Instrumentation and Monitoring of Tunnel Plug in ONKALO – 14261

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ABSTRACT

Posiva Oy has established a monitoring program that ensures the applicability of the constructed facilities to the final disposal of nuclear waste and the long-term capacities of engineered barrier systems. A monitoring system for a full-scale demonstration is installed to a tunnel end plug being built in a demonstration tunnel in the bedrock of Olkiluoto in Finland. The concrete plug will be instrumented with sensors continuously measuring displacements, strain, humidity, total and pore pressure and temperature. Further sensors will allow for monitoring the pressure being applied in a filter layer behind the plug and the observation and control of the main parameters needed during the pressurization of the structure by pumping water behind the plug. The general idea is to carefully measure the amount and pressure of incoming water in order to analyze the performance of sealing mechanisms of the structure. The out-flowing leakage and in-pumped water will also be determined by a monitoring system.

INTRODUCTION

Posiva Oy will demonstrate the full-scale construction and performance of a demonstration tunnel end plug during 2014. Within the project called POPLU a concrete plug will be built at the ONKALO underground rock characterization facility which separates the demonstration tunnel from the vehicle connection. The full details about the plug design, materials, modeling and monitoring is presented in [1]. POPLU is part of the EU project called DOPAS – Full Scale demonstrations of Plugs and Seals [2]. The plug demonstration is to fulfill the YJH-2012 plans [3] to:

- Construct a full-scale demonstration tunnel end plug (demonstration, workmanship, quality control)
- Develop detailed structural design, including concrete recipe development for plug
- Develop tunnel plug location excavation, with attention to the wire-sawing technique
- 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.

The plug structure is placed in a 20 m long demonstration tunnel and consists of the concrete structural element, along with the filter layer and the concrete backwall behind the plug. There is no bentonite backfill in this test. The design of Posiva’s plug consists of the structural design as well as a low-pH concrete and reinforcement steel used within the plug. The low-pH grout material and bentonite tape used as sealing between the plug and the host rock is also included.

In order to simulate the 100 year expected lifetime of the plug, an artificial pressurization routine is conducted. Water behind the plug exerts pressure on the plug, simulating an anticipated pressure of approximately 7.5 MPa during the lifetime of the demonstration tunnel end plug.

The goal of the POPLU project is to establish the methodology that will be used for designing and carrying out the instrumentation and monitoring of the plug. The instrumentation includes sensors in the concrete, behind the plug in the filter layer and in the concrete backwall at the end of the demonstration tunnel. The monitoring system includes aspects of the pressurization system, lead-through pipes, leakage measurement, and data acquisition system.

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

- Displacement of the plug (mm)
- Strain of reinforcement and concrete (-)
- Humidity of concrete (RH%)
- Pressure between the rock and the plug (MPa)
- Pressure in the filter layer (MPa)
- Temperature of the concrete (°C)
- Water leakage through and around the concrete plug (liters/hour).

The water leakage will be measured from the front plug face, as well as monitoring the potential impact to the surrounding areas such as leakage in other demonstration tunnels (near field assessment). The main idea of the filter layer monitoring behind the plug is to study the axial force to the concrete plug as a result of the applied water pressure.

Instrumentation and monitoring of the demonstration tunnel end plug is part of Posiva's overall monitoring concept, which includes a new discipline of monitoring the engineered barrier systems (EBS), concentrating on research and development of the monitoring techniques, methods, and strategies needed for the subsequent monitoring during the operational phase of the repository [4, 5]. The plug monitoring and instrumentation plan builds upon the experiences gained in the other ONKALO demonstrations that have been earlier conducted, such as the medium-scale buffer test [6]. In general, the monitoring should strengthen confidence in long-term safety, which is the key objective of radioactive waste disposal.

PLUG LOCATION

The plug is constructed in the ONKALO demonstration area 420 meters below ground. Two plug demonstration tunnels 3 and 4 were excavated at the end of 2013. Tunnel 4 was chosen to be suitable for the wedge-plug design (for further details see [1]) based on Posiva's rock suitability classification methodology [7]. There is no water leakage from fractures within the demonstration tunnel containing the plug structure. No tunnel surface rock bolting or grouting has been done in the plug location. The dimensions of the tunnels are 4.35 meters height by 3.5 meters wide, with an area of approximately 14.5 m^2, which are the same as in previous demonstration tunnels. The exact location of the plug slot is being excavated at the end of 2013 and early 2014.

