FORWARD MODELLING FOR ELECTRO-KINETIC EFFECTS

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Introduction

The electrokinetic effect represents a group of processes in which there is a conversion from electromagnetic to kinetic energy and vice versa. In the case of this transfer taking place in a porous medium we name the effects electro-osmotic for the transfer from electromagnetic to kinetic energy, and seismo-electric for the transfer from kinetic to electromagnetic energy. There exist other effects also called electro-kinetic like the piezo-electric effect or the modulation of rock resistivity by seismic waves, but we will not take those effects into account in this paper.

Although the existence of the seismo-electric conversion is known since the early 1930s, the development of the seismo-electric method has been greatly enhanced since the publication of the experimental work of Thompson and Gist (1993) and the theoretical work of Pride and Haartsen (Pride, 1994; Pride and Haartsen, 1996; Haartsen and Pride, 1997). In all the published papers it is shown that the seismo-electric method is a useful tool to characterize parameters like fluid content and fluid geochemistry in the porous Earth's subsurface; hence, possible applications include groundwater detection and the monitoring of pollutant migration. This effect can also find applications in borehole measurements as a way to determine permeable formations or monitoring multiphase flow through porous areas.

On the other hand the electro-osmotic effect has not received so much interest in the geophysical world,-although it does among the chemistry researchers-. Acording to A. H. Thompson (1993) this effect looks very promising as a tool for geophysical exploration: the amplitude generated in the subsurface in an average electro-osmotic effect experimental setup may be greater than the one generated by a vibrator truck. This may give the electro-osmotic surveying a very interesting future in the geophysical research.

Electrokinetic effects

Seismo-electric effect

The seismo-electric method is a surveying technique for the shallow subsurface of the Earth, in which seismic sources and electromagnetic receivers are used. The conversion from seismic to electromagnetic energy occurs due to the relative motion between the solid and the fluid phases in the porous rocks in the subsurface. This conversion takes place via two different mechanisms: (i) the body and surface waves during their propagation generate a series of compressions and rarefactions of the porous medium, creating a charge displacement that moves along with the wave, and therefore an electric field confined inside of it. (ii) the seismic waves when arriving at interfaces where there is a contrast in the mechanical or electric parameters generate electromagnetic waves. This EM wave generation can be approximated by an oscillating dipole placed at the interface. These EM waves and electric fields can be measured with simple electrodes placed on the surface of the earth, or along a borehole. To study this coupling between seismic and electromagnetic waves Pride (1994) derived a set of equations. When we solve them we find that they uncouple

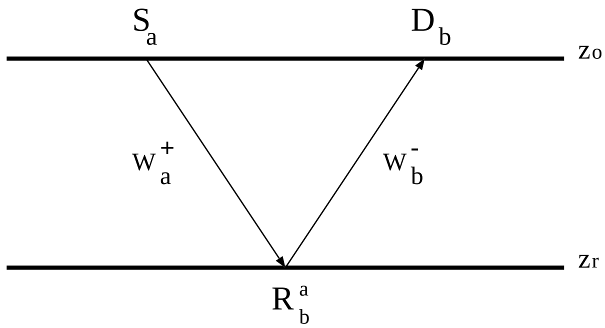

Figure 1: *Forward model for the electro-kinetic reflection.*

into two independent sets of partial differential equations. These two sets show us the different types of coupling existing in the seismo-electric effect. When a horizontally polarized shear wave (SH-mode) propagates in the x-z plane, its propagation is not coupled to the other three seismic wavefields (the fast and slow P-waves and the vertically polarized shear wave); however, the SH-wave generates electric currents in the y-direction and these currents couple to the electromagnetic wavefield with transverse electric polarization (TE-mode). When a fast P-wave, slow P-wave, or a vertically polarized shear wave (SV-mode) propagates in the x-z plane, it generates electric currents in the x-z plane and these currents couple to the electromagnetic wavefield with transverse magnetic polarization (TM-mode).

Electro-osmotic effect

The electro-osmotic method uses antennas on the surface as a source generating a time dependent electric field. This field generates a time dependent pressure on the discontinuities where there is a change in the mechanical or electric properties. This pressure propagates as a seismic wave that can be recorded at the surface with geophones. This effect used as a prospecting tool has its greatest signals with large permeability contrasts. The electro-osmotic effect is widely known among the chemistry researchers, but is almost new as a geophysical exploration tool.

