The electro-kinetic effect for compressional and shear waves

Antonio Ranada Shaw, Dennis van der Burg, Arthur Denneman, and Kees Wapenaar
Delft University of Technology

Summary

In this paper we present our results in the electro-kinetic effects. What is to be called here electro-kinetic effect is a very wide concept that includes both seismo-electric and electro-osmotic effects as two complementary parts of the same phenomenon. We will also study here the two type of coupling: the P-SV-TM the SH-TE coupling, a not very well known part of the electro-kinetic effect with all the potential to be a usefull prospecting tool.

Introduction

The electrokinetic effect represents a class 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 effect 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 sometimes 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.

The existence of the seismo-electric conversion is known since the early 1930s, however the development of the seismo-electric method was not greatly enhanced till 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 the main topic is the generation of an electromagnetic wave as a fast P wave hits an interface, showing this method to be a useful tool to characterize parameters like fluid content and fluid geochemistry in the Earth's subsurface.

The opposite effect, the so-called electro-osmotic effect has not received much attention in the geophysical world yet,-although it does among the chemistry researchers-. Acording to Thompson (1993) this effect looks very promising as a tool for geophysical exploration: the amplitude generated in the subsurface in an average electro-osmotic 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.

All this previously mentioned is known for P-waves, but for an unknown reason shear waves do not generate the same interest as their compressional counterparts do. In this paper we show, from a theoretical point of view, the many possibilities and characteristics of both compressional and shear waves in electro-kinetic prospecting. 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.

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. There are two kinds of conversion, a wave that travels along with the seismic wave, and an electromagnetic wave generated when reaching an interface. In the case of having an incoming fast-P wave the mechanisms are (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, and (ii) when the compressional wave hits a discontinuity in the medium properties, there is a change in the streaming current density leading to a charge separation that oscillates with the frequency of the incident seismic wave, this generates a polarized electromagnetic wave. 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 or coils placed on the surface of the earth, or along a borehole.

For the case in which a shear wave propagates in a fluid saturated porous medium there are also two conversions of energy (i) when these waves propagate through porous medium, grain accelerations induce current sheets, these currents induce magnetic fields with polarization orthogonal to the seismic displacement. Electric fields are generated by this magnetic field. Because there is no current imbalance within the shear waves, the magnetic field is confined within the wave. When the shear wave hits an interface (ii) there is, also like in the fast P-wave case, a change in the streaming current density that leads to a charge separation that generates a polarized electromagnetic wave.

To study this coupling between seismic and electromagnetic waves, Pride (1994) derived a set of equations. If we assume the earth to be a medium consisting of horizontal porous layers in which the waves propagate only in the x-z plane (with the positive z-axis directed downwards) we can apply the equations derived by Pride to it, and after a Radon transform we obtain the following two independent sets of partial differential equations:

$$\frac{\partial}{\partial z}\mathbf{Q}_{\mathrm{H}} = j\omega\mathbf{A}_{\mathrm{H}}\mathbf{Q}_{\mathrm{H}} = j\omega \begin{bmatrix} \mathbf{0}_{2\times 2} & \mathbf{A}_{1,\,\mathrm{H}} \\ \mathbf{A}_{2,\,\mathrm{H}} & \mathbf{0}_{2\times 2} \end{bmatrix} \mathbf{Q}_{\mathrm{H}}, \quad (1)$$

$$\frac{\partial}{\partial z}\mathbf{Q}_{\mathrm{V}} = j\omega\mathbf{A}_{\mathrm{V}}\mathbf{Q}_{\mathrm{V}} = j\omega \begin{bmatrix} \mathbf{0}_{4\times 4} & \mathbf{A}_{1,\,\mathrm{V}} \\ \mathbf{A}_{2,\,\mathrm{V}} & \mathbf{0}_{4\times 4} \end{bmatrix} \mathbf{Q}_{\mathrm{V}}, \quad (2)$$

