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Posiva Flow Log measurements in four boreholes at the Bukov underground research facility in the Czech Republic

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List of abbreviations:

PFL DIFF	Posiva Flow Log Difference Flow Method
SPR	Single Point Resistance
EC	Electrical conductivity
URF	Underground research facility

Explanation of terms:

Posiva

Finnish nuclear fuel management company.

SKB

Swedish nuclear fuel and waste management company.

Abstract

This report presents the main principles of the Posiva Flow Log Difference Flow Method (PFL DIFF) and results of measurements carried out in four boreholes in SURAO’s underground research facility in Bukov in September 2023. The report also aims to clarify the purpose of each individual measurement run and explain the decisions made in planning and during measurements in the field.

The PFL DIFF method is a measurement method that can be used in core drilled boreholes to investigate the hydraulic properties of bedrock around the borehole. The downhole probe measures different quantities enabling relatively quick identification of water flowing fractures and determination of transmissivity (T_{PFL}) and hydraulic head of these fractures.

The entire measurement programme contains two measurement runs in every borehole. Obtained results are used together to obtain the results of hydrogeological parameters. Measurements are conducted in two differing pressure sets, in open borehole conditions and while borehole pressure has been increased by pumping water into the borehole. The end results identify the locations of water flowing fractures along the borehole and the estimated transmissivity and hydraulic head of the fractures.

In addition to hydraulic properties, some chemical analysis can be done based water collected from a fracture. Water sample collection can be conducted efficiently as fracture locations are know very precisely based on flow loging.

In this measurement campaign, the measurement programme was conducted in four borehole. Two borehole were subhorizontal (1° and 2° inclination downwards) and two steeper downwards inclined.

Keywords

Hydrogeological investigations, Posiva Flow Log, borehole, groundwater flow, transmissivity, groundwater sampling

Abstract

Tato zpráva představuje hlavní principy Posiva Flow Log Difference Flow Method (PFL DIFF) a výsledky měření provedených ve čtyřech vrtech v podzemním výzkumném pracovišti SURAO v Bukově v září 2023. Součástí zprávy je objasnění účelu jednotlivých měření a popsat rozhodnutí učiněná při plánování a během měření v terénu.

Metoda PFL DIFF je metoda měření, kterou lze použít v jádrových vrtech ke zkoumání hydraulických vlastností horninového masívu v okolí vrtu. Měřící sonda měří různé veličiny, což umožňuje relativně rychlou identifikaci proudících puklin a stanovení transmisivity (TPFL) a hydraulické vodivosti těchto puklin.

Celý program měření obsahuje dva běhy měření v každém vrtu. Získané výsledky jsou společně použity pro získání výsledků hydrogeologických parametrů. Měření se provádějí ve dvou různých tlakových podmínkách, v podmínkách otevřeného vrtu a při zvýšení tlaku ve vrtu čerpáním vody do vrtu. Konečné výsledky identifikují umístění propustných puklin podél vrtu a odhadovanou transmisivitu a hydraulickou vodivost puklin a okolního horninového prostředí.

Kromě hydraulických vlastností lze provést I doběry vzorků vod pro chemické analýzy na základě vody shromážděné v odběrovém barelu. Odběr vzorků vody lze provádět efektivně, protože místa puklin jsou známa velmi přesně na základě protokolování průtoku.

V této měřicí kampani bylo provedeno měření ve čtyřech vrtech. Dva vrty byly subhorizontální (1° a 2° sklon dolů) a dva se strmějším úklonem.

Keywords

Hydrogeologický výzkum, Posiva Flow Log, vrt, podzemní voda, transmisivita, vzorkování podzemních vod

1 Introduction

The primary option for the long-term management of spent nuclear fuel in the Czech Republic comprises disposal in a deep geological repository that will be situated in a suitable rock formation. The approach is similar to that of Posiva in Finland and, therefore, similar strategies and techniques can be applied. One particular example of Posiva's expertise is the Posiva Flow Log Difference Flow method that has been used for hydrogeological investigation research purposes by Posiva for the last 30 years. The PFL DIFF method plays a key role in terms of obtaining the hydrogeological modelling data required for selecting the most suitable location for the repository. This project concentrated on the conducting of a PFL DIFF measurement campaign in SÚRAO's Bukov underground research facility and the demonstration of the capabilities of the PFL DIFF method and equipment.

The PFL investigation work at the Bukov URF concentrated on various types of boreholes. Two of the boreholes were inclined slightly downwards (1 and 2 degrees) and two were inclined more steeply downwards. The borehole lengths varied from 30.3 to 124 m. The Posiva Flow Log Difference Flow method comprises a measurement approach that enables the relatively rapid identification of water-flowing fractures and the determination of their transmissivity and hydraulic head. Using a custom-made borehole sealing mechanism, it is possible to close the borehole when the PFL probe is positioned in the borehole and to control the pressure in the borehole. Thus, it is possible to measure fracture flows under various pressure conditions in subhorizontal and short boreholes.

Details of the boreholes are presented in Table 1. The locations of the boreholes are presented in Figure 1.

Table 1. Details of the measurement boreholes at the Bukov URF.

Borehole	Coordinates in the S-JTSK system			Length	Diameter	Inclination
	X	Y	Z			
S-24	1127773.6	622694.7	18.4	124	76 mm	-2
S-33	1127790.2	622690.7	17.5	75.5	76 mm	-1
L7-87D	1127921.9	622632.5	18.9	50.6	76 mm	-88
L8-54DL	1127952.8	622670.2	19.4	30.3	76 mm	-44

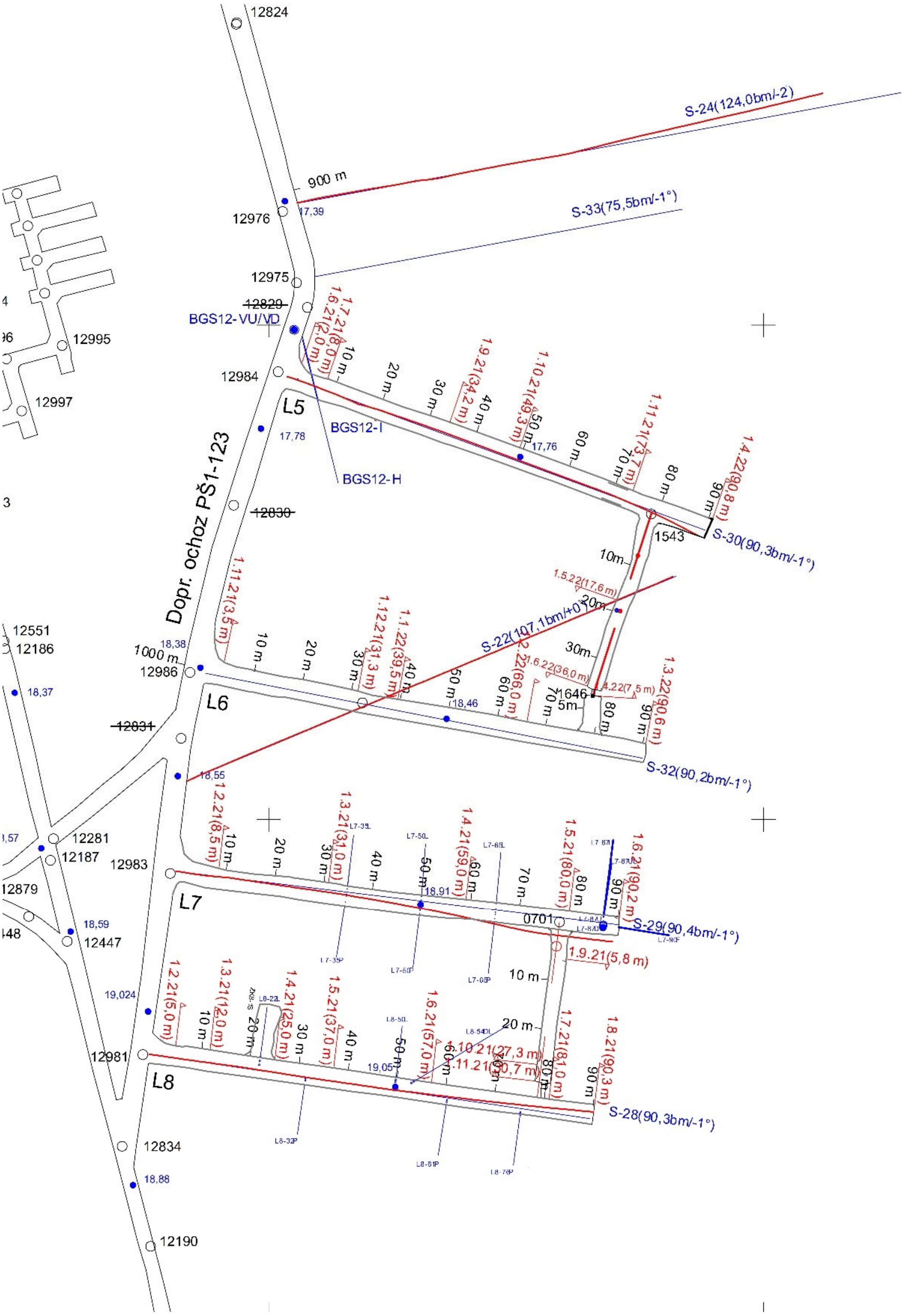


Figure 1. Locations of the measurement boreholes at the Bukov URF.

Boreholes S-24 and S-33 (Figure 2) commenced from the tunnel wall. The special measurement winch that forms part of the equipment was placed close to the borehole and the cable was guided into the borehole using a guiding wheel. Borehole L7-87D commenced from the tunnel floor and included a short casing pipe (Figure 3). Borehole L8-54DL commenced from the tunnel wall very close to the floor of the tunnel (Figure 4).

Figure 2. Borehole S-33 commenced at the tunnel wall.

Figure 3. Borehole L7-87D commenced from the tunnel floor.

Figure 4. Borehole L8-54DL and the wheel used for guiding the cable from the winch into the borehole.

This report documents the planning and performance of the fieldwork and presents the results obtained in the form of a measurement report. In addition, the report provides a detailed description of the measurement method. In addition, the delivery of the data is presented so that the data plotted into annexes can be found from the data files. The sections of the report that present the Posiva Flow Log method, the fieldwork and the results acquired were written by Posiva Solutions Oy.

