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Fracture flow characterization with low-noise Spontaneous Potential logging

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Abstract

Geophysical well logging has been applied for fracture characterization in crystalline terrains by physical properties measurements and borehole wall imaging. Some of these methods can be applied to monitor pumping tests to identify fractures contributing to groundwater flow and, with this, determine hydraulic conductivity and transmissivity along the well. We present a procedure to identify fractures contributing to groundwater flow using spontaneous potential measurements generated by electrokinetic processes when the borehole water head is lowered and then monitored while recovering. The electrokinetic model for flow through a tabular gap is used to interpret the measured data and determine the water head difference that drives the flow through the fracture. We present preliminary results at a test site in crystalline rocks on the campus of the University of São Paulo.

Introduction

Crystalline rocks commonly exhibit low primary porosity leading groundwater flow to be limited by fracture density, aperture, and connectivity (Busse et al. 2016).

Characterizing hydraulic properties of fractures is crucial for modelling groundwater flow in crystalline terrains with most of the existing techniques relying on active pumping or injection testing or, in some cases, well logging (NRC 1996). Paillet et al. (2012) monitored flow change in a well as a result of pumping an adjacent well to determine fracture transmissivity and storage parameters, subsequently validated with tracer tests.

Fracture characterization is also important for identifying open water-bearing fractures in tunnel construction to ensure safety standards for working. Stumm et al. (2013) employed 36 wells at a construction pit to map intervals with fractures connected to groundwater flow by using optical logging images with statistical characterization of fracture directions and apertures, increasing security during tunnel excavation. Keller et al. (2014) applied the FLUTe technique, in which a flexible liner is lowered into the borehole forcing the water flow formation inward, to estimate fracture transmissivities using Thiem's equation. Modeling of flowmeter measurements also provide means to estimate fracture transmissivities by measuring vertical flow within borehole intervals in ambient and stressed conditions (Day-Lewis et al. 2014). In this case estimates for the far field pressure applied to the fractures are still needed and usually rely on information from other existing boreholes. Isolating depth intervals for packer testing is also used to make fracture transmissivity estimates but inflating packers for each depth interval can be time demanding depending on borehole length to be investigated. Transportable tools were developed allowing water sampling, identification of water head and hydraulic testing, reducing time required for field setup (Shapiro 2001).

Another issue with packer testing is the length of interval to be tested which is limited by the type of sealing equipment used and in some cases, achieving an efficient packer seal can be challenging when the spacing between transmissible fractures is small. The methods described (FLUTE, flowmeter and packer testing) are usually time-consuming compared to indirect geophysical logging techniques. However, geophysical logging is of limited use for quantifying hydraulic parameters, such as hydraulic pressure field acting on water-bearing fracture systems (Day-Lewis et al. 2017). Spontaneous Potential (SP) logging, for example, is not commonly used for groundwater studies in fractured rocks but it can provide valuable information about flow through fractures. In principle, SP logging can detect the water flow through porous or fissured media by isolating potentials generated by electrokinetic phenomena. Just after drilling, the SP signal mostly originates from electrochemical gradients (concentration gradients between the formation and borehole waters) with amplitudes up to 100 mV (Telford et al. 1990). This potential dissipates as the borehole waters are homogenized by diffusion and advection. For aged wells, the SP signals are mainly of electrokinetic origin, nevertheless achieving much lower amplitudes of up to 10 mV (Revil et al. 2006; Mendonça et al. 2012). The electrokinetic potential appears when groundwater flow displaces ions from the diffuse layer of the electrical double layer (EDL) developed at the mineral-liquid interface (Revil et al. 2012; Kirkby et al. 2016). Thus, there is a direct relationship between electrokinetic signals and the velocity of groundwater flow through fractured or granular porous media. These electrokinetic potentials are observed either in natural flow conditions or when induced by pumping tests. The amplitude of the SP signal from electrokinetic contributions tends to be very low, usually at the background-noise level of data measured with multi-functional probes simultaneously measuring SP and resistivity data. Major potentials from current sources

(2 or 3 orders of magnitude higher) for resistivity measurements may generate noisy fields well above those expected from electrokinetic effects. To accurately measure smaller SP signals, passive probes with no current sources and careful treatment of electrodes are required.

