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PU grouting in cold environment at fully operating Fljótsdalur Powerplant

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ABSTRACT

Post grouting in rock was performed with polyurethane close to the pressure shaft valve chamber in the Fljótsdalur powerstation in autumn 2021 while the powerstation was in full operation. Sudden increase in leakage had been observed in the valve chamber during unit trips and associated water-hammering of the rockmass in the powerhouse area, in addition the total leakage in the tunnel system around the valve chamber, had gradually increased since commissioning of the powerplant in 2007 from 10 l/sec to 20 l/sec, going up to 50 l/sec during unit trips when the production is stopped. To prevent potential future problems caused by frequent transient state in the waterway, it was decided to perform grouting in the area. Detailed geological investigations of the rock mass between the valve chamber and the headrace tunnel gave premises for design of new grouting curtain and the choice of grouting material. Difficult conditions with cold water, highly permeable fracture zone and unpredictable changes in pathways resulted in challenging work where collaboration between contractor, client and consultants was essential. Roughly 17.000 liters of polyurethane was injected into the rock mass to seal the bedrock and the constant leakage was reduced down to 4 l/sec. Several unit trips have occurred since the work was completed and to-date, no increase in leakage has been observed.

KEYWORDS

Polyurethane; grouting, cold environment; hydropower plant

INTRODUCTION

The Fljótsdalur powerstation is a 690MW hydroelectric powerplant in eastern Iceland with a max gross head of 600 m. The hydropower plant consists of 40 km headrace tunnel (HRT) from the Halslón reservoir towards to the top of vertical shafts above the powerstation hall. Hraunaveita diversjon also supplies water to the powerplant. The pressure shaft valve chamber (PSVC) is located on the top of the vertical shafts where the water is divided into two vertical shafts of 400 m down to the powerhouse complex. This leaves approximately 200 m of water pressure in the headrace tunnel adjacent to the valve chamber.

Leakage has been constantly measured from the valve chamber area and in the rock next to the headrace tunnel concrete plug since the commissioning of the powerplant. During technical issues in the Aluminium smelter, the production in Fljótsdalur power station has been strongly reduced and frequently shut off causing sudden and heavy increase in water pressure (waterhammers) in the tunnel system. This has resulted in significant increase of leakage to the PSVC. Surveillance systems in the PSVC show increased leakage in the PSVC access tunnel immediately after shutdown. The volume of leakage has been high enough to overflood the drainage system in the PSVS and access tunnel. Under normal circumstances the recorded leakage is between 18 and 22 l/sec in a measuring weir downstream the valve chamber but increases to up to 50 l/sec during periods of unit trips.

A sudden increase in leakage can cause potential future problems for the operation and maintenance of the powerplant. To prevent this, a significant post grouting work with polyurethane (PU) was conducted in the area in 2021. The grouting design was done by Tomasz Najder at Najder Engineering in collaboration with Verkis consulting engineers and the owner Landsvirkjun, the grouting work was performed by Jan Najder at BESAB AB.

1. LAYOUT IN THE PRESSURE SHAFT VALVE CHAMBER AREA

The access to the valve chamber is through a roughly 1 km long Adit 1 tunnel from the top of the Fljótsdalur valley (Figure 1). There is a junction close to the valve chamber where the adit tunnel divides and continues to the right towards the headrace tunnel and concrete plug and left towards the access tunnel to the valve chamber. The shortest distance from the valve chamber to the pressurised headrace tunnel is 25 m. The drainage tunnel is located just upstream of the HRT manifold. The drainage tunnel drains water from the tunnel system to a creek in the valleyside in Fljótsdalur. Layout of the valve chamber area is shown in *Figure 2*.