2 Objectives and scope

The main objective of this research was to provide SÚRAO with information on the PFL DIFF method as related to investigation work under tunnel conditions. The information provided includes a demonstration of the taking of PFL DIFF measurements and the results that are provided. Although hundreds of PFL DIFF measurement campaigns have been conducted for both Posiva and SKB over the past twenty years, and the basic principles have been reported in publicly-available reports, until now SÚRAO has lacked the first-hand experience of this investigation approach. This measurement campaign was, therefore, designed to eliminate this deficiency.

SÚRAO's hydrogeologist participated in the fieldwork and the measurement programme was explained in detail by the measurement operators. In addition, the decisions that were made in the field were discussed in detail with the SÚRAO representative; while selected issues have been described in this report, it was not possible to include every detail that was discussed.

The general objective of PFL DIFF investigation work is to identify water-flowing fractures that intersect boreholes and to determine the transmissivity (denoted as T_{PFL}, see Section 5.2) and hydraulic head of the detected fractures, thus providing data for the hydrogeological modelling of the bedrock.

Following the detection of flowing fractures in borehole S-33, a sample of water was taken from a selected fracture. The fracture was isolated using a double packer that was installed in the borehole. The water that flowed from the fracture was drawn out of the borehole using a hose. The flow logging process consisted of two flow logging runs, one of which was conducted under pressurised conditions with the pumping of water into the borehole, which, inevitably, initiated a change in the pressure in the borehole. The disadvantage, however, was that prior to the taking of the water sample, it was necessary that the water that was pumped into borehole and the fracture was extracted. Concerning the S-24 borehole, it was also planned that a water sample would be taken; however, the flow measurement results indicated that it would have taken several days to attain a representative water sample.

3 Measurement principles

3.1 Posiva Flow Log

Unlike conventional borehole flowmeters that measure the total cumulative flow rate along boreholes, the PFL DIFF probe measures the flow rate into or out of defined borehole sections. The main advantage of the measurement of the flow rate in isolated sections concerns the accurate detection of incremental changes in the flow along the borehole. Since such changes are, generally, very small, they can be easily missed when using conventional flowmeters. Technical illustrations of the PFL DIFF tool are presented in Figure 5.

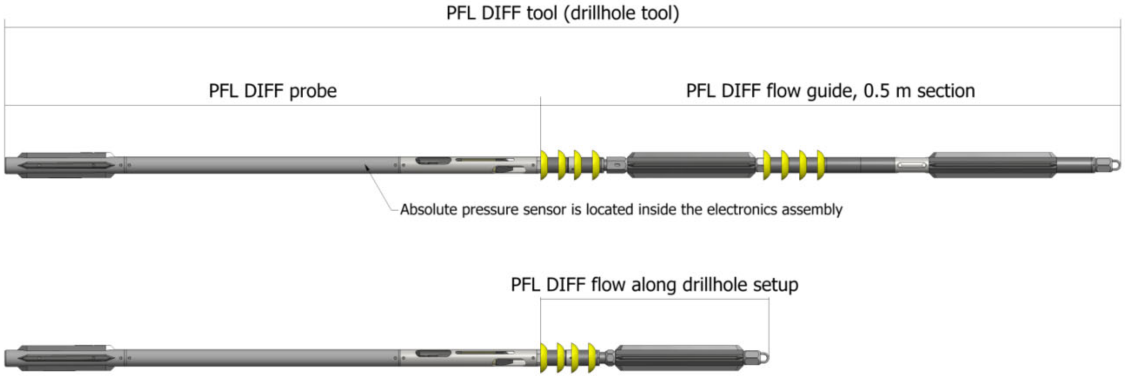


Figure 5. Technical illustrations of the PFL DIFF probe with different setups

Rubber sealing disks located at the top and bottom of the measurement section are used to isolate the flow of water in the test section from the flow in the rest of the borehole, see Figure 6 (in this measurement campaign, the measurement equipment was detached from the trailer due to the limited dimensions of the tunnel, i.e. there was no trailer). The flow inside the test section is directed through the flow sensor. The flow along the borehole is directed out of the test section by means of a bypass pipe and is discharged at either the upper or lower end of the probe. The entire structure is known as the flow guide. A schematic diagram showing a cross-section of the structure of the PFL DIFF probe is presented in Figure 7. It should be noted that, depending on the pressure difference between the fracture and the borehole, the direction of the measured flow can be from the bedrock into the borehole as shown by the magenta arrows in Figure 6 and Figure 7, or from the borehole into the bedrock, in which case the arrows in Figure 6 and Figure 7 should be inverted. The same applies to flow along the hole, i.e. it can flow either upwards or downwards depending on the prevailing conditions in the borehole at the respective depth.

Two separate measurement runs are usually performed under two differing sets of pressure conditions. In general, since tunnel boreholes are usually short, the installation process and the initiation of the measurement procedure takes up a disproportionate amount of time. Hence, only short (0.5 m) measurement sections are studied. In long boreholes, however, it is advisable to determine the fractured zones in the borehole applying longer measurement sections (acceleration of the measurement process); this does not apply to short boreholes.

In addition to flow, the PFL DIFF probe can also be used to measure:

- the electrical conductivity (EC) of the water. The EC electrode is located on top of the flow sensor; therefore, the water that flows to or from the flow sensor passes through the EC electrode, see Figure 6. The probe can be assembled so as to measure the fracture flow or the flow along the borehole, thus allowing for the measurement of the electrical conductivity of the fracture and the borehole water. With respect to tunnel boreholes, especially when water needs to be pumped into the borehole, it is necessary to carefully consider the representativity of the EC results. In some cases, since the water in the borehole comprises “filling” water, the EC results do not accurately reflect the properties of the local groundwater.

- the single point resistance (SPR) of the borehole wall (grounding resistance). The electrode used for SPR measurements is located between the uppermost rubber sealing disks, see Figure 6; it is used for the high-resolution depth matching of the various measurement runs and for the determination of the locations of fractures.
- the prevailing water pressure profile in the borehole. A pressure transducer is located inside the watertight electronics assembly and comes into contact with the borehole water via a tube, see Figure 5.
- the temperature of the water in the borehole. The temperature sensor forms a part of the flow sensor, see Figure 6.

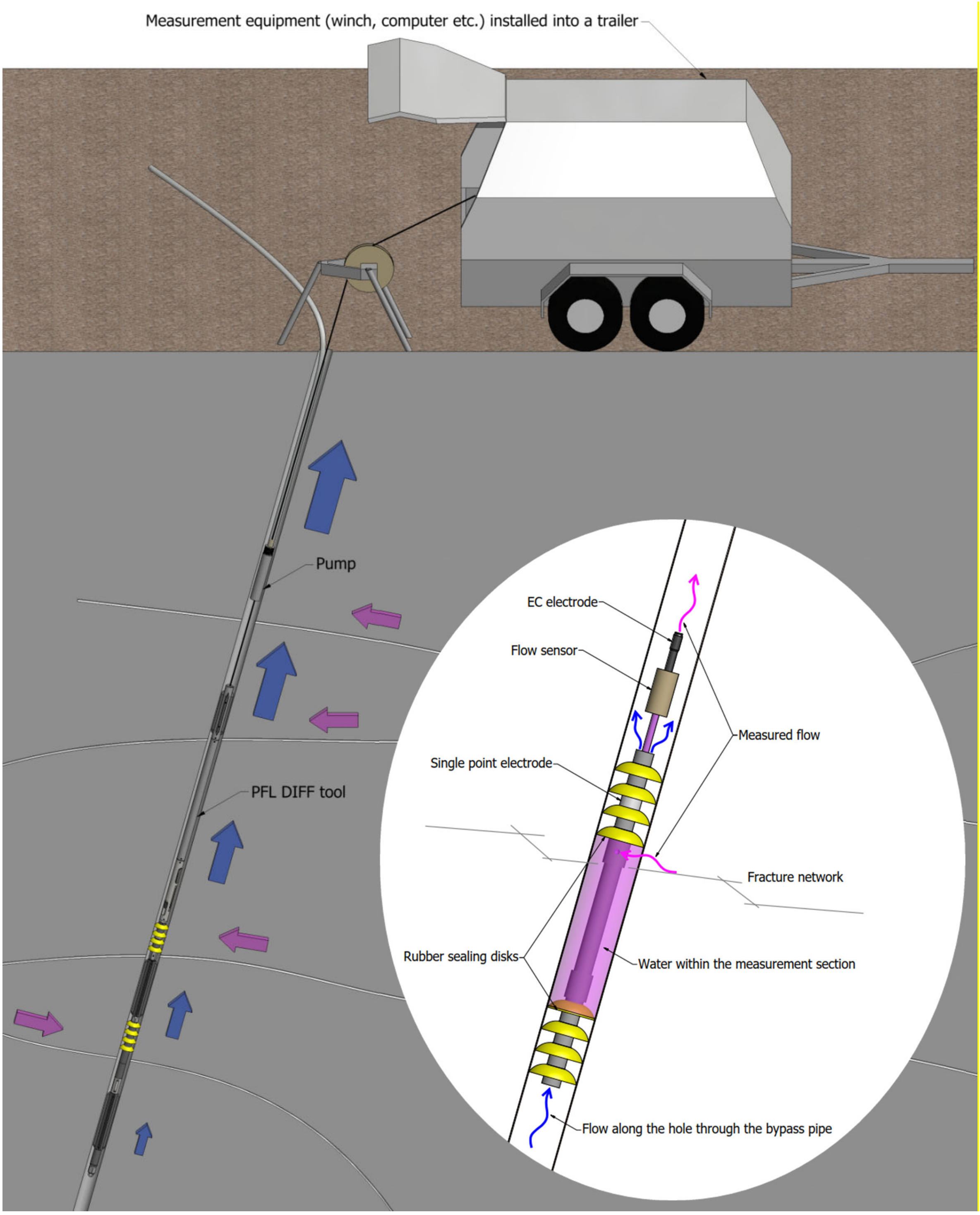


Figure 6. Scheme of the tool used in the PFL DIFF.

