The electro-kinetic effect: forward model and measurements

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Summary

In this paper we present our last results in modeling and measuring the electro-kinetic effect. We will show a classical WRW model applied to this effect in which the sources and receivers, both electro-magnetic and seismic, are taken into account. What is called in this paper electro-kinetic effect is a very wide concept that includes both seismo-electric and electro-seismic effects as two complementary parts of the same phenomenon. Finally we show some fieldwork results comparable with our model.

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 saturated porous medium we name the effect electro-seismic 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.

This interaction between seismic and electromagnetic waves is due to the relative motion of the electrically charged ions in the pore fluid. When in equilibrium a porous medium saturated with an electrolyte is electrically neutral, but if a wave, seismic or electromagnetic, perturbs this equilibrium, the relative motion of the ions in the pore fluid will generate both seismic and electromagnetic waves. In the case of a passing seismic wave the flow of ions and the consequent electric imbalance generates electromagnetic waves. If the passing wave is electromagnetic there will be an induced flow of fluid in the pores that will be transmitted as a seismic wave.

The existence of the seismo-electric conversion is known since the early 1930s, however in all the published papers the main topic is the generation of an electromagnetic wave as a fast P wave hits an interface (usually the water table), showing this method to be a useful tool to characterize parameters like fluid content and fluid geochemistry in the Earth's subsurface. Although the seismo-electric effect is the most known, in this paper we deal with it as a particular case of the electro-kinetic effect in our model, which contains all the interactions between seismic and electromagnetic waves in a layered porous medium. It is then very interesting to look at the possibilities offered by the use of shear waves as well as the not so well known electro-seismic effect, which could be a very promising prospecting tool.

Possible applications include groundwater detection and monitoring of pollutant migration. This effect can possibly be also employed in borehole measurements as a way to determine permeable formations or monitoring multiphase flow through porous areas.

Electrokinetic effect

To study the coupling between seismic and electromagnetic waves, Pride (1994) derived a set of equations that links the acoustic and the electromagnetic wavefields. 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 Fourier transform we obtain the following two independent sets of partial differential equations:

$$\frac{\partial}{\partial z}\vec{Q}_\sigma = j\omega \mathbf{A}_\sigma \vec{Q}_\sigma = j\omega \left[\begin{array}{cc} \mathbf{0} & \mathbf{A}_{1,\sigma} \\ \mathbf{A}_{2,\sigma} & \mathbf{0} \end{array}\right] \vec{Q}_\sigma + \mathbf{S}_\sigma, \quad (1)$$

where $\sigma = \{V, H\}$ and the vectors $\vec{Q}_\sigma$ are

$$\vec{Q}_{\mathrm{H}} = \left[\tau^{\mathrm{B}}_{yz},\ H_x,\ E_y,\ \dot{u}^{\mathrm{s}}_y\right]^T, \ \textit{and} \quad (2)$$

$$\vec{Q}_{\mathrm{V}} = \left[\dot{u}^{\mathrm{s}}_z,\ \dot{w}_z,\ \tau^{\mathrm{B}}_{xz},\ H_y,\ E_x,\ \tau^{\mathrm{B}}_{zz},\ -P,\ \dot{u}^{\mathrm{s}}_x\right]^T \quad (3)$$

where $\tau^{\mathrm{B}}_{yz}, \tau^{\mathrm{B}}_{xz}$ and τ^{B}_{zz} are components of the stress tensor, H_x and H_y are components of the magnetic field, E_y and E_x components of the electric field, $\dot{u}^{\mathrm{s}}_y, \dot{u}^{\mathrm{s}}_z$ and $\dot{u}^{\mathrm{s}}_x$ components of the particle velocity of the solid $\dot{w}_z$ is the relative solid-fluid velocity and P is the fluid pressure. 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 et al. (2000). This uncoupling of Pride's equations shows us the existence of two separate electro-kinetic couplings: the P-SV-TM coupling containing interactions between fast-P, slow-P, vertical shear and TM mode electromagnetic waves, and the SH-TE coupling containing the interactions between horizontal shear and TE mode electromagnetic waves. In the previous equations the subscripts V and H refer to the PSVTM and SHTE couplings respectively.

Note that the velocity of the electromagnetic waves is much higher than the velocity of the seismic waves, and since the frequencies are in the same range this means that the electromagnetic wavelength is much longer than the seismic wavelength, therefore is it more accurate to speak of a modulated electromagnetic field instead of an electromagnetic wave.

Forward model for electro-kinetic reflection.

In this section we show the application of a known seismic model, the so-called WRW model, to the electro-kinetic problem. In Figure 1 we can see a scheme of this approach. We will consider a porous layer over a porous half-space and under a vacuum half-space. There are two boundaries: vacuum-porous at z_o, and porous-porous at z_r. Since the porosity, permeability and ion concentration of the pore fluid are different in both porous mediums, there will be electro-kinetic conversions at both interfaces. The waves are generated at the source S_a, then they travel down the porous media, described by W_a^+, until the interface, there reflection takes place: R_b^a, part of the wavefield goes up: W_b^- and is measured at the surface by the receivers C_r. For the PSVTM coupling $a,b = \{pf, ps, sv, tm\}$ and for the SHTE coupling $a,b = \{sh, te\}$.