We present a conceptual model for interpreting SP data from electrokinetic origin when the water head of a well is lowered and its recovery is monitored with a low-noise SP probe. Signal variations in successive SP runs are interpreted using the planar gap model of charged interfaces (Masliyah and Bhattacharjee 2006) to recognize water heads at which there would be no groundwater flow through a fracture. We present preliminary field data showing that observed SP variations behave as expected from this gap model, allowing the identification of hydraulically active fractures and the respective water head each fracture is subjected to. The water head at a given fracture expresses its connectivity to local or regional aquifer systems as such of relevance in characterizing fractured formations. Our results are compared to other geophysical logs (optical imaging, normal resistivity) and core sample descriptions.

Electrokinetics in a planar gap

One simple way to represent a fracture is to consider two planes with constant spacing between them known as fracture aperture (Fig. 1). Considering the fracture planes as charged structures, an electrical double layer (EDL) is present at the mineral-liquid interface which is characterized by two layers: one with immobilized ions at the mineral surface (Stern layer) and another with displaceable ions (diffuse layer) (Revil et al. 2012). Groundwater flow within the fracture aperture can displace the ions in the diffuse layer of the EDL generating a conduction current opposite to the flow of water. Fracture apertures can vary from millimeters to centimeters while the thickness of the EDL is on

the nanometer scale, hence the thickness of the EDL tends to be much smaller than fracture apertures (Kirkby et al. 2016). This structure with two charged planes is known as ‘gap model’ (Masliyah e Bhattacharjee 2006).

[Figure 1]

Under a pressure gradient ($P_1 > P_2$, Fig. 1), water flowing through the fracture produces a difference of electrical potential with negative values where water enters the fracture and positive values where it exits. The pressure gradient within the fracture is related to the electrical potential ΔV (V) as (Masliyah and Bhattacharjee 2006)

$$\Delta V = \frac{\varepsilon \zeta}{\eta \sigma} \left[1 - \frac{\tanh(\kappa h)}{\kappa h} \right] (P_1 - P_2) \quad (1)$$

where ε is the water dielectric permittivity ($\text{C.V}^{-1}.\text{m}^{-1}$), ζ is the zeta potential (V), $2h$ is the fracture aperture (m), η is the water viscosity (Pa.s), and σ is the water bulk conductivity (Siemens.m^{-1}). Parameter

$$\kappa^{-1} = \left(\frac{\varepsilon k_B T}{2 e^2 z^2 n_\infty} \right) \quad (2)$$

is the Debye length (m^{-1}), a characteristic length for the EDL thickness; $k_B = 1.38 \times 10^{-23} \text{ J.K}^{-1}$ is the Boltzmann constant; T is the temperature (K); e is the elementary charge (C); z the electrolyte valence (1:1 solution assumed) and n_∞ the ionic concentration in the bulk solution (mol.L^{-1}). Term κ as in equation 2 has units of m^{-1} then making the characteristic Debye length scaling the EDL thickness be expressed as κ^{-1} . The thickness of the EDL is approximately given by $1.5 \kappa^{-1}$ and for typical groundwater salinities this is within nanometer scale as such much smaller than common pore voids existing in granular or fissured aquifers (Masliyah and Battacharjee 2006; Kirkby et al. 2016). Equation 1 shows that the electrokinetic potential is zero when $P_1 = P_2$. This condition is used to evaluate a field test to define the water head in which this potential

vanishes to zero, from variable pressure P_1 as water head within the well is recovering after having been lowered.

SP signals during recovery tests

In aged wells, with no concentration gradient between borehole and formation waters, the contribution of electrochemical potentials is minor, but an SP variation with depth is often observable. This background potential can be disturbed by subtle changes in the water flow regime, for example, by lowering the borehole water head by a few of meters (4 to 5 m in this case). Lowering water head triggers electrokinetic signals because water starts to flow into the well in order to recover its former equilibrium water head. Water inflow, however, occurs through distinct water-bearing fractures along specific zones of the well, which can be identified by tracking variations in the SP signal as the water head recovers.

