52	-0.03	1.62	1.62	-1
113.01	Analogue thermometer	0.05	0.00	-0.08	0.08	177
113.11	Digital thermometer	0.05	0.00	-0.08	0.08	177
114.01	Analogue thermometer	0.51	0.00	-1.15	1.15	180
114.11	Digital thermometer	0.51	0.00	-1.15	1.15	180
191.91	Piezometer (VW)	0.49	0.38	1.43	1.48	15
192.55	Temperature sensor of piezometer	0.50	-0.02	-0.12	0.12	-172
192.91	Piezometer (VW)	0.50	-0.02	-0.12	0.12	-172
193.55	Temperature sensor of piezometer	0.38	0.21	-0.92	0.94	167
193.91	Piezometer (VW)	0.38	0.21	-0.92	0.94	167

Table 7 - Sensors in profile F/E

no.	description	x	y	z	r	alfa
271.55	Temperature sensor of pressure cell	0.74	-0.06	1.58	1.58	-2
271.71	Pressure cell (VW)	0.74	-0.06	1.58	1.58	-2
272.55	Temperature sensor of pressure cell	0.73	-0.01	-0.00	0.01	-101
272.71	Pressure cell (VW)	0.73	-0.01	-0.00	0.01	-101
273.55	Temperature sensor of pressure cell	0.62	0.00	-1.06	1.06	180
273.71	Pressure cell (VW)	0.62	0.00	-1.06	1.06	180

Figure 63 - Piezometer installation in the pressurisation chamber

8.3.3. 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.

Figure 64 - Pressure cell on the rock face; cabling in protective tubing on “ladders”, thermometer

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.

Figure 65 - Sensors temporarily stored on the side of the niche

Table 8 - - Sensors in profile E2

no.	description	x	y	z	r	alfa
311.01	Analogue thermometer	1.35	0.28	1.75	1.77	9
311.11	Digital thermometer	1.35	0.28	1.75	1.77	9
311.12	Digital thermometer	1.74	0.38	2.40	2.42	9
312.01	Analogue thermometer	1.30	0.17	0.85	0.87	11
312.11	Digital thermometer	1.30	0.17	0.85	0.87	11
312.12	Digital thermometer	1.44	0.63	-0.11	0.64	100
313.01	Analogue thermometer	1.43	-0.84	0.03	0.84	-88
313.11	Digital thermometer	1.43	-0.84	0.03	0.84	-88
313.12	Digital thermometer	1.54	0.05	-0.76	0.76	176
314.01	Analogue thermometer	1.51	0.10	-1.47	1.47	176
314.11	Digital thermometer	1.51	0.10	-1.47	1.47	176
314.12	Digital thermometer	1.55	0.28	-2.25	2.26	173
315.01	Analogue thermometer	1.45	-2.38	0.64	2.47	-75
315.11	Digital thermometer	1.45	-2.38	0.64	2.47	-75
315.12	Digital thermometer	1.10	-1.78	0.38	1.82	-78
316.01	Analogue thermometer	1.45	0.20	0.07	0.21	69
316.11	Digital thermometer	1.45	0.20	0.07	0.21	69
316.12	Digital thermometer	1.57	1.38	0.05	1.38	88
316.13	Digital thermometer	1.54	1.75	0.12	1.76	86

Table 9 - - Sensors in profile E1

no.	description	x	y	z	r	alfa
451.50	Horizontal strain gauge (VW)	1.98	-0.24	1.52	1.54	-9
451.51	Vertical strain gauge (VW)	2.02	-0.06	1.72	1.72	-2
451.55	Temperature sensor of strain gauge	1.98	-0.24	1.52	1.54	-9
451.56	Temperature sensor of strain gauge	2.02	-0.06	1.72	1.72	-2
452.50	Horizontal strain gauge (VW)	2.14	-1.69	0.12	1.70	-86
452.51	Vertical strain gauge (VW)	2.16	-1.69	-0.03	1.69	-91
452.55	Temperature sensor of strain gauge	2.14	-1.69	0.12	1.70	-86
452.56	Temperature sensor of strain gauge	2.16	-1.69	-0.03	1.69	-91
453.50	Horizontal strain gauge (VW)	1.92	-0.17	0.14	0.23	-50
453.51	Vertical strain gauge (VW)	1.96	-0.17	-0.06	0.18	-108
453.55	Temperature sensor of strain gauge	1.92	-0.17	0.14	0.23	-50
453.56	Temperature sensor of strain gauge	1.96	-0.17	-0.06	0.18	-108
454.50	Horizontal strain gauge (VW)	1.95	1.31	-0.18	1.32	98
454.51	Vertical strain gauge (VW)	2.02	1.64	-0.29	1.67	100
454.55	Temperature sensor of strain gauge	1.95	1.31	-0.18	1.32	98
454.56	Temperature sensor of strain gauge	2.02	1.64	-0.29	1.67	100
455.50	Horizontal strain gauge (VW)	2.06	0.03	-1.42	1.42	179
455.51	Vertical strain gauge (VW)	2.10	-0.19	-1.52	1.53	-173
455.55	Temperature sensor of strain gauge	2.06	0.03	-1.42	1.42	179
455.56	Temperature sensor of strain gauge	2.10	-0.19	-1.52	1.53	-173

Table 10 - Pressure cells

no.	description	x	y	z	r	alfa
471.55	Temperature sensor of pressure cell	2.03	-0.26	2.43	2.44	-6
471.71	Pressure cell (VW)	2.03	-0.26	2.43	2.44	-6
472.55	Temperature sensor of pressure cell	2.13	-0.96	-2.05	2.26	-155
472.71	Pressure cell (VW)	2.13	-0.96	-2.05	2.26	-155
473.55	Temperature sensor of pressure cell	2.22	1.83	1.43	2.32	52
473.71	Pressure cell (VW)	2.22	1.83	1.43	2.32	52
474.55	Temperature sensor of pressure cell	2.18	1.21	-2.09	2.41	150
474.71	Pressure cell (VW)	2.18	1.21	-2.09	2.41	150

8.3.4. 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.

Figure 66 - Cable head assemblies installed, 1st part of the filter separation walls erected, pressurisation tubing into the filter installed (December 2014)

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.

