EUROPEAN COMMISSION

Community Research

DOPAS

(Contract Number: FP7 - 323273)

Deliverable n°D4.5

D4.5 POPLU Experimental Summary Report

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Final Date of issue of this report: 31.8.2016

Start date of project: 01/09/2012 Duration: 48 Months

Project co-funded by the European Commission under the Euratom Research and Training Programme on Nuclear Energy within the Seventh Framework Programme		
Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the partners of the DOPAS project	
CO	Confidential, only for partners of the DOPAS project	

Scope	Deliverable n°D4.5	Version:	1.0
Type/No.	Report	Total pages	140+30
		Appendices	2
Title	D4.5 POPLU Experimental Summary	Articles:	

ABSTRACT

This report gives an overview on all aspects of the POPLU construction, with attention to requirements, design, modelling, materials, instrumentation, construction and performance assessment based on pressurization to 4.1 MPa. The report provides insight about lessons learned and comparison to SKB's DOMPLU plug, representing Posiva's reference design. The report builds upon earlier deliverables of DOPAS WP2 and WP3, noting any deviations during construction of the full-scale plug at ONKALO.

Keywords: plug, wedge, design, modelling, concrete, materials, instrumentation, construction, monitoring, pressurization, performance, POPLU

REVIEW/OTHER COMMENTS:

The work reported here has been reviewed by the POPLU Part Leaders responsible for each aspect of the work. The DOPAS coordinator has reviewed the memorandum and approved for submission.

APPROVED FOR SUBMISSION:

Johanna Hansen 31.8.2016

RAPORTTI (POPLU TULPPAKOKEEN YHTEENVETORAPORTTI)

TIIVISTELMÄ

Posivan loppusijoitustunnelin päätytulppakokeen (POPLU) yhteenvetoraportissa esitetään kokeen toteuttamiseen liittyneet toimenpiteet mukaan lukien tulpalle asetetut vaatimukset, tulpan suunnittelu, mallinnus, instrumentointi ja rakentaminen sekä toimintakyvyn seuranta rakentamisen jälkeisessä tulpan painetestauksessa. POPLU-kokeen paineistaminen toteutettiin nostamalla vedenpaine tulpan takana keinotekoisesti 4,1 MPa:iin asti. Raportissa esitetään sekä kokeen suunnittelun ja rakentamisen aikaiset kokemukset että painetestauksessa saadut tulokset. Lisäksi raportissa esitettään johtopäätökset POPLU-kokeen kokemuksista SKB:n ruotsissa toteuttamaan vastaavaan DOMPLU-kokeeseen verrattuna. DOMPLU-kokeessa testattiin Posivan referenssitulppasuunnitelman kaltaista päätytulppaa. Yhteenvetoraportti laajentaa aikaisemmin DOPAS-työpakettien WP2 ja WP3 -raporteissa kerrottua kuvaa POPLU-tulpasta, huomioiden ONKALO:ssa tapahtuneen täydenmittakaavan tulpan rakentamisen aikana mahdollisesti tapahtuneet poikkeamat aiemmin raportoituu verrattuna.

Avainsanat: tulppa, päätytulppa, kiila, loppusijoitustunneli, suunnittelu, mallinnus, betoni, materiaali, instrumentaatio, rakentaminen, seuranta, monitorointi, paineistus, painetesti, toimintakyky, POPLU

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PREFACE

This report summarizes the design and construction of Posiva's repository tunnel end plug, POPLU. The POPLU deposition tunnel end plug project was implemented as a joint project between Posiva and SKB. The POPLU project core group has been responsible for the direction of the research and development leading to the plug commissioning, with tasks as noted in Appendix A. Review of the work progress and plans has been done by Posiva's technical review group. This report serves as a summary of the POPLU achievements. The POPLU tasks which were supported by the

DOPAS project with European Commission funding include: plug slot excavation, design, monitoring and performance assessment (Chapters 4.3, 5, 6.7.5 and 7, respectively). The report contributors and responsible persons have included:

- Chapters 1, 3, 9, 10, 12 and 13 by Erika Holt (VTT) as the Project Manager and Petri Koho (Posiva) as the Experimental Leader
- Chapter 2 Background is by Posiva and Matt White (UK), based on DOPAS Deliverable D2.1 [DOPAS 2014f]
- Chapter 4 Plug Location by Sanna Mustonen, Kimmo Kemppainen, Paula Kosunen, Petri Koho and Henrik Ittner (SKB)
- Chapter 5 Plug Design by: Kari Koskinen (Chapter 5.1 Modelling), Jari Dunder (Chapter 5.2 Structural Design), Erika Holt and Markku Leivo (VTT, Chapter 5.3 Materials); Antti-Jussi Kylliäinen (Posiva), Edgar Bohner Kalle Raunio and Arto Laikuri (VTT, Chapter 5.4 Monitoring), Petri Koho (Chapter 5.5 Foreign Materials).
- Chapter 6 Construction by Posiva including Hannu Leino, Juuso Hiltunen, Petri Koho and instrumentation aspects by Bohner, Raunio and Laikuri (VTT).
- Chapter 7 Performance Assessment by Petri Korkeakoski, with additions from Bohner and Raunio (VTT). Chapter 6.9 is based on DOPAS Deliverable D4.4 [DOPAS 2016b] assessments by Posiva and VTT.
- Chapter 8 Comparison to DOMPLU has been written in cooperation with Experimental Leader Pär Grahm (SKB)
- Chapter 11 is partially integrated from DOPAS D4.4 [DOPAS 2016b], including additions by Holt and Koho.

The report has been quality reviewed by Marja Vuorio of Posiva Oy. Photos and images within this report are copyright by Posiva Oy, unless otherwise noted in corresponding captions.

1 OBJECTIVES

This report is a summary of the development and work done for emplacement of Posiva Oy's full-scale deposition tunnel end plug, called POPLU. The information provided here covers activities associated with Work-packages 3 and 4 of the DOPAS project, from the start of project through the construction and performance monitoring of the POPLU plug. This report is also supplemented by additional reports and memos providing more details, which are referred to within the document. If changes have been made since the earlier submitted WP3 Deliverables, then the updated information is given here, otherwise the details remain as already reported and are not repeated here.

The commissioning of the plug experiment started in 2012 and continues with monitoring until the data freeze date of 1.6.2016. The plug has been constructed in the ONKALO underground rock characterisation facility in Olkiluoto, Finland. POPLU has demonstrated a wedge-type of deposition tunnel end plug that could be designed and constructed in crystalline-rock. POPLU is compared to the dome-type plug constructed by SKB in Äspö, Sweden in 2013, where performance assessment has also been carried out and analysed within DOPAS Deliverable D4.3 [DOPAS 2015]. Both plug types are intended to isolate the emplaced tunnel backfill, bentonite clay buffer and spent-fuel canister from the central tunnels during the operation phase. These structural plugs are typically made of low-pH concrete and possibly reinforcing stainless steel, with a design life in the range of 100 years. The development of construction materials for the plugs and seals meeting the repository requirements is included in the DOPAS experiments' work. Both demonstrations have the goal of monitoring the plugs' performance when pressurizing them to nearly the full dimensioning loads over a short (1–2 year) time scale to simulate 100 years of service life.

2 BACKGROUND

The Finnish disposal concept for spent fuel is based on KBS-3V at the ONKALO repository in Olkiluoto. The long-term safety principles are based on the use of a multi-barrier system consisting of engineered barriers and the host rock. The engineered barrier system (EBS) consists of canisters, buffer, backfill, deposition tunnel end plug, and the closure for open spaces. The EBS components provide the primary containment against the release of radionuclides. Deposition of Finland's spent fuel canisters will begin after receiving the operation license and operations will continue for ~100 years. The current plan envisages filling, backfilling and plugging of one deposition tunnel per year (thus approximately 100 tunnel end plugs) [Posiva 2012a]. A schematic of the EBS barriers at Olkiluoto is shown in Figure 2.1. Note that other types of plugs and seals also exist in the repository site, such as those necessary for closure after operation [Sievänen 2012], yet there were outside the scope of Posiva's work for DOPAS.

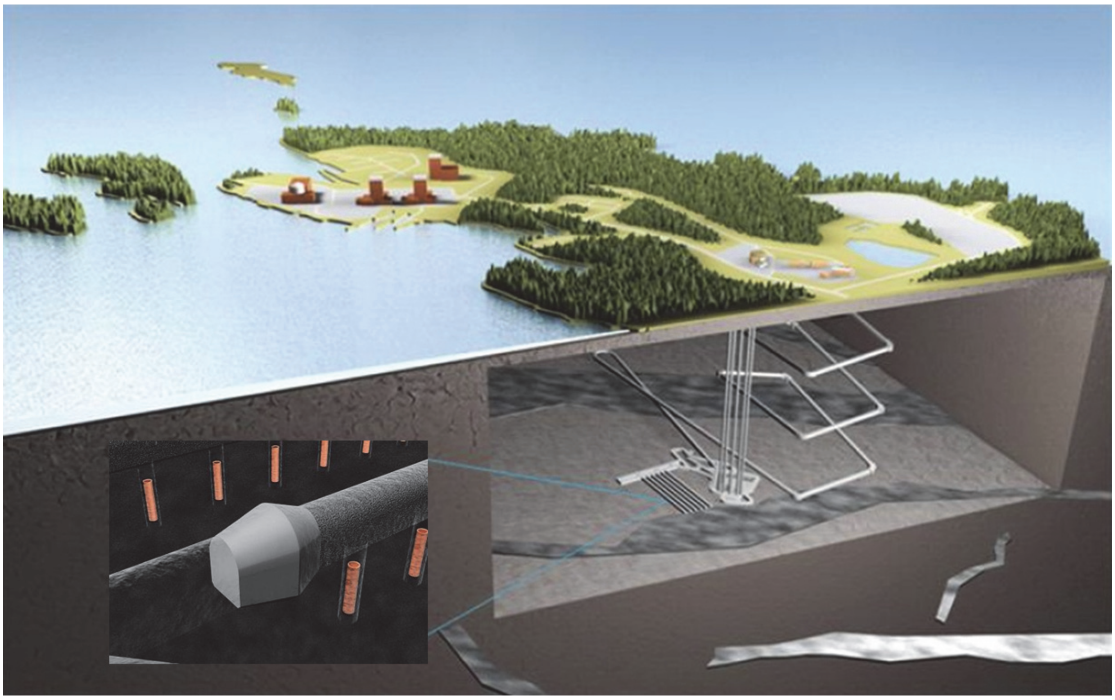


Figure 2.1. Repository schematic, including tunnel end plug graphic insert.

The POPLU demonstration is carried out to fulfil Finland's YJH-2012 [Posiva 2012c] plans to:

- Construct a full-scale deposition tunnel end plug (demonstration, workmanship, quality control)
- Develop detailed structural design, including concrete recipe development for plug,
- Develop tunnel plug location excavation,
- Produce a quality manual for quality control practices and risk mitigation for plug,
- Develop instrumentation and performance monitoring techniques (mechanical load transfer, concrete shrinkage, water tightness), including models,
- Observe and solve practical challenges prior to construction and implementation, related to occupational safety, documentation, quality assurance, practical work procedures etc.

POPLU is a full-scale experiment, testing Posiva's alternative design in a wedge-type plug. The reference dome-type design is tested by SKB and jointly funded by Posiva. The design basis for the plug is described in Posiva's VAHA requirements management system, with the focus being on post-closure safety. The VAHA requirements linked to POPLU are graphically represented in Appendix A. [Posiva 2012a] In general, the length of the POPLU plug is 6 meters, located in intact rock to fulfil its requirements for ensuring water tightness around the plug and for preventing leakages from the surrounding rock, in order to protect the plug from the dissolving effect of ground water and to prevent the formation and transport of cement leachates in bedrock fractures.

The full details about POPLU's Design Basis and Criteria, including the VAHA requirements, are described in detail in DOPAS Deliverable D2.1 [DOPAS 2014f]. POPLU's Conceptual design is described in DOPAS Deliverable D2.2 [DOPAS 2014e]. Both of these earlier reports compare the design basis and conceptual designs to the other international plug demonstrations of DOPAS. Posiva's requirements for the plug are described within the Structural Design document of DOPAS Deliverable D3.24 [DOPAS 2014c]. Assessment of monitoring system performance, specifically the sensors, is partially repeated in Chapter 6 here, from DOPAS Experimental Summary Report Deliverable D4.4 [DOPAS 2016b]. Evaluation of how POPLU construction showed compliance (or not) with the design requirements is also detailed in the DOPAS Deliverable D4.4 [DOPAS 2016b], and elaborated on here in Chapter 9.

The POPLU demonstration also builds upon Posiva's earlier experience within in-situ demonstrations, such as the 40% scale buffer test in ONKALO [Kivikoski 2014, Hakola 2015]. POPLU will be compared to SKB's DOMPLU experiment within the scope of DOPAS reporting, for evaluation of the design, requirements and performance. The POPLU demonstration contributes to the Finnish know-how needed prior to the operation license application to the Finnish National Nuclear Regulatory Authority, STUK, with is expected to be submitted in 2020. This includes knowledge on aspects of full-scale demonstrations of construction methodologies, performance verification, monitoring systems and safety assessment.

3 POPLU QUALITY MANAGEMENT

The quality management program for the POPLU experiment was overseen by the Project Manager and Experimental Leader. The quality management plan consisted of several parts describing how Posiva's Quality Management system was applied for the POPLU experiment and what were the quality practises used for POPLU.

The goal of quality management was to ensure that the quality assurance methods were used throughout the POPLU project. The Quality Plan created in the beginning of the project ensured that project was performed with high quality in all areas of the project:

- project management (plans, schedules, budget, task progress)
- change management
- handling of non-conformities
- technical design
- implementation (on-site and construction activities and scientific part)
- documentation (approval and filing of plans, memorandums, reports and other project material),
- procurement (of equipment and subcontractors),
- material supplies.

The quality management also ensured that the client of the project and project group were aware of responsibilities for decision making and approval of project documentation and outcomes. It also ensured that the quality control in different phases was done according to the practises and instructions defined.

Documentation and practises for the POPLU experiment were created as if the demonstrated POPLU plug had been constructed in actual operational repository conditions, meaning that proper regulatory guides on nuclear safety and quality assurance practises were used. The deposition tunnel end plug as a system in operational conditions belongs to STUK Safety Class 3. For the POPLU experiment the design and construction of the main components of experiment were performed as if they had been Safety Class 3. Design and construction of Safety Class 3 concrete structures are described in STUK's YVL Guide E.6.

4 PLUG LOCATION

To verify the suitability of the plug demonstration tunnel locations and to select the location for the plug within the tunnels, the Rock Suitability Classification (RSC) - system developed by Posiva Oy has been applied. A short description of the RSC-system and the rock suitability classification carried out for the POPLU are detailed in Deliverable D3.26 [DOPAS 2014d].

To prepare for the plug construction, tunnels were excavated (Section 4.2) based on pilot holes (Section 4.1) and then the plug slot itself was excavated (Section 4.3). The requirements for plug location within Posiva's VAHA management system include:

- Plug location shall not be intersected by the respect volumes of hydrogeological zones.
- Plug location shall not be intersected by the respect volumes of brittle deformation zones.
- Hydraulically conductive fractures shall not intersect the entire length of the plug.

Quality control steps were taken at each stage of tunnel and slot excavation, to ensure accuracy of excavations to meet the design criteria and the work safety in ONKALO. These aspects are described in the next sections.

4.1 Tunnel Locations

The plug is located in the ONKALO demonstration area, at -420 metres, where two plug demonstration tunnels were excavated northeast of the earlier constructed demonstration tunnels 1 and 2 (Figure 4.1). The design of the Demonstration tunnels 3 and 4 (DT3 and DT4, respectively) was made by Kalliosuunnittelu Oy (Rockplan Ltd). One tunnel, demonstration tunnel 4 (DT4), contains the plug and the second tunnel, demonstration tunnel 3 (DT3), contains the monitoring equipment. The tunnel lengths are approximately 21 and 25 metres from the centre line of the central tunnel, respectively. The dimensions of the tunnels are 4.35 metres (height) by 3.5 metres (width), with an area of approximately 14.46 m^2, similar to the demonstration tunnels 1 and 2 constructed with deposition tunnel specifications [Posiva 2012b].

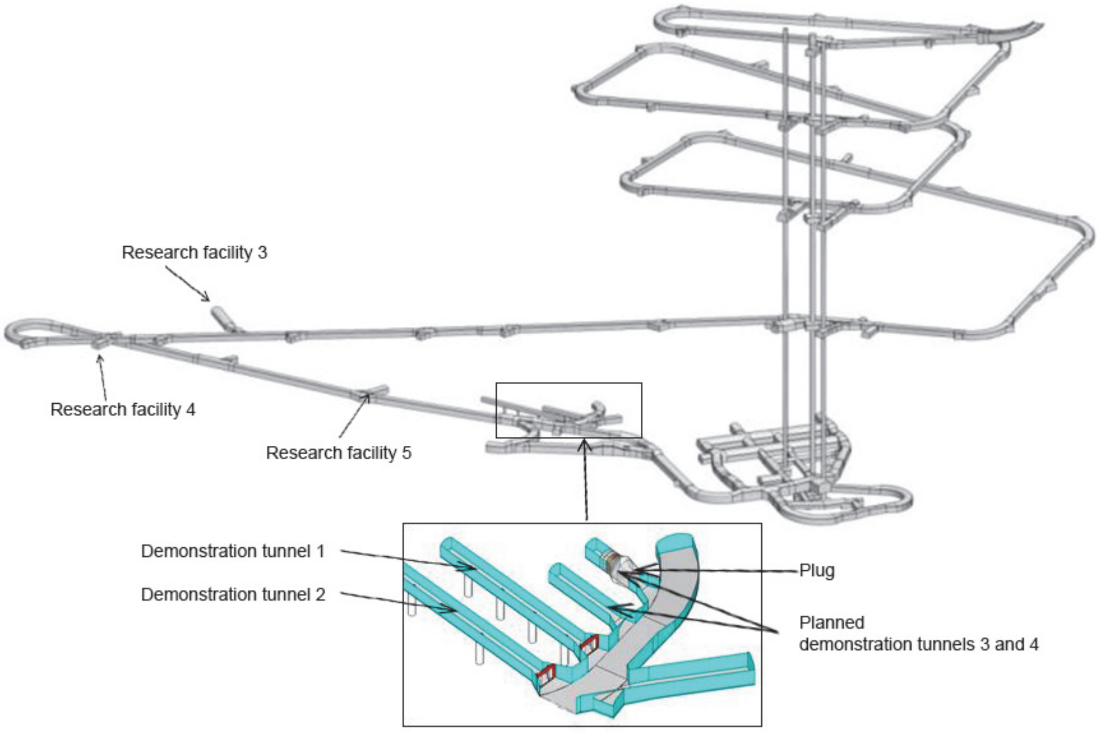


Figure 4.1. POPLU tunnel locations in ONKALO. View to north.

The first step for siting was to drill two pilot holes within the profiles of the planned tunnels, each of diameter 76 mm, which were used to assess the properties of the rock, for example to identify natural fractures and deformation zones. Flow logging was carried out and assessments were made on the connectivity of the fractures. The data were used to model the observed structures in detail, with an example shown in Figure 4.2. The plug slot was also modelled in 3D to identify the suitable locations meeting the requirements for the plug siting.

In the rock suitability classification, the criteria set for bedrock hosting a plug were determined to be fulfilled in the DT3 for chainage 16.20–27.30 metres and in the entire length of the DT4. Based on the pilot hole data, the first eighteen metres of DT4 were deemed to be less fractured than the rest of the tunnels. It was therefore suggested that chainage 11–17 m be used for the location of the POPLU plug, as this tunnel section had the best rock quality. Based on the pilot hole data, the suggested section was observed to be mainly composed of the veined gneiss typical of the Olkiluoto area. The tunnel excavation then commenced based on the pilot hole information.

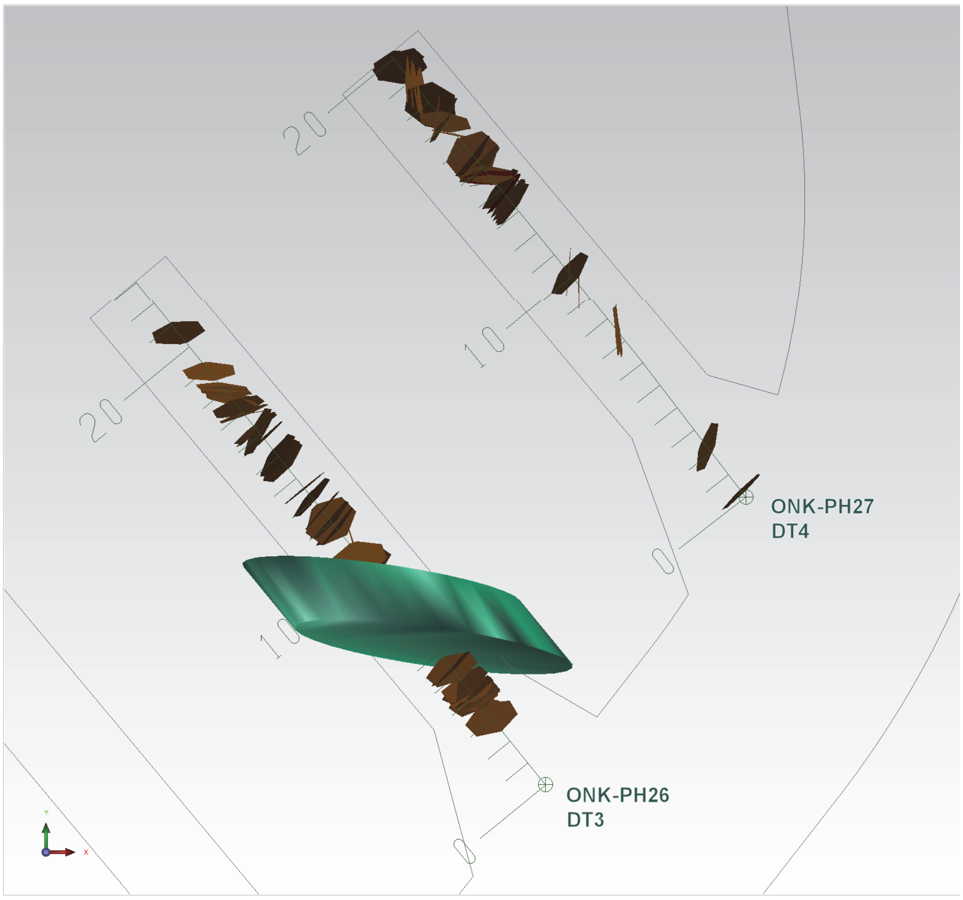


Figure 4.2. Structures observed in the pilot holes; the brown disks depict single natural fractures, the green solid is an interpreted intersection of a brittle deformation zone. The locations of the pilot holes (ONK-PH26 and ONK-PH27) are shown as green lines, and the numbers denote the hole depth in metres. DT3 and DT4 denote the demonstration tunnels 3 and 4, respectively (Deliverable D3.26, [DOPAS 2014d]).

4.2 Tunnel Excavation

Demonstration tunnels 3 and 4 were excavated during the period of September to December 2013 at -420 m level in the demonstration area in ONKALO. Both tunnels have a horseshoe cross-sectional shape, similar to the central tunnels. Demonstration tunnel 4 (DT4) was excavated first and extends 20.75 m from the central line of the main tunnel in the demonstration area. Demonstration tunnel 3 (DT3) was excavated after the finalisation of DT4 and extends 25.21 m from the central line of the main tunnel in the demonstration area (as shown in Figure 4.2). The distance between the central lines of the tunnels is 12 meters.

The design of DT3 and DT4 started with the assessment of the requirements. Demonstration tunnels 1 and 2 had previously been constructed in the demonstration area with deposition tunnel specifications. Essentially, the same requirements were used for the demonstration tunnels 3 and 4 than for the two previously excavated tunnels. Some adjustments were done to the requirements based on the experiences from the excavation of demonstration tunnels 1 and 2.

The method used for the excavation of the demonstration tunnels was drill and blast. During the tunnelling it is necessary to assure that the requirements on tunnel geometry and EDZ are fulfilled. This requires that the principle blast design that comes from the contractor's designer is adapted to the rock conditions and approved by Posiva's supervisor. Only small changes (iteration) are implemented on the blast design during the excavation. Updates to the blast design include the updates done to drilling, charging, and initiation plans.

The excavation cycle of demonstration tunnels 3 and 4 consisted of several steps:

1. Set up measurement
2. Assuring set up measurement
3. Drilling
4. Assuring drilling by surveyors
5. Charging (taking account the driller's remarks)
6. Blast
7. Mechanical scaling
8. Mucking
9. Mechanical scaling and hand scaling
10. Closing measurement and mapping (includes laser scanning)
11. Application of rock support
12. Cleaning of the floor.

After the excavation of DT3 and DT4, RSC was again applied to assess the planned slot location, from chainage 11–17. The location was found to be suitable and fulfilling the requirements (see Deliverable D3.26 [DOPAS 2014d]). Figure 4.3 shows the planned location of the plug in DT4, and Figure 4.4 shows examples from lead through drilling in the tunnels. Note that the tunnels' actual length was shortened during excavation, as less space was needed for equipment behind the plug. Thus the space behind the plug was reduced and later filled with a concrete backwall.

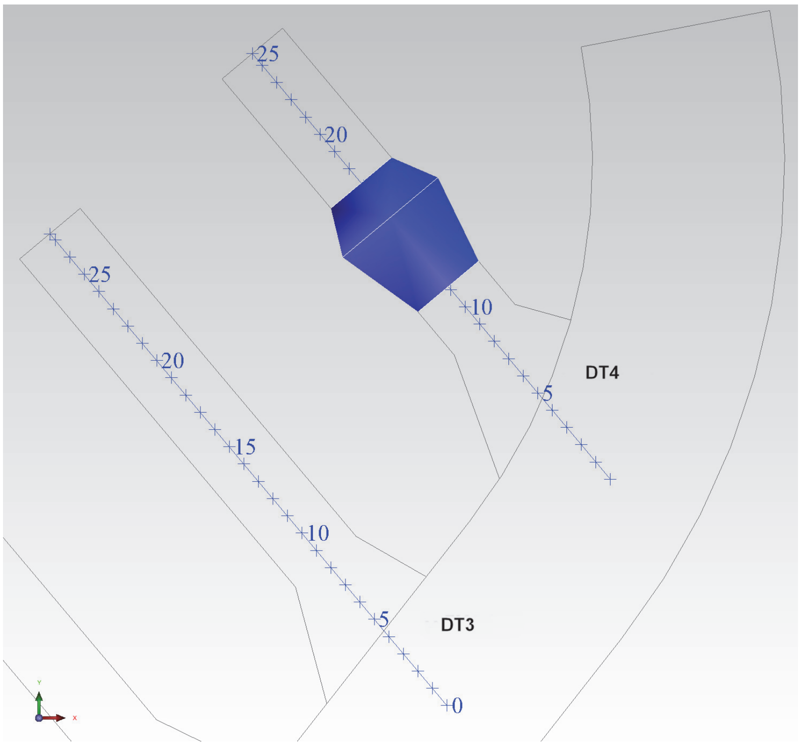


Figure 4.3. The final location of the POPLU experiment in DT4. The blue lines indicate the centre lines of the tunnels with tunnel chainage in metres.

Figure 4.4. Lead through drilling from DT4 towards DT3.

The application of rock support in DT 3 and 4 was based on systematic bolting and shotcreting. Rock support in DT3 was performed with systematic bolting of 2.4 m long bolts and installation of wire mesh on the tunnel roof. During the excavation two rounds without rock support was acceptable and after the third unsupported round, rock support was installed to the two previous rounds. In DT4 the roof of the tunnel was shotcreted after each round up to chainage 18 to preserve selected plug location from rock bolts. Tunnel end section from chainage 18 to 21 was reinforced with wire mesh and rock bolts.

Cleaning of the floor after each round was conducted because of work environment related reasons. To guarantee worker safety, it needs to be made sure that no explosives are left on the excavated surfaces. It is also important for long-term safety to have minimal residues remaining in ONKALO.

In general, the blast results in the excavation of demonstrations tunnels 3 and 4 were successful and the required dimensions of tunnels were fulfilled. As stated before, the blast design needs to be updated if the blast is not successful. The decisions about any possible updates to the design are taken within a short timeframe based on the results of blasting from the previous rounds. The excavation of the demonstration tunnels was done according to high requirements. This places more requirements to the blast design as the required quality of excavation excess that of conventional excavation works.

After the plug slot excavation was completed in DT4 (see Section 4.3), additional rock work was done on the floor surfaces of the demonstration tunnels to enable the collection of any possible leakage water from the pressurisation of the POPLU experiment. The floor of DT3 was levelled with grinding. The purpose of the floor levelling is to direct any water inflow from DT4 to the grinded water channel next to the tunnel wall on the side on DT4. The water channel leads the water inflows to the water collection ditch on the mouth of the tunnel. The water collection ditch includes a pump hole in the deepest level of the ditch that collects the water which is then pumped and the volume measured.

The one metre section of tunnel floor in front of the plug slot in DT4 was levelled with grinding. The levelled area has a lower elevation than the floor towards the tunnel mouth in front of the levelled area. The deepest level of the grinded section includes a pump hole that is used to pump and measure any possible leakage waters through the plug and the surrounding rock.

4.3 Plug Slot Excavation

4.3.1 Contractor Selection

The method used for the plug slot excavation was decided based on the best technology that could be safety demonstrated, in comparison to the cost. As the excavation work was partially financed by European Commission with the DOPAS project, the subcontracting was done by public procurement of a contractor. The initial public procurement announcement to the Finnish HILMA system was done in summer 2013, specifying the method to be used would be wire-sawing as Posiva’s reference method. Negotiations with four companies in October 2013 resulted in a suspension of the initial procurement on 16.1.2014 due to safety concerns about handling stone boulders resulting from wire sawing.

A second, revised public procurement was launched on 27.1.2014, where the handling of the slot’s rock masses were better defined and slot excavation and extraction methods other than wire sawing were allowed, the evaluation criteria were defined in the tender. Based on this procurement, seven companies (both Finnish and international) replied and progressed to negotiations in February 2014. Based on the initial negotiations, four companies were asked for more detailed price quotations. After receiving the contractors’ offers, two discussions meetings were held (23.4.2014 and 25.4.2014).

Contracts were also reviewed by Posiva’s parent company’s TVO’s legal experts. The final contractor was selected to be the Finnish company Lännen Kaivuu ja Louhinta Oy.

The method chosen for slot excavation was a drill-wedge-grind combination. This method was further developed, refined and optimized during the DOPAS project by enhancing the machining tool and optimizing the machining method. This included information about accuracy for drilling angle measurements and drilling depths. The practices for ensuring tolerances and excavation quality were verified. The cost estimate forecasting for time and labour were improved based on the experience.

4.3.2 Excavation Requirements

The design of the slot to be excavated to the rock was made by Kalliosuunnittelu Oy (Rockplan Ltd). Some of the requirements for the slot excavation needed to be developed during DOPAS. Although some requirements already existing with Posiva’s VAHA system (as described in DOPAS WP2 Deliverables, such as [DOPAS 2014e, 2014f]), others needed refinement. This proved challenging because the requirements may be defined differently for varying production methods (i.e. the length of cable cuts if using wire-sawing). The requirements for the rock surface were given within the public procurement Tender, and included details as noted below. After contactor selection, the requirements were discussed with respect to the detailed drawings, time schedule and sequence of excavation. The contractor was required to supply a method description prior to approval of their work commencing.

Requirements to the rock surface in the plug slot area included:

1. The size of the elevation and recess is: height 15 mm and width 40 mm maximum. There is no limitation of the number of the elevations and recesses on the surface.
2. The surface may curve 100 mm in 1.5 m distance in maximum.
3. The maximum height to an individual step is 15 mm.
4. Excavation Damage Zone shall be less than 20 cm.
5. The final, produced rock surface in the plug slot area between the chainage 11–17 and the filter layer between the chainage 17–18 are not allowed to be shotcreted.
6. There is not allowed to make any holes or rock bolts to the final, produced rock surface in the plug slot area and filter area (i.e. between chainage 11–18).

Posiva was responsible for verification if these requirements were met during and after the slot excavation. This verification was primarily done by laser scanning, which was done at least 15 times in an iterative process to give feedback during excavation for further drilling, wedging and grinding specific locations (see for instance Figure 4.7-Figure 4.9 and accompanying text).

4.3.3 Slot Excavation Work

Before excavation, two rock extensometer were installed from DT3, adjacent to the slot area. They were used to evaluate rock movements during excavation. The exact location of the slot was marked by laser scanning and surveying, by the company Prismarit Oy.

Excavation was carried out using two construction machines. The first machine was a Holland excavator with 235 planes that was used as the base for the grinding attachment. The excavator boom was modified with a hydraulic extension boom for this purpose. The second machine included both the wedging and grinding equipment. The wedging was done with a Nemek drill rig with a boom modified for this work by the Finnish company Stonepower Oy. The modification included adjusting the clamping device and how the drill device was aligned with the drill bar. The wedging head was manufactured by Kiimuvuori Oy, with using model Splitstone S200, with cylinder diameter of 200 mm and the drill crown head dize of 89-102 mm. The required hydraulic pressure for the equipment was 300 bar. The grinding work was done by having a Webster TD-140 hydraulic cutting unit installed at the end of the hydraulic extension boom of the excavator for milling the rock to the final dimensions. This cutting unit had a maximum hydraulic pressure of 450 bars and with maximum flow rate of hydraulic oil was 460 lbm.

The excavation crew usually consisted of two persons for drilling-wedging and one person for grinding, working two shifts per weekday in addition to the laser scanning company who was needed practically daily. The slot excavation work was done from 28.7.2014–13.2.2015. First the sides were excavated, then the floor section and then the ceiling. The plug area was roughly excavated to within 100 mm of the theoretical dimensions using the drill and wedge method. The control holes were drilled with a milling cutter, marked on the tunnel walls. The clamping drill was placed on the center line with a 89 mm drill diameter. The drill holes were spaced 400 mm apart. Initially, on the side walls, the section of rock removed by each drill section was very small and thus could be done unsupported. Records were kept of the volume of rock removed by drill and wedging. Final dimensions were achieved by grinding of the surface. During excavation, intermediate laser scans were taken by Prismarit Oy to control the dimensions and grinding locations. Example photos from the slot excavation process are given in Figure 4.5.

a)

b)

c)

Figure 4.5. Slot excavation work: a) locating with surveying, b) drilling, c) grinding.

After the slot excavation, geological point mapping was done in accordance with Posiva's standard procedure for tunnel documentation. Extra measurements were also done with high-frequency pulses (EDZ-GPR) to evaluate the amount of the excavation damage zone. These were done in three lines along the slot and at one metre increments. Figure 4.6 and Figure 4.7 shows how the EDZ was mapped around the plug slot area. From these scans, it was possible to assess the hydraulic conductivity risks around the plug area. The information is also used in 3D models for future end plug designs. The results also gave feedback to the assessing how the initial requirements were met.

Throughout the slot excavation, safety practices were of highest concern. It was necessary to have tunnel support against ceiling rock falls at all times, so as to not work unprotected in the tunnel. Shotcreting that was in the slot area for tunnel support prior to slot excavation was removed during the process. To ensure minimal fractures to the tunnel rock, no rock bolts or netting could be used in the excavated slot area to support the rock. The slot excavation was done by using remote controlled equipment so that it was not necessary to access the unreinforced slot area during standard operation. When the slot area needed to be accessed, a crane with a shelter against rock block falls was used. After excavation of the slot, a temporary sheltering system was built from scaffolding for protection during the construction activities.

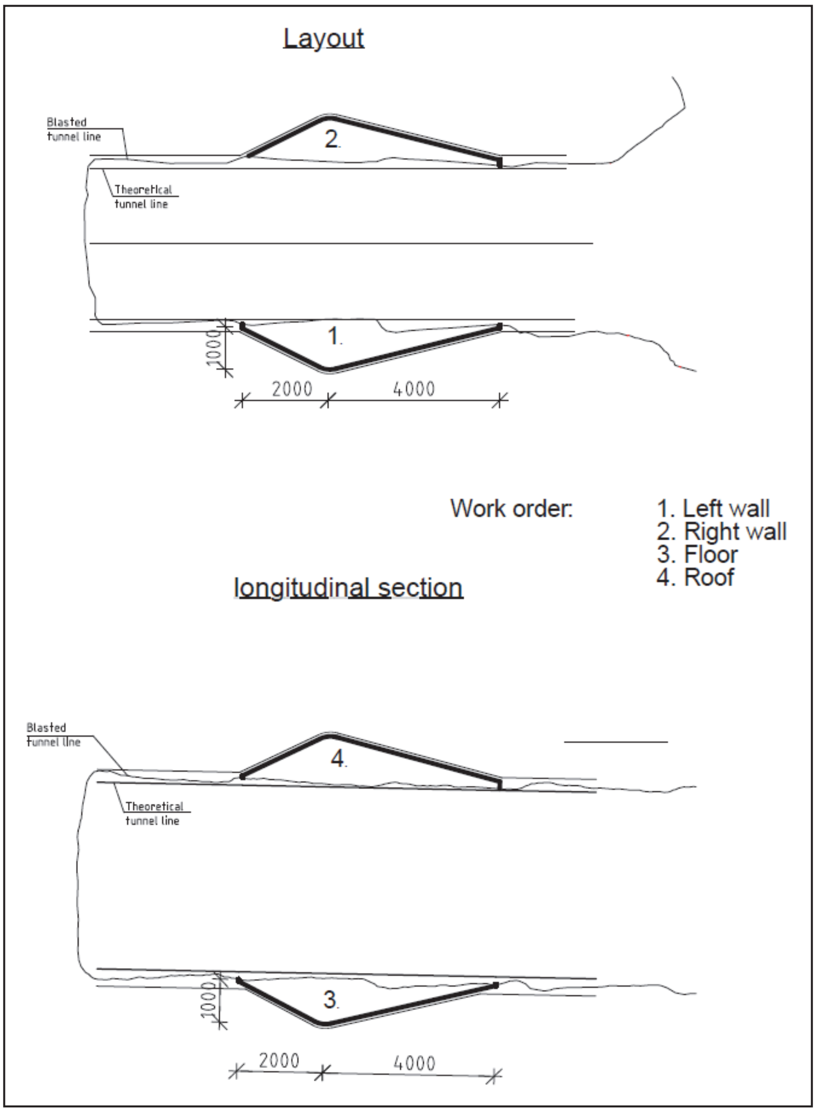


Figure 4.6. Plug slot area and corresponding EDZ removal at edges.

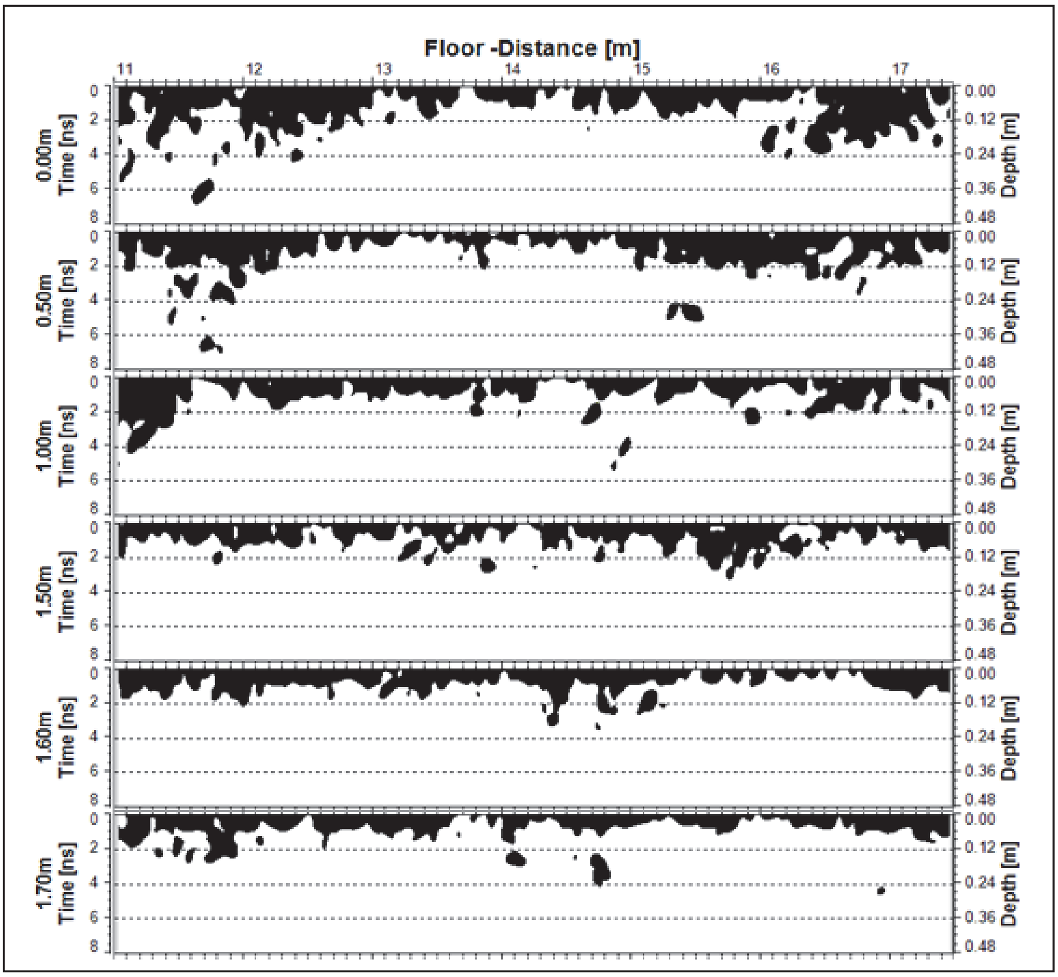


Figure 4.7. Assessment of EDZ damage amounts at various slot locations, after excavation.

The plug slot excavation and dimensions were achieved very accurately, in accordance with the plan. The surface excavation was done to a very low tolerance and was required for acceptance of work completion. It was necessary to have many iterations of laser scanning and additional localized grinding to final dimensions. An example of this iteration is shown by the laser scanning image of Figure 4.8 (with the red dot indicating an excavation area not yet achieving the zero tolerance. This frequent reiteration to reach final tolerances took more than one month of the work time.

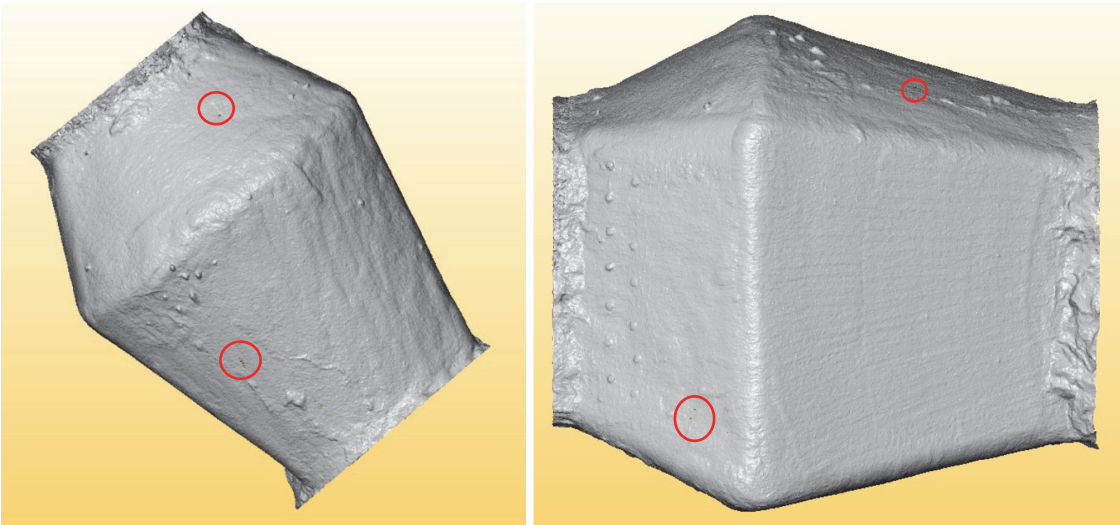


Figure 4.8. Example of laser scanning images to assess grinding during excavation compared to tolerances.

4.3.4 Lessons Learned

The tolerances defined for the dimensions of the slot excavation may have been stricter than necessary, for instance having an inner tolerance less than the zero line. In the future, the plug design and dimensioning should be completed after the slot excavation, while in this case a preliminary design was made first. In this case, it meant that the excavation work had no allowable tolerance because of the shape of the designed support structure.

The machine working time for the equipment was quite long. The tools should be further improved, for instance for the efficiency of machine grinding and exchange of the booms and/or clamps. There were more equipment breakdowns and resulting delays than expected. The contractor should have enough staff that are trained in use of the specialty equipment, so that work can progress faster without dependence on only a select few persons. In future operations, it is estimated that the required work time for slot excavation could be reduced to about half (from 6 months to 3 months) based on optimization of the equipment and ease of operations gained with experience, and access to the to the slot area from both directions of the tunnel. The results of this procurement round with potential contractors for the POPLU experiment showed that Posiva's reference method of wire sawing was not the best method from the operational safety production point of view. The wire sawing option for slot excavation is still being evaluated in the future.

4.4 Rock Lead-through

It was required to have lead-through holes between the ONKALO demonstration tunnel 3 (ONK-TDT-4399-56) and tunnel 4 ((ONK-TDT-4399-69), to hold the pressurization tubes and instrumentation wiring of POPLU. These rock-lead-throughs were for experimental purposes only and would not be part of an operational repository end plug design. The design was started based on the earlier work by SKB for the DOMPLU experiment within DOPAS. The POPLU rock-lead-throughs consisted of three holes, each approximately 9 m long and having a diameter of 196 mm. The starting points for the pilot holes were at the left hand wall of the DT4, and they ended into the right hand wall of the DT3. The main purpose of the drilling was to construct lead-through holes between the planned plugged DT4 and the DT3 used for instrumentation and observations during the POPLU test. They also give information to adjust the geological knowledge of the rock mass. The rock lead-through drilling was done by Suomen Malmi Oy. A schematic drawing of the lead-through arrangements is given in Figure 4.9, while Figure 4.10 shows photos of the excavation underway.

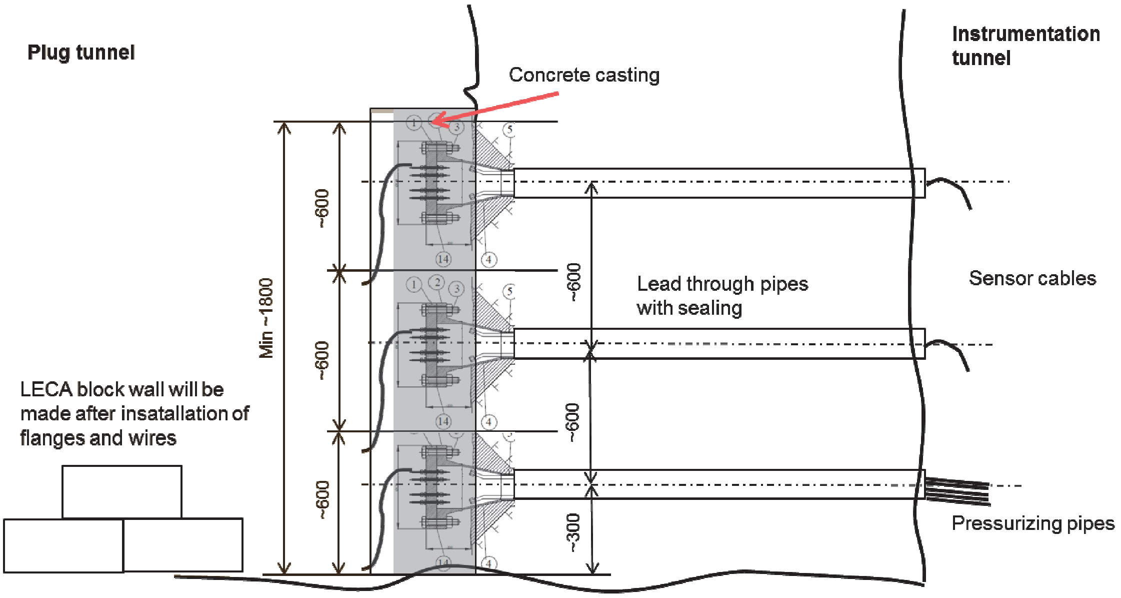


Figure 4.9. Schematic arrangement of rock-lead through between DT3 and DT4. Schematic © VTT.

The holes were drilled with the Sandvik DE 130 underground diamond drill rig (Figure 4.9). The rig is mounted on rubber tracks. The rig is powered by electric motor using hydraulic pumps. The pilot holes for the large diameter holes were drilled with Atlas Copco's NQ3 -triple tube core barrel with extra stabilizator and NQ drill rods. Drillhole diameter with NQ3 -triple tube core barrel is 75.7 mm and drill core diameter is 50.2 mm. The pilot holes were not drilled through, but stopped approximately 0.5 metres before breaking into the tunnel. This was done to control the drilling water during overcoring. The pilot holes were then overcored using a Hagby BHD 193 single tube core barrel. The core barrel was equipped with an inside fitted driver tube to steer the hole in the pilot hole direction. The drillhole diameter with BHD 193 is 196 mm. The BHD core barrel was driven with NQ drill rods.

Figure 4.10. Preparing rock lead-through between DT3 and DT4. a) siting location in DT3. b) Drill rig and crew at work in the DT 4.

The drillholes were drilled in one phase. The drill rig was moved to the site on the 27th of January 2014 and the drilling started on the 28th on the drillhole ONK-PP416. Drilling finished on the 6th of February 2014 on the drillhole ONK-PP418. The third drillhole was labelled as ONK-PP417. Drilling work was carried out as non-continuously, either as one or two shift work (mainly at 8 hours). The drilling team in a shift consisted of a driller and an assistant.

The drilling started from the tunnel wall with no casing drilling. Each drillhole was first pilot drilled with NQ size and then overcored with BHD 193 equipment. The drill rig was not moved when changing the equipment to keep the rig properly oriented. The drilling with BHD 193 equipment was done in one metre lifts and the lifts were cut by wedging as no breaker cone was used.

Handling of the core was based on the Posiva work instructions for triple tube coring. The NQ drill core samples were placed into about one-metre long wooden core boxes immediately after emptying the core barrel and taking the samples. In total, two core boxes were used for each drillhole. The NQ3 samples were stored as the core sample, except for the last few tens of centimetres of the holes which were not drilled with NQ3 but a BHD 193 size.

Table 4.1. The starting and the surveyed coordinates at the final drilling depths. The dip direction positive is upwards and negative downwards.

Station	x	y	z	Average azimuth (°)	Average dip (°)	Method
Start of hole ONK-PP416	6792189.98	1525766.78	-421.29	248.7	2.0	Location survey
End of hole ONK-PP416	6792186.79	1525758.62	-420.98			Location survey
Start of hole ONK-PP417	6792190.53	1525766.34	-420.51	248.2	1.2	Location survey
End of hole ONK-PP417	6792187.29	1525758.22	-420.32			Location survey
Start of hole ONK-PP418	6792190.54	1525766.34	-421.21	248.0	1.8	Location survey
End of hole ONK-PP418	6792187.29	1525758.29	-420.94			Location survey

The pilot hole samples were oriented using traditional spear method giving the bottom of the hole direction. The pilot hole drilling of ONK-PP416 (length 8.38 m) consisted of six, the drilling of the ONK-PP417 (length 8.05 m) of five and the drilling of the ONK-PP418 (length 8.36 m) of eight sample runs. The number of oriented sample runs were three for ONK-PP416, three for ONK-PP417 and four for ONK-PP418. Average lengths of pilot hole runs were 1.40, 1.61, and 1.39 metres respectively.

The flushing water was marked with the label agent sodium fluorescein. Sodium fluorescein is an organic powdery pigment, which is broken down by UV radiation. The labelled drilling water for drillholes was taken from the water pipeline in ONKALO. The mixing of the label agent was done by Posiva Oy before pumping water to the ONKALO pipeline.

5 PLUG DESIGN

5.1 Modelling

Modelling of POPLU's expected performance was done using computer simulations to assess the mechanical integrity (static and dynamic stresses) and watertightness (hydraulic performance). Modelling was done prior to construction and during the design phase, to assist in optimization of POPLU. The results of the structural and mechanical integrity modelling were used for design of reinforcement, planning of the mock-ups, and selection and placement of monitoring sensors. The hydraulic modelling results also influenced the selection and design of the bentonite tape sealing strips. Due to lack of time within the DOPAS project, there has not yet been validation of the modelling done based on the outcomes of the POPLU experiment. This is a potential topic for future work in Posiva. The achieved THM modelling of POPLU prior to construction is summarized in the DOPAS Deliverable D5.11 [DOPAS 2016a] and is shortly summarized here.

5.1.1 Static Stress

Static calculations were used to determine the stresses in the plug prior to the selection of the concrete grade and the required reinforcement. The concrete grade and required steel reinforcement are selected based on an understanding of the tension and compression forces in the concrete, the aperture of cracks that form in the concrete and the heat of hydration of the concrete.

The most critical load controlling the minimum reinforcement is the hydration load. Steel reinforcement is used in the plug structure to minimize the crack widths that may result due to loading, thermal gradients and shrinkage of the concrete material. The allowed maximum cracking width is 3 mm. The reinforcement is stainless steel ribbed bar type B600KA2. The amount of steel reinforcement is approximately 20,000 kg [DOPAS 2014c].

The initial POPLU experiment structural calculations were undertaken using Autodesk Simulation Mechanical (www.algor.com) using a linear elastic material model. The modelling results were output in graphical form as displacement and stress plots. The magnitude of the horizontal displacement and the resulting compressive stress perpendicular to the surface in contact with the tunnel in the event of an incomplete bond between concrete and rock were also estimated [DOPAS 2014c].

5.1.2 Dynamic Stress

The next set of structural modelling was done by Pöyry Oy to evaluate the mechanical integrity of the concrete plug together with the behaviour of the surrounding rock mass. This was simulated using the programme 3DEC 5.00 (Itasca Consulting Group, (2012)), which uses a finite-element approach for modelling structures represented as a continuum. Three scenarios were evaluated, which addressed varying degrees of heterogeneous rock. These focused on different fracturing associated with excavation of the POPLU experiment niche. The displacements modelled in these scenarios prior to pressurisation were a maximum of a few millimetres in the rock and less than 1 mm in the concrete wedge, as shown in Figure 5.1 (top figure). Following pressurisation, displacements are expected to be a maximum of 3 mm on the side of the concrete wedge facing pressurisation Figure 5.1 (bottom figure). The conclusions from this modelling were that the concrete wedge can be expected to deform more than the rock in response to pressurisation and that the concrete wedge deformations may be asymmetric due to the heterogeneous nature of the rock mass lithology and structure (Rautioaho *et al*., 2016).

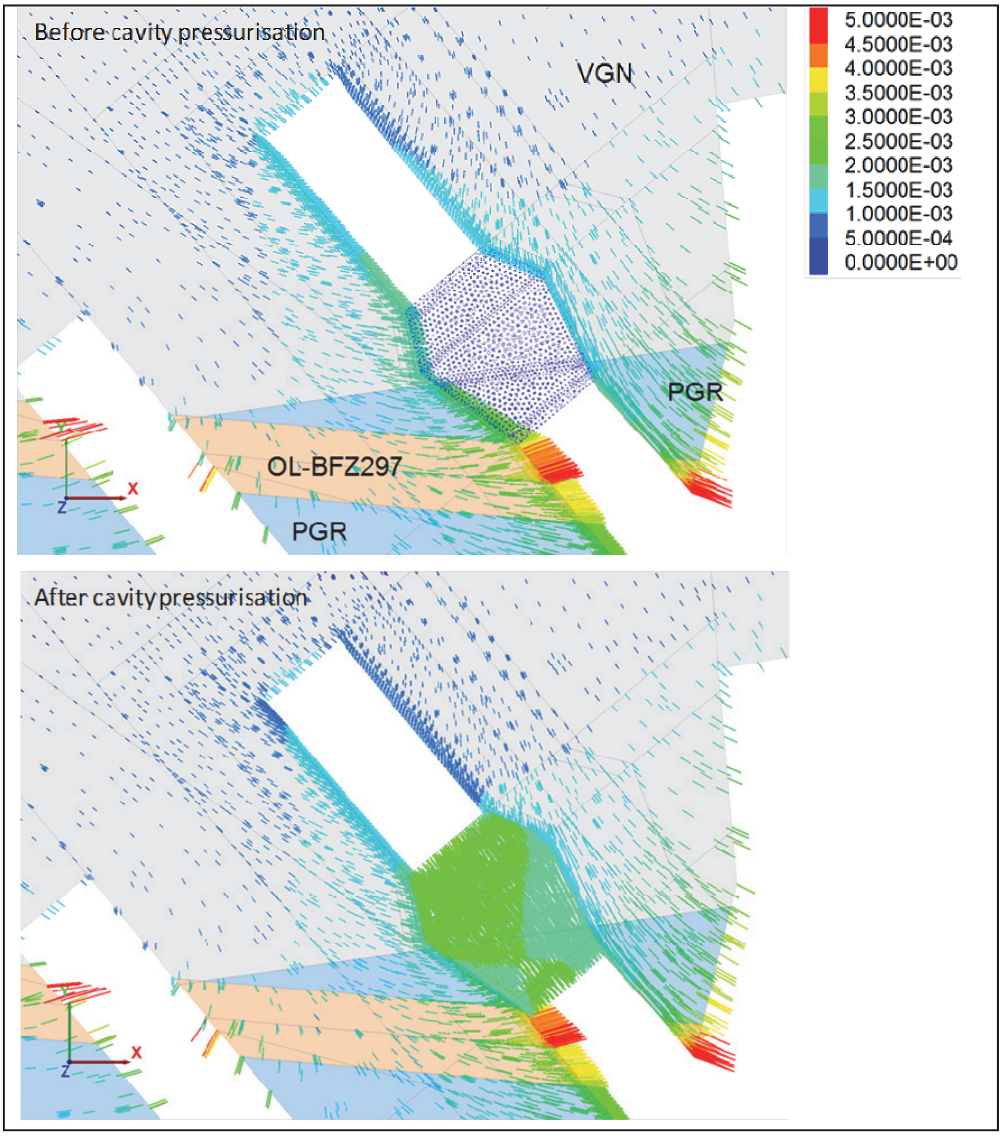


Figure 5.1. An example of the displacement simulations in [m] for scenarios of heterogeneous rock, modelled without (top) and with (bottom) cavity pressurisation to 10 MPa.

