Instrumentation And Monitoring Systems For Evaluation Of Plug Responses In Geological Disposal Demonstrations

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Three of the five demonstration plugs within the DOPAS project had extensive monitoring systems installed to evaluate material and structural performance. The massive full-scale tunnel end plugs were placed in-situ and their performance was evaluated for both the early- and late-ages. The evaluated properties included aspects of concrete hydration, such as temperature rise, as well as any potential responses of the structure and materials to accelerated pressurization to simulate the design-life. Concrete structural monitoring includes properties such as strain and displacement, while the total and water pressure are evaluated behind and around the plug, and in some cases within a bentonite clay layer. The selection of monitoring systems, including both sensors and data collection, has provided insight which can be utilized in various other applications for material performance in challenging environments.

1 Background

Instrumentation and monitoring of performance of engineered barrier systems (EBS) are often an integral part of demonstration of safety of a repository. Monitoring of experiments, from lab-scale to full-scale in-situ demonstrations, help establish protocols for understanding material evolution and risks. The inputs from monitoring are used for conformance assessment compared to requires and provide feedback to the design basis. Information gained from monitoring of demonstrations such as DOPAS is also used to develop strategies for subsequent monitoring during the operational phase of a repository [Posiva 2009, Posiva 2012].

The plug monitoring and instrumentation plans developed within DOPAS have built upon the experiences gained in other recent demonstrations, such as Posiva's medium-scale buffer test [Hakola 2015], the Dome Plug test by SKB [Grahm et al. 2015] and Mock-Up-Josef by CZ [Šťástka 2011]. The design of monitoring systems for the DOPAS experiments required high durability to extreme underground environments. Many of the requirements of the monitoring systems can also be representative of future operational repository demands.

2 Scope and Objectives

2.1 Monitoring System Requirements

The relative humidity in the tunnels can be close to 100 % and the temperature is nearly constant at +10 to 12 °C. The maximum pH-value inside the concrete and back structure can be around 11 due to the use of low-pH cementitious materials. The material of sensors and cables should highly resist corrosion and therefore be made of stainless materials, e.g. copper, stainless steel or titanium.

The water pressure within the POPLU and DOMPLU demonstrations was defined to be up to 10 MPa. Since in the operational use of a deposition tunnel the maximum pressure will raise slowly, the pressure uptake in this demonstration experiment was accelerated by means of high pressure pumps. The sensors and cables needed to be covered by protection pipes where possible. The high pressure with a maximum of 10 MPa will be gradually decreased from the back to the front face of the plug and reaching 0 MPa at the front part of the plug. On the other hand, deficiencies in the sealing system and possible cracks in the rock mass and concrete can raise the water pressure almost to its maximum and therefore the cables of pressure sensors in the gap between the plug and rock have to be sheltered.

During the concrete casting phase, the sensors needed to be protected from concrete vibration work, by installing them as far as possible from vibration alleys and sheltering them with protection tubes. During the hardening and cement hydration process of the concrete, the temperature can raise up to 60 °C, which is usually not a limitation for normal types of sensors.

The high water pressure can damage the sensors, but it can also penetrate to the cables and connections. The cables are selected to resist high pressure, but also to pass through the lead through flanges to prevent any leakage through the wire or on the surface of the wire. Since the concrete shrinks after the casting phase, the wires are sealed against possible water leakage using different methods (e.g. small bentonite belts around cables, flanges, sealing of sheltering pipes).

The duration time of the DOPAS plug tests was assumed to be about 5 years and most of the sensors, cables and connections cannot be replaced or maintained during operation. Therefore they needed to be durable enough to be in constant function without service or maintenance for the entire operation time. Almost all sensors will be installed permanently inside the structure (inside the concrete plug, inside rock or inside bentonite clay) and therefore they needed to work reliably without any calibration during the entire test duration. A post calibration may be possible on a few sensors later on, during the decommissioning phase after the test has been stopped. Additionally, special concrete specimens with embedded sensors will be produced parallel to the casting of the plug and stored inside ONKALO to enable calibration of sensors after the test.

For the POPLU case, all materials used in the instrumentation and monitoring program needed to be pre-approved by Posiva regarding foreign materials used in ONKALO, so as to ensure the environmental safety of the site.

2.2 Monitoring System Components

The monitoring system for the plugs consisted of multiple components, which are each described here with their constraints. All components need to be calibrated prior to installation. They are typically assembled and subjected to a test run in laboratory conditions prior to on-site installation to the demonstration.