One tunnel will contain the concrete plug (demonstration tunnel 4) and the second tunnel will contain the monitoring and pressurization equipment (demonstration tunnel 3), as shown in Fig. 1. The plug emplacement via concrete casting is scheduled for May 2014, with monitoring equipment to be installed in March and April 2014.

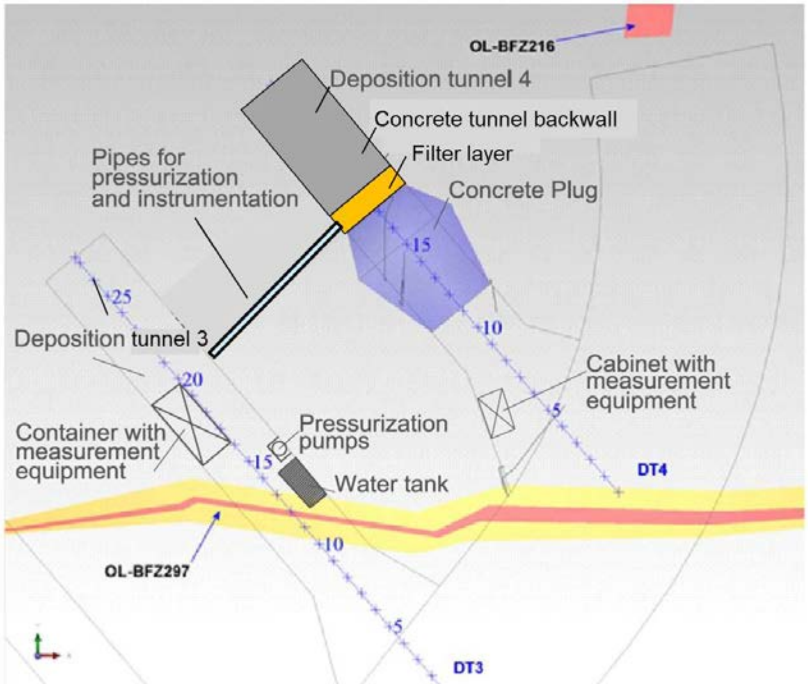

Fig. 1. Horizontal section of the demonstration tunnels 3 and 4 with the concrete plug, the measurement and pressurization equipment. Note that OL-BFZ297 indicates a brittle fault zone in the rock.

Three boreholes, each with a length of about 8.0 meters are connecting the filter layer behind the plug in demonstration tunnel 4 with the pressurization system and measuring devices in tunnel 3. Inside the boreholes there are pipes closed at their ends with lead through flanges for sheltering the sensor wires and providing inflow of water to the filter layer and outflow of air. Further lead throughs pass the concrete plug and connect the filter layer with the tunnel in front of the plug. The lead through design is optimized using 3-dimensional numerical models based on the finite element method.

The structural design of POPLU plug is a wedge plug (see Fig. 2). It is a reinforced concrete structure with a height of 4.35 to 6.35 meters and a width of 3.30 to 5.50 meters. The length of the plug is 6.00 meters. The concrete is cast in two parts, each being 3.0 meters in length. The tunnel behind the plug hosts a filter layer to guarantee a uniform distribution of the water and a concrete backwall. It was decided that there is no bentonite backfill in this demonstration.

The plug is expected to be extremely tight against the rock due to mechanical forces resulting from the water pressure. The wedge-shape is generated by designing a 1000 mm deep circumferential groove in the tunnel rock locking the plug in place. The watertightness of the plug shall be as high as possible, allowing only minimum 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 potential level of connectivity.

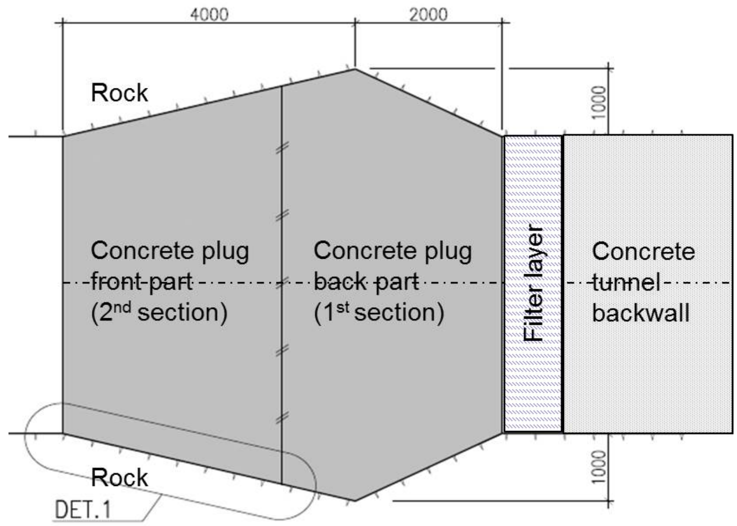

Fig. 2. Vertical section of Posiva's wedge plug (dimensions in mm) [1].