5.1.3 Hydraulic Modelling

In the hydraulic modelling, different design options for a bentonite seal were quantitatively evaluated and the flow through a saturated seal at the end of the concrete wedge and the interface between the wedge and the rock were assessed. The objective was to assess the effectiveness and suitability of different design options for the putative seal at the end of the plug, and to support the structural design of the POPLU experiment, specifically when deciding if a layer of bentonite clay blocks would be needed behind the plug to support water tightness (as discussed above).

A three-dimensional hydraulic numerical continuum model was created to simulate the flow through the seal and the gap in contact with the plug, and to predict the total outflow for the different design options and leakage scenarios in fully-saturated, steady-state conditions. The analyses were performed by B+Tech Oy and Clay Technology AB with the finite-element software CODE_BRIGHT [Olivella 1996]. The results showed that the outflow from the concrete wedge would be 17 to 1380 times lower when using a bentonite seal than the case without a bentonite seal, depending on the size of defect and type of sealing materials assumed in the calculations [DOPAS 2016a]. The results of this sensitivity study were used to support a decision that the POPLU experiment would not include a bentonite watertight seal, in order to focus on the performance of the concrete plug.

At the end of the project the models and the hydraulic data will be compared with pointwise and other measurements available from the POPLU monitoring system. In case the resulting comparison error is smaller than the related validation uncertainty and if the safety factor (according to structural design codes [EN1990 2002, EN1991 2004]) in terms of mechanical integrity in all assessments remains acceptable, the designed plug as it has been built can be judged to perform as targeted. In this connection, the plug is comprised of the concrete structure as well as the part of host rock in which changes in stress state are induced due to the pressurised plug.

5.2 Structural design

5.2.1 Overview of plug components

Table 5.1 summarizes the components of the POPLU experiment, with respect to their design and safety functions. The impact for experimental or actual repository plugging systems is also noted. More information on design basis and how POPLU experiment fulfils the design requirements is found from the DOPAS Deliverable D4.4 [DOPAS 2016b].

Table 5.1. POPLU Structural component summary.

	POPLU Experiment			Future Operational Plug	
Structural Component	**Experimental function**	**Objective**	**Design basis**	**Function**	**Design basis**
Concrete wedge	Concrete structure to be tested for the sealing of the demonstration tunnel, especially for wedging-effect	Watertightness and load carrying capacity	The hydraulic conductivity of the concrete mass shall be $<1x10^{-11}$ m/s. The compressive strength of the concrete shall be greater than 50 MPa at 91 days.	same	
Steel reinforcement	Prevent thermal, loading and shrinkage crack formation	Watertightness and load carrying capacity	Reduce the leakage across the plug to be "as low as possible".	same	
Bentonite tape	Improves concrete structure watertightness. Confines grout channels.	Watertightness	Reduce the leakage across the plug to be "as low as possible".	same	
Grouting, with tubes	Improve concrete structure watertightness by sealing interface	Watertightness	Reduce the leakage across the plug to be "as low as possible".	same	
Filter layer	Facilitate the pressurisation of the plug with even water pressure distribution to the concrete wedge	Acts as a water holding volume used for the pressurisation	Low-pH lightweight concrete blocks with high water permeability. Low-pH mortar for attaching blocks together.	Watertightness, by: 1) Preventing damage of the plug. 2) Enabling artificial wetting of bentonite.	1) The pressure against the plug shall be minimal before the concrete has cured and gained sufficient strength. Air or water can be released from the filter layer during early ages to prevent pressure accumulation. 2) Potential to add water behind the plug to induce swelling in the bentonite, to prevent leakage.
Plug lead-through pipe	Air and water exchange with the filter layer	Watertightness of the circumference and flange of the lead-through	Watertightness		

	POPLU Experiment			Future Operational Plug	
Structural Component	**Experimental function**	**Objective**	**Design basis**	**Function**	**Design basis**
Instrumentation system, including wires, ties, connectors and sheltering pipes.	Measurement of temperature, relative humidity, displacement, strain, pressure	Verification of plug performance	Reliable, durable, watertight, minimal foreign materials.	No	No
Pressurization system tubes	Carry water to filter layer	Pressurization for performance assessment	Reliable, durable, watertight, minimal foreign materials.	No	No
Rock (Tunnel-to-tunnel) lead-through pipes, including flanges	Carry the pressurisation pipes and instrumentation cables from one demonstration tunnel to the other	Watertightness	Watertightness	No	No
Concrete backwall	Fill the end of Deposition Tunnel 4 to shorten the experimental length	Fill in the tunnel section behind the filter with concrete to shorten tunnel of the excess space not need for experimental purposes	Low-pH plug concrete recipe used, served as a casting demonstration	No	No

5.2.2 Concrete Plug

The structural design of Posiva's reference plug is described in the Backfill Production Line report [Posiva 2012a], as a dome plug similar to SKB's DOMPLU experiment. The POPLU experiment demonstrates the alternative design of a wedge plug, with details described in DOPAS Deliverable D3.24 [DOPAS 2014c]. The following sections briefly summarize the structural design, though more details can be found in the DOPAS D3.24 report. The engineering structural design of POPLU and the corresponding construction method statements were made by Sweco Oy, earlier Finnmap Consulting Oy [Finnmap 2010, Parkkinen 2013], and approved by Posiva Oy.

The POPLU wedge design has a massive concrete length cast directly adjacent to a filter layer, which would be adjacent to the backfill clay blocks in an operational plug. The POPLU experiment includes only the concrete plug and filter layer, with a concrete backwall used to shorted the tunnel. The concrete plug includes a lead-through tube passing through the plug for potential air and water exchange to the area behind the plug, as a precautionary measure. There are circumferential strips of bentonite tape and grouting tubes placed at the plug to tunnel rock interface, for improved watertightness. The dimensions of the concrete plug are a length of 6000 mm, a width of tapered from 3500 mm (adjacent to the tunnel) to 5500 mm at the widest section of the wedge. The concrete is cast in two sections, each being 3000 mm in length. The plug needed to be cast in two parts to minimise the risks of: 1) cracking that could occur due to the maximum temperature rise (and gradients) associated with concrete hydration immediately after casting; 2) heterogeneity that could occur if insufficient concrete flow across the mould length when pumped into the mould without compaction. The concrete surfaces are of Class A with normal tolerances for cast-in-place concrete, in accordance with Finnish standards [BY40, BY47]. Figure 5.2 shows the planned dimensions of the experimental plug, while Appendix A graphics of sensor locations show the plug dimensions based on actual DT4 dimensions.

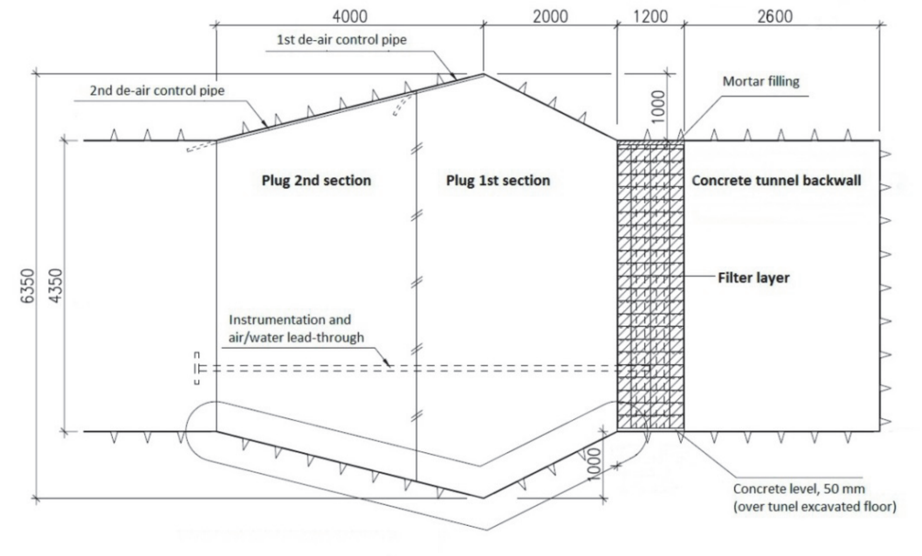


Figure 5.2. POPLU plug design and planned dimensions.

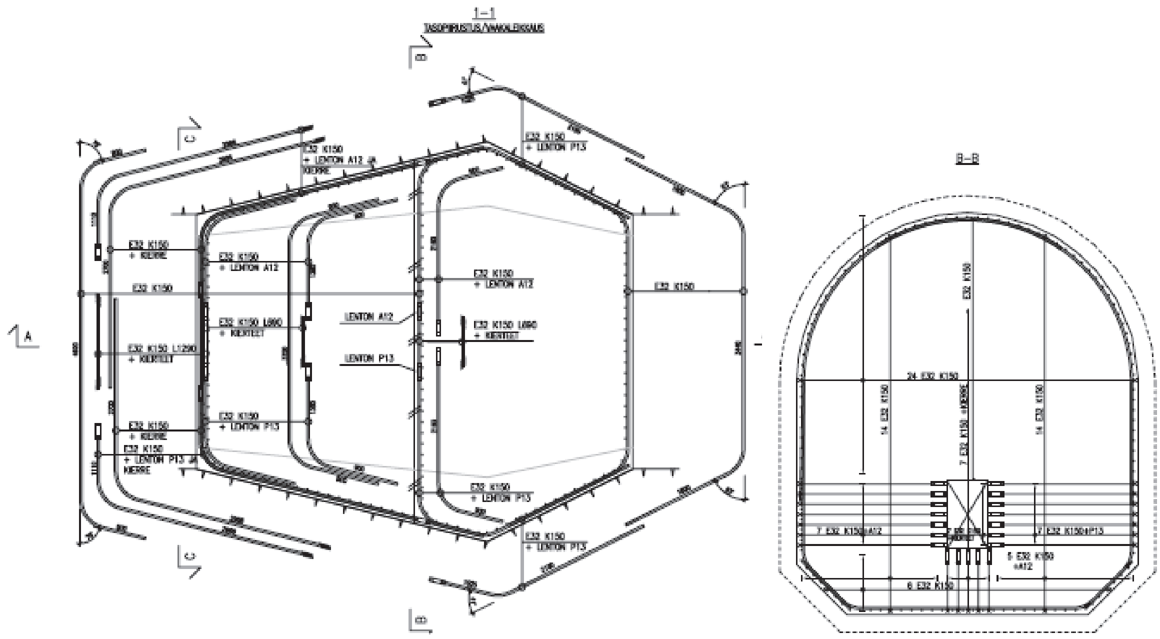
The plug is expected to be extremely tight against the rock due to mechanical forces resulting from the swelling backfill. The wedge-shape is generated by designing a 1000 mm groove in the tunnel rock, therefore locking the plug in place. The watertightness of the plug shall be as high as possible, including the leakage water around and through the plug. The quality of the tunnel rock excavated damage zone is very important, due to the amount of fractures and their level of connectivity. The structural dimensioning was based on the concrete grade and required reinforcement with respect to the imposed compression and tension forces, potential crack widths and concrete hydration temperature effects.

The structural parameters used for dimensioning the plug are given in Table 5.2 [Parkkinen 2013, DOPAS 2014c]. The loads acting on Posiva's plug are a water pressure of 4.5 MN/m^2 (representing a water column of 450 metres) and maximum average swelling pressure of 3.0 MN/m^2 from the bentonite backfill in operational repository conditions. The heat expansion arising through the bedrock from spent nuclear fuel canisters will also load the plug at a maximum level of 13 MN/m^2. The expected lifetime of the plug is 100 years. The whole structure on both side of plug is completed in this period and the water pressure shall reach equilibrium on both sides.

Table 5.2. Dimensions used in reinforcement calculation [Parkkinen 2013].

	Concrete	Steel	Bedrock
Quality	C35/45	Stainless reinforcing steel bars	
Compressive strength f, MN/m^2	45		
Flexural tensile strength, MN/m^2	3.2		
0,2 edge of steel, MPa		480	
Breaking strength, MPa		700	
Elastic modulus E, MPa	34 000	200 000	60 500
Poisson's ratio ν	0.2		0.25
Thickness ρ, kg/m^3	2400		2700
Temperature coefficient α	10^{-5}		10^{-5}

Steel reinforcement is used in the plug structure to minimize the crack widths that may result due to loading, thermal gradients and shrinkage of the concrete material. The allowed maximum cracking width is 3 mm. The reinforcement is stainless steel ribbed bar type B600KA2. The maximum bar size is 32 mm and the minimum concrete cover depth 50 mm. An example section of the reinforcement design is given in Figure 5.3, which was originally based on the plug theoretical design dimensions. The reinforcement detailed drawings were updated based on actual tunnel dimensions after slot excavation.



(a) (b)

Figure 5.3. Sample reinforcement design for POPLU. [Finnmap 2010]

From a monitoring perspective during the demonstration, use of reinforcement provides a better grid for attachment of monitoring sensors within the concrete. For instance, strain gauges attached to a long span of reinforcement give a more representative measure of the cracking risks than if they are freely suspended with the concrete. More details about POPLU's instrumentation and links to the structural design are within Chapter 4.4 and DOPAS Deliverable D3.25 [DOPAS 2014a].

The plug structure includes grouting of the plug to rock interface to aid watertightness and compensate for any shrinkage during the plug hardening (first 90 days). The grouting procedure is done according to the construction specifications written by Finnmap Consulting Oy, in accordance with Finnish national guidelines. The grouting sequence includes mounting grouting hoses and bentonite sealing bands to the slot rock surface at the time of building formwork and installing steel reinforcement prior to casting. There are 6 sets of injection tubes, with half being in part of the two concrete plug sections. There are three bands of bentonite, one is placed near the connection of the two separately cast sections of the plug, and the two others are near the front and back end of the concrete plug structure.

After casting the second section of the concrete plug, the concrete is allowed to harden a minimum of 90 days prior to grouting. The maximum injections pressure is 100 bar (10 MPa), with a speed of 10 bar/min. After injection, the pipes are flushed with water and then drained. Grouting is carried out via six hose loops and every loop includes four hoses (supply and return hoses). Loops 1 and 6 are first grouted and then after 8 days of hardening loops 2–5 can be grouted. Sensors within the concrete may be used to evaluate the influence of grouting on the plug properties, such as strains and displacements. More details about the grouting layers and work sequence are given in DOPAS Deliverable D3.24 [DOPAS 2014c].

The structural design of POPLU differs from the dome design, as used by SKB in the DOMPLU experiment, based on the size of the plug itself and the design properties of the structure. The key difference is that POPLU's design concept is that the plug dimensions vary little from initially, as-cast.. This is achieved by the use of reinforcement steel in POPLU and a low heat concrete. Different from DOMPLU, POPLU does not use cooling pipes within the plug to force contraction (thermal cooling gradient). Both plugs were designed and modelled so that the concrete heat development during cement hydration stay sufficiently low so as to not induce thermal cracking. The DOMPLU structural design was expected to have the concrete detach or pull away from the tunnel rock walls, while the POPLU structure is allowed to remain closer to the slot dimensions with potential adhesion between the concrete mass and tunnel rock wall. This also influenced the decisions about the slot excavation method and resulting smoothness or texture of the rock walls. Both designs utilize injection grouting of the concrete-rock interface. POPLU includes a lead-through via the plug for air and water release, while DOMPLU's central lead-through is primarily for instrumentation purposes. POPLU, as well as SKB's DOMPLU, uses bentonite tape around the circumference.

5.2.3 Backwall

The objective of the backwall at the end of Deposition Tunnel #4 was to shorten the tunnel for the experimental POPLU purposes. The tunnel was excavated based on the various alternative methods that could be used for slot excavation and the horizontal space they may require. As the POPLU experiment consisted only of a filter layer and concrete for the plug itself, there was no need to have excess space at the back of the tunnel and it was not to be filled with bentonite clay (backfill) for the POPLU experiment. Therefore the tunnel was shortened by filling with approximately 3 metres in length of concrete casted in tunnel dimensions. Thus the POPLU plug slot was positioned in a located in an area with the least amount of fractures, as noted in Chapter 3 about the RSC evaluation and siting process.

The backwall was constructed using low-pH concrete with the same recipe as to be used for the plug itself. In this way the backwall served as a demonstration of the material, including construction practices related to concrete batching, mixing, delivery and pumping. Formwork was constructed and steel reinforcement was used around the circumference of the backwall. Seven sensors, measuring temperature, relative humidity and displacement, were placed in the backwall to evaluate the initial performance, though these were later disconnected at the time of filter and plug construction.

5.2.4 Filter

The objective of the filter layer is to allow more even water distribution behind the plug, adjacent to the tunnel backfill material. The filter is connected to the front face of the plug, towards the central tunnel, via a plug lead-through containing air filled pipes. For POPLU experimental purposes, the filter layer provides a water holding volume to be used during the accelerated pressurization to simulate the operational conditions of the plug over the 100 years of service life. The filter layer can also serve as an air and water accumulation point, from which pressure can be released via the plug's concrete lead-through if the plug leakage or back-pressure is exceeded. The filter holds the water that is added via the pressurization system from the neighbouring tunnel (demonstration tunnel 3, ONK-TDT-4399-56). The filter layer also works as the backside form adjacent to the concrete casting of plug section 1. During actual repository operation, a filter layer may still be used for water collection from the backfilled tunnel during plug construction and initial state while the concrete is emplaced and hardening. The filter layer can also be used to artificially wet the watertight seal to enhance the watertightness of the plug.

For POPLU experimental conditions, the requirements for the filter layer are given in Table 5.3. The permeability was controlled by the void content, with a target being over 10% voids in concrete made with lightweight pervious aggregate (such as Leca expanded clay, having an aggregate void content of 46%). The paste was made of the same proportions as in the low-pH concrete, with maximum 200 kg/m^3 of binder used in a ratio of 40% silica fume and 60% cement.

Table 5.3. Suggested filter performance.

Property	Target Value	Method of measurement	Justification
High water permeability	1x10-4 m/s	Filtration: ASTM C1701/C1701M-09	Similar to SKB, for DOMPLU [DOPAS 2015].
Low pH	≤ 11, in reference deep groundwater conditions	VTT Leachate test method, 90 days	Safety expectation for bentonite long-term stability (similar to concrete plug requirement)
Compressive strength	≥1 MPa at 7 days	EN 12390-3	Construction need, to support concrete during casting (backside formwork)
Low bulk density	≤ 1000 kg/m^3	EN 12350-6	Ease of handling
Early-age (fresh mix) workability	Homogeneity	visual, based on placement	Ease of placement when making specimens

There was not a performance limit of the filter with regard to compressive strength during pressurization, thus allowing it to be broken or crushed during high pressurization of the plug. The filter layer was designed to be 1.2 metre thick, or deep, covering the whole surface area of the plug face at 5 metres height and 4 metres wide. This length or depth behind the plug was partially chosen based on the available dimensions of moulds for the pre-fabricated blocks used to build the filter wall. The filter layer had no reinforcement steel. During the course of the plug and filter design work, an alternative method of a pressurized rubber bag was also considered rather than water pressurization via the filter layer. Time limitations for POPLU construction prevented this alternative method to be further investigated.

5.2.5 Rock Lead-through

The main purpose of the rock lead-through pipes is to carry the pressurisation pipes and instrumentation cables from one demonstration tunnel to the other. In addition, the lead-through containing the pressurisation pipes is used during the water filling of the filter layer to evacuate air from the filter layer through one of the pressurisation pipes. Also it is possible to drain the filter layer through the pressurisation pipes if necessary. It is noted that these rock lead-throughs, containing the instrumentation and pressurization systems, are for research purposes of the POPLU experiment only. They would not be used in an operational repository plug.

Three rock lead-throughs were needed to carry the pressurisation pipes from DT3 to the filter layer behind the plug in DT4, and to carry the sensor wiring from the POPLU experiment in DT4 to the data acquisition system in DT3. The uppermost lead-through is for the pressurisation pipes and the two lower ones are for the instrumentation cables.

The design of the lead-through pipes is based on the design used by SKB in the DOMPLU experiment, as described in general in the Deliverable D4.3 [DOPAS 2015]. The design was modified by designers at Finnmap Consulting Oy according to the distance of the two POPLU demonstration tunnels and also some of the lead-though materials were changed based on the requirements of foreign materials control at ONKALO. The design drawing for the three rock lead-throughs is shown in Figure 5.4.

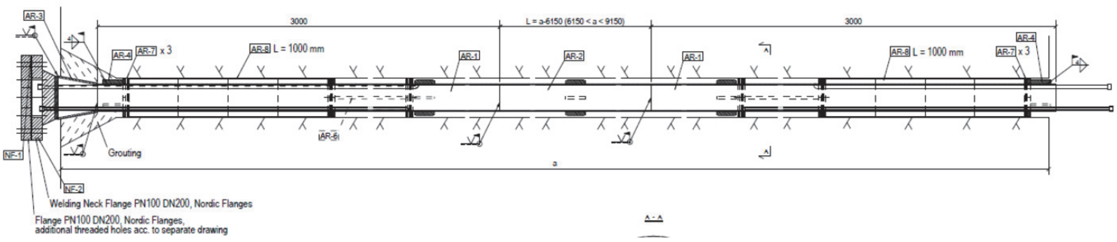


Figure 5.4. Rock lead-through design drawing.

For constructing the rock lead-through, Posiva ordered all parts and materials, which were inspected first on-site above ground at ONKALO. All components were then sent to IS Works Oy in Pori for assembly. The lead-through pipes made of stainless steel are 141 mm in diameter and 8 750 mm in length. The lead-throughs are equipped with flanges at each end and bentonite rings intermediately within the rock hole to ensure that the contact between the rock and the lead-through pipes is water tight. The lead-through pipes are also contact grouted between the bentonite sections to further ensure the watertightness.

5.2.6 Concrete Lead-through

The POPLU experiment contains a concrete lead-through pipe that goes through the concrete wedge structure from the front surface of the plug to the filter layer (Figure 5.4). The plug lead-through pipe is made of stainless steel and is 141 mm in diameter and 6 885 mm in length. It is made watertight by using flanges and bentonite tape around the pipe in several locations concentrated at the junctions of the formwork faces during casting.

The purpose of the concrete lead-through is to serve as a water and air inlet from the filter layer. There is no experimental purpose for the lead-through and it is only to be used in the exceptional case that the water pressure of the filter layer needs to be swiftly released. The lead-through may also be used during the plug operational lifetime in an actual repository to artificially saturate the watertight seal. The other purpose of adding the lead-through to the POPLU experiment is for future reference to test that such a lead-through can be made watertight. Posiva's current reference design presented in the Backfill Production Line Report [Posiva 2012a] includes the concrete lead-through pipe with the purpose to control the pressure of the filter layer during plug construction and also to possible artificially wet the seal layer for increased watertightness.

The design of the lead-through pipe is based on the design used by SKB in the DOMPLU experiment. The design was modified slightly by structural designers at Finnmap Consulting Oy to be adapted for use in the POPLU experiment. The design work including modelling of the watertightness and deformation with loading to 4.5 MPa. Figure 5.5 shows an example of the modelling of deformations, being maximum 0.15 mm.

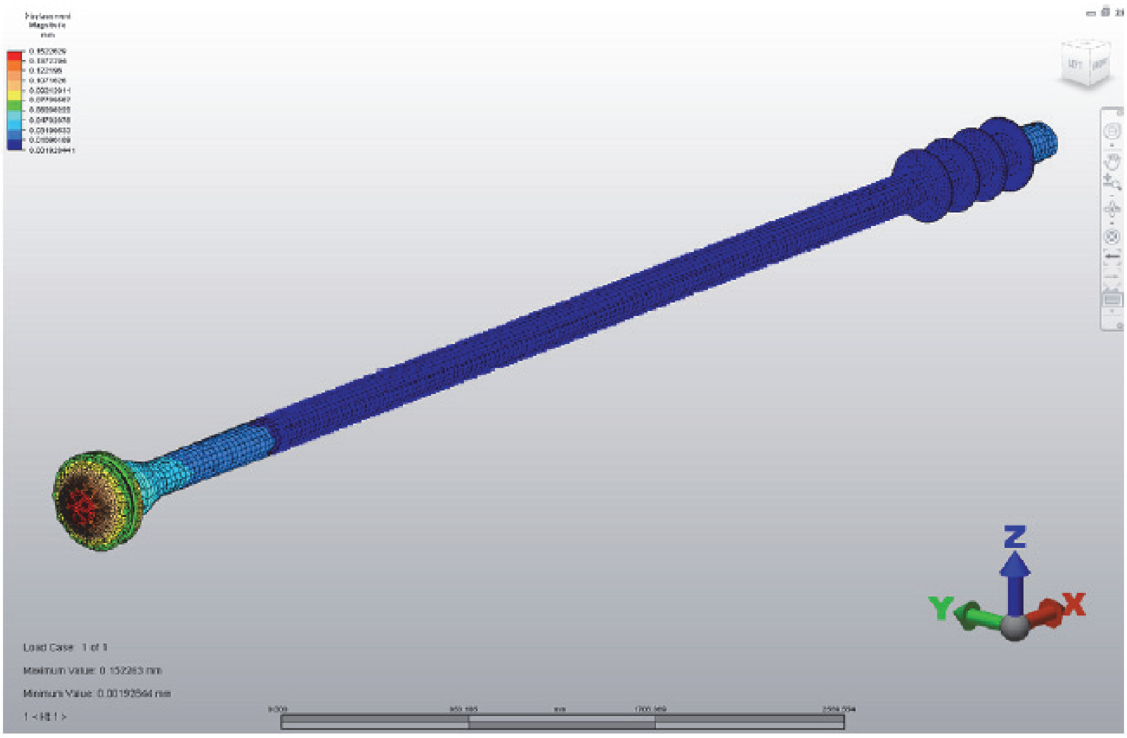


Figure 5.5. Modelling of deformation of concrete lead-through with 4.5 MPa pressure. Left side is embedded to filter, while right side rings indicate water flow stoppers and bentonite tape location.

For constructing the concrete lead-through, Posiva ordered all parts and materials, which were inspected first on-site above ground at ONKALO. All components were then sent to IS Works Oy in Pori, who assembled the lead-through into a two component system. Welding was checked with non-destructive testing. The materials were then returned to ONKALO, installed to filter layer and through the formwork.

The lead-through extends about 10 cm within the filter layer, with the inner opening covered by stainless steel mesh. The pipe extends about 5 cm outside of the formwork from the 1st section plug section. For extending through the 2nd formwork, there are metal flanges around the middle of the pipe and then about one metre of bentonite tape is placed adjacent to the formwork mould interior. Both the flanges and tape are used for extra watertightness. There are no wires through the concrete lead-through, unlike SKB's DOMPLU design.

5.2.7 Formwork

The formwork design was subcontracted by the plug construction contractor, Hartela Oy. As the formwork could not be attached to the rock in the immediate area of the plug, a design was created that allowed the formwork to be supported by jacks against a circumferential tunnel frame approximately 1 metre from the plug front face (towards the central tunnel). The formwork design included rock bolts into the tunnel for mould attachment, to which a reinforced concrete frame was cast approximately 2 months prior to use. The same frame was used for attaching jacks against the two formwork sections used in casting the two sections of the plug. The formwork frame is intended to be removed from the plug area after construction in repository conditions, thus the frame was made from normal (not low-pH) concrete and non-stainless steel.

The design of the formwork was based on hydrostatic pressure related to the SCC, with the estimated range during casting to be designed for 0.2 MPa at the base to 0.05 MPa at the top. The formwork was made of wood and supported by steel beams. More details are given within the construction section.

The formwork for the backwall was supported by rock bolts from the backwall of the tunnel. These rock bolts remained in the backwall structure after the removal of the mould.

5.3 Materials

The materials used in the plug consist primarily of low pH-concrete reinforced with stainless steel reinforcement. There are bentonite tape sealing bands placed around the circumference of the concrete plug adjacent to the rock of the slot. Injection grout made with a low-pH recipe is also used between the plug and rock interface. There is a filter layer constructed from pervious concrete blocks behind the plug for water and air distribution. These materials are further described in the next sections. All materials used in ONKALO are required to meet foreign material safety criteria and acceptance, which is also described below.

5.3.1 Low-pH Concrete

The low-pH concrete recipe requirements were based on requirements for bentonite long-term stability as well as low-heat development at the time of casting. A starting point for the recipe development was international experience, especially from SKB's DOMPLU experiment [Vogt 2009, Malm 2012] and AECL's tunnel sealing project in Canada [Martino 2011]. The POPLU experiment concrete development was part of the DOPAS project and is described in detail within DOPAS Deliverable D3.27 [DOPAS 2014b]. The following sections briefly summarize the recipe development by Aaro Korhonen Oy (since 1.1.2015 Sweco Rakennetekniikka Oy), VTT and Rudus Oy and then approved by Posiva Oy for method test and plug casting.

5.3.1.1 Mix Design and Test Methods

The POPLU low-pH concrete had to be developed to account for local materials, stricter requirements for repository in-situ foreign material safety regarding chemical admixtures, and the higher durability demands based on exposure classes and groundwater composition over the long service life. The plug concrete needs to be highly workable, with potentially slight vibration being used within the mould at the time of placement. The cement used was sulphate resistance CEM I 42.5 MH/SR/LA (Cementa, Annlägningscement). The silica fume incorporated to the mixture was in granular form (Finnsementti, Parmix-Silika). Aggregates were local materials available on-site at ONKALO, with the addition of quartz filler having d_{50} = 35 µm (Sibelco Nordic, Nilsiä). During initial trial batches, VTT laboratory Finnish aggregates were used to replicate the aggregate gradation of the earlier SKB reference mix. For the new POPLU mixtures, a naphtalene-based superplasticizer was used (HaBe, Pantarhit LK (FM)), while in the Swedish plug concrete (recipe labelled B200), a polycarboxylate-based superplasticizer (Glenium C151) was used.

The recipes were evaluated for early age performances, assessing workability by slump, flow, and rheology (SFS-EN 12350 and Contec5-viscometer), air content (SFS-EN 12350), setting time (SFS 5289), segregation and heat of hydration using semi-adiabatic conditions (RILEM TC119-TCE1). The hardened properties evaluated included compressive and split tensile strengths and density (EN 12390), elastic modulus (SFS 5450), watertightness (EN 12390), autogenous and drying shrinkage, non-steady state chloride migration (NT Build 492), sulphate resistance, and pH leachate. In the analysis, the Swedish “B200” mixture was used as reference comparisons in addition to traditional high performance normal concrete.

Two applicable mix designs and a reference mix were developed. The first mix design (Binary mix) had a binder composition equal to the Swedish DOMPLU concrete. In the modified version, the plasticizer was changed to naphthalene-based superplasticizer, limestone filler was replaced with quartz and the water content was lowered from 157 l/m^3 to 125 l/m^3 by modifying the aggregate grading curve. All of these mixtures required a high dosage of superplasticizer to achieve the workability, with dosages in the order of 4.5–7.5% by binder content. These new modifications, compared to the reference Swedish mixture, were expected to increase the durability of the concrete while not causing drastic changes in other qualities.

The second mix design was labelled as the Ternary mix design, in which a high quality fly ash was used in addition to the silica fume. Again a workable concrete was obtained with an effective water content of 126 l/m^3 though for this mixture it was not specified during the recipe development to be self-compacting, thus the slump and slump flow values were significantly lower. For reference purposes, the Swedish B200 mix design was also re-cast using Finnish laboratory materials. Figure 5.6 shows examples of the two final POPLU mixtures, with allowable variation in aggregate size and workability based on the initial targets.

Table 5.4. Final mix designs of Posiva's low-pH concretes.

	Final Ternary mix design	Final Binary mix design	B200 SKB mix, with Finnish laboratory materials
CEM I 42,5 MH/SR/LA	105 kg/m^3	120 kg/m^3	120 kg/m^3
Silica fume	91 kg/m^3	80 kg/m^3	80 kg/m^3
Fly ash	84 kg/m^3	-	-
Quartz filler	114 kg/m^3	256 kg/m^3	-
Limestone filler	-	-	370 kg/m^3
Local aggregate	1840 kg/m^3	1805 kg/m^3	-
VTT laboratory aggregates			1600 kg/m^3
Effective water content	126 kg/m^3	125 kg/m^3	157 kg/m^3
Water/binder -ratio	0.45	0.60	0.79

a) *b)*

Figure 5.6. Appearance of final laboratory mixtures developed for POPLU: a) binary, b) ternary blend.

5.3.1.2 Performance Results

The workability of all of these developed mixes was quite high. The Binary mix had a slump of 260 mm and the Ternary mix 190 mm. The Binary mix was almost self-compacting concrete, having slump flow 650 mm. The heat development is a concern for using concretes in this type of massive concrete tunnel plug structure, and thus lowering it was one of the key design targets. The temperature rise was low (under 10 °C change in semi-adiabatic conditions) in all of these concretes due to low cement content. The compressive strength target was only 50 MPa at 91 days measured on 15 cm cubes and all of these concretes exceed that target quite remarkably. Table 5.5 provides a summary of the achieved results for the two new Finnish plug mixtures are given. The target values, Swedish DOMPLU (B200 reference, [DOPAS 2015]) concrete as well as normal concrete values are also presented for comparison purposes.

Table 5.5. Summary of Finnish low-pH concrete (POPLU) performance results at lab-scale, compared to traditional high performance concrete and the target values.

	POPLU Target	**POPLU Binary**	**POPLU Ternary**	**Reference Swedish "B200"** [a]	**"Normal concrete"**
Compressive strength, MPa	> 50	91.5	79.5	67.5	50
Split tensile strength, MPa	3.2	5.6	4.5	-	3.2
Modulus of elasticity, GPa	34	37.4	34.2	-	34
Autogenous shrinkage, mm/m	(min)	0.22	0.15	0.03	0.1
Drying shrinkage, mm/m	(min)	0.17	0.22	-	0.6
Water tightness, mm	max 50	4.0	5.0	5.3	25
Chloride diffusivity, m^2/s	(min)	$2.1*10^{-12}$	$2.8*10^{-12}$		$10\text{-}20*10^{-12}$
Sulphate damage	(min)	None at 180d	None at 180d		
pH of leachate at 90 days (reference/Groundwater)	< 11	11.4/10.3	11.4/10.3	11.4/10.3	>12.5

[a] *Results are based on re-production of mix in Finland*

The results of the lab-scale testing were then verified by trial mixtures being reproduced in the laboratory facilities of a Finnish ready-mix company, Rudus Oy. Posiva decided to proceed with the Ternary mixture design, containing both silica fume and fly ash, and thus batch trials were done in Rudus Oy headquarter labs and then at the local Olkiluoto batch plant. Results from these trials included minor adjustments to the admixture dosages in preparation for the metric scale tests and then final POPLU casting.

5.3.2 Filter Layer

The filter layer was constructed from lightweight concrete blocks, manufactured by Rakennusbetoni- ja Elementti Oy using expanded clay (Leca) lightweight aggregate with 10 mm maximum size. The blocks were made using a low-pH paste having proportions similar to the plug binary concrete mix design, where there was 40% silica fume and 60% cement as the binder and a maximum binder content of 200 kg/m^3. Preliminary trials were done in the VTT labs to determine the mixture proportions and properties such as void content, density, water permeability and compressive strength. The main results of the pre-study are given in Appendix B. The blocks had compressive strength over 2 MPa at 7 days, bulk density under 1000 kg/m^3, water permeability greater than $1x10^{-4}$ m/s, and void content about 40%. Air escape during pressurization was measured by applying 150 bar water pressure, with no damage visually observed to the filter blocks. Based on the initial lab results, manufacturing proceeded to the factory where 1200 blocks of type RUH300 were produced for Posiva in spring 2015 (see Figure 4.4). The dimensions of the block were 590 mm long x 290 mm wide x 190 mm height, which was based on available moulds from the factory.

During installation, the blocks were secured together and to the rock wall with low-pH mortar. The mortar had a maximum paste binder content of 200 kg/m^3 and a ratio of 40% silica fume to 60% cement. The aggregate was natural Finnish sand with a maximum diameter of 1 mm. The first layer of filter layer blocks was secured on a footing, also made of low-pH mortar approximately 1.2 metre long and 2–10 mm thick depending on the tunnel floor roughness.

Figure 5.7. Low-pH LECA® blocks used for the filter layer in the POPLU experiment.

5.3.3 Bentonite Tape

The plug structural design includes bentonite tapes in the gap between tunnel rock walls and concrete plug. The bentonite tapes are intended to (i) to support the grouting process by keeping the grout in place during the first low pressure injections and (ii) to increase the long-term tightness of the plug by preventing seepage through the rock/concrete interface. Bentonite tapes are normally used in construction, e.g. between concrete elements where they swell and thus tighten the concrete structure when exposed to water.

The tapes run circumferentially around the plug, in three sections. They are fastened to the rock with small metal screws at the time of constructing the formwork and installing the reinforcement steel. The tape is subjected to fresh low-pH concrete (as detailed in [DOPAS 2014b]) cast against it during construction.

During the preliminary POPLU material laboratory-based studies, six different bentonite tapes were assessed to determine their swelling properties and select the material to be used in POPLU. These were the producers and products named: Meltex Oy: Super Stop; Solcon Oy: Bentorub; Semtu Oy: PC.; Betonstrip, Kaitos Oy: Waterstop RX 101; Muottikolmio: CJ; Muottikolmio: CJTA. The swelling was assessed for unconfined samples in different water types. The swelling was greatest in tap water compared to groundwater or concrete-simulating capillary water. The final bentonite tape chosen for use in POPLU was Superstop (manufactured by RPM/Belgium N.V.), which had a high level of swelling in the first day in both capillary water and groundwater. This brand was also chosen as it had the highest amount of bentonite within the tape compared to the other products (and thus the lowest amount of foreign materials). The results from the lab study are given in Appendix B as part of DOPAS.

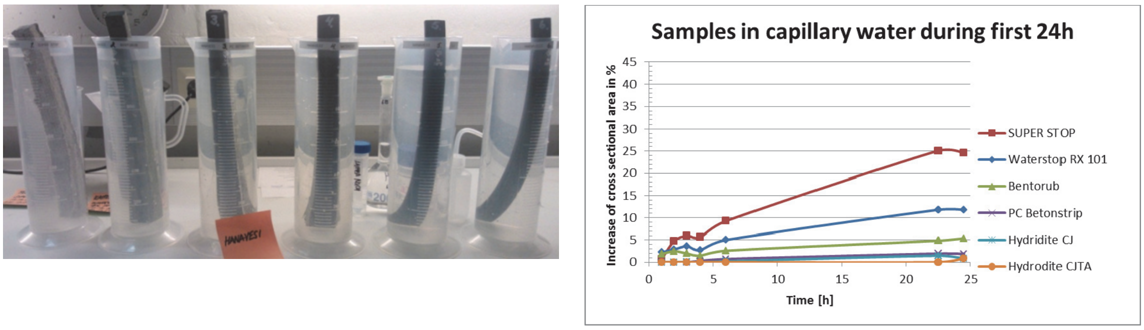


Figure 5.8. Bentonite tape studies. a) materials tested for use in POPLU, b) example of swelling capacity (change in volume) of tapes in simulated concrete capillary water.

5.3.4 Plug Grout

Cementitious grout was used for sealing the interface between the concrete plug and the rock. The grout recipe was developed earlier at Posiva [Raivio 2007, Ranta-Korpi 2007], including a blend of ultrafine cement and silica fume slurry, with an effective water-to-binder ratio under 1.0. A slurry superplasticiser was used to aid workability, instead of powder superplasticiser. Accelerating agents were not included in the grout mix because they restrict the penetrability. The recipe was modified by Posiva in 2015 to account for new source materials due to the earlier used cement and chemical admixtures being no longer being commercially available. The new grout recipe used in POPLU was to have nearly the same performance requirements as earlier. The exact proportions and materials used in the POPLU injection grouting recipe are confidential, based on Posiva’s internal development which was outside the scope of DOPAS.

5.4 Monitoring Systems

The following sections present the POPLU plug monitoring and instrumentation plan. The design of the monitoring system is described in detail in the DOPAS Deliverable Report 3.25 [DOPAS 2014a]. It builds upon the experiences gained in the other ONKALO demonstrations that have been conducted earlier, such as the medium-scale buffer test [Kivikoski 2014, DOPAS 2014a].

The monitoring system was developed by VTT based on the requirements and conditions given by Posiva’s structural design and modelling experts. Further valuable input to the instrumentation plans was received by a pilot expert elicitation (EE) process. This EE process was performed in summer 2013, in addition to the POPLU project’s internal quality assurance procedures. The process and consensus outcome of the EE is described in the DOPAS WP6 Task 6.1 Consensus Memorandum of Pilot EE for POPLU Test Plan [DOPAS 2013]. The expert feedback included 25 discussion items, which were apprehended and implemented in the instrumentation and test plan described below.

The instrumentation is based on sensors in the concrete, behind the plug in the filter layer and in the concrete backwall at the end of the demonstration tunnel. Additionally, the monitoring system includes the pressurization system, leakage water measurement, and data acquisition system. The location of the planned monitoring components is summarized in Figure 5.9, with detailed locations of each type of sensor given in Appendix A.

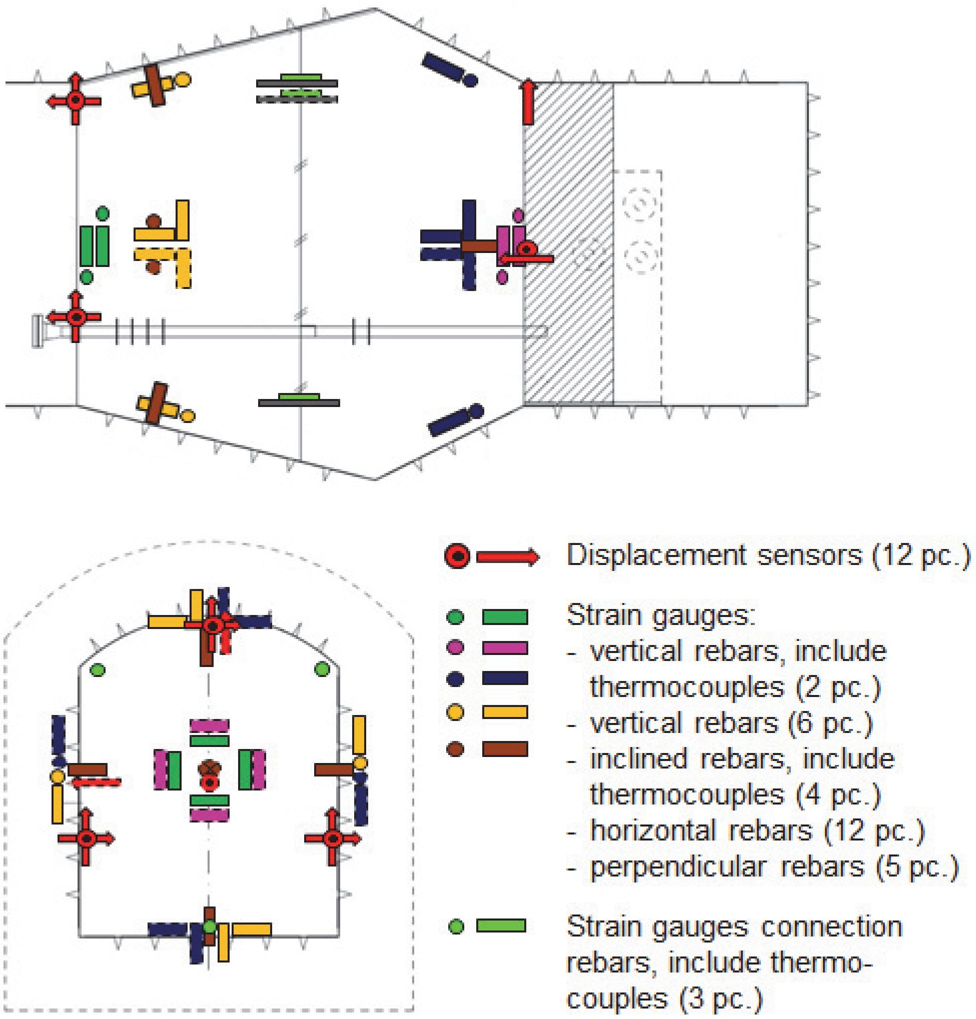


Figure 5.9. Designed location of monitoring system components.

The concrete plug, rock-plug gap (interface), filter layer and concrete tunnel backwall behind the plug are monitored for changes in condition with time and due to the pressurization. These monitored parameters during early stages and pressurization include:

- Displacement of the plug (mm)
- Strain of reinforcement and concrete (μS)
- Relative humidity of concrete (RH%)
- Pressure between the rock and the plug (MPa)
- Pressure in the filter layer (MPa)
- Temperature of the concrete (K)
- Water leakage through and around the concrete plug (dm^3/hour).

It should be noted that redundancy was also built into the monitoring program. This was also demonstrated by the use of some wireless sensors in POPLU, though that work was outside the scope of DOPAS. The POPLU experiment provided added-value to Posiva to have the opportunity to demonstrate new wireless technologies that may be further developed in the future for monitoring of large-scale experiments.

5.4.1 Monitoring System Requirements

The relative humidity in the tunnel is around 80% and the temperature is nearly constant at 10 to 12 °C. The maximum pH-value inside the concrete is expected to be 12. The material of sensors and cables should highly resist corrosion and are sheltered by protection housings and pipes. Therefore most of the sheltering materials and sensor components in direct contact with the plug or filter layer materials are made of stainless steel. For the ease of the installation, some sections of the wire sheltering tubes were made of polyvinylidene flouride (PVDF – thermoplastic fluorpolymer). In general, all materials used for the instrumentation and being installed inside the POPLU plug including the filter layer, concrete backwall and rock lead-throughs, are pre-approved by Posiva regarding foreign materials used in ONKALO. This was done to preserve the natural environment of the repository site.

The water pressure within the demonstration is defined to be up to 4.2 MPa. Since in the real use of a deposition tunnel the maximum pressure will raise slowly, the pressure uptake in this demonstration experiment is accelerated by means of high pressure pumps. The high pressure with a maximum of 4.2 MPa will be gradually decreased from the back to the front face of the plug and reaching tunnel atmospheric pressure at the front section of the plug. On the other hand, deficiencies in the sealing system and possible cracks in the rock mass and concrete could allow penetration and an increase of the water pressure almost to its maximum and therefore the pressure sensors in the gap between the plug and rock have to be sheltered.

During the concrete casting phase, the sensors are protected from any possible concrete vibration work, by installing them as far as possible from potential vibration routes through the formwork and reinforcement, and sheltering them with protection tubes. During the hardening process of the concrete, the temperature can raise up to 50 °C, which is usually not a limitation for normal types of sensors (a preliminary data analysis shows that during hydration of the concrete in plug section 1 the maximum measured concrete temperature was 42 to 44 °C).

The high water pressure can damage the sensors, but it can also penetrate to the cables and connections. Since the concrete shrinks after the casting phase, the wires are sealed against possible water leakage and sheltered with stainless steel tubes and PVDF hoses where possible. All sheltering tubes pass through lead-through flanges (see Figure 5.10) to prevent any leakage on the surface of the wire.

Most sensor types (unless they were too large for the testing equipment) as well as sealing and connection systems were tested prior to installation in VTT’s laboratory inside a pressure vessels for hydraulic pressures of 100 bars.

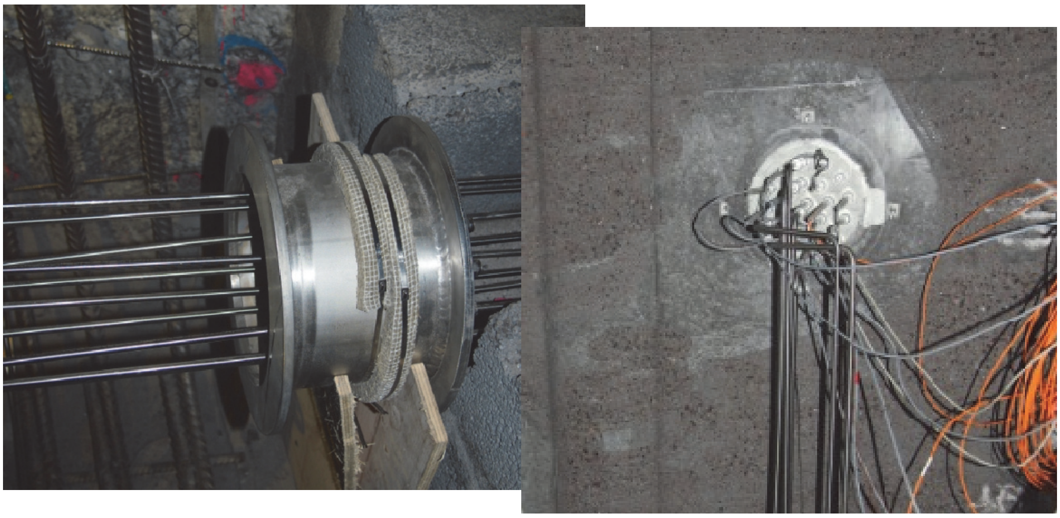


Figure 5.10. Wire flange for sealing of cables passing between filter layer and plug section 1 during construction (left) and between the two concrete plug sections after casting of plug section 1 and during installation of wires (right)

In case of the unintended event that water manages to penetrate through a local leakage (e.g. at a connection joint or a damage) inside the sheltering tubes or between the insulation of the wire and the copper thread, all wires pass through specially designed leakage boxes after they are coming out of the plug or rock lead-throughs respectively and continue to the data loggers. These leakage boxes prevent that water penetrates to cables of other sensors or destroy the channel extension modules and data loggers. Figure 5.11 shows a leakage box for the filter layer and plug pressure sensors and displacement sensors.

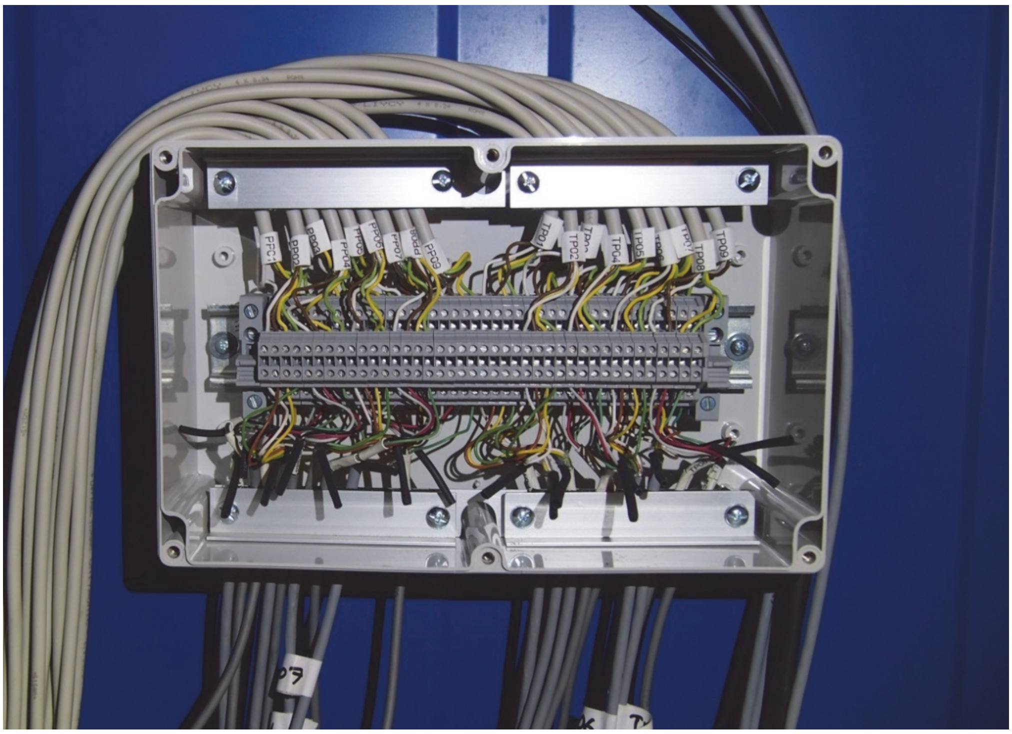


Figure 5.11. Leakage box for interrupting potential water leakage along and inside the wires.

The duration time of the plug test is more than five years and most of the sensors, cables and connections cannot be replaced or maintained during operation. Therefore they should be durable enough to be in constant function without service or maintenance for the entire operation. Almost all sensors are installed permanently inside the structure and therefore they have to work reliably without any calibration during the entire test duration. A post calibration is planned for selected samples later on, during the decommissioning phase after the test has been stopped, prior to repository operation. These are casted inside the same concrete as used for the plug and stored under similar conditions underground in ONKALO in the close vicinity of the plug. Calibration is done to evaluate potential sensor drift, and measurement accuracy. It also can influence sensor selection in the future for monitoring in repository conditions.

5.4.2 Instrumentation/Sensors

The sensors were fixed in the concrete backwall, the filter layer and both sections of the plug. The sensors were selected to measure during the concrete casting, the hydration process and finally the pressurizing phase. During and after the casting phase the sensors measure pressure, humidity and temperature of the concrete. In the pressurization phase, both the concrete condition and performance are measured by displacement sensors and strain gauges.

<u>Displacement sensors</u>

Any possible movement of the plug (e.g. during the grouting phase) are measured by displacement sensors located on the front face of the plug. The sensors measure the relative movement between the rock and plug in three locations at the plug front face. The sensors are located outside the plug and are easy to install and have been selected for a relative humidity of up to 100%. The type of displacement sensor has been selected according to a maximum displacement of 10 mm. The sensors are able to measure with accuracy of 0.05 mm.

In addition, three displacement sensors were installed on the back section of the plug to ensure the plug movement in horizontal, vertical and longitudinal directions. The back face sensors have been selected to resist the high water pressure of about 10 MPa.

Figure 5.12 shows a photo of a horizontal displacement sensor, installed between the filter layer and the concrete plug section 1 as well as the specially designed sensor holder which guarantees a safe and stable location of the sensor during filter layer construction and the rebar installation.

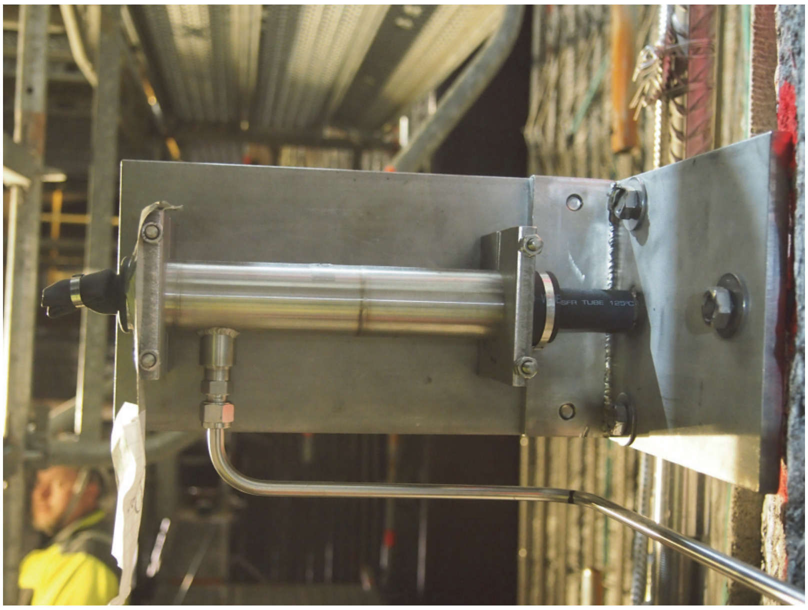


Figure 5.12. Displacement sensors at the back face of the plug and specially designed sensor holder.

<u>Strain gauges</u>

Posiva's wedge plug is designed to be a reinforced concrete structure with rebars at all outer surfaces enveloped by a concrete cover. The rebars underlie stresses due to shrinkage of the concrete and hydration-induced thermal gradients as well as strains due to high pressure during the pressurization phase. The high pressure will take effect mainly on the back face of the plug and also inside the gap between the rock and plug. The stresses inside the plug are mainly compression stresses, but in the corners and on the front face also tension stresses occur.

The strains in the plug are measured by strain gauges fixed on the rebars with an accuracy of about 0.05% within a measuring range of up to 5.0%. It is assumed that the average strains of concrete and rebars are identical, thus no concrete strains will be measured directly. The locations of strain gauges are mainly on the outer sections of the plug and no gauges were installed in the centre of the plug, where no high strains are expected to appear. The sensor locations were selected in compliance with the structural design to allow for an easy comparison between the measured and calculated strains. The detailed locations of the strain gauges inside the plug sections 1 and 2 are shown in Appendix A.

Figure 5.13. Strain gauge on a rebar and sealed with epoxy resin. The wires are sheltered with a PVDF hose.

Relative humidity sensors

The hardening process of the concrete used in the construction of both sections of the plug is investigated by means of in total seven relative humidity sensors in both the front and back sections of the concrete plug. The intention of the measurements is to monitor the hydration process of the unique low-pH concrete. The data provided by the relative humidity and temperature sensors will allow for an evaluation of the concrete quality and condition. The sensors in the plug operate with an accuracy of about 1% within a relative humidity range of 50 to 100%.