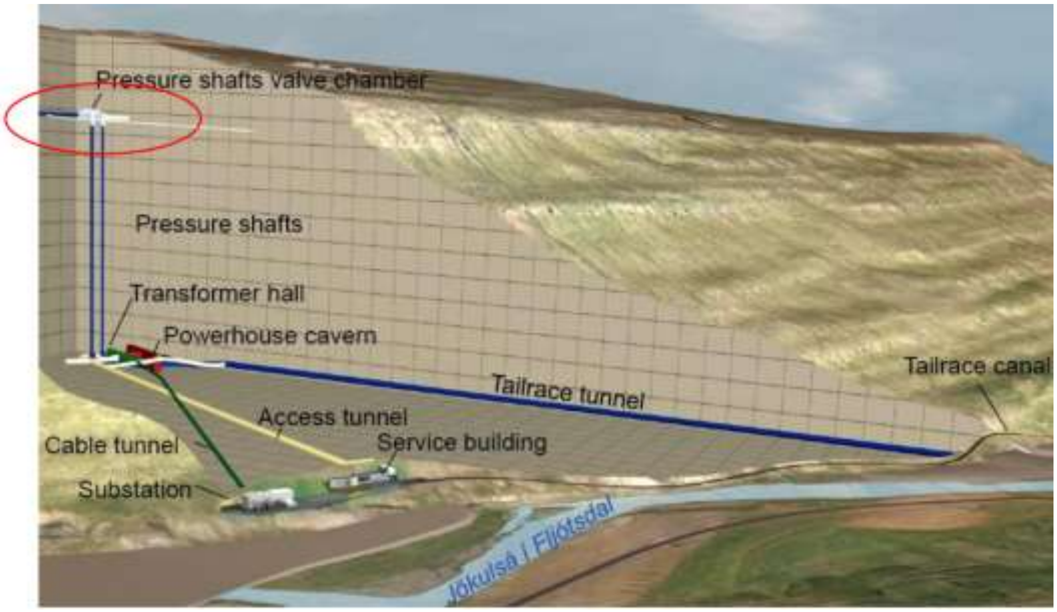

Figure 1. The powerstation area in Fljótsdalur valley. Pressure shaft valve chamber at the top of the vertical shafts.

The headrace tunnel is mostly unsupported, and limited lengths are supported with shotcrete at various places. A concrete lining was placed starting a short distance upstream the manifold, about 25 m upstream of the drainage tunnel centreline. The concrete lining is drained and after contact grouting, drain holes were drilled through the lining with 2x2 m grid above the springline, hence, leaving direct access for the water into the surrounding bedrock. Grout curtains, consisting of 3 row of grout holes for cement grouting in each curtain, were installed in the manifold tunnels, drainage tunnel and the concrete plug.

During pressurization of the headrace tunnel in 2007, there was a significant leakage from the Headrace tunnel into the valve chamber, to the main extent into the access tunnel. Additional grouting curtain with polyurethane (K-ring in *Figure 2*)) was performed in 2008 to seal off the inflow, when 8.500 liters of polyurethane was injected into the rock mass, and PVC membrane was placed on rock walls for protection of electrical equipment in the valve chamber and the access tunnel. The total leakage through the valve chamber after the grouting in 2008 was approximately 10 l/sec.