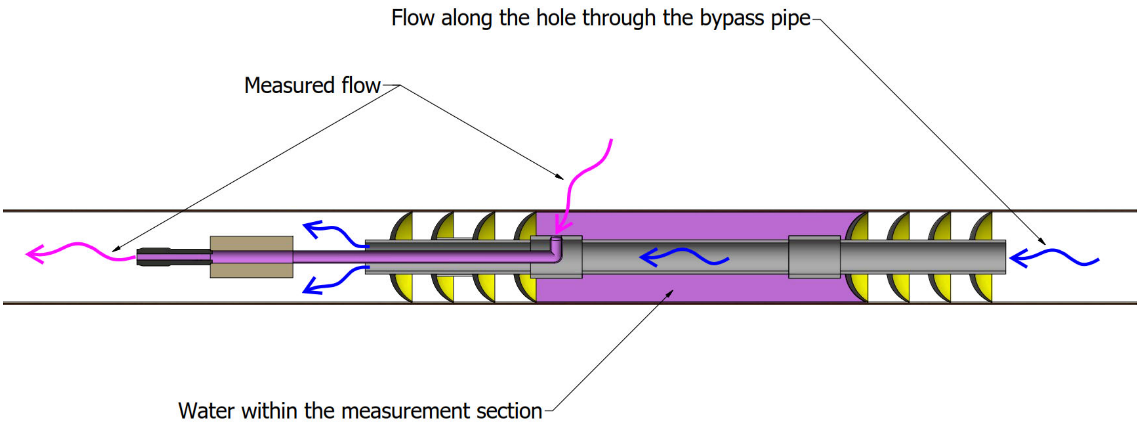


Figure 7. Scheme of a cross-section of the PFL DIFF tool.

Flow rates into or out of the test section are measured using thermistors, which serve to track both the dilution (cooling) of a thermal pulse and the transfer thereof by the flowing water. The thermal dilution method is used for the measurement of flow rates due to its being faster than the thermal pulse method; the latter is used only to determine the direction of flow within a given time frame. Both methods are used simultaneously for each of the measurement locations.

The flow is measured when the probe is at rest. After transferring the probe to a new position, a "rest" period (which can be adjusted according to the prevailing borehole conditions) is allowed before the heat pulse (**Chyba! Nenalezen zdroj odkazů.** b) is applied. The measurement period following the release of the constant-power thermal pulse can be adjusted. The flow rate, which is determined based on the thermal dilution, is determined based on 10-second measurement periods; however, the determination of the flow direction of the smallest flows takes a longer period of time. The detection of the heat pulse with a side thermistor can take up to 100 seconds; therefore, one longer measurement is taken for each borehole section. When using 0.5 m section lengths and a 0.1 m step, every fifth measurement takes 100 seconds. This approach ensures that the flow rate is determined for every measurement; however, the direction is indicated only once for each 0.5 m-long section.

In general, the flow rate measurement range is 30 mL/h to 300,000 mL/h. The PFL DIFF probes have been calibrated for a flow range of 6 mL/h to 300,000 mL/h under laboratory conditions; however, the conditions in the field usually act to raise the lower limit to around 30 mL/h. Therefore, in certain cases it is possible to measure flow rates of below 30 mL/h. On the other hand, the lower limit of 30 mL/h is not always attained under borehole conditions. Examples of potential disturbances to the measurement process include drilling debris that is present in the borehole water, bubbles of gas in the water and high flow rates (around 30 L/min, i.e. 1,800,000 mL/h or more) along the borehole. The measurement range of 30 mL/h to 300,000 mL/h was determined based on practical experience and is valid in most cases; however, exceptions sometimes occur, as detailed above.

It is also possible to assemble the PFL DIFF probe to measure the flow along the borehole. In practice, the lower rubber disks are removed and the entire flow along the borehole is guided through the flow sensor (see Figure 8). Using this setup, the relative accuracy is the same as that attained using the PFL DIFF setup. In cases where higher flow rates (>300,000 mL/h) have to be measured, a special flow divider must be attached to the front of the flow sensor (see Figure 9). The flow divider comprises a torpedo-shaped component which divides the flow along the hole into and beyond the flow sensor. The purpose is to maintain the flow rate through the flow sensor at below 300,000 mL/h. While the use of the flow divider lowers the accuracy of the flow measurements, it allows for the measurement of higher flows. The measurement accuracy using the flow divider is approx. ±20% of the measured value. The measurement range is from 10,000 ml/h to 2,000,000 ml/h. The PFL DIFF flow along the borehole setup evinces the same limitations as conventional flow meters, i.e. small changes in the flow rate may remain undetected under high borehole flow rate conditions. This is typically the case in the upper part of boreholes if the borehole is pumped.

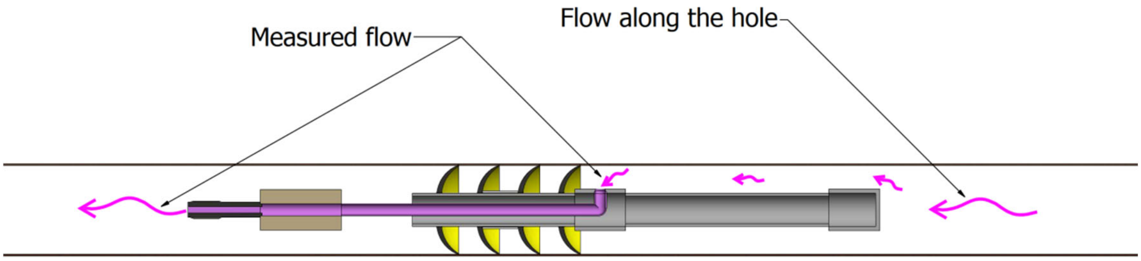


Figure 8. Scheme of a cross-section of the PFL DIFF tool in the flow-along-the-borehole setup with the addition of the flow divider.

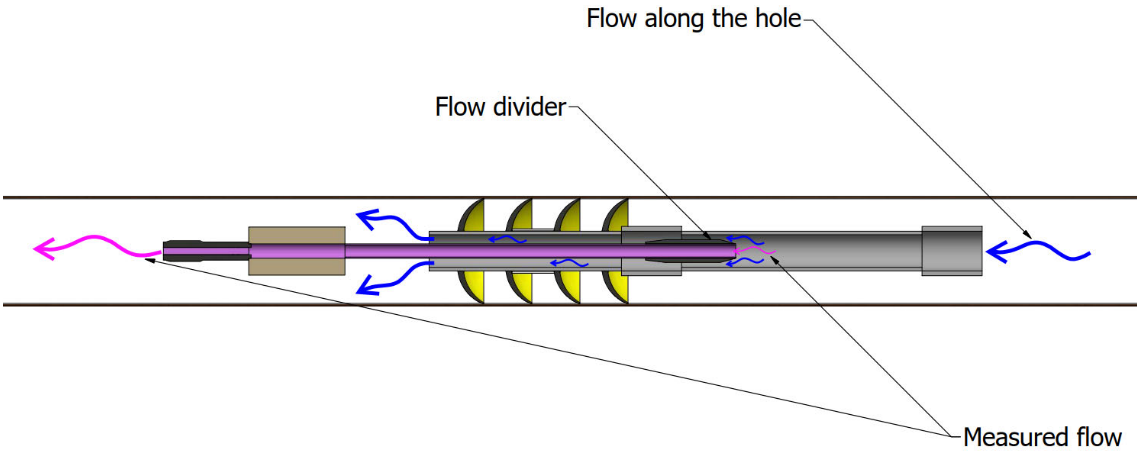


Figure 9. Scheme of a cross-section of the principle of measuring the flow along a borehole with the PFL DIFF tool with the removal of the lower rubber disks and the attachment of the flow divider

4 Equipment specifications and calibration

The PFL DIFF equipment was designed for the taking of hydrogeological measurements in core drilled boreholes. Several quantities are measured so as to provide comprehensive data on the hydrogeological properties and to verify the representativeness of the measurement results.

The PFL DIFF measurement equipment consists of the so-called PFL DIFF tool that measures the properties of the borehole and supporting equipment (winch, computer, air pressure sensor, etc.) that are positioned outside the borehole (Figure 10). The measurement computer is used to regulate the measurement process and to display the data from the ongoing collection of measurements. The data communication process between the measurement computer and the down-hole probe is digital; therefore, it is not affected by the 1500 m-long cable.

The measurement process is fully automated once it starts and can be monitored remotely (provided a network connection is available). This function provides a cost efficient approach to the taking of measurements since human input is required only when it is necessary to change the measurement setup and to initiate a new measurement run. This can usually be done during the daytime and, for example, depending on the length of the measured borehole, the measurement process can be performed during the following night.

Figure 10. PFL DIFF measurement equipment at a measurement site.

The range and accuracy of the measurements taken by the PFL equipment are presented in Table 2. The values were taken either from the sensor manufacturer's instructions or determined based on calibration in the laboratory. The specifications were subsequently verified based on the calibration process; however, the flow and temperature measurements may be affected by the conditions in the respective borehole. For example, the measurement of flow may be affected by salinity changes in the borehole water. In most cases, this is reflected in an elevated lower measurement range limit; however, it has not been seen to affect the accuracy of the measurements.

Table 2. Range and accuracy of the PFL DIFF measurements

Measured quantity	Range	Accuracy
Flow	6–300,000 mL/h	± 10% current value
Temperature (central thermistor)	0–50 ºC	± 0.1 ºC
Temperature difference (between outer thermistors)	-2–+2 ºC	± 0.001 ºC
Electrical conductivity of water (EC)	0.02–11 S/m	± 5% current value
Single point resistance (SPR)	5–500,000 Ω	± 10% current value
Groundwater level sensor	0–0.1 MPa	±1% full-scale
Air pressure senor	800–1,060 hPa	± 5 hPa
Absolute pressure sensor	0–20 MPa	± 0.01% full-scale
Pumping rate	0.5–60 l/min	± 10% current value
Measurement depth	0–1500 m	± 1 m at depth of 1000 m

The quality of the PFL DIFF measurement results is verified annually using the calibration equipment. Moreover, quality checks are performed during each of the measurement campaigns including an estimation of the rationality of the measured values (large errors), the comparison of the measured parameters when possible (changes in the values obtained from the water level sensor and the pressure sensor should be equal provided that the probe is not moved and the three thermistors should indicate the same temperature value) and the comparison of the flow rate calculated applying differing calibration functions.

The PFL DIFF probes are calibrated on an annual basis. The basic annual calibration procedure includes the calibration of flow, electrical conductivity (EC), single point resistance (SPR), absolute pressure and the temperature sensors. In addition to the PFL DIFF probes, the PFL trailers are fitted with sensors that are used in the measurement process, i.e. a pressure sensor for the monitoring of the borehole water and an air pressure sensor, both of which are also calibrated annually. The PFL trailer is fitted with a cable with length markings and, due to the stretching of the cable, the locations of the length markings are also calibrated. The procedures applied for the various calibrations are listed below.