The critical locations to monitor the relative humidity of the concrete are the centre of the plug sections, where the hydration heat is highest and influences from outside are weakest, and the areas inside the plug that are closer to the rock or filter layer, where possible changes of the relative humidity might occur after a certain time due to penetration of water into the concrete during the pressurization phase.

Pressure sensors

Two types of pressure sensors were installed to show both the pore water pressure and the total mechanical pressure in the gap between the rock and plug during the pressurization phase. The pore water pressure and mechanical pressure sensors (called in the following total pressure sensors) are designed to measure pressure with a magnitude of up to 10 MPa at an accuracy of 0.1 MPa.

Due to gravity forces and heterogeneities of the rock, the pressure and leakage can be different at various locations around the plug, e.g. in top and low surfaces, and inside the filter layer. The relative locations of pore water pressure and total pressure sensors are shown in Figure 5.14 (detailed locations are shown in Appendix A).

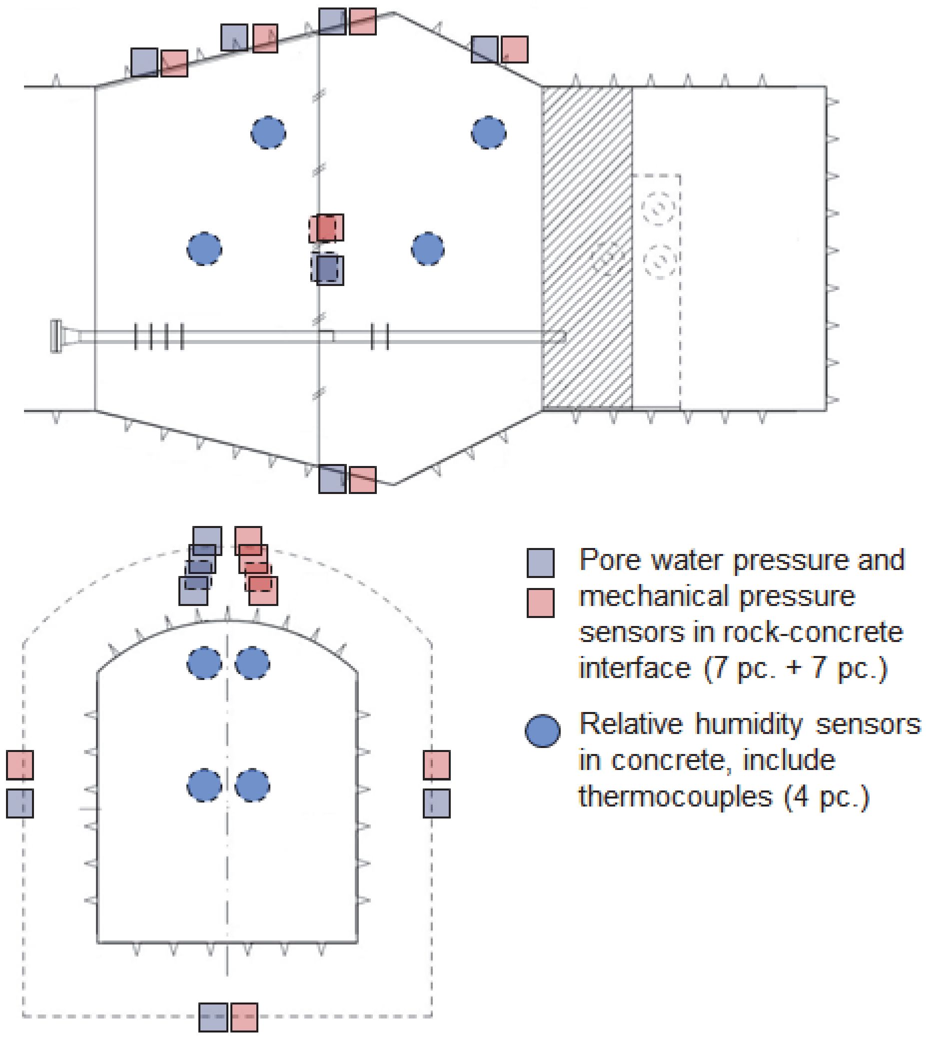


Figure 5.14. Location of pore and total pressure sensors, as well as relative-humidity sensors.

Temperature sensors

The temperature in the demonstration tunnels is quite consistent throughout the year, in average at 10 to 12 °C. However, during the first days after the concrete casting the temperature of the early age concrete can rise up to 50 °C due to exothermic reactions caused by hydration of the cement and additives in the concrete mix. The temperature gradient has an effect on the quality and strength of the concrete.

The concrete temperature is measured in multiple locations of the plug, both as individual temperature sensors and coupled with other sensors. There will be plain temperature sensors in eight locations close to the outer surfaces of the two plug sections using thermocouples with an accuracy of 0.5 K (Figure 5.15). In addition, other installed sensors, e.g. nine strain gauges, all relative humidity sensors and all pressure sensors, will also allow for temperature measurements for instance in the centre section of the plug to monitoring concrete heat of hydration. These sensors help indicate when the formwork can be removed after casting.

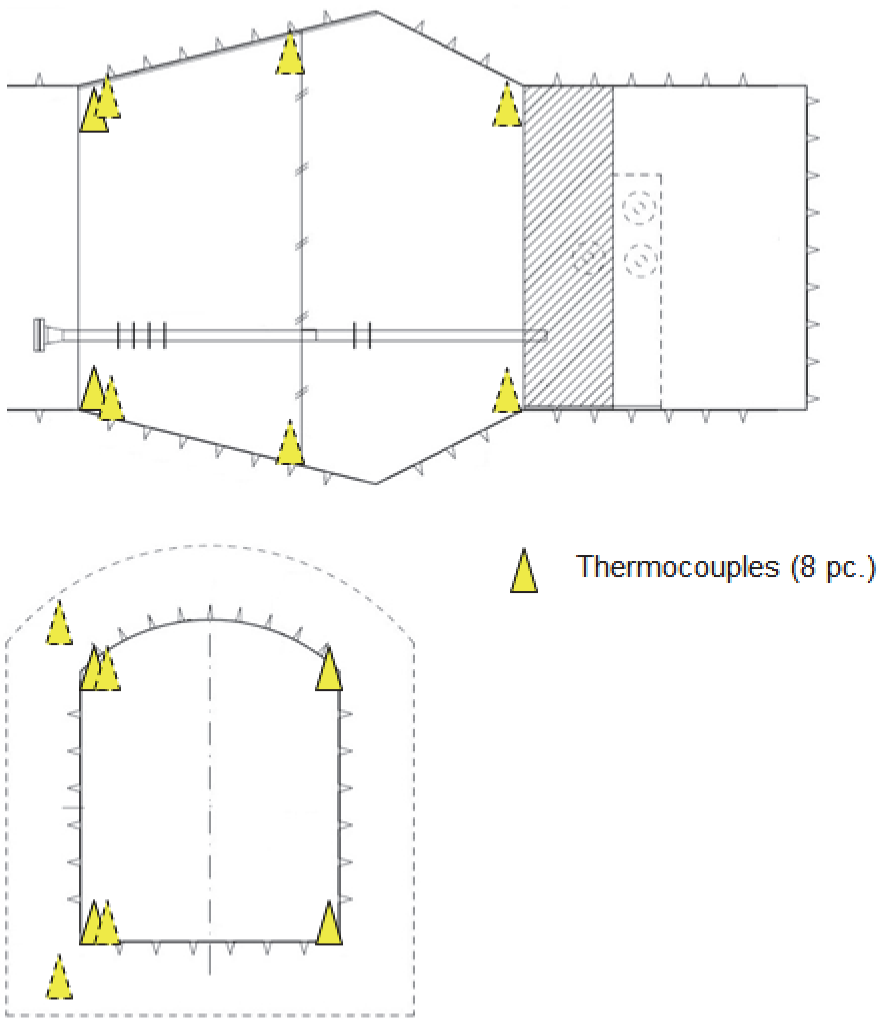


Figure 5.15. Location of extra temperature sensors around the circumference of the plug. Additional temperature measures are coupled with other sensors, such as strain and relative humidity, in the centre of the plug.

5.4.3 Data acquisition system

The data acquisition system was designed to collect the sensor data from the various sensors described in the previous section of this document. The data acquisition system is also responsible for securing and storing the collected data and providing data transfer out from the ONKALO demonstration area.

The ONKALO data acquisition network consists of two segments. VTT measurement network shown in Figure 5.16 contains all the measuring equipment and local data storages, which can operate independently of any external networks. Power supply to the VTT measurement network and data collection equipment is secured with an Uninterruptible Power Supply System (UPS). Second segment of the data acquisition network consists of the Posiva/TVO maintained ONKALO measurement network shown in Figure 5.17, which provides the connection to the ground level and in to the Posiva/TVO network and further.

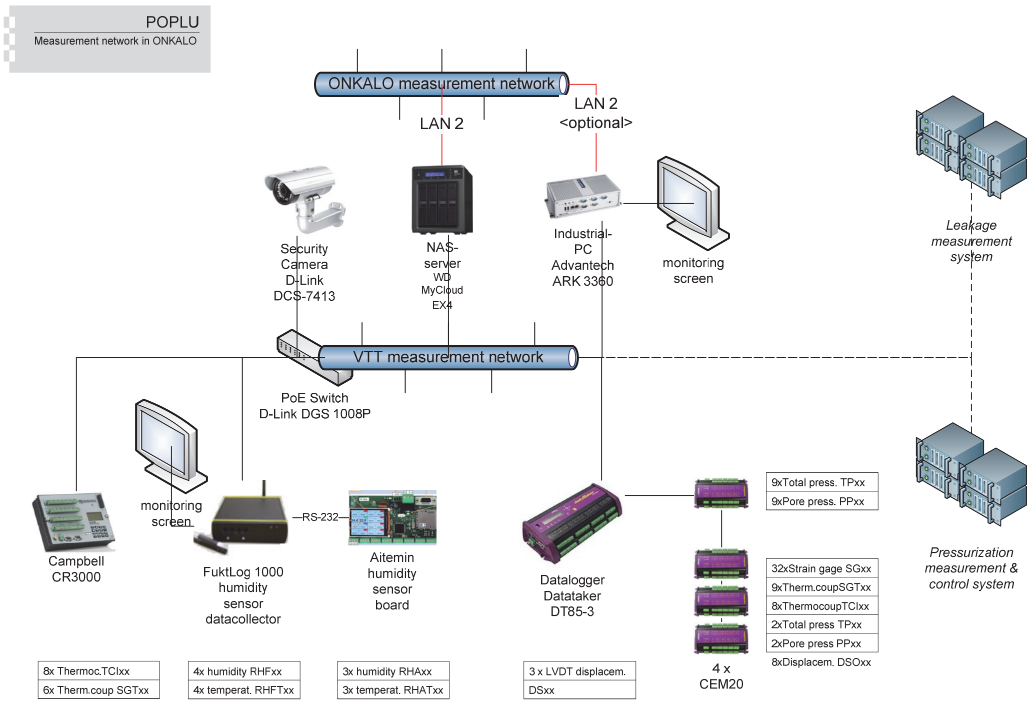


Figure 5.16. POPLU measuring and datalogging network layout.

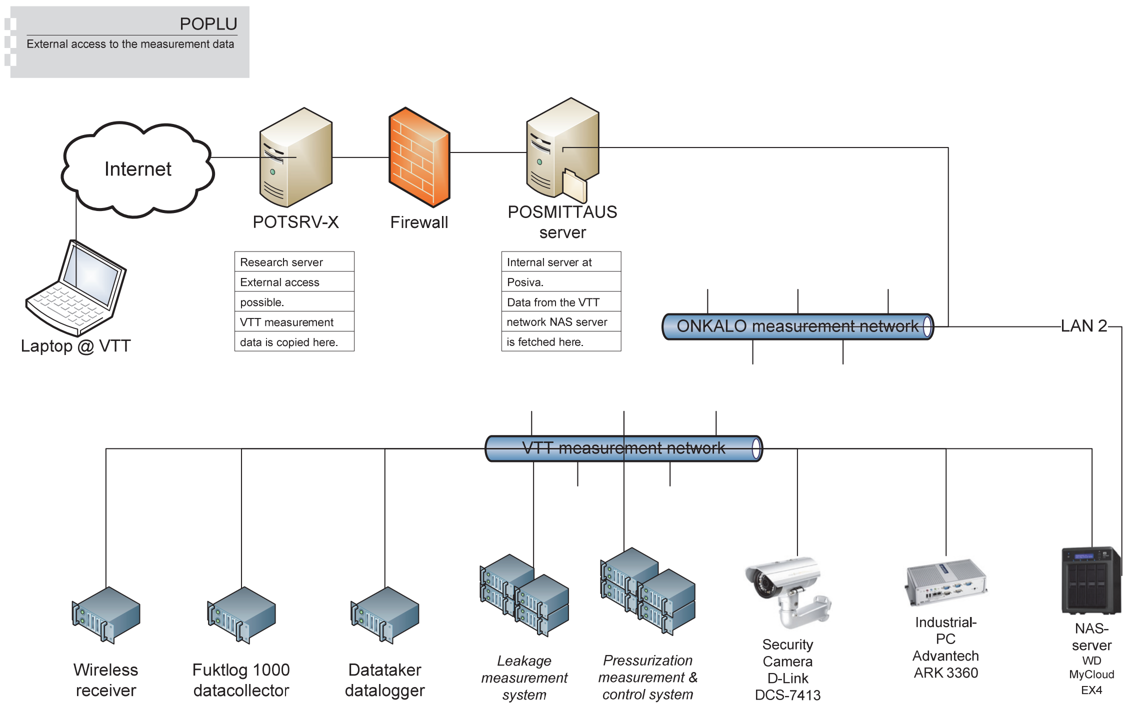


Figure 5.17. External access to the ONKALO measurement data.

<u>Measurement data collection from the sensor</u>

All sensors are installed inside the plug or on the outer surface of it. The main measurement equipment was installed in the (blue) measurement container in DT3 shown in Figure 5.16. Supporting measurement equipment was installed in the temporary (red) measurement cabinet in front of the DT4. After concrete casting of the front section of the plug, the temporary small measurement cabinet was replaced with a bigger and permanent measurement cabinet. The water leakage system located in front of the plug in DT4 was linked to a water collection channel grooved into the floor (as seen in Figure 5.18).

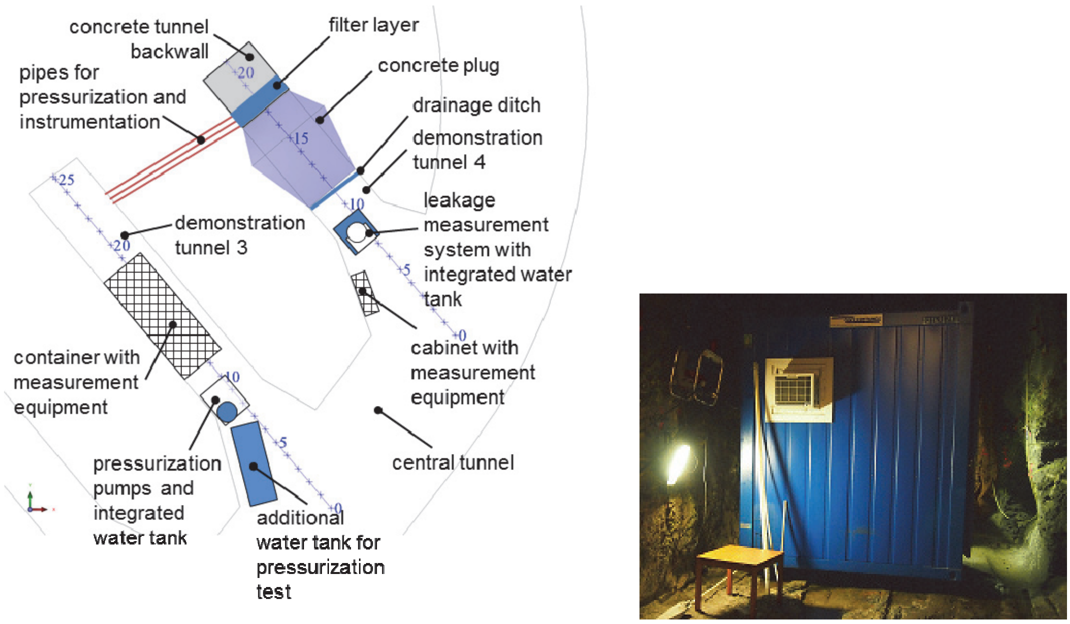


Figure 5.18. Locations of measurement equipment; including blue measurement container in DT3.

Sensors are connected in to four (4) different datalogging devices shown in Figure 5.16. These are the Datataker datalogger, Fuktlog 1000 embedded data collector in to which also the Aitemin humidity measurement board is connected and a Campbell CR3000 data logger for connection of a several temperature sensors. Datataker datalogger with its four channel extension modules (CEM) collect most of the measurement data, as all total pressure and pore pressure sensors with their included temperature sensors as well as all strain gages and other thermocouple sensors are connected in to Datataker's measurement channels.

Fuktlog 1000 data collector is an embedded Windows operating system based computer, which collects the data from the relative humidity and attached temperature sensors. Aitemin humidity measurement board is connected in to the Fuktlog 1000 computer with a serial cable and it provides the measurement of the further relative humidity and attached temperature sensors.

Each of these data logging device contains internal memory, where data is collected independently from other equipment. Each of these devices can store in minimum several weeks of measurement data. They are also equipped with Ethernet connectivity to connect them in to the VTT measurement network.

During autumn 2015 the pressurization measurement and monitoring system as well as the leakage monitoring system were brought in to the ONKALO demonstration area and connected in to the VTT measurement network.

Security camera is installed in front of the plug area and it is taking a snapshot of the area in front of the plug once a minute. Pictures can provide information, if something extraordinary happens in the plug area.

Measurement data storing and backups

As mentioned in the previous section, each datalogging device can store a minimum of several weeks of measurement data on their own memory systems.

To secure and backup the measurement data, all data is automatically transferred into a Network-Attached Storage (NAS) system. It is a file server, where the redundant array of independent disks (RAID) option is enabled, which secures the measurement data in two separate hard disks. So in case one of the hard disks malfunctioned, the data would still be secured.

Measurement data is transferred with the File Transfer Protocol (FTP) from the datalogging equipment automatically with daily and hourly (Datataker datalogger) data transfers. The security camera also uses a FTP to transfer the pictures in to the NAS server, which is done immediately after taking the picture.

The measurement data is also copied automatically from the measurement network NAS server in to a file server in the Posiva/TVO network and duplicated into the research server accessible outside of Posiva/TVO network. From this server data also is then copied to VTT's own research servers for data interpretation and quality control observations on the system. Measurement data will in this operation model be stored in four different locations.

Using the measured data

During the concrete casting of the two sections of the plug, the most interesting measurement data for the constructors was the temperature development in the cast concrete inside the plug. Because of this, the monitoring screens connected to the data acquisition system were programmed to show the temperature trend curves. Naturally all other measurement data was also accessible during the concrete casting.

Figure 5.19. Monitoring the temperatures during concrete casting.

The monitoring system produced a huge amount of raw sensor data, which provides various options for data analysis and interpretation.

5.4.4 Pressurization system

The pressurization system will supply high water pressure for the plug test. The pressure will be gradually raised to investigate the sealing performance of the wedge plug. The pressurizing equipment should work reliably and keep the adjusted pressure behind the plug. The required pressure will be adjusted manually. The long term reliability of the pressurizing setup is high since redundancy is achieved by doubling the most important equipment, to be used in case of failure. The amount of pumped inflow water will be measured carefully and compared to the possible outflow from the front face of the plug.

The pressurization system is located in the neighbouring DT3. Its main components are two high pressure piston pumps, two unloader valves, two electrical motors with gearing box, thyristors with automation and control units, a switchboard, a water tank, manifold connection pipes and a main frame.

The pumping unit comprises of two pumps: low capacity pump (0.15–1 dm^3/min) and high capacity pump (1.5–10 dm^3/min).Pumping unit is designed so that it can operate one pump at the time. Pump’s flow can be adjusted lower from the specified minimum capacity of the pumps by using pass flow valves. Both the low and high capacity pump can generate maximum pressure of 14 MPa and the operating pressure can be adjusted from 0–12 MPa. Figure 5.20 shows the schematic representation of the pressurization system design by FinFinet Oy.

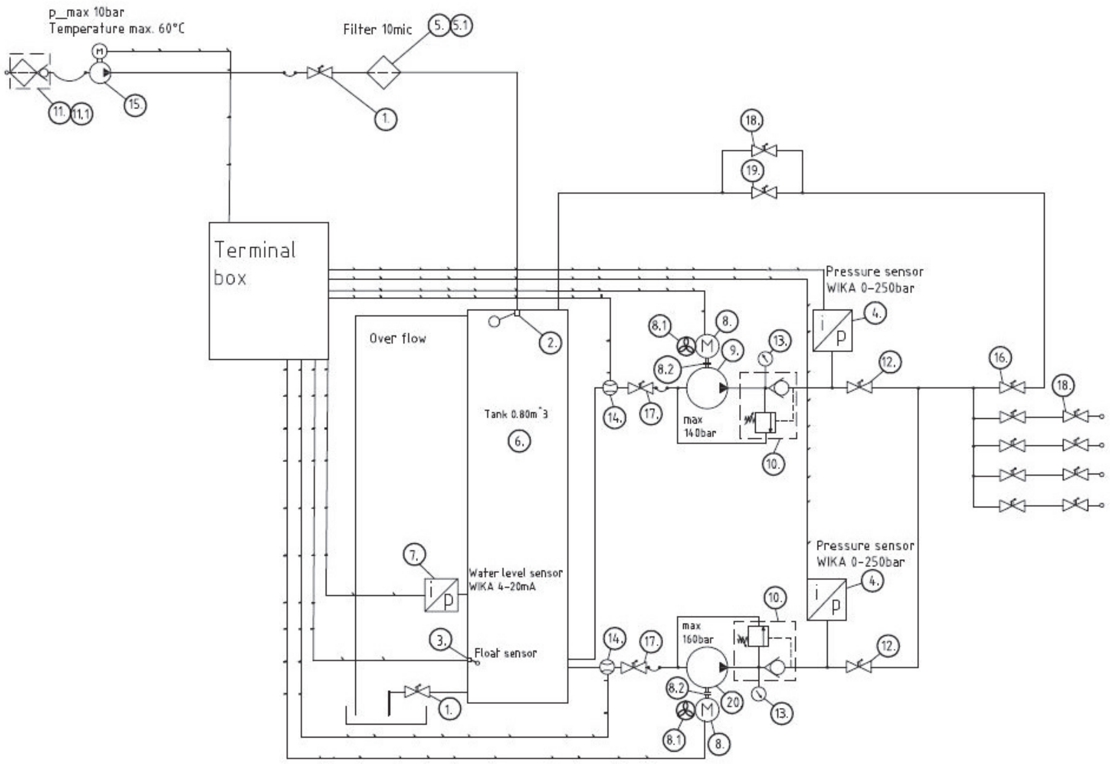


Figure 5.20. Pressurization system design (© Finfinet Oy).

The equipment includes various installations, which include five pressure pipes with ball valves. The pressure pipes are connected to the pipes leading through the rock to the filter layer. Finally, the pipes are connected to the rock lead-through flanges located on the wall of the tunnel behind the plug, and furthermore to the filter layer.

There is also a de-airing pipe placed within the upper part of the filter layer, to allow air escape via the lead-throughs during water addition.

The main part of the water supply system is a water tank with a volume of 800 dm^3 including high and low water level sensors, a water overflow system and filtering units. The water tank includes an in-pumping system with setback. The amount of pumped water is monitored using water level sensors installed in the water tank. The system is able to measure the amount of inflow water calculated from the water tank level sensors.

It is important that the pressure behind the plug can be maintained at the required level and therefore the pressurizing system consists of two separate pumping units. Each of them can work independently and can produce the required pressure for the test, yet not working at the same time. A power backup system is installed to supply electricity for the data collection system in case of a power interruption. There is no back-up electricity supply for the pump systems.

The pressurization system was designed by VTT in cooperation with FinFinet Oy. The system was built and assembled at FinFinet and delivered to VTT in winter 2014. From winter to summer 2014 the pressurization system was thoroughly tested in VTT's laboratory. Several pressurization scenarios were simulated and all components of the system were checked and tested with regard to their functionality, safety and reliability.

Table 5.6. Components of pressurization system [Finfinet 2013].

No.	Component
1.	Ball valve AISI316 PTFE DN20 PN64
2.	Float valve 3/4" ASI 316
3.	Flow meter HUBA 210
4.	Pressure sensor WIKA 0-160
5.	Filter cover HH 3/4"
5.1	Filter 60mic
6.	Water tank 0,8m^3
7.	Water level sensor WIKA 4-20mA
8.	Electric motor 2.2kW 1000rpm
8.1	Electric motor fan 230/400 V
8.2	Flexible Spider Type Coupling 24x28
9.	Pump Speck NP10/15-140 seawater
10.	Unloader valve VB80/280 AISI 316
11.	Ball valve POM PN500 3/8" AISI 316
12.	Check valve 3/8" 400bar (5800psi)
13.	Pressure gauge 0-160bar

All pressurization pipes and nozzles inside the filter layer and passing through the rock lead-throughs to the neighbouring instrumentation tunnel were installed in ONKALO during May 2015. The pressurization system was installed in the instrumentation tunnel in ONKALO in December 2015.

5.4.5 Leakage monitoring system

The main purpose of the leakage measurement system is to measure the local and global leakage from the tunnel through the plug. With the system, only the leakage water coming through the concrete plug itself or through the gap between the plug and rock can be measured. In order to be able to better identify possible flow paths and the origin of the leakage water, the pressurizing water is marked with an additional tracer of Rhenium. Thus any collected leakage water can be analysed and tracked.

Leakage measurement systems weighing unit was manufactured by FinFinet Oy and the measurement system program was made by VTT. Leakage measurement systems was designed to handle leakage flow between 4–70 l/hour. Any leakage water through the plug front face is measured by collecting the water into a canal on the floor in front of the plug. From there the water runs to a small well on the deepest part of the channel to be pumped using two bilge pumps to the total water weighing bottle for measurement. With that device the amount of leakage water will be weighed and then emptied into a container using a magnetic valve. The system has been designed to work periodically;

the drainage valve and inflation valve are not open during weighing or filling operations. The system is designed to operate during power blackouts and the two bilge pumps increase the operation security.

Finally, the water will be led to a small water tank or bottle for storing. Water and other liquid samples can be taken from the bottle for further analyses, such as chemical composition and pH.

There is a separate leakage measurement for the plug lead-through. This is done in order to separate any possible leakage from the lead-through from that coming through the concrete plug itself or through the gap between the plug and rock. The lead-through measurement equipment consists of a tipping bucket rain gauge that can be connected to the same logger with the main leakage measurement unit. It measures volume of the water into the collection funnel. The bucket tips 5 times for each 10 ml and it gives out the count of the tips that is read by the logger. The gauge was prepared for use in case of leakage emerging from the plug lead-through. It was not taken into use.

The leakage measurement system was delivered to VTT spring 2014. The system in total and all of its important components were tested in detail during 2014. As a result of the performance tests at VTT, some malfunctions of the magnetic valve could be identified and corrected based on a re-design of the weighing system. Afterwards the system was tested again in winter/spring 2015. Since the leakage water may contain suspended solids a filtering system was designed and added to the leakage measurement system in 2015.

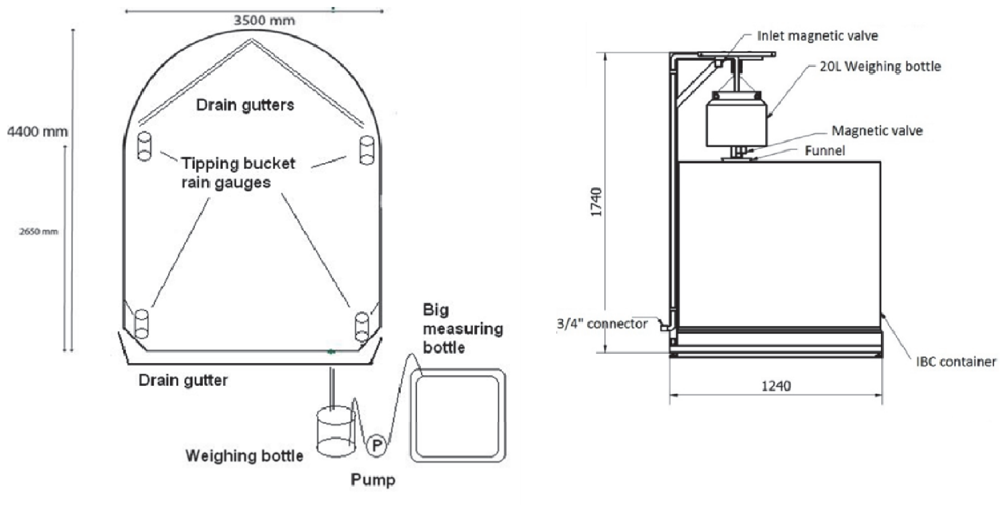


Figure 5.21. Schematic illustration of the design of the leakage measurement system. © VTT.

The water leakage measurement system was installed at the front face of the POPLU plug in ONKALO during December 2015. The drain gutters and tipping buckets, including the rain gauges were not installed until further requested by Posiva.

5.4.6 Near field monitoring

Prior to the pressurization, there will be inflow mapping and inflow measurement in the neighbouring tunnels for establishing the baseline for the water inflow volumes in the area. This will be repeated several times during the pressurization phase, before each pressure increase. Inflow measurements will be done from four (4) pumping holes and two (2) separate inflow collectors. The evolution of groundwater pressure in the surrounding rock mass will be monitored from existing investigation boreholes in the area. Locations of these are shown in Figure 5.22 and Figure 5.23. During the inflow measurements, water samples will be collected and analysed to assess the added tracers which can indicate the POPLU water combination to the groundwater via leakage paths. Also possible rock movements will be monitored with already existing extensometers in the area (including DT3). Locations of extensometers are shown in Figure 5.24

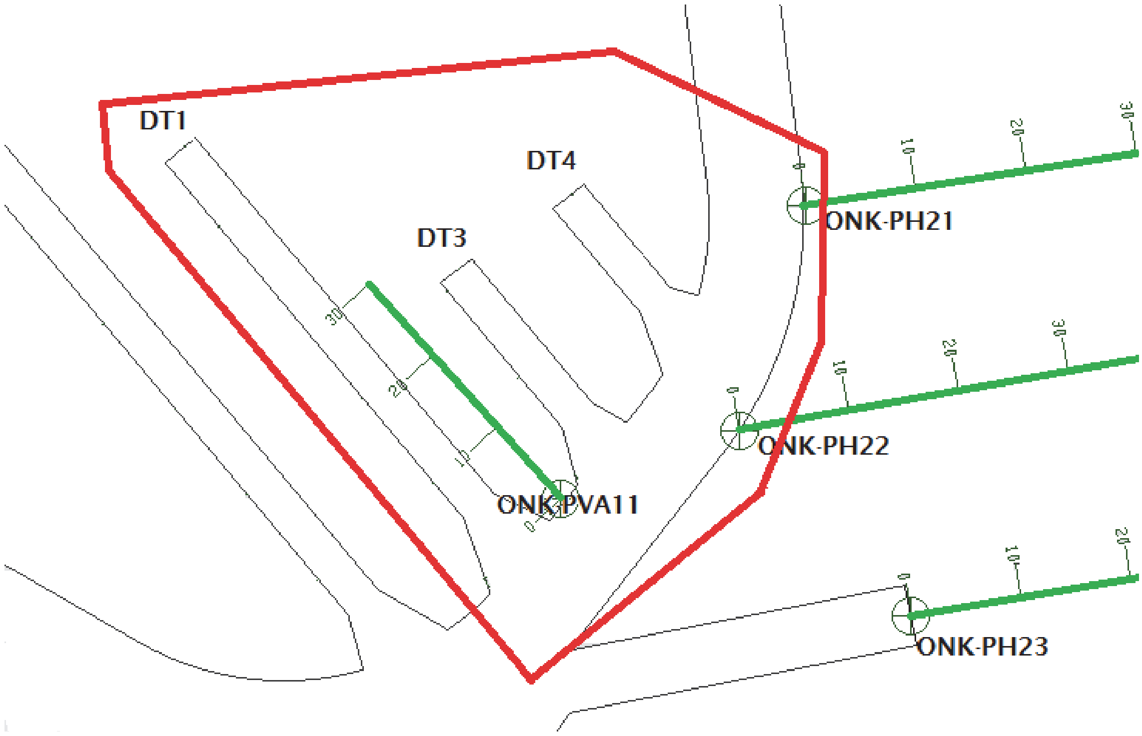


Figure 5.22. Mapping area of the water inflows (inside the red area) and locations of ground water pressure measuring boreholes.

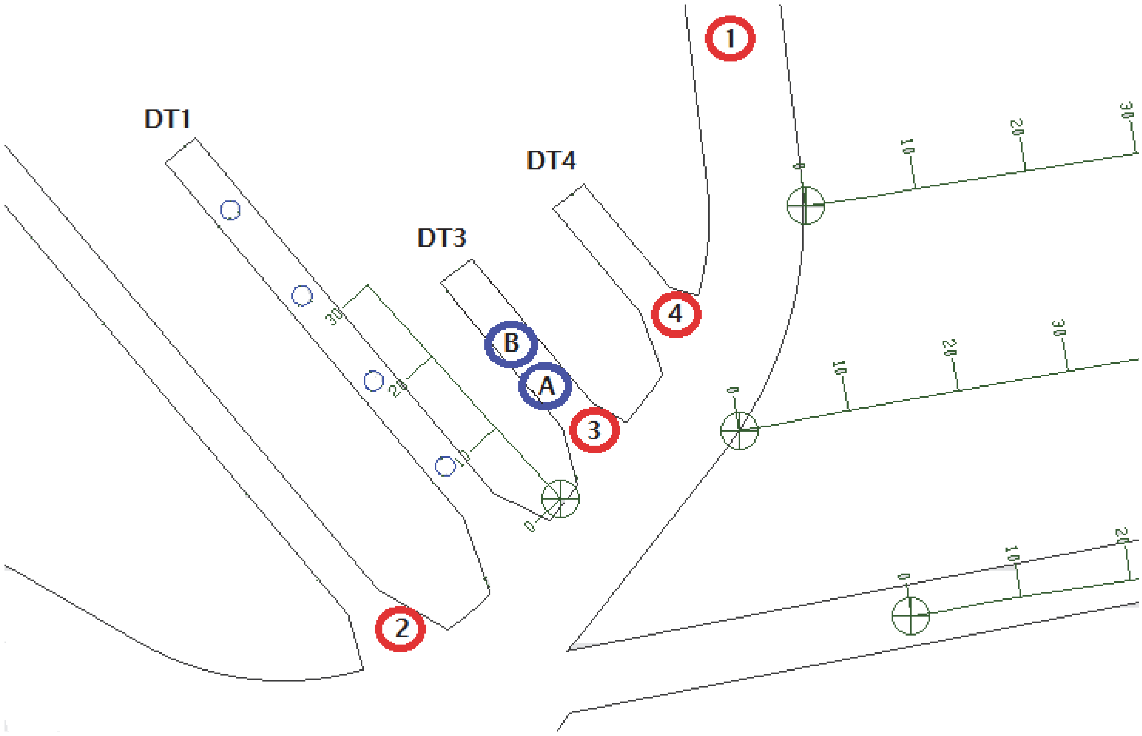


Figure 5.23. Inflow measurement and water sampling locations (Red circles 1-4 are pumping holes and blue circles A-B are inflow collectors at the roof of the tunnel).

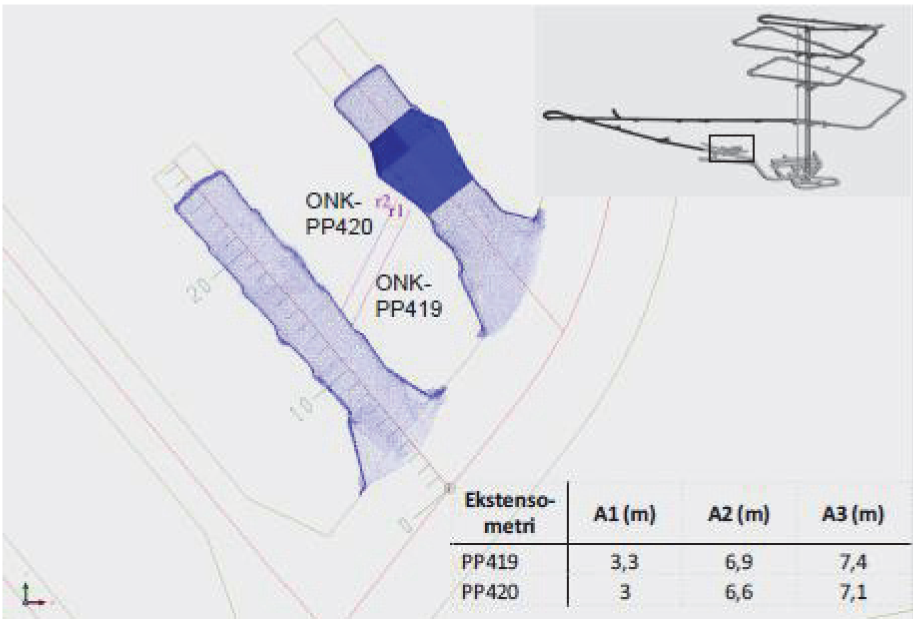


Figure 5.24. Locations of the extensometers.

5.5 Foreign Material Acceptance

Foreign materials are materials that are not part of the engineered multi-barrier system or the natural environment. [Sacklén 2015] They could have an impact on the long-term safety of the repository deposition and thus their use in ONKALO needs to be monitored.

The expected lifetime of the deposition tunnel end plug is 100 years, though the components will be in-place for thousands of years, and therefore the materials used in the plug should not impact the long-term performance and safety of the repository deposition. As the POPLU plug demonstration is being constructed in the future repository location of ONKALO, caution must be taken for materials used in experimental research and development. Even if POPLU materials will later be removed from the site prior to repository operation, they have the potential to leave traces to the surrounding groundwater and bedrock environment. Therefore, in the POPLU Experiment it was important to use the same materials as in real operational-phase plugs, to see if the initial state of the plug will be achieved. All materials used in POPLU were still subjected to Posiva's review process and documentation for Foreign Material acceptance.

Foreign materials monitoring was introduced into ONKALO at the start of the construction in 2004. It covers the approval procedure for the materials used in the construction of ONKALO, bookkeeping of the materials used in the underground facilities, and monitoring of the effect of foreign materials on the groundwater. [Sacklén 2015] The processes of foreign material acceptance are described in Posiva's Material Handbook, as also briefly summarized here.

The Material Handbook is a collection of documents providing information of the materials allowed in ONKALO. It includes separate instructions for the use of each material, material safety data sheets (MSDS) and other relevant information. These materials have been divided into two safety levels: Safety level A (the highest safety level) includes materials that could have an impact on long-term safety. Materials in safety level B have no detrimental influence on long-term safety according to present knowledge. Safety level A includes cementitious materials and additives, organic compounds, and some inorganic compounds (e.g. nitrogen compounds). Safety level B includes metals and inorganic compounds not included in level A. [Sacklén 2015]

The instructions for introduction of a new material are found in the material handbook. A new material can be approved for the use in ONKALO, if it is not harmful for long-term safety and it has been evaluated to be suitable for ONKALO conditions. Its functionality for ONKALO conditions must have been tested. For a material in the safety level A the disadvantages of its use must be less than the possible disadvantages if it is not used. [Sacklén 2015]

6 PLUG CONSTRUCTION AND EMPLACEMENT

The plug construction took place from February through September 2015, with follow-up injection grouting of the plug-to-rock interface in December 2015. Posiva oversaw the work of the primary contractor Hartela Oy, and concrete supplier Rudus Oy. Quality control of the construction process was also addressed in weekly meetings with the contractor, including tracking of the schedule, risks and change management processes.

The overall schematics of the emplaced components (backwall, filter, lead-throughs, concrete plug section 1 and 2) are shown in Figure 6.1.

Before actual construction, four different metric scale tests were done to assess the concrete and grout recipes used for the plug. The actual plug construction included aspects of the lead-throughs, backwall, filter layer and both concrete sections' installation. Some of the sections had integrated instrumentation for performance monitoring. Each of these steps is described in the sections below.

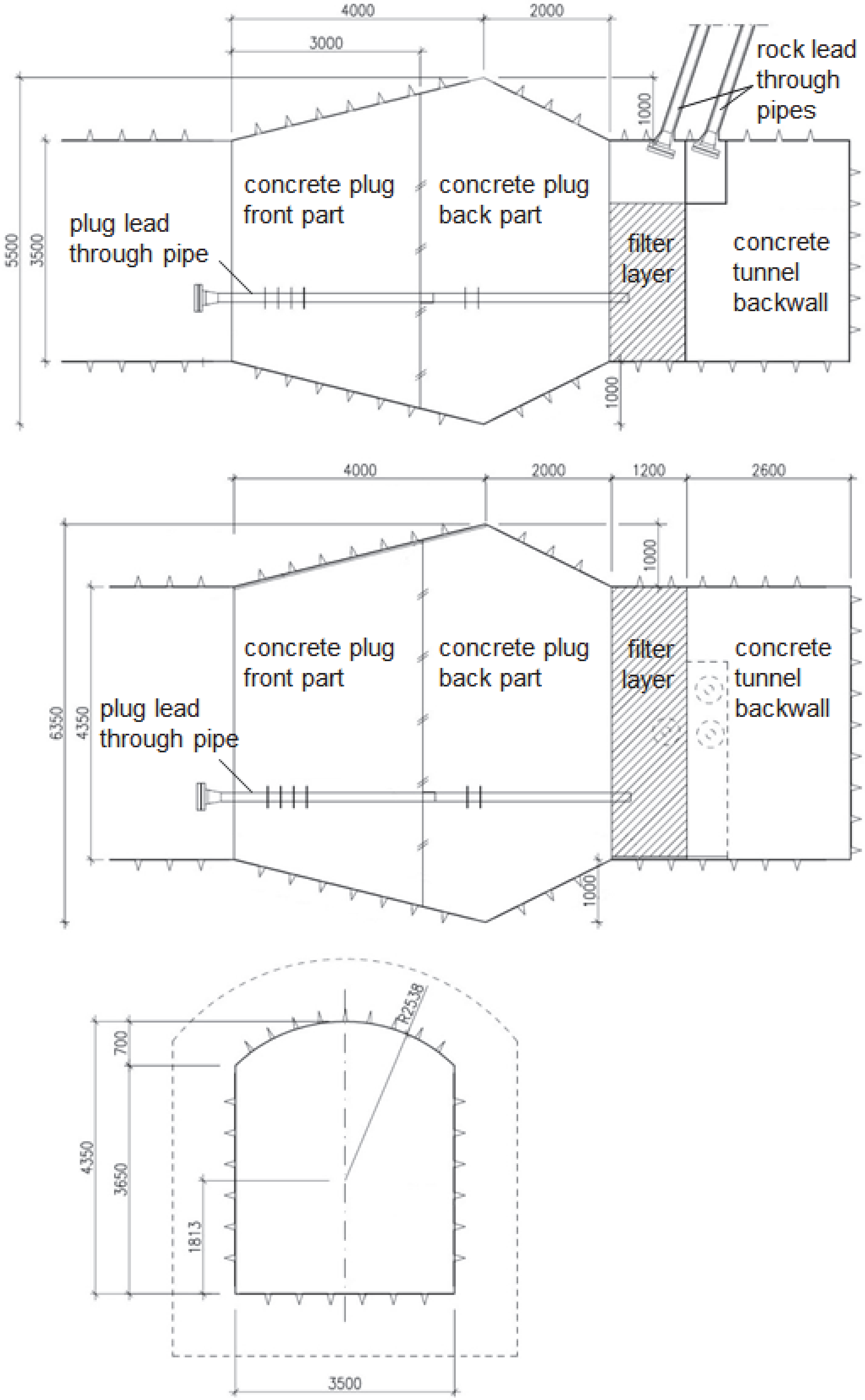


Figure 6.1. Schematic of plug components in preparation for emplacement. From top: top view, side view, tunnel (axial) view.

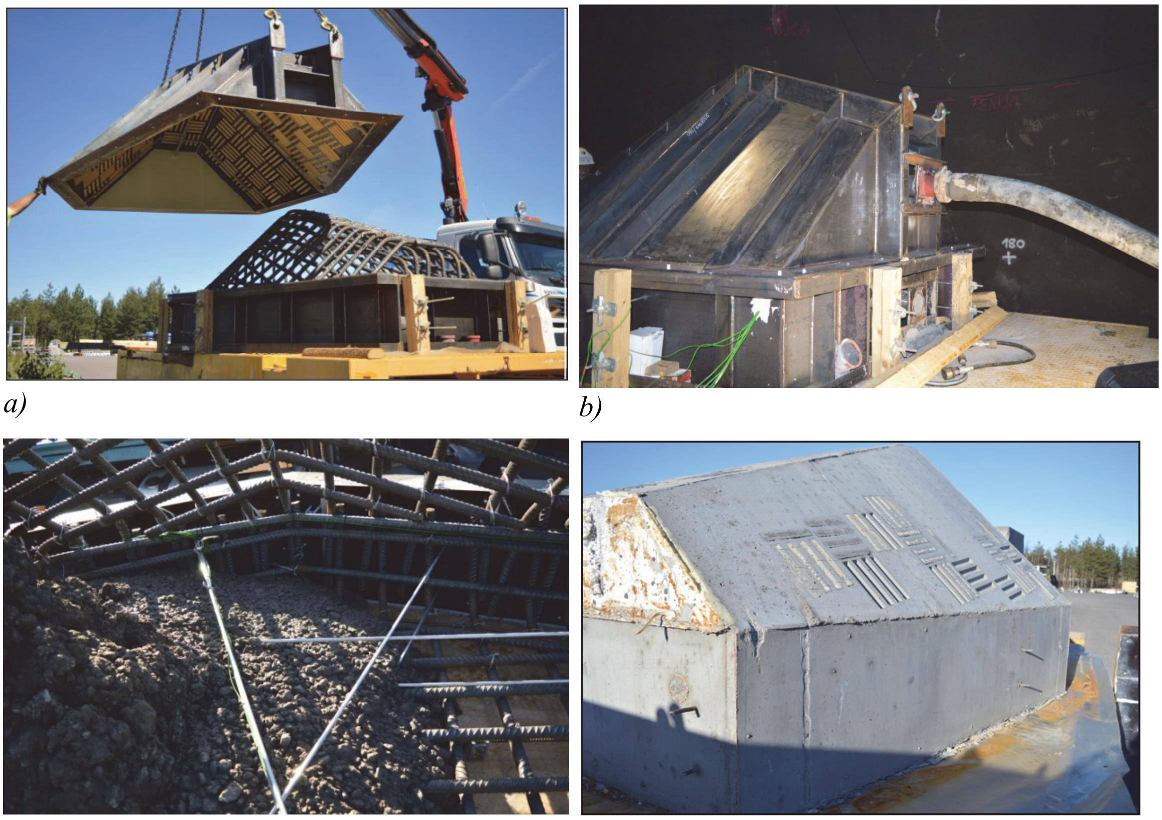
6.1 Method Test Demonstrations

The performance of the end plug is highly dependent on the successful execution of the concrete casting. The casting is to be performed in such a way that the end result of the casted concrete structure is as watertight as possible and that the structure is as homogenous as possible. To be able to gain these conditions in the best possible way, the working methods used are of great importance. In addition to the working methods, the concreting equipment and the uniform quality of the concrete mass have a great effect to the end result. The limited space available inside ONKALO brings its own challenges to the concreting as it affects the used working methods and equipment, e.g. equipment that is in standard use above ground does not necessarily fit to limited spaces.

It was realised in the early stages of the POPLU project the concreting of the plug structure is a demanding task. For this reason it was decided that it was necessary to test the planned working methods and the properties of the concrete before the casting of the plug concrete structure in method tests (or mock-ups). Overall, four method tests were performed underground in ONKALO. The general aim in all of the method tests was to develop and test the working methods suitable for ONKALO conditions and the workability of the concrete mass. The method tests significantly contributed to the lessons learned during the plug construction preparation phases and provided feedback to the structural design and concrete material development. Each of these four method tests is described in the next sections. Based on these results, the final decisions about the concrete used in the plug emplacement (Chapter 5.7.7) were decided. It should be noted that the four method tests were not part of the DOPAS project, yet are reported here for learning purposes and demonstration of quality practices.

6.1.1 First Method Test

The purpose of the first method test performed in July 2014 was to simulate the conditions present in the concreting of the plug concrete structure. The steel mould of the method tests was designed to contain the conditions of the actual plug concrete component. The shape of the mould mimicked the shape of the concrete component including the sharp crest at the top of the mould. The method test also included steel reinforcement inside the mould, similar to the reinforcement to be actually used in the plug concrete structure. In addition, bentonite tape strips were attached to the inner surface of the mould and also hindrances to mimic unevenness on rock surface. The concrete casting of the method test was performed as pressurised casting using a single casting connection in the bottom part of the mould. The concrete recipe was the ternary recipe containing both silica fume and fly ash, with 32 mm maximum aggregate size (as described in Chapter 4.3). Figure 6.2 shows the mould configuration and concrete after casting for the first method test.



a) b) c) d)

Figure 6.2. First method test: a) mould assembly, b) ready for casting, c) concrete flow between reinforcement, d) end product.

During the casting of the first method test, it was noted that even though the concrete mix in properties is slowly reactive, the working time when the mix is pumpable is short. The first casting had to be aborted because the effective time of the superplasticiser admixture had passed. The concrete mass blocked the casting connection tube and was no more flowing and setting to the mould. To perform the second casting on the first method test, the mould was opened and the casting connection cleaned. The amount of superplasticiser in the concrete mix was increased at the concrete factory, which made the concrete mix more pumpable and increased the time available for casting. However, it was also still necessary to add plasticiser on site to the concrete batches before pumping the mass into the mould.

When the mould of the first method test was opened after sufficient concrete hardening, it was observed that the mould had filled completely and that even the most critical part at the top of the mould was completely filled with concrete. However, at the far end of the structure it was noted that 32 mm aggregate in the concrete mix had partly been unable to penetrate between the tightly configured reinforcement bars and had also blocked the finer materials from filling the space between the reinforcement and the mould wall.

Quality control sampling of this first method test included taking cores for measurement of compressive strength and watertightness at the age of 28 and 91 days. Results are given in Chapter 5.10.

6.1.2 Second Method Test

Based on the experiences from the first method test, the planning of the second method test was commenced focusing on the means to increase the workability of the concrete mass and the planning to use working methods that would aid the flowability of the concrete inside the mould. It was decided to use an escort tube to be able to deliver the concrete mass closer to the far end of the mould to be able to prevent segregation of the concrete mix at the areas close to reinforcement. It was also decided to use multiple casting connections in the mould.

The second method test was performed in October 2014, using nearly the same concrete recipe mineral ingredients and proportions. The only raw material change was the higher dosage of superplasticizer in the second method test. The environmental conditions were different, due to the lower ambient temperature in autumn compared to summer. The goal was to keep the temperature low, representing POPLU in-situ casting. The mould used in the second method test was different than the one used in the first method tests. The mould in the second method test was rectangular and had several casting connections. There was no bentonite tape used. The mould was open from the top and one corner of the mould was made of plexiglass to be able to observe the flowing and possible segregation of the concrete mix. The pumping of concrete was started from the lowest casting connection and the concrete was pumped until the level of concrete reached the casting connection. The escort tube was then moved to the next casting connection higher on the mould on the other side of the front face of the mould. The casting in each casting connection was started from the far end of the mould and the escort tube was pulled out from the casting connection as casting progressed to distribute the concrete evenly inside the mould. Figure 6.3 shows the mould configuration and concrete after casting for the second method test.

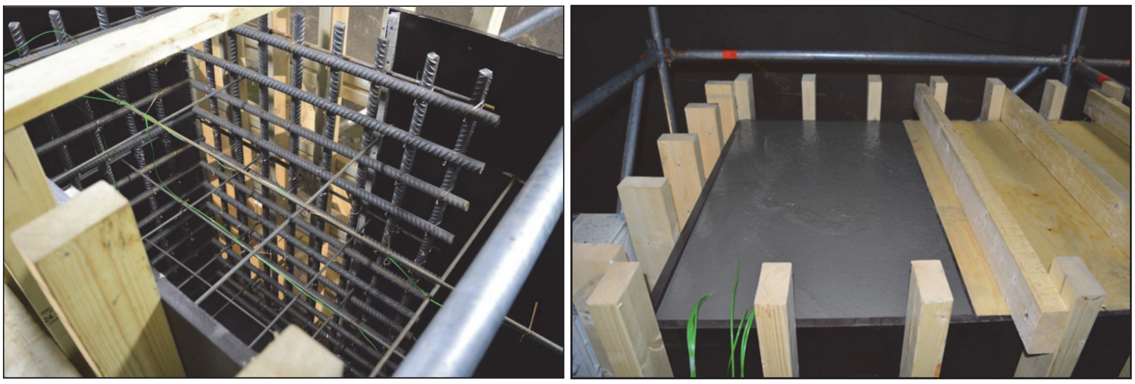


Figure 6.3. Second method test mould and reinforcement.

It was observed during the casting of the second method test that the concrete had a longer workability effective time than in the first method test based on the superplasticizer chemical dosing and time. It was necessary to add more superplasticiser to the concrete mix at the concrete factory to get a flowable mass, but there was no need to further add plasticiser on site before pumping. The conclusion was that the longer effective time occurred based on the greater amount of superplasticiser in the concrete mix. Even if the results from the second method test partly overrules the result from the first method test that the concrete had a short workability time, the concreting and concrete delivery of the plug concrete component has to be designed so that there are no unnecessary breaks in concreting or concrete delivery. In practise this means that the delivery of concrete to the site needs to be continuous and the pumping of concrete has to be constant so that a new batch of concrete is pumped on the top of the previous batch before the effective time of the superplasticiser has expired.

Even though the workability of the concrete mass was better in the second method test compared to the first one, there were problems in the beginning of the casting to get the concrete mass flowing in the tubing from the concrete pump to the casting connection. The reason for this was suspected to be the low internal friction of the concrete mix, which caused the coarse and fine materials to segregate. Also the high amount of superplasticiser in the mix contributed to this. The conclusion was that in the plug concrete structure casting a separate lubricant mass is needed. This lubricating mass is pumped through the tubing before the actual concrete mass to coat the tubing to allow the actual concrete mass to flow easier.

The same problem that was noted in the first method test that the 32 mm aggregate was not able to penetrate the reinforcement, was also noted during the second method test. The coarse aggregate blocked the reinforcement net so that the finer material was partly unable to fill the space between the reinforcement and the mould surface. Even the use of the escort tube did not complete eliminate this problem. These conclusions commenced the planning of whether a smaller size aggregate should be used on the areas of dense reinforcement in plug concrete structure.

There were no quality control samples taken from this second method test.

6.1.3 Third Method Test

The purpose of the third method test was to test the properties and working methods of concrete having a smaller maximum aggregate size of 16 mm rather than 32 mm. The proportion of aggregates used was adjusted. The aggregate to paste ratio (cement, silica fume and fly ash) remained the same. The concrete mass then had further adjustments of the chemical superplasticizer dosage to maintain the workability range. The third method test was performed in February 2015 and the same steel mould that was used for the first method test was also used for the third method test. The mould again included steel reinforcement as the assumption was that the 16 mm aggregate would better penetrate the dense reinforcement especially on the bottom and top section of the plug concrete structure compared to the earlier method tests using the 32 mm aggregate mix. Bentonite tape was not used.

There were no problems observed during the casting of the third method test. The concrete mass flowed well in the tubing and the concrete was able to penetrate the reinforcement without segregation. It was noted from the samples taken from the third method test after the concrete had hardened that the concrete on the space between the reinforcement and the mould surface was very homogenous. It was concluded from the third method test that 16 mm aggregate size concrete mix is easier to handle in concreting and that it would be advantageous to use it on the areas of dense reinforcement in concrete plug structure.

Quality control sampling of this third method test included taking cores for measurement of compressive strength at 7, 28 and 91 days and watertightness at the age of 28 and 91 days. Results are given in Section 5.10.

6.1.4 Fourth Method Test

A fourth method test for contact grouting was performed in December 2015, to verify the newly developed low-pH grout mix prior to contact grouting of the plug. This test was performed in ONKALO at -437 m below depth with a test arrangement cast on the rock tunnel floor. A reinforced concrete cap of diameter 2.5 metres was cast using normal (not low-pH) concrete having reinforcement steel and tie-down bars. The test arrangement was equipped with grouting tubes separated by the strips of bentonite tape.