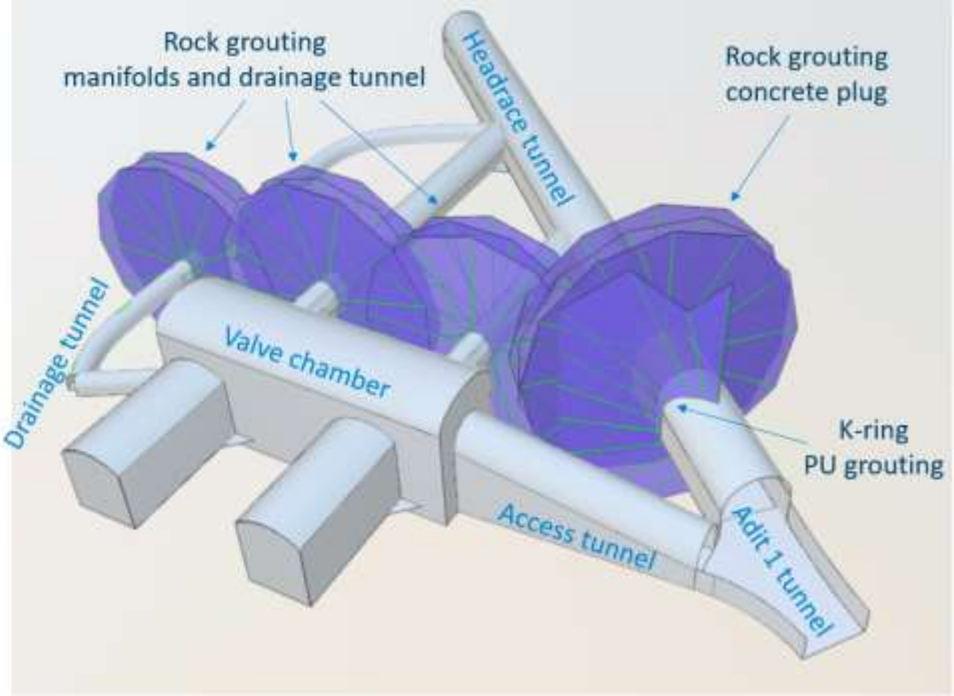

Figure 2. Layout in the valve chamber area and location of additional grouting curtain from 2008 (K-ring).

2. RECORDED LEAKAGE IN THE VALVE CHAMBER

A measuring weir was installed in the drainage tunnel at the downstream end of the valve chamber in 2010, for measuring all leakage water from the valve chamber and the Adit 1 tunnel. The leakage was recorded manually in the period from 2010 until in September 2018 when automatic measuring device was installed after sudden increase in leakage was first noticed.

Figure 3 shows records from the monitoring system and reflect the transient state in the waterway during water hammering pressure pulses and associated increased in leakage measured by the measuring weir. Pressure gauges installed at the top of the penstock are representative for the state in the pressurized headrace tunnel. Review of the data from the monitoring system and video records show that the leakage comes in three pulses where the top of the first pulse is measured 4-6 minutes after the first pressure peak in the penstocks, which then increases by up to 40 m (mH_20) during the episodes. The effects of the initial water hammer seems not to affect the leakage due to the short time that such a high pressure is occurring in the system. Considering 4-6 min delay in response time, leakage seems to start to increase when pressure in the penstock and headrace tunnel reaches roughly 20 mH_2O above normal state.

Review of records from CCTV cameras in the valve chamber show clearly that the leakage increases in both sides of the access tunnel as well as up through the center of the concrete invert. Leakage is also observed coming from the junction in adit 1 tunnel, under the portal between the access tunnel and the adit tunnel (*Figure 4*).

Study of as build documents and geological mapping from the construction time indicate that water is flowing through similar pathways as prior to the grouting of the K-ring, and the water is being transferred by joint sets and fracture zone orientated diagonal to the tunnel system. It was though uncertain if the water was flowing above or under the grouting curtains or even through them. Field investigations showed also signs of increased leakage during unit trips in the adit 1 tunnel. Orientation of possible leakage ways is shown in *Figure 5*.

