Posiva Flow Log (PFL), Tool for detection of groundwater flows in bedrock

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Abstract Groundwater flow in borehole is conventionally measured with inline spinner or thermal pulse flow loggers that measure water flow along a borehole. This is fast way to find the most flowing fractures but measurement accuracy depends on total flow below measurement depth. If total flow along a borehole is very large it is very difficult to detect smaller flow changes that indicate flowing fractures. Posiva flow log tool avoids the deterioration of measurement accuracy by introducing a flow guide that bypasses flow along a borehole and measures only the flow coming from a certain borehole depth interval, associated with fractures.

Key words Posiva flow log, groundwater flow, borehole, hydrology, flow measurement

Introduction

Posiva flow log (PFL) tool has been developed by Pöyry for hydrogeological investigations in design and construction of repository of high-level spent nuclear fuel. The development of the tool started 30 years ago and first measurements were conducted in early 90s. The device has been used mostly in investigations for Posiva and SKB, the nuclear waste management companies in Finland and Sweden, and hundreds of boreholes have been measured during more than 20 years. In recent years couple of measurement campaigns have been conducted also for mining companies. Posiva Oy is the owner of the PFL measurement tools but Pöyry conducts the PFL measurements.

The measurement technique of PFL tool is unique and it combines accuracy and resolution of double packer hydraulic testing and measurement speed of inline spinner or thermal pulse flow logger. The idea of the PFL measurement is different than the basic double packer hydraulic measurement. In double packer measurement the measurement section is isolated by inflatable packers and pressure in the measurement section is changed in order to obtain flow changes. The isolation by inflatable packers is a slow process and the pressure change after packer inflation takes some time too. With PFL tool the isolation of measurement section is done with flexible rubber discs (*Figure 1*) that maintain the isolation of measurement sector even during movement of the tool and therefore no time is needed for isolating the measurement section after moving the probe to a new location. Apart of lacking requirement for inflatable packers, the measurement is speeded up by using constant drawdown created by borehole pumping to create pressure changes to obtain flow values in different pressures. With PFL measurements two different pressure conditions are obtained with two individual measurement runs. During both of the measurement runs the pressure (drawdown) is kept steady. Usually the first measurement run is conducted in natural (non-pumped) conditions and another one while water level is kept lower by pumping continuously. This way pressure conditions are steady during flow measurements and there is no need to wait for pressure changes in all measurement locations.

Figure 1 *PFL tool with measurement section setup. Yellow disks are used to isolate measurement section from rest of the borehole.*

PFL Method

The PFL tool measures water flow, pressure, electrical conductivity (EC) and temperature of the borehole water and single point resistance of borehole wall. All these, except single point resistance, are measured in every measurement location when probe is at standstill. The measurement time at each station is 45 seconds. Resistance is measured also during moving the probe between measurement stations. As the measurement time is so short the entire measurement speed depends on number of measurement points and speed that the probe is moved. The speed of movement cannot be very fast but about 5cm/s speed can be obtained. The flow sensor in the probe is very small and that is the component which has required most development. The flow sensor is a plastic tube with three thermistors inside. All of the thermistors measure temperature and the one in the middle also has a heating function. The determination of flow rate through the flow sensor is based on giving a heat pulse with the central thermistor and monitoring the cooling of the thermistor. The faster the temperature drops after the heat pulse the larger is the flow rate. Using different heating powers flow rates of 30 – 300 000 ml/h can be determined. The temperature of water is recorded also before the heat pulse.

High precision pressure measurement is needed to record the exact pressure conditions in which flow rates are obtained. Especially the pressure difference between the two measurement runs has to be determined with high accuracy. The pressure sensor fitted into PFL probes works in pressure range from 1 bar to 150 bar.

Electrical conductivity of water is measured with a commercial sensor which has been modified to endure high pressure and fitted to the PFL probe. The electrical conductivity can be measured from borehole water or from flow channel before the fracture water mixes with the borehole water. EC readings are calibrated with laboratory reference liquids (KCl) to a high accuracy.