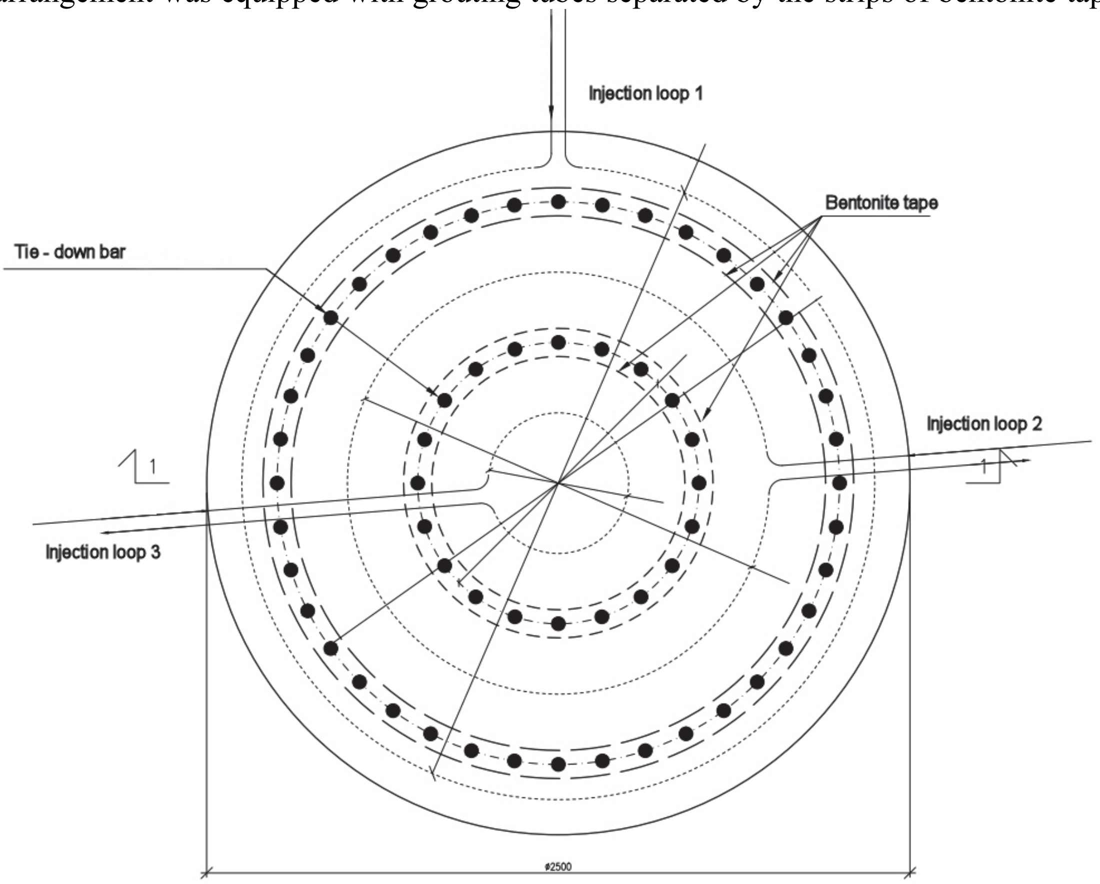


Figure 6.4. shows an example of the configuration.

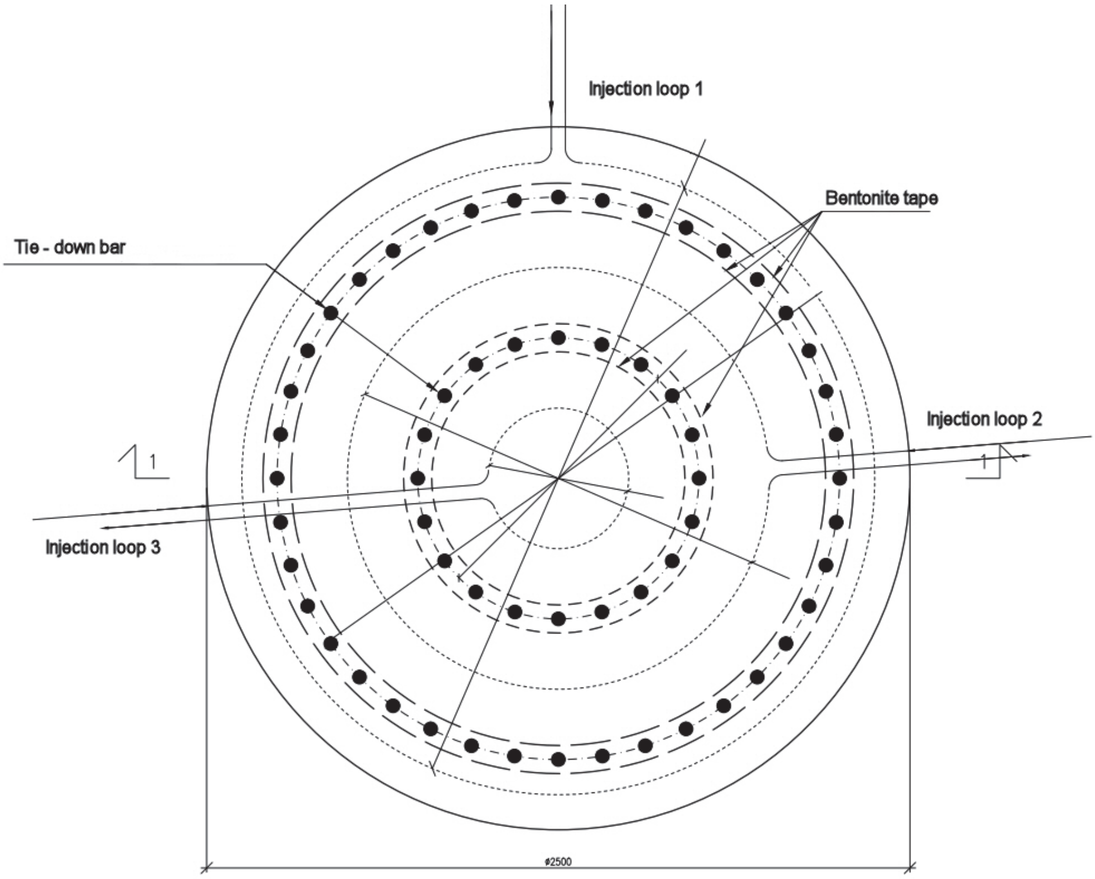


Figure 6.4. Schematic of grouting lines and bentonite tape, in method test.

Grouting tubes were led to the interface of the concrete base and rock, which was then contact grouted using the method planned for the concrete wedge. The mock-up showed that the testing arrangement was not properly designed or constructed, because no grout could be injected. Post-test concrete core sampling and analysis showed that the gap was probably too small to allow the grout to infiltrate and that the grouting tubes were clogged with concrete. The tubes were installed as per the contractor's instructions, but would need to be re-designed for future mock-up tests on grout. The work done during this mock-up test was helpful in verifying the grout mix and injection techniques, so the POPLU contact grouting was planned to proceed based on the available work, and no further mock-up tests were undertaken.

Figure 6.5. Injection grout method test arrangement and sampling.

6.2 Rock Support

The first step when proceeding with construction of the actual plug was to build a protective shelter and scaffolding against falling rock within the plug slot area of DT4. In February 2015 a temporary sheltering area was built, including a walk-through platform across the plug slot. This provided access to the area behind the plug during construction. It was necessary due to the plug requirements that no rock support, in the form of rock bolts or netting, can be used in the slot area so as not to create further fractures or impact the EDZ.

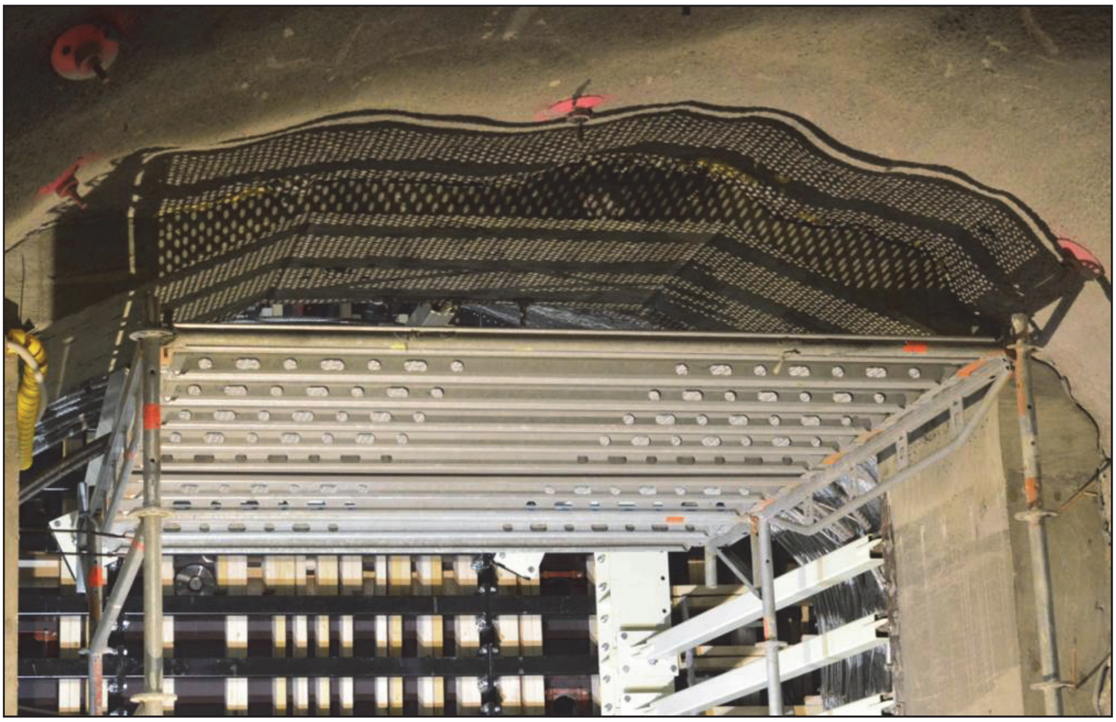


Figure 6.6. Example rock support scaffolding within the slot area, in front of section 1.

6.3 Rock Lead-throughs

The materials for the stainless steel lead-through were ordered by Posiva and took about a month for procurement and delivery of the various parts. TVO quality managers inspected all materials after delivery to ONKALO. All components were then sent to IS Works Oy in Pori, who assembled the various components. This included the flange on each pipe within Demonstration Tunnel 4 (DT4). All three pipes were a designed to be combination of three sections. Non-destructive testing by x-ray scanning and surface quality assessment was also done at IS Works Oy. The three parts for each lead-through were welded together after delivery back to Olkiluoto. The welding was done underground and took approximately one day per pipe. The welding was again quality control tested by NDT coating evaluation upon completion of the welding.

Installation of the rock-lead-throughs on-site at ONKALO was done in March 2015. For installation, the first step was to put bentonite blocks around the ends of the pipe, 1 metre from the end of each pipe, to be within the rock lead-through and add watertightness. After assembly, each of the three pipes was pushed through the predrilled rock holes. Each metal lead-through also had three separate metal smaller diameter tubes (18 mm) that were through the lead-through wall and faced the rock. Contact grouting was done through these tubes from both DT3 and DT4 to fill the junction between the lead-through pipe and rock surface. The polyurethane flanges that were originally planned to be used (as in the SKB DOMPLU design, [DOPAS 2015]) to add watertightness were omitted due to non-acceptance by ONKALO foreign materials review. This aspect could be improved in the future, so that the design is modified earlier to account for acceptable materials.

The next step was to install the five pressurization tubes within the lead-through pipes. This work was done by Vesi-Vasa Oy, including installing, bending and connecting water pipes and then connecting their nozzles. The average length of each pipe was approximately 35 m (20 m visible in DT3 and 15 m within the structure), from the pressurization pump system connection to within the filter layer, going via the rock-lead-through pipes.

The lead-through installation work took approximately two week of time by IS Works Oy (2 persons) in addition to the non-destructive testing work for welds. Injection grouting took one day by Lännen Kaivuu ja Louhinta Oy subcontracted by Hartela Oy. The work by Vesi-Vasa Oy took approximately 4 days by two persons. All of these companies were effective and did good quality work.

After the lead-throughs were installed, the work continued with installation of the monitoring system (instrumentation wiring) and pressurization pipes.

6.4 Formwork

The plug formwork was built by the contractor, starting with building a tunnel circumferential footing or frame along the floor, wall and ceiling, one metre in front of the plug slot. The width of the frame was approximately 1 metre. 113 holes were drilled for rock-bolts around the circumference of the tunnel in the frame location. Within these holes were installed the rock bolts: 48 bolts of 900 + 900 mm in length, 20 mm diameter with a 90 degree bend; 65 bolts of 1200 mm long and 20 mm diameter. The bolts were on average 800 mm depth inside the rock. Normal strength concrete was used for this formwork frame, provided by Rudus Oy, similar to other on-site ONKALO concrete structures. Casting was done over a 3 day period (taking 1 hour for the floor, 3 hours for the walls, and 2 hours for the roof). Fresh mix quality control samples of air content were taken on each delivery. No hardened concrete testing samples were made for quality control. This circumferential footing for formwork support used approximately 5 m^3 of concrete. The moulds were removed after approximately one month. Bolts were extruding from the footing, for attachment of jacks and plug formwork steel beams. The formwork was constructed simultaneously as the rock-lead-through work by IS Works Oy. The work took about 1 month of interspersed work time.

Beams were used to hold the actual formwork mould in place, which was attached to a bracing frame (or circumferential footing) in the rock. A forklift was used to position the largest beams, which were about 400 kg each. The bracing pieces were designed to be mostly installed by hand, for instance with three components that could be screwed together.

Building of the formwork for the plug sections took 20 days (4 weeks) for each section and it was occurring at the same time as other activities like installation of monitoring systems and reinforcement. Figure 6.7 shows an example of the erected formwork and bracing.

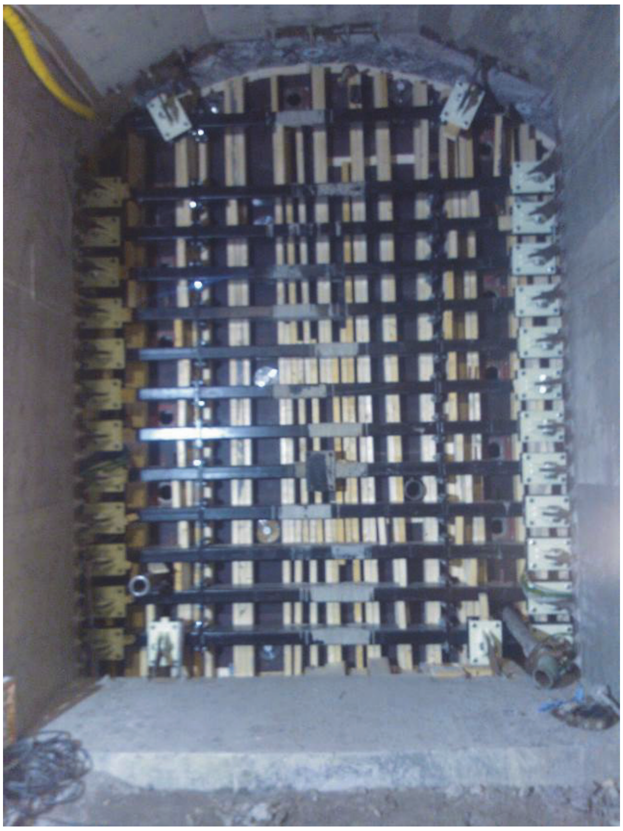


Figure 6.7. Formwork before plug section one.

Lessons learned on the formwork design was that formwork design was good and avoided drilling attachments to the rock. The formwork system was very heavy and maybe more massive than needed. The design was based on hydrostatic pressure related to the self-compacting concrete, with the estimated range during casting to be designed for 2 bars at the base to 0.5 bars at the top. Pressure meters were put on the formwork to observe actual pressure during casting. The actual pressure was highest in the middle section of the plug at 0.5 bars, due to the lower section hardening and the reinforcement removing some of the pressure from the bottom of the plug section.

6.5 Tunnel Backwall

The 2.6 metre long tunnel backwall was constructed in April 2015, for shortening the tunnel adjacent to the plug since no backfill clay was used. The backwall had no steel reinforcement, and was cast with the same low-pH concrete as used in the plug. Four L-beams were placed in the backwall for the purpose of attaching instrumentation sensors for performance monitoring. Approximately 11 days were taken for the formwork construction and preparation for backwall casting.

For casting, a smaller concrete pump was used that fit easily and was manoeuvrable in the tunnel. This same pump was not available for the plug casting, but it was good equipment that should be used in the future in confined spaces. Approximately 40.5 m^3 of concrete were placed using 11 delivery trucks, over a 6 hour period on April 28, 2015. Quality control included measurements of slump and air content, as well as cube samples made for long-term testing of strength, permeability and pH leachate. The temperature, humidity and displacement of the backwall were monitored for the first weeks after casting. The formwork was demoulding approximately 10 days after casting. The backwall was then used as an attachment location for water pressurization pipes entering the filter layer.

The primary lessons learned during backwall casting were the practical arrangements to be utilized during the actual plug casting. It was important to practice the formwork erection, monitoring methods, concrete delivery sequence, concrete pumping and quality control methods. The backwall structure would not be used in plugs for an actual repository, but it was helpful in POPLU as a learning experience and was needed for the experimental purposes for shortening the tunnel.

6.6 Filter Layer

The filter layer construction by Hartela Oy started in June 2015 by attaching the pressurization water pipes to the backwall. The pipe installation was done by Vesi-Vasa Oy over 4 days, plus one day for inspections. The exact locations for the pipes were slightly adjusted and tailored based on the available geometry. These changes were inspected and approved by Posiva before filter wall construction.

The filter layer construction was started by casting a thin floor, 2–10 cm thick, along the tunnel floor to be under the filter. This footing was made from the low-pH mortar, similar to that used for securing filter blocks to each other. After hardening, one layer of lightweight blocks was installed for two days. The blocks were attached with a masonry mortar that was prepared in a mixer on-site underground. The mortar was good to work with and no problems occurred. No quality control tests were taken on the mortar. After installation of the sensors over four days, the filter layer erection continued for another two days, working in double shifts due to schedule delays. The filter blocks were cut on-site with a hand saw to match the geometry of the tunnel. The gaps between the blocks and tunnel wall were filled with the same mortar. Extra overtime hours were needed compared to the original schedule. Figure 6.8 shows the filter layer block wall being erected during construction and a close up of the Leca blocks.

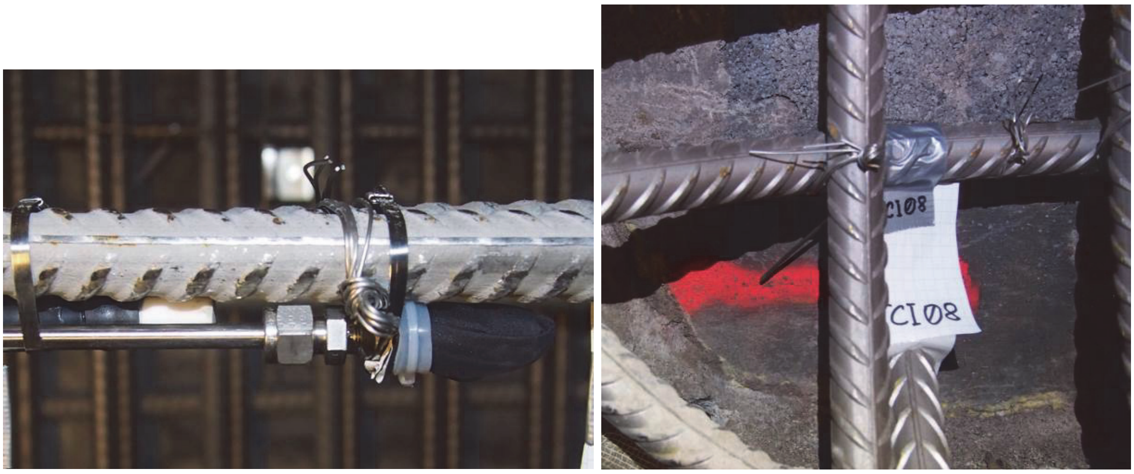
(a) *(b)*

Figure 6.8. Filter layer wall, a) wall structure and b) individual blocks. Photographs taken during installation of the filter layer, a) against tunnel back wall, b) around rock lead-through flange.

It was time consuming to protect the water pressurization pipes and rock-lead-through flanges within the filter. The space around the flanges was left free from blocks in an area about 5 cm diameter around the flange, which was then filled with lightweight aggregate (Leca) pellets to give flexibility for any movement or displacements. It was critical that the flanges would not be damaged by displacements of the plug during pressurization. There was not a good construction plan or method description how to build this transition area around the flange within the filter layer. It would have been preferred by the contractor to have a first draft idea from the designers, rather than having to make the initial plan themselves.

A lesson learned during the filter installation was the importance of communication between the contractor and the instrumentation team for monitoring installations. The contractor had assumed the filter layer would be fully constructed prior with the sensors would go on the face, yet actually the sensors were installed simultaneously within the filter wall during construction (in the middle of the blocks). This created scheduling delays and crowded on-site working conditions. The time schedule should have allowed approximately 5 extra days of filter layer construction time, which was compensated for by working double shifts.

Another lessons learned was the necessity to accurate describe all materials to be used for the installation. There was not an accurate description of how to attach the water pipes to the backwall and thus it took the contractor extra time to find the proper attachment parts. These materials and parts were not accurately specified in the drawings, because of the small pipe sizes and requirement to be stainless steel.



(a) relative humidity sensors *(b) thermocouple*

Figure 6.9. Examples of sensors installations in the plug sections.

6.7 Plug Concrete Sections

The following sections describe the actual plug construction, consisting of the reinforcement, instrumentation, grouting tubes and bentonite tape installation, and concreting. These are grouped together for both plug section one (work from mid-May to mid-July 2015) and plug section two (work from beginning of August to mid-September 2015), since most of the steps are identical for each section. Differences in the two sections are noted accordingly.

6.7.1 Reinforcement installation, phase 1

The steel reinforcement of the plug sections was designed to serve the secondary function of rock support within the slot area. So the first construction aspect of the plug was to remove the temporary rock support scaffolding and tunnel floor platform, then proceed with reinforcement bar installation around the plug circumference (adjacent to the rock) for both plug sections one and two.

The reinforcement installation started with the external circumference, so as to cover the rock surface. This was installed from the front face (near the central tunnel) working towards the filter layer, so as to protect the worker safety. The contractor noted that the plug construction was challenging due to the regulations to not be working under un-supported rock. This required about double the time as needed for building reinforcement. About 1 metre of empty space, or a gap, remained open around the plug circumference in the middle section of the plug to position the formwork between parts one and two of the plug sections. This area was covered with a temporary metal mesh for tunnel rock fall protection. The plug's steel reinforcement installation around the whole plug circumference took 7 days, with four persons working. Examples of the conditions of the reinforcement are shown together within instrumentation of Chapter 5.7.5.

6.7.2 Grouting tubes and bentonite tape installations

The six sets of grouting pipes (three for each section) and three sets of bentonite tape were attached to the rock surfaces around the slot circumference, with a layout as shown in Figure 6.10. It took detailed planning by the contractor regarding how to attach these materials to the rock. The designer's original plans showed using clips made of aluminium by using a nail gun approach, but it was changed to use stainless steel and concrete screws instead. These screws were installed to 6 mm diameter with 50 mm deep holes around the rock face, spaced every 200 mm for length for pipes and 300 mm for bentonite tape. Some other method for attachment of pipes and tapes should be considered in the future, so as to avoid making so many small holes in the rock (~ 900 holes). It took 3 days of work in plug section one for attaching the pipes and bentonite tape.

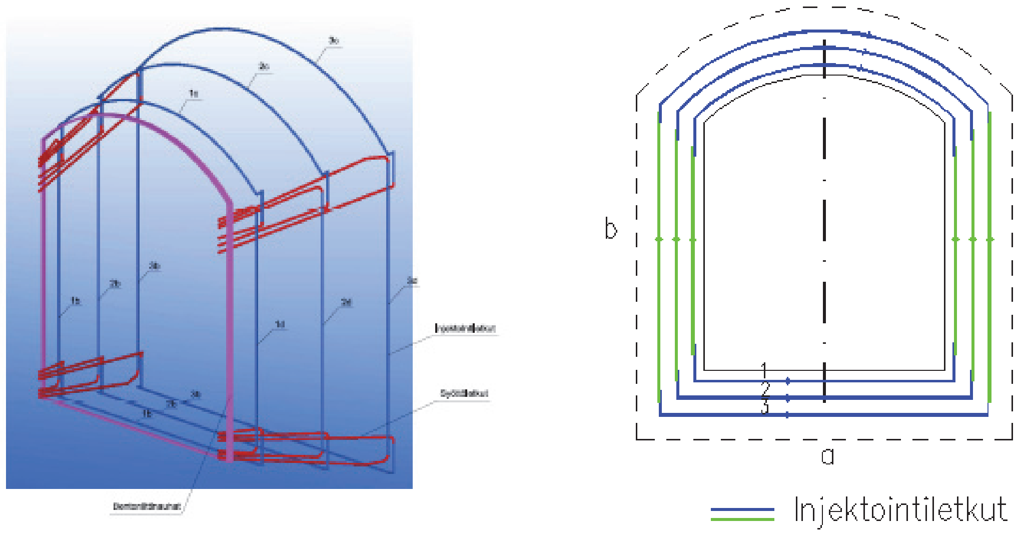


Figure 6.10. Injection grouting tube design. (Label in right graphic: "injektointiletkut" = injection tubes, in Finnish).

6.7.3 Reinforcement installation, phase 2

The final sections of reinforcement within plug section one needed to be placed near the ceiling after the grouting pipe and tape installation. After that point there was no exposure to the tunnel slot rock. This ceiling reinforcement installation took an additional two days. Then the next reinforcement was installed for the inner reinforcement and back-section reinforcement in front of the filter layer. The whole ceiling area for both plug sections had some problems during installation due to an error in the size and amount of reinforcement available on-site (between re-design checking and procurement). There were four days of work needed but this could have been done faster in the future.

Another subsequent short step was attaching the grouting feed pipes to the circumferential grout tubes. This was done after the reinforcement was ready in each plug section one and two. The feed pipes were attached for support to the reinforcement bars using stainless steel tie wire. This took one person one day of work for each of the two plug sections.

After instrumentation installation in plug section one, it was observed that the 11 mm diameter uppermost section of ceiling reinforcement had shifted down, towards the centre of the plug; by about 50 mm. Extra work was needed to re-lift the upper reinforcement towards the ceiling using a jack. The man-hole in the formwork was closed in preparation for concreting.

6.7.4 Concrete lead-through installation

The concrete lead-through pipe was installed by Hartela Oy during the phase of final reinforcement installation of plug section one. As the lead-through was embedded in the filter layer and then supported by the formwork, it did not need much support beside a few ties to the internal reinforcement bars. The lead-through pipe had been initially assembled above-ground and quality control checked by IS Works Oy.

After casting of the first plug section, IS Works Oy welded the second lead-through section or pipe to the first section, and again did NDT testing of the weld quality. Bentonite tape was added adjacent to the internal flanges along the tube and against the formwork. After the second casting, IS Works Oy welded the final flange including pipe closure valves, to the lead-through opening on the front face of the plug. Welds were again checked by quality control methods. Each of the two sections and flange installations took 1 day of work on-site for welding and then the quality control testing. Figure 6.11 shows examples of the lead-through.

Figure 6.11. Concrete lead-through within plug section 2, prior to attachment of bentonite tape. Formwork mould opening at right bottom corner.

6.7.5 Instrumentation Installation

6.7.5.1 Backwall

The tunnel backwall casting was used to gain first experience on the sensor installation in the low pH concrete. For that purpose, four thermocouples and three relative humidity sensors were installed on 31.3.2015 and 1.4.2015 at different locations inside the concrete backwall for a temporary test. The monitoring of the concrete backwall was not intended to be permanent, but to serve as a temporary test run for the systems for a duration of about two months.

The thermocouples were installed in the centre location of the concrete backwall as well as next to the lateral rock wall, the concrete mould and a lower edge in the direct vicinity of the rock wall and mould. The thermocouples provided important information about the hydration heat development during concrete hardening and the maximum temperature gradients within the massive concrete structure.

All three relative humidity sensors were installed at the same location in the centre of the backwall. There were two different types of humidity sensors, based on a temperature compensated resistance meter, and an electronic capacitive hygrometer respectively. The latter is not designed to get into direct water contact. Therefore, two sensors of this type were casted into the backwall, one as commercially available and one additionally covered with a Goretex cloth to prevent direct water contact, but allow for the transport of relative humidity.

The plain electronic capacitive hygrometer failed after contact with fresh concrete. All other sensors survived and provided accurate data before the wires were cut when the rock lead-throughs had to be closed during construction of the filter layer.

6.7.5.2 Filter Layer

Five pressurizing pipes were installed inside the filter layer. Four of the five pipe ends carry nozzles to guarantee an evenly distributed outflow of the pumped water used for pressurizing. One pipe end was left open, but protected with a wire mesh against blockage. The pressurizing pipes were mounted onto the concrete backwall surface and led to the top rock lead-through flange. After passing the flange, which serves as a tight barrier, the pressurizing pipes were continued to the instrumentation tunnel, which hosts the pressurization system including a water tank. Figure 6.12 shows the pressurization pipes mounted onto the concrete backwall and running to the rock lead-through flange.

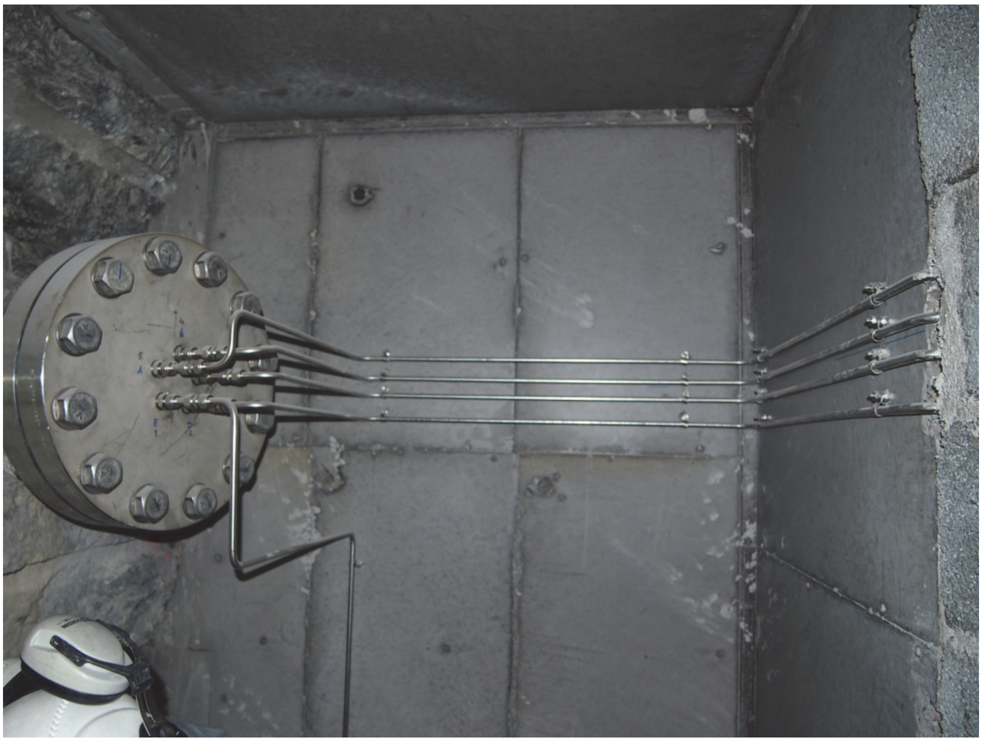


Figure 6.12. Pressurization pipes mounted onto the concrete backwall surface and passing through a flange of the rock lead-through pipes.

The design and layout of the pressurization pipe system was done by VTT. The installation of the pipes was primarily plumbing work and was done by Vesi-Vasa Oy as a subcontractor of Hartela Oy.

During three installation campaigns on 4–5 June 2015, 15–18 June 2015 and 22–23 June 2015 preparatory works were done and sensors installed inside the filter layer. At first the rock lead-throughs were prepared (installing Teflon pipes inside the rock lead-throughs, see Figure 6.13 left, attaching locks and closing of the flanges) and necessary arrangements done inside the measurement container in the instrumentation tunnel. Afterwards the installation of four pore pressure sensors, four total pressure sensors (see Figure Y left and right) and three displacement sensors inside the filter layer took place. An essential part of the work was the wiring of the sensors. Due to the high expected hydraulic pressure, all cables and wires had to be sheltered by stainless steel tubes. The tubes were fixed inside and along groves that were cut into the filter layer blocks, see Figure 6.13 right.

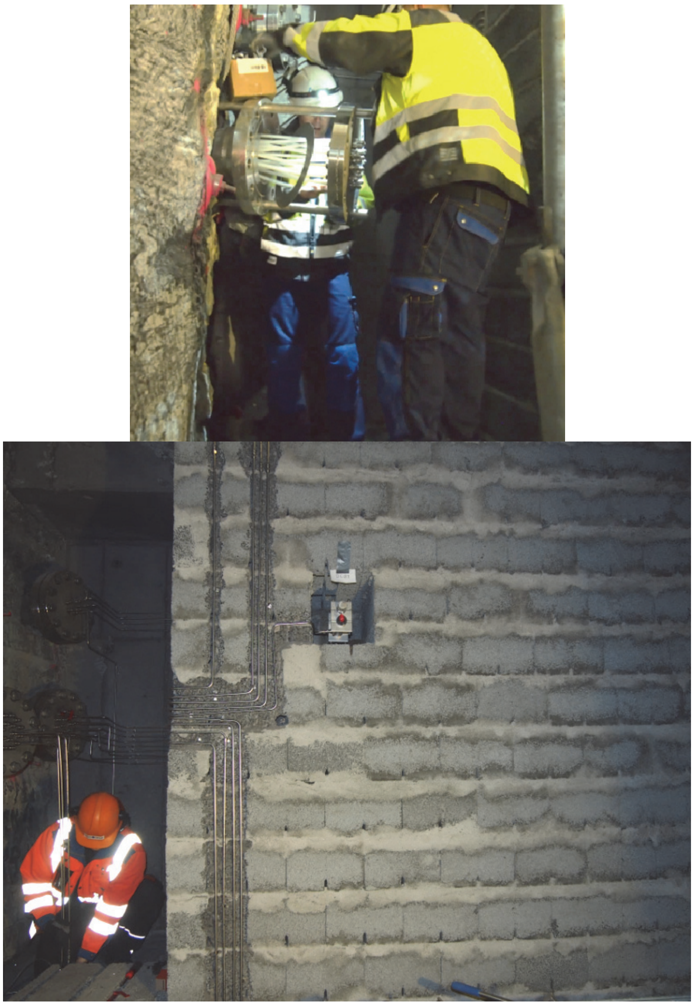


Figure 6.13. Installation of Teflon pipes into the rock lead-throughs (left) and stainless steel tubes for hosting the sensor wires, mounted onto the filter layer wall, and a displacement sensor in the centre of the filter layer wall (right).

Figure 6.14. Total pressure sensor and pore pressure sensors (not visible) during installation (left) and after closing of the holes in the filter layer wall with a low-pH mortar (right).

Between 3 and 7 people from VTT were involved in the instrumentation of the filter layer at the same time. About 39 person-days on site were needed to commission this task.

6.7.5.3 Plug Section One

The instrumentation for plug section one was then installed over a 5 day period. The instrumentation and monitoring installation work including Vesi-Vasa Oy working to bend pipes for instrumentation wire shielding. In total five pore pressure sensors, five total pressure sensors, three relative humidity sensors, two standalone thermocouples and 13 strain gauges were installed inside plug section 1. Figure 6.15 shows a relative humidity sensor as well as total and pore pressure sensors installed in plug section 1.

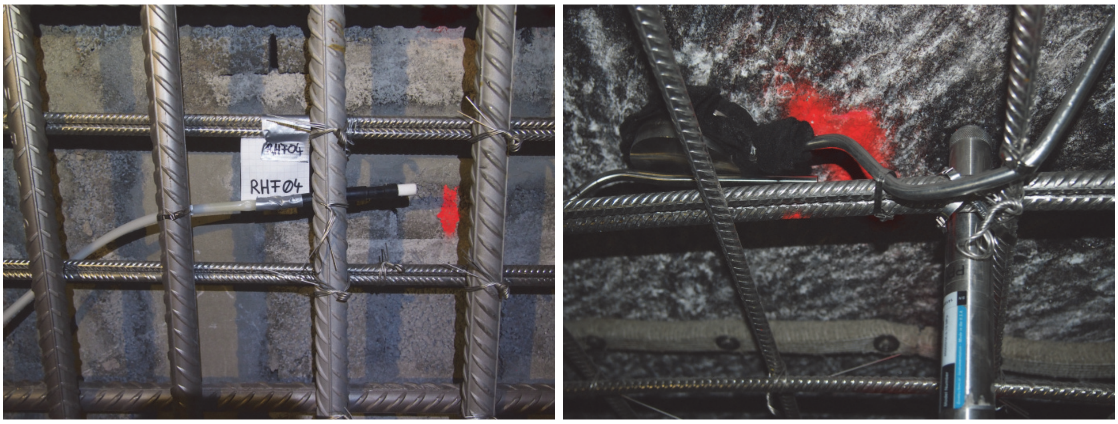


Figure 6.15. Relative humidity sensor (left), total pressure sensors and pore pressure sensor (right).

The wires of the pressure sensors, each of them running inside a stainless steel sheltering tube, were directed through a cable flange towards the rock lead-through flanges in the filter layer. Therefore, all ten pressure sensors had to be installed prior to the final construction of the filter layer on 22–23 June 2015. Only after closing the rock lead-through flanges, the filter layer could be finalised.

The wires of the remaining sensors were led to a cable flange, which was located between plug section 1 and 2. The wires of the strain gauges and relative humidity sensors were sheltered by tubes out of PVDF, which are more flexible and easier to install between and along the reinforcement bars. Figure 6.16 shows several PVDF and stainless steel tubes running towards the cable flanges to the filter layer (right) and plug section 2 (left) after finalising of the instrumentation work inside plug section 1.

Figure 6.16. PVDF and stainless steel tubes, directing the pressure sensor cables to the cable flanges towards the filter layer (right) and plug section 2 (left).

The sensor installation was performed during 2 installation campaigns at 22–23 June 2015 and 1–8 July 2015. In total about 38 person-days were needed for the installation work inside plug section 1 at ONKALO.

After all sensors were placed, their exact location was measured and documented. Before closing the manhole in the reinforcement, a laser scanning was done by Prismarit Oy in order to document all sensor and wire locations as part of the quality control.

Simultaneously to the installation work, the data acquisition system was setup and all sensor wires connected to the loggers located in a cabinet in front of the plug or at the measuring container in the instrumentation tunnel. Data logging started in the beginning of July as a test run. Right before the plug casting at 15 July 2015, all sensor data was checked again and data acquisition started officially.

6.7.5.4 Plug Section Two

The great amount of sensors was installed in plug section 2. In total 19 strain gauges, six standalone thermocouples, four relative humidity sensors, two pore pressure sensors and two total pressure sensors were installed. Figure 6.17, left and right, shows three strain gauges and a standalone thermocouple.

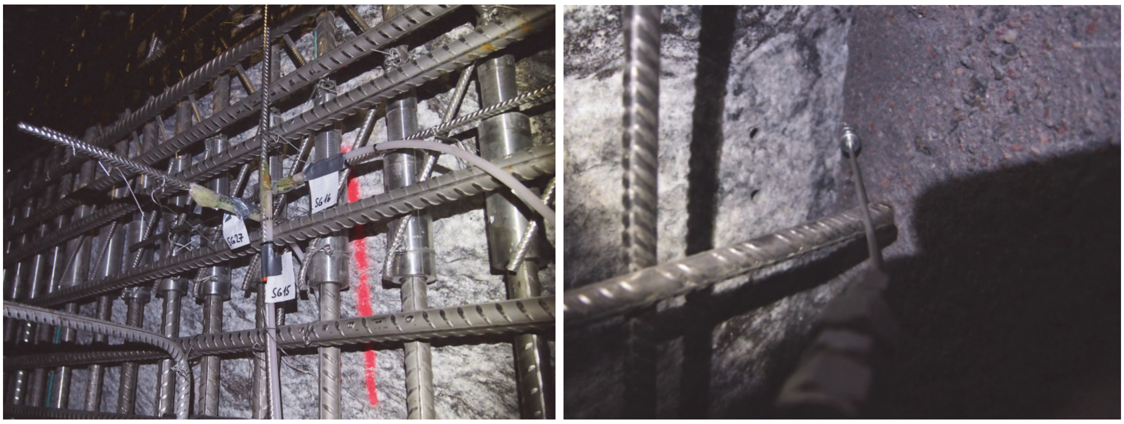


Figure 6.17. Three strain gauges vertical, horizontal and perpendicular direction (left), standalone thermocouple (right).

The sensor wires were sheltered by PVDF tubes. Before the wires inside the PVDF tubes reached the three cable flanges, which were used to lead the wires outside of the plug, the sheltering tubes were changed from PVDF to stainless steel. This measure guarantees that in case of pressurized leakage water gets inside a tube, it will not burst where it is exposed to atmospheric pressure outside of the plug concrete. Vesi-Vasa Oy was used to bend pipes for the instrumentation wire shielding.

Figure 6.18 shows the cable flanges, that lead all wires inside the sheltering tubes from inside plug section 2 to the front face of the plug, were they were bundled and continued to the measuring cabinet in the plug tunnel.

Figure 6.18. Three cable flanges, which carry in total 51 sensor wires, photographed from inside (left) and outside (right) plug section 2.

The installation of the plug section 2 sensors took place on 24–28 August 2015. The connection of all wires to the data loggers and the update of the data acquisition system on site were performed from 31 August 2015 to 2 September 2015. For the instrumentation of plug section 2 about 33 person-days of work inside ONKALO were needed.

As already done in plug section 1, all sensors locations were exactly measured and documented. Again a laser scanning of all installations inside the plug section took place as part of the quality control concept.

Data logging was continued for the sensors in the filter layer and in plug section 1, and started for all sensors in plug section 2. Again, all sensor data was checked right before the concrete casting of plug section 2 to guarantee a flawless function of the sensors and data logging systems. A few of the earlier sensors, in the backwall, were disconnected at the time of filter installation and plug construction.

6.7.6 Reinforcement installation, phase 3

The third phase of reinforcement installation was done in the 2nd section of the plug. It proceeded similar to the phase 2 installation, with the exterior bars being added to supplement the existing reinforcement used as rock protection. The instrumentation then proceeded, followed by ceiling and central reinforcements. For the plug section two, the reinforcement work took a total of six days.

6.7.7 Concrete casting

6.7.7.1 Concrete emplacement

Casting of the plug was done in a one day period, over 10–12 hours. The first plug section was cast on July 15, 2015 and the second plug section on September 16, 2015. The procedures for both plug sections were nearly identical, and are thus described here together.

A concrete casting readiness review meeting was held a few days prior to POPLU casting, where the regulatory authority (STUK) was invited as an observer. The pump truck was positioned underground the day before casting and all quality control equipment was ready. A small gully or ditch had to be temporarily excavated about 50 cm deep in the tunnel floor gravel, to accommodate the extension of the pump truck boom arm. The small concrete pump truck was not available for the plug casting and a larger one needed to be used.

A preliminary 0.5 m^3 concrete slurry batch, made from 8 mm maximum aggregate size, was used to flush through the pump truck and tubes. This was done to lubricate the equipment approximately 30 minutes before the actual plug concrete delivery. Concrete was delivered underground to ONKALO in intervals of approximately 20–30 minutes. The drive time from the batching plant was approximately 20 minutes. Quality control tests were done prior to the truck dispatching concrete to the pump truck.

Pumping was arranged via a rigid steel pipe which was input through the lowest window in the formwork mould. The pipe was slowly extracted during pumping, so as there was not a far distance for the concrete to flow or drop. Visual observations through the lower formwork indicated that the concrete remained level. This could also be seen when casting the $1m^3$ quality control blocks. No internal or external vibration was used.

For the 1st plug section casting, 24 trucks of concrete were delivered starting from 9.30 am. For the 2nd plug section casting, 20 trucks of concrete were delivered, at $4m^3$ each, starting from 8 am. The concrete volume needed for casting the whole plug was estimated to be 161.5 m^3, based on dimensional scanning of the tunnel by Prismarit Oy after slot excavation. In actuality, a total of 172 m^3 was used, comprised of 94 m^3in the first section and 78 m^3 in the second plug section. The extra material was utilized partially for the quality control samples. Figure 6.19 shows examples from the casting of monitoring formwork pressure.

Figure 6.19. Example of formwork monitoring of pressure development, with silver circular pressure gauge (centre lower section) for measurement at lowest level.

Temporary scaffolding was built during casting to support workers' access to the formwork windows and the concrete pumping. For plug section one the scaffolding was done by Telinekataja Oy, while in section two it was done by Hartela Oy themselves. The scaffolding and walking platforms was made in two separate levels to accommodate the height change.

A de-airing pipe was used to evaluate when the mould was full. When concrete came from air tube, then the air tube was withdrawn. The uppermost or last hole in the formwork had concrete pumping or casting with an applied pressure of 0.5 bars maintained for 30 minutes.

After casting, the concrete temperature development was monitored as an indication of cement hydration and setting (Figure 7.1). The formwork was removed after approximately 7 days based on the temperature measurements. The plug area was cleaned, including preparations of the floor of leakage water collection systems. The front face of the plug was covered with plastic sheeting to prevent air circulation and concrete drying. An automatic camera surveillance system continues taking frequent images of the plug, for quality control.

The on-site construction crews on the day of concrete casting included 6 persons from Hartela (2 for quality control tests, 4 persons for casting concrete), in addition to 1 person from Rudus Oy for controlling the pump truck and then the delivery truck driver. Posiva's construction quality manager was present the whole time, as well as the POPLU Experimental leader. At some phases of the casting there were additional observers from Posiva, STUK, VTT, and Rudus Oy.

6.7.7.2 Casting Materials

As noted earlier in the materials chapter, two different concrete types were used, both being used in both sections of the plug. The smaller, 16 mm maximum aggregate size, concrete was used in the areas of more congested reinforcement (which included for 1st plug casting: first 4 trucks and last 5 trucks; 2nd plug casting first 4 trucks and last 6 trucks). The middle section of the plug was cast with 32 mm maximum aggregate size. The final material amounts used in both sections of the plug casting are given in

Table 6.1 below.

Table 6.1. Proportions of materials used in plug section castings.

	Summary of Mixture Proportions				
	Laboratory Design	Plug: Casting 1		Plug: Casting 2	
Item	**Ternary Mixture**	**16 mm**	**32 mm**	**16 mm**	**32 mm**
CEM I 42,5 MH/SR/LA (kg/m^3)	105	106	108	107	106
Silica Fume (kg/m^3)	91	89	90	89	89
Fly Ash (kg/m^3)	84	85	86	85	85
Slag (kg/m^3)	0	0	0	0	0
Quartz Filler (kg/m^3)	114	115	116	115	115
Limestone Filler (kg/m^3)	0	0	0	0	0
Sand (kg/m^3)	926	1142	938	1142	929
Gravel (kg/m^3)	915	669	924	669	911
Effective Water Content (kg/m^3)	126	137	117	136	128
Super-plasticiser (kg/m^3)	12.6	23.5	18.9	22.5	18.6
Retarding Admixture (kg/m^3)	0	0	0	0	0
Water/Cement Ratio	1.20	1.29	1.08	1.28	1.20
Water/Binder Ratio	0.45	0.49	0.41	0.48	0.46
Water/Powder^A Ratio	0.27	0.30	0.26	0.30	0.28

Note: ^{A} The powder content includes the minus 125 micron material from all aggregates.

	Casting 1		Casting 2	
Item	**16 mm**	**32 mm**	**16 mm**	**32 mm**
Volume Placed (m^3) =	36	60	44	36
Volume Relative to Casting (%) =	38 %	63 %	55 %	45 %

6.7.7.3 Quality Control

Quality control tests were done for each concrete truck delivered underground. The quality control on-site was done by Hartela Oy, including measurements of air, density, temperature, and slump. Cylindrical and cubes samples were made for testing compressive strength, watertightness (permeability) and pH leachate at various ages. Quality control tests were also done by the ready-mix concrete supplier, Rudus Oy, at the factory at the time of batching, before truck delivery. Posiva staff oversaw both of these sets of quality control.

Two quality control cubes, 1 m^3 each in size, were cast underground beside the plug, for providing future large samples of each mix (16 mm and 32 mm maximum aggregate sizes). For plug section one, these large cubes did not include any reinforcement steel. For plug section two, the bottom and one side included 32 mm diameter steel bars, so the concrete flow adjacent to the formwork could be observed. Formwork on the quality control 1 m^3 cubes was removed after 2–4 weeks and the concrete cubes remain for future coring samples, as needed. The quality control cube moulds were re-used for plug section two casting.

During construction, it was possible to monitoring the temperature of the plug and pressure on the formwork. The demoulding was done at approximately 5 days after casting, based on the temperature development profiles and a preliminary measurement of the compressive strength. The plug surface appearance is very good, with no defects or pockets visible. The transition area around monitoring wires, pipes and lead-throughs looks good. Plastic sheeting covered the front face of the plug for the first 3 weeks after casting, to prevent drying and shrinkage. The plug second section concrete was allowed to harden for 90 days prior to injection grouting of the rock-plug interface.

6.7.7.4 Lessons Learned

It was noted by the contractor that the concrete was very good, having high workability and being easy to work with. There was a good workability time, so there was enough time for quality control tests and placement via pumping. During the second plug section casting, only once truck needed to have slightly more superplasticizer chemical added to obtain the target range of slump spread.

Lessons learned from casting were that it would be feasible to consider casting the plug in one section rather than two. The concrete was self-levelling and did not require vibration, thus it could flow for larger distances. There were no problems in using two different concrete recipes, with varying maximum aggregate sizes. It was very helpful to work with the contractor to make mock-up or metric scale demonstration tests prior to actual POPLU plug casting. The contractor noted that there could have been more detailed plans for the many phases of construction, to save time and utilize best on-site experience and practices.

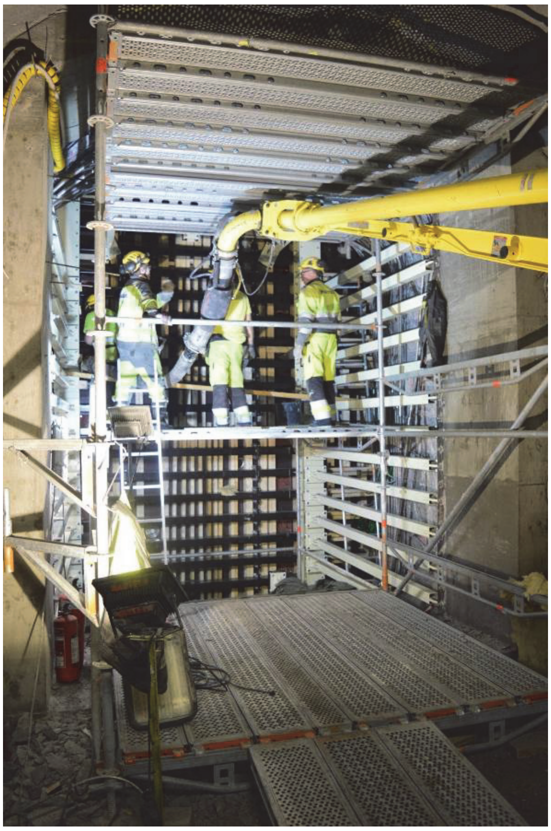


Figure 6.20. Plug section and concrete during emplacement period.

6.8 Grouting of Interface

Contact grouting of the plug-rock interface around the circumference of the plug was performed during a five-day period in December 2015. A total of six grouting loops were grouted according to the work method descriptions. The work began with grouting of the first two loops, being the outer most two loops on each end, on consecutive days, and was then halted for a drying period of eight days and for Christmas holidays. Grouting continued on the 28th December 2015 by grouting the inner four loops and was completed in three consecutive days.

The grout was mixed on the POPLU experiment site and quality control testing was performed before accepting the grout for use. During contact grouting, the grouting pressure, consumption of grout and visible leakages of grout for each loop was recorded. The contact grouting was done by Lujitustekniikka Oy subcontracted by Hartela. The amount of contact grouting used in total for all six lines was 750 litres.

Table 6.2. The grouting pressure, consumption of grout and visible leakages of grout during contact grouting.

Date	Grouting loop	Grouting pressure	Grout consumption	Visible leakage
16.12.2015	1	20 bar	Yes	No
17.12.2015	6	20 bar	Yes	Yes
Drying				
28.12.2015	2	90 bar	Yes	No
29.12.2015	5 (floor and walls)	76 bar	Yes	Yes
30.12.2015	5 (roof)	90 bar	No	No
30.12.2015	3	80 bar	Yes	No
30.12.2015	4	90 bar	Yes	Yes

6.9 Material Quantities Summary

The total amounts of materials used in the POPLU plug are given in Table 6.3. There were 12000 kg of lightweight aggregate blocks produced for making the filter layer wall and 6290 kg of low-pH mortar used for the footing and attaching the blocks when making the filter wall. There was approximately 750 litres of injection grout used for contract grouting the plug-rock interface. Materials used for the tunnel backwall are not included in this table, as the backwall was done for experimental purposes to shorten the tunnel. Materials used for the formwork are not included, as they are removed from the repository after construction or before closure. The material amounts for contact grouting and rock stability (such as shotcreting in the plug area around the slot) are not listed in the table due to confidentiality reasons, though they would be part of operational plugs and foreign materials acceptance reviews.

Table 6.3. Total material amounts used in POPLU, no including materials for backwall, contract grouting or rock stability.

Structural Plug	Cement (CEM I)	18 400 kg
	Superplasticiser	3 560 kg
	Silica fume	15 370 kg
	Fly ash	14 680 kg
	Quartz filler	19 840 kg
	Aggregate (sand + gravel)	315 520 kg
	Reinforcement steel	24 270 kg
Filter layer components (blocks + joining mortar)	LECA® lightweight aggregate, 0–4 mm	1 400 kg
	LECA® lightweight aggregate, 4–10 mm	3 450 kg
	Sand 0-8 mm (in mortar)	6 900 kg
	Fine sand (filler, in mortar)	790 kg
	Cement (CEM I)	2240 kg
	Silica fume	1500 kg
Other components	LECA® lightweight aggregates used individually (not in blocks, but around circumference)	3 000 litres
	Other steel components, including attachment wires/screws/supports and	55 kg
	Grouting tubes	45 kg
	Bentonite tape strips	60 kg
	Plug lead-through (pipe + flange; stainless steel)	230 kg

The total amounts of materials used in the plug instrumentation are given in Table 6.4. The materials are grouped according to the main categories. These were for experimental purposes only, and would not be representative of operational plugs.

Table 6.4. Total material amounts for instrumentation system used in plug.

Material type	Material content [kg]
Stainless steel	374.5
Copper	20.0
Aluminium	1.0
Constantan	0.2
Polyvinylidene fluoride (PVDF)	92.4
Teflon	18.5
Polyvinylchloride (PVC)	5.5
Other plastics and elastomers	1.2
Sand (quartz)	1.1
Other materials	1.5

6.10 Material Quality Control

Quality control testing was done for the various concrete and grout materials used during the various castings, including primarily the backwall and both sections of the plug. Table 6.5 summarizes the overall concrete properties based on these quality control tests. These values are an average of multiple tests. Fresh concrete properties of slump flow, air content and mixture temperature were taken underground at the time of delivery from each concrete truck, prior to acceptance for pumping into the formwork. The quality control was also done on each truck prior to dispatch from the factory. Hardened concrete properties were measured on companion cubes (150 mm) and cylinders (150 mm diameter by 300 mm height) cast and cured (covered) underground at the same time as sample delivery. Examples of the quality control tests are shown in Figure 6.21.

Figure 6.21. Quality control testing of fresh concrete upon delivery underground, a) 1m3 cubes, b) slump flow.

Quality control 1m^3 blocks were also cast for each of the two plug sections, for each of the two recipes (16 and 32 mm maximum aggregate sizes) for future use if needed for comparison to the plug. These blocks have not had any sampling at the time of this report. Quality control results from the injection grouting are not included here, as the development work was not part of DOPAS and is confidential information.

Table 6.5. Average concrete material quality control tests results from plug construction.

	Summary of Concrete Properties					
	POPLU	Laboratory Design	Plug Section 1		Plug Section 2	
Item	**Target**	**Ternary Mixture**	**16 mm**	**32 mm**	**16 mm**	**32 mm**
Volume placed (m^3), at $4m^3$/truck	n.a.	n.a.	36	60	44	36
Average Slump Flow (mm)	610	290	610.0	610.7	607.3	597.8
Slump flow standard deviation (mm)	n.a.	n.a.	14.1	18.3	12.7	33.1
Range (+/-) in Slump Flow (mm)	40	n.a.	590-630	580-650	590-630	560-650
Air content (%)	n.a.	n.a.	2.5	1.8	2.6	0.8
Fresh mix temperature (°C)	~20	n.a.	21.7	21.1	18.4	18.6
Compressive Strength at 91 days (MPa)	> 50	79.5	77.7	92.3	79.4	81.2
Water Tightness at 91 days (mm)	max. 50	5.0	3.0	3.3	1.0	1.0
Leachate pH at 28 days (Sim. Olkiluoto Groundwater)	n.a.	n.a.	10.9	10.9	10.9	11.0
Leachate pH at 91 days (Sim. Olkiluoto Groundwater)	< 11	10.3	10.9	10.9	10.8	10.8

Quality control test results from preliminary tests including the mock-ups and backwall are summarized in Table 6.6. Here it can be seen there are differences in the recipe development during the mock-up method tests and backwall, yet the backwall final demonstration had concrete with similar properties to the concrete used in the actual plug (Table 6.5 above). The strength, watertightness and pH leachate values were similar between the backwall and average values between plug sections 1 and 2. These values fulfilled the target requirements. The uncertainty associated with these values and other laboratory tests, quality control tests and monitoring systems was not addressed within DOPAS yet will be further evaluated by Posiva in the future. Analysis of standard deviations of measurements on quality control samples was outside the scope of the DOPAS project, but has been addressed by Posiva internally.

Table 6.6. Average concrete material quality control tests results from method-tests and backwall.