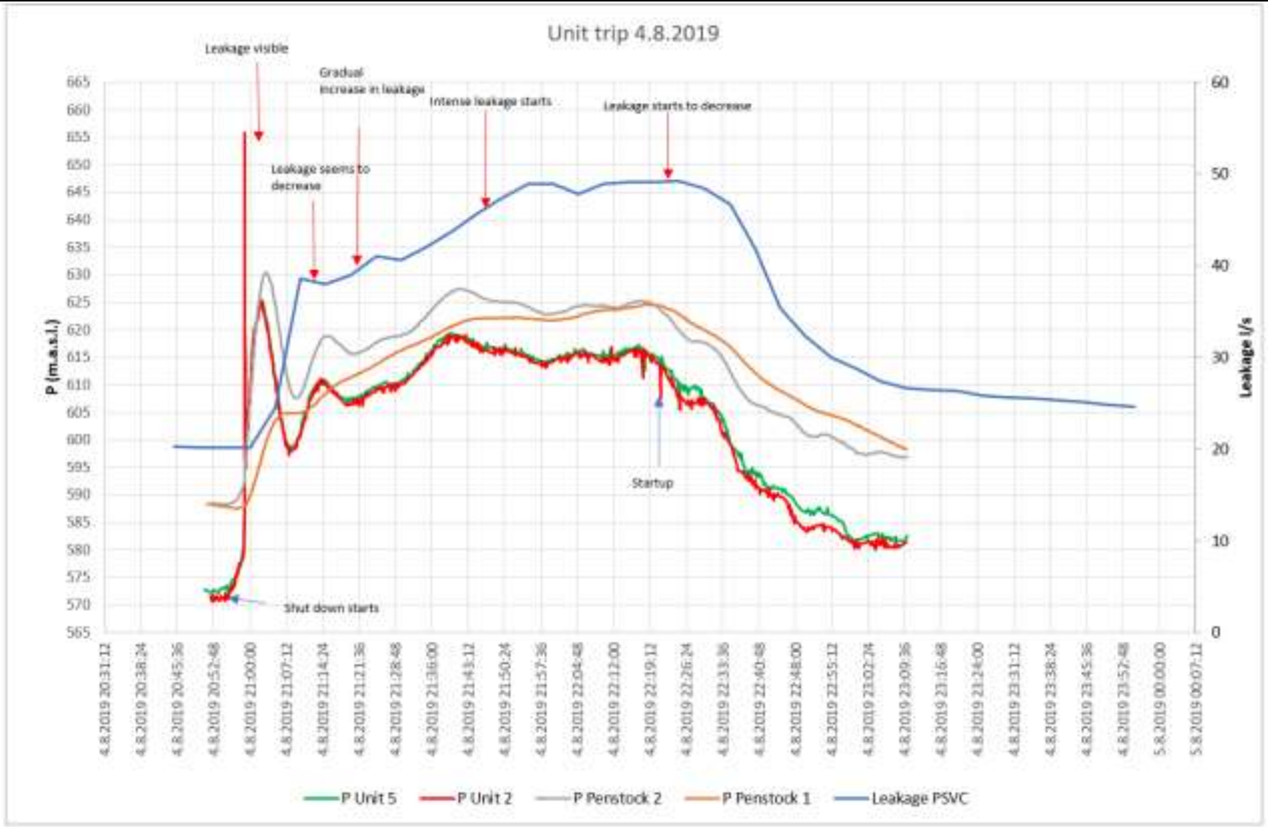

Figure 3. Graph showing water pressure at units and penstocks and during unit trip 4. august 2019 and recorded leakage from PSVC. Text above graph with observation on video records.

Figure 4. Observed increased leakage in access tunnel during a unit trip in august 2019. Note water flowing under portal door.

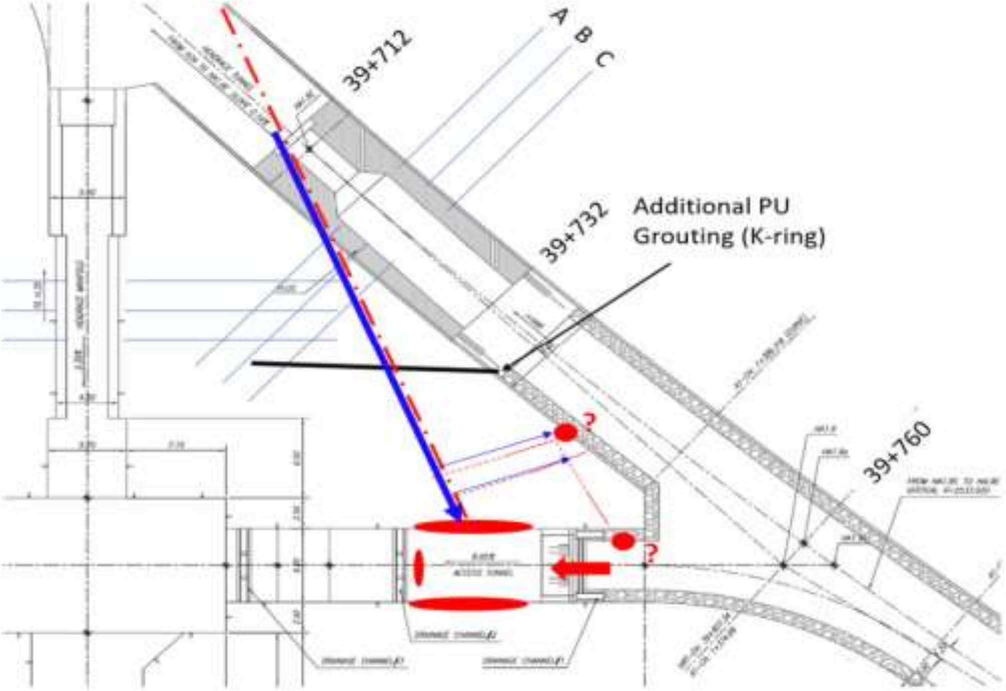

Figure 5. Possible flow pathway (blue) from the headrace tunnel to the access tunnel and adit tunnel. Note possible leakage areas with question marks in the adit tunnel outside the access tunnel to valve chamber.