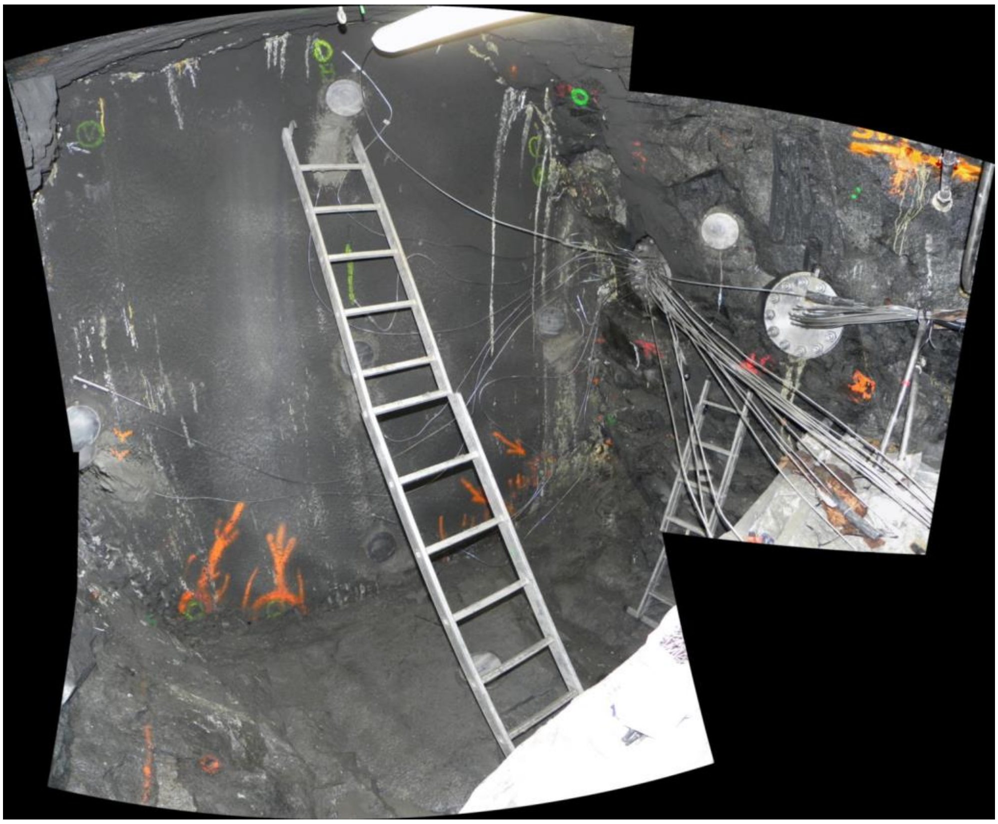


Figure 67 - Sensors on the rock and plug face prior to bentonite emplacement (June 2015)

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 (Figure 47).

Table 11 - Sensors in profile D1-D5

no.	description	x	y	z	r	alfa
501.10	Temperature sensor of TDR	2.46	-0.06	0.06	0.09	-45
501.11	Water Content (TDR)	2.46	-0.06	0.06	0.09	-45
501.12	Electric conductivity (TDR)	2.46	-0.06	0.06	0.09	-45
501.13	Dielectric permitivity (TDR)	2.46	-0.06	0.06	0.09	-45
571.55	Temperature sensor of pressure cell	2.35	0.00	1.58	1.58	0
571.71	Pressure cell (VW)	2.35	0.00	1.58	1.58	0
572.55	Temperature sensor of pressure cell	2.56	-1.58	-0.03	1.58	-91
572.71	Pressure cell (VW)	2.56	-1.58	-0.03	1.58	-91
573.55	Temperature sensor of pressure cell	2.32	0.01	0.00	0.01	80
573.71	Pressure cell (VW)	2.32	0.01	0.00	0.01	80
574.55	Temperature sensor of pressure cell	2.47	1.50	0.08	1.50	87
574.71	Pressure cell (VW)	2.47	1.50	0.08	1.50	87
575.71	Pressure cell (VW)	2.42	0.02	-1.29	1.29	179
591.55	Temperature sensor of piezometer	2.36	0.00	1.87	1.87	0
591.91	Piezometer (VW)	2.36	0.00	1.87	1.87	0
592.55	Temperature sensor of piezometer	2.42	-1.55	0.25	1.57	-81
592.91	Piezometer (VW)	2.42	-1.55	0.25	1.57	-81
593.55	Temperature sensor of piezometer	2.33	0.13	0.43	0.45	17
593.91	Piezometer (VW)	2.33	0.13	0.43	0.45	17
594.55	Temperature sensor of piezometer	2.50	1.75	0.28	1.77	81
594.91	Piezometer (VW)	2.50	1.75	0.28	1.77	81
595.55	Temperature sensor of piezometer	2.38	-0.02	-1.03	1.03	-179