Single point resistance is measured between single point electrode between rubber disks (*Figure 1*) and body of the probe. Borehole features visible in the resistivity data are fractures that allow water flow over the rubber disks and changes in electrical conductivity of borehole wall rock. The resistance is recorded while the probe is moved to next flow measurement point and therefore depth resolution of the resistance data is about 1/cm. The single point resistance anomalies can be used for depth matching between different measurement runs, and it also reveals position of a flowing fracture because fractures typically are seen as low resistance anomaly along logging profile in the rock mass.

The boreholes can be up to 1500 m long and diameter in range from 56 mm up to 200 mm. The most typically measured borehole diameter is 76 mm (NQ). The quality of drilling affects the quality of measurement results as smooth borehole wall ensures that the rubber disks isolate the measurement section well. Therefore diamond (core) rotary drilled boreholes are preferred as the quality of borehole wall is better than in boreholes made with other drilling techniques.

Finding water flowing fractures in a borehole is probably the most important task for the PFL tool. While a borehole is pumped and sufficient drawdown has been created all water-flowing fractures should be visible to PFL probe. Usually all flowing fracture locations can be found with one measurement run under pumped conditions. The PFL probe measures the flow that comes from the measurement section and therefore the total flow along a borehole doesn't affect the ability to detect flowing fractures along a borehole. The inline spinner flow logger on the contrary measures the flow along a borehole and therefore as the flow rate increases in upper part of a borehole the measurement accuracy deteriorates. The *Figure 2* illustrates the difference of fracture flow determination using PFL probe when flow is measured from measurement section and when flow along a borehole is measured. Red line represents the PFL measurement with 2 m section length and green line represents the measurement of flow along a borehole (measured with PFL probe by removing lower rubber disks and blocking bypass tube). Two fractures are detected from the flow along a borehole flow but no more. The flow along the borehole changes between depths of 10 – 50 m by 2 litres per minute but the exact depth of the change is difficult to be said. In this case fractures above depth of 52 m cannot be detected based on flow along the borehole measurement (spinner or thermal pulse) even though there are fractures with total flow of more than 1 l/min. The PFL tool can differentiate between each of the fractures, provide their exact position in borehole length and fracture specific transmissivity. Minimum duration of the PFL measurement in 1000 m long borehole using 5 m long section and 1 m measurement interval is about two days.

Using other borehole logging and core logging data, like acoustic or optical televiewer images and borehole geophysical data, it is possible to associate the flow data into borehole conditions, faults, as well as fracture orientations and aperture. Associating the flow data to fractures, and for example to fracture network analysis or numerical hydraulic modelling, is requiring depth matching to core data, which is enabled by dense station interval, good position accuracy and depth reference data provided by single point resistance logging.