Due to concrete shrinkage, the gap created between the plug and rock will need to be filled with injection grout to make the plug as watertight as possible. The shrinkage and tolerances of the excavated tunnel rock surface also result in an uneven and possibly unpredictable gap size. Grouting with cementitious low-pH mortar into this gap seals the plug, and fills possible cracks of the rock and minimizes the paths for potential leakage.

REQUIREMENTS FOR THE INSTRUMENTATION EQUIPMENT

The relative humidity in the tunnel is close to 100% 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 therefore be made of stainless materials, e.g. copper, stainless steel or titanium.

The water pressure within the demonstration is defined to be up to 10 MPa. Since in the real use of a deposition tunnel the maximum pressure will raise slowly, the pressure uptake in this demonstration experiment will be accelerated by means of high pressure pumps. The sensors and cables will 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 pressure sensors in the gap between the plug and rock have to be sheltered.

During the concrete casting phase, the sensors will be protected from vibration work, by installing them as far as possible from vibration alleys 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.

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.

The duration time of the plug test is more than 5 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 time. Almost all sensors will be installed permanently inside the structure and therefore they have to work reliably without any calibration during the entire test duration. A post calibration may be possible on a few samples later on, during the decommissioning phase after the test has been stopped, prior to repository operation.

DATA COLLECTION EQUIPMENT

The design of the data collection equipment is based on sensor quantities and types. The total amount of sensors is about 65 pieces in the concrete and about 10 in the filter layer. The measurement equipment is suited for slow sample rate measurements over a long time period. Durability and redundancy aspects were also taken in consideration during the design of the system.

The measurement chain including the sensors is thoroughly tested and calibrated prior to installation. Calibration of the sensors measuring the total pressure and the pore pressure may require design and construction of a special pressurized calibration environment.

Measurement Equipment

The main measurement device is a data logger with up to five channel required extension modules. It can handle the reading of all the pressure sensors as well as the strain gauges and thermocouples. The logger has a capability of sending the measured values directly to a remote FTP server as well as saving them to its internal memory. This adds redundancy to the measurement system and removes the need of a separate computer to control the data logger.

Optional wireless sensors will be connected to a separate industrial grade computer, which handles the reading of measurement values from the wireless receiver. The measurement files will be stored on this computer as well as on the main computer or a separate network attached storage (NAS). Also the humidity sensors can be handled with the same computer.

The water collection data acquisition will be implemented with a special data logger. This device is selected because of direct and easy implementation of water collectors directly to the logger. The pressurization system has a need for fast real-time measurements and this is why the above mentioned data logger cannot be used. Data from each of these separate systems is transferred to the FTP server and combined in the main computer.

Measurement Equipment Connections

The measurement equipment is connected to a small local area network including the measurement computers, the main computer, IP cameras and the data loggers. In addition the main computer is connected to the Posiva network which enables the data to be transferred to a remote database above ground in ONKALO.

Posiva provides a separate control room facility (see Fig. 3) for a remote desktop connection to the measurement system. This facility is above ground with a network connection to the main computer of the measurement system. It enables the configuration of the devices without the need to go underground and allows for a real time view of the test facility from the IP surveillance cameras.