595.91	Piezometer (VW)	2.38	-0.02	-1.03	1.03	-179
601.10	Temperature sensor of TDR	2.73	-0.05	1.54	1.54	-2
601.11	Water Content (TDR)	2.73	-0.05	1.54	1.54	-2
601.12	Electric conductivity (TDR)	2.73	-0.05	1.54	1.54	-2
601.13	Dielectric permitivity (TDR)	2.73	-0.05	1.54	1.54	-2
602.10	Temperature sensor of TDR	2.56	0.64	-1.58	1.70	158
602.11	Water Content (TDR)	2.56	0.64	-1.58	1.70	158
602.12	Electric conductivity (TDR)	2.56	0.64	-1.58	1.70	158
602.13	Dielectric permitivity (TDR)	2.56	0.64	-1.58	1.70	158
603.10	Temperature sensor of humidity sensor	2.69	-0.04	1.00	1.00	-2
603.11	Relative humidity sensor	2.69	-0.04	1.00	1.00	-2
603.12	Abs. humidity of air from relative humidity sensor	2.69	-0.04	1.00	1.00	-2
604.10	Temperature sensor of humidity sensor	2.86	-0.05	0.06	0.07	-40
604.11	Relative humidity sensor	2.86	-0.05	0.06	0.07	-40
604.12	Abs. humidity of air from relative humidity sensor	2.86	-0.05	0.06	0.07	-40
605.10	Temperature sensor of humidity sensor	2.90	0.06	-1.13	1.13	177
605.11	Relative humidity sensor	2.90	0.06	-1.13	1.13	177
605.12	Abs. humidity of air from relative humidity sensor	2.90	0.06	-1.13	1.13	177
791.55	Temperature sensor of piezometer	3.41	0.65	1.89	2.00	19
791.91	Piezometer (VW)	3.41	0.65	1.89	2.00	19
792.55	Temperature sensor of piezometer	3.30	-1.75	0.15	1.75	-85
792.91	Piezometer (VW)	3.30	-1.75	0.15	1.75	-85
793.55	Temperature sensor of piezometer	3.10	-0.09	0.10	0.13	-42
793.91	Piezometer (VW)	3.10	-0.09	0.10	0.13	-42
794.55	Temperature sensor of piezometer	3.54	1.62	0.79	1.80	64
794.91	Piezometer (VW)	3.54	1.62	0.79	1.80	64
795.55	Temperature sensor of piezometer	3.25	0.40	-1.49	1.54	165
795.91	Piezometer (VW)	3.25	0.40	-1.49	1.54	165
801.10	Temperature sensor of TDR	3.19	-0.29	0.09	0.30	-73
801.11	Water Content (TDR)	3.19	-0.29	0.09	0.30	-73
801.12	Electric conductivity (TDR)	3.19	-0.29	0.09	0.30	-73
801.13	Dielectric permitivity (TDR)	3.19	-0.29	0.09	0.30	-73
871.55	Temperature sensor of pressure cell	3.59	0.03	1.68	1.68	1
871.71	Pressure cell (VW)	3.59	0.03	1.68	1.68	1
872.55	Temperature sensor of pressure cell	3.30	-0.03	0.73	0.73	-2
872.71	Pressure cell (VW)	3.30	-0.03	0.73	0.73	-2
873.55	Temperature sensor of pressure cell	3.21	-0.33	0.16	0.37	-64
873.71	Pressure cell (VW)	3.21	-0.33	0.16	0.37	-64
874.55	Temperature sensor of pressure cell	3.44	0.01	-0.79	0.79	179
874.71	Pressure cell (VW)	3.44	0.01	-0.79	0.79	179
875.55	Temperature sensor of pressure cell	3.45	0.03	-1.59	1.59	179
875.71	Pressure cell (VW)	3.45	0.03	-1.59	1.59	179
876.55	Temperature sensor of pressure cell	3.52	-1.63	0.03	1.63	-89
876.71	Pressure cell (VW)	3.52	-1.63	0.03	1.63	-89
877.55	Temperature sensor of pressure cell	3.46	-0.86	0.06	0.86	-86
877.71	Pressure cell (VW)	3.46	-0.86	0.06	0.86	-86
878.55	Temperature sensor of pressure cell	3.37	1.08	0.04	1.08	88
878.71	Pressure cell (VW)	3.37	1.08	0.04	1.08	88
879.55	Temperature sensor of pressure cell	3.73	1.65	0.84	1.85	63
879.71	Pressure cell (VW)	3.73	1.65	0.84	1.85	63
901.10	Temperature sensor of TDR	4.05	-0.22	1.14	1.16	-11
901.11	Water Content (TDR)	4.05	-0.22	1.14	1.16	-11
901.12	Electric conductivity (TDR)	4.05	-0.22	1.14	1.16	-11
901.13	Dielectric permitivity (TDR)	4.05	-0.22	1.14	1.16	-11
902.10	Temperature sensor of TDR	4.01	-0.20	-1.60	1.62	-173
902.11	Water Content (TDR)	4.01	-0.20	-1.60	1.62	-173
902.12	Electric conductivity (TDR)	4.01	-0.20	-1.60	1.62	-173
902.13	Dielectric permitivity (TDR)	4.01	-0.20	-1.60	1.62	-173
903.10	Temperature sensor of humidity sensor	4.13	0.14	0.99	1.00	8

903.11	Relative humidity sensor	4.13	0.14	0.99	1.00	8
903.12	Abs. humidity of air from relative humidity sensor	4.13	0.14	0.99	1.00	8
904.10	Temperature sensor of humidity sensor	3.72	0.02	0.06	0.06	20
904.11	Relative humidity sensor	3.72	0.02	0.06	0.06	20
904.12	Abs. humidity of air from relative humidity sensor	3.72	0.02	0.06	0.06	20
905.10	Temperature sensor of humidity sensor	3.96	0.28	-1.15	1.18	166
905.11	Relative humidity sensor	3.96	0.28	-1.15	1.18	166
905.12	Abs. humidity of air from relative humidity sensor	3.96	0.28	-1.15	1.18	166
1091.55	Temperature sensor of piezometer	4.23	0.17	1.89	1.90	5
1091.91	Piezometer (VW)	4.23	0.17	1.89	1.90	5
1092.55	Temperature sensor of piezometer	4.18	-1.83	0.19	1.84	-84
1092.91	Piezometer (VW)	4.18	-1.83	0.19	1.84	-84
1093.55	Temperature sensor of piezometer	4.01	-0.02	0.06	0.06	-21
1093.91	Piezometer (VW)	4.01	-0.02	0.06	0.06	-21
1094.55	Temperature sensor of piezometer	4.33	1.76	0.82	1.94	65
1094.91	Piezometer (VW)	4.33	1.76	0.82	1.94	65
1095.55	Temperature sensor of piezometer	4.13	-0.14	-1.59	1.60	-175
1095.91	Piezometer (VW)	4.13	-0.14	-1.59	1.60	-175
1101.10	Temperature sensor of TDR	4.27	-0.00	0.10	0.10	-2
1101.11	Water Content (TDR)	4.27	-0.00	0.10	0.10	-2
1101.12	Electric conductivity (TDR)	4.27	-0.00	0.10	0.10	-2
1101.13	Dielectric permitivity (TDR)	4.27	-0.00	0.10	0.10	-2
1171.55	Temperature sensor of pressure cell	4.50	0.33	1.09	1.14	17
1171.71	Pressure cell (VW)	4.50	0.33	1.09	1.14	17
1172.55	Temperature sensor of pressure cell	4.53	-1.55	-0.19	1.56	-97
1172.71	Pressure cell (VW)	4.53	-1.55	-0.19	1.56	-97
1173.55	Temperature sensor of pressure cell	4.51	0.03	-0.01	0.03	103
1173.71	Pressure cell (VW)	4.51	0.03	-0.01	0.03	103
1174.55	Temperature sensor of pressure cell	4.48	1.45	0.03	1.45	89
1174.71	Pressure cell (VW)	4.48	1.45	0.03	1.45	89
1175.55	Temperature sensor of pressure cell	4.52	0.02	-1.36	1.36	179
1175.71	Pressure cell (VW)	4.52	0.02	-1.36	1.36	179

8.3.5. 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.