where the vectors $\mathbf{Q}_{\mathrm{H}}$ and $\mathbf{Q}_{\mathrm{V}}$ are

$$\mathbf{Q}_{\mathrm{H}} = \left[T^{\mathrm{B}}_{yz},\ H_x,\ E_y,\ \dot{u}^{\mathrm{s}}_y\right]^T,\ \textit{and} \quad (3)$$

$$\mathbf{Q}_{\mathrm{V}} = \left[\dot{u}^{\mathrm{s}}_z,\ \dot{w}_z,\ T^{\mathrm{B}}_{xz},\ H_y,\ E_x,\ T^{\mathrm{B}}_{zz},\ -P,\ \dot{u}^{\mathrm{s}}_x\right]^T. \quad (4)$$

These vectors contain all the parameters that must be continuous across the interfaces between the horizontal porous layers [i.e., we apply the open-pore boundary conditions of Deresiewicz and Skalak (1963)]. The complete expression for the matrices $\mathbf{A}_{\mathrm{H}}$ and $\mathbf{A}_{\mathrm{V}}$ can be found in Shaw (2000).

These two sets show us the different types of coupling existing in the seismo-electric effect. According to Biot theory, three kind of waves can propagate through a porous medium, two compressional waves and a shear wave. When a fast P-wave, slow P-wave, or a vertically polarized shear wave (SV-mode) propagates in the x-z plane, each of them can generate the others when reflecting or crossing a discontinuity in the medium properties. If the porous medium is saturated with an electrolyte, the interaction with the waves generates electric currents in the x-z plane and these currents couple to the electromagnetic wavefield with transverse magnetic polarization (TM-mode). But 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, when arriving at an interface with a discontinuity in the properties of the medium the SH-wave generates electric currents in the y-direction and these currents couple to the electromagnetic wavefield with transverse electric polarization (TE-mode). Note that because the SH-TE case only involves two wave types its boundary conditions are just four, less than the P-SV-TM case that needs eight boundary conditions.

Electro-osmotic effect

The electro-osmotic method uses electrodes or coils on the surface as a source generating a time dependent electric field, or electromagnetic wave. 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. According to Thompson (1993) this effect used as a prospecting tool has its greatest signals with large permeability contrasts, which can be seen in the reflection coefficients calculated for this case. The electro-osmotic effect is widely known among the chemistry researchers, but is almost new as a geophysical exploration tool. Thompson (1993) suggested an alternative to this method in which an electric current is injected into the subsurface, and the seismic response is measured. This works better in permeable wet soils where electric currents have less attenuation than electromagnetic waves. In this kind of soils the seismic response can be very good while in solid rock environments, where most of the permeability is due to cracks in the rock formation, using EM waves as a source is preferred. Furthermore, it is easier to excite the TE modes in the subsurface than the TM modes, therefore the coupling SH-TE seems very apropiate for the electro-osmotic prospecting.

Forward model for electro-kinetic reflection.

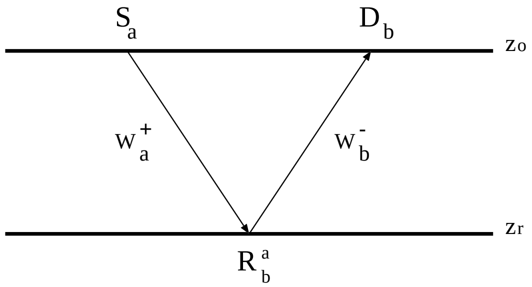

Fig. 1: *Forward model for electro-kinetic reflection.*

In this section we show the application of 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 $a, b = \{pf, ps, sv, tm\}$ for the P-SV-TM coupling and $a, b = \{sh, te\}$ for the SH-TE coupling. The plus sign is for downgoing waves and the minus is for upgoing waves. Therefore these operators will be