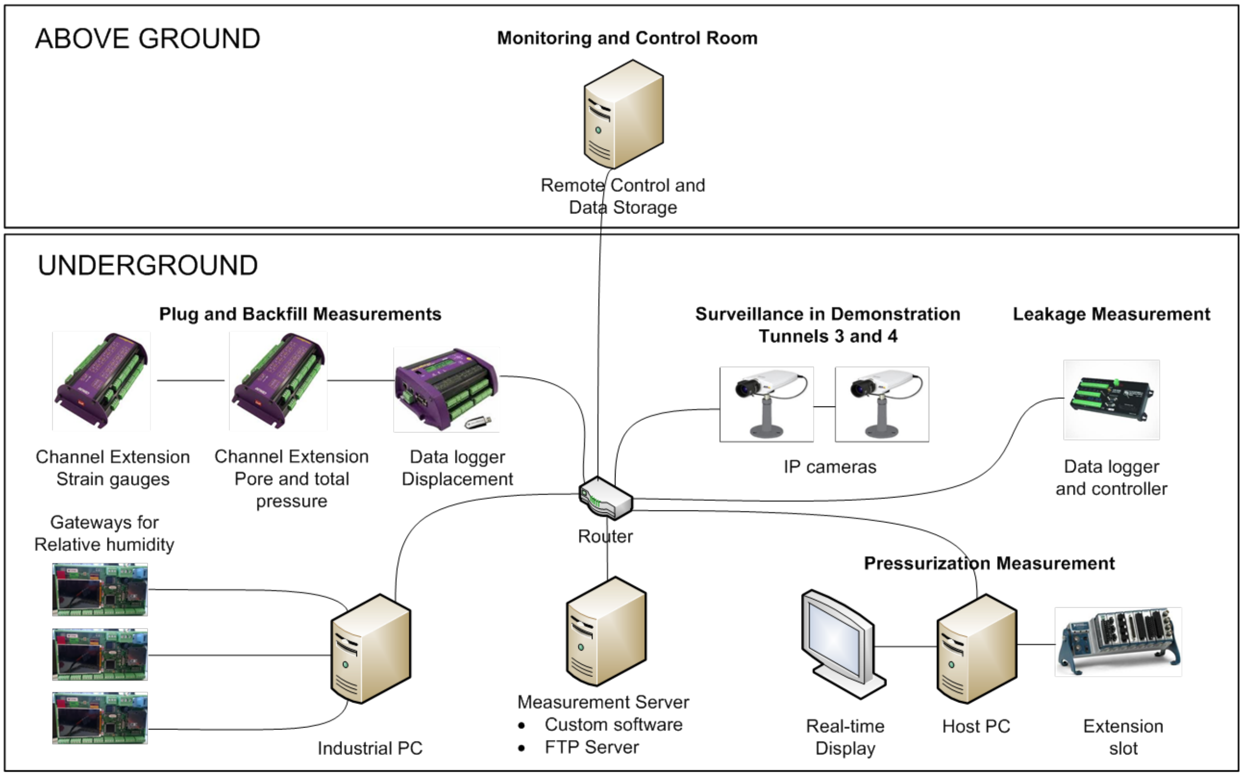

Fig. 3. Local area network including measurement server and computers, IP cameras and data loggers underground and a control room facility for a remote desktop connection to the measurement system above ground.

The data from the loggers and measurement computers is transferred to an FTP server running on the main computer or a separate NAS. The same procedure can be implemented on the computer reading the wireless system and the humidity sensors. The main computer runs a routine to combine the data from the different systems. The data is added to an Access database as well as Posiva's own database.

The data collection systems had also been designed for future in-situ engineered barrier system experiments and for comparing and visualizing measured data-series.

PLUG SENSORS

General

The plug concrete will be cast in two phases. First the back part of the plug will be made and after required hardening time, the formwork will be removed and the second part will be casted, approximately two weeks later. The plug sensors will be fixed in both parts of the plug after installing the formwork frame and steel reinforcement.

The sensors are selected to measure 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 will be 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 behavior of the plug and the surrounding rock mass being thoroughly investigated by 3-dimensional numerical modeling based on the finite element method. Examples of the modeling results that were done by Finnmap Consulting (FCM Group) are shown in Fig. 4.

