Hydrogeological Bedrock Characterisation Based on Posiva Flow Log Measurement Data

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Abstract

The hydrogeological characterisation of soil and bedrock at a mining site is needed for both planning dewatering and for environmental risk assessment in mining projects. The required level of detail is dependent on both the project's development phase and site-specific requirements. This also requires a flexible investigation approach.

The Posiva Flow Log (PFL) is a measurement method which has been developed based on the high requirements needed for spent nuclear fuel repository studies. Nevertheless, the PFL method is very flexible and the measurement speed vs. measurement accuracy can be adjusted even during a measurement. Therefore, PFL utilization was also introduced in the mining industry. This paper summarizes how the PFL method can support bedrock characterisation.

Keywords: Posiva Flow Log, PFL, hydrogeology, bedrock characterisation, borehole

Introduction

Water management planning is one of the most critical tasks in the mining industry and requires a good understanding of the site hydrogeology. Hydrogeological studies start with site conceptualisation. This includes a description of the relevant water bodies and catchment areas, the topography, position of the bedrock surface, bedrock characteristics, known fractured zones, soil layers, information on the groundwater table, climate data and a draft of the planned operations. The first conceptualization enables planning the hydrological and hydrogeological field measurement campaigns. Field measurements are needed for gaining representative input data for assessments and modelling work. Field data is also used for reviewing and updating the conceptualization.

The first hydrogeological field testing campaigns should take place well in advance during the early mining project development stages. Mines also expand, and complementary hydrogeological measurement and hydrogeological model updates are also needed by operating mines. Furthermore, complementing the data during the mine's operational time allows further model calibration.

Conceptualization and field data are used further in the generation of a numerical hydrogeological model. Numerical hydrogeological modelling is used for estimating the water quantities leaking into the underground workings or open pits. Modelling is also used for understanding how mine dewatering affects the groundwater table in the surroundings. The need to understand the mine site hydrogeology is not limited to the mine operational time: to a reasonable extent, also post-closure groundwater flows must be understood. The risks of contamination transport via groundwater may increase after mine closure. After pits or underground workings are filled with water, groundwater no longer flows into the mine – it flows away from the mine, and its extent depends on the site-specific circumstances.

In addition to flow data, hydrogeological field campaigns can also provide information on electrical conductivity, redox potential measurements, pH and chemical substances. Sometimes also isotope samples are taken. This data can help to understand groundwater regime and contact with surface water bodies. Water quality data, for example information on salinity, is also needed for water management planning.

Requirements for groundwater field measurement data include its representativeness, (correct and adjustable) accuracy and suitability as input data for the modelling work. Also, effective ways to collect both physical and chemical field data are increasingly needed for generating better input data for both water management planning and environmental impact assessments. To serve these objectives, utilization of Posiva Flow Log (PFL) measurements in mining environments was initially started. The following chapters summarize some benefits of the method and suitable utilization situations based on experience.

Posiva Flow Log (PFL) measurement methods

In crystalline bedrock most of the groundwater movement occurs in fractures. Therefore, a definition of fractures and their properties is highly important. A common solution to collecting actual water conductivity data is through water flow measurements in boreholes drilled into the bedrock. There are a large range of flow measurement techniques. At one end of the range are pumping tests in which the entire borehole is treated as one source. At the other end of the range are very detailed double packer measurements, in which individual fractures can be studied separately isolating them from rest of the borehole. The cost and required time to conduct measurements varies, and selecting a suitable measurement method requires an understanding of the different measurement techniques. Additionally, understanding the measurement conditions at the study area affects the reasonable usage of the measurement data.

Posiva Flow Log (PFL) devices have been developed for use in boreholes drilled into crystalline bedrock in which the borehole walls are smooth and the collapse of the borehole is not likely. This ensures that rubber disks isolating the target borehole section do not leak and the flow from a specific borehole section is guided through the flow sensor. Fractures and fractured zones in a borehole naturally cause rubber disks to leak but this is not a problem when the length of a fractured zone along a borehole is shorter than length of the measurement section used, and as long as the measurement interval is short enough. The measurement section length can be tens of meters. Figure 1 shows a PFL tool that is lowered into a borehole.

In any measuring approach, it is very important to know if the measuring affects the measured quantity and how. The existence of groundwater in bedrock fractures and pores can be estimated based on geophysical studies without drilling holes into the bedrock, but an estimation of flow rates in fractures requires steering the actual flow through a flow sensor. Drilling a borehole into the bedrock definitely affects the ground water flow conditions and this has to be taken into account in the modelling. Before drilling a borehole, water flows along fractures and there are usually no large pressure gradients along a fracture. After a borehole has been drilled, the water flow along a fracture is affected by the borehole and large pressure gradients are possible in fractures close to borehole.