- Temperature: The flow sensor is fitted with three thermistors and the temperature calibration process must be performed prior to the flow calibration. The resistivity of the thermistors changes in relation to the temperature. Therefore, based on the calibration function, the temperature is determined based on the resistivity. The calibration process involves the measurement of temperatures of between 5–50 degrees Celsius using a high precision thermometer accompanied by the recording of the resistivity of the thermistors. The calibration function is fitted based on the dependency between the resistivity and the temperature.

- Flow rate: The flow sensor is calibrated via the pumping of water through the flow sensor and the comparison of the measured flow value with the PFL DIFF probe and reference values. The reference value is obtained by measuring the amount of water that flows through the flow sensor in one minute. The annual calibration process serves to confirm the previous calibration results at room temperature. In the case of calibration functions that have been proved to be valid, no changes are required. A full flow sensor calibration is required if the calibration functions need to be changed based on the results of the basic calibration. This means that calibration is necessary to two different temperatures.

- Electrical conductivity: The EC sensor is calibrated in the field using at least two different conductivity standard liquids. A full calibration with at least 6 liquids is conducted annually or whenever the calibration function needs to be changed based on the results of the field calibration. The actual quantity measured by the EC electrode comprises the electrical resistivity (Ω), which is converted to the conductivity (S/m). The calibration process includes the measurement of the temperature of the liquid and the plotting of the EC value at the measured temperature as a function of the resistance measured using the PFL DIFF probe.

- Single point resistivity: The SPR sensor is calibrated by connecting the SPR electrode to the body of the PFL DIFF probe with a known reference resistor and verifying that the measured value is the same. A total of 18 reference resistors of between 1 Ω and 200 kΩ are used for calibration purposes.

- Absolute pressure: The pressure sensor inside the PFL DIFF probe is calibrated by comparing it to the reference pressure sensor. If the pressure value exhibits a constant error throughout the measurement range, this is compensated for by adding an offset calibration. If the linearity (the error depends on the pressure value) of the sensor changes, the sensor must be sent to the manufacturer for calibration.

- Air pressure: The air pressure, as measured using the barometer in the PFL Trailer, is compared to the air pressure data from the other on-site barometric measurements. The pressure offset can be compensated for; however, in the case of linearity errors, the sensor must be returned to the manufacturer for calibration.

- Water level sensor: The pressure sensor for the measurement of the water level is calibrated using a calibration pump that includes a reference pressure sensor. Small changes are compensated for via the calibration function. In the case of large errors, the sensor is replaced with a new sensor.

- Cable length: The cables in the PFL Trailer are known to stretch under tension, and such stretching is partially permanent, meaning that the cable becomes slightly longer with use. In order to compensate for the stretching effect, Posiva always attaches cable marks to new cables before use. The cable calibration process involves the laying out of the cable on the calibration course and the comparison of the marks with the calibration points along the cable course. During the comparison process, the tension of the cable is around 120 kg (the average tension of the measurements). The cable length marks are not removed; however, the error is recorded in the cable calibration file so that it can be compensated for when the measurements are interpreted. The cable calibration is valid for a period of two years following calibration. Since the cable tension during the measurement process depends on a number of factors, i.e. the borehole inclination, the logging direction and the probe setup, the tension may vary from 120 kg (the tension during calibration). Based on information provided by the manufacturer of the cable, the stretching of the cable is 1.15 m/km/kN, whereas in the PFL DIFF loggings, the cable tension is between 75 kg and 175 kg; therefore, the error in the depth determination is estimated at less than one metre at a depth of 1000 m. Dynamic stretching is not taken into account in the depth determination. In short tunnels, borehole cable stretching is not a major cause of inaccuracy in terms of the determination of the depth.

The depth of the downhole tools (PFL DIFF) is determined using an oedometer that is fixed to the winch. Prior to the start of the measurement process, the oedometer is set to display the correct depth, which is determined by measuring how many pushing rods were pushed into the borehole. The depth of the last measurement point at the top of the borehole can be checked using a tape measure following the end of the measurement run.

The PFL probe is pushed to the bottom of the borehole. In steeply downwards-inclined boreholes, it is possible to use extra weights positioned below the probe to ensure that the probe reaches the bottom of the borehole; however, this acts to reduce the measurable length of the borehole. Thus, no weights are used in the calibration process. Pushing rods are used in this case to push the probe towards the bottom of the borehole. In the longer boreholes at the test site (S-24 - 124 m and S-33 - 75.5 m) a drill-powered push rod machine (Figure 11) was used to push the probe with the pushing rods.

Figure 11. Drill operated pushing rod device

5 Interpretations

The main measurement results that are used in the interpretations comprise the flow and the pressure. The other measured values are used mainly to confirm the quality of the measurements and to enable the matching of the depth between the individual measurement runs. The interpreted values comprise the hydraulic heads of fractures, which allows for the estimation of the pressure in the fracture at distance from the borehole, and the fracture transmissivity, which enables the estimation of the ability of the fracture to transport water.

5.1 Hydraulic head in the borehole

The absolute pressure sensor of the PFL DIFF probe measures the sum of the atmospheric pressure and the hydrostatic pressure in the borehole. The atmospheric pressure is also recorded separately. The hydraulic head along the borehole under natural and pumped conditions can be determined from the measurement data. The atmospheric pressure recorded at the site is first subtracted from the absolute pressure as measured by the pressure sensor, thus allowing for the calculation of the hydraulic head.

The hydraulic head (*h*) at a certain elevation *z* is calculated using the following equation:

$$h = \frac{p_{\mathrm{abs}} - p_{\mathrm{b}}}{\rho \cdot g} + z, \tag{1}$$

where

- **h is the hydraulic head (masl),**
- **p_{abs} is the absolute pressure (Pa),**
- **p_{b} is the barometric (atmospheric) pressure (Pa),**
- **ρ is the density of water 1000 kg/m^3,**
- **g is the standard gravity 9.80665 m/s^2, and**
- **z is the elevation at the measurement location (masl).**

Determining the *z*-coordinates is important in the hydraulic head calculation since an error in this parameter leads to an equal error in the calculated head.

5.2 Transmissivity and the hydraulic head of fractures

The interpretation of data is based on Thiem's or Dupuit's formulae, which describe the steady state and two-dimensional radial flow into the borehole (Marsily 1986):

$$h_s - h = \frac{Q}{T \cdot a}, \tag{2}$$

where

- **h is the hydraulic head in the borehole (at borehole radius r_0),**
- **h_s is the hydraulic head at the radius of influence (R),**
- **Q is the flow rate into the borehole,**
- **T is the transmissivity of the test section, and**
- **a is a constant that depends on the assumed flow geometry.**

For cylindrical flow, the parameter *a* is:

$$a = \frac{2\pi}{\ln(R/r_0)}, \tag{3}$$

where

- **r_0 is the radius of the borehole, and**
- **R is the radius of influence, i.e. the zone inside which the effect of pumping is felt.**

If the measurement of the flow rate is carried out using two hydraulic head levels in the borehole, i.e. the natural and pump-induced heads, then the undisturbed (natural) hydraulic head and the transmissivity of the borehole sections tested can be calculated. Equation 2 can be reformulated in the following two ways:

$$Q_{s0} = T_s \cdot a \cdot (h_s - h_0) \text{ and} \tag{4}$$

$$Q_{s1} = T_s \cdot a \cdot (h_s - h_1), \tag{5}$$

where

- **h_0 and h_1 are the hydraulic heads in the borehole at the test level,**
- **Q_{s0} and Q_{s1} are the measured flow rates in the test section,**
- **T_s is the transmissivity of the test section, and**
- **h_s is the undisturbed hydraulic head in the tested zone far from the borehole.**

In general, since very little is known about the flow geometry, cylindrical flow without skin zones is assumed. The use of the cylindrical flow geometry is justified due to the borehole being at a constant head; no strong pressure gradients exist along the borehole except at the 2 ends of the borehole.

The radial distance R to the undisturbed hydraulic head h_s is not known and must, therefore, be assumed. In this case, a value of 500 for the quotient R/r_0 is selected. This corresponds to a radius of influence in the order of 19 m when the diameter of the borehole is 76 mm.

The hydraulic head h_s and the PFL transmissivity $T_{PFL,s}$ in the test section can be deduced from the two measurements by

$$h_s = \frac{h_0 - bh_1}{1-b} \text{ and} \tag{6}$$

$$T_{PFL,s} = \frac{1}{a}\frac{Q_{s0} - Q_{s1}}{h_1 - h_0}, \tag{7}$$

where $b = Q_{s0}/Q_{s1}$.

The PFL transmissivity ($T_{PFL,f}$) and the hydraulic head (h_f) can be calculated for individual fractures provided that the flow rates at the fractures are known. Similar assumptions to those employed above must be applied (the steady-state cylindrical flow regime without skin zones).

$$h_f = \frac{h_0 - bh_1}{1-b} \text{ and} \tag{8}$$

$$T_{PFL,f} = \frac{1}{a}\frac{Q_{f0} - Q_{f1}}{h_1 - h_0}, \tag{9}$$

where

- **Q_{f0} and Q_{f1} are the flow rates at a fracture, and**
- **h_f and $T_{PFL,f}$ are the hydraulic head (at distance from the borehole) and the transmissivity of the fracture, respectively.**

Since the actual flow geometry and potential skin effects are unknown, the PFL transmissivity values should only be considered as an indication of the prevailing orders of magnitude. Since the calculated hydraulic heads do not depend on the geometrical properties but only on the ratio of the flows measured at different heads in the borehole, they should be less sensitive to the unknown fracture geometry. The assumed constant radius of influence used in the formula of transmissivity leads to uncertainty in terms of the determination of the transmissivity. The assumption of a constant radius of influence (R = 19 m) leads to the definition of the PFL transmissivity, which is, practically, ΔQ/Δh, i.e. the specific capacity ($T_{PFL} \approx \Delta Q/\Delta h$). Finally, an elevated noise level may affect the flow measurements and act to decrease the resolution of the flow measurements. This may, in turn, affect the determination of the transmissivity values in low-conducting sections, where an increased noise level may mask smaller flow anomalies.