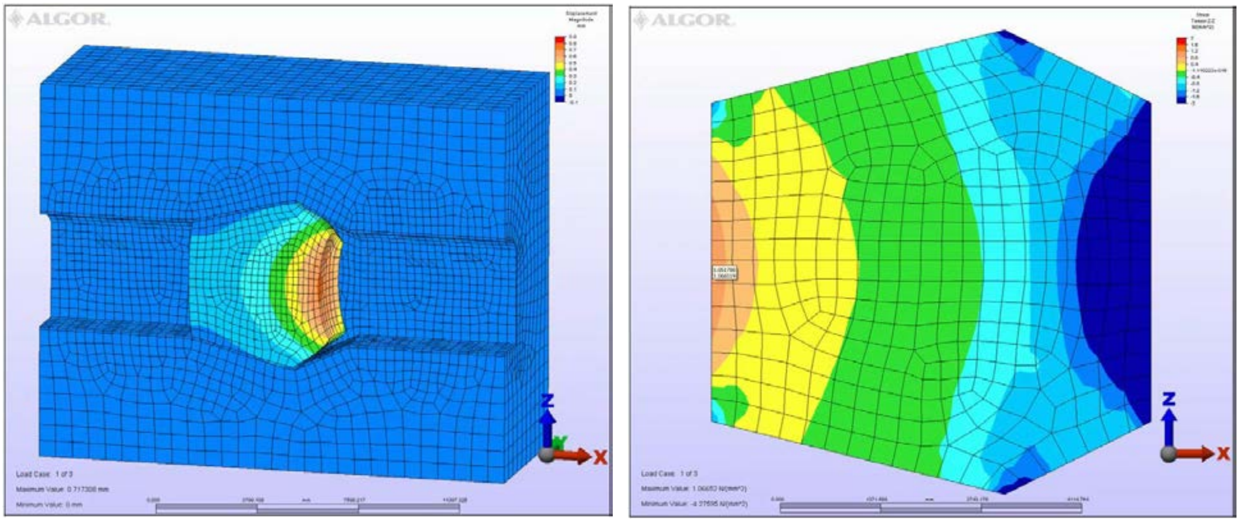

Fig. 4. Displacements (left) and principal stresses (right) in vertical direction (z-direction) due to hydraulic pressure on the back face of the plug.

Displacement Sensors

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 plug is a massive reinforcement concrete structure, which is assumed to behave rigidly with no deformations and therefore the global movement can be calculated according to the front surface displacement. The sensors are located outside the plug and are easy to install and have been selected for a relative humidity of up to 100%. According to the plug strength analysis for the pressurization phase the maximum displacement of the plug is below 1 mm in both the radial and axial directions. 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, two displacement sensors will be installed on the back part of the plug to ensure the plug movement in horizontal and vertical directions. The back face sensors have been selected to resist the high water pressure of about 10 MPa.

The axial location of plug is measured as part of the near field monitoring, at a distance of some meters to the front of the plug. The displacement sensors in the front and back face of the plug are shown in Fig. 5. The wires of the back face sensors are directed to the lead through flanges located in the tunnel wall beside the filter layer, from where they run through pipes inside the rock mass and connect the data loggers situated in a container in the adjacent demonstration tunnel.

Strain Gauges

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 (see Fig. 4).

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 parts of the plug and no gauges will be installed in the center of the plug, where no high strains are expected to appear. The sensor locations are selected in compliance with the structural design to allow for an easy comparison between the measured and calculated strains. Fig. 5 shows the locations of strain gauges.