	Summary of Concrete Properties			
	POPLU	**Method-Tests**		**Backwall**
Item	**Target**	**#1**	**#3**	
Compressive Strength at 28 days (MPa)	n.a.	57.3	45.9	-
Compressive Strength at 91 days (MPa)	> 50	71.9	63.5	79.9
Water Tightness at 56 days (mm)	n.a.	-	-	7.0
Water Tightness at 91 days (mm)	max. 50	11.3	-	2.0
Leachate pH at 28 days*	n.a.	-	-	11.1
Leachate pH at 91 days*	< 11	-	-	10.8

** note: in simulated deep groundwater ONKALO.*

Another example of quality control testing was the visual microscopy assessment of concrete cores taken from the mock-ups. Visual observations were done to evaluate the distribution of aggregates to identify if there were any problems with uneven consolidation of the self-compacting mass. Visual observations were also done of the bentonite tape to concrete interface in method test #1, as shown in Figure 6.22. Here it can be seen that there was no problem of bonding, or severe heterogeneities in the interface zone between the concrete and bentonite tape. The attached bentonite tape strips performed as planned.

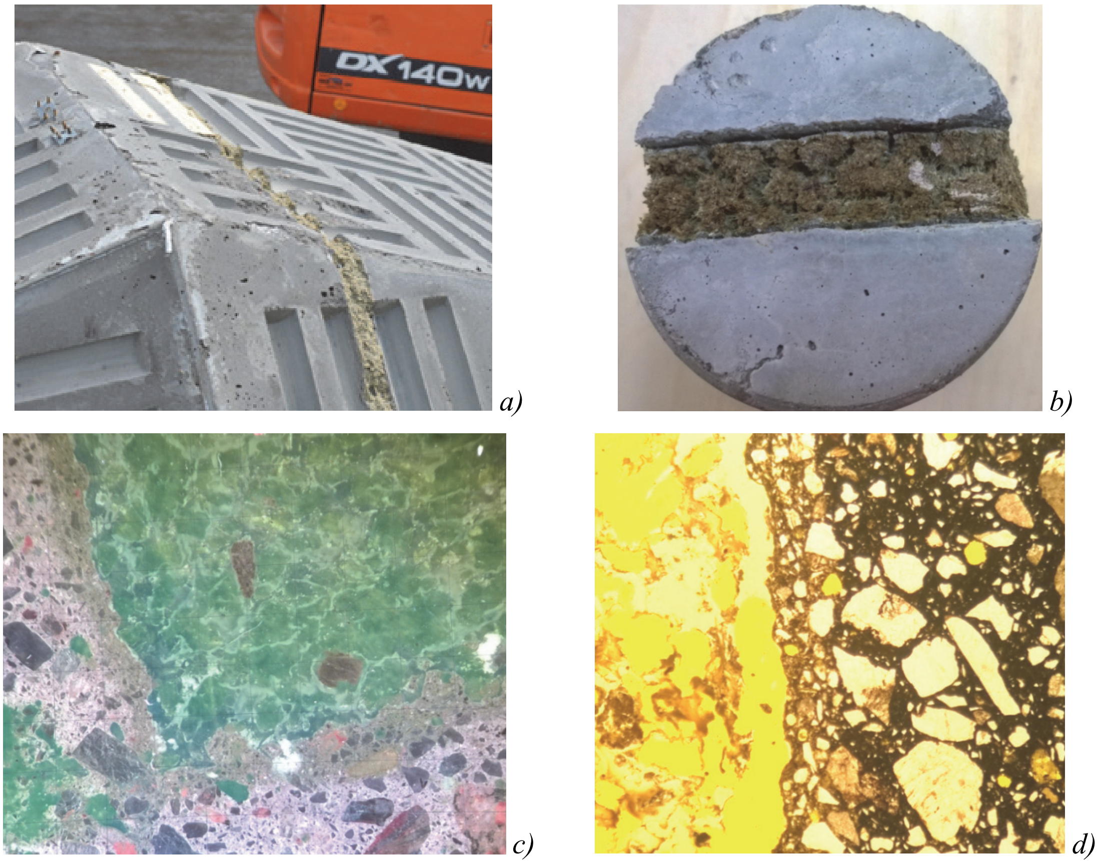


Figure 6.22. Method test #1. a) sample location of bentonite tape to concrete interface. b) Core of concrete with bentonite in middle. c–d) Microscopy image of bentonite tape to concrete interface, showing 1 mm thick layer between materials.

7 PERFORMANCE ASSESSMENT

7.1 Plug Instrumentation as Basis for Performance Assessment

The primary source of information for the performance assessment of the plug is the data provided by the sensors in and around the plug. The different sensor types were selected to provide essential information during the different phases of the plug construction and operation, starting already with concrete casting and following the plugs service life through and after pressurization. Table 7.1 provides and overview of monitoring data utilisation during the different phases of the plug performance. Details about the sensor types are provided in Deliverables D3.25 [Hakola 2015] and D4.4 [DOPAS 2016b].

Table 7.1. Overview of monitoring data utilisation for plug performance assessment.

Data from plug monitoring systems	concrete casting	concrete hydration	initial pressurization	rapid pressurization (wedge test)
temperature		X		
relative humidity		X	X	X
pore pressure			X	X
total pressure	X	X	X	X
strain			X	X
displacement	X		X	X
leakage amount			X	X

There were not many limit values or acceptance criteria set for the monitoring parameters, as the function of the monitoring system was to provide insight to validate and aid future design decisions, Only the temperature had a limit value of 60 °C, while strain was targeted to be minimal. Displacement and pressure changes were expected and desired based on the plug structural and water pressurization system design. Relative humidity changes were expected based on water intrusion due to pressurization, with intentions that it remains low near the front face of the plug in the interface (indicating watertightness).

7.2 Concrete Casting, Hydration and Curing

Right after the concrete has been cast into the formwork, the temperature evaluation as a result of the concrete hydration is monitored as a key performance indicator of the plug concrete. The temperature was followed at many locations inside and around the plug with multiple temperature sensors (stand-alone thermocouples, thermocouples in connection with strain gauges, temperature sensors inside the relative humidity and pressure sensors). Figure 7.1 shows the temperature development inside the plug during concrete casting and hydration of the first and second plug section, measured with temperature sensors connected to relative humidity sensors. The sensors are located in the centre of the two plug sections (estimated to be the hottest areas) and in a distance of approx. 10 cm to their outer surface (colder areas due to the expected high heat flux to the surrounding components).

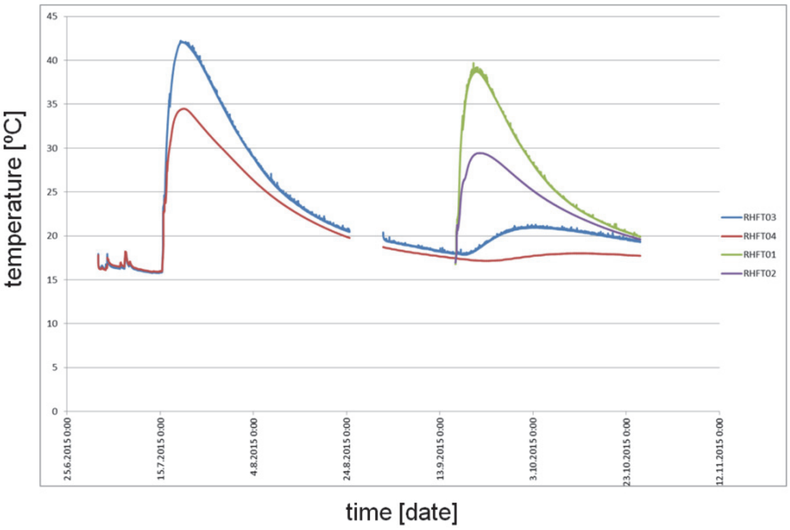


Figure 7.1. Temperature development during concrete casting and hydration of plug sections one and two.

During the concrete casting, any potential displacement or movement of the reinforcement inside plug section one could be recognised by the displacement sensors. The measurement results did not indicate any displacement. As well the hydraulic pressure of the fresh concrete is of interest when assessing its workability and the pressure that acts on the formwork. The data that was collected from total pressure sensors, which are located in the interface between the surrounding rock and the concrete of both plug sections. Figure 7.2 shows an example of the measurement results obtained from the total pressure sensors TP05-09 and TP10-11, which are located around plug section one, and section two respectively.

The data received from the sensors TP10 and TP11 show the hydraulic pressure inside the fresh concrete of plug section two during the casting and initial hydration phase of the concrete in September 2015. The total pressure sensors TP05 to TP09 show the pressure response in the interface rock/concrete that was generated by the thermal expansion of the already hardened plug section one, which was casted in July 2015. The thermal expansion was caused by the exothermic concrete hydration of plug section two, which led to a temperature increase of plug section one (see Figure 7.2) and consequently to a pressure increase as a result of the constraint generated by the stiff surrounding rock against the expansion of plug section one.

Whereas the total pressure sensors of plug section two (TP10 and TP11) start at a zero pressure level at the start of concrete casting (zeroing of the sensors was done prior to the begin of casting on 15.9.2015), the sensors of plug section one (TP05 to TP09) start at a negative pressure level. This is a consequence of the first casting process. Plug section one was subject to a negative deformation due to autogenous shrinkage and cooling of the hardened concrete after reaching the peak temperature due to hydration. This effect "pulls" the sensors away for the concrete/rock interface. A negative reading of the sensor is possible, since they were surrounded by the concrete, which creates a bond between the rock surface and the sensor with a certain adhesion strength. It can be assumed that the sensor surface was not detached from the rock surface due to the shrinkage and cooling deformation.

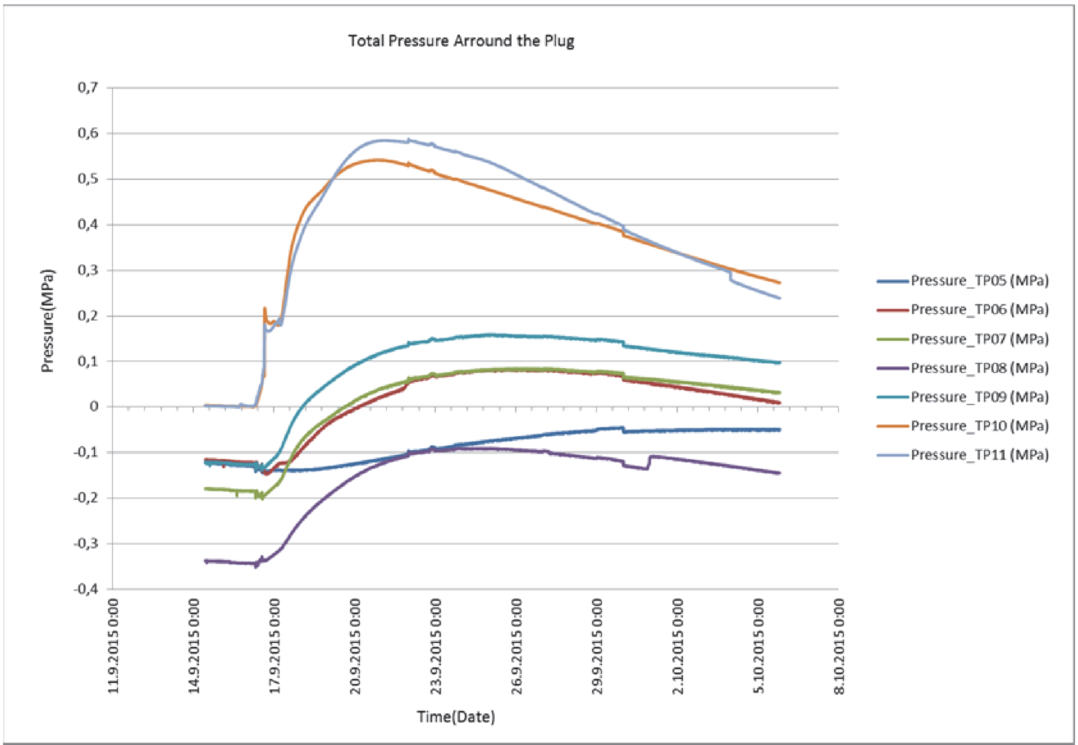


Figure 7.2. Total pressure development in the interface between rock and concrete plug during casting of plug section two.

All total and pore pressure sensors in the filter layer and in plug part one were set to a value of zero on 15.7.2015 prior to the concrete casting. Zeroing of the total and pore pressure sensors in plug part two took place on 15.9.2015, again before concrete casting. No further change of these initial settings of the sensor values were done afterwards, which is the general basis of the pressure readings that can be seen in the following graphs (Chapters 7.4 to 7.6).

7.3 Plug Pressurization Plan

7.3.1 Pressurization Background

The POPLU experiment will be evaluated for leakage and performance by the use of water-based pressurization, to simulate the expected 100 year lifetime operation of a tunnel end plug. The pressurization level target was at least 4.2 MPa, representing the hydrostatic pressure at 420 metres underground. Additional pressure increases could also be made corresponding to potential future scenarios where backfill bentonite/clay would exert an additional swelling pressure at a maximum of 3 MPa. The POPLU wedge-plug is structurally designed to withstand a 10 MPa pressurization test.

The pressurization can start only after the concrete plug and components are emplaced and have gained sufficient strength as expected from the structural design. This was selected to be after 105 days, representing at least 90 days after casting of the 2nd section of the concrete plug plus and additional one two weeks after grouting of the plug-rock interface. The duration of contact grouting was three calendar weeks, thus the pressurisation was started 125 days after the casting of the 2nd section.

The pressurization is designed to be achieved by use of water added via a pipe from the neighbouring tunnel. The water is added to a filter layer towards the back of the tunnel and shall contain a tracer to evaluate its flow paths. The rate and impact of water filling is monitored by the moisture (relative humidity) and pore pressure gauges. After an even distribution of water has been achieved behind the plug, the pressurization increase commences. The Pressurization system and equipment was detailed in Chapter 4.4 for design and Chapter 5.7.5 for construction installation.

It was originally targeting that stages of pressurization should correspond between the POPLU and DOMPLU (SKB) experiments, so that the performance of the two different types of plugs can be compared as much as possible. It was initially expected that the POPLU loading should follow the same pressurization steps already established by SKB and given in the DOPAS Deliverable about DOMPLU [DOPAS 2015]. Yet the two plugs are different in their use of bentonite clay, which changes the watertightness sealing functionality. Thus the pressurization rates, and corresponding bentonite saturation, do not need to coincide.

SKB's DOMPLU pressurization with water only in spring 2014 to approximately 4 MPa induced leakage in the rock adjacent to the plug, as described in the DOPAS Deliverable D4.3 [DOPAS 2015]. Thus the POPLU pressurization plan is designed to first reach this target level of 4.2 MPa. The rate at which the pressurization is increased has been decided in a manner as to allow time for the plug response with monitoring. It has also been considered the need to generate information and knowledge to meet the DOPAS project deadlines and final reporting within the project duration (to be completed by August 2016).

7.3.2 Planned Pressurization Steps

There were two different pressurization actions taken to evaluate the POPLU performance: 1) slow pressurization to evaluation initial leakage; 2) fast filling to evaluate wedging effect of path.

The pressurization ramping plans, or time steps with load, are shown in and 6.4 for slow and fast respectively, and are described for each of the two series below.

The pressurization plan for fast pressure increase includes the following steps:

1) Water filling behind the plug for 48 hours (2 days filling, with resting period at night to allow for air escape). Maximum pressure of 100 kPa, or less acceptable.
2) Pressure remains or increases to level of 100 kPa over a 2 day period.
3) Pressure increase to 500 kPa over a 1 day period.
4) Pressure increase to 1000 kPa over a 1 day period.
5) Pressure increase to 1500 kPa over a 1 day period with a mid-day check (hold for at least 2 hours at approximately 1250 kPa).
6) Pressure increase to 2000 kPa over a 1 day period with a mid-day check (hold for at least 2 hours at approximately 1750 kPa).
7) Pressure increases of 200 kPa once a week (for 11 weeks).

Before each step listed above (and for step #7 approximately 24 hours before), the POPLU Pressurization group will evaluate the response and make a decision if the next step can start. The decision making will be based on:

- Functioning of the pressurization system,
- Response of the plug based on instrumentation monitoring and leakage measurement system and predictions made (i.e. assessment of water tightness, mechanical integrity, disturbances caused by injection pipe brackets, etc.),
- Monitoring of response of the near field rock environment, as described in Chapter 4.4.6.

The pressurization plan for fast pressure increase includes the following steps:

1) Pressure increase to 1000 kPa over a 1 day period for deairing.
2) Pressure increase to 4200 kPa as fast as possible with checkpoints at 2800 kPa and 3600 kPa.
3) Pressure is upheld until one of the predetermined criteria for test termination is fulfilled.

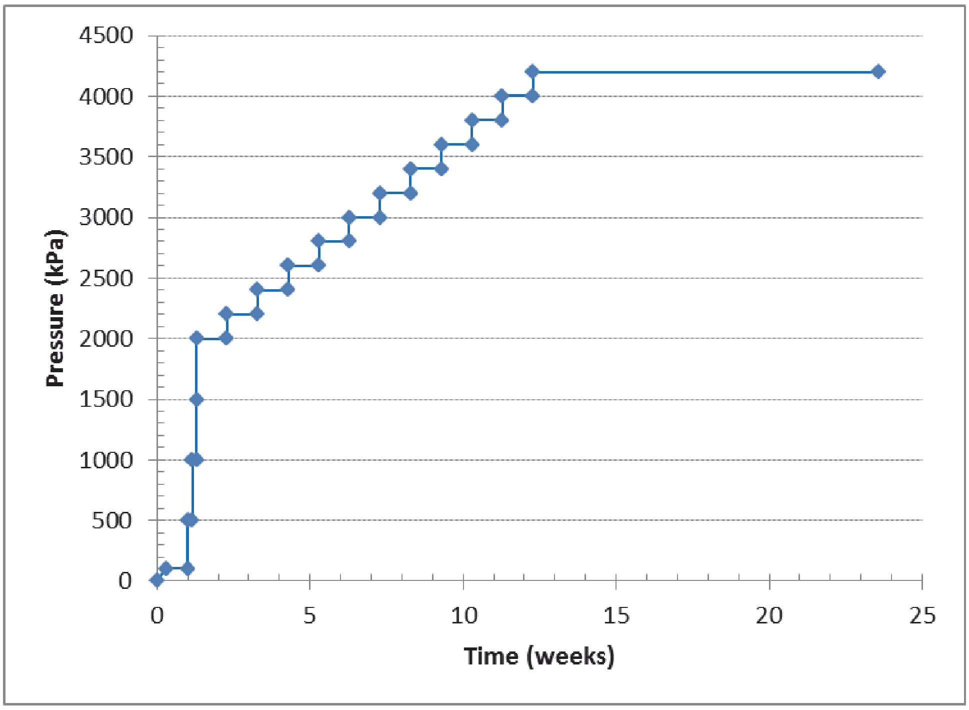


Figure 7.3. Pressurization levels and schedule for slow pressure increase (blue line plan, as of December 2015).

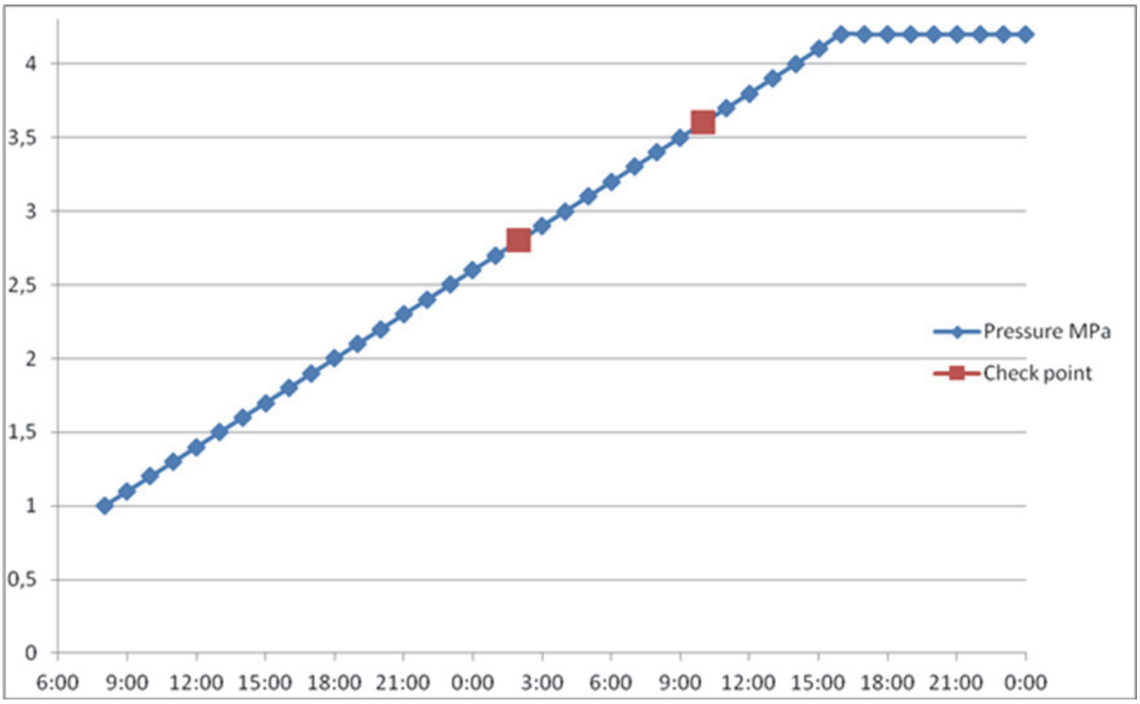


Figure 7.4. Pressurization levels and schedule for fast pressure increase.

It was noted during the planning phase that the pressurization plan could further evolve or change during the course of the monitoring and was subject to further optimisation. This was realized after seeing the leakage response during the slow water filling and low pressurization to 1.2 MPa. Thus the second pressurization test was planned, simultaneous to re-grouting preparations.

7.3.3 Pressurization and Response Risk Handling

If a leak is observed during the slow pressure increase phase, the following steps were identified to be taken:

A) Should there occur leaks (tens of ml/min) or other unexpected events, pressure incrementing will be terminated. The pressure level will be retained if leakage is from:

- (2) bulk of concrete
- (3) rock-concrete interface or
- (4) EDZ

B) Test will be continued if leakage (is less than 100 ml/min) is from:

- (1a) cabling or (1b) tubing
- (5) far-field rock fractures
- (6) rock lead-through.

During the fast pressure increase phase leakages is expected and therefore no limits for leakage is set, instead phase termination criterion is used. Test phase is terminated with following actions if

1. Pressure is 4200 kPa and plug is wedging and the leakage is less than 100 ml/min
   - Pressure will be uphold and monitoring is continued
2. Pressure is 4200 kPa and leakage from the concrete/rock interface is more than 100 ml/min and plug is not moving
   - test phase is terminated by stopping the pump and letting the pressure to decrease naturally.
3. Pressure is 4200 kPa and leakage from the concrete/rock interface is more than 100 ml/min and plug is moving
   - extend test phase for 24 hours to monitor possible decrease in leakage.
   - If leakage is decreased below 100ml/min, pressure will be uphold and monitoring is continued
   - if leakage is not decreasing, test phase is terminated by stopping the pump and letting the pressure to decrease naturally.
4. Pressure of 4200 kPa is not reached and plug is leaking more than 100ml/min from the interface
   - test phase is terminated by stopping the pump and letting the pressure to decrease naturally.

7.4 Actual Realized Pressurization

The actual pressurization began with slow pressure increase phase on 20 January 2016. The pressurization steps for this phase are shown in Figure 7.3 and described as follows:

1) Water filling behind the plug for 48 hours (2 days filling, with resting period at night to allow for air escape).
2) Pressure remains at level of 100 kPa for a 5 day period.
3) Pressure increase to 500 kPa over a 1 day period.
4) Pressure increase to 1000 kPa over a 1 day period.
5) Pressure remains 1000 kPa for a 8 day period.
6) Pressure increase to 1200 kPa over a 1 day period.
7) Pressure remains 1200 kPa for a 7 day period.
8) Pressure increase to 1400 kPa over a 1 day period.
9) Pressure remains 1400 kPa for a 7 day period.
10) Pump was stopped and pressure was allowed to decrease naturally to 600 kPa over 21 day period.

Pressurisation commenced with the filling of the filter with water, which took approximately seven days. Water filling was undertaken slowly to allow for air escape from the filter layer. The total volume of water used to fill the filter was 13 m^3. During this period, the total pressure within the filter layer remained below 100 kPa. Figure 7.14 shows the response of the total pressure sensors in the filter layer during the water filling.

Once the filter was filled with water, pressurisation could commence. In the early stage of pressurisation, the water pressure in the filter was increased to 1 MPa in two steps. After that pressure increase was done according to the plan with 200 kPa increase step that was held for one week.

After the slow pressure increase phase the fast pressure increase phase was initiated on 25, April 2016. The objective of this 2nd fast pressurization series was to increase and decrease the pressurization quickly, to evaluate the potential wedging effect and response of the plug. This also included evaluation of the pressurization and monitoring systems' functionality. The pressure was taken to over 4 MPa and held, then dropped immediately and re-pressurized four additional times (labelled B–E). The pressurization steps for this phase are shown in Figure 7.5 and described as follows:

1) 2A-1. Pressure increase to 1000 kPa over 1 day period
2) 2A-2. Pressure increase to 4100 kPa over 24 hour period
3) 2A-3. Pressure remains 4100 kPa for a 12 hour period

4) 2B-1. Pressure decrease to 500 kPa over 15 min period
5) 2B-2. Pressure increase to 4100 Kpa over 40 min period
6) 2B-3. Pressure remains 4100 kPa for a 2 hour period

7) 2C-1. Pressure decrease to 500 kPa over 6 min period
8) 2C-2. Pressure increase to 4100 Kpa over 30 min period
9) 2C-3. Pressure remains 4100 kPa for a 4 hour period

10) 2D-1. Pressure decrease to 1000 kPa over 3 hour period
11) 2D-2. Pressure increase to 4100 Kpa over 30 min period
12) 2D-3. Pressure remains 4100 kPa for a 4 hour period

13) 2E-1. Pressure decrease to 600 kPa over 6 min period
14) 2E-2. Pressure increase to 4100 Kpa over 20 min period
15) 2E-3. Pressure remains 4100 kPa for a 2 hour period
16) 2E-4. Pump was stopped and pressure was allowed to decrease naturally.

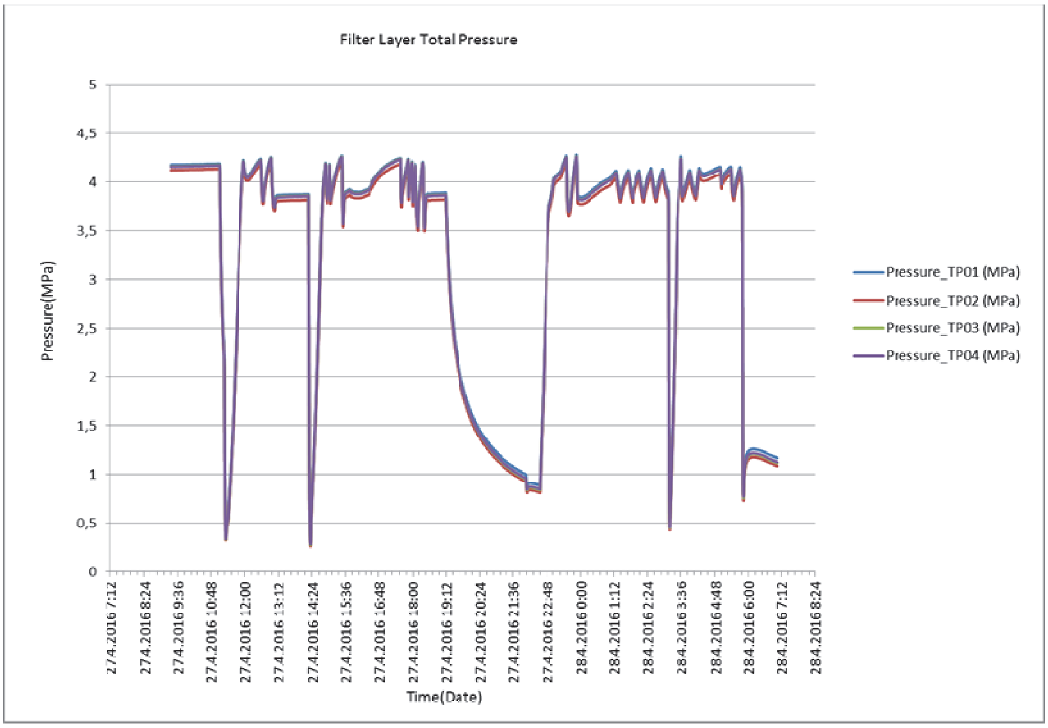


Figure 7.5. Graphic representation of actual pressurization steps achieved in fast pressure increase phase.

7.5 Leakage

During the slow pressure increase phase the leakage measurement system was collecting all the leakage water from the plug and the adjacent rock mass. Measured total leakage is presented in Figure 7.6. There were leakages via grouting pipes, instrumentation cables and concrete-rock interface. Exact amounts of leakages from different points were not measured, but according to visual estimation quarter of the total leakage came from instrumentation and grouting pipes. There was also small leakage from the concrete lead through in a middle of the plug, but that sealed very quickly (within hours) indicating that the bentonite tape was effective. There was no leakage detected on the rock lead through between DT3 and DT4. The separate leakage collection system was not utilized due to watertightness of the lead-throughs.

During the fast pressure increase phase, the leakages were so large that the measurement system by water weighing within the leakage collection system was not able to cope with them. Therefore the only estimation from the leakages come from the amount of water that was needed to pump to uphold the pressure. In the beginning the amount of water needed was 10 l/min, but after the fourth pressure decrease-increase (labelled E above) the amount had reduced to an average of 2 l/min. Thus the fast pressurization test was deemed to be valuable in creating a response in the plug due to the pressurization over 4 MPa and cycling loading.

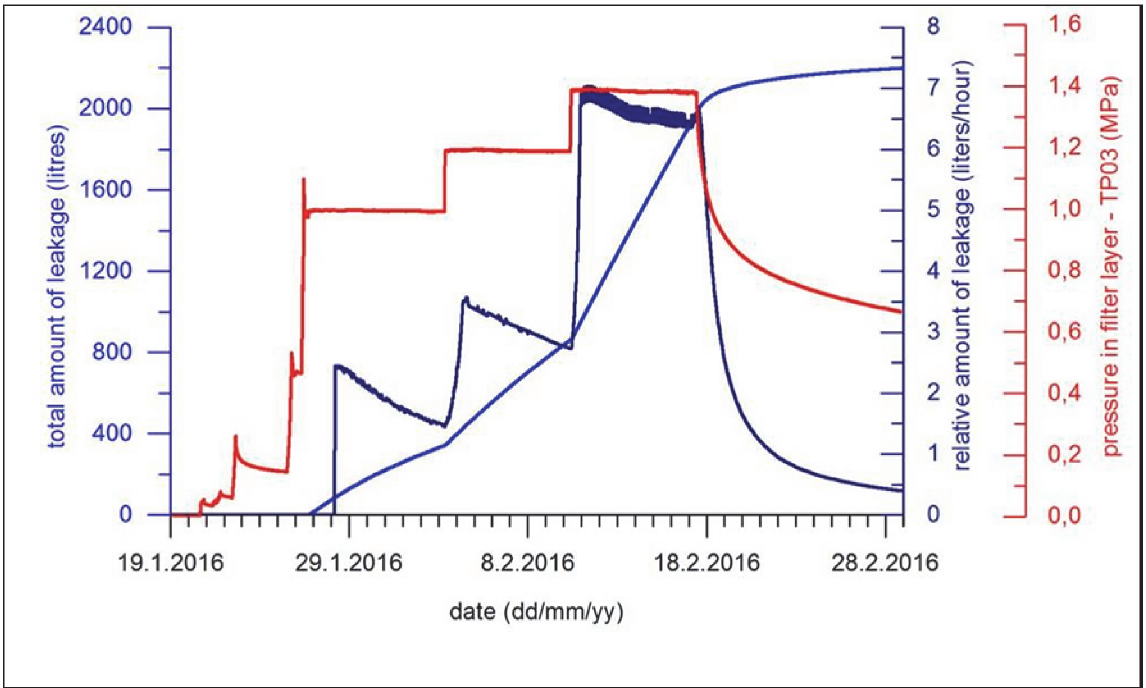


Figure 7.6. Plot of cumulative leakage, leakage rate and pressure in the filter layer (as measured by total pressure sensor TP03) during the slow pressure increase phase of the POPLU experiment.

7.6 Plug and Filter Response

Plugs response to pressurization is monitored with several different kinds of monitors. The analysis section is divided for the slow and fast pressurization tests.

7.6.1 Slow Pressurization, to ~1.4 MPa

The responses to slow pressure increase phase to about 1.4 MPa are shown in Figure 7.7–Figure 7.13. This included the water filling in the filter and then pressurization over a one month period.

Both total and pore pressure sensors show instantaneous reaction to pressure steps, both in increasing and decreasing changes as seen in Figure 7.7 and Figure 7.8. Also the total pressure sensors around the plug seem to react to all changes in the water pressure behind the plug, but the magnitudes of pressure changes are smaller, Figure 7.9. This would indicate open, but limited, connection with the water in the filter layer and the sensors around the plug. The pore pressure sensors results around the plug show in Figure 7.10 indicate even more limited connection between sensors and the filter layer. The sensor responses indicate that some of the pore pressure sensors in the plug/concrete interface might have been blocked by the injection grout (PP06 and PP11), or some clogging of the filter stone inside the sensor happened during the contact grouting process, which might affect the sensor reading (PP08 and PP10).

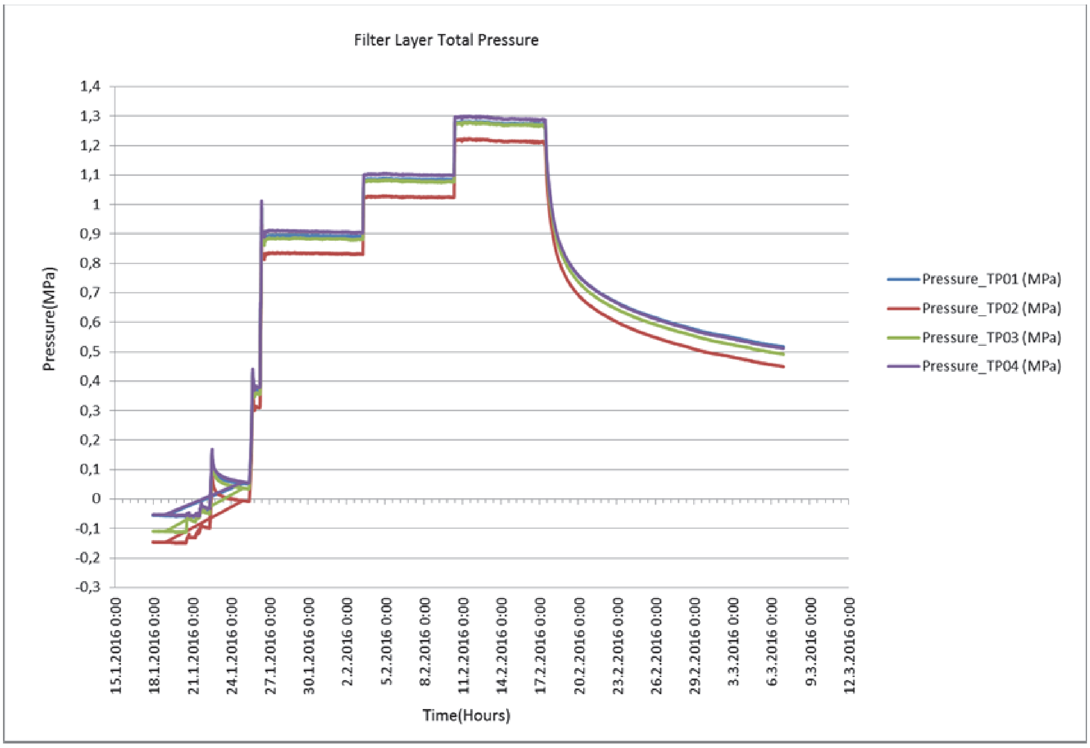


Figure 7.7. Total pressure sensors in filter layer.

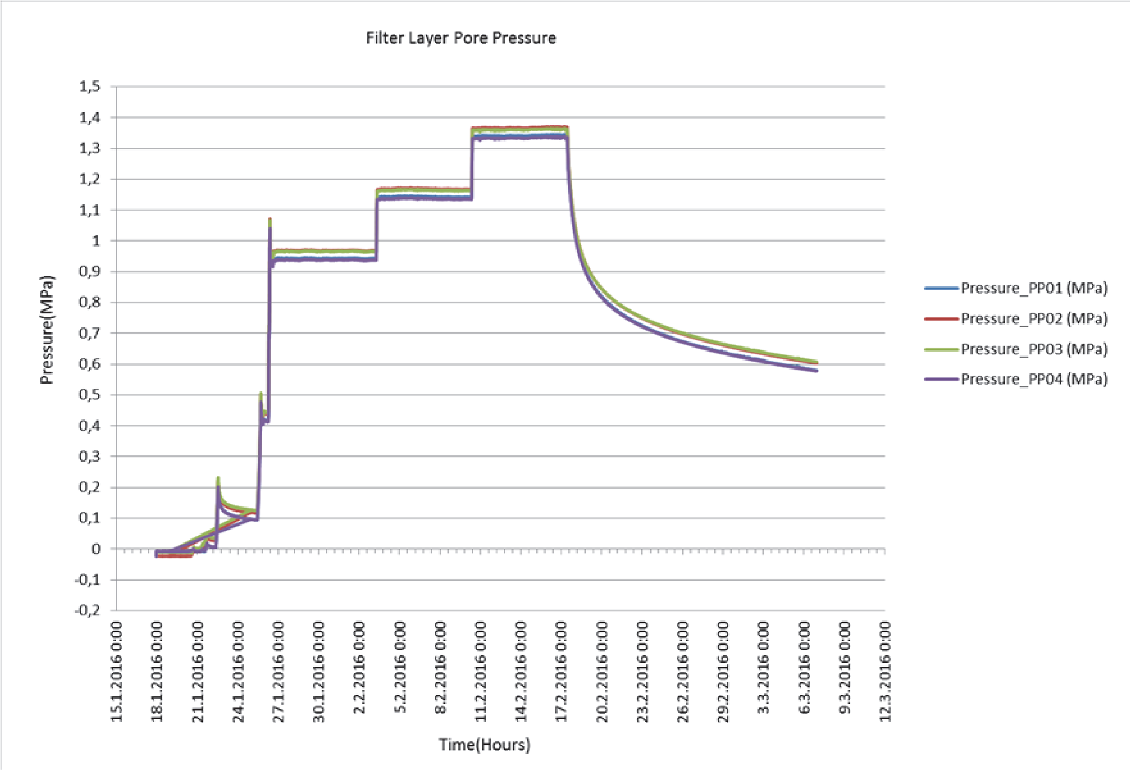


Figure 7.8. Pore pressure sensors in filter layer.

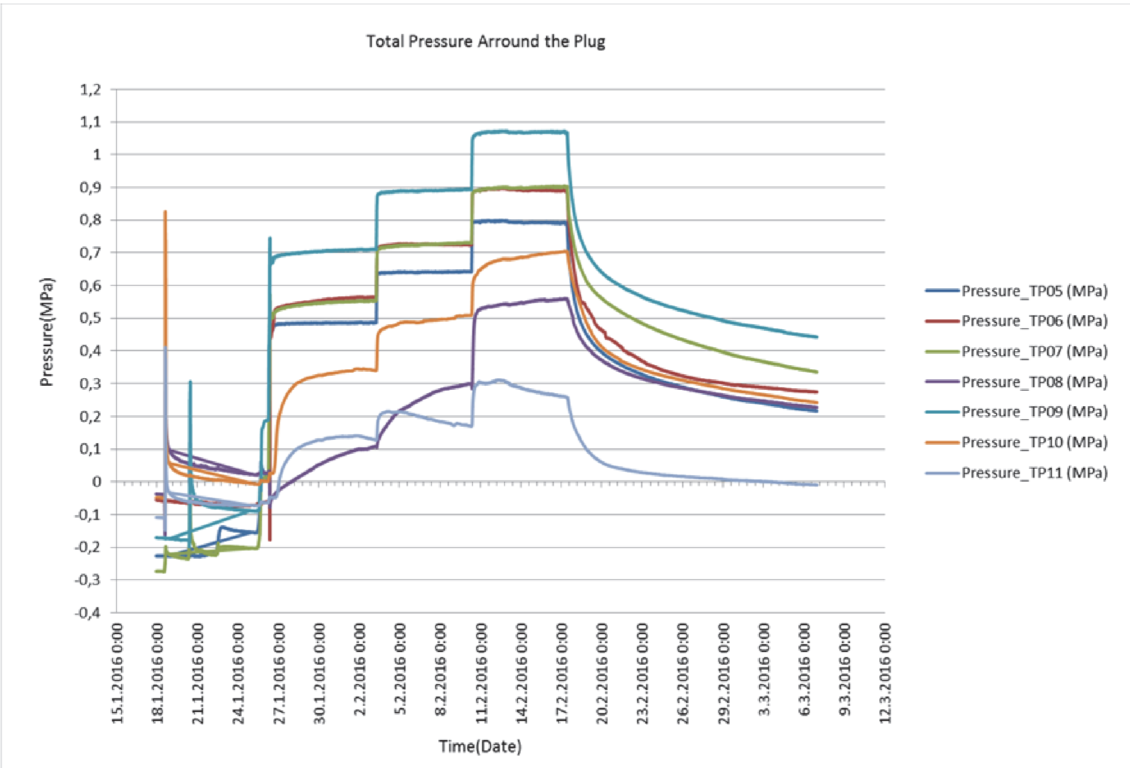


Figure 7.9. Total pressure sensors around the plug.

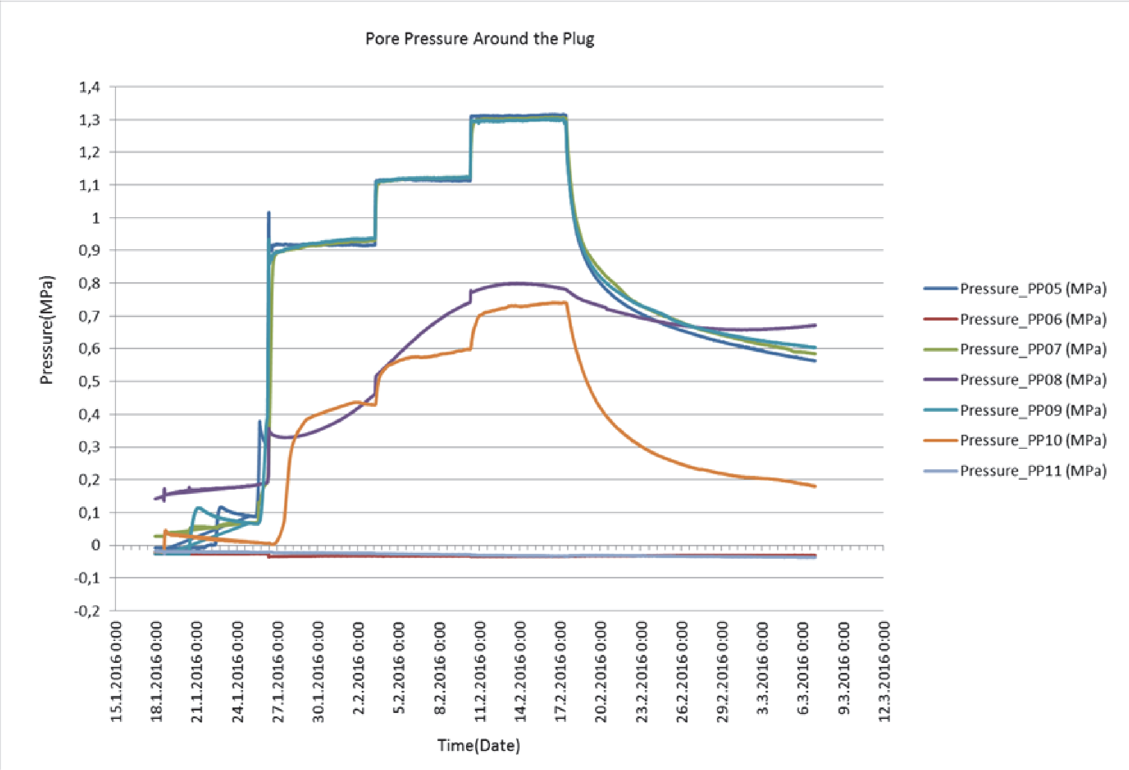


Figure 7.10. Pore pressure sensors around the plug.

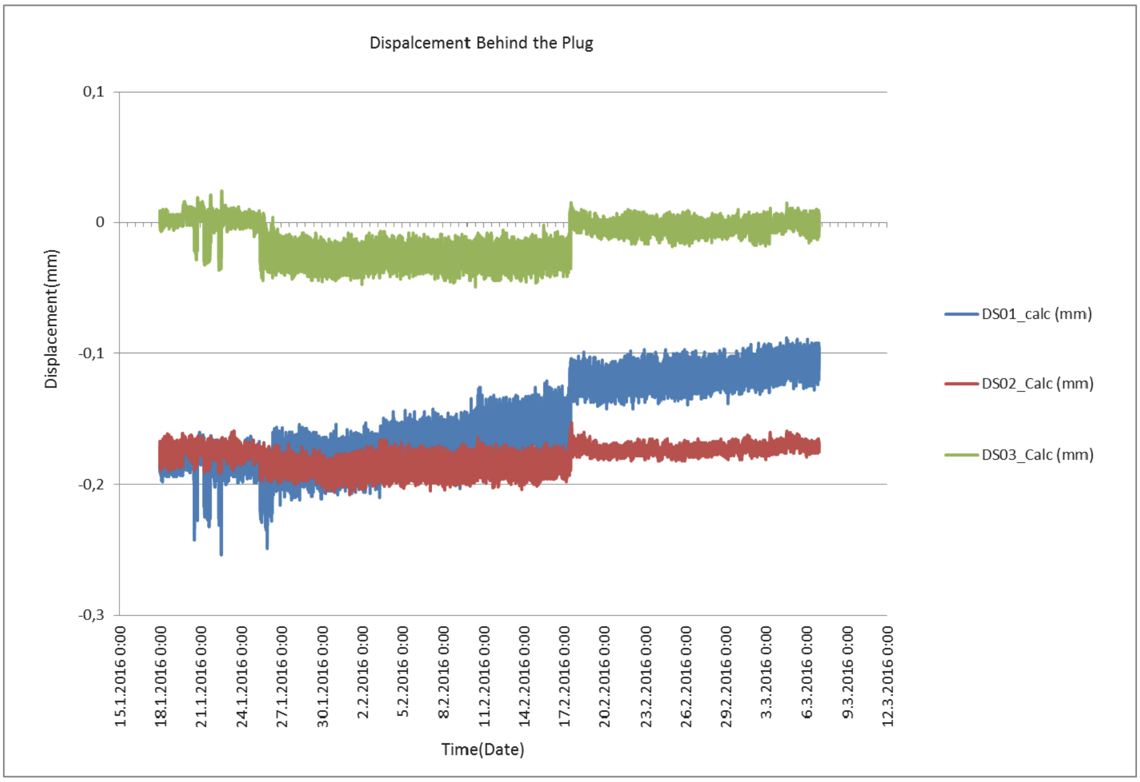


Figure 7.11. Displacement sensors behind the plug.

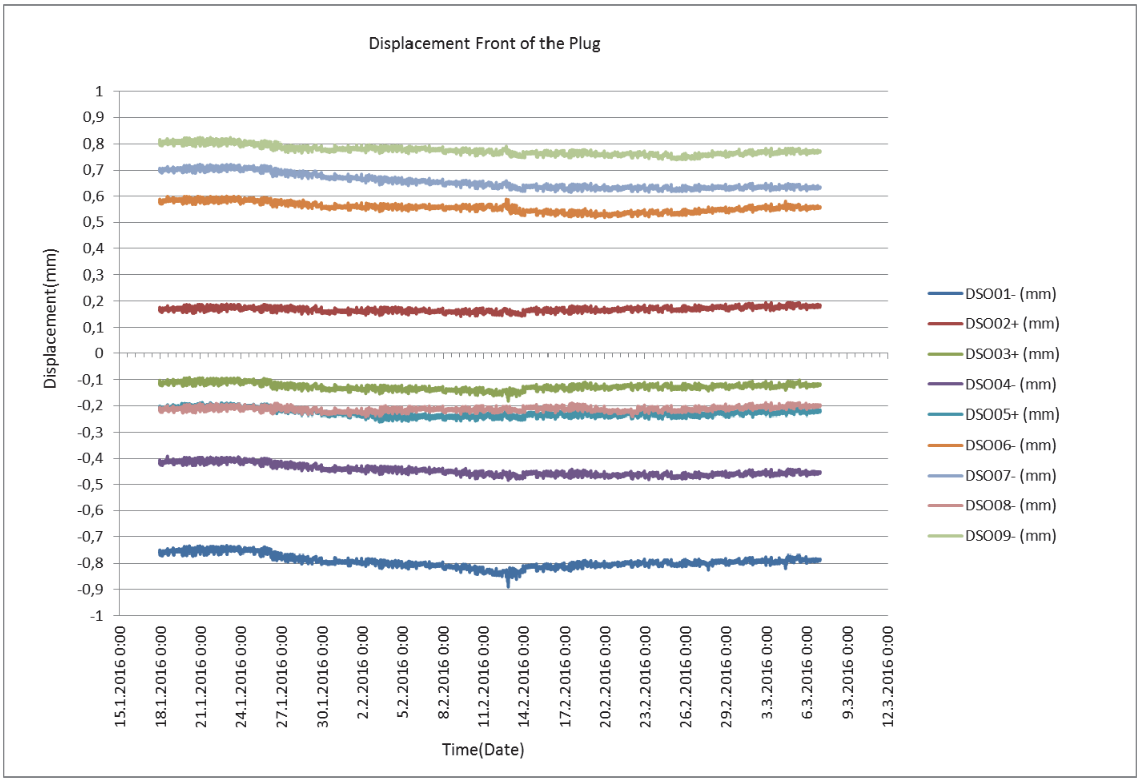


Figure 7.12. Displacement sensors in front of the plug.

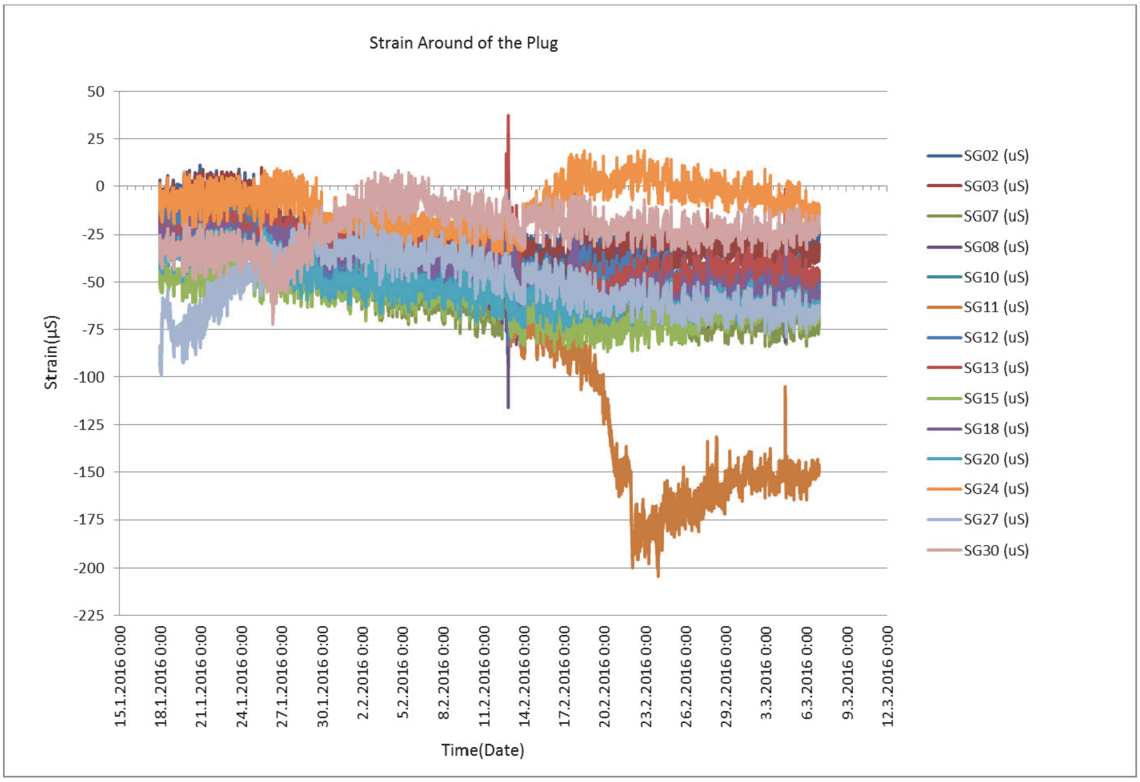


Figure 7.13. Strain Gauges in around the plug.

There were not significant changes seen in the displacement sensors readings during pressure increase (Figure 6.11–Figure 6.12). Also strain measurement did not show any indication of deforming of the plug during the low pressurization phase.

7.6.2 Fast Pressurization, to ~4 MPa

The responses to the fast pressure increase phase are shown in Figure 7.14–Figure 7.20. This pressurization was done over a three day period to approximately 4 MPa.

This data shows also the instant changes in pore and total pressure sensor readings in filter layer, which is expected due to connection to water source (Figure 7.15 and Figure 7.16). The total and pore pressure measurements around the plug during this phase of pressurization test (Figure 7.17 and Figure 7.18) are in conjunction with the measurements from the previous phase, showing open but limited connection between filter layer and sensor locations.

Displacement sensors showed that plug moved permanently during the high/fast pressure increase phase as shown in Figure 7.18 and Figure 7.19. The maximum displacement measured from sensors DS01, DSO01, DSO04 and DSO07 during the test was 0.4 mm and permanent displacement was around 0.3 mm to Z-direction. Displacement followed consistently the pressure fluctuation during the whole tests. Also some of the strain sensors show correlation between pressure increases (Figure 7.20). There was no significantly recovery of the plug location (displacement) after the pressure was released, indicating a wedging effect occurred. Laser scanning has been used to assess the plug location after the higher pressurization test, compared to the as-built plug conditions. Further analysis of the plug's response, especially regarding displacement and strains, is still on-going at Posiva and will be reported in the future.

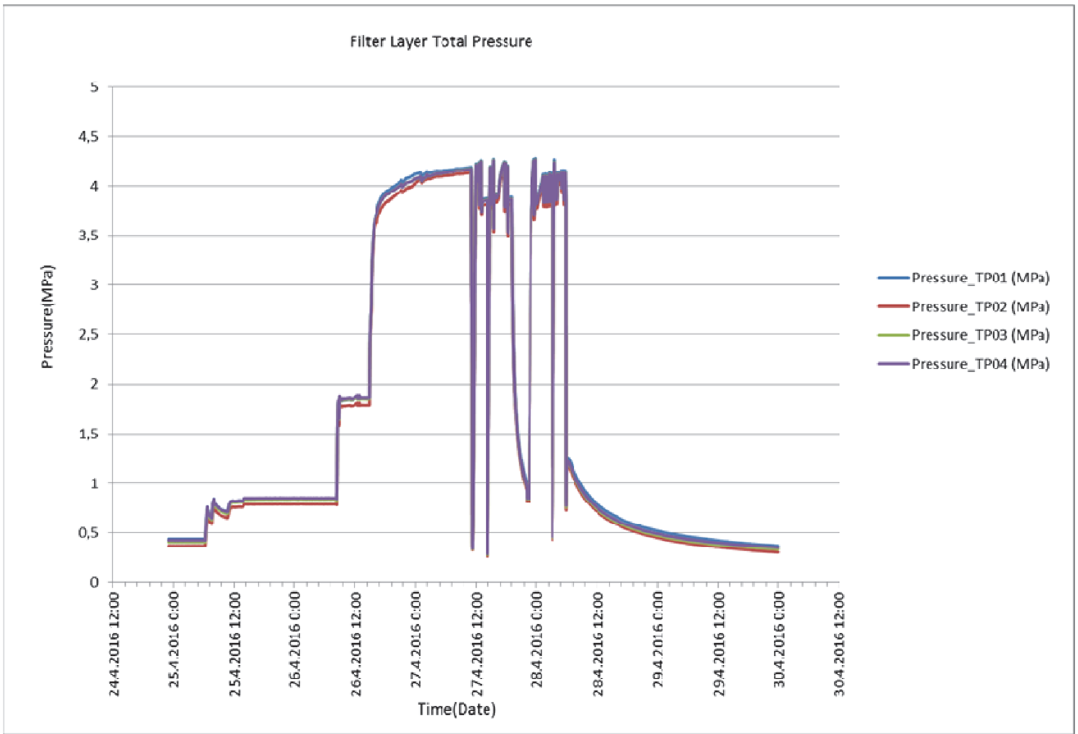


Figure 7.14. Total pressure sensors in filter layer.