A discussion of the potential uncertainties in the calculation of the transmissivity and the hydraulic head can be found in Aalto et al. (2019). The main uncertainties in the report concerned leaking rubber discs caused, particularly, by poor borehole conditions (highly fractured rock) and changing salinity and density conditions along the borehole, especially during pumping. In addition, the constant radius of influence applied in the transmissivity formula leads to inaccuracy in terms of the determination of transmissivity. Finally, noise in the base-flow level may affect the flow measurements and act to decrease the resolution of the flow measurements, a factor that may affect the transmissivity calculations in low-conducting sections due to the masking of small flow anomalies if the base-flow level is increased. Improvements to the measurement devices have improved the quality of the results; however, the same uncertainties remain to a certain extent. In particular, changing salinity and density conditions are not such a major problem as they once were. In addition, the base-flow level is generally lower following modifications to the device. All the transmissivity values provided in this report were calculated based on the equations presented above.

5.3 Sensitivity of the transmissivity and the head to uncertainties in the flow and pressure measurements

The flow measurements are taken under two pressure conditions so as to provide data for the calculation of the fracture- and section-specific transmissivity and the head. In theory, the two pressure conditions can be any pressure as long as they are not the same. In reality, the difference between the pressures must be great enough so as to cause notable flow changes but still maintain a reasonable total borehole flow rate so that most of the fracture flows are beneath the upper measurable flow rate limit. It is important to initiate notable flow changes since if the flow rates are almost equal, even a small error in the measured flow value can lead to a significant error in the calculation of the transmissivity and the head. The most frequently applied drawdown concerning PFL DIFF measurements is 10 m in boreholes that are drilled from the surface. With respect to underground measurements, the pressure difference between the measurement runs is usually in the order of several bars.

Figure 12 shows how the accuracy of the flow rate and pressure measurements affects the precision of the transmissivity and fracture/section head interpretation. The blue and red dots, measurement runs 1 and 2, respectively, represent the measured flow and head values. The slope of the black line that has been drawn through the measurement runs 1 and 2 points is inversely proportional to the transmissivity (Equation 2). The head of the fracture or section is the head value at which the flow is zero, which is marked with a black cross in Figure 12.

The error in the flow rate measurement is within ±10% of the measured value, and the accuracy of the absolute pressure sensor ±2 kPa, which implies a ±0.2 m error in the head. The blue and red lines with arrow endings in Figure 12represent the errors of the measured flow and head values (±10% in the flow, ±0.2 m in the head). The square shape formed by the lines represents the accuracy of the measurements, i.e. the measurement run value should be within the squares when the errors are taken into account. The orange line in the figure indicates the maximum transmissivity (Tmax, PFL) and the green line the minimum transmissivity (Tmin, PFL) that is calculated with the error limits. The highest fracture head value (hmax) is marked with an orange cross and the lowest head value (hmin) with a green cross.

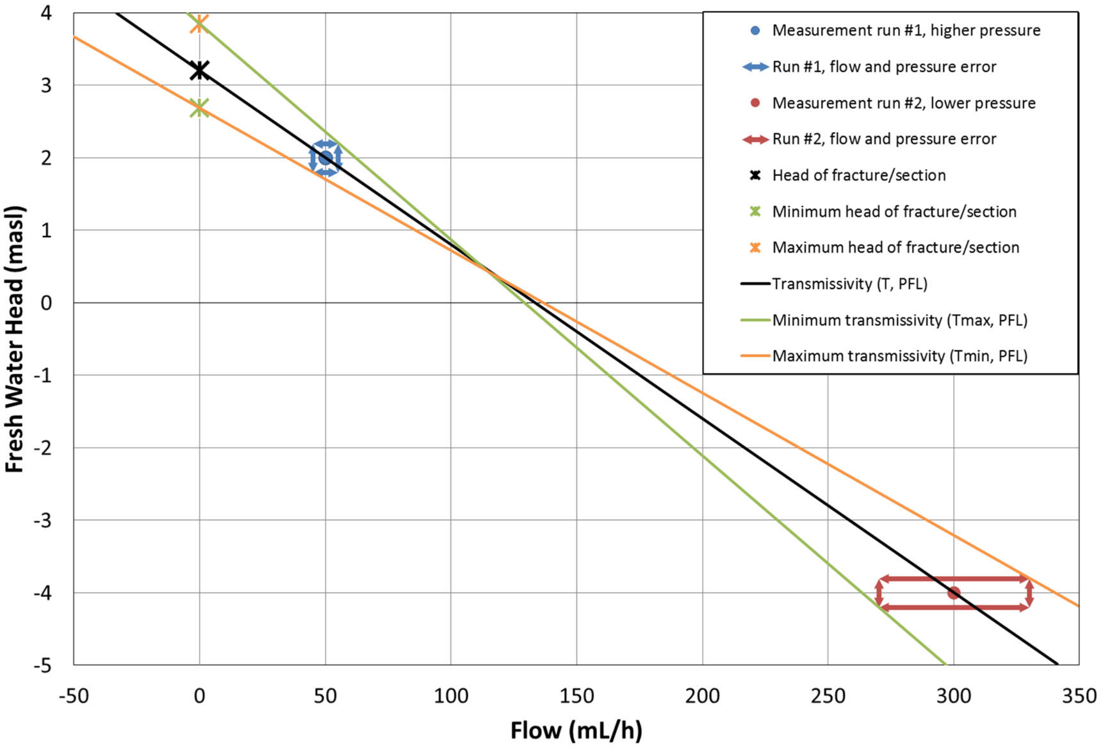


Figure 12. Demonstrative graph of how the ratio of the flow rates affects the accuracy of the transmissivity and formation head interpretation

Figure 12 represents a case in which the flow rates in both the pressure conditions were positive. It is possible that flow direction changes between the measurement campaigns or that the flow rate cannot be determined under both of the pressure conditions. If the flow directions differ, the lowest fracture/section head is not necessarily determined by the line representing the greatest transmissivity as in Figure 12; however, the same principles apply. In general, the error limits determine four potential flow and pressure values for both measurement campaigns, which results in 16 transmissivity and head combinations. The error limits comprise the maximum and minimum values of these 16 values. If the flow rate cannot be determined based on the two measurement campaigns, a zero flow value is used as a flow value that was determined for the calculation of the transmissivity and the head.

6 The fieldwork

6.1 Preparations

Before transporting the measurement equipment to the site, certain preparations are necessary to ensure the success of the fieldwork. Nevertheless, not all the aspects related to the site (borehole stability, working environment, etc.) and the measurement equipment (damage during transportation) can be taken into account.

The calibration of the equipment must be valid up to the end of the planned duration of the measurement campaign. The measurement equipment must be checked using exactly the same combination of equipment as is planned for the taking of the field measurements. The same equipment verification procedure must be followed before transportation and after the equipment arrives at the measurement site.

The items listed below are not intended as advice or recommendations on how the measurement campaign should be approached; rather they should be carefully considered when planning the fieldwork.

The technical details of the boreholes: The technical details include the borehole diameters, inclinations, lengths, possible deviations from the starting inclination along the boreholes and technical details of the casing pipes. Moreover, it is important to be armed with information on possible highly fractured zones in the boreholes so as to avoid damage to the measurement equipment.

Concerning this particular measurement campaign, the equipment had to be detached from the trailer that usually contains all the necessary measurement equipment and support tools and accessories. The dimensions of the access tunnel prevented the transport of the whole of the trailer into the mine complex. The resulting setup had to be tested before being moved to the measurement site.

6.2 Quality control and data management during the fieldwork

The measurement data is recorded in the measurement computer from which the measurement operator copies the data to the processing laptop. At this point, the measurement data is stored in two different places. The measurement operator processes the data and plots the measurement results in figures that are included in the draft results. The draft results are checked on a daily basis by a different measurement operator. Once a measurement run has been completed, the results are verified once more and a quality control form is completed. The form contains basic information on the measurement process and the issues that need to be taken into account when processing the data in the office. The data from each of the measurement campaigns is backed up in Posiva’s server.

6.3 Measurement programme

The measurement programme consists of two measurement runs under two differing sets of pressure conditions. The first measurement run is conducted under open borehole conditions. Subhorizontal boreholes need to be closed using the borehole sealing mechanism so as to keep the borehole entirely filled with water; however, the borehole pressure is not increased. The borehole sealing mechanism must be installed in the borehole at a depth of 1 - 2 m depending on the quality of the borehole wall. This precludes the measurement of the top part of the borehole. In steeper boreholes that do not have to be closed with the sealing mechanism, the borehole can be open, thus allowing for the measurement of the top section.

6.3.1 Dummy probing

Dummy probing is conducted in order to assess the stability of the borehole and to verify that the borehole is open. The dummy probe also cleans the borehole wall of loose rock and other particles that might interfere with the measurement process. Any loose rock is collected inside the dummy probe and, when the probe is lifted out of the borehole, the collected material is analysed. If there are any rocks present that could possibly interfere with the measurement process or even cause the jamming of the probe, the dummy probing campaign must be repeated. The dummy probe has to be able to move down and up smoothly and no large rock fragments must be collected inside the dummy probe when extracted from the borehole before the measurement process proper commences.

6.3.2 Flow logging in open borehole conditions

Flow logging is first conducted under open borehole conditions. Downwards inclined boreholes can be open but horizontal boreholes must be closed in order to ensure that the borehole remains filled with water. In both cases, water is allowed to flow out of the borehole, thus ensuring that there is no increase in the pressure. In the optimal case, the borehole is left open over a long period of time prior to flow logging so that it can be assumed to have reached the steady state. The flow logging process requires that the measurement section is isolated from the rest of the borehole with rubber disks, thus ensuring that the fracture flow in the section moves exclusively through the flow sensor. The measurement section length is half a metre and the increment between the flow measurement locations is 0.1 m. The flow measurements are always taken with the winch in the stationary mode.

The flow, pressure, temperature and electrical conductivity are measured when the probe is in the stop position. The single point resistance is measured at a sampling rate of 1 reading/cm between the flow measurement locations. At ground level, the air pressure and water level are recorded in the same phase as the flow in the borehole. The measurement speed is around 10 m/h; however, depending on the borehole conditions, it is sometimes necessary to change the stabilisation and measurement times in order to obtain better quality results. This, naturally, affects the measurement speed.

The logging of flow under open borehole conditions detects flowing fractures with a depth accuracy of 0.1 m. The measurement of the pressure defines the pressure conditions in which the flow rates are measured.