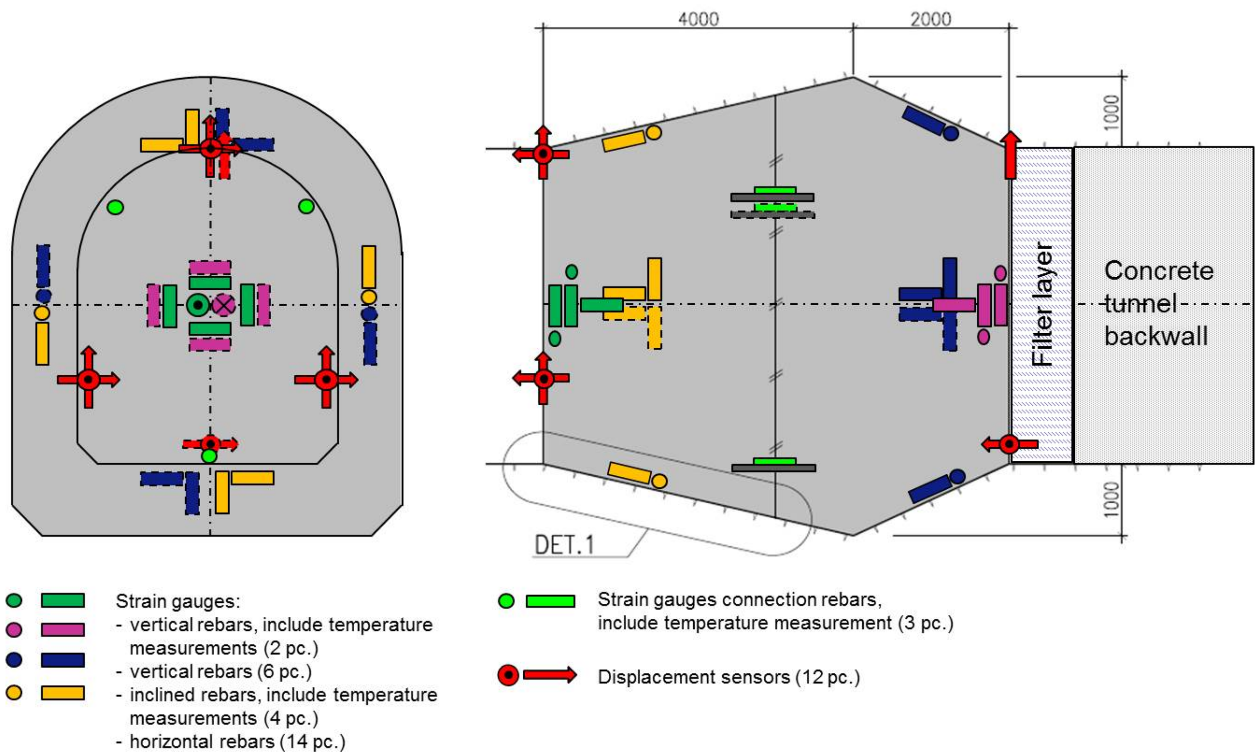

Fig. 5. Locations of displacement sensors at front and back face of the plug and strain gauges inside the plug.

In addition, three extra rebars with a length of approximately 1.0 meter are selected to be installed in the middle part of the plug. The strain gauges are fixed on each rebar to indirectly measure the possible displacement of the two plug parts in the axial direction. The extra rebars will be fixed to the formwork before casting of the first plug part.

Relative Humidity Sensors

The hardening process of the concrete used for the construction of both parts of the plug will be investigated by means of two relative humidity sensors in both the front and back parts 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 center of the plug parts, where the hydration heat is highest and influences from outside are weakest, and the corner points of the plug parts, where possible changes of the relative humidity might occur after a certain time due to migration of water into the concrete during the pressurization phase. The locations of relative humidity sensors are shown in Fig. 6.

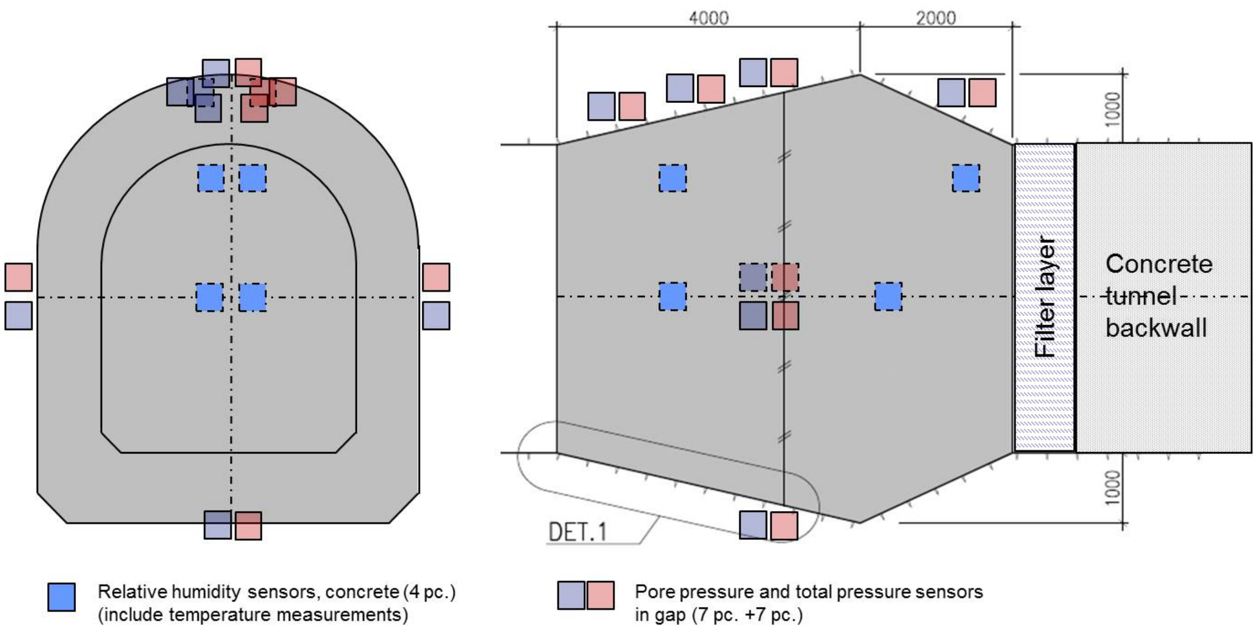

Fig. 6. Locations of relative humidity sensors inside the plug as well as total and pore pressure sensors around the plug.

Pressure Sensors between Rock and Plug

Two types of pressure sensors will be installed to show both the pore pressure (pressure corresponding to the water pressure) and the total pressure in the gap between the rock and plug during the pressurization phase. The pore pressure and 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 inhomogeneities of the rock, the pressure and leakage can be different for various locations around the plug, e.g. in top and low surfaces. The locations of total pressure and pore pressure sensors are shown in Fig. 6.