3. INVESTIGATIONS 2021

Geological investigations were performed in March 2021 by probe drilling as permeability- and tracer tests were performed in all holes. The drilling was conducted from the adit tunnel, in the rock pillar between the headrace tunnel, and the access tunnel towards the valve chamber. The aim of the investigations was to identify possible leakage pathways from the pressurized HRT to the access tunnel in order to gather information about permeability in the rock mass for further use in detail design of a new grouting curtain. The measured temperature of the leakage water during the tests was between 1,5 and 2,1°C, but the temperature of the leakage water annually varies between 1 and 4°C.

The results from the investigations supported the assumption that the leakage from the HRT was confined to permeable joint zones both above and under the grouted K-ring, however, the rock mass itself has relatively low permeability. Permeable joints were observed outside of 18 m from the boreholes drilled in the same direction as the grouting curtain. Location of permeable zones in the boreholes with respect to the HRT and the leakage points in the access tunnel corresponded well to the previously mapped steep dipping (85-90°) joint set with strike direction diagonal to the adit tunnel.

Figure 6. Clear connection between probe hole and leakage in the access tunnel during permeability test.

Permeability tests indicated moderate to medium LU values (generally between 4-25 LU) with respect to the actual test sections. If the LU values are calculated with the assumed thickness of actual permeable zones, the leakage values could be classified as high or very high (50 to over 200 LU). Registration of flow with different pressure stages during permeability testing indicated that infillings in the joints were being pressed further into the joints causing lower flow rate with decreasing pressure stages. This was also seen in the access tunnel during permeability tests where brownish water was observed leaking from the joints during the tests.
Permeability tests with Fluorescein sodium blended into the injected water showed that the response time, from pumping until the colored water appeared in the access tunnel, was ranging between 9-15 minutes (*Figure 6*).

With respect to the test results, it was concluded that a new grouting curtain should be placed approximately 5-6 m downstream the K-ring curtain with grouting holes up to 24 m long to reach the permeable joint zones.

4. GROUTING DESIGN

4.1. Grouting curtain

In the original design it was planned to use the drill holes from the investigations in March as primary holes for grouting, and after completion of the grouting to drill secondary holes by forming a double array umbrella in the rock pillar between the headrace tunnel and the valve chamber (*Figure 7*). All primary and secondary holes were drilled to the minimum 24 m depth. Penetration rate and colour of flush water was registered to map in more detail the geology of the rock mass and permeability tests were performed with colored tracer material in all holes.

Grouting was performed through grout sets composed of steel pipes, two Bimbar packers and a plastic pipe to feed the grouting material to the desired depth in the hole, i.e. closest to the water bearing areas. The two components were mixed in 1:1 ratio in a static mixer before injected into the strata through the packers.

