Experimental simulation of self-potential electrokinetic signals as observed in fractured aquifers during geophysical well logging

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Abstract

Although it is not common the use of indirect geophysical methods in well loggings when studying groundwater flow through fractured media, the self-potential method can be an asset regarding these types of investigation since it can provide estimates of the pressure gradient to which the fractures are subjected. Through a laboratory experiment simulating a well pumping test, we show that it is possible to identify signals of self-potential generated by electrokinetic mechanisms, verifying the linearity between the water head variation and the electrical response. We present preliminary results obtained with a sample of porous medium with equivalent hydraulic conductivity of an average fractured media.

Introduction

The self-potential (SP) method is a passive geophysical method that measures electrical responses that occur spontaneously in nature. This method is highly sensitive both with respect to water flow direction, pore water chemical properties, and water-mineral interface properties (Revil et al., 2012). The SP response can be attributed to the water flow through a fractured or porous medium dragging ionic species dissolved in water , thus changing the local electrical field (Sill, 1983). The SP method is one of the oldest geophysical methods, with a long history of applications in oil/gas exploration, mainly to differentiate sandstones from shales in layered reservoirs (Vereecken et al., 2006). Despite its wide use in this area, well-logging SP profiles have found minor applications in groundwater studies. This is usually due to low SP signals observed in groundwater studies since data is often acquired in wells many months (or years) after drilling, when concentration gradients with respect to the pore water have already dissipated. (Mendonça et al., 2012).

Recent applications in groundwater studies have shown that the SP method can be a promising tool for aquifer characterization. Rizzo et al. (2004) used an electrode network to map the subsurface water flow, allowing the visualization of preferential pathways during pumping tests. This methodology also provided quantitative information regarding hydraulic conductivity in the vicinity of the well. Titov et al. (2005) used a numerical approach to model water column experiments of SP signals associated with pumping tests in unconfined aquifers. Their data showed a linear relationship between the water level and the electrical signal measured at the ground surface, demonstrating that the hydraulic head distribution can be inferred from indirect geophysical measurements.

Kowalski et al (2021) illustrate an application of the SP logging method during a pumping test for a well located at a crystalline terrain to infer the water head to which each of the fractures intercepting the borehole were subjected and determine whether the associated aquifer was confined or unconfined. The fractures were previously mapped by an OPTV probe (optical televiewer) and then, by comparing the SP logs before and during the water head recovery it was possible to determine which fractures mostly contribute to water flow as well as the inflow/outflow direction for these fractures. Although geophysical methods are limited to quantify hydraulic parameters (Day-Lewis et al., 2017), the SP investigations as developed by Kowalski et al. 2021 can be advantageous (or complementary) when compared with other direct methods such as flowmeters and packer testing (Kowalski et al.,2021). If compared with typically used direct testing methods, the SP logging surveys are less time demanding and easier to be applied in the monitoring mode.

This paper aims to simulate, in laboratory conditions, an experiment to verify some core results obtained from field studies by Kowalski et al. (2021), more specifically: whether it is possible to observe a clear SP response associated with water flow through fractured or equivalent media; whether the measured signal obeys a linear relationship with the hydraulic gradient between the two ends of the system; and whether the polarity of the signal is related to the direction of the flow and its inversion point indicates the change from inflow to outflow or vice versa.

Since a laboratory experiment using an actual fracture extension is virtually impossible due to its dimensions being incompatible with laboratory scales, we applied the principle of equivalency between the specific surface of a porous medium and the geometrical surface spanned by the gap between two planes representing a fracture to evaluate the SP response. The results achieved in the laboratory were qualitatively compared with the ones described by Kowalski et al. (2021).

Theory

The electrical double layer (EDL) (Fig. 1) is a physicochemical phenomenon that occurs at solid grainspore water interfaces. When a silica containing mineral is in contact with water, its surface becomes electrically charged due to chemical reactions. The charge polarity at the mineral surface is pH dependent, often negative for typical groundwater pH values between 5 and 8 (Revil and Jardani, 2013). The inner layer in the EDL, also known as Stern layer, has an excess concentration of counter-ions that remain immobile as the pore water moves. The second layer, known as diffuse layer, also has an excess of these electric charged particles (though not as much as in the Stern layer) but with a certain degree of mobility since they are not attached to the mineral surface.