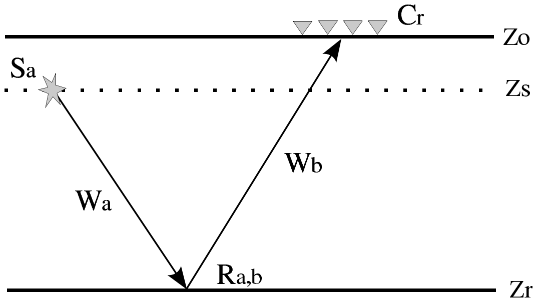

Fig. 1: *Forward model for electro-kinetic reflection.*

To calculate the propagation and reflection of waves we use one-way wavefields that are converted to and from two way wavefields at the source and receivers by the decomposition and composition operators C_S^{-1} and C_r.

Concatenating the operators previously mentioned we obtain our model for the electro-kinetic reflection:

$$\vec{Q}_\sigma(z_o) = \mathbf{C}_r(z_o)\mathbf{W}^-(z_o, z_r)\mathbf{R}^+(z_r)\mathbf{W}^+(z_r, z_o)C_s^{\vec{-}1}(z_o)S(\omega). \tag{4}$$

Note that the matrices in the model are mutiplied from right to left starting with the source and ending with the receiver.

Source

Among all the possible sources we have chosen the volume injection as a seismic source (e.g. dynamite) and a current distribution as an electromagnetic source (e.g.coils). $S(\omega)$ is the source signature, for this model we have used a Ricker's wavelet. $C_s^{-1}(z_o)$ is the source decomposition operator and it relates the source signature $S(\omega)$ to the downgoing one way wavefield at a boundary below which the source is placed.

$$\vec{D}_\sigma^+ = C_s^{-1}(z_o)S(\omega), \tag{5}$$

where $\vec{D}_\sigma^+$ is the downgoing wavefield at the surface. We also take into account the downgoing wavefield reflected from the source at the surface.

Propagation operators

These operators describe the propagation of a wavefield across a medium, they are

$$W_V^\pm = \begin{pmatrix} W_{pf}^\pm & 0 & 0 & 0 \\ 0 & W_{ps}^\pm & 0 & 0 \\ 0 & 0 & W_{sv}^\pm & 0 \\ 0 & 0 & 0 & W_{tm}^\pm \end{pmatrix} \tag{6}$$

where

$$W_H^\pm = \begin{pmatrix} W_{sh}^\pm & 0 \\ 0 & W_{te}^\pm \end{pmatrix} \tag{7}$$

where

$$W_\alpha^+(k_x, z_r, z_o, \omega) = W_\alpha^-(k_x, z_o, z_r, \omega) = e^{-j\sqrt{\frac{\omega^2}{v_\alpha^2} - k_x^2}(z_r - z_o)} \tag{8}$$

The positive sign means the wave is propagating downwards and the negative sign upwards.

Reflection coefficients

The reflection coefficients relate the incoming wavefield to a boundary with the outgoing wavefield.

$$\vec{D}_{\sigma,u}^- = \mathbf{R}_\sigma^+ \vec{D}_{\sigma,u}^+ \tag{9}$$

where the u refers to the upper medium. 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). The reflection coefficients have the folowing structure:

$$\mathbf{R}_V = \begin{pmatrix} R_{\mathrm{pf}}^{\mathrm{pf}} & R_{\mathrm{ps}}^{\mathrm{pf}} & R_{\mathrm{sv}}^{\mathrm{pf}} & R_{\mathrm{tm}}^{\mathrm{pf}} \\ R_{\mathrm{pf}}^{\mathrm{ps}} & R_{\mathrm{ps}}^{\mathrm{ps}} & R_{\mathrm{sv}}^{\mathrm{ps}} & R_{\mathrm{tm}}^{\mathrm{ps}} \\ R_{\mathrm{pf}}^{\mathrm{sv}} & R_{\mathrm{ps}}^{\mathrm{sv}} & R_{\mathrm{sv}}^{\mathrm{sv}} & R_{\mathrm{tm}}^{\mathrm{sv}} \\ R_{\mathrm{pf}}^{\mathrm{tm}} & R_{\mathrm{ps}}^{\mathrm{tm}} & R_{\mathrm{sv}}^{\mathrm{tm}} & R_{\mathrm{tm}}^{\mathrm{tm}} \end{pmatrix} \tag{10}$$

and

$$\mathbf{R}_H = \begin{pmatrix} R_{\mathrm{sh}}^{\mathrm{sh}} & R_{\mathrm{te}}^{\mathrm{sh}} \\ R_{\mathrm{sh}}^{\mathrm{te}} & R_{\mathrm{te}}^{\mathrm{te}} \end{pmatrix} \tag{11}$$