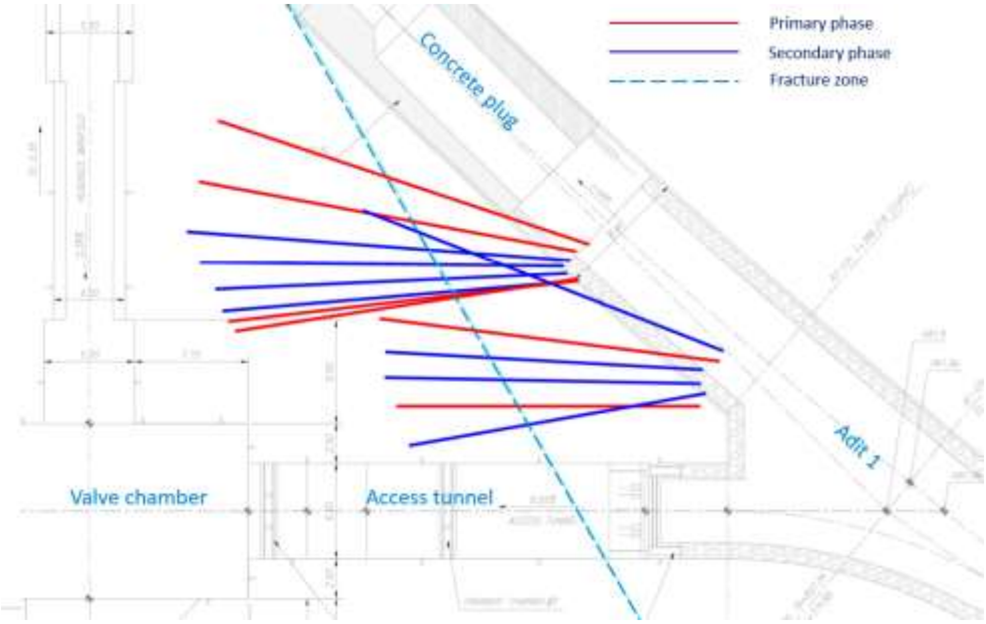

Figure 7. Original plan for grouting with primary (red) and secondary (blue) phase, location of potential fracture zone along dashed line.

4.2. Grouting material

Two component PU resin from DSI Schaum Chemie Ltd. was selected for the grouting. The PU properties were chosen based on the result of the investigation program in March 2021 with detailed information on permeability and response time. PU with the following properties was preferred for the grouting work:

Table 1. PU properties for grouting.

Product	Viscosity	Start foaming	End foaming	Foaming factor
DSI Inject PUR LV	70-100 mPas	180-300 s	ca 10 min	1,0 – 1,1
DSI Inject PUR HF	300±100 mPas	180-300 s	< 10 min	1,0 – 1,1
DSI Inject PUR HF ffx5	300±100 mPas	<60 s	< 3-4 min	5
DSI Inject PUR HF ffx10	300±100 mPas	<60 s	< 2 min	10 - 15

Grouting was mainly intended with low and medium expansion PU to avoid fracturing of shotcrete and rock during grouting and PU with higher foaming factor should be used for filling of cavities and high-water bearing joints. Additives, accelerator, and thixotropic agents for thickening, where also planned for challenging conditions.

The grouting was performed with pressure of 60 bar injection pressure above the groundwater pressure in the boreholes (measured at pump) giving a real overpressure of 3-5 bars when head loss in the hose system is taken into account. Refusal pressure of 100 bars (at pump) was used as a stoppage criterion or when grout take was exceeding 25 l of resin pr 1 m grouting length of the borehole. The grouting pressure was monitored closely during the work where the bedrock cover in the area is 120 m giving vertical stress about 3,2 MPa, and lowest stress in the area assumed even lower according to stress measurements down in the powerhouse area.

4.3. Preventive measures

The powerplant was planned to be in full operation during the grouting work. The tunnel system around the valve chamber includes drainage pipes and measuring weir which had to be protected from clogging. In addition, the leakage water is led through drainage tunnel to the slopes of Fljótsdalur Valley and the client posed strict restrictions for reacted PU in the leakage water to spill through the drainage tunnel onto the environment. Traps and dams composed of wooden planks, fishing nets and geotextiles were installed in the drainage tunnel to both calm the water in order to get the PU to react and collect reacted PU (*Figure 6,7 and 8*). The owner also monitored the outlet water from the powerplant to identify potential PU fragments and unreacted materials.

Figure 8. Provisional drainage system constructed on surface with open channel towards drainage tunnel to protect the permanent drainage system in the cavern.

Figure 9. Measuring weir (left) and drainage tunnel invert installed with fishing net and wooden planks to catch reacted PU downstream the valve chamber.

5. GROUTING WORK

The actual grouting work can be divided into three main phases; primary and secondary as described in the grouting design, and tertiary with changes in strategy after completion of original plan. Location of all boreholes and location of highly leaking zones was modelled in 3D after each day and the model frequently used for further decisions during the progress.

The grouting work started the 21st of October 2021 by extending and grouting the primary exploratory holes from the investigations. The grouting of all primary holes was finished grouted on the 26th of October with total consumption of 4880 l of PU. After this stage was finished, the constant leakage had decreased down to 15 l/sec in the drainage tunnel (*Figure 11*). Visible decrease in leakage was observed in the right wall of the access tunnel and the Adit 1 tunnel, but still high leakage was observed from the invert and left wall.