The plug sensors are selected to measure properties of the materials and structure during the concrete casting, the hydration process and finally the pressurizing phase. During and after the casting phase the pressure, humidity and temperature of the concrete are measured. In the pressurization phase, both the concrete condition and performance are measured by displacement sensors and strain gauges. Subsequently, the measurement results are compared to the structural behaviour of the plug and the surrounding rock mass. Sensor data provides feedback to design and modelling.

The sensor wires and sheltering are placed inside the concrete plug, in the gap between the rock and plug and in the different layers behind the plug. The sensor wires and their sheltering cables or tubes are selected to resist mechanical forces and high pressure. Water is not allowed to penetrate inside the cable, but should also not permeate using flow paths on the surface of the cables. The wires can pass through lead through flanges that prevent water leakage out of the structure. The wire and sheltering connects are critical for watertightness.

The data collection equipment, were designed based on sensor quantities and types. The measurement equipment should be suited for slow sample rate measurements over a long time period. Durability and redundancy aspects are also taken into consideration during the design of the system. Data collection is done from measurement computers, the main computer, IP cameras and the data loggers. Data can be downloaded on-site or can be connected to a local area network for transfer to a remote database.

The pressurization system used in some of the DOPAS experiments was to provide high water pressure simulating hydrostatic pressure and bentonite swelling. The pressurizing equipment should work reliably and keep the adjusted pressure behind the plug at various levels and rates. A pressurization system has main components such as two pressure piston pumps, two unloader valves, two electrical motors with gearing box, thyristors with automation and control units, electric centre, water tank, manifold connection pipes and main frame.

The near field monitoring of the plug includes assessment of leakage water volumes and chemical composition passing through the plug or rock fractures of the demonstration area. It can also include additional sensors placed in boreholes in the rock adjacent to the plug demonstration area. Such borehole monitoring can include water pressure, water leakage volume and chemical composition, temperature, strains and dislocations of the rock mass. The water used in pressurization can be marked with a tracer, such as sodium fluorescein, to evaluate the flow paths.

3 Methods

In all experiments, sensors were located in positions anticipated to have the greatest response. For instance, temperature sensors were placed at the centre point of the concrete that would have the greatest heat due to cement hydration during curing. Total pressure sensors were located along the plug circumference at the rock interface which could be subjected to leakage water. The sensor locations were planned in conjunction with the structural designers and modelling. Sensors were installed throughout the plugs' construction sequence. Sensors were attached to rock and reinforcement using tie wire and nails. Wiring and protective shielding were simultaneously connected and fed via lead-through pipes. Installation proved challenging and in some cases added complexity to the construction process, for instance by necessity to avoid creating of shadows due to obstacles created by monitoring equipment for the sprayed concrete in EPSP. The following sections give a short overview of the monitoring system locations, though more details can be found in project deliverables.

3.1 POPLU Experiment

The design of the monitoring system for POPLU is described in the Deliverable D3.25 [Hakola 2014]. POPLU's monitoring system had 141 sensors installed within the backwall, filter layer and plug section. The monitoring system of the tunnel backwall, filter and plug section one was routed 8 metres through the bedrock to the neighbouring tunnel (Demonstration Tunnel 3), while the monitoring system from the plug section two was fed via lead-throughs the front face of the plug in Demonstration Tunnel 4 (as seen in Figure 1).

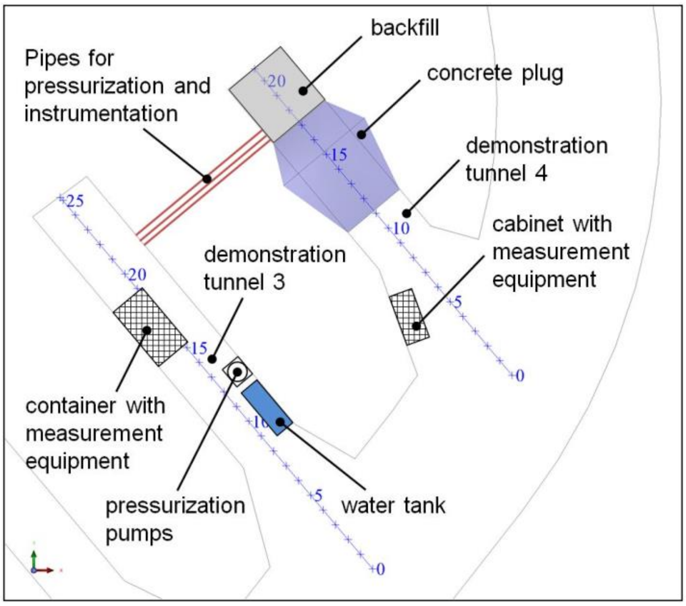

Figure 1. Top view of POPLU monitoring system arranged in demonstration tunnels 3 and 4, including pressurization system and data collection measuring equipment.