After borehole has been drilled, the ground water flow between the borehole and fractures stabilises to a certain level. Alternatively, if flow rates in pumped conditions are needed, the borehole is pumped and flow stabilisation is allowed. These are the flows that can be measured but should not be affected by the measurement device. This is valid for measurement methods that require steady state conditions and the duration of the entire measurement is kept short by maintaining a steady state throughout the entire measurement. If steady state flow condition cannot be maintained while the measurement device is placed into a fracture, some stabilisation time is required at each measurement position to achieve a steady state.

Figure 1. PFL tool with 0.5 m long measurement section. Yellow rubber disks isolate the measurement section.

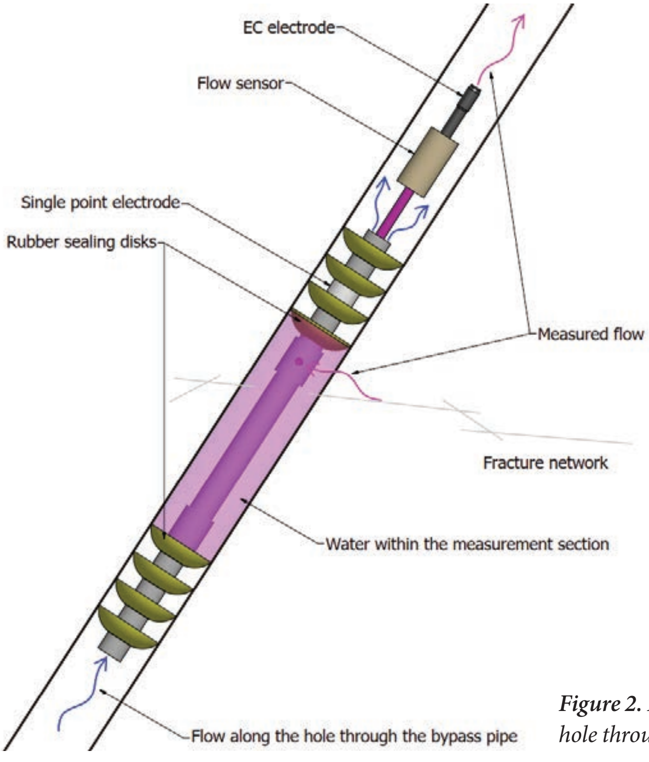

Figure 2. *Flow from the bedrock into a borehole through the flow sensor in a PFL probe.*

The PFL measurement method has been designed so that it does not affect the water flow from the fracture or the flow in a borehole. Figure 2 illustrates how the flow from a bedrock fracture is guided through the flow sensor in a PFL probe and how the flow in a borehole is steered past the probe. The two flow paths through the PFL measurement tool have been designed so that the flow in the borehole can be quite large, up to 100 L/min, and it does not cause friction that would prevent the water flow in the borehole or cause a pressure difference over the probe. The flow channel from the measurement section over the flow sensor and electrical conductivity electrode is smaller to enable very accurate measurement, and therefore large flows can be affected by the probe. Based on experimentation, flows smaller than 5 l/min through a flow sensor do not result in large flow changes.

One of the key features of the PFL method is the adjustable section length and measurement interval. These two elements determine how accurately an individual fracture's flows are measured and localised in a borehole. A short section length helps to identify and measure individual fractures' flows: if only one fracture is within the measurement section the measured flow comes from the individual fracture. On the other hand, a short measurement section length and interval increase the measurement time and the possibility of rubber disk leakages in fractured borehole sections.

An example of a measurement that has been conducted with two measurement section lengths is presented in Figure 3. Theoretically, all four fractures can be found and flow rates can be determined based on both measurements, but the spatial accuracy is lower when a longer measurement interval is used. All fractures between consecutive measurement points are treated as one fracture. A longer measurement section length also increases uncertainty in the definition of the flow rate. In this example, the flow rates of fractures at depths of 41.5 m and 44.8 m can be measured directly, but determination of flow rates for fractures at depths of 42.6 m and 43.8 m requires observing changes in the flow curve when a 2 m section length is used.