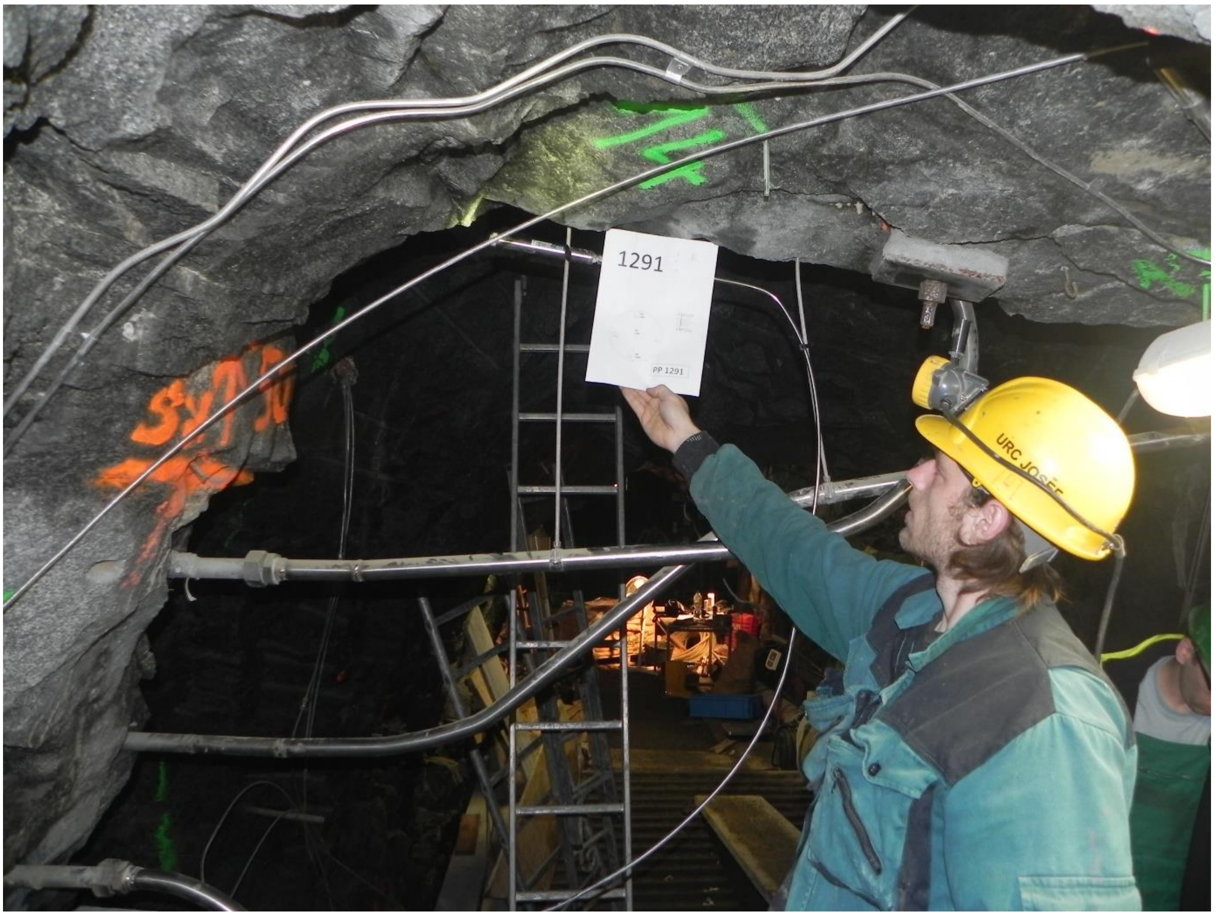


Figure 68 - Piezometer in the filter area

no.	description	x	y	z	r	alfa
1211.01	Analogue thermometer	5.01	0.06	1.72	1.72	2
1211.11	Digital thermometer	5.01	0.06	1.72	1.72	2
1212.01	Analogue thermometer	4.97	-1.86	-0.10	1.86	-93
1212.11	Digital thermometer	4.97	-1.86	-0.10	1.86	-93
1213.01	Analogue thermometer	4.96	1.56	0.25	1.58	81
1213.11	Digital thermometer	4.96	1.56	0.25	1.58	81
1214.01	Analogue thermometer	4.83	0.29	-1.52	1.54	169
1214.11	Digital thermometer	4.83	0.29	-1.52	1.54	169
1291.55	Temperature sensor of piezometer	4.96	0.96	1.81	2.05	28
1291.91	Piezometer (VW)	4.96	0.96	1.81	2.05	28
1292.55	Temperature sensor of piezometer	5.04	0.44	-0.16	0.47	110
1292.91	Piezometer (VW)	5.04	0.44	-0.16	0.47	110
1293.55	Temperature sensor of piezometer	4.83	0.29	-1.49	1.52	169
1293.91	Piezometer (VW)	4.83	0.29	-1.49	1.52	169

8.3.6. 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.

Figure 69 - Installation of cable head assembly B (June 2015)

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.

Figure 70 - Temperature sensor installation (20 June 2015)