3.2 DOMPLU Monitoring

The design of the monitoring system for DOMPLU is described in the Deliverable D4.3 [Grahm 2015]. DOMPLU's monitoring system had 38 sensors installed in the concrete dome. In addition 45 sensors were installed within the backfill, the bentonite sealing and the filter layers. The monitoring system of the sensors positioned inside the bentonite sealing was routed 21 metres through the bedrock to a neighbouring tunnel niche, while the monitoring system from the sensors in the concrete dome was fed directly through the front face of the plug. The cables from a few sensors, positioned in the slot for the dome, were routed in a special lead-through in the front face of the plug. Figure 2 shows an overview of the experimental tunnel and the lead-throughs drilled to the neighbouring niche. The two uppermost lead-throughs were used for cables from sensors installed on the downstream side of the bentonite seal while the bottom lead-through was used for water pressurization pipes.

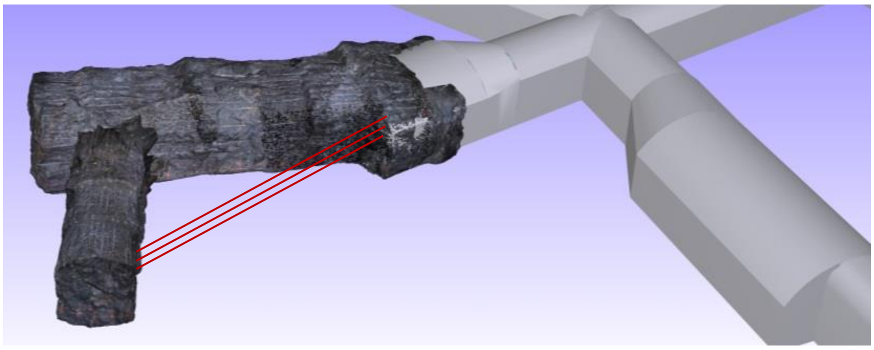

Figure 2. Left: Sketch of the three lead-through pipes going from the experimental tunnel,. b) photo of the lead-throughs inside the experiment tunnel.

3.3 EPSP Monitoring

The design of the monitoring system for EPSP is described in D4.7 [SÚRAO 2016]. EPSP's monitoring system had over 130 sensors installed within the backfill, filter layers, plug section and rock. To prevent possible longitudinal preferential path along the cable through the experiment, all sensors were connected via 23m long cased boreholes to the data loggers in the adjacent niche where all technology was installed. All the cabling was protect using stainless steel tubes inside the experiment. The set-up of the monitoring system in shown in Figure 3.