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 will be measured on the front faces of the two plug parts by thermocouples with an accuracy of 0.5 °C. The sensors will be removed after removing of the formwork. In addition, some other installed sensors, e.g. strain gauges and relative humidity sensors, will also allow for temperature measurements. These sensors are used for temperature monitoring during the pressurization phase, if slight changes of temperature occur.

Fig. 7 shows both the locations of the thermocouples placed at the front faces of the two plug parts and also the locations of other sensors, which enable temperature measurements.

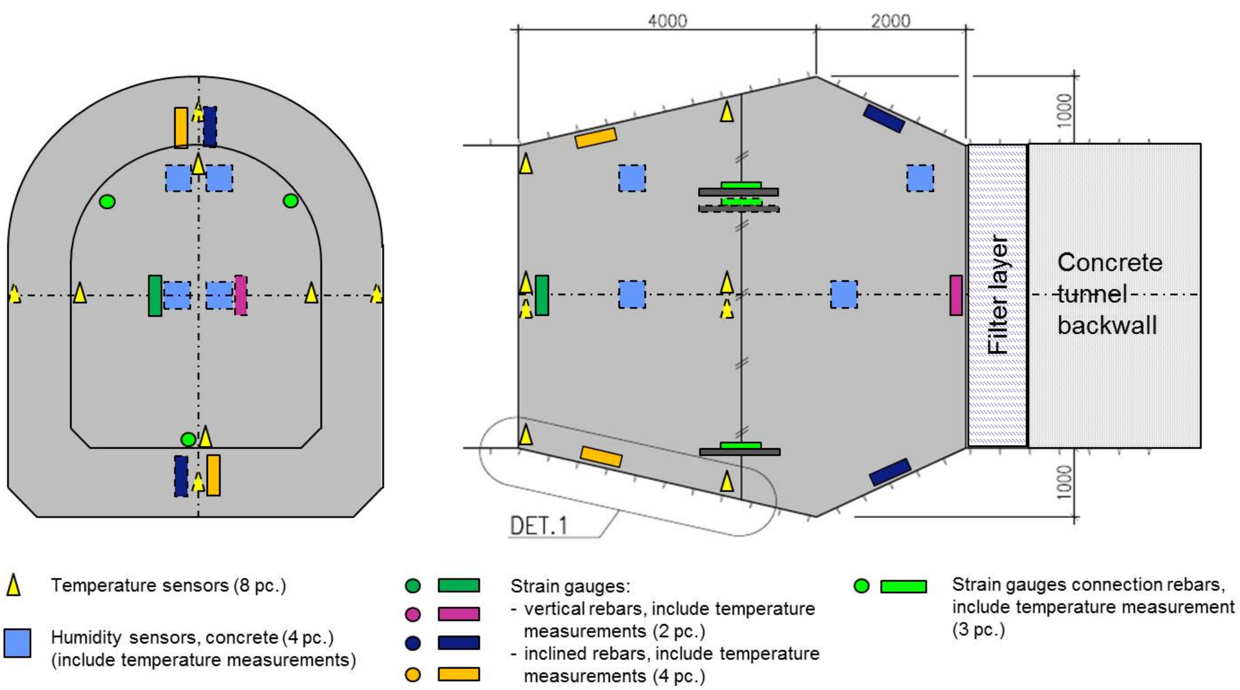

Fig. 7. Locations of thermocouples and other sensors that allow for temperature measurements.

FILTER LAYER MONITORING

The main purpose of the filter layer monitoring is to provide the required data to evaluate the condition behind the plug. Approximately 10 sensors are installed inside the filter layer.

The measurements will provide information about the current condition of the water distribution in the filter and magnitude of pressure during pressurization phase. The main parameters to be measured are pore and total pressure, and possible displacements of the filter layer or concrete backwall respectively.

WIRING OF PLUG AND FILTER LAYER SENSORS

The sensors and related wires will be placed inside the concrete plug, in the gap between the rock and plug and in the filter layer. The sensor wires and cables were 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 are combined to pass through especially installed sealing flanges (lead through flanges), which prevent water leakage out of the structure. On the front faces of both plug parts, lead through flanges will be installed. The flanges include a steel cylinder closed with covers that have holes for each measuring cable. The watertightness will be assured by applying a sealing material inside the cylinder. The wires of sensors located in the filter layer and partly in the gap between the rock and plug are directed to two lead through flanges which are located on the tunnel walls near the filter layer. These cables run through installed pipes within the lead through tube to the adjacent demonstration tunnel hosting the data loggers.