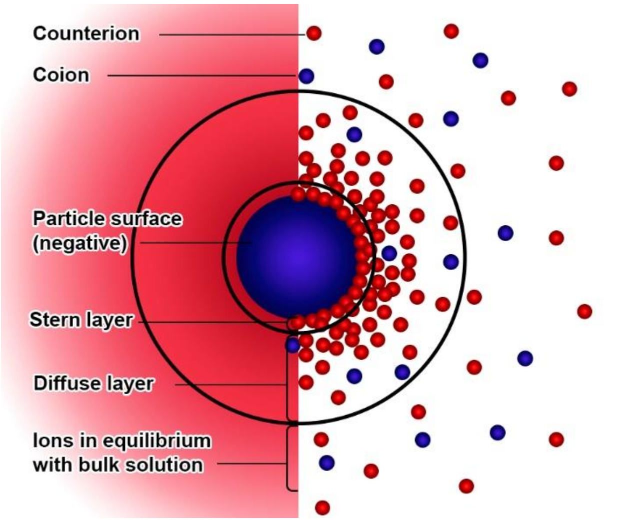


Fig. 1 – Model of the electrical double layer (EDL) around the surface of a silica grain in contact with the pore water

Based on EDL models it is possible to understand the source mechanism of electrokinetic origin. A pressure gradient generates a primary flow, dragging the charge excess accumulated at the mineral interface. This charge distribution generates a secondary electric field, establishing an ohmic current opposing the primary flow. The resulting potential can be described according to the equation:

$$V = L\Delta H, \qquad (1)$$

where V is the electrokinetic potential (V), ΔH is the water head variation between the two ends of the pathway in which the fluid flows (m), and L is the electrokinetic coupling parameter (V/m) represented by:

$$L = -\frac{\varepsilon\zeta}{\eta}\frac{\rho g}{\sigma_f(1+2Du)}, \qquad (2)$$

where ε, η and σ_f are the electric permittivity of the pore fluid (F.m^{-1}), its viscosity (Pa.s), and its electrical conductivity (S.m^{-1}) respectively. ζ is the ζ-potential (V), ρ is the water density (kg.m^{-3}), g the local gravitational field strength (m.s^{-2}), and Du (Dukhin number) is the ratio of surface to bulk electrical conductivities (Delgado et al., 2007; Bolève et al., 2007). The ζ-potential is the characteristic potential at the interface between the Stern and the diffuse layers. This interface defines a shear plane separating the fixed and the movable parts of the EDL.

For a planar gap, the source of the electric potential gradient between the two ends of a fracture can be written as (Masliyah and Bhattacherjee, 2006):

$$\Delta V = \frac{\varepsilon\zeta}{\eta\sigma}\left[1 - \frac{\tanh(kh)}{kh}\right], \qquad (3)$$

where ΔV (V) is the potential gradient, h is half the aperture of the fracture (m), k is the inverse of the Debye length (m^{-1}) and P_1 and P_2 the respective hydraulic pressures to which each respective end is subjected; $P = \rho g H$, where H is the height of the respective water column. The Debye parameter, k^{-1}, given by (Masliyah and Bhattacharjee 2006)

$$k^{-1} = \sqrt{\left(\frac{\varepsilon k_B T}{2e^2 z^2 \eta_\infty}\right)} \qquad (4)$$

is a critical length describing the width of the EDL, where k_B=1.38 × 10 − 23 JK^{-1} is the Boltzmann constant, T is the temperature (K), e is the elementary charge (C), z the electrolyte valence (in this case assumed to be 1:1), and η_∞ the ionic concentration in the bulk solution (mol/L). For practical applications, the EDL width can be considered approximately as 1.5 k^{-1}.