As for the secondary holes, in total of 9 holes were drilled in order to close two half umbrellas in the rock pillar between the HRT and the valve chamber. The secondary holes took almost the same amount of PU as the primary holes with no significant decrease in total leakage, as the constant leakage had actually increased up to 18 l/sec in the measuring weir (*Figure 11*). Results were whatsoever visible in the access tunnel where the right wall had at this point became almost completely dry. High leakage was though still coming from the left wall and the invert. Grouting of secondary holes was finished 4th of November.

Result from drilling and permeability testing of the primary and secondary holes showed that the water was clearly flowing through a subvertical fracture zone crossing diagonal through the rock pillar, now mainly below the invert. The highest change of completing the task was thereby to search for the water bearing part of the zone and grout directly in the main water source. By drilling directly into the water bearing zone, a leakage of 180-200 l/min with water pressure of up to 15 bars was measured. Grouting into this fracture zone was highly complicated as the leakage of this magnitude caused unreacted PU to flow out of the joints in the access tunnel and the polyurethane did not start to react until it was through the pillar and settling on the invert. The result of using higher foaming factor, adding accelerator or use thicker mixture resulted either in clogging of the holes or the water found new pathway through the fracture zone and into the tunnel. A unit trip occurring in the middle of the grouting process also gave leading information as now one could see which areas where tight and which were responding to the transient state in the headrace tunnel. As the result, it was decided to drill and grout umbrellas between the highly leaking zones and the periphery of the access tunnel where the water was leaking out, in the attempt to make a barrier closer to the tunnel and slowing the flowing rate through the rock mass before attacking the main water-bearing areas. After a reasonable tightness was accomplished, two additional holes were drilled in the main vain and packer with a valve was placed in one hole to control the water pressure and flow rate in the fracture zone while the other one was being grouted. This procedure proved to be successful and stopped the main leakage in the access tunnel. Location of grouted holes from all phases are shown in *Figure 10*.

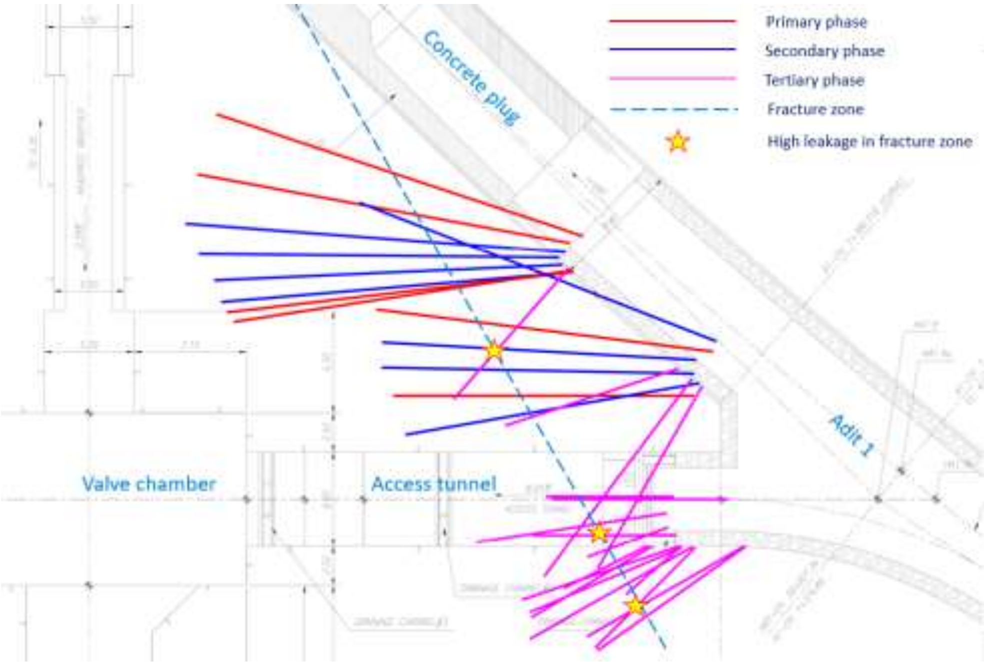

Figure 10. Final layout of grouting holes after all three phases. Tertiary phase with unregular pattern after chasing new pathways in the bedrock, mainly below the invert.

Seventeen holes were drilled and grouted in this tertiary phase of the grouting work and roughly 8000 liters of PU was injected, thereof 3000 liters in the main fracture zone. The total leakage measured at the measuring weir had at this point decreased down to 4 l/sec, the main leakage mainly coming from the 1 km long Adit 1 tunnel. The grouting work was finished 24th of November.