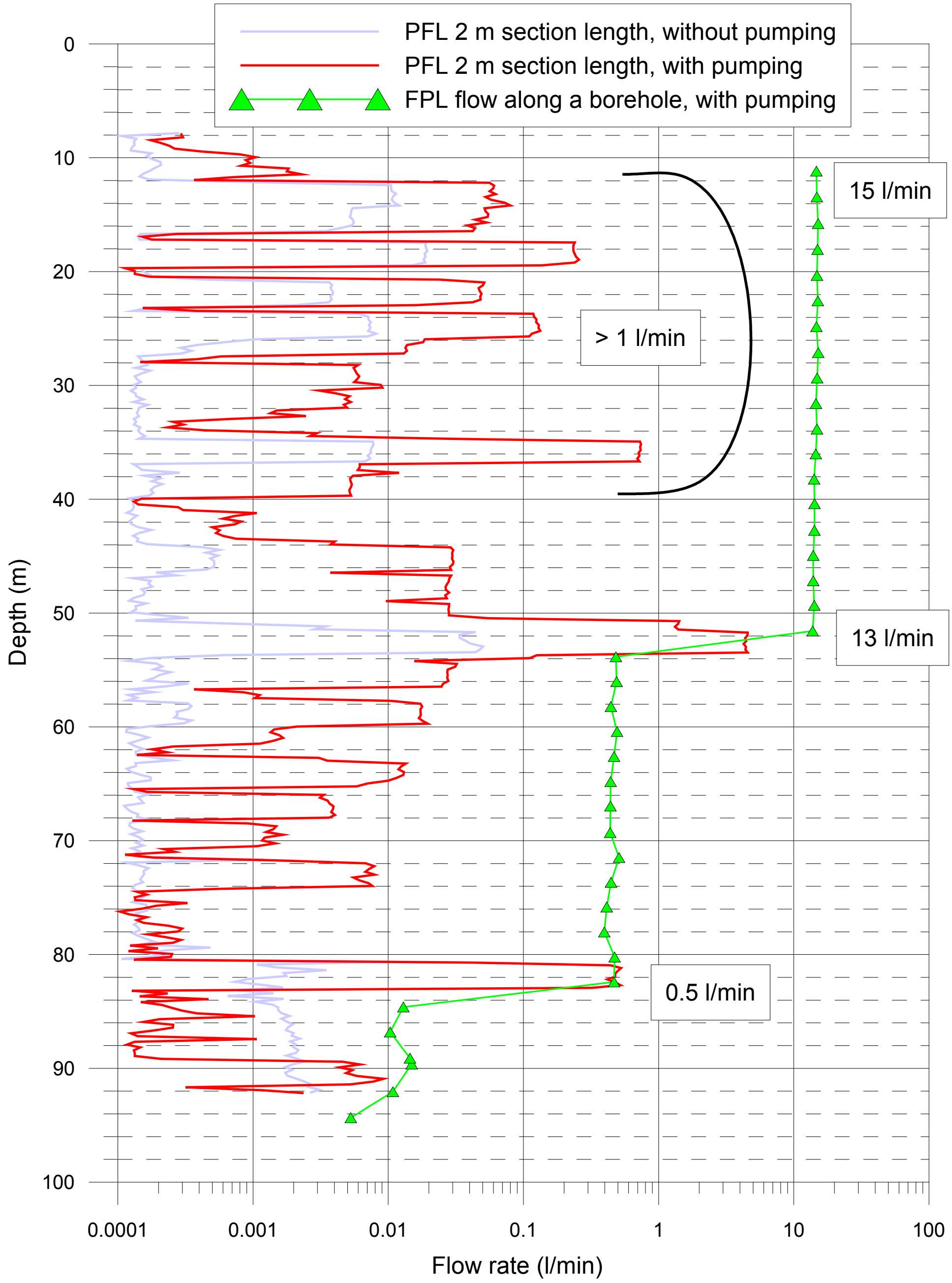

Figure 2 *Comparison of flow logging results obtained with PFL tool using flow guide to measure flow from measurement section and flow along a borehole. Each rectangular shaped level has width of sector length (here 2 m) and has eight flow records (here at 0.25 m spacing).*

Length of the measurement section can be from 0.5 m to 10 m and measurement interval is usually about 1/5 of the measurement section length. The reason for measuring flow more frequently than once at a certain borehole section is that not all flow measurements are successful and because interleaved measurements improve flow interpretation in regards to both flow rate and fracture location. Bad borehole sections might cause rubber disk leakages at one measurement point but the flow rate at the depth can still be determined based on previous and next measurement points. The measurement interval determines how accurately flowing fractures can be located in a borehole.

Transmissivity of borehole section can be estimated based on single measurement run in pumped conditions with an assumption that fracture flows are zero in natural (unpumped) conditions. In reality not all flow rates are zero in natural condition but usually so small that they can be neglected in order to get estimate of transmissivity. However in some cases pressure conditions in the surrounding bedrock are affected by hydraulic sinks (hydraulic connections to lower pressure potential) like underground tunnel or a valley nearby. In these cases fracture flows might be directed out of a borehole even during pumping of a borehole. In these cases transmissivity cannot be estimated based on one measurement as flow rate into bedrock in unpumped conditions is larger than during pumping and it cannot be estimated. Using minimum two drawdown levels, it is possible to define structure or fracture specific hydraulic head even in case of topographic differences (valleys and hills) and in case of tunnels and underground workings (openings). Usually the other pressure condition is natural conditions without pumping of measured borehole. When flow rate in unpumped conditions has been measured the transmissivity can be estimated based on flow and pressure differences between the two measurements taking into account certain assumed flow geometry (Marsily 1986).