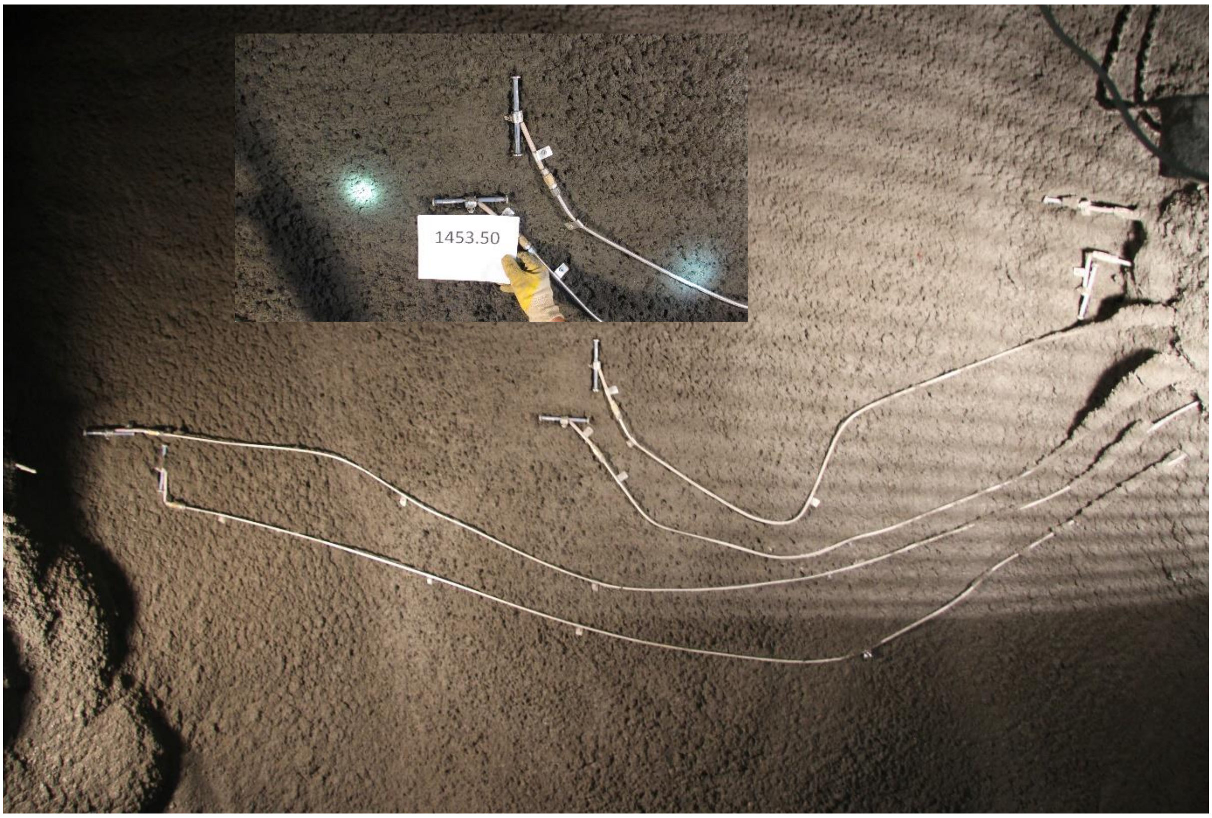


Figure 71 - Vibrating wire strain gauge installation

Table 12 - Temperature sensors in profile B2

no.	description	x	y	z	r	alfa
1311.01	Analogue thermometer	6.09	0.03	1.76	1.76	1
1311.11	Digital thermometer	6.09	0.03	1.76	1.76	1
1311.12	Digital thermometer	6.02	0.21	2.44	2.45	5
1312.01	Analogue thermometer	6.05	-0.07	0.81	0.82	-5
1312.11	Digital thermometer	6.05	-0.07	0.81	0.82	-5
1312.12	Digital thermometer	6.12	0.88	0.06	0.88	86
1313.01	Analogue thermometer	6.16	-0.78	-0.04	0.79	-93
1313.11	Digital thermometer	6.16	-0.78	-0.04	0.79	-93
1313.12	Digital thermometer	6.27	0.20	-0.80	0.82	166
1314.01	Analogue thermometer	6.26	0.22	-1.79	1.80	173
1314.11	Digital thermometer	6.26	0.22	-1.79	1.80	173
1314.12	Digital thermometer	6.22	0.39	-2.46	2.49	171
1315.01	Analogue thermometer	6.49	-2.25	0.04	2.25	-89
1315.11	Digital thermometer	6.49	-2.25	0.04	2.25	-89
1315.12	Digital thermometer	6.22	-1.47	0.03	1.47	-89
1316.01	Analogue thermometer	6.13	-0.12	0.03	0.12	-78
1316.11	Digital thermometer	6.13	-0.12	0.03	0.12	-78
1316.12	Digital thermometer	6.17	1.29	0.07	1.30	87
1316.13	Digital thermometer	6.37	1.99	0.28	2.01	82

Table 13 – VW sensors in profile B1

no.	description	x	y	z	r	alfa
1451.50	Horizontal strain gauge (VW)	6.78	0.03	1.60	1.60	1
1451.51	Vertical strain gauge (VW)	6.68	0.09	1.31	1.31	4
1451.55	Temperature sensor of strain gauge	6.78	0.03	1.60	1.60	1
1451.56	Temperature sensor of strain gauge	6.68	0.09	1.31	1.31	4
1452.50	Horizontal strain gauge (VW)	7.05	-1.63	-0.03	1.63	-91
1452.51	Vertical strain gauge (VW)	6.97	-1.50	-0.18	1.51	-97
1452.55	Temperature sensor of strain gauge	7.05	-1.63	-0.03	1.63	-91
1452.56	Temperature sensor of strain gauge	6.97	-1.50	-0.18	1.51	-97
1453.50	Horizontal strain gauge (VW)	6.68	-0.16	0.01	0.16	-85
1453.51	Vertical strain gauge (VW)	6.66	-0.06	0.18	0.19	-18
1453.55	Temperature sensor of strain gauge	6.68	-0.16	0.01	0.16	-85
1453.56	Temperature sensor of strain gauge	6.66	-0.06	0.18	0.19	-18
1454.50	Horizontal strain gauge (VW)	6.65	1.28	0.68	1.45	62
1454.51	Vertical strain gauge (VW)	6.70	1.32	0.46	1.40	71
1454.55	Temperature sensor of strain gauge	6.65	1.28	0.68	1.45	62
1454.56	Temperature sensor of strain gauge	6.70	1.32	0.46	1.40	71
1455.50	Horizontal strain gauge (VW)	7.14	-0.03	-1.53	1.53	-179
1455.51	Vertical strain gauge (VW)	7.14	0.19	-1.57	1.58	173
1455.55	Temperature sensor of strain gauge	7.14	-0.03	-1.53	1.53	-179
1455.56	Temperature sensor of strain gauge	7.14	0.19	-1.57	1.58	173

Table 14 - Pressure cells

no.	description	x	y	z	r	alfa
1471.55	Temperature sensor of pressure cell	6.67	-0.08	2.17	2.17	-2
1471.71	Pressure cell (VW)	6.67	-0.08	2.17	2.17	-2
1472.55	Temperature sensor of pressure cell	6.85	-1.22	-2.11	2.43	-150
1472.71	Pressure cell (VW)	6.85	-1.22	-2.11	2.43	-150
1473.55	Temperature sensor of pressure cell	6.86	1.99	1.24	2.34	58
1473.71	Pressure cell (VW)	6.86	1.99	1.24	2.34	58
1474.55	Temperature sensor of pressure cell	6.67	1.78	-2.12	2.77	140
1474.71	Pressure cell (VW)	6.67	1.78	-2.12	2.77	140

8.3.7. Technology

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 2014.