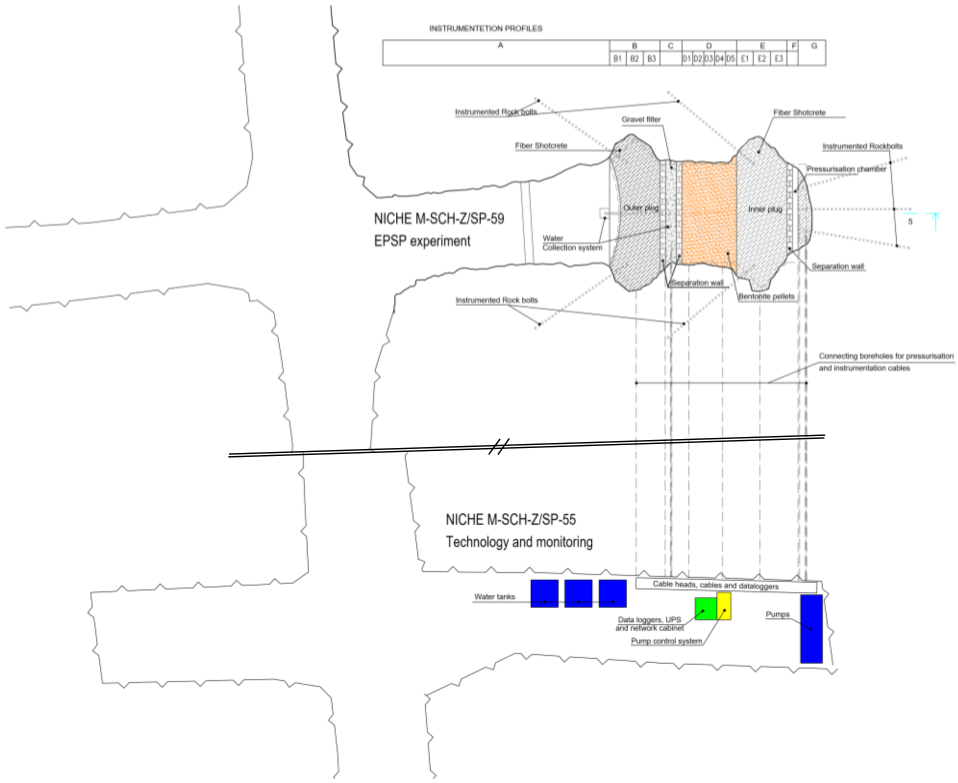

Figure 3. Top view of EPSP monitoring system arranged in SP59+SP55, including pressurization system and data collection measuring equipment.

4 Results and Discussions

Almost all of the installed sensors in the concrete plugs have worked successfully and captured the behaviour from before casting through pressurization. Monitoring of temperature, relative humidity, total pressure, pore pressure and displacement within the three experiments has demonstrated performance consistent with most of the design specifications. For example, the hydration temperatures during concrete casting have helped regulate the cooling system of DOMPLU and the formwork removal times in all experiments. Pressure sensors have shown the saturation level of bentonite clay within EPSP. Displacement sensors have shown the wedging effect of POPLU due to high pressurization. The work in the DOPAS experiments has demonstrated some of the complexity in installing monitoring systems, with complex routing of wires required, issues arising with unexpected electromagnetic fields underground (generated in other experiments and other equipment used in ONKALO) and the need to check compatibility between sensors and data loggers.

There have been challenges with the monitoring system, which can be used as learned experiences for future EBS and repositories, and for other applications' complex monitoring scenarios. For instance, after grouting of the plug to rock interface, some sensors have failed as a result of the increasing water pressure. This was also as expected, since some of the concrete-related sensors were not designed to withstand the water pressure and contact with water was not always anticipated in some locations around the plug. During the build-up of pressure behind the plugs, all three experiments saw water-bearing fractures opened in the rock and leakage in the near field. Water pathways were also created in the concrete plugs themselves via some of the wiring cable bundles and thus leakage was measured independent of the plug watertightness. However, owing to the swelling of the bentonite seal layers and bentonite tapes, water leakages have decreased over time in all experiments.

The performance of all three plugs as detected from the monitoring systems has mostly been consistent with modelling predictions, providing confidence in the modelling and its application for detailed design of repository plugs. A parameter-by-parameter evaluation of the sensor components of the monitoring systems for each experiment is detailed in DOPAS Deliverable D4.4 [White 2016].

5 Conclusions

Monitoring systems were designed to assess plug performance based on properties of temperature, relative humidity, total pressure, pore pressure, strain and displacement of the concrete, clay and rock. The monitoring system was composed of sensors, wires and shielding, data collection systems, pressurization systems and near field monitoring including leakage assessment. In general, the monitoring systems of POPLU, DOMPLU and EPSP have performed well, and have been used to evaluate the performance of the experiment with respect to design specifications. The systems were designed and installed based on past experiences, including improvements to aspects especially related to watertightness for the extreme environment associated with pressurization. Monitoring results have fed back to the design basis and form an integral part of repository safety demonstration. The DOPAS monitoring system design and experience can also be utilized in various other applications when evaluating material performance in challenging environments.

6 Acknowledgements

We grateful acknowledge the many researchers, engineers and contractors who assisted in planning, calibrating, installing and interpreting results from the monitoring systems in the DOPAS experiments.

The research leading to these results 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, the DOPAS project. Complimentary funding provided by partner organization of Posiva, SKB, CTU and VTT which have contributed to the results in this paper are also acknowledged.

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