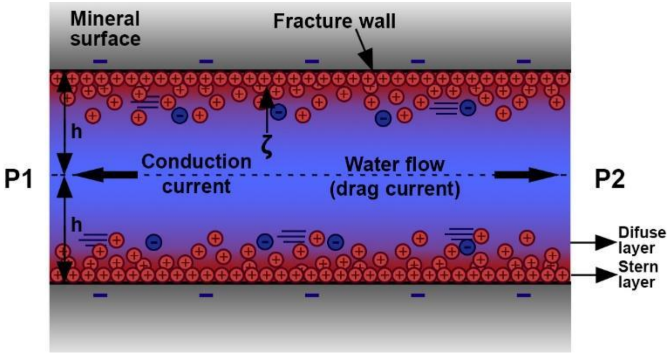


Fig. 2 – Schematic representation of the electrokinetic potential in a planar gap (adapted from Masliyah and Bhattacherjee, 2006). The EDL is represented at both surfaces of the fracture. The fracture aperture is given by 2h; P1 and P2 are the water pressures at each end of the fracture (P1>P2); ζ is the Zeta-potential

As in Fig 2, the water flow along a gap with $P_1 > P_2$ drags the counter-ions from the diffuse layer of the EDL, thus originating a streaming current. According to the theory of coupled flows (Sill, 1983) this current generates a conduction current in the opposite direction, which in turn generates an electric potential known as electrokinetic potential.

Experimental procedures

The experimental equipment consists of two cells (Fig. 3) with a pair of non-polarizable silver electrodes (coated with a solution of sodium hypochlorite) and a cylindrical sample of 25,0 ± 0,5 mm in diameter and 30,0 ± 0,5 mm in height. Each cell sample consists of a different material: sample 1 quartzite, and sample 2 a porous ceramic plug sintered with #120 (mesh) alumina. These materials were chosen because of their hydraulic conductivities, which are comparable to those of average fractures in borehole environments.

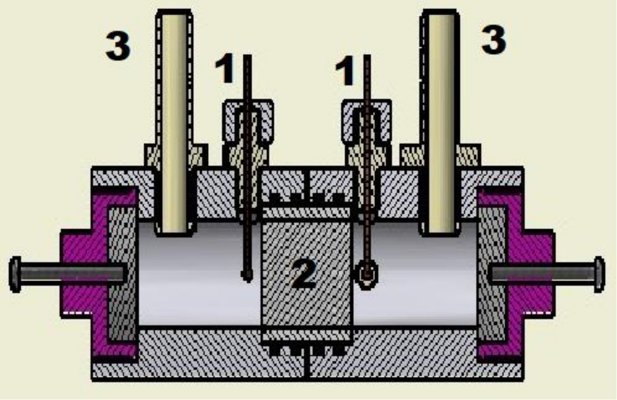


Fig. 3 – Schematics for the cell chamber and connections used in the experiment: 1. non-polarizable electrodes; 2. porous medium sample; 3. tubes where the hoses are connected.

Each side of the chamber in which the porous media is confined is connected to a 10 L keg filled with water of electrical resistivity **ρ_w** 120,6 ± 0,1 Ω.m (at a room temperature of 20,8 ± 0,1 ºC). One of the kegs remains at a fixed height, thus representing the pressure to which the aquifer is subjected, while the other one is placed on a mobile platform that can be raised or lowered by a mechanical elevator thus representing the water head within a well. The electrodes are connected to a high-impedance digital multimeter, which, in turn, is optically connected to a computer for data logging as illustrated in Figs. 4 and 5.

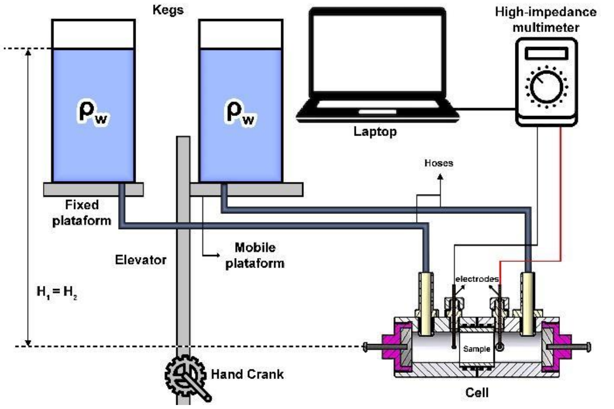


Fig. 4 – Assembled experimental setup at the initial condition (both kegs at the same level). H_1 and H_2 are, respectively, the water heads applied to each termination of the equivalent fractured media; ρ_w is the water electrical resistivity.