Water sample collection

To obtain information from electrical conductivity of groundwater in the fractures rather than in the open borehole, the PFL probe can be stopped at a fracture location for longer time to measure electrical conductivity of water. At a constant drawdown the EC of groundwater gradually changes to level representative for the fracture. Continuing monitoring several minutes until the EC reading would be stabilised onto a low or high level compared to surrounding borehole, the fracture EC value (and time series) can be stored, and this data further used in groundwater salinity interpretation.

In addition to measuring ground water flows from fractures the water coming from fractures can be collected into a container. The water sample collecting process is similar with normal PFL flow logging but when a target fracture has been reached the probe is stopped on the fracture. While the probe is on the fracture and ground water flow coming from the fracture is measured also the electrical conductivity of water is measured. After the flow and EC values are stabile valves of the sample container are opened. The measurement of flow and EC are on all the time during water sample collection and when the water contained has been filled with fracture specific water the valves are closed. Selection of a fracture from which sample is taken is based on preceding PFL measurements, and the sampling is a separate downhole run for each specimen. Container is retrieved after each sampling, and brought to laboratory for more precise analysis.

The basic procedure of collecting a water sample from a water flowing fracture is described above but what are the factors that should be considered when choosing where to take water samples. It is clear that the more the borehole is pumped the larger are the fracture flows and the faster the sample collection is. But how do we make sure the water coming from a fracture really is originally from the same fracture? Estimations of representativeness of fracture specific water can be made based on fracture flow rates in natural conditions.

Example case for selecting fractures for water sampling is presented in *Figure 3*. In this case most of the fracture flows are large and taking water sample looks easy. But what if the borehole has stayed as it is several months after it was drilled. Is it possible that some of the fractures had had flow into the bedrock? This can be cleared up by measuring the fracture flows in unpumped conditions (gray line in *Figure 3*). In this case the fracture at depth of 65 m seems to have flow into the bedrock (triangle pointing up means flow direction from bedrock into a borehole and triangle pointing down flow into bedrock). The flow is not large, only 0.1 l/min, but over time large quantities of water can flow into the fracture. In this case 0.15 l/min flow continuing one month accumulates to total of 6500 litres of water. All this water is originated from other fractures in the borehole. When water sample collection is started flow rates in unpumped and pumped conditions should be known in order to estimate how long pumping period is needed before representative water sample can be taken. In this case it would take more than 4 days to get same amount of water out from the fracture than entered the fracture during a month in natural conditions.

The water sample container maintain the water pressure when brought up therefore possible dissolved gases stay inside the container and can be analysed in a laboratory. The container has been rated up to pressure of 150 bar so it can be used to collect samples from depth between 0 – 1500 m.

Measurement sites

Most of the PFL measurements have been conducted for nuclear waste management companies in Finland and Sweden which means the measurement tools pass the high quality requirements (Ludvigson et al. 2002). In mining industry requirements are a bit different but still high quality results and cost effective measurements are expected. The flow measurement accuracy (ml/h) of PFL tool is always the same so lowering the accuracy requirements doesn't speed up the measurement. But lowering the accuracy in which flowing fractures are localized does speed up the measurement because less flow measurements have to be done per borehole. In 1000 m long borehole 10 000 individual flow measurements are needed to obtain 0.1 m accuracy in fracture localization. While localizing fractures with the accuracy of 1 m requires only 1000 individual flow measurements and actual flow measurement time is 1/10 of the measurement time. Time for moving the probe in the borehole remains the same therefore the entire measurement duration is not reduced according to the same ratio.