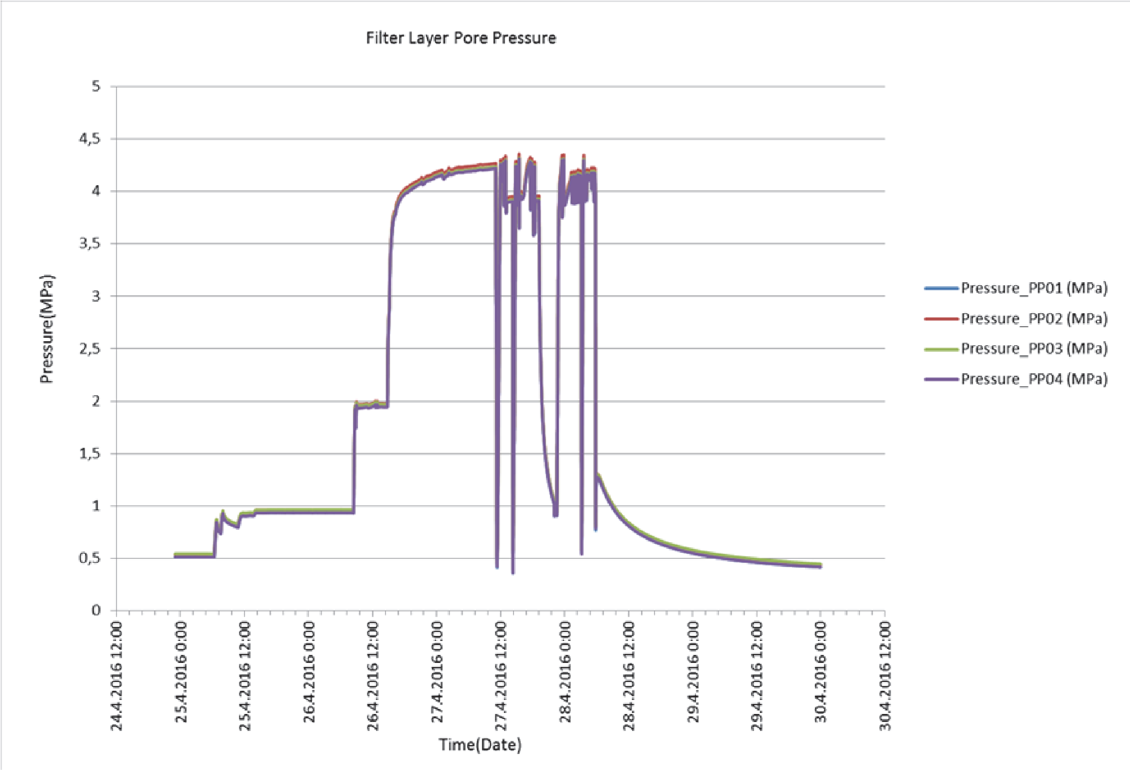


Figure 7.15. Pore pressure sensors in filter layer.

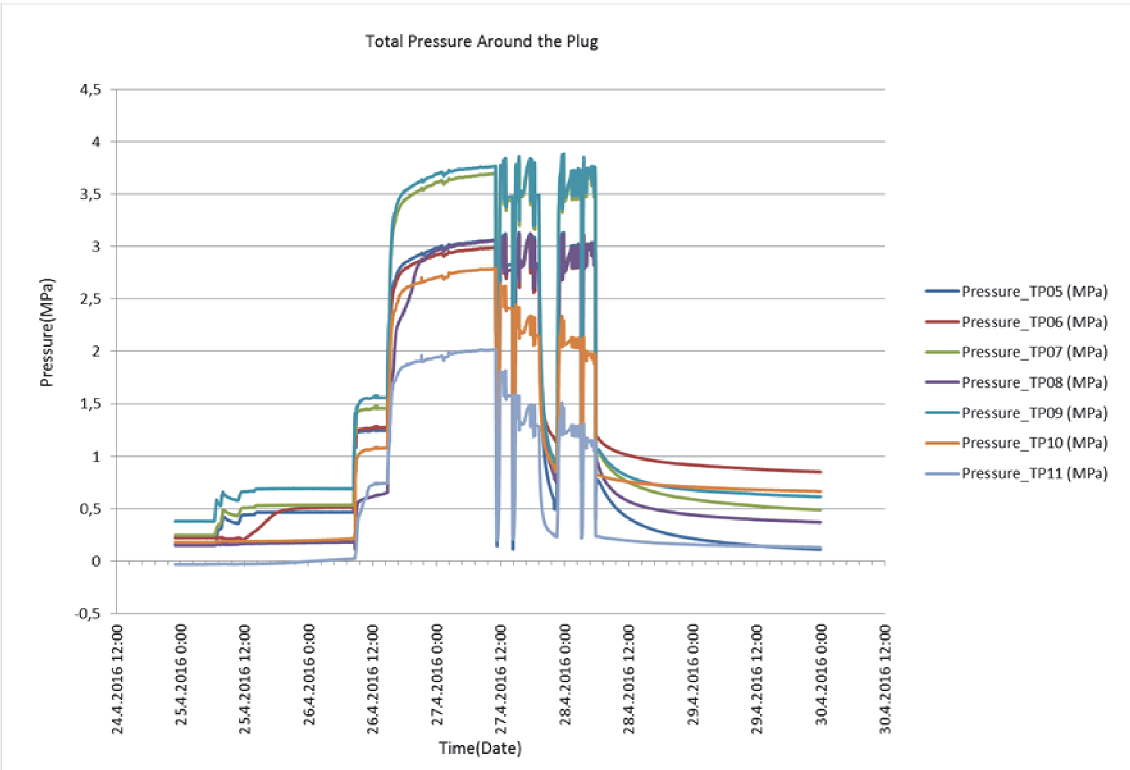


Figure 7.16. Total pressure sensors around the plug.

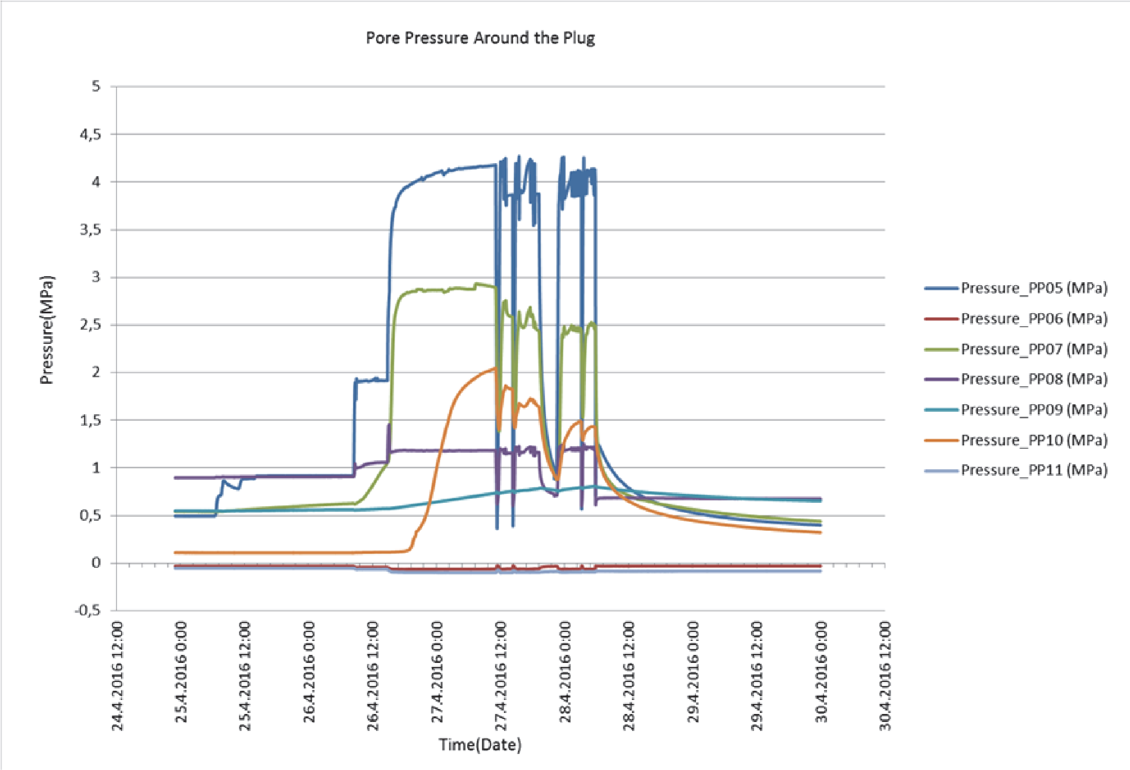


Figure 7.17. Pore pressure sensors around the plug.

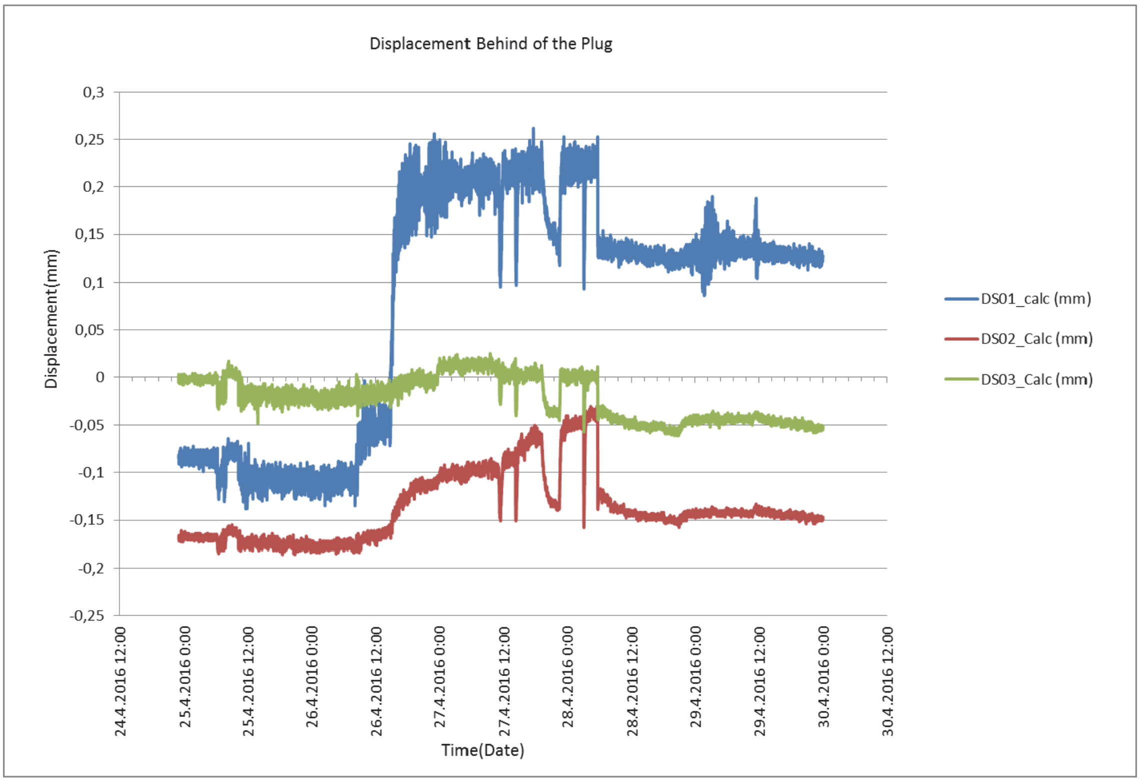


Figure 7.18. Displacement sensors behind the plug.

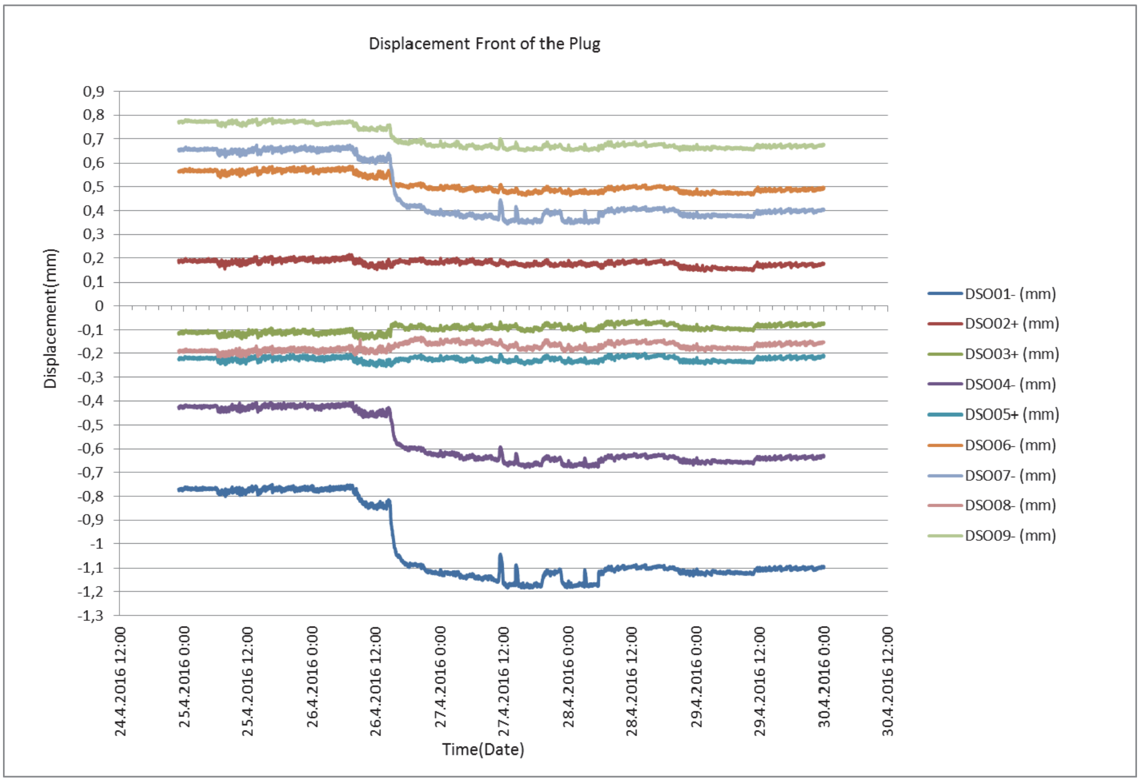


Figure 7.19. Displacement sensors in front of the plug.

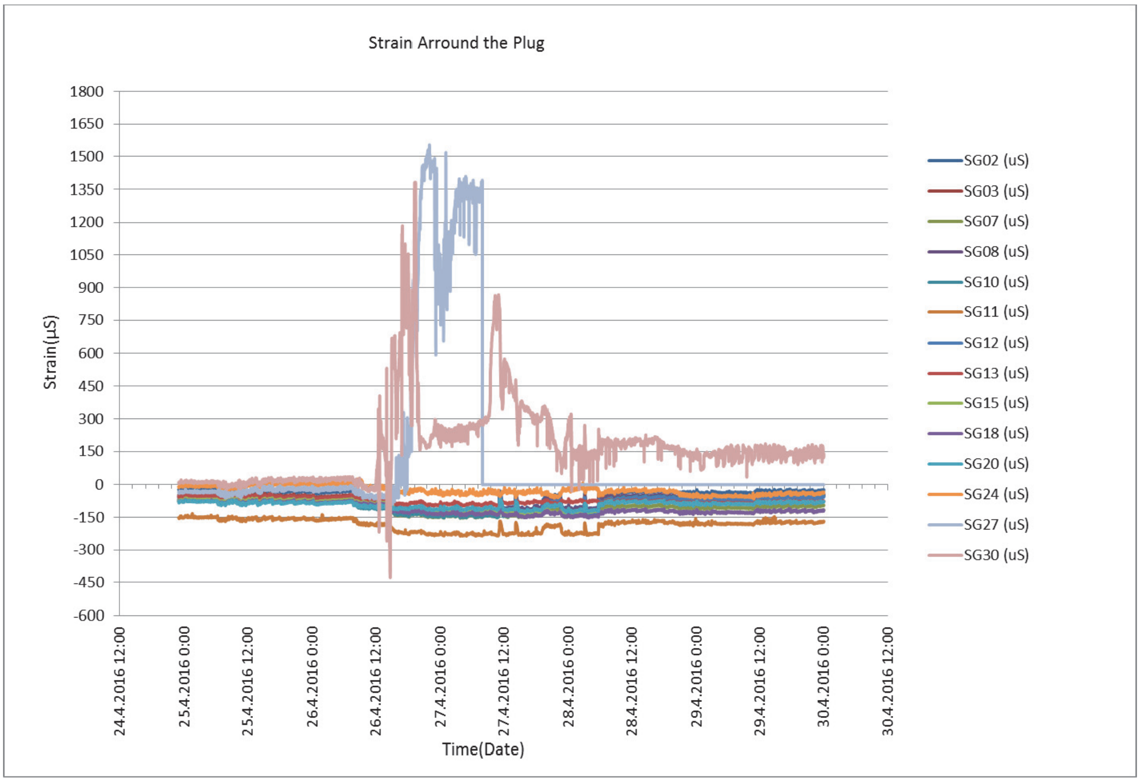


Figure 7.20. Strain gauges in and around the plug.

7.7 Rock and Near-Field Monitoring

During the slow pressure increase phase, small increases in inflows to near field were detected in inflow mapping, but these could not be linked to pressurization with certainty. Increases were so minimal that sample collection was not possible to try to analyse the tracer content. Inflow mapping done prior to the pressurization and during are shown in Figure 7.21 and Figure 7.22 respectively. Groundwater pressure was unaffected by pressurization (Figure 7.23) as were the extensometers (Figure 7.24). It should be noted that the extensometers had been measuring through construction, starting from slot excavation (summer 2014). The extensometers did not detect changes in the rock environment due to construction and thus are only shown here (Figure 7.24) from the time of pressurization.

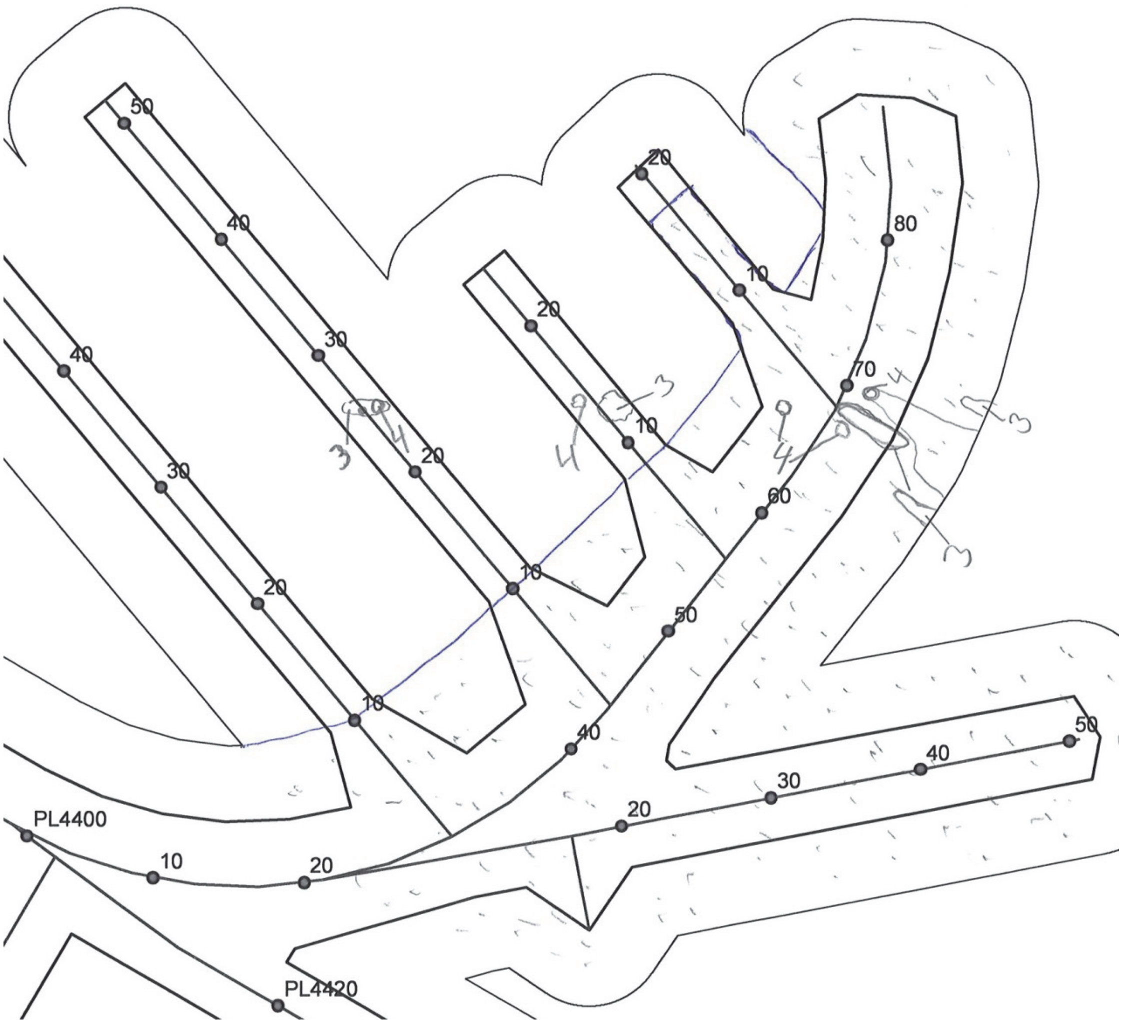


Figure 7.21. Baseline mapping of the inflow in the near field of the plug, before pressurization (wet = 3, dripping = 4).

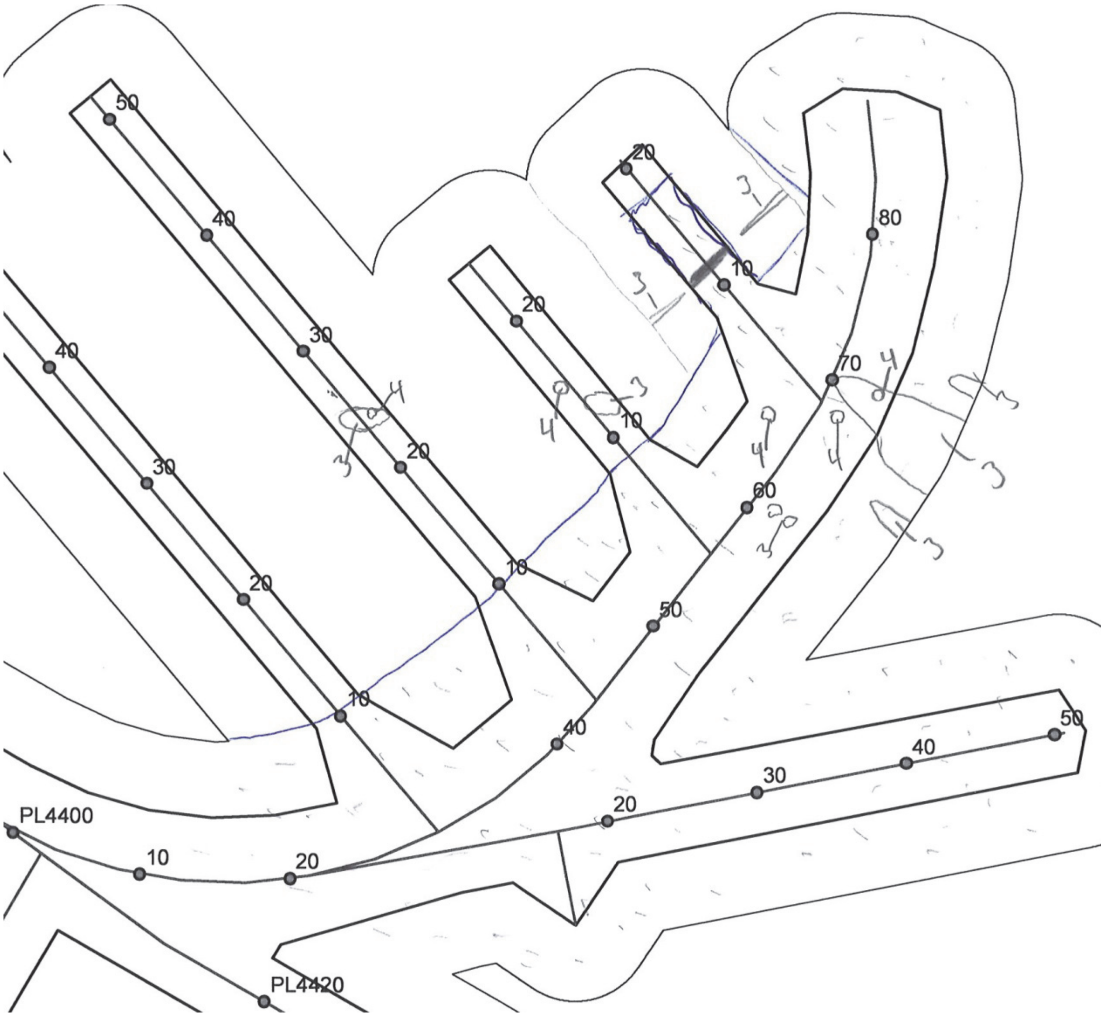


Figure 7.22. Example of inflow mapping in the near field of the plug (wet = 3, dripping = 4) during the pressurization.

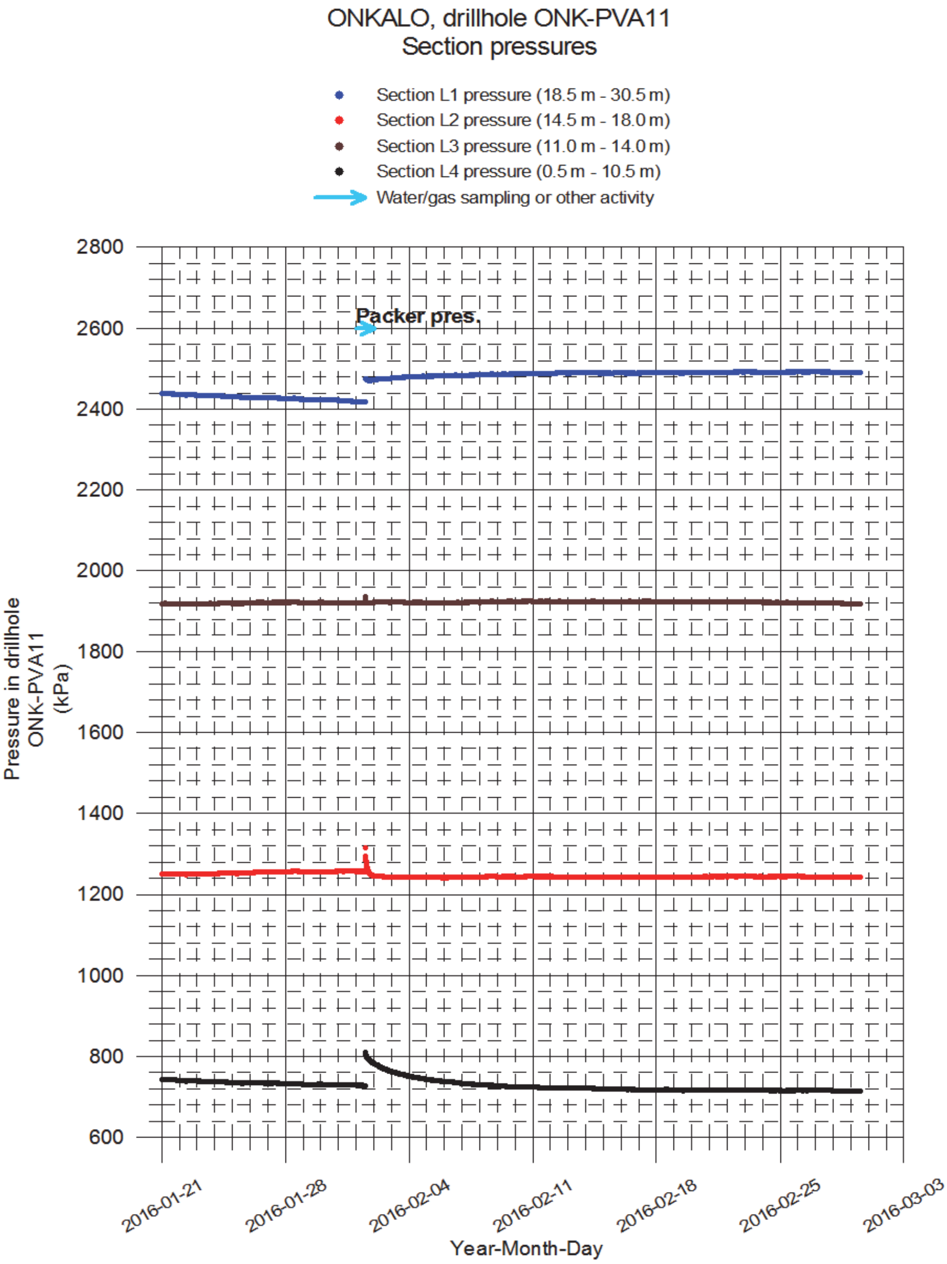


Figure 7.23. Example of groundwater pressure response to pressurization of the plug.

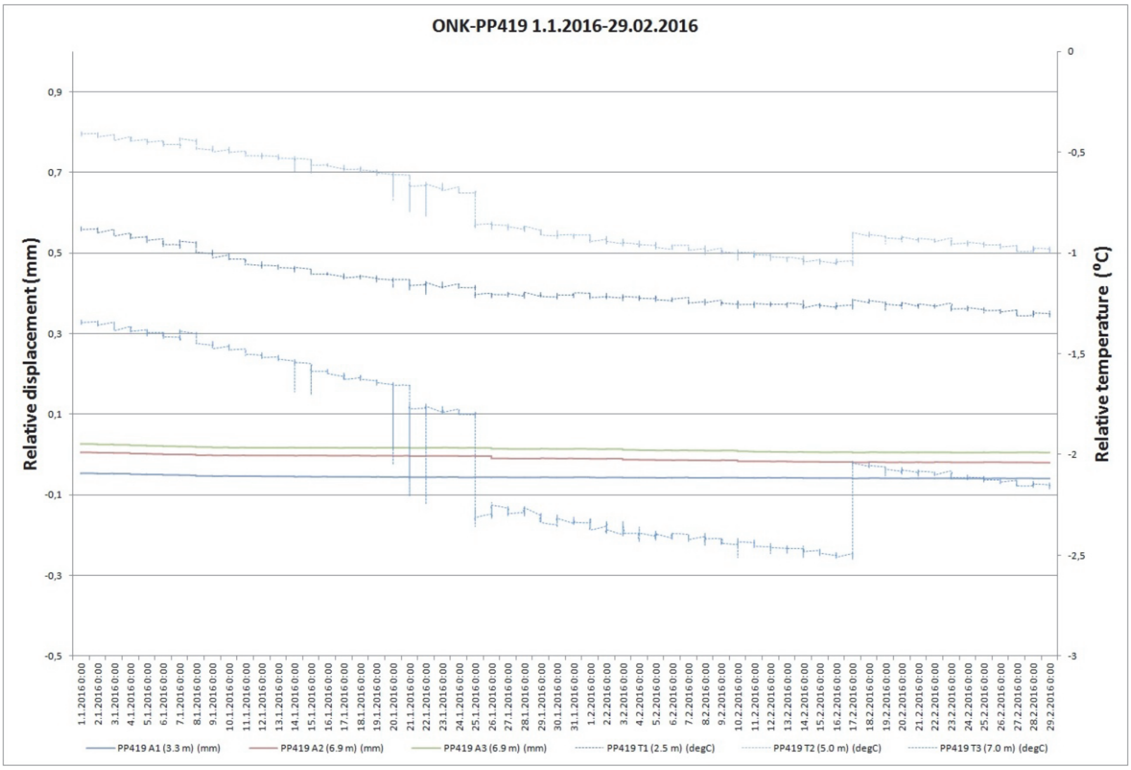


Figure 7.24. Extensometer measurements during the pressurization.

During the fast pressure increase phase the ground water pressures and extensometers were unaffected as well (Figure 7.25), but quite substantial increases in inflows were detected. These inflows were situated very close to the plug and most likely were from EDZ and not from the actual rock mass.

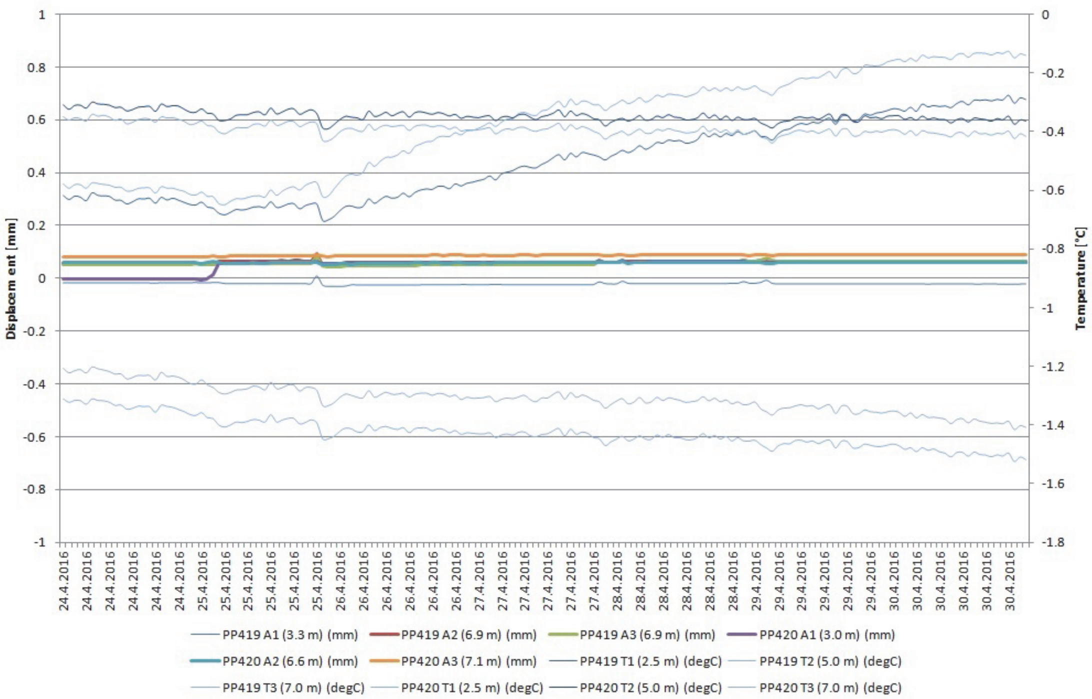


Figure 7.25. Extensometer measurements during the fast pressure increase phase.

During both phases water samples were collected and all together 45 samples were send for Rhenium analysis. These include samples taken from the water tanks before pumping for background data as well as samples taken from the pumping holes and water collectors. These samples are now in analyses and the data will be published by Posiva later in 2016–17.

7.8 Lessons Learned from Monitoring

The instrumentation, pressurisation system and leakage detection system components of the monitoring system have performed well. The data collection, transfer and back-up system have also performed well. The system has given reliable information during the construction and casting activities, which have helped in decision making.

For long-term performance of the POPLU experiment, the primary concern with the sensor arrangement within plug section two is the risk of a pathway for water leakage that has been realised. Approximately seven sensors have shown water running along their cabling and/or sheltering tubes at the front face of the plug. The amount of water leakage along the monitoring system is less than the estimated plug interface (rock) leakage in the slot area. The experience leads to lessons about the best selection for materials and sheltering, including fasteners and other components. The instrumentation system was designed with redundancies and variable configurations, so as to learn which solutions for the harsh environment of repository monitoring are the best.

A parameter-by-parameter evaluation of the monitoring system, is provided in Table 7.2, which is a similar summary as provided in the DOPAS Experimental Summary report Deliverable D4.4 [DOPAS 2016b]. There are additional details about the common lessons learned between monitoring systems between the different DOPAS experiments, as presented in the DOPAS Seminar proceedings [Holt 2016].

Table 7.2. Evaluation of the POPLU experiment monitoring system [DOPAS 2016b].

Sensor	Parameter(s)	Evaluation
K30-2-506 K-type INOR TCA-M10-MT1	Temperature in the concrete plug and concrete back wall	Temperature measurement was mainly used to follow temperatures during and after casting where the sensors performed consistently. Inor type sensors showed incompatibility with data loggers. A new logging solution had to be installed. Cause for incompatibility is still unknown. Temperature measurement suffered from distortions before final installation, when all shielding was connected properly. There is still noise superimposed on the measurements. Its cause is not yet identified.
Fuktcom, FE102 Aitemin, SHT75 V3	Relative humidity in the concrete plug and concrete back wall	Two of three Aitemin sensors failed before or during pressurisation. Three of four Fuktcom sensors show constantly 100% RH, partly interrupted by failure signals. Either the sealing of some of the sensors has failed or the sensor itself failed in contact with pressurised concrete pore water (RH close to 100%). Some of the measurement readings include distortion.
Kyowa, KFG-5-120-C1-11L1M2R	Strain in the concrete plug, measured with strain gages attached to rebars of 100 cm length.	With increasing time of pressurisation, more and more strain gages showed conspicuous readings or failed. For some of the sensors, the sealing of the sensor connections to the sheltering has failed and readings include distortion. Although tested for pressures up to 100 bars and for 48 hours in a pressure vessel prior to installation, the sealing concept can be considered as not sufficient for the harsh environment inside the pressurised concrete.
RDP Electronis LTD, SSD500/1425 Kyowa, BCD-5B	Displacement of the plug is measured relative to the surrounding rock. LVDT-sensors (SSD500/1425) measure displacement from the back section of the plug and Kyowa “Omega” sensors from the surface of the plug.	Generally, all sensors are performing well. Little distortion is superimposed to the measurements, caused by strong electromagnetic fields of unknown source.
Geokon, 4800-1X-10	Total pressure in the filter layer and in the interface between concrete plug and rock surface	Sensors are generally performing well, showing pressure changes in the filter layer and plug/rock interface accurately. For the sensors in the interface, the pressure values cannot be considered as absolute pressure values due to the stiff embedment of the sensors, which are meant to be used in soil, or other non-rigid media.

Sensor	Parameter(s)	Evaluation
Geokon, 4500SHX-3-10	Pore pressure in the filter layer and in the interface between concrete plug and rock surface	Sensors are generally performing well, showing pressure changes in the filter layer and plug/rock interface accurately. The sensors demand a pre-filling with water prior installation. Owing to the long period between installation and concrete casting, some of the water might have evaporated and been replaced by air. The sensors showed only accurate reading, after pressurised water contacted the sensor and replaced or dissolved the air inside the sensor. After that, sensor readings are considered to be reliable.
Drück PTX 1830 + DataTaker	Water pressure in near-field rock, Hydraulic head (mH2O) in nearby boreholes (ONK-PH21, -PH22, -PH23 and ONK-PVA11)	Sensors are performing well. Some distractions in ONK-PH21 between L5 (22.25 m) – L9 (2.5 m) since 12.4.2016. Might be due to packer pressure increasing. Monitoring the situation weekly. In other boreholes, no indication from POPLU pressurisation.
Interfels Multi-Point Borehole Extensometer (MPBX)	Displacement measurements of the rock and temperature inside the borehole	All the sensors are working well. Measurements of the rock displacement during the pressurisation. Measurements of temperature used to correct the errors of the displacement measurements due to thermal expansion of the extensometers.

Based on the experience of the POPLU experiment to date, the following lessons are noted:

- The choice of sensors and the data acquisition must be considered for the harsh repository working environment. In addition to climatic and pressure conditions, there can also be disturbances caused by simultaneous on-going construction and machines (such as blasting from nearby rock excavation) and signal disturbances/noise caused by electromagnetic fields. These items need to be factored in when designing the monitoring systems and evaluating performance data.
- The quality control methods for sensors in laboratory conditions prior to on-site installation needs to be developed for the complexity of the harsh repository environments, especially since post-monitoring sensor retrieval and calibration is often not possible. For example, the strain gauge connects were quality-control tested at 100 bars for 1 hour in laboratory conditions prior to installation to evaluate watertightness and durability. After field installation for POPLU, some of these sensors had questionable readings and the associated data may be disregarded or considered inaccurate in POPLU performance interpretation.
- The complex structure and building process influences the instrumentation support aspects, such as the need for long wires and wire extension possibilities on-site; need for temporary re-location and adjustment of sensor location; re-connection of wiring and data collection boxes so as to avoid damages during construction (i.e., use of temporary sheltering cabinets).
- Access to the plug construction area should be protected from unnecessary visitors and/or contractors as much as possible so as not to disturb the monitoring system during the installation phases. For instance, some of the POPLU sensors (including sheltering tubes and connectors) show leakage which may be attributed to unintentional movement of components of the monitoring system after experts had finished installation but before concrete casting.
- The use and functionality of relative humidity sensors in plug environments needs to be evaluated, together with their sheltering system. POPLU has experienced failure with all (3) Aitemin and 1 of 4 Fukton sensors, which is potentially attributed to moisture levels close to the saturation level (100%).
- Both polyvinylidene fluoride (PVDF) and steel tubes have been used for shielding of wires connecting the sensors to the data logging system. The selection of tube type depended on the geometry of the plug and where the wires were being fed. The tube material mechanical properties (like brittleness) may be variable, and thus the connection method between tubes could be influencing the risk of defects and thus leakage.
- There is a lack of compatibility between some sensors and data takers, such as conflict between the Inor thermocouples and data loggers used in POPLU. Such compatibilities should be evaluated before installation or possibly addressed even before equipment procurement.
- There needs to be accurate planning about how to store, transfer and back up the data frequently. The ease of data access is needed for rapid response addressing risk mitigation (i.e., in response to sensor readings and leakage, if the pumps then need to be lowered).

7.9 Feedback from POPLU Monitoring to Design

The monitoring system during the two pressurization phases provided valuable feedback to the plug design and modelling of expected performance. This information is also relevant for other large-scale in-situ demonstrations planned for Posiva and internationally. Some of these key feedback issues include:

- temperature monitoring: concrete recipes performed well, temperature was within tolerance
- relative humidity (RH): consequences only to monitoring design → RH monitoring shows until today 100% RH; if values are accurate, cannot be evaluated by now, but maybe later on after continuous hydration. Therefore, there is not any relevant information gained so far. Future monitoring designs need to take monitoring and evaluation timeline into account
- strain: after a brief preliminary analysis of strain measuring results, there is no indication that concrete has severely cracked (crack width > 0.5 mm) during curing and/or pressurization
- displacements: Permanent displacements after fast pressure increase phase were recognised, but their magnitude is small. The implications of such a wedging effect to the plug tightness performance need to be evaluated separately
- total and pore pressure: Measuring results show that filter layer worked as designed and fulfilled its purpose; presence of water around concrete plug (e.g. leakage paths) could be followed; pressure sensors provided information on leakage even without active leakage measurement
- role of sensors and wires with regard to inherent leakage risk: sensors, their wires and the sheltering tubing were not the primary reason for leakage (only few leakages along sensors cable insulation, which can be plugged at any time) – for future: if instrumentation and leakage prevention along wires is designed and constructed well, the risk for leakage due to presence of monitoring devices can be considered as very low
- During the fast pressure increase phase, it was evident that the leakage measurement system had insufficient capacity to cope with leakages over 1 l/min due to too small magnetic valve under the weighing bottle.
- lead-throughs proved to be well-designed and watertight, both through the concrete plug and the rock between tunnels.

Monitoring of this test gives also feedback to plug design to be used in actual repository. The fundamental idea of wedging the plug was proven, but the extent and effect to the tightness of the plug remained unclear. Also the use of wired sensors in these plugs should be avoided so as to prevent leakage paths and the possible wireless sensors should be developed and tested. Monitoring also showed that the contact grouting was not satisfactory and the materials and procedures need to be re-evaluated and developed for better results.

8 COMPARISON TO DOMPLU

The POPLU and DOMPLU experiments were implemented as joint projects between Posiva and SKB. One purpose of the joint work was to compare the experiences and results from these two experiments to feed input to the continuation of the deposition tunnel end plug development at Posiva and SKB. DOMPLU is separately described in SKB's experimental summary report [DOPAS 2015].

The experiments constructed at ONKALO and Äspö HRL had differences in the experiments' design and working methods used. This included the design and number of plug components and the excavation method of the plug slot. The main points of interest in the comparison of the two experiments are the structural differences both in the experiment and in the concrete component itself. The main differences of the experiments are given below with explanation and judgement on their effect on the experiment.

The slot excavation methods used for POPLU and DOMPLU were different; for POPLU drill-wedge-grind combination was used and for DOMPLU wire sawing was used. Wire sawing is Posiva's reference method for slot excavation, but it was not used for POPLU. This decision was made during procurement due to the current occupational safety concerns related to the handling of stone boulders resulting from wire sawing, especially in the ceiling section of the slot. Ahead of DOMPLU excavation, bearing pillars, beams and steel netting were installed. The risk of working under suspended loads could thus be minimized and accepted by SKB. It was also deemed beneficial by both Posiva and SKB to apply different slot production methods in POPLU and DOMPLU to be able to compare and contrast the methods. Both methods were successful in producing the slot for the siting of plug according to the specifications. The production speed of the methods was different. Taking note the volume of rock to be removed it can be stated that wire sawing as a method is more effective for production use. However, it must be noted that the drill-wedge-grind combination for the POPLU experiment was done with prototype equipment and a gain in effectiveness was seen during the excavation. The use of wire sawing requires the drilling of additional boreholes for the blind cuts that exceeds the intended slot profile. If wire sawing is kept as Posiva's reference method for slot excavation a method to minimise and fill in these boreholes during construction needs to be developed as the intention is to preserve the rock as much as possible in the proximity of the plug slot. Also the safety related concerns to use wire sawing at ONKALO need to be resolved.

The main difference between the POPLU and DOMPLU experiments is that the POPLU experiment does not include the swelling clay (bentonite) components of backfill and seal that are present in the DOMPLU experiment. The absence of swelling clay components in the POPLU experiment has on one hand made possible the rapid pressurisation of the experiment and on the other hand subjected the concrete component to more conservative conditions in relation to the DOMPLU experiment. The conservative conditions were observed during the pressurisation of POPLU in the form of high level of water leakage. It is also assumed that the contact grouting of POPLU was not successful due to the insufficient penetration of the contact grout. Contact grouting for DOMPLU was evaluated as successful since water tightness was observed up to 3 MPa of water pressure [DOPAS 2015]. It can be contemplated whether the tightness of the POPLU experiment would improve with time if a bentonite seal had been included behind the POPLU plug. Assessments of DOMPLU at a stable pressure of 4 MPa show a decreasing leakage with time, which most likely is related to the bentonite swelling. It is assumed that if the POPLU experiment would have included a seal or backfill component made of bentonite, the response to leakages in reducing them may have been similar to DOMPLU after a period of saturation.

The approach used for design of the concrete component of the plug structures between POPLU and DOMPLU was different. Besides the differences in the shape and dimensions of the wedge and dome plug the approach to prevent thermal loading and shrinkage crack formation was different. Posiva used dense steel reinforcement and low heat concrete to minimise the shrinkage of the concrete wedge and to prevent the crack formation during hydration. POPLU's slot excavation method also resulted in a more textured rock surface, which would aid adhesion and friction between the concrete and rock, whereas the DOMPLU slot with a smooth wire sawn slot attempted to have less bond between the rock and concrete and thus allow a wider space for contact grouting. SKB used a different design and construction approach by using cooling of the concrete during casting and also to contract and detach the non-reinforced concrete dome from the rock with cooling before performing the contact grouting. Subsequent to grouting, cooling was turned off which resulted in reciprocating expansion and pre-stressing of the concrete dome. Both approaches are evaluated to be suitable for their designed purpose. It is noted in conjunction with the POPLU plug that both the material and labour cost for the procurement and installation of reinforcement are significant.

The concrete mixes used in the POPLU and DOMPLU experiments were different. The material development of the concrete mix was tied to the development of the structural design. The DOMPLU experiment aimed for a concrete mix with higher shrinkage than the POPLU experiment in order to be able for the concrete to detach from the rock during hydration and cooling prior to contact grouting. The wish for a higher shrinkage and detachment also affected the dome design to be without reinforcement. The aim in the POPLU experiment was to develop a concrete mix with low level of shrinkage. The aim for the low level of shrinkage of the concrete wedge also justified the use of reinforcement around the plug circumference. It is noted that both approaches were successful even though the pre-stressing of the DOMPLU concrete dome was less than expected by modelling.

The construction of the DOMPLU experiment included the installation of concrete backwall, backfill, filter and seal layers behind the concrete dome, while the POPLU experiment included the installation of concrete backwall and filter layer behind the concrete wedge. The amount of different layers and the way they were constructed affected the total construction time of the experiments, but the main factor was still the construction of the concrete component of the experiment. The difference in construction time is reflected by the volume of concrete needed for the concrete component of the plug. The volume of concrete needed for POPLU and DOMPLU was 172 m^3 and 93 m^3, respectively. The construction time of the POPLU experiment was in addition increased by the time needed for the installation of the dense reinforcement, and the casting of the concrete wedge in two separate sections to ensure the proper filling of the sections. Based on the experiences from the POPLU experiment, it is initially considered whether a similar wedge structure could be cast in one section. In any case, the construction time of a plug during repository operation would be shorter in both instances because the arrangements needed for experimental evaluation such as the instrumentation are not needed during repository operation.

The construction of the POPLU experiment in two sections also required the construction of two formworks for the casting of the two sections. This was also a factor affecting the cost and time needed for construction. POPLU and DOMPLU experiments had different approaches to formwork construction. The formwork for POPLU was constructed on site from lumber and attached to a casted bracing frame by jacks and beams. The formwork for DOMPLU consisted of an outer frame adjusted to the contours of the excavated tunnel and four main prefabricated formwork pieces attached to the outer frame. The formwork was supported by struts to the tunnel floor. The design of the DOMPLU formwork was more complicated due to the fitting of the curvature of the concrete dome, but it is now estimated that the formwork struts may have been more massive than needed.

The high leakage values of the POPLU plug were partly contributed to the insufficient penetration of the grout mix used for the contact grouting of the concrete wedge. The grout mix used for the POPLU experiment was a low-pH grout. The contract grouting of the DOMPLU plug resulted in better watertightness as the concrete dome was able to resist water leakages up to 3 MPa of pressure compared to POPLU's 1 MPa. The grout mix used for DOMPLU was normal in pH and based on proven technology. However, the differences in grouting concept between DOMPLU and POPLU make it difficult to assess whether the divergent results are due to mainly the method used or the grout recipe itself. The development of Posiva's low-pH contact grout mix continues based on the experiences gained from the POPLU experiment.

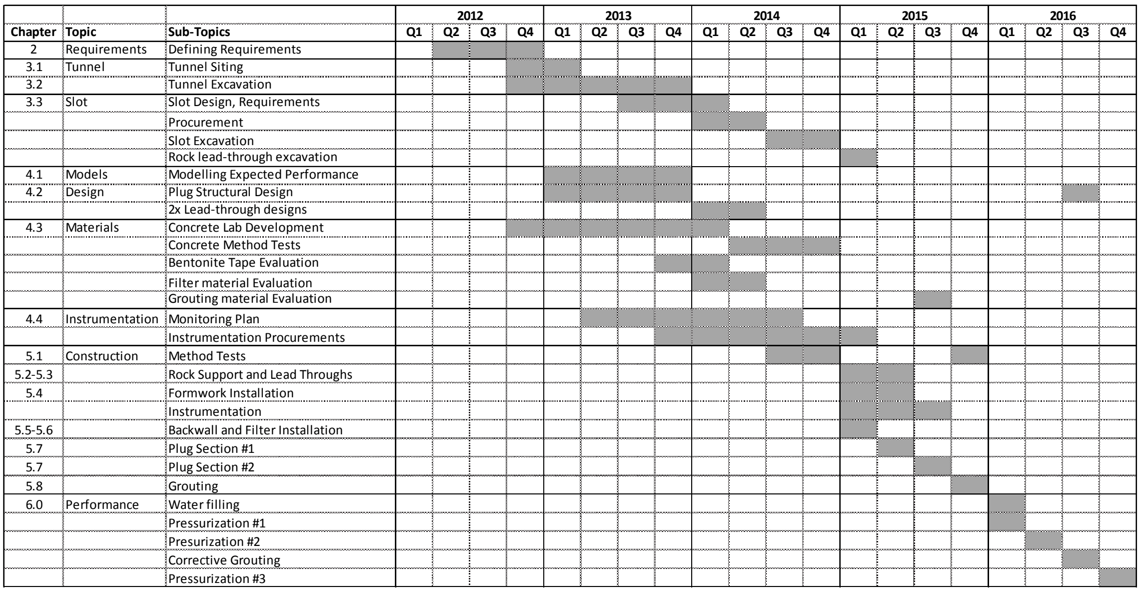
To conclude it can be stated that the longer construction time of the POPLU wedge compared to DOMPLU dome was mostly contributed to the reinforcement installation of the plug and the casting of the plug in two sections. These items are optimised and develop further in the continuing deposition tunnel end plug development at Posiva.

A further assessment of the technology readiness level (TRL) comparison between POPLU and DOMPLU can be found in Chapter 10.4.

9 SCHEDULE

The overall POPLU schedule is summarized in Figure 9.1 (graphic by months), with headings corresponding to the chapters and sub-chapters identified in this report.

Figure 9.1. Abbreviated version of actual POPLU tasks (with Q1 representing Quarter 1 as in January-March, etc.).



Within the original DOPAS and POPLU project plan, the POPLU concrete installation of the plug was scheduled for February 2014, with pressurization to start in autumn 2014. This was delayed by approximately 15 months when the actual POPLU process was realized. The project delays resulted primarily from demonstration of the plug in an actual repository which caused more site safety precautions being taken. This included:

- Foreign materials acceptance review to prevent introduction of harmful materials to the repository. More time and effort was spent than planned addressing material alternatives and compositions, such as with the bentonite tapes (see Chapter 4.5).
- Regulatory authority (STUK) reviews. This was particularly true with respect to the tunnel and slot excavation work, including reviews of planned designs, construction method statement, on-site construction work and safety.
- Posiva also chose to impose Level 3 safety class requirements and documentation practices for POPLU, as a practice for future repository operational practices. This led to extra level of work in documentation and quality assurance.
- Within the Posiva organization, the POPLU experiment was a first-of-a-kind for full-scale underground EBS demonstration. Thus the project did experience some delays due to processes associated with the large project and complexity of multi-disciplinary cooperation necessities. POPLU provided an extremely valuable process for learning how to manage operations issues from design through construction in a repository site.

The schedule for POPLU experimental construction required negotiations about various contractors on the site. The extra work of installing pressurization and monitoring systems also added more complexity and time demands compared to initial plans. These extra tasks associated with performance assessment of an accelerated pressurized experiment, which would be different than actual plug construction in a repository, included issues for installation of the rock lead-throughs, sensor and wire mounting, sheltering tubes, data collection systems and all associated protection.

As the POPLU project was partially funded by the European Commission within the DOPAS project, there were requirements to use public procurement procedures for subcontractors of DOPAS tasks. This included the slot excavation contractor for POPLU. The public procurement process needed to be re-started due to safety concerns, and thus there was a delay associated with re-defining slot excavation requirements and evaluation criteria (see Chapter 4.3).

10 LESSONS LEARNED

10.1 Technical Lessons

Many of the lessons learned have been noted within the previous sections, especially based on the construction experience. Some of the key additional lessons are summarized in the following points.

- ***The way in which <u>construction activities</u> have been influenced by ONKALO being the site of a future operating repository.***

  The construction in ONKALO has had a higher level of safety precautions due to it being a future operational repository. These precautions and practices have included aspects such as: 1) Within tunnel excavation, plug slot excavation and rock works (including items like drainage trenches), there is required safety authority (STUK) approval. They review all documents and drawings before giving approval to continue. 2) For construction and concreting aspects of POPLU, it was Posiva's own decision to make the full-scale demonstration conforming as much as possible to Safety Class 3. This means we had our own imposed level of scheduling, tracking tasks, documentation and own obligation to make mock-ups of the concrete plug to demonstrate concepts (3 mock ups of concrete in summer 2014-spring 2015, 1 mock-up for injection grouting in autumn 2015). 3) Foreign material requirements for all materials entering ONKALO were followed. This Posiva/TVO procedure requests extra level of documentation and time demands for review of new materials, to gain their approval before use. The clearance requirement put limitations on some materials which cannot be used, such as certain concrete admixtures, which means extra development work is sometimes needed if earlier approved materials/chemicals are no longer available and we need to find a suitable substitute. 4) As ONKALO will be an operational repository, our R&D work cannot damage or harm the existing environment/rock in anyway. Therefore we may have more precautions when pressurizations so as not to increase the hydraulic conductivity paths or fractures (i.e. caution pressurizing over 4.2 MPa).

- ***Practical application of the <u>Rock Suitability Classification</u> approach to plug siting.***

  Posiva finds RSC as a suitable methodology to quantify the rock masses to ensure safety in selection of locations. Experience to-date has been successful for plug site locating, meaning that it was a dry area with minimal fractures based on RSC of pilot holes. This early phase RSC (with pilot holes) was supported/verified by tunnel excavation and subsequent RSC, which deemed the same slot location suitable. Even after the actual plot slot excavation, the RSC was again further confirmed for supporting the exact same location.

- ***The rejection of <u>wire sawing for the slot excavation</u> and the reasons that meant that wire sawing was not used to construct the wedge for POPLU.***

  Wire sawing was not selected for the POPLU construction because of the occupational (worker) safety demands. The wire sawing contractor candidates during the public procurement process could not show in a sufficient method that they could do the construction safely. The primary safety concern was pertaining to removal or dropping of the ceiling rock mass/blocks during sawing. A secondary aspect was that the requirements for the slot's rock surface changed during the scope of the project due to the structural design choices. The structural design was so that the plug had steel reinforcement to handle shrinkage and a low-shrinkage concrete recipe (proportion and chemical composition of binders combined with aggregates). The slot surfaces no longer needed to be flat or smooth (untextured) to prevent adhesion of the concrete plug. There was no expectation to have the plug concrete disjoined from the rock surface for the injection grouting gap (to be larger, as in DOMPLU).