Total consumption of polyurethane was 17.410 liters injected into 46 boreholes. Total drilled length of probe- and grouting holes was 777 m, thereof were 583 m grouted length giving 29 liters grout pr meter in average.

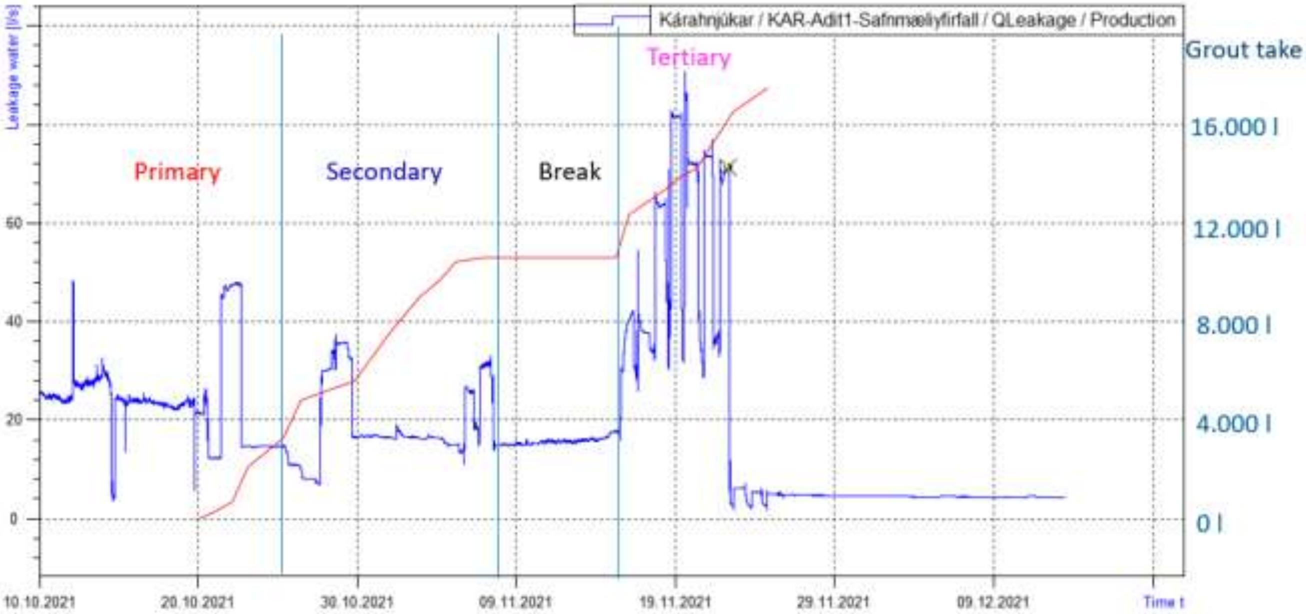

Figure 11. Total amount of leakage water from measuring weir (blue) and accumulated grout take (red) during grouting work. Irregularities due to preventive measures in the measuring weir (see Figure 9).

6. CLOSING REMARKS

Grouting of highly permeable fracture zones in cold environment with an operating hydropower plant close by is achievable with rigid polyurethanes. However, it requires good preparations and detailed investigations to accomplish with reasonable results. It is also vital to bring in experts in chemical grouting and flexible contractors, where decision making and evaluation on site must be taken frequently and change plans. All participants on site were aware of the complexity of the work and that results were not guaranteed. This time it was a success where remaining leakage after the work was mainly coming from leakage of groundwater in the roughly 1 km long adit tunnel and not the headrace tunnel itself. All remedial measures to reduce or eliminate polyurethane in the environment and the powerplant systems also worked as planned.

The main reason for good results was good and thorough preparations and daily meetings with all parts during the work. Location of all boreholes and results from permeability tests was modelled in 3D after each day giving valuable input in further decisions, especially in the tertiary phase of the work. The selected materials, both type of polyurethane, pumps and packers proved to be valid after several rounds with different suppliers. Above all, involving highly experienced specialists with knowledge about Icelandic conditions was a key factor.

A number of unit trips have occurred at the powerplant since the completion of the work and to-date, no increase in leakage has been observed.

7. ACKNOWLEDGEMENTS

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