$$\tilde{W}^+_a(p, z_r, z_o, \omega) = e^{-j\omega q_a(z_r - z_o)} \quad (5)$$

$$\tilde{W}^-_b(p, z_o, z_r, \omega) = e^{j\omega q_b(z_o - z_r)}. \quad (6)$$

Then, e.g. $\tilde{W}^+_{sh}\tilde{S}_{sh}$ would represent the downgoing horizontally polarized shear wavefield. The reflection is represented by the operator $\tilde{R}^a_b$ where "a" and "b" represent the reflected and incident wave types 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 $\tilde{D}_b\tilde{W}_b^-\tilde{R}_b^a\tilde{W}_a^+\tilde{S}_a$ represents the signal from the first 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 in the subsurface, seismic or electromagnetic, and for any kind of coupling between the seismic and the electromagnetic waves.

Theoretical results and fieldwork

To illustrate the analytical results obtained so far, we now consider the reflection coefficient $R_{\rm pf}^{\rm tm}$ belonging to an interface between two nearly identical porous half-spaces, i.e., they differ only in the ion concentration of the pore fluid. The reflection coefficients needed here have been derived following the same approach as in Shaw et al. (2000) from the coupled equations deduced by Pride (1994). In Fig.2 can be clearly seen the relation between the contrast and the response. The reflection from that interface grows with increasing difference in the ion concentration of the fluids. It can be seen also that in the narrow angle of incidence where the TM wave is homogeneous, the amplitude of the wave grows with increasing angle of incidence.

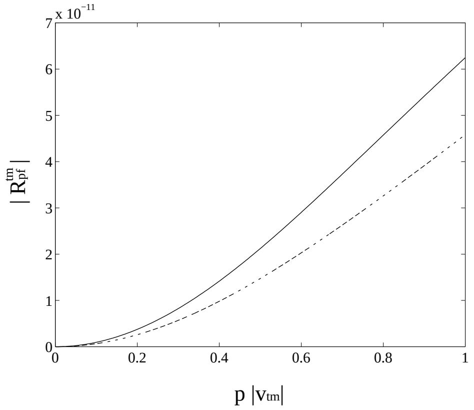

Fig. 2: *Reflection coefficient for an incoming fast P-wave and a generated TM mode EM wave at a boundary with a change in the ion concentration between the two media. In the upper medium the concentration is* $C_1 = 10^{-6}$. *In the lower medium:* $C_1 = 10^{-4}$ *(dashed line), and* $C_1 = 10^{-2}$ *(solid line).*

In many papers on seismo-electric reflection in near-surface experiments it is shown that contrasts as in Fig.2 result in a measurable response (after some signal processing to improve the signal to noise ratio). The current availability of the reflection coefficient $R_{\rm pf}^{\rm tm}$ (and all the other coefficients) is especially useful to acquire more physical insight in the dependencies of the seismo-electric reflection on the many possible contrasts at interfaces between two porous materials.

For the SH-TE case we can see in Fig.3 that the amplitud of the reflection is in the same order of magnitude as in the P-SV-TM case, this makes SH-TE case also suitable for geophysical prospecting. These coefficients show some interesting features, the largest generation of TE-waves takes place right below the source, and decreases with increasing angle of incidence, just the opposite as in the P-SV-TM coupling. 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 larger seismo-electric response are contrasts in the permeability as it can be seen in Figure 3.

In the generation of SH-waves the trend of the coefficient depends on the ion concentration contrast. If the electrolyte in the upper medium has a higher concentration than the electrolyte in the lower medium the reflection will decrease with increasing angle of incidence, but if the ion concentration of the lower medium is larger then the reflection will increase with increasing angle of incidende. The example in Fig. 4 shows only a contrast in porosity and permeability, we only present the reflection coefficient for this contrast because the SH-TE coupling in the electro-osmotic effect is much more sensitive to changes in permeability.