Table 15 – Technology – monitored parameters

no.	description	x	y	z	r	alfa
1502.12	Scales (water mass)	7.50	0.00	-1.80	1.80	180
1791.10	Thermometer of pressure transducer	0.50	25.00	0.00	25.00	90
1791.90	Pressure transducer	0.50	25.00	0.44	25.00	89
1792.10	Thermometer of pressure transducer	0.50	25.00	0.00	25.00	90
1792.90	Pressure transducer	0.50	25.00	0.00	25.00	90
1793.10	Thermometer of pressure transducer	0.50	25.00	0.00	25.00	90
1793.90	Pressure transducer	0.50	25.00	0.00	25.00	90
1794.10	Thermometer of pressure transducer	0.50	25.00	-0.44	25.00	91
1794.90	Pressure transducer	0.50	25.00	-0.44	25.00	91
1795.10	Thermometer of pressure transducer	4.95	25.00	0.00	25.00	90
1795.90	Pressure transducer	4.95	25.00	0.44	25.00	89
1796.10	Thermometer of pressure transducer	4.95	25.00	0.00	25.00	90
1796.90	Pressure transducer	4.95	25.00	0.00	25.00	90
1797.10	Thermometer of pressure transducer	4.95	25.00	0.00	25.00	90
1797.90	Pressure transducer	4.95	25.00	0.00	25.00	90
1798.10	Thermometer of pressure transducer	4.95	25.00	-0.44	25.00	91
1798.90	Pressure transducer	4.95	25.00	-0.44	25.00	91
1799.10	Thermometer in the rack	2.00	26.00	-0.45	26.00	91
1800.00	Water level in reservoir	7.50	25.00	0.00	25.00	90
1801.10	Total inflow into experiment	0.00	25.00	0.00	25.00	90
1801.20	Water inflow rate	0.00	25.00	-0.44	25.00	91
1802.90	Pressure from first stage supply pump	0.00	26.00	0.45	26.00	89
1803.14	Speed of high pressure pump	0.00	26.00	0.00	26.00	90
1803.15	Requested speed of high pressure pump	0.00	26.00	-0.45	26.00	91
1803.90	Pressure from high pressure pump	0.00	26.00	0.45	26.00	89
1804.35	Energy consumption (power)	8.00	25.00	0.00	25.00	90
1804.36	Total energy consumption	8.00	25.00	0.44	25.00	89

8.3.8. Documentation

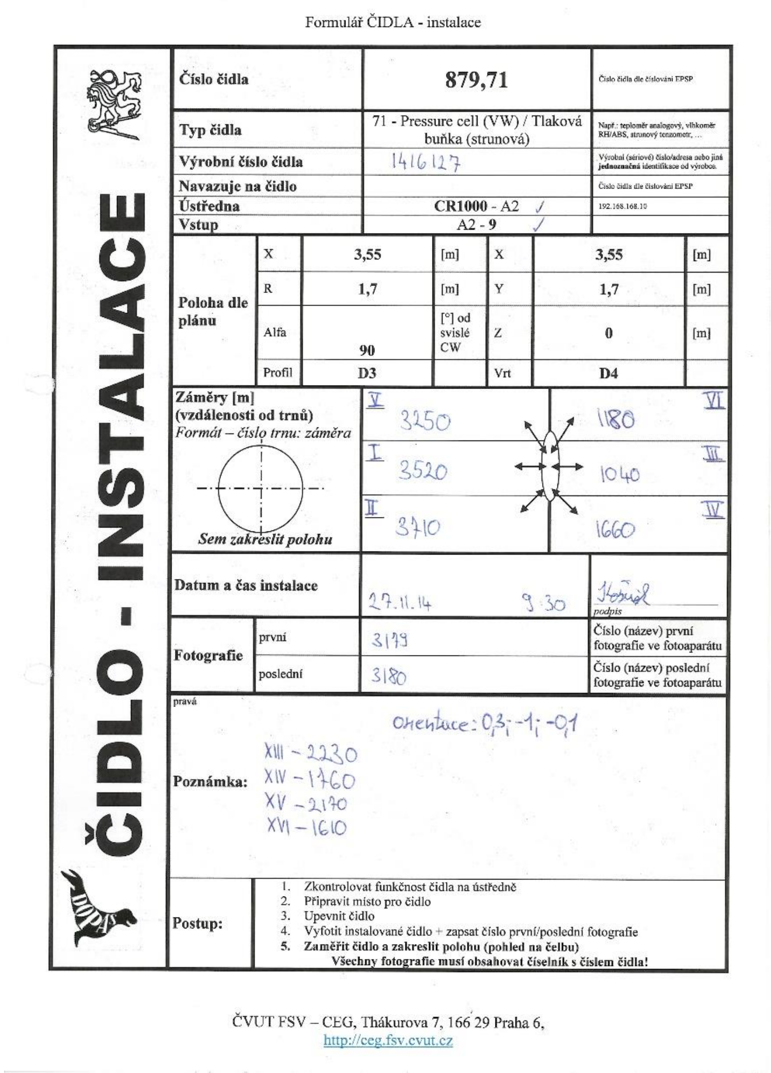
Documentation forms an important part of the preparation and installation of the monitoring system by allowing for the tracking of the production of the sensor probes and their installation in-situ.

Each installed sensor has two passports – the first from when the probe was manufactured and the second related to probe installation. These passports contain all the important data on each sensor and assist in the accuracy of installation in-situ. Moreover, photo documentation was compiled during the installation of each sensor.

The sensor installation passport made up the primary tool in terms of the installation documentation. Each passport was partly pre-filled in using data from the monitoring plan and the sensor's manufacturing passport. Where necessary a supplementary sensor location diagram was used in order to speed up sensor installation.