6.3.3 Flow logging with increased borehole pressure

The second flow logging run is conducted under pressurised conditions. Ideally, steady pressure has been applied for such a time that all the fracture flows have stabilised. In reality, however, it is impossible to determine whether the flow rates have stabilised in all the fractures. The flow out of or into the borehole can be monitored until the flow is seen to have stabilised. However, in most cases, one or more fractures dominate; thus, it is not possible to estimate the conditions in fractures with small flows.

Flow logging under pressurised conditions is conducted in a similar way as under open borehole conditions, and the same quantities are measured. The logging procedure also detects those water conductive fractures that did not flow under open borehole conditions but which are in fact water conductive and are connected to a water source or sink. Based on the two flow logging runs, it is possible to calculate the hydraulic heads and transmissivities.

7 Results

7.1 Single point resistivity

Single point resistivity (SPR) measurements are taken for two main reasons with respect to the PFL DIFF measurements. Firstly, they enable the very precise depth matching of the measurement runs and, secondly, they can be used for the determination of the locations of fractures. The first objective, depth matching, is crucial since, due to the stretching of the cable, the determination of depth based on the cable length is prone to error. PFL flow logging is very sensitive to depth errors between measurement runs since errors in the determination of the depth causes similar errors in the pressure results. These errors can be avoided by the depth matching of the various measurement runs. In addition to the depth matching of PFL flow logging runs, depth matching can be performed using the geophysical measurement data (e.g. electrical resistivity) if available. In this way, a more extensive set of data can be used for the depth matching of different runs. Although the standard geophysical resistivity measurement process differs slightly from PFL SPR, in most cases it can be used for depth matching purposes.

The second objective, i.e. the determination of the positions of fractures, is less important since they are determined principally based on the flow logging data. Nevertheless, if a fracture position has been determined based on the flow logging data, which has a resolution of 0.1 m, the SPR data may provide a more precise indication of the location.

With respect to all four boreholes considered in this report, the quality of the SPR data was very high, thus simplifying the depth matching process. The SPR data is shown in graph form in the Annexes, i.e. in “Flow rate, pressure and single point resistance”.

7.2 Flow

The measured flow rates are shown in graph form in the Annexes, i.e. “Flow rate, pressure and single point resistance”. The fracture flow rates were interpreted based on the flow data. The triangles shown in the figures represent the interpreted flow rate and the direction of flow. The triangle that is pointed upwards denotes the flow from the bedrock into the borehole and the triangle that is pointed downwards denotes the flow from the borehole into the bedrock. The interpreted fracture depths are shown between the flow rate and SPR graphs.

7.2.1 L7-87D

Two flow logging runs were conducted, the first under open borehole conditions and the second when the borehole pressure was increased to around 2000 kPa. No flowing fractures were found during either of the logging runs. The noise level was good, i.e. below 10 mL/h along most of the length of the borehole.

7.2.2 S-33

When the borehole was open, 16 flowing fractures were detected and the same fractures plus four additional fractures were detected when the borehole pressure was increased to 20 bar. The flow direction was from the bedrock into the borehole when the borehole was open and from the borehole to the bedrock when the borehole pressure was increased. The noise level was low along most of the borehole. However, at a depth of 24 – 29 m, the noise level was somehow elevated during the taking of measurements under the increased pressure conditions. Concerning the measurements conducted under open borehole conditions, no fractures were undetected as a result of the elevated noise level. The depth interval from 6 m to 12 m featured no less than 9 fractures; however, since the flow anomalies were clear, the interpretation of the fracture locations and the flow rates was straight forward. Fractures at depths of 60.8 m, 63.6 m, 64.1 m and 64.6 m were detected only when the borehole pressure was increased. It was conjectured that the reason concerned the fact that these fractures are not connected to a water source that would cause the flow of water through them. Flow was detected when the pressure was elevated, thus indicating that these fractures are in fact water conductive.

7.2.3 S-24

9 fractures were detected under open borehole conditions and 14 fractures under elevated pressure conditions. The flow direction was into the borehole under open borehole conditions and into the bedrock under elevated pressure conditions. The noise level was mostly under 10 ml/h. The fractures at depths of 69.5 m, 69.8 m and 72.6 m were detected only when the borehole pressure was elevated. It was conjectured that the reason concerned the fact that these fractures are not connected to a water source that would cause the flow of water through them. Flow was detected when the pressure was elevated, thus indicating that these fractures are in fact water conductive.

7.2.4 L8-54DL

Borehole L8-54DL was measured three times since interference was detected concerning the measurement run conducted under pressurised conditions. In the 9 m to 21 m depth interval, the noise level was very high. The reason for this was unclear; however, the second attempt was successful and high quality measurement results were recorded along the whole length of the borehole. Three fractures were detected under open borehole conditions and nine when the borehole pressure was increased. The flow direction was into the bedrock under open borehole conditions and into the borehole under pressurised borehole conditions.

7.3 Pressure

The pressure was measured by the PFL DIFF probe during all the measurement runs. The measured pressure was converted into the hydraulic head value as presented in the Annexes entitled “Fresh water head in the borehole”. The figure shows the difference in the fresh water head between the un-pumped and pumped conditions. The fresh water heads were calculated using the density of fresh water; therefore, if the salinity increased towards the bottom of the borehole, the hydraulic head would increase accordingly.

The boreholes were first measured under open borehole conditions since the boreholes had been open prior to the measurement run and, thus, the flows had most probably had time to stabilise. In addition, open boreholes provide the best conditions for the detection of flows from the bedrock into the borehole. The second measurement run was conducted when the borehole pressure was increased to 20 bar. A 20 bar pressure difference is sufficient for the calculations since the greater the pressure difference, the less sensitive is the transmissivity calculation to measurement errors. The 20 bar pressure was created by pumping water into the boreholes. The pressure remained stable during the measurement runs.

7.4 Electrical conductivity and the temperature of the water

The electrical conductivity and the temperature of the water in the flow channel were measured during the flow logging procedure. Both values are important with regard to the quality control of the measurement procedure; however, they do not necessarily represent the real borehole conditions. Since the measurement probe carries water within its measurement section, the water measured is not necessarily from the depth at which it was measured. Moreover, horizontal boreholes must be filled with water prior to flow logging; therefore, the water measured may in fact be the filling water rather than the actual fracture water. The EC of the water is presented in the Annexes under the “Electrical conductivity of water”. The temperature of the water is presented in the Annexes under the “Temperature of the water”. All the reported EC values were temperature compensated to 25ºC. The compensation coefficients were modelled for Olkiluoto water by Posiva (Heikkonen et al. 2002).

The temperature in all the boreholes was higher at the bottom of the borehole than at the top.

7.4.1 L7-87D

The L7-87D electrical conductivity value was a straight line. This is natural since no flowing fractures were detected in the borehole.

7.4.2 S-33

A certain degree of variation in the EC values was detected in the top part of the borehole under open borehole conditions, whereas under pressurised conditions, the water pumped into the borehole definitely affected the EC results. At a depth of around 57 m, the EC values of the measurements taken under the open and pressurised borehole conditions were observed to merge. The reason for this was, most probably, that the pumped water does not reach greater depths. Flows into the bedrock were detected at a depth of between 60 m and 65 m.

7.4.3 S-24

The EC data for S-24 was similar to that of S-33. A variation was evident concerning the open borehole condition measurements and a higher measurement value under the pressurised conditions. Moreover, the curves were observed to merge close to the deepest fractures in the borehole. The pumped water evidently enters these fractures rather than flowing deeper into the borehole. While these fractures are located below 100 metres, the EC value changed at a depth of 97 m. The difference was due to the structure of the measurement probe. Between 97 m and 100 m, the water in the measurement section comprised the water that entered the measurement section deeper in the borehole when the borehole water already had a different salinity. This is why EC value changed at depth of 97 m instead of 100 m where the actual change most probably occurred.

7.4.4 L8-54DL

This borehole was flow logged three times, two times on one day and once on the following day. A difference was evident in the EC value concerning the results obtained under the pressurised conditions between the first and second days.

7.5 Transmissivity and hydraulic head of the fractures

The transmissivity and hydraulic heads of the fractures are presented in the Annexes under “Transmissivity and head of the detected fractures”; the same data is shown in tabular form in the Annexes under “Table of the transmissivity and heads of the detected fractures”. Section 5.3 provides an explanation of the effect of the measurement accuracy concerning the derived transmissivity and hydraulic heads. Limits must be calculated separately for each fracture since there are several factors that need to be taken into account.

Transmissivity values of between $2.96 \cdot 10^{-11}$ m/s^2 and $2.83 \cdot 10^{-8}$ m/s^2 were calculated from the measurement results. The noise level was low and the quality of the results was high, thus there are no significant uncertainties in the presented transmissivity results. The fracture head values were quite low considering that the boreholes were around 500 m below ground level. However, this is understandable since the boreholes were drilled in a mine environment and there could well be connections to other tunnels.

7.6 Water sample collection and in-situ measurement

A water sample was collected from the S-33 borehole using a double packer to isolate the target fracture. A fracture at a depth of 31.2 m was selected for the water sample collection. The double packer was installed at a depth of 30.6 m – 31.8 m. During the time that water was pumped into the borehole, approximately 1.32 litres of water flowed into the fracture. The length of the double packer section was 1.12 m and the borehole diameter 0.076 m; hence, the volume of the double packer section was around 5.1 litres. A 4 mm inner diameter hose was used to extract the water sample from the double packer section; the volume was around 0.4 litres. Thus, in total, a minimum of 6.82 litres of water had to flow out of the hose prior to obtaining the fracture water sample. The flow rate from the packer section was 444 ml/h; thus, it took at least 16 hours to extract the fracture water from the hose. In reality, the fracture water mixed with the water in the packer section; therefore, a longer waiting period is advisable. These calculations were presented to SURAO personnel on site; SURAO personnel also transferred the water sample to the container in which it was transported to the laboratory.

7.6.1 In-situ measurement and chemical analysis

The in-situ measurements were taken using a Multi 3620 IDS device supplied by the company WTW. The device measured the pH, the total dissolved solution, the temperature, etc. Only boreholes S-33 and S-24 were measured during the Posiva Flow Log campaign. This report presents the measurement and chemical analysis results obtained from the S-33 borehole only.