- ***The reasons for selecting <u>wedging-grinding for slot excavation</u>.***

  Public procurement was renewed for the slot construction, so that wire sawing was not specified as the only accepted method. In this 2nd round, the contractors' suggestions of methods could be made to best suit the defined criteria. The requirements for the slot surface had a certain tolerance for dimensions, but not for roughness. The wedging-grinding method was proposed by some contractors based on their own experience. The evaluation of all contractors during the procurement stages showed that this method (wedging-grinding) met both the occupational safety demands for handling the rock masses (i.e. removing smaller pieces) and the technical requirements. The equipment that was used was remote controlled, which meant that worker safety was ensured by not working directly in the slot area (under the unreinforced rock) at the time of excavation. There was not a significant cost difference in the contractors' budgets between the wire-sawing and wedging-grinding. The time estimate for slot excavation work in the contractors' budgets for the wedging-grinding method was approximately 30% higher than the expected time duration needed for wire-sawing. The initially estimated time for wedging-grinding was 3 months, though the actual time used was 6 months of work The time overrun resulted from additional work necessary for laser scanning, extra grinding to meet strict tolerance requirements, cleaning and finalizing the slot for construction readiness. This process has led to re-evaluation of the plug slot tolerance requirements and their justification.

- ***Experience in use of <u>low-pH materials</u>***

  The low-pH concrete recipe development and performance evaluation proceeded well from the lab, through factory trials, method tests, backwall casting and then finally the plug sections. The foreign material acceptance evaluation procedure set limitations on the materials that could be used, such as the use of Glenium brand carboxylate superplasticizer, yet alternative materials were found. The high quality Danish fly ash was deemed suitable for experimental purposes in POPLU. The lightweight filter beams, jointing mortar and injection grouts could also be developed following similar proportions of calcium to silica, to ensure the pH leachate below 11 in Olkiluoto simulated deep groundwater. The early age properties of the concrete, including slump flow to ensure workability over time, were suitable for the underground construction delivery times. The long-term mechanical and durability properties of compressive strength, watertightness (permeability) and resistance to chemical attack were also sufficient to meet the design expectations of 100 years' service life.

- ***Experience in <u>casting the concrete wedge in two pours</u> and the potential for being able to construct the wedge in one pour***

  POPLU was made in two sections, based on concerns for concrete mass. It needed to be workable enough to fill the mould, which was limited to 3 metres in the horizontal direction based on using 2 sections (rather than 6 metres if cast in 1 section). There was also a concern for the specialty low-pH concrete, about the maximum temperature rise and temperature gradients to the rock. The experience from POPLU showed that the temperature in the centre of the concrete mass stayed below 50 °C (which was also less than modelled based on laboratory testing). The concrete mass was also very flowable, meaning that it was self-compacting and did not need external vibration to get it flowing into and around the whole mould and between the congested reinforcement bars. A type of superplasticizer was chosen that was approved by foreign materials review for site safety. Based on the construction experience, the plug could potentially be built in one section rather than two. This could also result in less reinforcement being used. The temperature difference (gradient) between the tunnel rock walls to the concrete core should be considered, so that it is not too extreme to cause thermal cracking. Options such as temporary wire heating along the rock surface could be explored, so as to minimize the gradient during concrete early age hydration (first days-week). A retractable tube with varying heights of concrete pouring through the formwork should be used to ensure the concrete flows across the whole plug volume.

- ***Experience emplacing the <u>bentonite tape</u>***

  A few types of bentonite tapes were assessed in pre-tests in the laboratory, which showed they could swell significantly in various water compositions. The tape selected was used according to the manufacturer's instructions. The concrete mock-up demonstrations showed that the bentonite tape did not adversely affect the fresh concrete cast against it. The tape allowed for injection grouting areas to be established between the rock and plug. The tape was emplaced around the circumference of the slot using screws. There were no problems in attachments or construction works simultaneously while the tape was in-place. It should be noted that the POPLU slot was a dry area, thus the tape was not exposed to water prior to concrete casting. The effectiveness of the bentonite tape to reduce water flow around the plug during pressurization can only be estimated later in 2016 with continued performance evaluation after re-grouting.

- ***Experience for <u>injection grouting</u>***

  The low-pH injection grout was not effective in creating a watertight seal between the concrete plug and rock within the slot area. The grout recipe had been re-designed due to the unavailability of the same cement type as used in earlier Posiva underground work. The grout recipe did not have sufficient penetration to fine fissures. The grouting method itself could also be improved by parameters such as grouting tube spacing and pressure sequences used during injections. Upon subsequent pressurization, the greatest leakages were from the interface area of the slot. The higher pressurization test (#2) to 4.1 MPa showed the greatest leakage paths, which provided valuable insight when planning the corrective actions.

- ***Experience from <u>quality control systems</u>***

  Posiva was able to set requirements during various stages of the POPLU project, to ensure high quality of the workmanship. This included aspects such as design expectations and acceptance criteria during construction. Examples of this were during the procurement of the slot excavation method, where the evaluation criteria and weighting factors were pre-defined. Quality control was done by upscaling of material performance studies, for instance in demonstration of concrete recipes in the lab, with suppliers and via method-test and the tunnel backwall before casting. Also quality control methods during the construction works were done on-site on a daily basis, through contractor discussions, safety reviews, documentation systems and quality management practices. Posiva implemented quality control practices in accordance with the regulatory safety class 3 expectations, so that the POPLU experiment represented many processes that would be similar to repository operation.

- ***Experience for <u>lead-through tubes</u>***

  Both sets of lead-through tubes, via the rock between the plug and the monitoring area (demo tunnel #3, 8 metres through the rock), and via the concrete plug from the filter to the front face, proved to be watertight. The design was aided by SKB's DOMPLU initial designs. POPLU made slight modifications, for instance with watertightness rings of bentonite tape and the style of flanges in the concrete lead-through.

- ***Experience for the <u>pressurization system for experimental purposes</u>***

  The dual pump pressurization system via the lead-throughs to the filter layer behind the plug worked exactly like designed. Much experience was gained from SKB's DOMPLU system at the on-set of POPLU. Only minor adjustments needed to be made between the design and operation phases, for instance in accounting for degradation of pump components due to saline (simulated Olkiluoto) groundwater and then sediments if re-circulating water. The pumps were able to apply pressures at both low and high rates. The emergency shut off and release systems worked well and were demonstrated during the 2^{nd} pressurization round.

- ***Experience from <u>monitoring system</u> to evaluate plug performance and safety***

  The monitoring system of 141 sensors in the backwall, filter layer and two plug sections performed well. Redundancies were built into the system based on some expected loses, which were realized. Knowledge was gained about the suitable types of sensors, including their compatibility with data loggers. There were failures of some sensors due to water leakage based on the types of shielding connections within flexible or rigid tubing. Fastening of sensors inside the plug and adjacent to the rock provided some challenges, and these attachment materials should be clearly specified and discussed with contractors. Working in tight spaces in conjunction with construction contractors proved challenging at some points. There were some leakages along the cabling and sheltering tubes coming out the front face of the plug. Lessons were learned about the need for amounts of wires and location of protective data logging stations around the plug, which should not infringe upon the construction processes. Monitoring of leakage showed some adjustments needed for the water collection system.

10.2 Project Lessons

The following sections give more generic lessons that were learned during the overall POPLU and DOPAS project, which can be beneficial to other programs and in future large-scale demonstrations.

- ***Project Management***

  The POPLU project brought together numerous experts from varying disciplines, also working with contractors. The interaction of many parts required frequent communication. There was a lack of time for documentation. The schedule was rigid but needed to be adjusted due to repository safety and security requirements. Resource availability imposed some limitations for the speed at which progress could be made. Overall, the project was deemed a success but had a different level of organization than has been experienced in Posiva as this was the first full-scale EBS demonstration underground at ONKALO.

- ***Quality Management Systems***

  During the project Posiva further developed the quality management systems associated with full-scale deposition tunnel end plug construction. This included the use of YVL guides to design and construct the POPLU experiment as Safety Class 3 device. This was a highly valuable exercise to practice and implement the practises needed for the construction of the deposition tunnel end plug in the operational repository.

- ***Competence Development***

  The POPLU project enhanced the knowledge on plug and seals for various technical details for various groups active in the project. This included know-how at Posiva, as well as their supporting organizations and subcontractors including structure design, materials, modellers, construction, quality management, safety. Within the DOPAS partners working to support POPLU, there were approximately 45 staff members of which about a third were junior (under three years of experience in the specific field) who gaining significant experience from POPLU. One MSc thesis was generated during the project [Hiltunen 2015] and 2 PhD theses were advanced during the project.

- ***International Cooperation***

  It was beneficial for POPLU to gain experience from the other DOPAS experiments, especially the DOMPLU demonstration that is similar to Posiva's reference plug design. The most cooperative issues between POPLU and DOMPLU included knowledge gained from slot excavation comparing wire sawing and the wedge-grind method, complimentary low-pH concrete recipes and performance tests, monitoring systems (including similar pressurization systems, some sensor selection, sensor watertightness with wire sheltering, lead-through designs. The results from the

EPSP experiment are also beneficial for gaining experiences in crystalline rock, especially regarding re-grouting activities to reduce leakage and fractured rock. FSS experience with clay will be beneficial for Posiva's future demonstrations of integrated buffer, backfill and plug interaction with similar bentonite components (blocks and pellets).

10.3 Risk Management

Project management aspects of POPLU also included risk management aspects. During the course of the project, 27 experimental risks were identified that covered all phases of the project from design through construction and performance assessment. The risk management plan also included actions for avoidance and mitigation of risks. Over the project lifetime of four years, a total of four pre-identified risks were realized. Lessons learned from the realized risks have been addressed in the previous section. The realize risks and their future avoidance plans are noted in Table 10.1

Table 10.1. POPLU realized risks, mitigation and future avoidance.

Realized Risk	Mitigation Action Taken	Future Avoidance
Delay of overall project schedule	Re-scheduling. Working overtime (double shifts, weekends during construction). Revising pressurization plan for faster test	Accuracy in documentation. Flexibiity built into schedule to account for contractor work delays (on-site construction).
Regulatory review identifies need for changes (delay of schedule)	Extra meetings. Providing extra documents.	Open dialogue with regulatory about expectations and needs.
Contacting grouting material or method was not sufficient (plug not watertight).	Re-design of recipe (grout materials and proportions). Re-evaluate injection methodology. Repeating method test prior to plug re-grouting. Overcore and re-grout.	Sufficient time for laboratory-based performance tests. Proven success of method test(s). Accept schedule delay if needed.
Pressurization (accelerated performance test) was changed, not equivalent to SKB's DOMPLU. Risk of not being able to directly compare performance.	Accepted pressurization change of time steps and pressure level (since POPLU had minimal bentonite needing time for swelling).	Set comparison criteria for parameters that are similar enough.

10.4 Technology Readiness Level

The DOPAS experiments advanced many scientific technologies associated with the individual aspects of the plug. A summary of the change of technology readiness level (TRL) over the course of the POPLU (and 4-year DOPAS) project is given in Table 10.2. For comparison purposes between plugs, values for SKB's DOMPLU plug are given. The TRL values were assessed by the experimental teams and are in accordance with the European Commission's guidelines, as given in Figure 10.1. Note that the assessment addresses the DOPAS experiments themselves for each individual component, not the overall TRL of the whole system (i.e. Posiva's reference plug). The objective of this analysis and reporting is to demonstrate the knowledge gained during the course of the DOPAS project, and address areas where technology development is strong or needs further attention.

It was as expected that the DOMPLU levels of TRL were higher than POPLU at the start of the project due to SKB's previous experience in constructing and demonstrating plug structures at their Äspö HRL as the operational facility for experiments. DOMPLU also utilized a bentonite seal which allowed for greater knowledge gained in material interactions and related THMC modelling.

Table 10.2. TRL of POPLU, comparing based on start and end dates of DOPAS project.

		POPLU TRL		DOMPLU TRL	
		start	end	start	end
design basis (requirements)		3	7	5	7
slot location siting		5	7	3	7
tunnel excavation relevant to slot		5	7	5	7
plug and seal location excavation		3	6	3	7
structural design		3	7	5	7
THMC modelling of plug experiment		4	5	4	7
Material (inc. Purchase, production, emplacement)	concrete	2	7	4	7
	grout	5	6	5	7
	bentonite	2	6	6	7
	steel	5	7	-	-
Material interactions		3	3	3	7
monitoring strategy for operation (parameter selection)		4	7	6	7
monitoring technology (sensors, wiring, data collection, etc.)		5	7	6	7
construction logistics		5	7	6	7
compliance assessment		2	5	4	7
quality management (procurement, contractor selection, documentation, etc.)		3	6	6	7
safety case		5	5	6	7

Where a topic description refers to a TRL, the following definitions apply, unless otherwise specified:

- TRL 1 – basic principles observed
- TRL 2 – technology concept formulated
- TRL 3 – experimental proof of concept
- TRL 4 – technology validated in lab
- TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 7 – system prototype demonstration in operational environment
- TRL 8 – system complete and qualified
- TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

Figure 10.1. European Commission TRL levels, from H2020 Work Programme.

11 IMPACT OF POPLU TO DESIGN BASIS

With the conclusion of the POPLU experiment within the DOPAS project, feedback is provided to the original requirements and design basis. This serves as inputs to Posiva's decisions about the plug reference design for the next operational licensing application and repository operations. The assessment of how POPLU experiment fulfils the design requirements is detailed in Table 11.1, which is derived from Table 7.4 of the DOPAS Deliverable D4.4 [DOPAS 2016b]. The table shows the design and performance parameters from POPLU, together with the evaluation of their compliance.

Table 11.1. Compliance assessment for key design specifications on the POPLU experiment, including notation of corresponding VAHA requirements were applicable.

Requirement/Design Specification	Compliance Assessment	Feedback to Design Basis
The cementitious materials that are used in plugs shall have a calcium to silica mass ratio less than 1:1 (updated from VAHA L5-BAC-27).	Compliance with this requirement has been met by adopting a ternary concrete mix containing silica fume and fly ash. In addition, as this requirement responds to the expectation for the pH of the concrete leachate to be <11, testing of the mix at 28 days and 91 days in simulated Olkiluoto groundwater confirmed that the pH of the concrete leachate was <11.	It is still an option to consider specifying a pH for concrete leachate along with defined method for measurement.
The compressive strength of the concrete shall be greater than 50 MPa at 91 days.	The compressive strength of concrete mixes tested lay in the range 77.7-92.3 MPa, confirming compliance with this requirement.	This requirement appears appropriate to maintain within the design basis.
Fresh concrete workability 560–640 mm of slump flow.	Compliance with this requirement was met for all but one batch of concrete, which had a slump flow of 650 mm, i.e. higher than the stated range. Based on early age quality control tests of the mixture, greater than 97% of the concrete batches met the requirement before emplacement.	This requirement appears appropriate to maintain within the design basis, but there may be a further consideration of the range of acceptable slump flow test results, especially for slump flows that exceed the maximum value stated in the current specification.
The temperature in the concrete wedge shall not exceed 60 °C.	The peak temperature measured in the concrete wedge was approximately 42 °C (Figure 7.1), confirming compliance with this requirement.	This requirement appears appropriate to maintain within the design basis.
Reduce the leakage across the plug to be "as low as possible".	Based on the initial stages of monitoring of the POPLU experiment, with pressures up to 1 MPa, the detected leakage rate was over 0.1 litres/minute (6 litres/hour), thus corrective actions are being taken by re-grouting.	The final evaluation of the performance of the POPLU experiment with respect to this requirement will be undertaken at a later date, and will consider the lessons learned regarding contact grouting.
The hydraulic conductivity of the concrete mass shall be $<1x10^{-11}$ m/s. (VAHA L5-BAC-18)	Based on the initial stages of monitoring of the POPLU experiment, with pressures up to 1 MPa, the detected leakage rate was over 0.1 litre/minute (6 litres/hour) at the interface. However, there was no leakage through the concrete mass itself and quality control tests showed a watertightness under 15 mm. Therefore, the concrete was accepted as being compliant with a requirement on the hydraulic conductivity of the concrete mass of $<1x10^{-11}$ m/s.	This requirement appears appropriate to maintain within the design basis based on the concrete mass itself. A final evaluation of the performance of the POPLU experiment with respect to this requirement will be undertaken at a later date, and will consider the lessons learned regarding contact grouting.

Requirement/Design Specification	Compliance Assessment	Feedback to Design Basis
A bentonite seal shall consist of bentonite with montmorillonite content of 75–90%. The sealing layer shall be pre-saturated to ensure water tightness after installation of the plug. (VAHA L5-BAC-19)	A bentonite tape was selected for use. It was exposed to water during concreting and when water flushing the grouting tubes. The time between tube flushing and grouting was some hours, which is likely insufficient to reach saturation.	This requirement appears appropriate to maintain within the design basis. The construction sequence should be evaluated to allow time for bentonite seal (tape) to reach saturation prior to grouting and/or pressurization. Bentonite should be used behind the plug in the form of backfill blocks or a wall sealing layer, to provide sufficient bentonite for sealing and aiding watertightness.
The filter layer shall consist of sand or crushed rock with grain size distribution optimised for filtering. (VAHA L5-BAC-20)	The void content of the pervious pavement blocks was measured in the lab to be over 30%. The hydraulic conductivity of the blocks was measured to be 2E-03 m/s. The blocks were manufactured from sand and pervious aggregate.	This requirement for filtration capacity appears appropriate to maintain within the design basis. The requirement for materials shall be adjusted, to not specify the use of crushed rock but rather bound pervious aggregate.
The plug shall maintain its hydraulic isolation capacity for at least 100 years. (VAHA L5-BAC-21)	The compressive strength, shrinkage, resistance to chemical (chloride and sulphate) attack was verified in laboratory testing when determining the mixture proportions. The field compressive strength tests showed equivalent mixtures. Thus there is confirming compliance with this requirement based on durability requirements of the Finnish national concrete code [BY50 2012]. The fresh concrete workability was in the range of 580–640 mm, thus the mass was flowing and assumed to penetrate between reinforcement bars and to the crown of the wedge. The temperature remained below 60°C, so as not to induce thermal cracking or expansive ettringite.	This requirement appears appropriate to maintain within the design basis.

Requirement/Design Specification	Compliance Assessment	Feedback to Design Basis
The main material component in the plug shall be quartz sand or crushed rock. (VAHA L5-BAC-32)	Compliance with this requirement was demonstrated during the foreign material review of material data sheets and approval for use (i.e. concrete raw materials). The ability of the concrete recipe to meet design requirements when using this type of aggregate material was verified in laboratory experiments (i.e. properties of workability, strength, shrinkage, watertightness, etc.). Thus the concrete would fulfil the 100 year service life requirement for durability as well.	This requirement appears appropriate to maintain within the design basis.
The plug shall have a service life of 100 years, with concrete compressive strength of 50 MPa.	Monitoring of strain and total pressure within concrete plug will indicate any potential cracks occurring during pressurization (see Chapter 6.6 preliminary results).	Still under analysis, based on pressurization to 4.2 MPa.
The pressure against the plug shall be minimal before the concrete has cured and gained sufficient strength.	Monitoring of strain and total pressure within concrete plug during casting and initial phase have shown the pressures to be low, and in compliance (See Chapter 7.6). Formwork pressure measured during casting remains under 0.1 MPa.	This requirement appears appropriate to maintain within the design basis.
The plug location shall be selected so as to not have hydraulically conductive fractures intersecting the entire length of the plug. The plug location shall not be intersected by brittle deformation zones.	RSC was used for plug location siting. Monitoring of water pressure and water quality in near field boreholes during pressurization will indicate potential fracture paths for water transport.	This requirement appears appropriate to maintain within the design basis, in accordance with RSC methodology (See [DOPAS 2014d]). The requirement based on monitoring of boreholes is still to be determined, based on pending results during pressurization to 4.2 MPa.
The organics content in the plug shall be lower than 1 wt-%. (VAHA L5-BAC-28)	Compliance with this requirement was demonstrated during materials development and testing, and during the foreign material review of material data sheets and approval for use (i.e. concrete raw materials).	The organics content requirement is appropriate to maintain within the design basis.
The total sulphur content in the plug shall be less than 1 wt-%, with sulphides making, at most, half of this. (VAHA L5-BAC-29)	Compliance with this requirement was demonstrated during materials development and testing, and during the foreign material review of material data sheets and approval for use (i.e. concrete raw materials).	The total sulphur content requirement is appropriate to maintain within the design basis.

Requirement/Design Specification	Compliance Assessment	Feedback to Design Basis
The pressure against the plug shall be minimal before the concrete has cured and gained sufficient strength.	Compliance with this requirement was demonstrated during emplacement by a formwork pressure maximum value of 0.9 bars at the middle of the plug height (maximum allowed 1.5 bars). Total and pore pressure monitoring sensors within the plug also showed that the pressure remained under 1 bar within the first 90 days after casting, until grouting. For an operational plug, air pressure or water accumulation from the backfill behind the plug could be released via the filter and concrete lead-through during early ages, so as to prevent pressure accumulations.	This requirement appears appropriate to maintain within the design basis.
The plug location shall be selected so as to not have hydraulically conductive fractures intersecting the entire length of the plug. The plug location shall not be intersected by brittle deformation zones.	Compliance with this requirement was demonstrated during tunnel and slot siting and post excavation, by application of the RSC methodology.	This requirement appears appropriate to maintain within the design basis.
Wedge design allows for movement of the plug due to pressurisation.	Compliance with this requirement was demonstrated during performance evaluation based on pressurisation to 1.4 MPa. Displacement monitoring sensors attached to the plug can detect movements (see Chapter 6.6, pending further analysis).	This requirement appears appropriate to maintain within the design basis.

12 FUTURE WORK

The next steps for Posiva related to tunnel end plugs is the preparation and decisions for Posiva's reference plug, intended to be used in the repository operational license application. The reference plug will be demonstrated as part of Posiva's full-scale in-situ system test (FISST), to be designed, constructed and monitored in ONKALO within the next five years. In order to make this decision about Posiva's reference plug, the steps listed below are envisioned in the near future. These are not in any order for chronology or importance, but are grouped by thematic topics.

- Comparison of SKB DOMPLU and Posiva's POPLU results,
- Feedback iteration from actual POPLU performance assessment (monitoring results) back to POPLU THM models, for further improvements of plug requirement and design,
- Evaluate plug acceptance criteria for quantitative maximum water leakage (i.e. flow volume or rate) ,
- Development of contact grouting recipe for better emplacement ability,
- Evaluation and potential improvement of contract grouting construction methodology for better watertightness,
- Optimize plug materials (concrete, grout, steel, bentonite), including raw source materials (such as cement and admixtures),
- Optimize the plug structure (dimensions), to optimize long-term safety and efficiency of construction,
- Optimize plug slot excavation methods (requirements, design, equipment),
- addressing reliability and potential uncertainties in the monitoring system,
- Evaluation of safety case relevant to plugs, especially for materials which is also part of the CEBAMA project [H2020, 2016-2020] on cement-bentonite interaction.
- Optimize the monitoring plans for future plugs, including both FISST and operational environments (linked to MODERN2020 project [H2020, 2016-20]).
- Continued and strengthen cooperation with international partners on plug development and demonstrations,
- final proof of plug functionality and integration with buffer and backfill at the real repository site within FISST.

13 CONCLUSIONS

Posiva has successfully demonstrated the design, modelling, instrumentation, construction and monitoring of a full-scale deposition tunnel end plug. The work has also included excavation of tunnels and the plug slot area prior to construction. The work was unique due to the nature of conducting the research and development in a future operational repository facility, ONKALO, thus extra precautions were needed with respect to safety of the site.

This report has given an overview of the processes that went into the plug construction and the response for the accelerated pressurization test to simulate the 100 years design life. The structural designs and tunnel excavations with RSC and concrete recipe development were done in 2013. Concurrently, modelling was done to support the design and instrumentation plan for performance monitoring. The slot excavation and mock-up trials for materials were done in 2014 and 2015. Approximately 172 m^3 of low-pH concrete was placed in summer 2015 during the construction of the plug. This also included pre-work of the tunnel backwall and filter construction, formwork installations, reinforcement placement, and use of bentonite tape and injection grouting as watertightness precautions.

The plug was monitored to evaluate the materials at the time of construction, such as the early age temperature development in the low-pH concrete recipe. Long-term monitoring was done to assess changes in the plug due to pressurization to 4.1 MPa over two different pressurization periods. The monitoring included assessment of displacement, strain and pressure accumulation around the plug. Water leakage from the plug and the near field surrounding tunnel environment were documented. The leakage amounts were greater than anticipated and corrective actions have been instigated for re-grouting. The pressurization test to 4.1 MPa provided valuable insight regarding risk handling, mitigation of leakage, and identifying routes for re-grouting. Assessments were made to compare the POPLU demonstration to Posiva’s reference design and SKB’s DOMPLU experiment.

Based on this work, it has been concluded from POPLU that:

- POPLU showed a good ternary blend low-pH concrete, coupled with a filter layer behind a wedge-shaped plug that was successfully emplaced.
- The pressurization system was able to apply a load simulating evolution over the plug’s service life. The monitoring and leakage measurement systems were able to detect the plug and near field responses to pressurization.
- The leakage was greater than expected yet is expected to be corrected by re-grouting of the contact interface between the rock-plug.
- Modelling and monitoring techniques exist which can be utilised in other EBS components and repository operational conditions.
- The design of POPLU fulfilling the majority of requirements. Results are being used to evaluate Posiva’s reference design for the repository’s operational license application.

REFERENCES

DOPAS Documents:

DOPAS (2013). Palmu, M. Deliverable D6.1.1: Pilot EE Consensus Memorandum for D3.25 POPLU Test Plan. (Posiva).

DOPAS (2015). Grahm, P., Malm, R., Eriksson, D., Deliverable D4.3: DOMPLU Experiment Summary Report. System Design and Full-scale Testing of the Dome Plug for KBS-3V Deposition Tunnel. (SKB)

DOPAS (2014a). Hakola, I., Halonen, M., Bohner, Ed. Deliverable Report D3.25: Test plan for the full-scale test including the instrumentation plan for POPLU plug. (VTT)

DOPAS (2014b). Holt, E. Deliverable Report D3.27: POPLU Concrete Test Memorandum: Concrete Mix Design and Performance Study. (Posiva Oy)

DOPAS (2014c). Holt, E., Dunder, J. Deliverable Report D3.24: Detailed design of POPLU deposition tunnel end plug. (Posiva Oy)

DOPAS (2014d). Kosunen, P. Deliverable Report D3.26 URCF RSC Work Memorandum (POPLU). (Posiva Oy)

DOPAS (2014e). White, M.J. Doudou, S. (eds). Deliverable D2.2: Design of Reference Concepts and DOPAS Experiments: DOPAS Reference Design Report. (Galson Sciences Ltd).

DOPAS (2014f). White, M.J., Doudou, S., Neal, F. (eds). Deliverable D2.1: Design Bases and Criteria. DOPAS Work Package 2 (Galson Sciences Ltd, UK).

DOPAS (2016a). Rautioaho, E., Börgesson, L., Åkesson, M., Kristensson O., Valli, J., Hakala, M., Pintado, X. and Koskinen, K. Deliverable D5.11: Assessment of Watertightness and Mechanical Integrity of POPLU Plug. DOPAS Work Package 5 Deliverable D5.11.

DOPAS (2016b). White, Doudou, Bosgiraud, Foin, Czaikowski, Gentles, Grahm, Holt, Jobmann, Koho, Svoboda. Deliverable D4.4: WP4 Integrated Report: Summary of Progress on, and Performance Evaluation of, Design, Construction and Monitoring of Plugs and Seals. 2016.

Other documents:

BY40, 2003. Concrete Structure Surfaces (Betonirakenteiden Pinnat), Finnish Concrete Association, 168 p. (in Finnish)

BY47, 2007. Concrete Construction Quality Guidelines (Betonirakentamisen Laatuohjeet). Finnish Concrete Association, 159 p. (in Finnish)

BY50, 2012. Concrete Code 2012 (Betoninormit 2012). Finnish Concrete Association, 215 p. (in Finnish)

EN 1990:2002, Eurocode - Basis of structural design, December 2005.

EN 1992-1-1 :2004: Eurocode 2: Design of concrete structures - Part 1-1 : General rules and rules for buildings , December 2004.

Finfinet 2013.POPLU pressurization system operating and maintenance annual for Finfinet high pressure water pumping unit FF2-210T, Version Rev2, 31.12.2014. Finfinet Oy, Tampere. 81 p.

Finnmap Consulting Oy. 2010. Posiva Wedge Design Calculation Report (Loppusijoitustilan Tulppa Laskentaraportti), Memo to Posiva Oy, 8.10.2010, 9 p + 10 p appendices + drawing. (in Finnish)

Hakola, I., Kivikoski, H., Löija, M., Marjavaara, P. 2015. Designing, Commissioning and Monitoring of 40% Scale Bentonite Buffer Test. Posiva Working Report 2015-08, Posiva Oy, Eurajoki. 148 p.

Hiltunen, Juuso. 2015. Loppusijoitustunnelin betonitulpan rakentamisen suunnittelu (*Construction design of disposal tunnel concrete plug*). Satakunta University of Applied Sciences, Pori, Bachelor Degree thesis, 60 p. (in Finnish)

Holt, E., Bohner, B., Sanden, T., Malm, R., Pacovsky, J., Svoboda, J. 2016. Instrumentation and Monitoring Systems for Evaluation of Plug Responses in Geological Disposal Demonstration. Proceedings of the DOPAS Seminar, 25-26 May 2016, Turku, Finland, 7 p.

Kivikoski H., Marjavaara P. and Rantamäki, P. 2014. Designing, commissioning and monitoring of 40% scale bentonite buffer test. Proceedings of WM2014 conference, 2–6 March 2014, Phoenix, Arizona, 10 p., Paper No. 14260.

Malm, Richard. 2012. Low-pH concrete plug for sealing the KBS-3V deposition tunnels. Svensk Kärnbränslehantering AB, Stockholm, Sweden. SKB. R-11-04.

Martino, J.B., Dixon, D.A., Holowick, B.E., Kim. C-S. 2011. Enhanced Sealing Project (ESP): Seal Construction and Instrumentation Report. Atomic Energy of Canada Limited, NWMO APM-REP-01601-0003, 108 p.

Olivella, S., Gens, A., Carrera, J., Alonso, E.E. 1996. Numerical formulation for a simulator (CODE-BRIGHT) for the coupled analysis of saline media. Eng. Comput., 1: 87– 112.

Parkkinen, I., Mäntynen, A. 2013. Concrete wedge plug design report (Betonitulpan Laskentaraportti), Finnmap Consulting Oy, Memo to Posiva Oy, 23.5.2013, 30 p. + appendix drawing 1 p. (in Finnish).

Posiva 2012a. Backfill Production Line 2012. Design, production and initial state of the deposition tunnel backfill and plug. Posiva 2012-18, Eurajoki, Finland: Posiva Oy, 182 p.

Posiva 2012b. Underground openings production line 2012 - Design, production and initial state of the underground openings. Posiva Report 2012-22. ISBN 978-951-652-203-9. Eurajoki, Finland: Posiva Oy. 160 p.

Posiva 2012c. YJH-2012. Nuclear Waste Management at Olkiluoto and Loviisa Power Plants: Review of Current Status and Future Plans for 2013-2015. Eurajoki, Finland: Posiva Oy, 370 p.

Raivio, Paula, Hansen, Johanna. 2007. Technical Performance of Cementitious Grouting Materials for ONKALO: Laboratory Tests 2006. Posiva Oy. Working Report 2007-78, 108 p.

Ranta-Korpi, R., Karttunen, P., Sievänen, U. 2007. R20 programme: Field testing of grouting materials. Posiva Oy. Working Report 2007-102, 132 p.

Sacklén, N. 2015. Results of Monitoring at Olkiluoto in 2012- Foreign Materials. Posiva Oy. Working Report 2013-46. 42 p.

Sievänen, U., Karvonen, T., Dixon, D., Hansen, J., Jalonen, T., 2012. Design, Production and Initial Sate of the Underground Disposal Facility Closure. Posiva Oy. Posiva Report 2012-19, 112 p.

Vogt, C., Lagerblad, B., Wallin, K., Baldy, F. & Johasson, J-E. 2009. Low pH self compacting concrete for deposition tunnel plugs. Svensk Kärnbränslehantering AB, Stockholm, Sweden. SKB R-09-07.

APPENDIX A

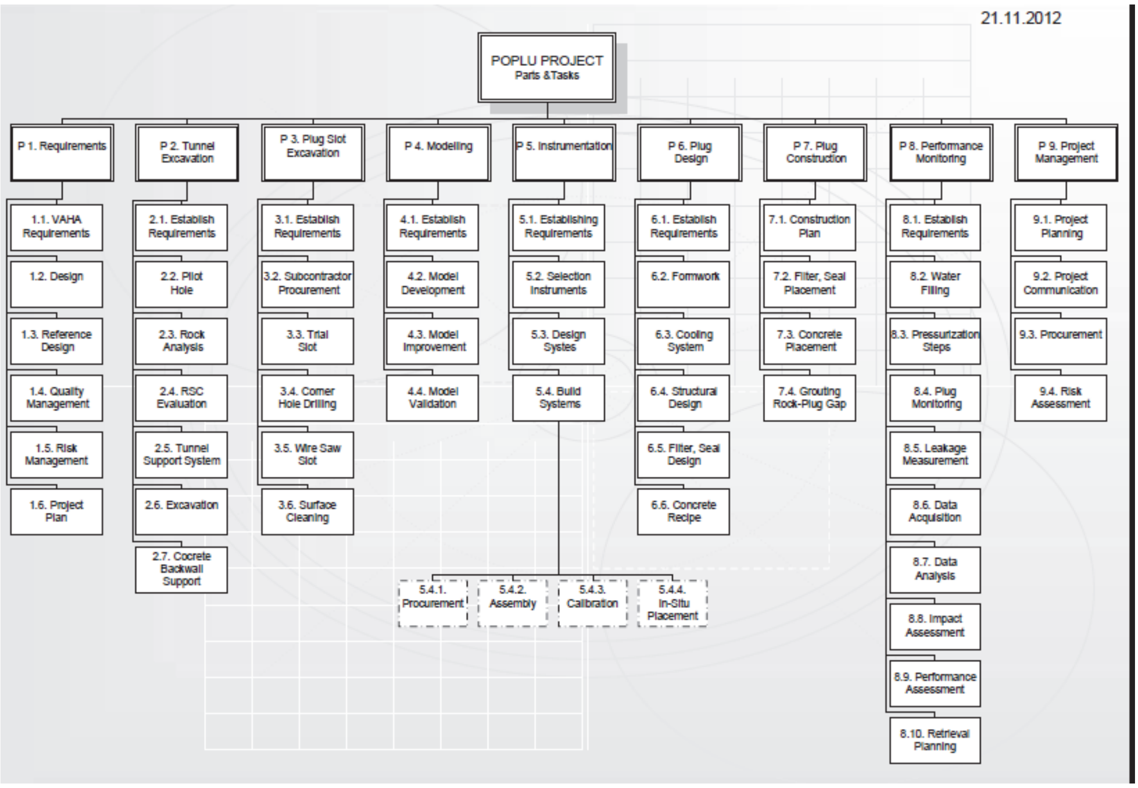


Figure A-1. Original POPLU Project structure (as of autumn 2012).

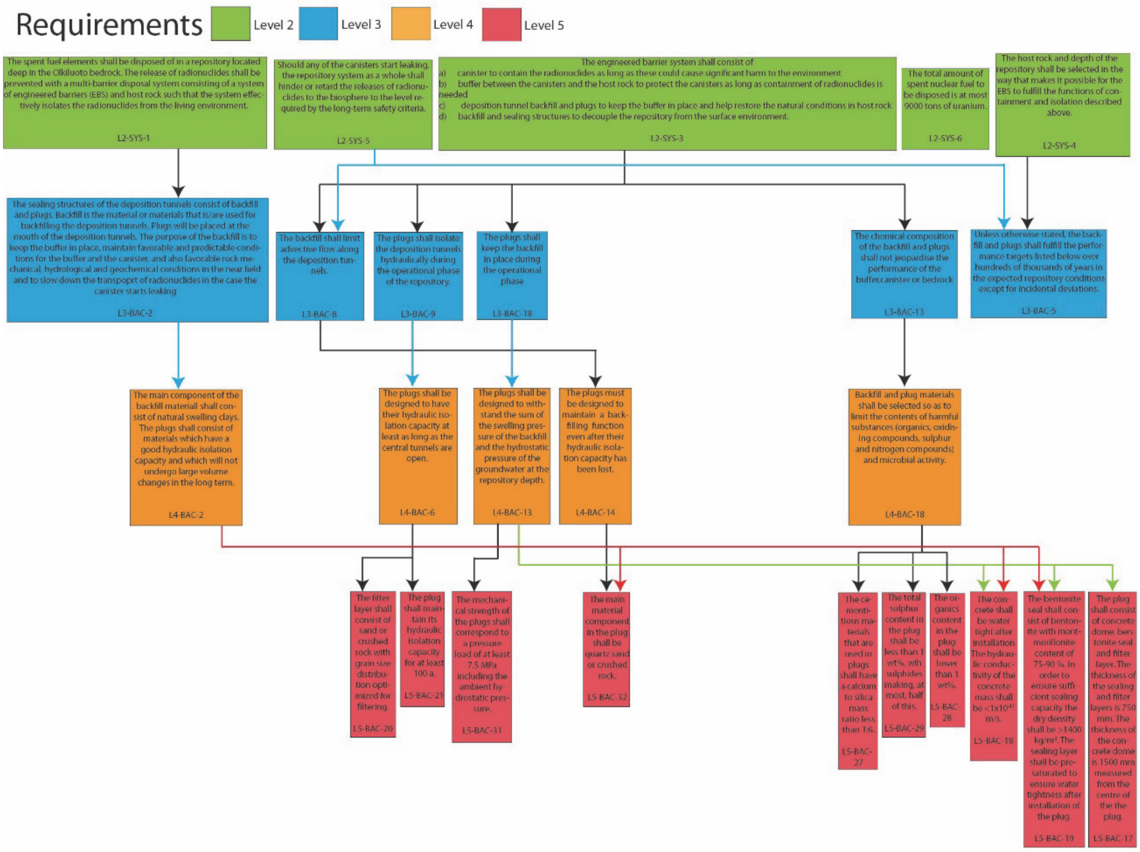


Figure A-2. Plug requirements [modified from Posiva 2012a].

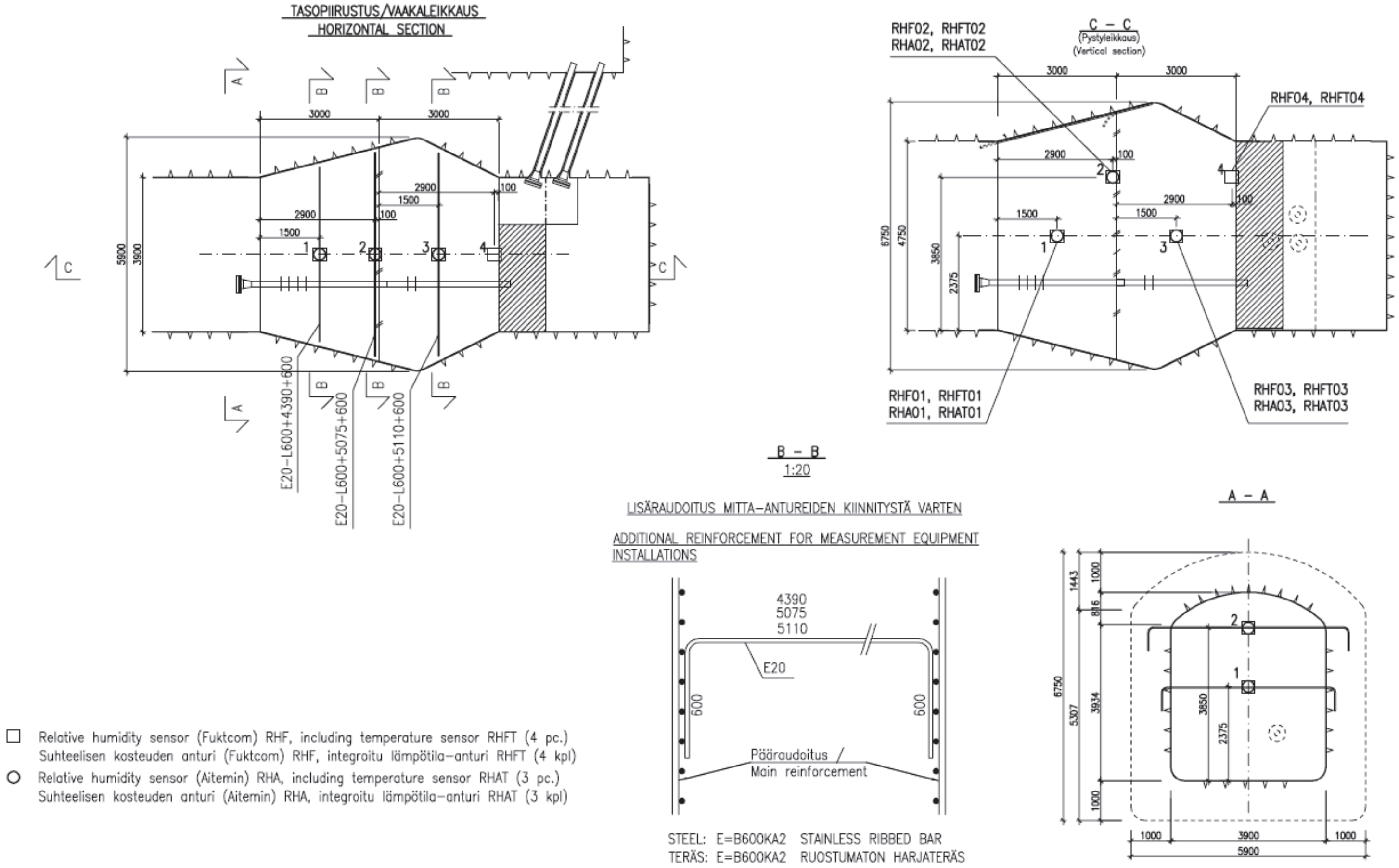


Figure A-3. Plug relative humidity sensor locations. Note dimensions are in accordance with actual DT4 and slot dimensions.

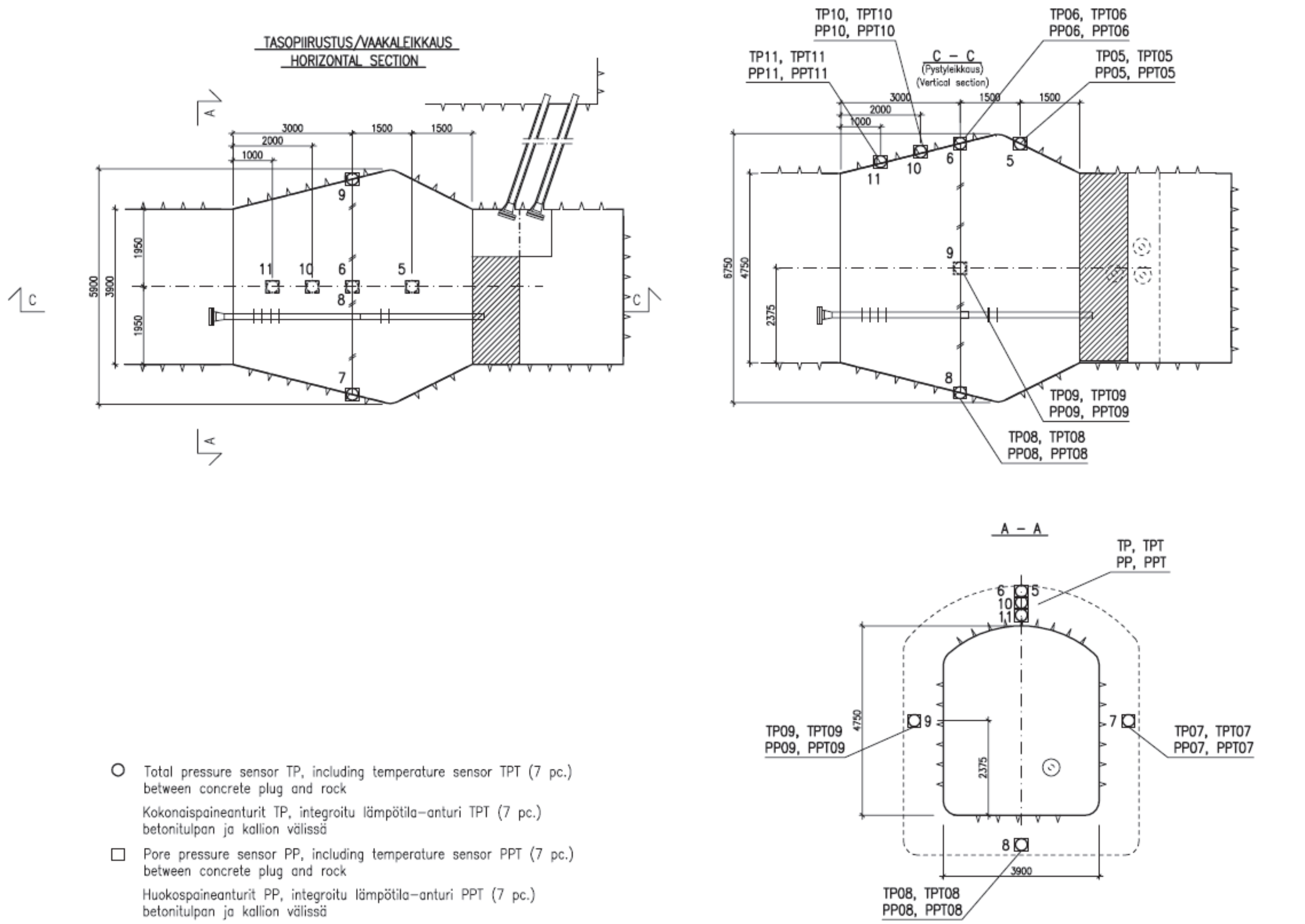


Figure A-4. Plug total pressure and pore pressure sensor locations. Note actual DT4 and slot dimensions shown.

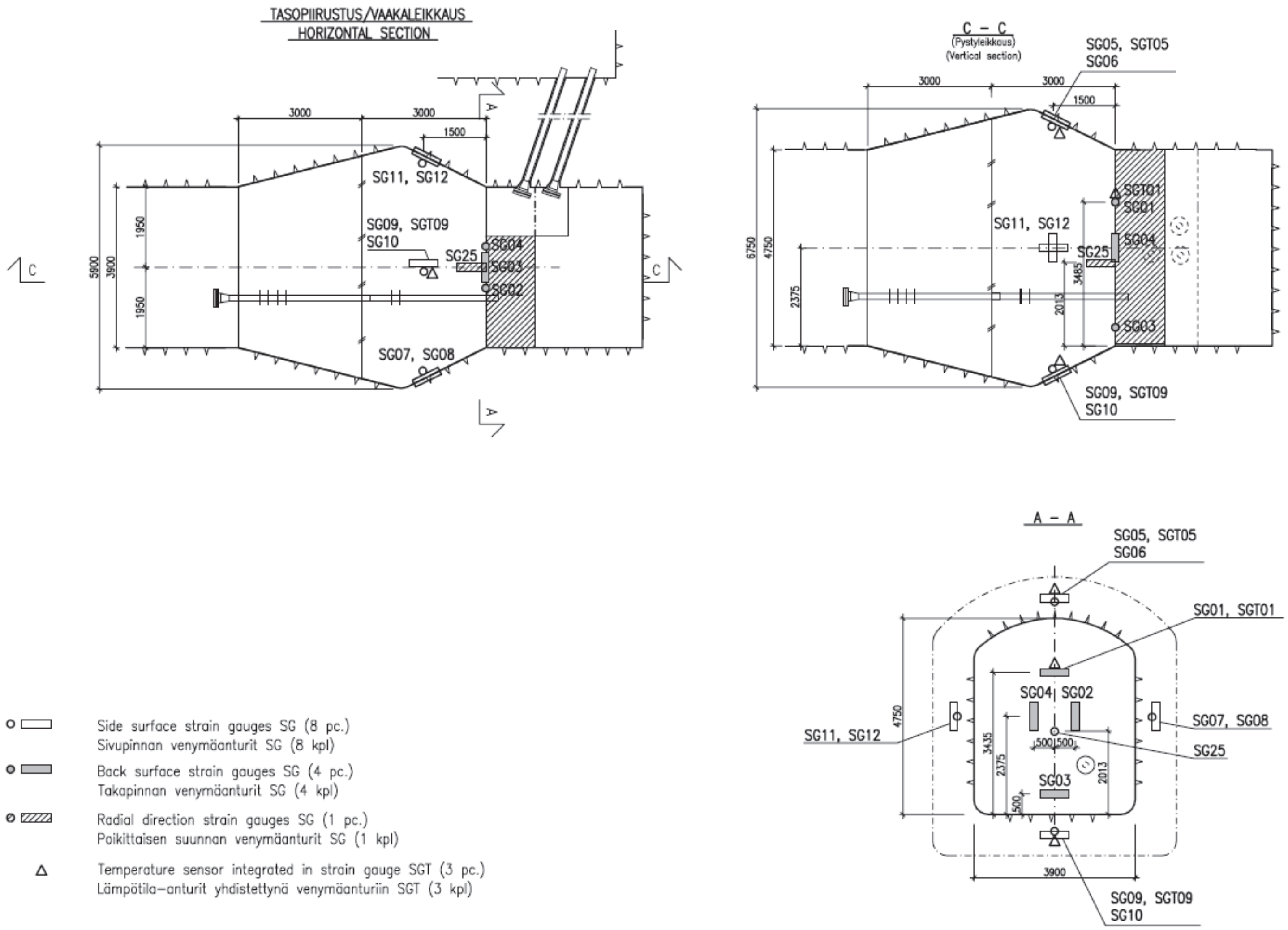


Figure A-5. Plug strain gauge sensor locations, section one. Note actual DT4 and slot dimensions shown.

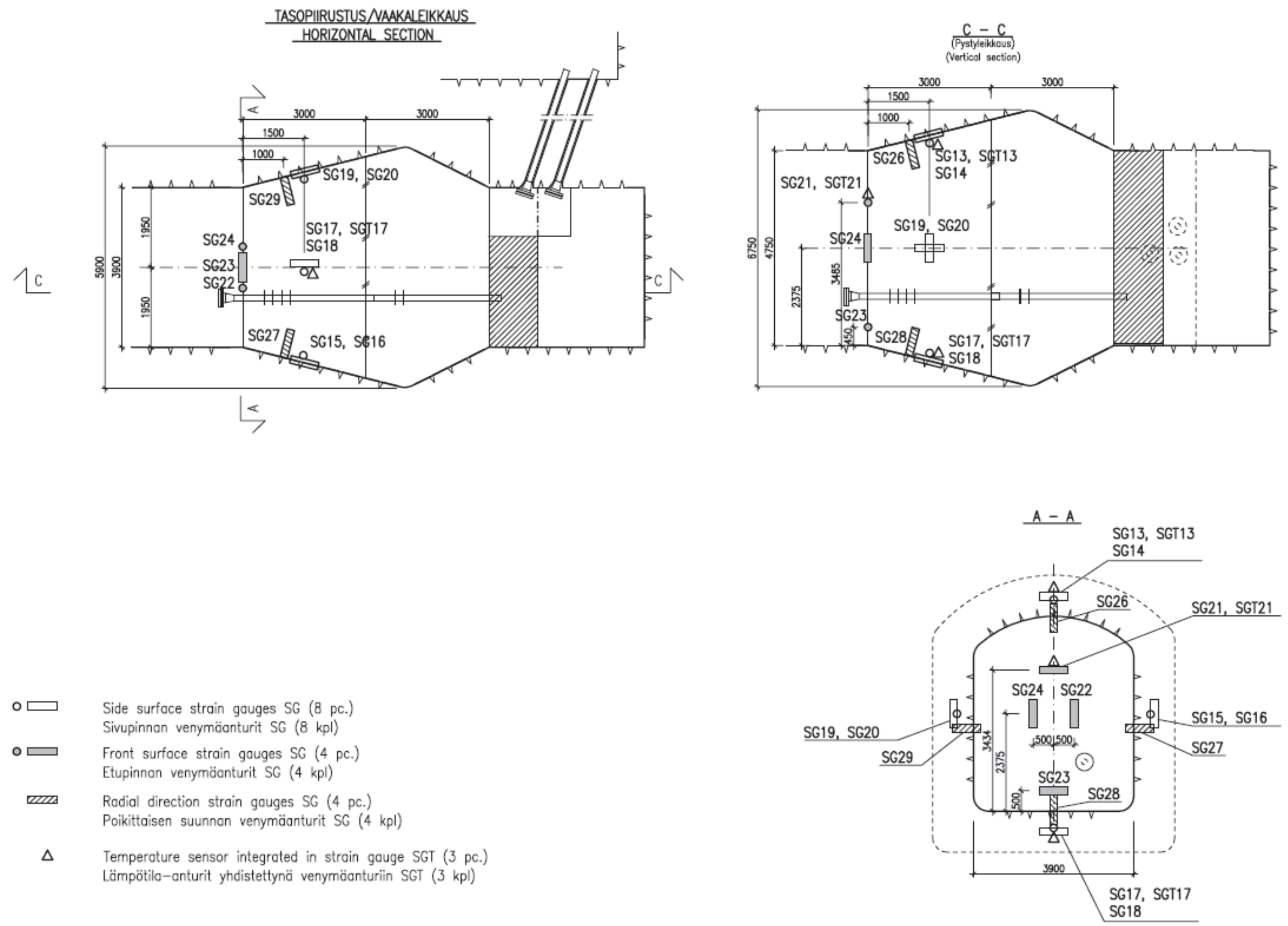


Figure A-6. Plug relative humidity sensor locations, section two. Note actual DT4 and slot dimensions shown.

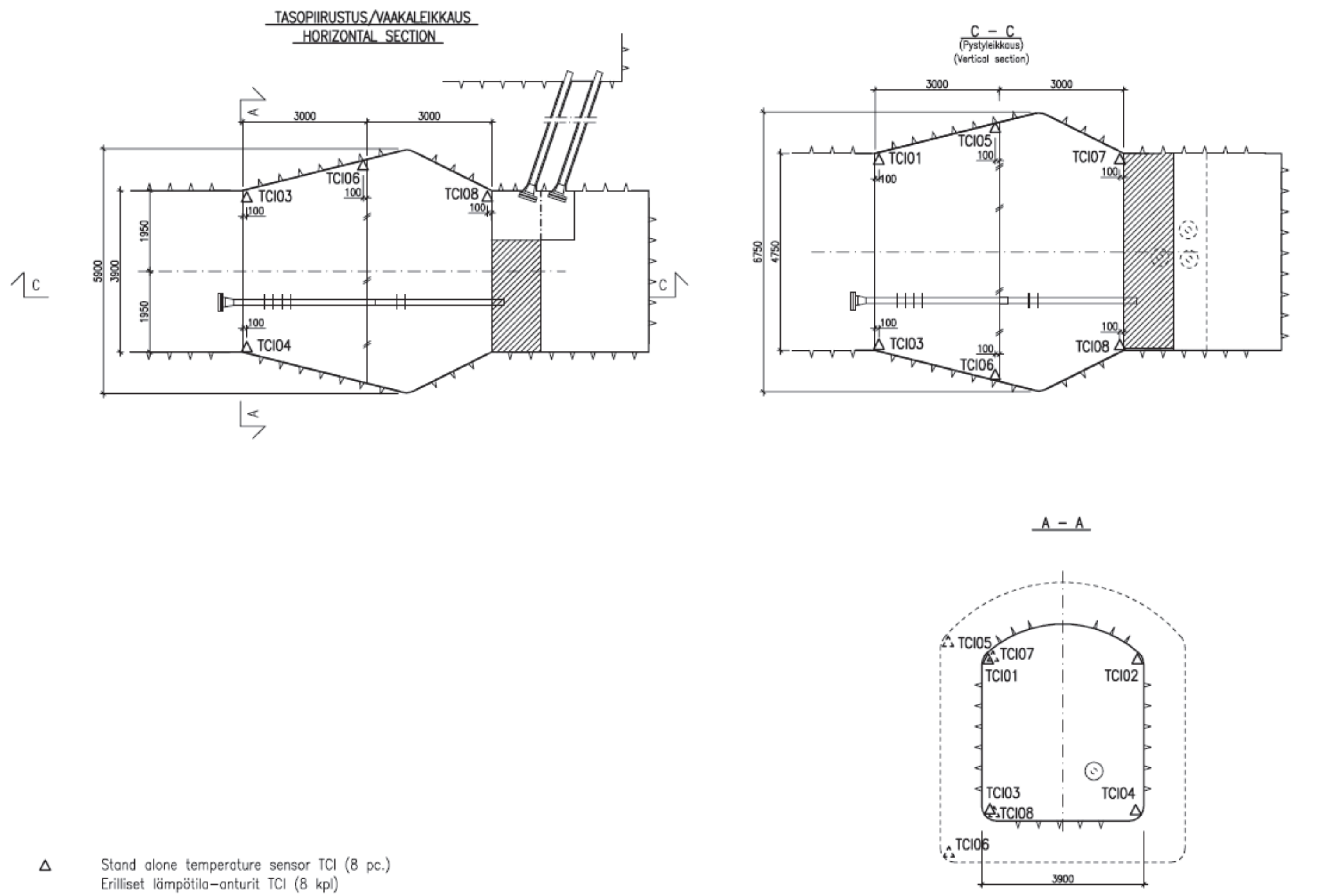


Figure A-7. Plug extra temperature sensor locations. Note actual DT4 and slot dimensions shown.