The sensor installation passport tracks the following:

- Sensor ID (pre-filled in)
- Sensor type (pre-filled in)
- Sensor serial number
- Data logger to be connected to (pre-filled in)
- Input of the data logger to be connected to (pre-filled in)
- Planned sensor position (pre-filled in)
- Distance to stabilised points
- Sensor orientation
- Installation date
- Photo documentation (reference)



Formulář ČIDLA - instalace

ČIDLO - INSTALACE

Číslo čidla		879,71				Číslo čidla dle číslování EPSP	
Typ čidla		71 - Pressure cell (VW) / Tlaková buňka (strunová)				Např.: teploměr analogový, vlhkoměr RH/ABS, strunový tenzometr, ...	
Výrobní číslo čidla		1416127				Výrobní (sériové) číslo/adresa nebo jiná **jednoznačná** identifikace od výrobce.	
Navazuje na čidlo						Číslo čidla dle číslování EPSP	
Ústředna		CR1000 - A2 ✓				192.168.168.10	
Vstup		A2 - 9 ✓					
Poloha dle plánu	X	3,55	[m]	X	3,55	[m]	
	R	1,7	[m]	Y	1,7	[m]	
	Alfa	90	[°] od svislé CW	Z	0	[m]	
	Profil	D3		Vrt	D4		

Záměry [m] (vzdálenosti od trnů)
Formát – číslo trnu: záměra
Sem zakreslit polohu

V 3250	VI 1180
I 3520	III 1040
II 3710	IV 1660

Datum a čas instalace	27.11.14 9:30	podpis
Fotografie – první	3179	Číslo (název) první fotografie ve fotoaparátu
Fotografie – poslední	3180	Číslo (název) poslední fotografie ve fotoaparátu

pravá

Poznámka: Orientace: 0,3; -1; -0,1
XIII – 2230
XIV – 1760
XV – 2170
XVI – 1610

Postup:
1. Zkontrolovat funkčnost čidla na ústředně
2. Připravit místo pro čidlo
3. Upevnit čidlo
4. Vyfotit instalované čidlo + zapsat číslo první/poslední fotografie
5. **Zaměřit čidlo a zakreslit polohu (pohled na čelbu)**

Všechny fotografie musí obsahovat číselník s číslem čidla!

ČVUT FSV – CEG, Thákurova 7, 166 29 Praha 6,
http://ceg.fsv.cvut.cz

Figure 72 - Sensor installation passport (sample)

8.3.9. Sensor location triangulation

Prior to the commencement of the various structures of EPSP a network of stabilised points (stainless steel rods fixed into the rock mass) was installed within the experimental niche. The network consisted of:

- a stabilised point on the experiment axis on the front face of the niche ("0" experiment coordinates),
- a set of six points making up a ring in the bentonite section close to the inner plug,
- a set of six points making up a ring outside of the experiment close to the outer plug,
- a point on the concrete floor in front of the experiment (experiment axis direction).

This network was subsequently used for the determination of the position of all the installed sensors. Triangulation was employed. Once the sensor was installed, the distance to all the available and unblocked stabilised points was measured using a tape and recorded in the installation protocols.

The coordinates of each sensor were then calculated using the GNU GAMA program (http://www.gnu.org/software/gama/) which was co-developed by the CTU. GNU Gama is a project dedicated to the adjustment of geodetic networks and is intended for use alongside traditional geodetic surveying which continues to be used in connection with special measurements (e.g., underground or high-precision engineering measurements) with concern to which the Global Positioning System (GPS) cannot be used.

Table 16 - Stabilised points

ID	x	y	z
0	0	0	0
1	2.883533	-1.71187	0.202637
2	2.766279	-1.42356	-1.01786
3	2.74179	1.485395	1.101871
4	2.954938	1.699044	-0.60686
5	2.729356	-1.40722	1.414271
6	3.007844	1.101681	1.605752
7	7.536615	-1.37174	-1.13914
8	7.58675	-1.60927	0.546932
9	7.297816	-0.92876	1.360231
10	7.567647	1.113699	1.359467
11	7.38028	1.800765	0.164
12	7.403805	1.801259	-0.81015
H	10.01689	-0.0006	-0.86751

8.4. SYSTEM SETUP AND INTEGRATION

The data acquisition and monitoring systems are based on components previously developed and used at the Czech Technical University in Prague (CTU), Centre of Experimental Geotechnics (CEG) (Pacovský et al. 2006, 2010; Levorová, Vašíček 2012, 2013).

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

The system has been built as a heterogeneous system; where possible, standard IT components are being used with an Ethernet network as the backbone. Such an approach allows the separation of components where only sensors and data loggers/convertors need to be (in place of the experiment itself). This approach provides benefits in terms of cost savings and efficiency.

The system consists of:

- DAQ system
  - Sensors within the experiment itself and the surrounding rock (instrumentation)
  - Data loggers and convertors
- Online monitoring system
  - Backend
  - Frontend