ID	S-33	unit
Date	13.09.2022	
Time	10:00	
TDS	506	mgl/l
pH	8,65	--
ORP	235,1	mV
Temperature	15	^{0}C
Notes		

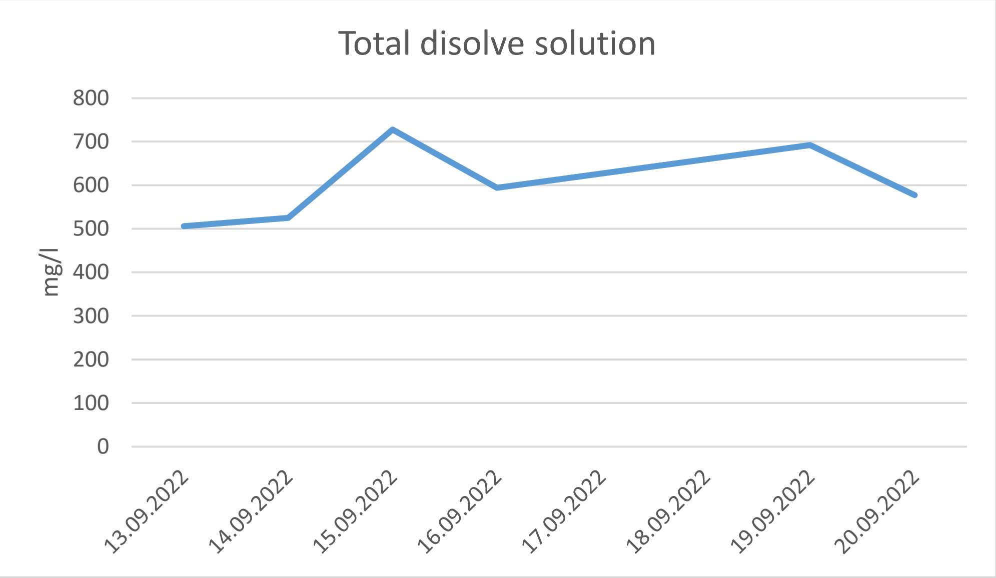
ID	S-33	unit
Date	14.09.2022	
Time	9:20	
TDS	525	mgl/l
pH	8,61	--
ORP	266,7	mV
Temperature	15,3	^{0}C
Notes		

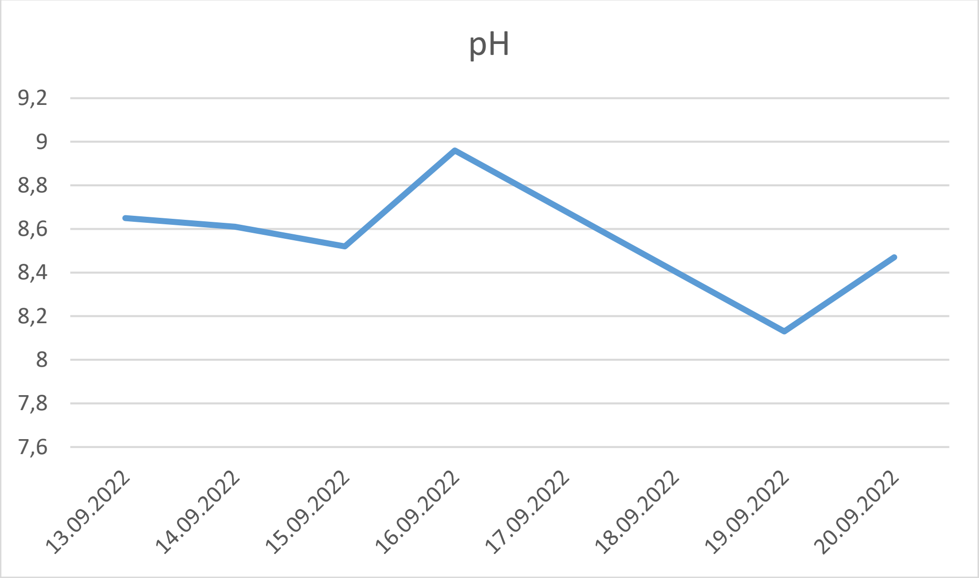
ID	S-33	unit
Date	15.09.2022	
Time	9:00	
TDS	728	mgl/l
pH	8,52	--
ORP	207	mV
Temperature	15,8	^{0}C
Notes		

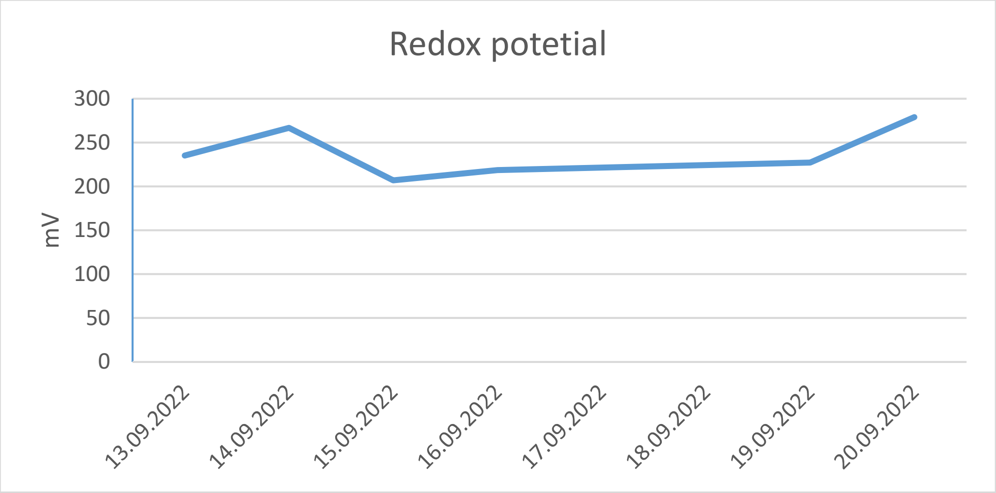
ID	S-33	unit
Date	16.09.2022	
Time	9:30	
TDS	594	mgl/l
pH	8,96	--
ORP	218,6	mV
Temperature	15,5	^{0}C
Notes		

ID	S-33	unit
Date	19.09.2022	
Time	11:00	
TDS	692	mgl/l
pH	8,13	--
ORP	227,2	mV
Temperature	15,7	^{0}C
Notes		

ID	S-33	unit
Date	20.09.2022	
Time	11:00	
TDS	577	mgl/l
pH	8,47	--
ORP	279	mV
Temperature	15,2	^{0}C
Notes		







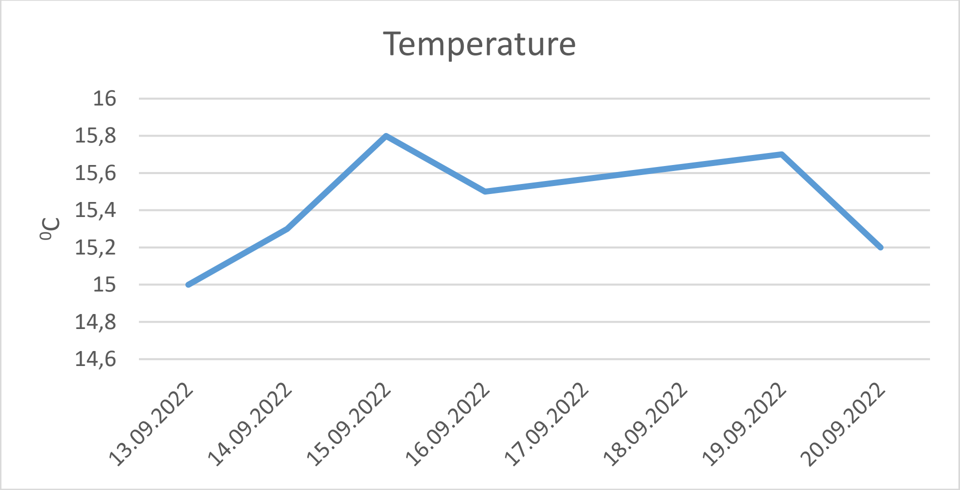


Table 6 provides details of the chemical analysis of the water sample extracted from borehole S-33. The double packer was installed at a depth of 30.6 m – 31.8 m; the total depth of this borehole is approx. 75 m. During the time in which water was pumped into the borehole, approximately 1.32 litres of water flowed into the fracture.

Table 6. Chemical analysis water from S-33 borehole.

Date sampling	ID depth # (m)	Type sample
19.09.22	S-33, 30.6 m – 31.8 m	water

Type	Method	A/N	Unit	S-33 Uncer.
Amonné ionty	SOP 1.8.1	A	**mg/l**	**<0,05** -
CHSK-Mn	SOP 1.2.1	A	**mg/l**	**0,99** 7%
Cl^-	SOP 1.1.1	A	**mg/l**	**22,4** 10%
NO^{3-}	SOP 1.1.1	A	**mg/l**	**<0,50** -
F	SOP 1.1.1	A	**mg/l**	**0,68** 11%
pH	SOP 1.3.1	A	**-**	**8,68** 0,1
SO_4^{2-}	SOP 1.1.1	A	**mg/l**	**102** 9%
Conductivity at 25°C	SOP 1.7.1	A	**mS/m**	**47,8** 3%
HCO^{3-}	SOP 1.13.1	A	**mg/l**	**91,5** 5%
Total volume beta activity	SOP 4.8.1	A	**Bq/l**	**<0,10** -
Rn (Rn 222) - 1. det.	SOP 4.11.1	A	**Bq/l**	**28,8** 14%
Rn (Rn 222) - 2. det.	SOP 4.11.1	A	**Bq/l**	**28,7** 14%
Ra (Ra 226)	SOP 4.10.1	A	**Bq/l**	**<0,05** -
As	SOP 5.20.1	A	**mg/l**	**0,00222** 25%
Ba	SOP 5.20.1	A	**mg/l**	**<0,0050** -
K	SOP 5.13.1	A	**mg/l**	**1,19** 15%
P total	SOP 5.13.1	A	**mg/l**	**<0,05** -
Al	SOP 5.20.1	A	**mg/l**	**0,0690** 15%
Mg	SOP 5.13.1	A	**mg/l**	**1,5** 15%
Cr	SOP 5.20.1	A	**mg/l**	**<0,00050** -
Li	SOP 5.20.1	A	**mg/l**	**0,00512** 15%
Mn	SOP 5.20.1	A	**mg/l**	**0,00518** 15%

Pb	SOP 5.20.1	A	**mg/l**	**<0,00050** -
Cu	SOP 5.20.1	A	**mg/l**	**0,00125** *25%*
Mo	SOP 5.20.1	A	**mg/l**	**0,00484** *25%*
SiO_2	SOP 5.13.1	A	**mg/l**	**13,8** *15%*
Ni	SOP 5.20.1	A	**mg/l**	**0,00061** *25%*
Sr	SOP 5.20.1	A	**mg/l**	**0,0732** *15%*
Na	SOP 5.13.1	A	**mg/l**	**84,0** *15%*
U	SOP 5.20.1	A	**mg/l**	**0,0190** *25%*
Ca	SOP 5.13.1	A	**mg/l**	**7,4** *15%*
Zn	SOP 5.20.1	A	**mg/l**	**<0,0050** -
Fe	SOP 5.20.1	A	**mg/l**	**0,103** *15%*
TOC	SOP 6.4.1	A	**mg/l**	**2,08** *15%*

7.7 Nonconformities and sources of inaccuracies

The taking of the measurements went as planned except in the case of L8-54DL, concerning which one additional measurement run was performed. The second measurement run, for which the borehole pressure was increased to 20 bars, was only partially successful, the reason for which is unclear. However, the repetition of the measurement procedure under the same conditions was successful and high quality results were obtained.