A crucial point in this analysis is identifying the natural background field, from which variations due to electrokinetic effects are observed near fractures with water inflow. Deviations in SP amplitudes V_i can be measured for different water head elevations Z_i ($i = 1:n$), as the original static level Z_S is recovered. Assuming that water pressure acting within the fracture is given by $P_i = \rho g Z_i$, where ρ is the water density (kg.m^{-3}) and g the gravitation acceleration (m.s^{-2}). While the pressure at the borehole P_1 is known from direct measurements of the water head, pressure $P_2 = \rho g Z_c$ applied at the opposite end of the fracture can be determined from the extrapolation of SP measurements. The characteristic water head Z_c (subscript “c” standing for zero-crossing) is defined as the water head in the borehole for which $\Delta V = P_1 - P_2 = 0$, which means that for this pressure gradient there would be no flow through the fracture. This procedure can be repeated for each fracture along the well showing SP variations

to determine the pressure field driving the flow through them. A fracture with $Z_c = Z_S - Z_F$ (difference between static water head and fracture depth) points to a fracture connected to an unconfined aquifer (Fig. 2a) while condition $Z_c > Z_S - Z_F$ is indicative of a fracture under confined conditions (Fig. 2b).

[Figure 2]

Figure 3 illustrates characteristic points to be identified in tracking SP variations as the water table is recovered by natural water inflow.

[Figure 3]

Experimental procedures

The SP probe is composed by three Pb-Cl coated electrodes where the reference electrode (N) is at the top of the probe and two roving electrodes at distances of 50 and 100 cm below the reference one (Fig. 4). This setup is similar as used in normal resistivity logging (Keys, 1990) in which measurements are taken by applying electrical current at the lowermost electrode with potential readings at the electrodes above. For SP measurements no electrical current is injected at electrode N which is used as ground-reference to measure difference of potential with respect to electrodes below (M1, M2).

[Figure 4]

The probe was adapted to a Robertson Geologging winch (mini winch with 175 m range) and data acquisition was carried out with an Arduino control system specifically developed for the test. Differences of potential were recorded by an ADC (analog to digital converter) ADS1115 16-bit with a gain of 2/3 and a given resolution of 0.1875 mV. The electrodes were left immersed in the borehole water until repeated measurements had an error of about ± 1 mV, which is acceptable for measuring

electrical signals with magnitudes of tenths of mV. This error margin was reached after 1 hour and 30 minutes. At common probe velocities (2 m/min) in SP logging, the adoption of Pb-Cl coated Pb-electrodes prevents the generation of spurious potentials. This can be verified by repeating readings with different velocities or stopping the probe at single depth and verifying no changes in SP reading while the probe is moving. Since potential differences are taken along the well, a single fracture with water inflow associated with a positive ΔV (Fig. 5a) gives a “plus-to-minus” response for measurements between a rover electrode M (below) and reference electrode N (above). This plus-to-minus response is illustrated in Figure 5b where depth of fracture with water inflow matches where the SP signal crosses zero. For a single fracture, maximum absolute ΔV values are expected when one of the electrodes (M or N) is leveled with the fracture, therefore the positive and negative deviations must then show the same amplitude. Once the ambient SP field (before pumping) is removed, this characteristic response can be regarded as indicative of electrokinetic signals associated with a single fracture. The sign of ΔV changes for fractures with borehole-to-formation flow, when the signal polarity varies from negative to positive values (“minus-to-plus” signature).

[Figure 5]

Test area and results

The proposed procedure was tested at a borehole within the SCGR (Shallow Geophysics Controlled Test Site) of IAG-USP drilled in 2003. The well is cased to 53 m to prevent sedimentary layers from collapsing and then open to almost 80 m with occurrence of crystalline rocks, i.e. fractured gneiss (Porsani et al. 2004). A 20 m thick argillite layer occurs at the bottom of the sedimentary sequence confining the crystalline aquifer from the unconfined aquifer developed in poorly-sorted sandstones above the

argillite. Due to lateral extent of the argillite, recharge of the crystalline aquifer is expected to happen through wider sub-horizontal fractures connected to local hills where the crystalline basement outcrops.