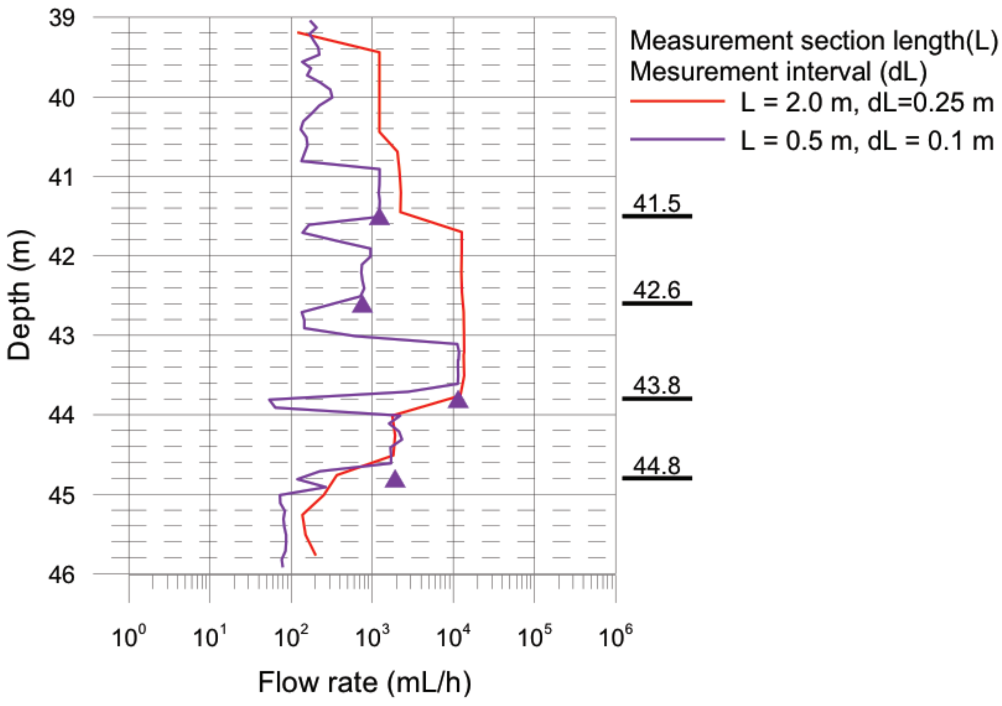

Figure 3. *Fracture flows measured with 0.5 m and 2 m measurement section lengths.*

When a 0.5 m section length is used, all fracture flows can be measured separately.

In addition to measuring groundwater flows a PFL tool can be equipped with a water sample container to take samples of the water coming from the fracture. The water samples can be taken from fractures without mixing the water with the borehole water. Water sample container can be closed at a fracture and the water pressure can be maintained until the water sample is released from the container in a laboratory.

Monitoring

Once an initial site-specific survey has been performed and construction of underground workings begins, a hydrogeological monitoring programme should be determined. The programme needs to be specified depending on the hydrogeological conditions, assessed effects on groundwater pressure and water table, and possible risk of contamination transport. Typically, hydrogeological monitoring covers both the groundwater table in the soil layer and pressure in the bedrock. Groundwater sampling and analysis are an essential part of conventional monitoring programmes.

Hydrogeological monitoring can be composed of both automatic measurements, which provide continuous time series information on short-term changes, and measurement campaigns. Different kinds of PFL-measurements are suitable for monitoring campaigns, e.g., when information on flow, pressure, or groundwater composition at varying depths are needed.

Parameters for numerical modelling

One modelling parameter that is obtained from PFL measurements is the specific capacity of the fractures (Q/Δh). This parameter is obtained by measuring fracture flows in two different pressure conditions. Usually, the first measurement run is conducted in non-pumped conditions where the flow rates are usually small. The second measurement run is conducted while the borehole water level is lowered by pumping water out of the borehole. The water level in the borehole is kept stable before and during flow logging in order to maintain steady state conditions. Another way to obtain the specific capacity is to conduct only one measurement run while the water level is lowered and to assume that the flow rates in the non-pumped conditions are equal to zero. This is reasonable if the flow rates are assumed to be small in non-pumped conditions. If the studied area is flat and there are no underground facilities, large flows under non-pumped conditions should not occur. This is also a matter of accuracy for which the specific capacity needs to be defined. If only a rough estimation is needed, the flow rate in non-pumped conditions can be disregarded and Q can be the flow rate in pumped conditions. For modelling purposes, the specific capacity is usually converted to transmissivity by assuming the flow geometry for the flow coming from the bedrock into the borehole and using Thiem's equation (Marcily 1986). In addition to the transmissivity, the hydraulic head of a fracture can be determined based on flow measurements under two different pressure conditions. This is done assuming a linear dependency between the fracture flow and the borehole pressure and extrapolating a pressure that corresponds to a zero flow rate. Theoretically the calculated pressure should be equal to measured value when the fracture is isolated by double packer. PFL probe can be modified by replacing rubber disks by double packer to measure pressure while fracture flow is zero. This setup is suitable only for measuring individual fractures.