NEAR FIELD MONITORING

The demonstration tunnel 4 in ONKALO was excavated in autumn 2013. It is possible that there is pressurized water flow through paths (e.g. small cracks) to the adjacent tunnels and also to the front part of the demonstration tunnel. A second, similar demonstration tunnel (no. 3) was excavated next to the plug tunnel to host the instrumentation and pressurization equipment. ONKALO's existing monitoring practices will be applied to assess the plugs' near field responses during the experiment. For instance, water pressure, water leakage, temperature, strains and dislocations of the rock mass can be more frequently measured using new or pre-established measuring points.

PRESSURIZING SYSTEM

General

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 reliable and keep the adjusted pressure behind the plug. The long term reliability of the pressurizing setup is high since redundancy is given by doubling the most important equipment, to be used in case of failure. Also the amount of pumped inflow water will be measured carefully and compared to the outflow from the front part of the plug. The required pressure will be adjusted manually, but the main parameters can be seen remotely from the control room above ground.

Components of Pressurization System

The pressurization system is located in the neighboring demonstration tunnel 3. Its main components are two high pressure piston pumps, two unloader valves, two electrical motors with gearing box, thyristors with automation and control units, electric center, water tank, manifold connection pipes and main frame.

The volume of the pumping unit is two times 2 to 10 liters/minute and the out-coming pressure can be adjusted from 1 to 100 bars. The equipment includes various installations, which include 5 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 lead through flanges located on the wall of the tunnel behind the plug and furthermore to the filter layer.

There are also de-airing pipes placed within the upper and lower 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 liters 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 pumped water is monitored using water level sensors installed in the container. The system is able to measure the amount of inflow water and water pressure.

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. A power backup system is installed to supply electricity for the system in case of a power interruption.

WATER LEAKAGE MEASUREMENT SYSTEM

General

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. However, part of the added pressurizing water can penetrate to the rock or adjacent tunnels. Thus extreme care has been taken during excavation to minimize the excavated damage zone and to limit fracture flow paths.

In order to be able to better identify possible flow paths and the origin of the leakage water, the pressurizing water is marked with a tracer (sodium fluorescein). Thus any collected leakage water can be analyzed and tracked.

The amount of leakage water is expected to be very low. Partly it might be recognized only by visual inspection of moist areas on the concrete and/rock surface. Therefore, evaporation of water from the rock and concrete surface in the front of the plug is minimized by hanging plastic sheets that help to provide an environment between the surfaces and the sheets with a relatively high relative humidity.

Components of Leakage Measurement System

Any leakage water through the plug front face is measured in a first phase from four equal sized sectors on the plug wall. In the second phase the water is collected into a canal on the floor in front of the plug and is pumped up to a weighing bottle for measuring the total amount of leakage water. In the third phase the water will finally be collected in a container for later analysis.

The main idea of the first phase is to verify if the water leakage can be different especially at the top and at the bottom of the plug due to e.g. the dead weight of the plug. In each corner the water will be led by steel gutters to corner bottles for weighing. The amount of water will be measured by a rain gauge measuring devices, which will first weigh and then tip the water to the bottom.

In the second phase the total water, including also tipped water from the plug corners, will be led to a channel excavated in the floor in front of the plug. From there the water runs to a small well at the end of the channel to be pumped using two bilge pumps to the total water weighing device. With that device the 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.

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

SUMMARY AND CONCLUSIONS

An example of a monitoring program has been shared, including all aspects needed to build a system for evaluating performance and safety of a key engineered barrier system component. The design and setup of sensors, measuring devices and other instrumentations being used to monitor the behavior and sealing properties of a full scale *in-situ* tunnel end plug being constructed in a demonstration tunnel in ONKALO were presented.

The measuring and monitoring equipment being installed to collect the measured data and also the systematic database structure which is required to utilize the data efficiently were described in detail. The monitoring system allows for the observation and control of the main parameters needed during the pressurization by pumping water behind the structure. The water leakage through and around the plug will be measured by weighing devices, which will collect and weigh the out-coming water.

The results obtained by instrumentation and monitoring of the demonstration tunnel end plug are essential in order to develop the design and verify performance of safe plugs and seals. The monitoring also helps to identify the trigger values for evaluating performance, especially tightness. The project provides valuable information about the reliability of the sensors, cables and other instruments installed in any engineered barrier system within repositories worldwide.

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