Optical televiewer (OPTV) imaging of borehole wall (Fig. 6) identifies depths of 36 fractures as well as their orientations and dips. Statistical analysis identifies two main sets of fractures, from which most fractures (75%) have horizontal to sub-horizontal dipping angle (smaller than 30°). Despite the large number of fractures, only four of them show centimeter-scale apertures, most situated within top half of the profile at depths of 54.5, 56, 60, and 65 meters (numbered I to IV in Fig. 6).

[Figure 6]

In addition to SP logs, electrical resistivity logging was conducted with measurements of electrical resistance (short, N16, and long, N64, normal) and single point resistance (SPR) which are shown in Figure 7c. Normal resistivity logs N16 and N64 measures the formation resistivity with different spacings (16" and 64") between current and potential electrodes (Keys 1990), with larger electrode separation providing a deeper investigation into the rock mass surrounding the borehole. The point resistance log detects electrical resistance variations of a single electrode lowered in the well with respect to a fixed electrode at ground surface (Keys 1990), this resistance being very sensitive to fractures or changes in fracturing degree (Stumm et al. 2007). Both normal resistivity and point resistance logs are sensitive to fractures but unable to distinguish between fractures allowing water flow or not.

It is possible to identify some deflections toward lower values in these logs, mainly on the resistivity curves; these deflections' depths match those from fractures with centimeter scale apertures identified from OPTV log. One of these depths is around 56 m where there is deflection on both resistivity curves as well as on the SPR log.

There is a close association between the open fracture at 56 m with zero-crossing potential in the plus-to-minus SP variation (Fig. 7b). This suggests that out of 36 fractures identified in the well, the fracture at 56 m depth is a major contributor to water inflow recovering the well's water head. In general, water head recovery in this well is very slow (5 m recovered in 4 days) suggesting that most of the fractures contributing to groundwater recharge have low permeability.

As shown in Figure 5b, the plus-to-minus deflection expected from the planar gap model for SP deviations are observed in field conditions as long as water head of the well returns to its original position after having been lowered by water extraction. Plus-to-minus deflections are restricted to the top of the crystalline aquifer. Superposition of individual contributions in some levels prevents identification of single plus-to-minus patterns. Deflections are compatible with water inflow, since they go from positive to negative downhole (reference electrode at the probe's upper position). It is worth noting that SP deviations decrease as water level recovers since pressure gradients are dropping. SP runs 2, 3, and 4 were taken 30, 100, and 170 min after water extraction of 80 L, with corresponding water head variations of 0.992, 1.334, and 1.608 m above Z_L elevation of 17.901 m.

[Figure 7]

Although difference between water head for the three logging runs after pumping is small, SP deflections are evident at 56 m depth with magnitudes of tenth of mV as expected for the electrokinetic potentials. Amplitude variations for this depth were -13.01, -7.34, and -1.15 mV for water heads of 16.909, 16.567, and 16.293 m, respectively, and these data are plotted in Figure 8. If we apply a linear fit to this plot we can find the water head at which the potential is zero, in this case Z_C is 16.2 m. Since Z_S is 9.404 m the difference $Z_C - Z_S$ implies a water head of +6.8 m driving the

flow through the fracture at depth 56 m. The value of +6.8 m is then indicative of the confining water head at this fracture.

[Figure 8]

This procedure can be repeated for any depth interval with variations in the SP signal between each logging run and the ambient field before pumping. The SP deviations are plotted against measured water head in the well and linear regression provides the water head Z_C at which SP crosses from positive to negative or the other way around. This water head is then compared to static level before pumping and fracture's depth allowing characterizing a confined or unconfined groundwater flow system.

Discussion

In general, the field test at the SCGR shows promising results in applying low-noise SP probes to detect electrokinetic signals generated by induced water flow through open fractures. We observed SP variations as expected from fractures modeled as simple gaps with electrokinetic response despite the presence of significant noise in the data as compared to the low amplitude of observed signals. Future work must cover a broader range of water levels in the borehole, possibly by additional background measurements following well recovery. Further procedures to remove noisy static shifts, as the peak observed on run 4 at 65 m depth (Fig. 7a, blue line) are required to improve data quality.