To determine if it is possible to observe an electrical signal derived from a pressure gradient during a well pumping test and verify if the measured electrical potential has a linear relationship with the hydraulic head to which the system is subjected, the measurements, for each cell, were carried out as follows. Initially, with the kegs at the same height, the electric potential was registered by a high-impedance digital multimeter (Agilent U1252A). After one minute of signal monitoring, the "null" function of the device was applied to cancel electrode shift. Signal then was recorded for another minute with intervals of 1 s. The keg placed on the mobile platform was then lowered by 375,0 ± 0,5 mm which corresponds to five steps of 75,0 ± 0,5 mm each. At the beginning of every subsequent minute of recording the keg is elevated by one step until the initial level is reached again. This procedure was repeated once more, then the "null" function was deactivated for the final minute of measurement.

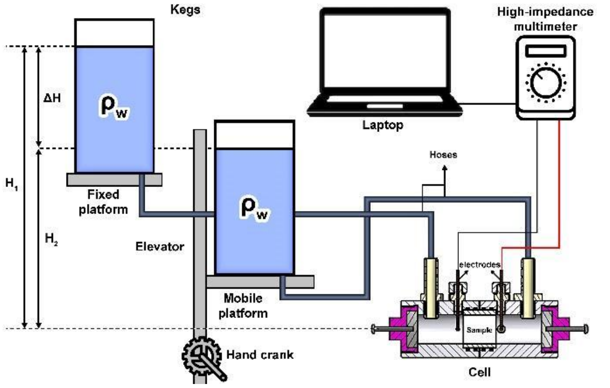
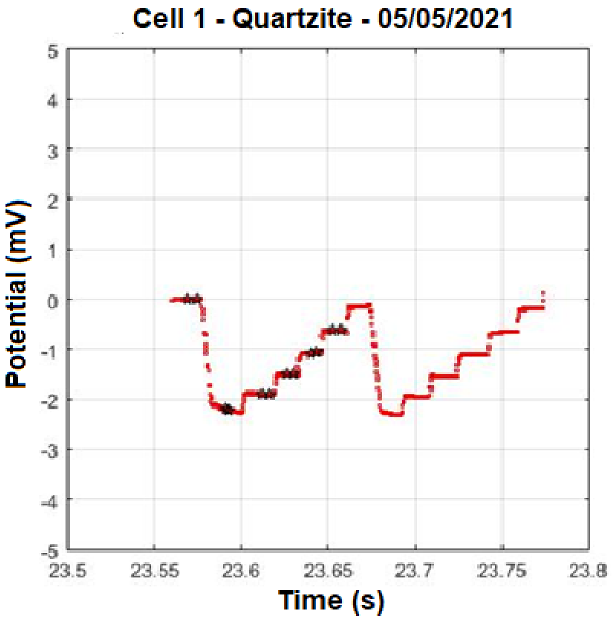
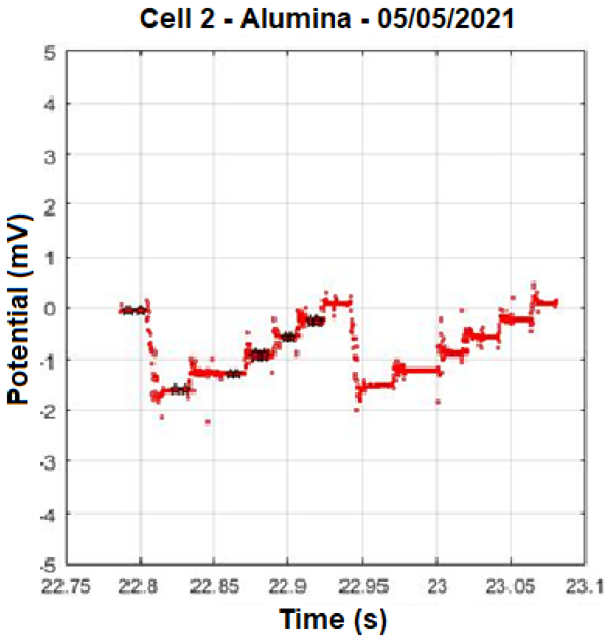


Fig. 5 – Experimental setup after lowering the keg on the mobile platform (hand crank elevator).

A MatLab 2007 (MathWorks) code was used to read and analyze the data recorded by the multimeter and generate graphs to interpret the results. The following graph shows the potential measured as a function of time, where each step in the potential staircase represents an individual height level for the keg located in the elevator.