Forward model

This section shows how we apply a known seismic approach to the electrokinetic problem. Let $\tilde{S}_a$ in Figure 1 be the source function, it can be both seismic or electromagnetic. The operators that represent the down and upgoing wavefields are $\tilde{W}_a^+$ and $\tilde{W}_b^-$ respectively, where $a, b = \{pf, ps, sv, sh, tm, em\}$ represent the different waves mentioned in the previous section. The plus sign is for downgoing waves and the minus is for upgoing waves. Therefore these operators will be

$$\tilde{W}_a^+(p, z_r, z_o, \omega) = e^{-j\omega q_a(z_r - z_o)} \tag{1}$$

$$\tilde{W}_b^-(p, z_o, z_r, \omega) = e^{j\omega q_b(z_o - z_r)}. \tag{2}$$

Then, e.g. $\tilde{W}_{pf}^+ \tilde{S}_{pf}$ would represent the downgoing fast-P wavefield. The reflection is represented by the operator $\tilde{R}_b^a$ where "a" and "b" are the reflected and incident waves respectively. The reflected wave is measured at the surface by an array of detectors, this is represented by the operator $\tilde{D}_b$. Finally the product of all these operators $\tilde{D}_b \tilde{W}_b^- \tilde{R}_b^a \tilde{W}_a^+ \tilde{S}$ represents the signal from the first

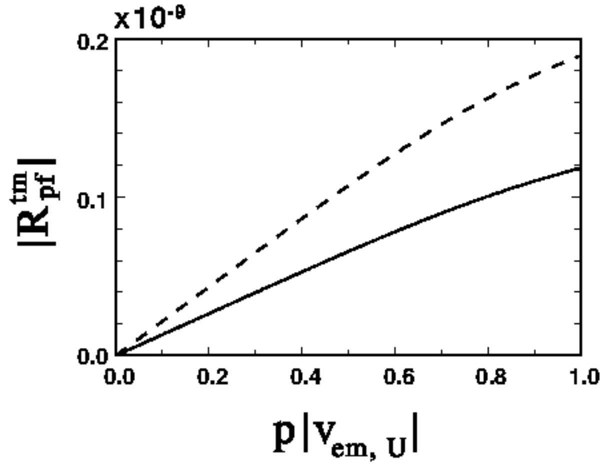

Figure 2: *Incoming fast P-wave and reflected TM-wave with velocity* $v_{\mathrm{em,U}}$ *(*$f = \omega/2\pi = 100$ *Hz): the reflection coefficient* $R^{\mathrm{tm}}_{\mathrm{pf}}$ *as a function of the horizontal slowness* p *times velocity* $|v_{\mathrm{em,U}}|$*. In upper porous half-space: salinity* $C = n_{\mathrm{Na}} = n_{\mathrm{Cl}} = 10^{-6}$ *mol/liter, porosity* $\phi = 0.2$*, and permeability* $k_0 = 0.16$ *Darcy. In lower porous half-space:* $C = 10^{-5}$ *mol/liter (solid line) and* $C = 10^{-4}$ *mol/liter (dashed line) with* $\phi = 0.2$ *and* $k_0 = 0.16$ *Darcy.*

reflector recorded by the detectors. The main advantage of our approach to this problem is that this scheme is valid for any kind of wave propagating or reflecting at the subsurface, seismic or electromagnetic.

The reflection and transmission coefficients needed in this calculation have been derived by Shaw et al. (2000) from the coupled equations deduced by Pride (1994). These coefficients show a clear dependency between the contrast in the properties of the media and fluids and the strength of the electro-kinetic response. The interfaces that show a greater seismo-electric response are contrasts in the ion concentration of the pore fluid and the permeability as it can be seen in Figure 2.

Theoretical results and fieldwork

The next step in this project will be to implement the whole scheme in order to obtain a theoretical model and results for the wavefield recorded at the detectors.

During the fieldwork we expect to measure the two electro-kinetic phenomena related with the streaming potential, seismo-electric and electro-osmotic effects. There are already papers published about experimental results with the first of these two, but it is our purpose to experiment with new configurations and types of receivers in an attempt to improve the signal-to-noise ratio caracteristic of this effect.

Regarding the electro-osmotic effect we have not found any paper apart from the one by Thompson and Gist (1993) in which such an effect is mentioned as a useful geophysical surveying technique. It is now our aim to study and experiment this effect in the frame of the electro-kinetic phenomena.

Concluding remarks

In this paper we presented our point of view in the electro-kinetic effects. We presented a wide view that includes both seismo-electric and electro-osmotic effects as part of the same phenomenon. This way allows us to easily calculate the theoretical responses of the medium for any case of incident and reflected waves.

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