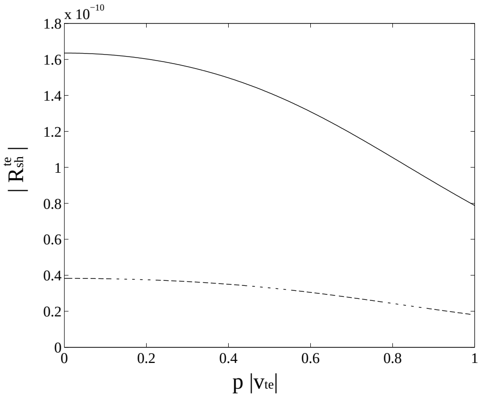

Fig. 3: *Reflection coefficient for an incoming SH-wave and a generated TE mode EM wave at a boundary with a change in the porosity and the permeability between the two media. In the upper medium: porosity* $\phi_1 = 0.2$ *and permeability* $k_1 = 0.16D$. *In the lower medium:* $\phi_1 = 0.3$ *and* $k_1 = 0.54$ *(dashed line), and* $D\phi_1 = 0.4$, $k_1 = 1.28D$ *(solid line).*

During the fieldwork we expect to measure the SH-TE coupling in 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 characteristic 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.

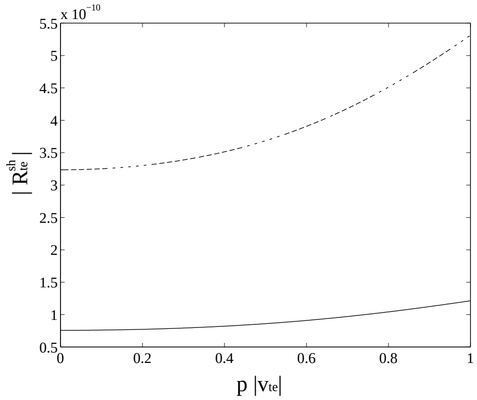

Fig. 4: *Reflection coefficient for an incoming TE mode EM wave and a generated SH-wave at a boundary with a change in the porosity and the permeability between the two media. In the upper medium: porosity* $\phi_1 = 0.2$ *and permeability* $k_1 = 0.16D$*. In the lower medium:* $\phi_1 = 0.3$ *and* $k_1 = 0.54$ *(solid line), and* $\phi_1 = 0.4$*,* $k_1 = 1.28D$ *(dashed line).*

Concluding remarks

In this paper we presented our point of view in the electro-kinetic effects. We presented parts of the electro-kinetic effect not very well known in a general scheme that includes both seismo-electric and electro-osmotic effects as two directions in the same phenomenon. This way allows us to easily calculate the theoretical responses of the medium for any case of incident and reflected waves. We also present here the SH-TE coupling, a not very well known part of the electro-kinetic effect with the potential to be a usefull tool.

Acknowledgment

The research described in this paper is part of the DIOC project "Heterogeneities at different scales"

References

Deresiewicz, H., and Skalak, R., 1963, On uniqueness in dynamic poroelasticity: Bull. Seis. Soc. Am., **53**, 783-788.

Haartsen, M. W., and Pride, S. R., 1997, Electroseismic waves from point sources in layered media: J. Geophys. Res, **102**, 24745-24769.

Mavko, G., Mukerji, T., and Dvorkin, J., 1998, The rock physics handbook: Tools for seismic analysis in porous media: Cambridge Univ. Press.

Pride, S. R., and Morgan, F. D., 1991, Electrokinetic dissipation induced by seismic waves: Geophysics, **56**, 914-925.

Pride, S. R., 1994, Governing equations for the coupled electromagnetics and acoustics of porous media: Phys. Rev. B.,**50**, 15678-15696.

Shaw, A. R., Denneman, A.I.M., Wapenaar, C.P.A., 2000, Porosity and permeability effects on the seismo-electric reflection: EAGE Proceedings 2000.

Thompson, A., and Gist, G., 1993, Geophysical applications of electrokinetic conversion: The Leading Edge, **12**, 1169-1173.

Zhu, Z., Haartsen, M. W., and Toksoz, M. N., 1999, Experimental studies of electrokinetic conversions in fluid-saturated borehole models: Geophysics, **64**, 1349-1356.