Fractures that can be detected by PFL measurements have to be connected to a water source either directly or through a fracture network. Fractures crossing a borehole can have large transmissivities but if they are not connected to a water source or there is small transmissivity in the fracture network between a borehole and water source large transmissivities will not be detected. This has to be taken into account while using the measurement data in modelling.

Modelling methods

PFL results can be used in hydrogeological models. These models can be parametrised from the hydraulic conductivity data obtained from the PFL measurements. Especially important parameters include the fracture locations and fracture transmissivities. Different models have different requirements for the input data. For example, for the Discrete Fracture Network (DFN) model, accurate fracture locations are beneficial, but if the model is constructed from cubic blocks the block size determines how accurately the fracture locations are required. The PFL measurement method can be adapted to different requirements.

The Discrete Fracture Network (DFN) model represents that ground water flows mainly occur in fractures in crystalline bedrock (Hartley 2013a). The model assumes that the ground water flows are constrained by the fracture walls and there is no flow between fractures if the fractures do not intersect. The model can be calibrated and tested by simulating actual measurements taken with a PFL device.

The PFL measurement data is a key resource for DFN modelling as individual fracture locations can be determined to a high degree of accuracy and connected to fractures determined from core samples. This makes it possible to assign hydraulic properties for individual fractures. With other measurement methods individual fractures cannot be assigned to single fractures identified from core sample as the hydraulic properties are determined for borehole sections - not for individual fractures. In those cases, either the hydraulic data has to be divided for multiple fractures, or the fractures have to be lumped together for the assignation of hydraulic properties.

The Continuous Porous Media (CPM) model assumes that over a specified volume in crystalline bedrock the ground water flows can be presented homogenously (Hartley 2013b). Typically, the hydraulic properties of each hydrostratigraphic volume are specified using available measurement data. Another approach is to divide the bedrock into blocks and specify the hydrogeological properties of the blocks. The advantage to this approach is that the location of the measured values can be taken into account more accurately.

Hydraulic interference tests

After a general hydrogeological bedrock characterisation has been made, some specific structures might require more detailed studies. Especially structures that do not fit into a model that assumes a homogeneous porous media might need special attention. Hydraulic interference tests can be performed by causing temporary interference to a hydrogeological structure or by monitoring changes caused by excavations or similar activities.

A conventional approach to measuring and evaluating changes in hydrogeological structures crossing boreholes is to install multipacker pressure monitoring systems into the boreholes. For small scale testing, this might be a simple and cost effective method, but if the number of observed fractures or borehole sections is large, there are better solutions. Also, if the fractures are close to each other and need to be treated separately, using packers to isolate fractures might not work due to packer dimensions. With the PFL measurement method, flow changes caused by interference can be evaluated for individual fractures. A basic configuration of the test is to measure the fracture flows before interference is initiated, to obtain reference values - and during the interference, to evaluate possible changes in fracture flow rates.

The magnitude of the interference affects the ability to detect flow changes. Therefore, detailed planning is essential. Causing interference in a surface borehole is usually done by isolating a borehole section from the rest of the borehole and changing the pressure by pumping water out of the test section. Theoretically this works well, but depending on fracture properties and other technical details, achieving large pressure changes might be challenging. Causing interference in a borehole that has been drilled from underground workings makes the pumping out of the borehole easier. In a subsurface borehole, isolating a borehole section and letting the water flow out of a section while the rest of the borehole is closed can be considered the same as pumping in a surface borehole.

During both PFL measurements, the entire borehole should be under same the pressure conditions (same water level). Therefore, if a flow change caused by interference is large, the flow change can affect the water level in the borehole and in that way affect the flow rates at other fractures which are not directly connected to the interfered structure. These two kinds of affects can be separated if the specific transmissivities of the fractures are known and the flow change caused by water level changes can be subtracted from the flow rate.

In a mining environment, there are usually multiple events that can cause changes to fracture flow rates. Therefore, it is beneficial to keep the duration of the test short so that the changes caused by the intended interference can be detected. Another way to make sure that observed flow change has been caused by an intended interference is to position the PFL probe at a fracture and change the interference. This requires more time per fracture than measuring flow rates systematically, but it is an efficient addition to the observation of steady state changes.

Summary

PFL measurements are a useful way to provide hydrogeological data for mine operations throughout the lifecycle of a mine. Conceptualization before operations begin, dewatering during the production phase and post closure monitoring, all require knowledge about water flows in the bedrock. Modelling of the bedrock properties should be done systematically throughout the lifecycle of a mine taking into account the requirements of the different phases.

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