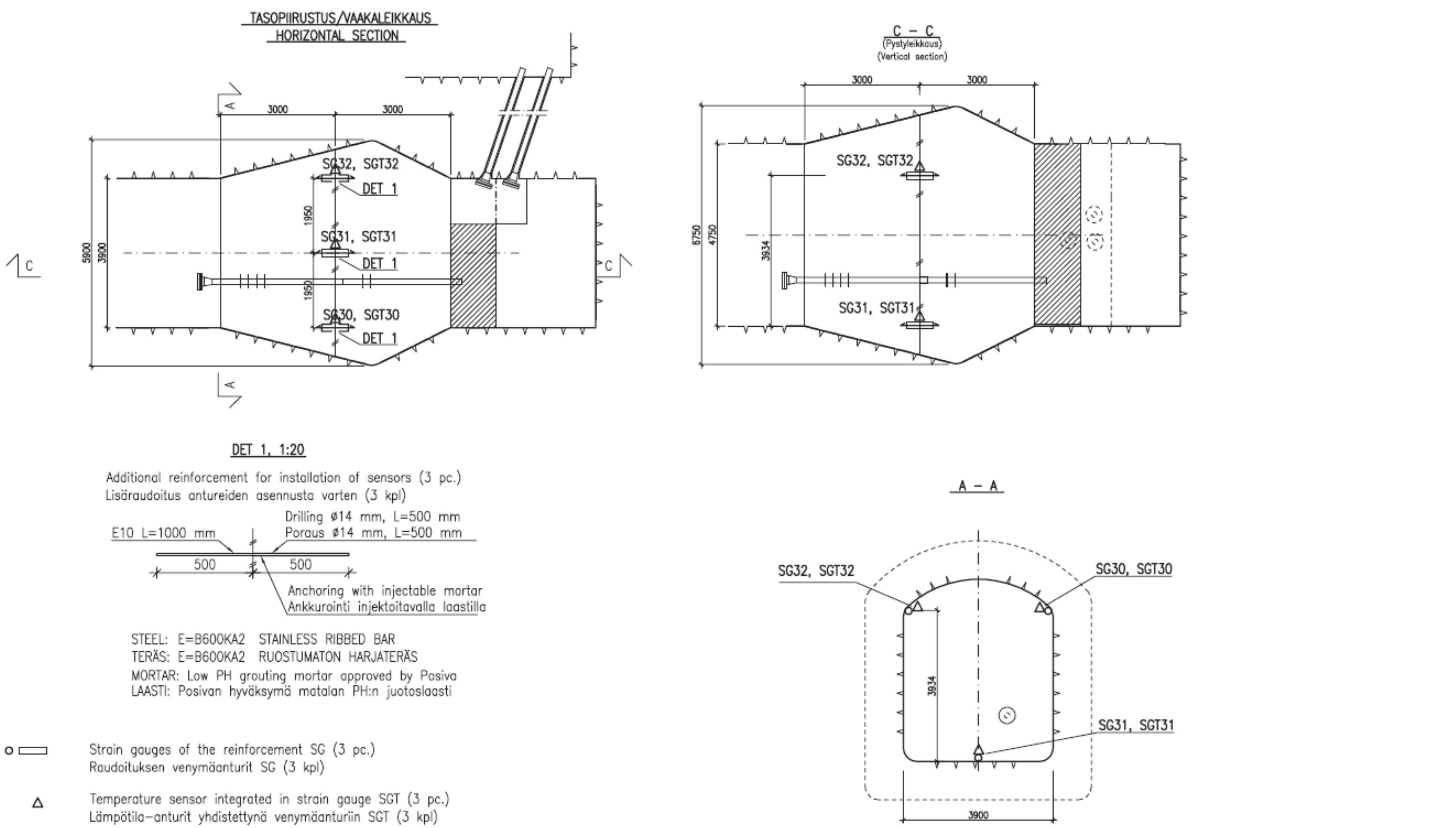


Figure A-8. Plug additional strain gauges locations on reinforcement. Note actual DT4 and slot dimensions shown.

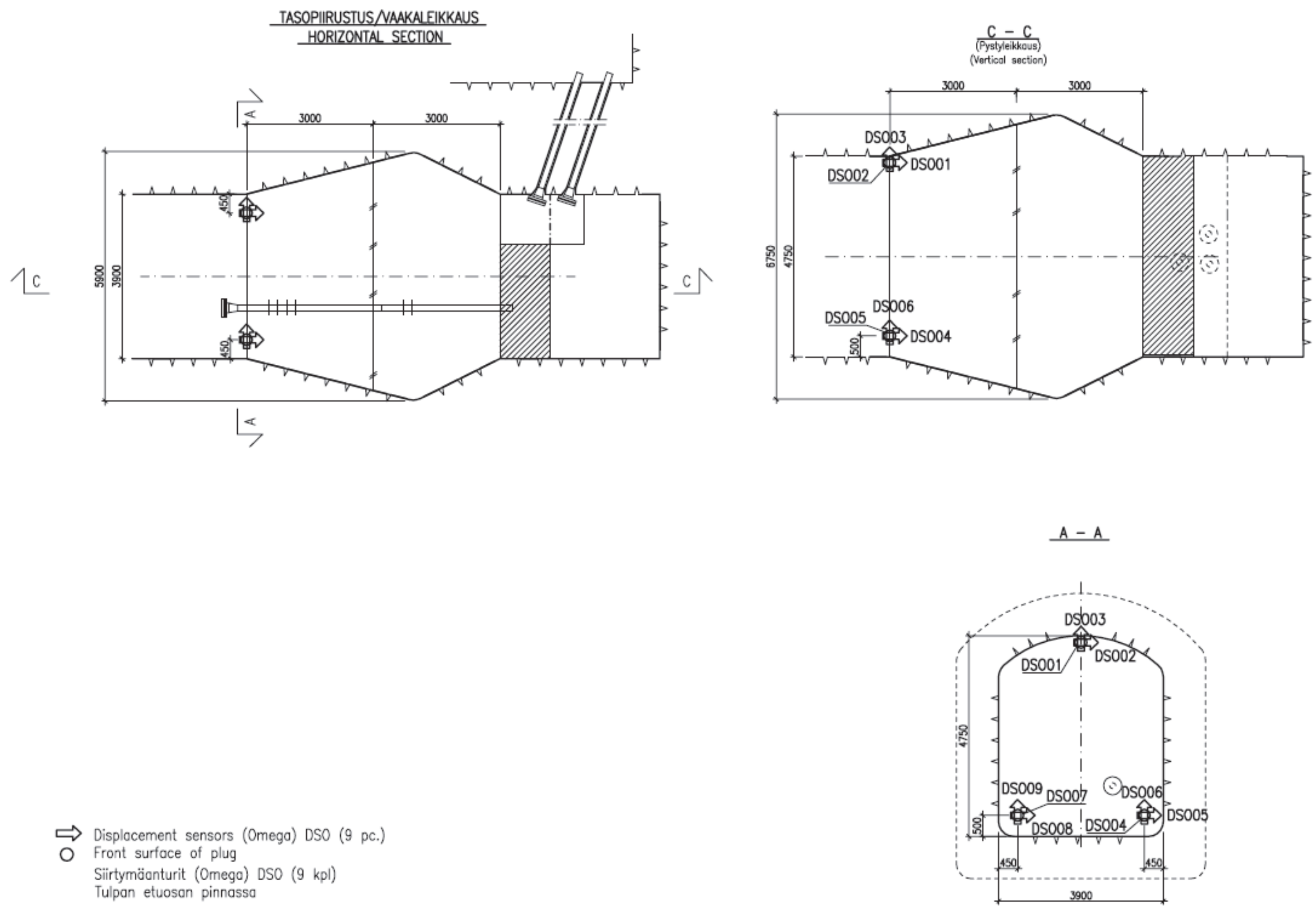


Figure A-9. Plug displacement sensor locations. Note actual DT4 and slot dimensions shown.

APPENDIX B-1: VTT REPORT ON FILTER LAYER MATERIALS

RESEARCH REPORT VTT-R-03982-14
3 (9)

Contents

1. Introduction

The objective of the study was to verify properties of lightweight blocks to be used for Posiva's Plug (POPLU) filter layer. The filter layer was designed by Finnmap Consulting Oy [Holt 2013]. Later public procurement was to be done by Posiva Oy (via construction contractor) for producing the filter blocks or beams. The expected volume of blocks needed is approximately 18 m^3, to create a wall of 1.2 metres depth across the circumference of the tunnel 4.35 metres height by 3.5 m wide (~15 m^2). The structural dimensions of the plug and filter layer are given in Figure 1. The circumference of the filter, adjacent to the tunnel walls, will also be filled with high-quality (i.e. MX-80 roller compacted) bentonite pellets. The filter layer is adjacent to a concrete backwall within the POPLU experiment, though in actual repository operation it would be adjacent to the backfill bentonite tunnel filling. There is a deairing pipe connecting the filter layer towards the central tunnel, through the concrete plug.

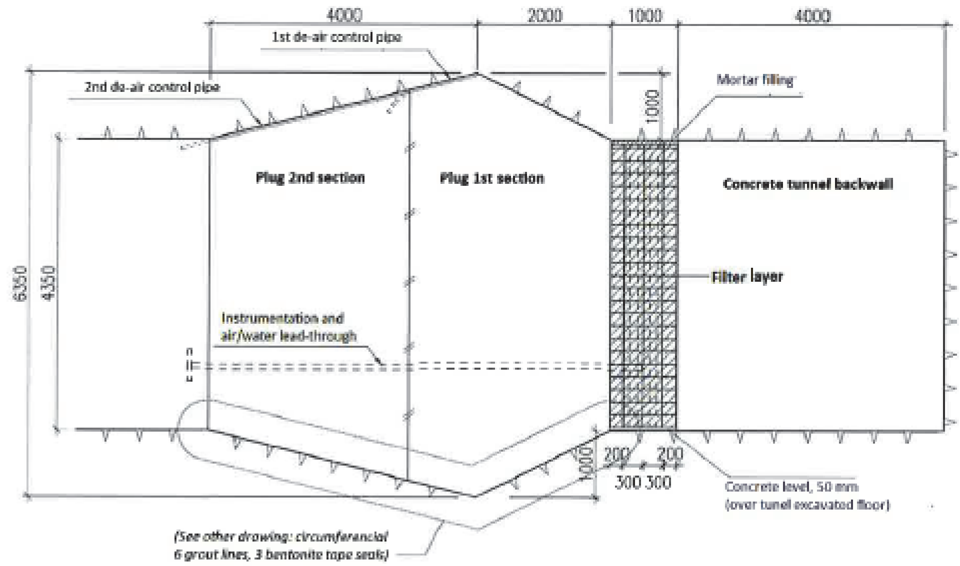


Figure 1. POPLU structural design, with filter layer as hatched area on right, adjacent to the backwall.

Within the POPLU experiment, there are also lead-through pipes (~8 metres long) coming into the filter layer, through the rock from the neighbouring tunnel and running perpendicular to the tunnel. The lead-throughs contain pipes and wiring. The pipes allow for movement of water and air, to be used for the pressurization system to simulate the plug loading. The lead-throughs also carry instrumentation to the filter layer, for assessing: 1) water distribution inside the filter, magnitude of pressure (total and pore pressures) and the potential movement (displacement) of the plug due to pressure changes during testing. Approximately 10 sensors are expected in and around the filter layer.

The expected dimensions of the lightweight blocks of the filter are suggested to be similar to the backfill clay blocks (550 x 470 x 330 mm), which would potentially be easy to handle in future operation with equivalent block placement equipment. The suggestion to not use lightweight beams the full width of the tunnel is based on SKB's experience in the DOMPLU project, as they had some difficulties in handling and placing of such beams (as described by ClayTech Oy at DOMPLU Project Meeting, November 2013 at Åspo, Sweden).

In December 2013 and January 2014, a small test series was done in VTT's building materials lab in Espoo, to assess the production and performance of lightweight filter blocks that could be used for the filter. This memo gives the input parameters to the study and the outcomes of the laboratory results.

2. Filter Requirements

The suggested requirements and properties of the filter layer structure are given in Table 1. These are only suggestions, as there are no set requirements as defined by the Backfill Production Line [Posiva 2012] or the structural designer. The expected low pH level was to support the safety requirements regarding bentonite long-time stability, similar to the concrete plug requirements [Holt 2014, Posiva 2012]. The additional suggested target parameters were based on the need to have sufficient strength and ease of handling during construction.

Table 1. Suggested filter performance.

Property	Target Value	Method of measurement	Justification
High water permeability	$1x10^{-4}$ m/s	Filtration: ASTM C1701/C1701M-09	Similar to SKB for DOMPLU [Börgesson 2013]. Easy water flow in and out of area behind plug. During pressurization during POPLU experiment, but also for water and/or gas collection during operational plugs (safety to be able to remove air/water).
Low pH	≤ 11, in reference deep groundwater conditions	VTT Leachate test method, 90 days	Safety expectation for bentonite long-term stability (similar to concrete plug requirement [Holt 2014])
Compressive strength	≥1 MPa at 7 days	EN 12390-3	Construction need, to support concrete during casting (backside formwork)
Low bulk density	≤ 1000 kg/m^3	EN 12350-6	Ease of handling
Early-age (fresh mix) workability	Homogeneity	visual, based on placement	Ease of placement when making specimens

3. Materials

Lightweight expanded clay aggregates (commercial name "Leca") from Saint-Gobain Weber Oy were used, in the size of either 4-10 or 8-20 mm. The filter also contained natural Finnish aggregates from Astrakan, size 0-1 mm. Binder materials included Swedish Annlägningscement (type CEM I 42,5 MH/SR/LA) from Cementa AB and Parmix type silica fume from Finnsementti Oy, which are the same binders as in the POPLU low-pH concrete recipe development [Holt 2014]. No chemical admixtures were used. Tap water was used in all cases.

4. Laboratory Results

Five different mixtures were designed for laboratory performance assessments. The proportions of the binder combining cement and silica fume were chosen based on the POPLU concrete recipe development (see [Holt 2014]), to achieve the low-pH associated with the chemical composition and groundwater leachate. The binder ratio of silica fume to cement was maintained at 40% to 60%, respectively. The water-to-binder ratios (w/b) were selected to achieve sufficient paste to coat the aggregate particles. In the case where a low binder content of 200 kg/m^3 was used, an additional amount of fine filler (aggregate) was added to generate a sufficiently high amount of paste. The proportions of the mixtures are given in Table 2.

Table 2. Composition of lightweight concrete for filter blocks.

Mix design	Binder, kg/m^3	Water, kg/m^3	Filler, kg/m^3	Leca 4/10, kg/m^3	Leca 8/20, kg/m^3
1	300	173	0	290	0
2	300	171	0	0	287
3	200	173	95	290	0
4	200	149	95	304	0
5	200	125	95	318	0

The mixing was done in a 170 litre Zyklos mixer for 5 minutes. First, the Leca aggregates were mixed with water for 1 minute to ensure homogeneous moisturization on the surface of the Leca. Then the dry powders were added, followed by an additional 4 minutes of mixing. The lightweight concrete was visually assessed to see that sufficient paste coated the aggregates. The concrete was then placed by hand and compacted into cubic moulds of 150 mm size and a single slab of 505 x 505 x 150 mm (for the permeability measurements). The compaction was performed by either a compaction hammer (cubes) or a roller compactor (slabs). The compaction hammer had a droppable weight of 4,5 kg and a dropping height of 45 cm. The roller compactor had a weight of 25 kg. The density for fresh concrete was measured from the cubic moulds according to EN 12350-6.The samples were covered with plastic sheets and stored at room temperature (20°C) for the first 24 hours, then demoulded and moved to a climate room at 20°C and 95% RH or accelerated curing at 50°C and 100% RH until the age of testing. Figure 2 shows an example of the final lab-scale blocks.

Figure 2. Appearance of filter material, both close up (left) and of final blocks (right).

Three samples were tested for compressive strength after 7 days of accelerated (heated) curing or 28 days of traditional curing. There was no significant difference in the accelerated early-age strength compared to later 28-day (normal curing) measurements (as seen from Mix #1 results). The properties of the five mixtures are given in Table 3.

Table 3. Test of lightweight blocks. Empty cells indicating the test was not done.

Mix design	Water permeability, m/s	Accelerated 7d strength, MPa	Strength 28d, MPa	Density of fresh concrete, kg/m^3
1	1,11E-03	3,7	3,7	826
2	4,74E-03	-	2,2	748
3	6,03E-05	3,9	-	891
4	1,78E-03	3,3	-	828
5	1,14E-02	2,2	-	736

The pH measurements were not done at this time, as the expected results should be similar to the concrete studies due to the equivalent proportions of the POPLU binary mixture reported in [Holt 2014]. In the future when the full-scale plug is constructed, it is recommended to take samples for actual measurement of pH leachate during the quality control process.

5. Discussion

The results showed that it was possible to produce low-pH lightweight concrete that could have low density with sufficient strength and also showing good filtration. The results indicate than four of the five mixtures would be acceptable, as they met the performance expectations. Only mix design #3 had improper paste qualities and insufficient permeability or filtration.

The results of the VTT study on Posiva's lightweight blocks showed similar results to those obtained by ClayTech Oy for SKB's DOMPLU experiment. The Swedish preliminary laboratory tests on the plug materials were reported by Börgesson et. al. (2013). Their hydraulic conductivity (filtration) of the DOMPLU lightweight beams was approximately 1.1 to 1.4 x 10^{-4} m/s for their Leca samples, compared to 1.3 x 10^{-7} for normal lightweight concrete having similar density and strength. It should be noted that their samples had been surrounded by bentonite clay pellets, prior to conducting the test, to prevent edge drainage. The compressive strength of SKB's lightweight Leca beams (produced by Nyströms Cement AB in Norrtälje) was approximately 2.7 MPa at a late age (over 28 days).

It is the authors' opinion that there are no concerns about constructing the filter wall of blocks, using joining mortar. The plug concrete can be cast directly against the wall of filter blocks, as it is not expected that the fresh concrete penetrates much deeper than into the blocks' surface layer voids. This can be further studied in laboratory pre-tests if needed, or commented on by the structural designer and/or block producer.

The air escape out from the filter beams was not evaluated, which may be a concern with rapidly adding high amounts of water from the pressurization system. Air escape tubes should be in-place, either through the rock lead-through (in POPLU pressurization system) and/or through the concrete plug face lead-through (i.e. in future plugs during repository operation). This air escape from the lightweight blocks could be a topic of further calculations and/or laboratory-based studies.

6. Construction Recommendations

The recommendation for full-scale industrial production of lightweight filter layer includes:

- Producing blocks rather than beams, for ease of handling and placement. Suitable dimensions could be 550 x 470 x 330 mm, similar to the expected backfill clay blocks. Or the block size can be tailored to the product factory moulds for producing standardized lightweight blocks that are commercially available (i.e. 498 x 300 x 195 mm).
- The paste should be composed of 40% silica fume to 60% cement (similar to the POPLU concrete binary recipe), to achieve the expected low-pH levels during leachate tests.
- Maximum paste binder content should be 200 kg/m^3.
- Lightweight aggregates should be used, i.e. Leca products or equivalent.
- Other proportioning of aggregate-to-paste ratio can be in accordance with normal practices of the production factory, related to lightweight block manufacturing.
- A minimum of 20 m^3 of blocks will be needed to produce the filter layer, though excess should be produced to account for quality control testing needs. A similar amount of blocks will also be needed in Posiva's future full-scale integrated test (FISST) planned for year 2017, which could also be produced now.
- Samples should be taken for quality control testing in accordance with EN772. Additional tests of permeability and pH leachate (90 days [Vuorinen 2005]) should be done for POPLU purposes.

During construction, it is expected that the blocks are placed in the tunnel with the aid of a mortar to hold the blocks together and in place. The mortar should also be made to have low-pH properties. The suggested composition of the low-pH mortar could be similar to the composition (sand, binder types, and their ratios) used for the filter blocks and in the low-pH concrete development for the structural plug. This would consist of 60% cement and 40% silica fume. Construction practice typically has mortar proportions of approximately 1:5 for binder:sand ratio, and an unspecified water-to-binder ratio but sufficient to achieve the desired workability. For the POPLU mortar, it is sufficient if natural Finnish sand is used for the aggregate, for instance in the size range of 0–2 mm. The addition of an air entrainment chemical could also be used to aid in workability. The mortar can be mixed on-site. It should be noted that the mortar will hydrate slower than normal due to the inclusion of silica fume, so precautions may be needed regarding construction and curing duration in the nearby area.

For the mortar, the contractor should take quality control samples (i.e. sets of prisms 40 x 40 x 160 mm) on-site during each day of production, and test in accordance with EN 1015-11:1999. An alternative would be to follow concrete sampling and testing standards (i.e. EN12390-3 with 10 cm or 15 cm cubes). A additional samples should be stored in plastic bags and tested at 90 days to determine pH leachate [Vuorinen 2005].

Acknowledgement

The research described within this memo has received funding from the European Union's European Atomic Energy Community's (Euratom) Seventh Framework Programme FP7/2007-2013 under Grant agreement no. 323273 for the DOPAS project (2012-2016).

References

Börgesson, Lennart, Sandén, Torbjörn, Andersson, Linus, Johannesson, Lars-Erik, Goudarzi, Reza, & Åkesson, Mattias. 2013. End Plug for Deposition Tunnels: Preparatory Modelling and Test of the Sealing and Draining Components. Clay Tech Oy, Sweden, 220 p. (draft only)

EN 772-1:2011. Methods of test for masonry units. Determination of compressive strength.

EN 1015-11:1999. Methods of test for mortar for masonry. Determination of flexural and compressive strength of hardened mortar.

EN 12390-3:2009. Testing hardened concrete. Compressive strength of test specimens.

Holt, Erika; Dunder, Jari. 2013. Detailed design of POPLU deposition tunnel end plug. DOPAS project Deliverable Report D3.24. Posiva Oy, Eurajoki, 13 p.

Holt, Erika. 2014. POPLU concrete test memorandum: Concrete mix design and performance study. DOPAS project Deliverable Report D3.27. Posiva Oy, Eurajoki, 34 p.

Posiva. 2012. Backfill Production Line 2012. Design, production and initial state of the deposition tunnel backfill and plug. Posiva Report 2012-18, Posiva Oy, Eurajoki, 182 p.

Vuorinen, U., Lehikoinen, J., Imoto, H., Yamamoto, T., Alonso, M. C.. 2005. Injection Grout for Deep Repositories. Subproject 1: Low-pH Cementitious Grout for Larger Fractures, Leach Testing of Grout Mixes and Evaluation of the Long-Term Safety. Posiva Working Report 2004-46, Posiva Oy, Eurajoki, 101 p.

APPENDIX B-2: VTT REPORT ON BENTONITE TAPE MATERIALS

Contents

1. Introduction

Within the project, called POPLU, Posiva Oy will demonstrate during 2014 the full-scale construction and performance of a demonstration tunnel end plug [Hansen 2013]. The plug is an alternative to the reference design described in the Backfill Production Line [Posiva 2012].The POPLU concrete plug will be built at the ONKALO underground rock characterization facility and separates the demonstration tunnel from the vehicle connection. In order to test the plug performance, an artificial pressurization routine is conducted by pumping water into a filter layer behind the plug. The pressure build-up will be periodically increased up to a maximum pressure of approximately 4.5 MPa.

In the current plug structural design for POPLU by Finnmap Consulting Oy [Holt 2013] there are bentonite tapes in the gap between tunnel rock walls and concrete plug. The tapes run circumferentially around the plug, in three sections. They are fastened to the rock at the time of constructing the formwork and before installing the reinforcement steel. The tapes will be subjected to fresh low-pH concrete (as detailed in [Holt 2014] cast against it during construction.

The bentonite tapes are intended to (i) to support the grouting process by keeping the grout in place during the first low pressure injections and (ii) to increase the long-term tightness of the plug by preventing seepage through the rock/concrete interface.

Bentonite tapes are normally used in construction, e.g. between concrete elements where they swell and thus tighten the concrete structure when exposed to water.

There are several bentonite tapes available on the market in Finland. The purpose of this project was to make some applicability pre-tests to gain a better understanding of the bentonite tape swelling properties, to create the basis for further decisions on tape selection and design aspects of the plug test and to identify the needs for possible further tests.

2. Objectives

The purpose of this bentonite tape applicability pre-test was to identify how different environmental conditions affect the properties of the bentonite tapes, so that some tapes can be selected for further and more detailed tests. The bentonite tapes can be exposed to different environments, represented by three solutions: concrete capillary water, natural groundwater and tap water. The tap water may be the case when the plug is artificially wetted, though the intention in the POPLU experiment is to used local (deep) groundwater.

3. Methods

3.1 Materials

In the pre-test, six different types or brands of bentonite tapes were obtained from Finnish suppliers. Table 1 summarizes these tapes and the short information, Table 1. More information of the tapes can be found from the material data sheets (MDS) in Appendix 3.

Table 1. Bentonite tapes used in capability pre-test.

Number	Supplier	Product name	Dimension (mm)	Composition (from MDS)	Notes
1	Meltex Oy	Super Stop	26 x 21	Sodium based material	grey, net (otherside)
2	Solcon Oy	Bentorub	24 x 19	Blend of butylrubber / Sodium bentonite	green, rubbery, flexible
3	Semtu Oy	PC Betonstrip	24 x 21	Sodium bentonite / butylrubber	Black, rubbery, flexible
4	Kaitos Oy	Waterstop RX 101	26 x 21	Sodium based material	Black, sticky
5	Muottikolmio Oy	Hydridite CJ	25 x 7	Chloroprene rubber /	Blue & Green, flexible
6	Muottikolmio Oy	Hydrodite CJTA	25 x 7	Styrene-butadiene rubber and others	Green, flexible

Figure 1 shows the bentonite tape appearance before the test. There are three tapes in each picture, to be used in each of the three different solutions. A few notes about the specific tapes are summarized as:

- The Superstop tape included a glue surface for adhesion and on top of that plastic protection which would be removed away when the tape is installed. On both side of that tape there is white net which is probably intended for keeping the tape coherent when it start to swell.

- The other five tapes visibly appeared to be homogeneous materials, across the whole tape length and circumference.

- Tapes Hydrodite CJ and CJTA contain decelerator also in the tape, so they should not start to react and swell immediately.

- Tape CJTA also had additional surface treatment of water protection so it should not start to react earlier than the CJ tape.

The evaluation of the composition of the six different tapes was done by Posiva's safety group, to check the amount of foreign materials present based on the tape composition as shown in the Material Data Sheets (APPENDIX 3). Note that the foreign materials assessment might be a controlling factor for the tape selection.

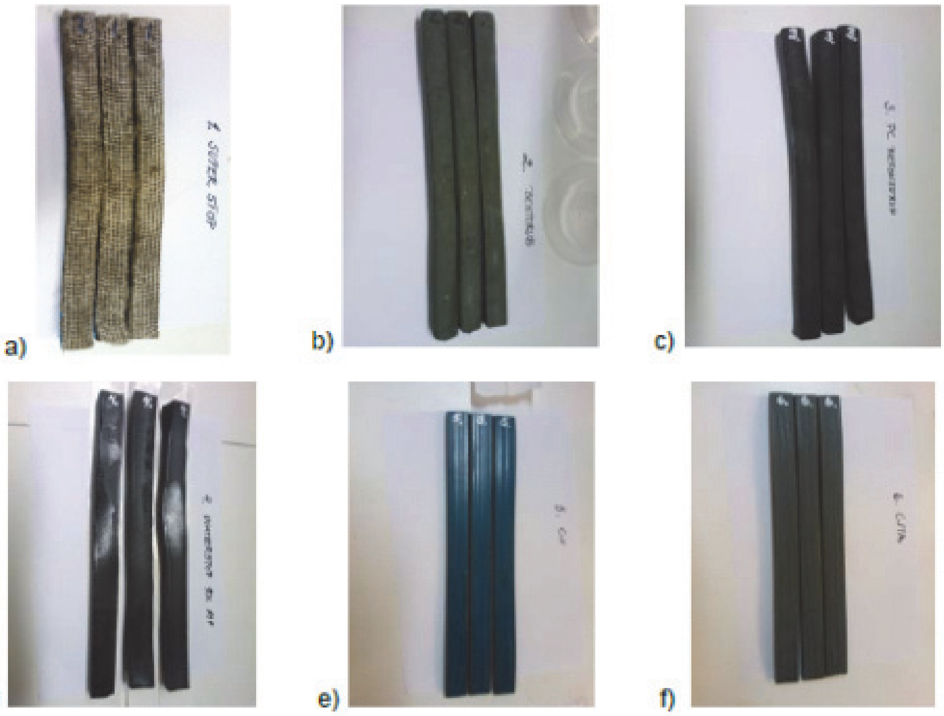


Figure 1. Bentonite tapes before the test, a) Superstop, b) Bentorub, c) PC Betonstrip, d) Waterstop RX101, e) Hydrodite CJ, f) Hydrodite CJTA.

3.2 Test procedure

The test was prepared by taking a 30cm sample of each bentonite tape for each solution (Table 2), for a total of 18 samples tested (6 tapes, 3 environments). The reference groundwater was prepared according to [Vuorinen 2005], representing deep underground conditions of Olkiluoto with a pH of 7.2. The low pH concrete capillary water (pH 12.4) was prepared to represent when the tape would be in direct contact with fresh and/or hardened concrete. Low pH concrete pH measurements for this application have studied in the following report. (VEHMAS. The pH 12.5 manufactured with saturated $CaOH_2$ solution (2 g/l). Tap water pH was ~8.3, as noted by the Helsinki Region Environmental Services Authority literature.

Table 2. Recipes of the water solutions for bentonite tapes exposure.

Concrete capillary water	Groundwater pH 7,2	Tap water
Saturated solution CaOH: 2g/l	NaCl: 12,1157 g/l $CaCl_2*2H_2O$: 14,6722 g/l NaBr: 0,134 g/l	20°C

All the bentonite tapes samples placed in to the graduated glasses which filled 1liter per different solution. No additional solution was added to the graduated glasses during the test, as seen in Figure 2. The tests were carried out for 37 days, between 30.12.2013 to 5.2.2014 and changes of the tapes' cross sectional area (mm^2) was collected. Before and during the test, the width and depth of the tapes were measured with slide gauge from three different cross-sections of bentonite tapes (to an accuracy of 0.01 mm). It was decided only to quantify the change in cross-section of the tape and not to measure the change of its height. Also there were not big changes in height, comparing to width and depth during the test.

Table 3 shows the dimensions from the beginning of the test. All measurement data can be found in APPENDIX 2.

Figure 2. Bentonite tapes prior to the test starting, in the graduated cylinders.

Table 3. Tape dimensions at the beginning of the test.

width & depth dimensions (mm2) in the beginning of the test				
Number	Product name	Capillary	Ground	Tap
1	Super Stop	569,9	547,6	577,1
2	Bentorub	463,1	429,1	432,8
3	PC Betonstrip	492,8	506,4	508,2
4	Waterstop RX 101	510,8	511,2	489,9
5	Hydridite CJ	181,5	179,6	179,2
6	Hydrodite CJTA	184,3	186,9	186,4

4. Results

Immediately after starting the test it was evident that the tapes started reacting. The changes were almost immediately within minutes when they were in contact with the different solutions. As seen in *Figure 3*, in the first 24 hours the swelling and the dimension change was the largest in the tap water. The second largest dimension change was in the concrete capillary water and then in groundwater. As assumed before the test, the Hydrodite CJTA did not react even in the tap water during the first 24 hours because of the decelerator in the tape.

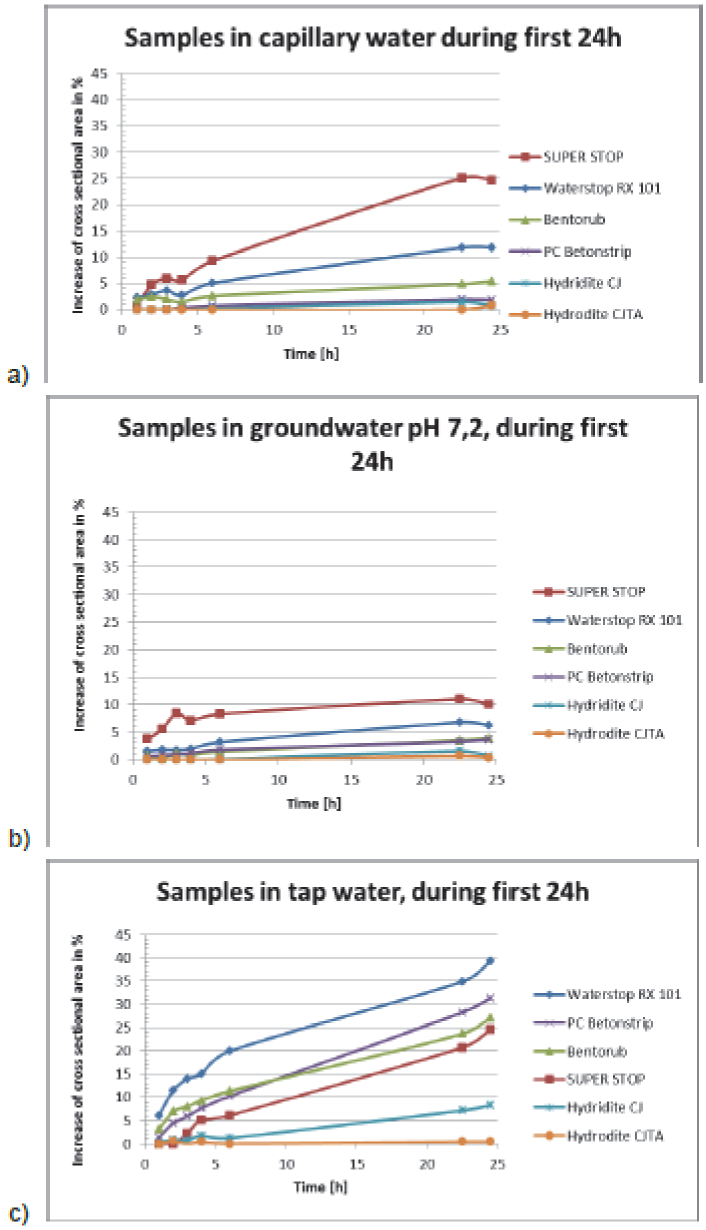


Figure 3. Samples in different solutions, a) capillary water, b) groundwater, c) tap water.

The swelling after 24.5 h and 72.5 h in different solution is shown in Figure 4. The tap water was also the most aggressive environment after 72.5 hours. Groundwater was the least aggressive environment also after 72.5 hours, so the same trend seen after 24 hours (Figure 3.) between the different solutions was continuing.

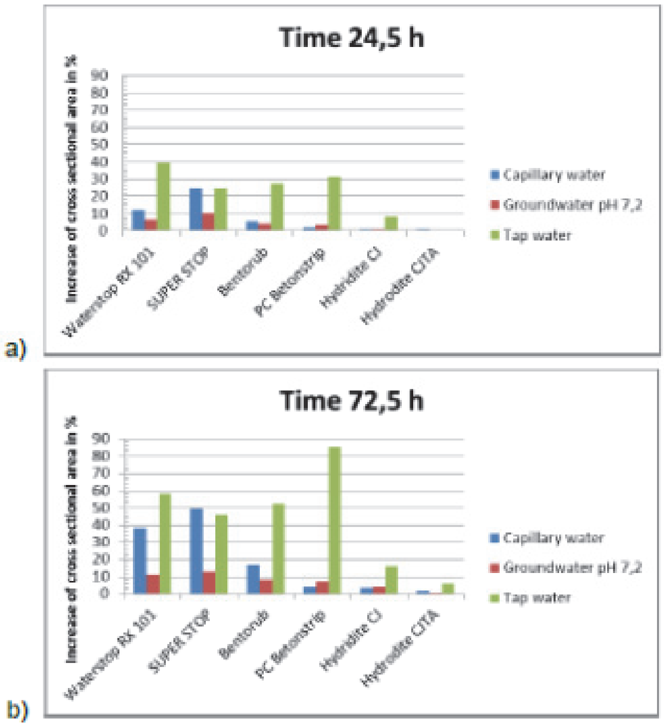
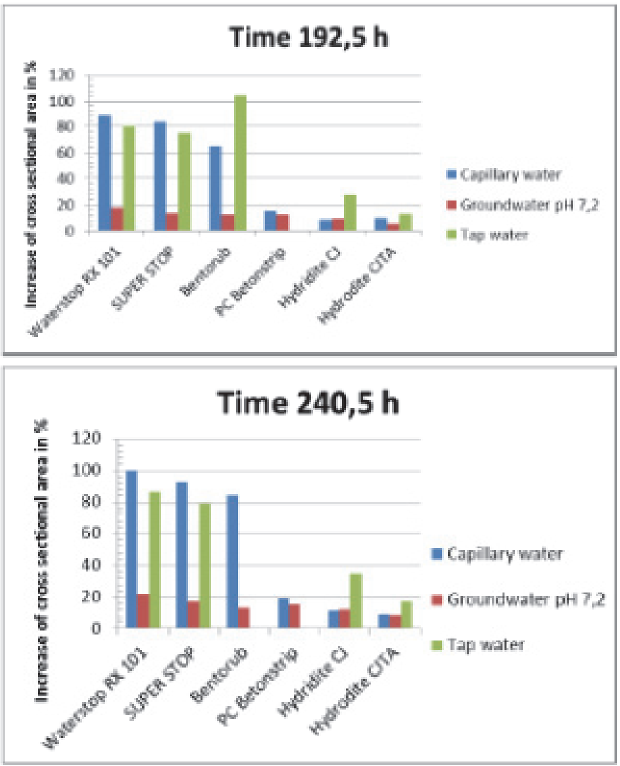


Figure 4. Bentonite tapes in different solutions, a) after 24.5 h, b) after 72.5 hour.

In tap water after 216.5 hours (9 days) the Bentorub tape broke into two different parts at which time the dimensional change was 120.7%. Also PC Betonistrip tape broke after 96.5 hours (4 days) with 108.5% dimension change. Thus in tap water after 192.5 hours there are no PC Betonstrip tape results (Figure 5a) and after 240,5 hours both tapes results, PC Betonstrip and Bentorub cannot be presented (Figure 5b).

If comparing different solutions from the test start, the most swelling happened in the tap water but in the end it seems that the concrete capillary water can further the swelling process as much as tap water (Figure 5). There are some swelling differences due to tape material, for example tapes Bentorub and PC Betonstrip swelled the most in tap water before breaking (Figure 4b) whereas Waterstop RX 101 and Superstop swelled as much or even more in concrete capillary water than tap water after 240.5 hours (10 days).



a) b)

Figure 5. Bentonite tapes in different solutions, a) after 192.5 h, b) after 240.5 hours.

As noted before, in tap water Bentorub tape broke after 216.5 hours and PC Betonstrip after 96.5 hours. The trend appears that the largest swelling was with Waterstop RX 101 and Superstop, while the lowest with Hydrodite CJ and CJTA. With all tapes, there were not significant dimension changes at the later ages, within the period from 10–37 days.

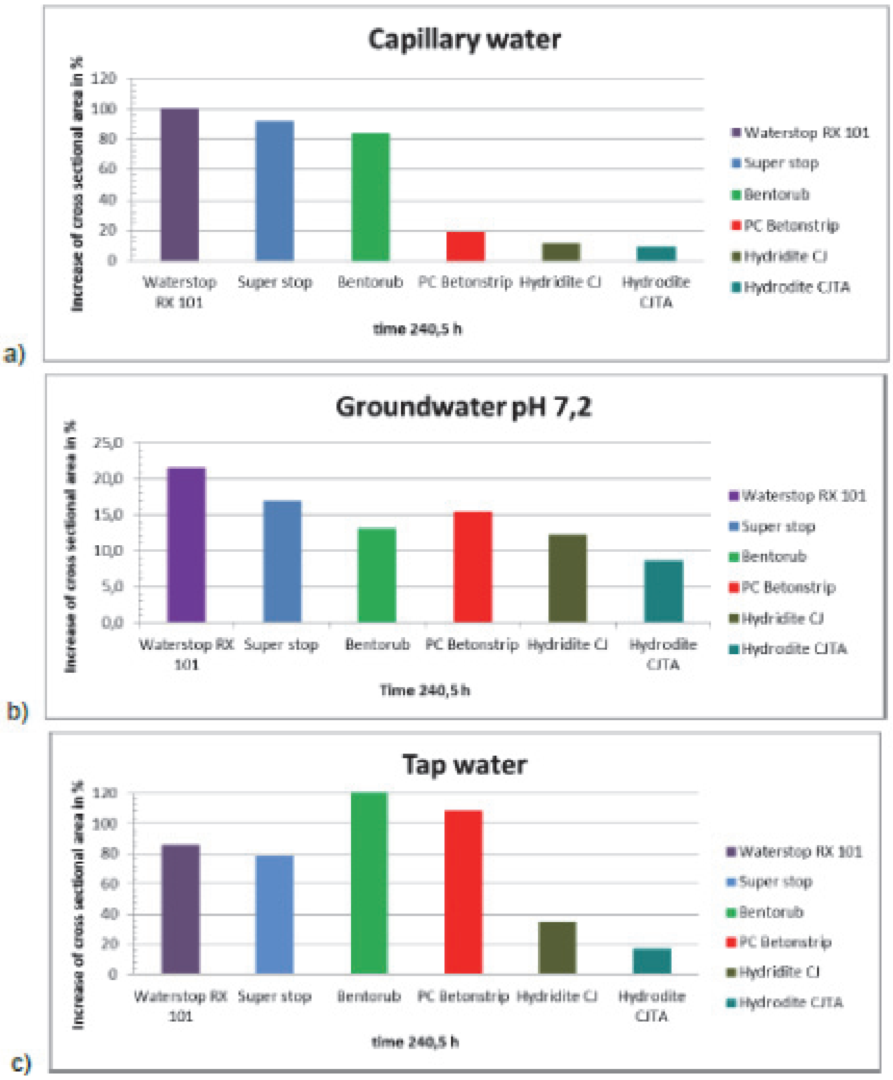


Figure 6. Cross-sectional area changes (%) after 240.5 hours in different environment solution, a) capillary water, b) groundwater, c) tap water.

As seen in Figure 6 and also in other photos below, the tape in groundwater had significantly lower (20% vs. 100%) potential to further swelling than tape in capillary water and tap water.

The visual appearance of the swollen tapes after 8 days immersion are presented below: capillary water (Figure 7), groundwater Figure 8) and tap water, (Figure 9).

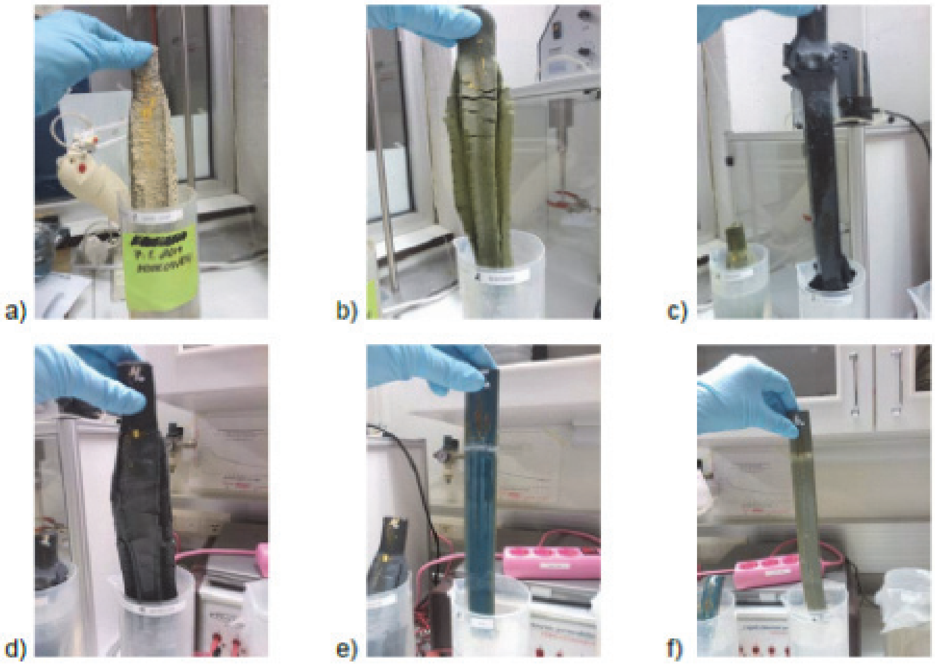


Figure 7. Bentonite tapes after 8 days immersion in capillary water: a) Superstop, b) Bentorub, c) PC Betonstrip,d) Waterstop RX101 e) Hydrodite CJ, f) Hydrodite CJTA.

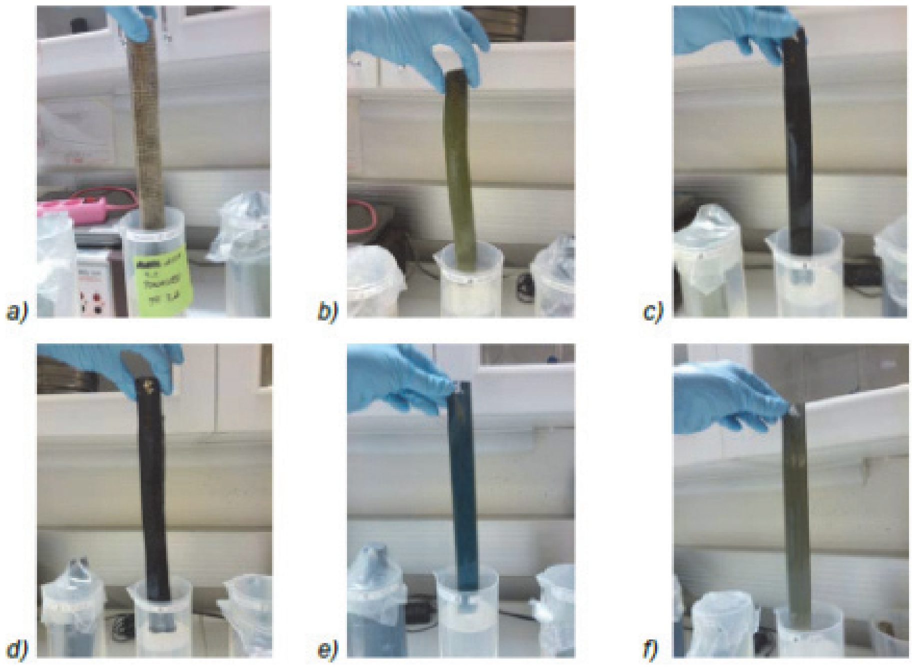


Figure 8. Bentonite tapes after 8 days immersion 8 in groundwater: a) Superstop, b) Bentorub, c) PC Betonstrip, d) Waterstop RX101 e) Hydrodite CJ, f) Hydrodite CJTA.

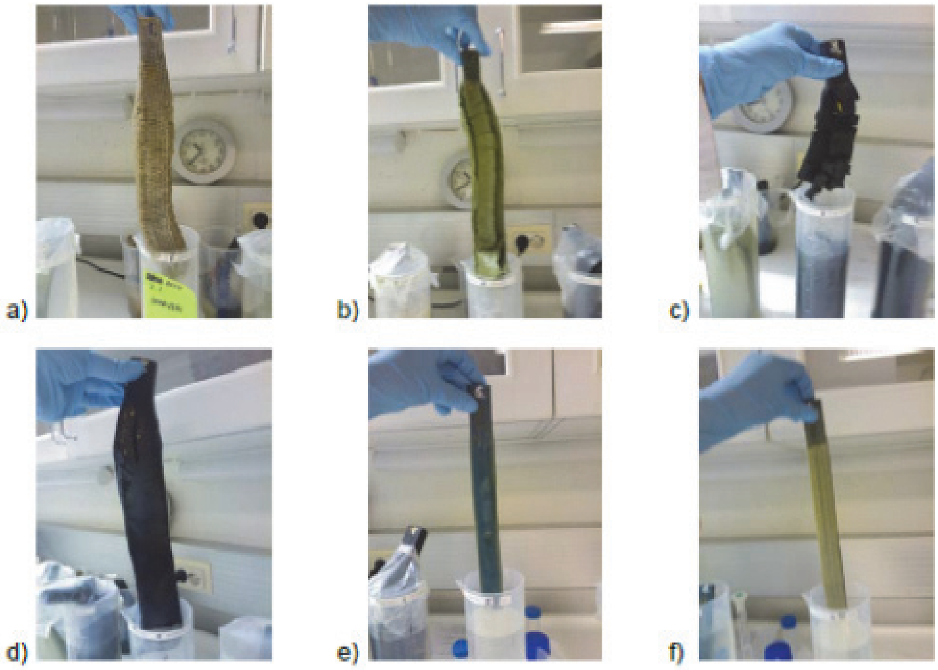


Figure 9. Bentonite tapes after 8 days in tap water: a) Superstop, b) Bentorub, c) PC Betonstrip, e) Waterstop RX101 f) Hydrodite CJ, f) Hydrodite CJTA.

The width and depth dimension changes (mm^2) during the tests in each solution can be seen in Figure 10.

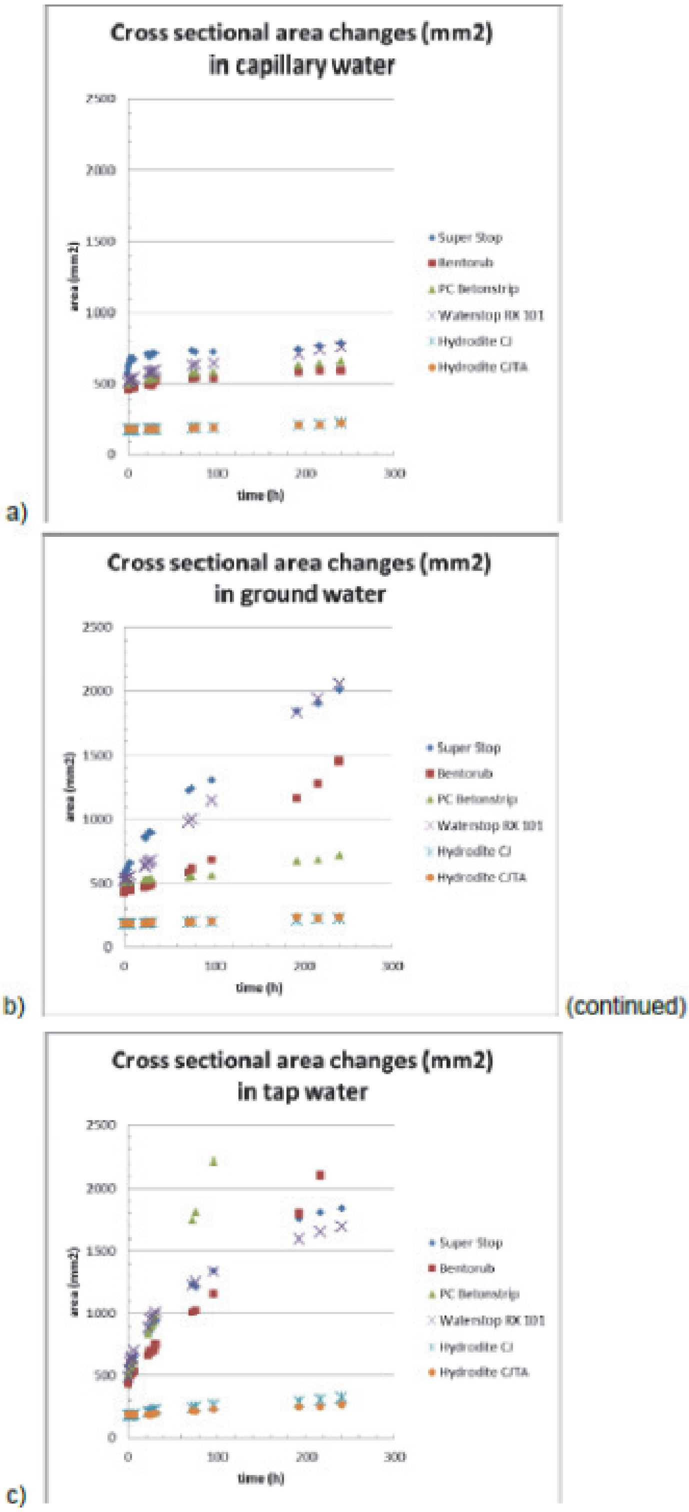


Figure 11. Dimension changes (mm^2) during the test in different solution, a) capillary water, b) groundwater, c) tap water.

5. Summary

The photographs of all samples' appearance after the whole test (37 days) are in APPENDIX 1. The next paragraphs give a short summary of all the bentonite tapes regarding how they react in different solutions during the whole test.

The Superstop tape did not swell so much in groundwater, approximately 17%, yet the groundwater rose inside the tape totally above the water level into the end of the tape. The Superstop tape swelled significantly more in the concrete capillary water (90%) and in the tap water (80%) but it swelled only in that part of tape that was immersed.

Bentrorub tape did not swell so much in groundwater when compared to other tapes, approximately 13% but after 2 weeks it started to slightly cracking. After the test the tape was "gummy" and it broke to two parts. In capillary water Bentorub tape started to break in tap water after 9 days and again more after 14 days. In general, the tape swells a lot in tap and ground water and may start to disintegrate after 1.5–2 weeks if exposed to a large amount of water.

PC-Betonstrip tape swelled in groundwater, approximately 15% and it broke in the middle part of the tape but it was still tough. In tap water it broke to two parts after four days and before that it swelled formlessly. In the end it crumbled total. In capillary water the tape broke after 15 days in the area above the water level. It withstood much more in concrete capillary water than tap water (100 % vs. 20 %). After the test the tape felt like plastic material.

Waterstop RX101 tape swelled in groundwater approximately 22%. After the test it felt stretchy and it attached in the surface of the graduated glass. In tap water after 9 days the swelling decelerate and the tape withstood the whole test only breaking a little on the sides of the bentonite. In capillary water it withstood the whole test without breaking but it cracked more on the sides of the tape than in tap water. After 15 days the swelling decelerated in capillary water and the tape felt rubbery.

Hydrodite CJ and Hydrodite CJTA withstood all water solutions, and had the least swelling compared to other tapes. The swelling rate decelerated slightly, after approximately 20 days in both tapes. After the test on the front surface of the CJ tape there was blistering in localized spots. The CJTA tape did not swell as much in tap water and groundwater compared to the CJ tape and in tap water both tapes swelled the most compared to other water types.

6. Conclusions and Recommendations

Six different bentonite tapes were evaluated in three different water types. All of the bentonite tapes were observed to swell. The swelling magnitude was different between the types of tapes, and especially the early age (first days) reaction rate was different. The reaction was also greatest in tap water compared to groundwater or capillary water.

The swelling effect on the crystalline rock to concrete plug interface is not a known situation according to instructions available from the manufacturers. It is possible that the use of swelling bentonite tape causes negative effects to plug tightness, for instance if it reacts poorly with the fresh concrete and causes a more accessible water path.

One potential mechanism considered was cracking during concrete setting, by swelling bentonite tape pressure. In the swelling study, it was observed that a quick and drastic volume change does not happen immediately after water exposure. Because the swelling is a slow process, it is unlikely that the above described mechanism damages concrete having normal strength development. However, the strength development of the concrete is very slow due to its special composition (low pH-concrete [Holt 2014]). For verification of the cracking risk, further tests based on the interaction of bentonite tapes and low-pH concrete are recommended.

Between tapes there are differences in properties depending on the tape material and environment in which the tapes are used. The bentonite tapes' swelling behaviour vary a lot depending on the solution they are exposed. Thus it would be important that before choosing any tape for real in-situ construction, more attention should be given to understand what the final assembly conditions are.

There are several open questions which are in need of further investigation and testing:

1. Will the concrete hydration be affected by the bentonite tapes, which could cause e.g.an increased permeability? The uptake of available water might cause the concrete surrounding the tape to be impaired in its hydration and thus will have a higher porosity which in turn could cause a flow path for the pressurized water.

2. Does the tape withstand the pressure of injection grouting? The tape swelling requires water and needs several hours or days to take place. The grouting process and thus the grouting pressure increase is quick. There is a risk that the tape is dislocated or ruptured by the grout penetrating the interface.

3. How is the long-term performance (e.g. after several years) of the bentonite tape? How does that tape react to changing humidity or water content in its surrounding, as well as to potentially flowing water?

It is also noted that the decision about what type of bentonite tape to use should be considered together with the ONKALO foreign materials acceptance review, based on the material composition of the tapes. There may also be other tapes available on the Finnish or international markets, which were not reviewed in this preliminary study. The cost of the bentonite tapes should not be considered when evaluating the selection.

References

Hansen, J., Holt, E. and Palmu, M. 2013. DOPAS: Full scale Demonstrations of Plugs and Seals. in Proceedings of the Euradwaste '13 conference by European Commission held in Vilnius, Lithuania 14-16 October, 2013.

Holt, Erika; Dunder, Jari. 2013. Detailed design of POPLU deposition tunnel end plug. DOPAS project Deliverable Report D3.24. Posiva Oy, Eurajoki, 13 p.

Holt, Erika. 2014. POPLU concrete test memorandum: Concrete mix design and performance study. DOPAS project Deliverable Report D3.27. Posiva Oy, Eurajoki, 34 p.

Posiva. 2012. Backfill Production Line 2012. Design, production and initial state of the deposition tunnel backfill and plug. Posiva Report 2012-18, Posiva Oy, Eurajoki, 182 p.

Vehmas, Tapio, Leivo, Markku. 2015. POPLU Concrete mix design and performance study, VTT Research Report VTT-R-00571-15, Espoo, 41 p.

Vuorinen, U., Lehikoinen, J., Imoto, H., Yamamoto, T., Alonso, M. C. 2005. Injection Grout for Deep Repositories. Subproject 1: Low-pH Cementitious Grout for Larger Fractures, Leach Testing of Grout Mixes and Evaluation of the Long-Term Safety. Posiva Working Report 2004-46, Posiva Oy, Eurajoki, 101 p.

Acknowledgement

The research described within this report has received funding from the European Union's European Atomic Energy Community's (Euratom) Seventh Framework Programme FP7/2007-2013 under Grant agreement no. 323273 for the DOPAS project (2012–2016).