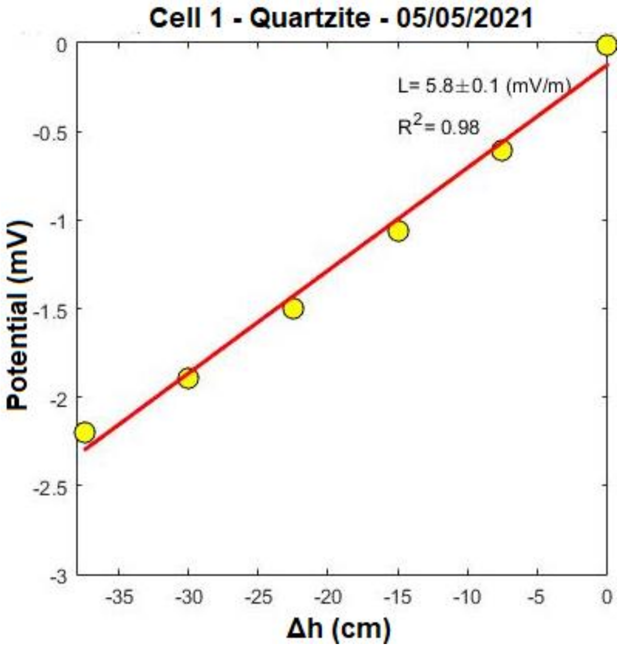


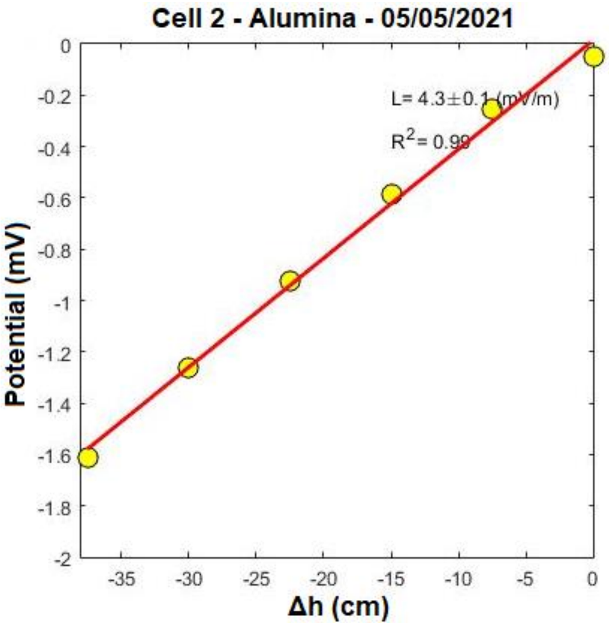


Figs. 5 and 6 – Electrokinetic potential as a function of time showing the data recorded by the multimeter and the selected averaging intervals (between star-shaped marks) corresponding to hydraulic gradients in mm from left to right: 0,0; 375,0; 300,0; 225,0; 150,0; and 75,0 (± 0,5 mm) (in absolute value)

Results

Each average potential value is then plotted on a new graph as a function of its respective water column height. This graph shows a linear relationship between these two quantities and provides the electrokinetic coupling parameter (L), which is the slope of the line.





Figs. 7 and 8 – Electrokinetic potential as a function of hydraulic gradient, showing their linear relationship and corresponding coupling parameter L

The electrokinetic coupling parameter (L) obtained from the graphs can provide important information about the properties of the pore water, such as density, electric permittivity, viscosity, and electrical conductivity.

Conclusions

It was possible to observe an electrokinetic potential signal related to the variation of the hydraulic pressure applied in a simulated fracture, and the relationship between them shows linearity. It was also possible to obtain the electrokinetic coupling parameter for each system.

As this is an ongoing study, these preliminary results appear to be very promising since they could be qualitatively compared with field test results. Future research will incorporate an initial pressure gradient in order to evaluate if it is possible, through self-potential measurements, to determine the hydraulic pressure to which the systems are subjected. For the tested experimental setup, the position of the zero-crossing point for $\Delta H = 0$ illustrates the consistency of the experimental procedure since no electrokinetic signal is expected under a no-flow condition.

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