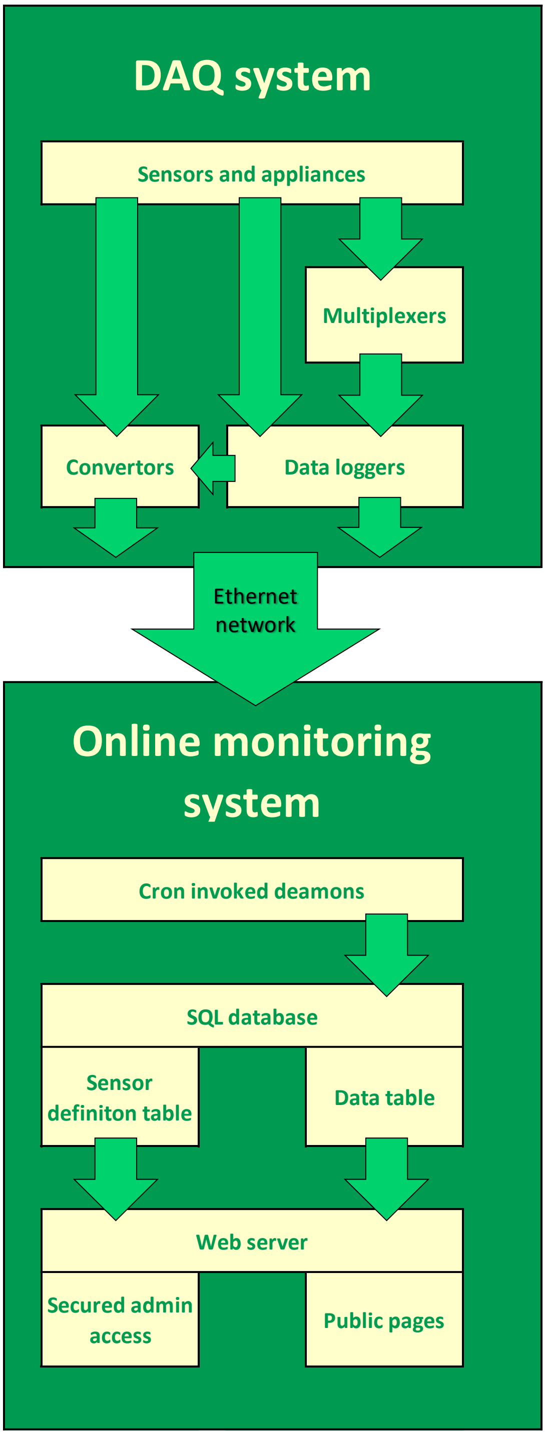


Figure 73 – Measurement system of EPSP

8.4.1. DAQ

The system (DAQ part in particular) was assembled in the Josef URC laboratory prior to installation. During the dry run manufactured sensor probes were gradually connected to the data loggers and the whole system subjected to testing. Once the full hardware setup had been successfully tested (and the location made ready), the DAQ was moved into the underground complex. A scheme of DAQ is shown in Figure 74.

Installation in-situ began with the installation of the data loggers and network connection. The sensors were gradually connected following the progress of EPSP construction.

8.4.2. Backend

The online monitoring system was developed in parallel with DAQ preparations. The main aim consisted of the development of a system backend which was DAQ hardware specific. Data collection from DAQ is handled by a set of daemons each of which is custom built to fit a specific data logger or digital sensors/equipment. This also includes the interfacing with the technology control system.

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

The database forms the heart of the system in which all the data is collected and stored; the MySQL (http://www.mysql.com/) open source SQL database and MariaDB (https://mariadb.org/) are used for this task. The database itself contains two main tables: a table containing raw data and a table detailing sensor definition/description (type, position, calibration etc.).

All the data provided by the sensors or technology via the daemons is stored in primary units thus allowing for the easy adjustment of the calibration curves when required without the loss of information.

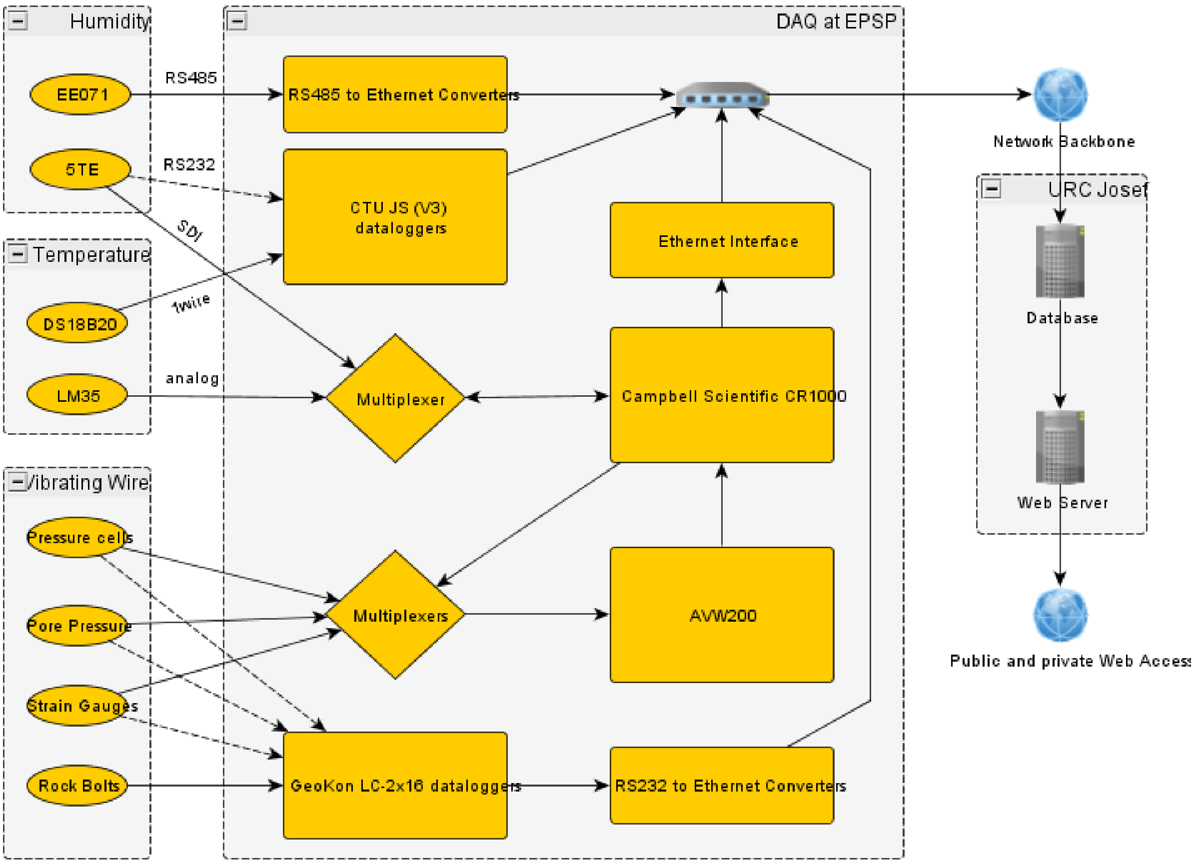


Figure 74 – EPSP monitoring system setup

8.4.3. Web 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 the simple data visualisation interface (2D charting and 3D visualisation). For more comprehensive analysis purposes, direct data export is available using specialised URLs.

Figure 75 - EPSP measurement system web frontend UI

9. CONCLUSION

The EPSP has been successfully installed and the experimental phase is under way. The initial objective of EPSP – the demonstration of technologies suitable for plug erection has been achieved. 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. 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 humans, 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 shot clay 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.

One of the minor tasks of the experiment was to check if the shotcrete plug can be used without contact grouting. The initial testing of the inner concrete plug of the EPSP experiment, however, demonstrated that contact grouting was necessary in order to ensure that the concrete seals perform 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 shot clay 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. More information on the materials used can be found in D3.21 - Final results of EPSP laboratory testing.

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.

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