The measurement plan included two water sample collections from two boreholes. One of the water samples was collected from a depth of 31.2 m from borehole S-33. It was planned that a water sample would be extracted from borehole S-24; however, due to the time required to pump water into the borehole, it was decided that it would not be possible to obtain a representative water sample from the borehole in sufficient time. The pressurisation of borehole S-24 was initiated at 11:00 on 16.9.2022 and terminated at 10:10 on 19.9.2022; thus, the pumping period was 71 hours. The direct calculation of how much water flowed into the fracture at a depth of 50.8 m during pumping and the time it would take to flow out of the fracture indicated that the waiting period prior to the collection of the water sample would have been around 24 hours. However, considering that more than 100 litres of water flowed into the fracture and, most probably, mixed with the fracture water, it was considered that it would not be possible to collect a representative water sample within the time available. Moreover, concerning the other fractures, the waiting time would have been considerably longer.

8 Data evaluation

8.1 Quality control of the final data

The processing of the data that commences in the field is finalised in the office. Once the measurement results have been processed, interpretations are made of the transmissivity and hydraulic heads. Following the creation of figures and tables of the results, a report is compiled that explains the details of the field work and the data processing procedure. Once the report has been finalised by the main author, it is reviewed by an expert familiar with the PFL measurement process.

8.2 Data delivery

The data deliverables include all the raw data gathered during the measurement campaigns and the processed data presented in the final report. The raw data was delivered to SURAO to be stored in the data management system. Posiva Solutions is not responsible for maintaining the data once it has been delivered to the client. Nevertheless, Posiva Solutions will provide all the necessary knowledge concerning how the raw data is converted to processed data.

The processed data includes only that data that has been presented in this report. Some measurement runs were conducted for quality verification purposes only and some of the measurement runs were classified as having “failed”; thus, they have not been presented in the report. The reason for omitting such data is to ensure the ease of use of the processed data. No erroneous data has been presented or delivered in the form of processed data.

The processed data is delivered in the .CSV file format. The file names include all the necessary information on the measurement location and the types of measurement. A file named “BUS-24EC00E005D105.CSV” is shown as an example below.

Tab. 1. Description of the processed data file names

1	2	3	4	5	6	7	8	9
BU	S-24	EC	00	E	005	D	1	05

1	Measurement site (2 digits), Bukov (BU)	
2	Borehole (4 digits), S-24 (S-24)	
3	Type of data (2 digits)	
	EC	Electric conductivity of water
	SP	Single Point Resistance
	FL	Flow logging
	PR	Pressure profile along the borehole
	GW	Groundwater level in the borehole during flow logging
	GL	Groundwater level measurements
4	Length of top of casing to water level sensor in metres (2 digits), 0 m (00) In tunnel boreholes water level sensor is not used.	
5	Type of measurement (1 digit)	
	A	Borehole EC and temperature without pumping
	B	Flow logging without pumping
	D	Borehole EC and temperature with pumping
	E	Flow logging with pumping (in tunnel all flow logging measurement are considered to be conducted in pumped conditions)
	G	Flow logging and fracture EC measurement with pumping

6	Section length (3 digits) 020 = 2.0 m, 005 = 0.5 m	
7	Data format (1 digit)	
	R	Raw data
	D	Processed data as a function of depth
	T	Processed data as a function of time
8	Number of repeated measurements (1 digit)	
9	PFL probe number (2 digits)	

All the measurement activities that were reported are listed below in Tab. 2.

Tab. 2. The reported measurements and delivered files

Borehole	Start	End	Activity	Deliverables
L7-87D	6.9.2022	7.9.2019	Dummy logging. Two repetitions were required.	-
L7-87D	07.09.2022 10.26	08.09.2022 09.07	Flow logging, open borehole(L= 0.5 m, dL=0.1 m)	BUL787EC00E005D105.CSV BUL787FL00E005S105.CSV BUL787SP00E005D105.CSV BUL787GW00E005D105.CSV
L7-87D	08.09.2022 12.12	09.09.2022 09.07	Flow logging, borehole pressure c. 2000 kPa (L= 0.5 m, dL=0.1 m)	BUL787EC00E005D205.CSV BUL787FL00E005S205.CSV BUL787SP00E005D205.CSV BUL787GW00E005D205.CSV
L7-87D			Fractures table	L7-87DFracturesTandHead.csv
S-33	07.09.2022 10.25	07.09.2022 16.00	Dummy logging. Two repetitions were required.	-
S-33	12.09.2022 12.51	13.09.2022 08.57	Flow logging, borehole pressure c. 2000 kPa (L= 0.5 m, dL=0.1 m)	BUS-33EC00E005D205.CSV BUS-33FL00E005S205.CSV BUS-33SP00E005D205.CSV BUS-33GW00E005D205.CSV
S-33	13.09.2022 11.42	14.09.2022 13.13	Flow logging, borehole pressure c. 2000 kPa (L= 0.5 m, dL=0.1 m)	BUS-33EC00E005D205.CSV BUS-33FL00E005S205.CSV BUS-33SP00E005D205.CSV BUS-33GW00E005D205.CSV
S-33			Fractures table	S-33FracturesTandHead.csv
S-24	13.09.2022 11.42	13.09.2022 12.44	Dummy logging.	-
S-24	15.09.2022 11.03	16.09.2022 08.45	Flow logging, borehole pressure c. 2000 kPa (L= 0.5 m, dL=0.1 m)	BUS-24EC00E005D205.CSV BUS-247FL00E005S205.CSV BUS-24SP00E005D205.CSV BUS-24GW00E005D205.CSV
S-24	16.09.2022 11.34	19.09.2022 10.08	Flow logging, borehole pressure c. 2000 kPa (L= 0.5 m, dL=0.1 m)	BUS-24EC00E005D205.CSV BUS-24FL00E005S205.CSV BUS-24SP00E005D205.CSV BUS-24GW00E005D205.CSV
S-24			Fractures table	S-24FracturesTandHead.csv
L8-54DL	20.09.2022 08.30	20.09.2022 10.17	Dummy logging.	-
L8-54DL	20.09.2022 10.17	20.09.2022 13.08		BU54DLEC00E005D205.CSV BU54DLFL00E005S205.CSV

			Flow logging, borehole pressure c. 2000 kPa (L= 0.5 m, dL=0.1 m)	BU54DLSP00E005D205.CSV BU54DLGW00E005D205.CSV
L8-54DL	20.09.2022 14.47	21.09.2022 08.54	Flow logging, borehole pressure c. 2000 kPa (L= 0.5 m, dL=0.1 m)	BU54DLEC00E005D205.CSV BU54DLFL00E005S205.CSV BU54DLSP00E005D205.CSV BU54DLGW00E005D205.CSV
L8-54DL	21.09.2022 09.45	21.09.2022 09.42	Flow logging, borehole pressure c. 2000 kPa (L= 0.5 m, dL=0.1 m). Repeated measurements due to the poor data quality from the previous measurement run.	BU54DLEC00E005D305.CSV BU54DLFL00E005S305.CSV BU54DLSP00E005D305.CSV BU54DLGW00E005D305.CSV
L8-54DL			Fractures table	L8-54DLFracturesTandHead.csv

8.3 Recommendations

The basic PFL DIFF measurement programme for tunnel boreholes is very simple. Two measurement runs are performed under two differing sets of pressure conditions. In this case, the first run was conducted under open borehole conditions and the other with elevated pressure. In certain cases, it might be beneficial to apply different pressures; for example, if the outflow from the borehole is significant, it can be reduced by increasing the borehole pressure.

The collection of water samples needs to be planned in particular detail. If water is pumped into a borehole prior to the collection of water, it could be difficult to obtain representative water samples from the fractures since the pumped water may have mixed with the fracture water. It is also possible to conduct the open borehole flow logging process first, followed by the collection of water samples and then to conduct the flow logging procedure under pressurised conditions. This approach ensures that the fracture water is not contaminated by the pumped water.

The measurement equipment was surrounded by reflecting tape and equipped with flashing lights; however, these precautions covered only the equipment. The personnel involved in the measurement process also worked outside the marked area. In the vicinity of boreholes S-24 and S-33 a mine train passed several times and, sometimes backwards, i.e. the carts were pushed by the engine from the back, which meant that the driver was unable to see in front of the carts. The appraisal of safety following the completion of the fieldwork concluded that a risk was posed to both the equipment and the personnel and that such a situation should not be allowed in the future. The whole of the area in which the work is performed must be isolated from all the other activities in the underground environment. In practice, this means that the railway track must be temporarily blocked so that it is not possible to drive trains through the area used for research purposes.

9 Summary

SURAO requested that Posiva Solutions take PFL DIFF measurements in four research boreholes and to demonstrate the capabilities of the equipment and the method.

Water flowing fractures were identified to a depth accuracy of 0.1 m. The transmissivities and hydraulic heads of the fractures were estimated based on the measurement results. The transmissivities and hydraulic heads were represented as fracture-specific values. In addition to the measured and interpreted values, the technical details of the measurement equipment and the related interpretations were explained to the Client’s representatives.

A total of 43 flowing fractures were detected in three of the boreholes. No fractures were identified in borehole L7-87D.

One water sample was collected from a fracture at a depth of 31.2 m in borehole S-33.

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