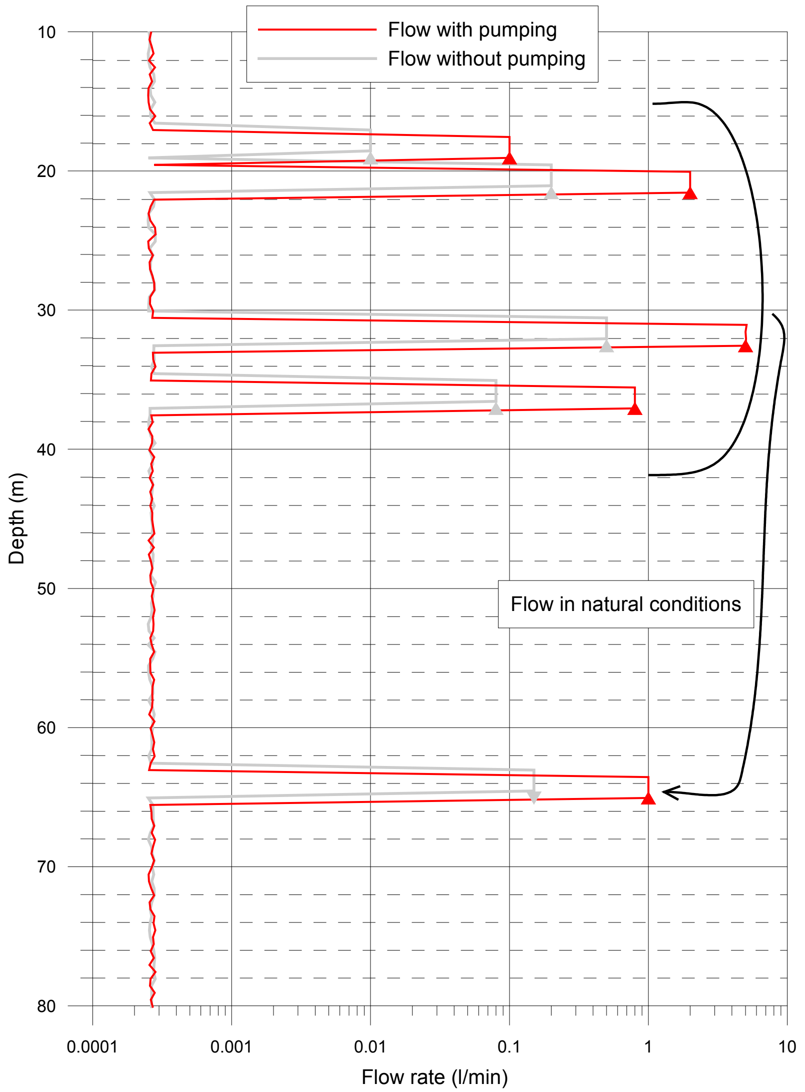

Figure 3 *Example of flow conditions in natural conditions. Water from fractures at the upper part of the borehole flow into fracture lower in the borehole.*

The PFL equipment is packed in to a trailer which can be taken into different kind of sites. Two examples of measurement sites are presented in *Figure 4*. At Suhanko in Ranua (Gold Fields Arctic Platinum Oy) several boreholes were measured under pumped conditions in 2013. The measurement sites were not accessible with van and trailer so the measurement trailer was lifted on forestry tractor and transported with it. At Nussir mountain in Norway (Nussir ASA) the measurement site located up on a mountain and a bulldozer was used to pull the measurement trailer to the measurement site. Also at Nussir only one measurement run per borehole was conducted in 2016.

Figure 4 Examples of measurement locations. On the left Suhanko (Gold Fields Arctic Platinum Oy) and on the right Nussir mountain (Nussir ASA)

Conclusions

Posiva flow log method is a fast measurement technique to investigate hydraulic conditions in bedrock around a core drilled borehole. The measurement accuracy is high enough for investigations related to high level spent nuclear fuel repository building but the measurement setup can be modified to meet lower accuracy requirements and higher cost efficiency requirements of mining industry. Results have been applied for groundwater management in feasibility assessment stage, and during mining operation.

Water sample collector can be attached to the PFL probe. With the water sampling configuration the measurement is conducted similarly as without water sampler but water sample can be taken at wanted depth and lifted out of a borehole.

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