The SP variation suggests that water entering into the well occurs at the interface between weathered and fresh rock at the top of the crystalline massif. This weathering degree contrast was observed in core samples and recognized by darker colors for the gneiss at the top levels. Because the crystalline aquifer is confined by the 20 m thick argillite layer, fractures contributing to well inflows are not expected to show

connection to the aquifer within the overlying sedimentary sequence, instead they should have lateral connectivity with the confined aquifer, possibly as a result from major local stress events. Another indication of water flowing in this upper interval showing SP deviations is the presence of iron-hydroxides coating fissure interfaces, indicative of ongoing weathering processes.

Our results show that SP logs can be applied to characterize and define hydraulically active fractures in crystalline rocks. The polarity of the SP signal can be used to identify the direction of the water flow entering or exiting the well. This approach can also be used as a tool to identify specific depth intervals from borehole imaging for specific packer testing. Further validation of the proposed procedure includes testing the same borehole with packers isolating specific depth intervals and analysis of flowmeter logs to compare these with flow inferences from SP results.

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Figure 1 – Schematic representation of fracture gap model. The electrical double layer is formed when a charged fracture plane is immersed in an electrolyte. Water flows from left to right according to pressure gradient $P_1 > P_2$ between fracture ends. Polarity of the electrical potential V_i changes according to water inflow or outflow (adapted from Masliyah and Bhattacharjee 2006).

Figure 2 – Schematic of conceptual models for fractures connected to (a) unconfined or (b) confined aquifer. Z_S , Z_F and Z_C are the static water head in the borehole, the fracture depth and water head elevation at which $\Delta V = 0$ (zero-crossing), respectively.

Figure 3 – Schematic of two fractures in a borehole subjected to water heads Z_1 and Z_2 . Elevation Z_S is the static water head of the well (a) and Z_L is the water head after pumping (b). Elevation Z_C in which $\Delta SP = 0$ (zero-crossing water head) gives the water head that drives the flow through the fracture (c). Different circles indicate SP measurements taken from borehole intervals Z_{F1} (green) and Z_{F2} (violet) while water head recovers to its initial value. Reversal in electrical signal polarity from positive to

negative indicates water inflow from fractures while changes from negative to positive values reflect outflow.

Figure 4 – Diagram of electrode configuration of SP tool. Three Pb-Cl coated electrodes move within borehole depths where electrical potentials are measured between potential electrodes and a reference electrode at the top of the tool with two separating distances.

Figure 5 – Expected potential signals from water inflow to a borehole from a fracture at depth Z_F , measured by a pair of electrodes M-N with centers at depths Z_1 , Z_2 , and Z_3 . Positive potential for water inflow (a) and ΔV variation along the well (b). V_b is the base value measured away from fractures with groundwater flow, while V_{max} and V_{min} are limiting values for the SP variation, such that $V_{min} - V_b = V_b - V_{max}$.

Figure 6 – Optical log of borehole wall at crystalline section of the SCGR testing well. Red lines indicate fracture locations and tadpole plot shows fracture dip by a red dot while its tail corresponds to dip direction. Fractures with visual apertures on the centimeter scale are indicated by Roman numerals I to IV.

Figure 7 – Electrical logs of crystalline rocks of the SCGR of IAG-USP. (a) Low-noise SP signals with 100 cm spacing between electrodes; Run R1 as the ambient field, and runs R2, R3, and R4 after pumping as water head in the well was 16.909, 16.567, and 16.293 m, respectively; (b) Difference of SP signals with respect to ambient field of Run R1; (c) Normal 16'' and 64'' resistivity logs and SPR log. Depths I to IV indicate fractures with apertures greater than 1 cm identified from optical log.

Figure 8 – Spontaneous potential amplitude variations at depth 56 m for three SP logging runs (100 cm electrode spacing) compared to ambient SP field measured before pumping. Linear fit was done in order to find the water head at which $\Delta SP = 0$. The value for water head crossing Z_C corresponds to pressure field applied within fracture plane.