Receiver

The receivers can be geophones in the electro-seismic

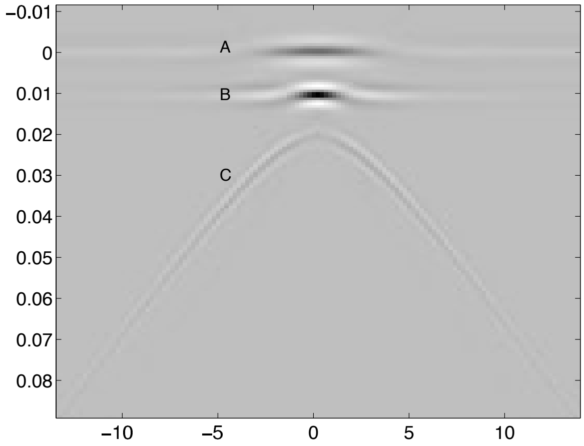

Fig. 2: *Arrival at electric receivers (E_y) from a horizontal shear wave source(τ_{yz}). The porous-porous boundary at z_r has a contrast in the ion concentration and porosity. In the upper medium the concentration and porosity are $C_u = 10^{-6}$ and $\phi_u = 0.2$. In the lower medium $C_l = 10^{-3}$ and $\phi_l = 0.4$*

case, and coils or electrodes in the seismo-electric case. The receiver composition operator describes the relation between the one way wavefields and the two way wavefield recorded at the receivers.

$$\vec{Q}'_\sigma = C_r(z_o)\vec{D}^-\sigma(z_o), \tag{12}$$

where the vector Q' contains the quantities measured at the receivers

$$\vec{Q}'_H = \begin{pmatrix} E_y \\ \dot{u}^S_y \end{pmatrix} \quad \textit{and} \quad \vec{Q}'_V = \begin{pmatrix} H_y \\ E_x \\ \dot{u}^S_z \\ \dot{u}^S_x \end{pmatrix} \tag{13}$$

For simplicity we have assumed the receivers to be on the free surface at (z_o), this means that the seismic receivers will be geophones that measure particle velocity, and the electromagnetic receivers will be electrodes or coils. In the case of using receivers below the surface -hydrophones- it should be taken into account in the mathematical derivation of the receiver composition operator. All this calculation is done in the (k_x, ω) domain. With an inverse 2D Fourier transform the data can be taken to the (x, t) domain, which is the domain where the results are presented.

Theoretical results

The final result of this model represents the signal that, after being generated at the source, travels down to the reflector and up to the receivers. Bear in mind that this model is equally valid for both electro-seismic and seismo-electric effects since the sources and the receivers can be seismic or electro-magnetic. Furthermore it is also valid for both cases of the electro-kinetic coupling: the SHTE and the PSVTM.

To illustrate the theoretical results obtained we assume there is a contrast at the z_r boundary in the ion concentration of the pore fluid, the permeability and porosity. In the upper medium the concentration, permeability and porosity are $C_u = 10^{-6}$ mol/l, $k_u = 1.6 \cdot 10^{-13}$ D and $\phi_u = 0.2$. In the lower medium $C_l = 10^{-3}$ mol/l, $k_l = 1.28 \cdot 10^{-13}$ D and $\phi_l = 0.4$

In Figure 2 we see the arrival at electric receivers (measuring E_y) from a horizontal shear wave source (τ_{yz}). We find 3 arrivals in this graph labeled as A, B and C. Arrival A has a zero arrival time, this is the electromagnetic wave generated at the seismic source that travels at almost the speed of light and therefore its arrival time is negligible compared with the seismic arrival time. Arrival B is the seismo-electric conversion at the porous-porous boundary at z_r. The third arrival C is the electric field that travels confined inside the seismic wave and, although it looks like a seismic arrival to a geophone, it can be measured by the electric receivers. There are other different reflections and conversions when using a seismic source and electric receivers, but the travel times overlap with those shown in the graph.

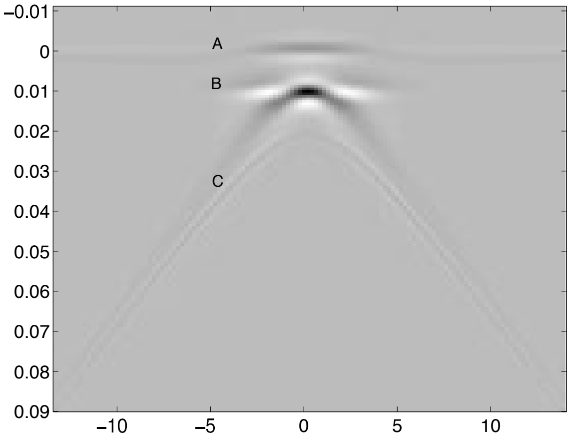

Fig. 3: *Arrival at geophones -measuring $\dot{u}_y$- from a TE mode electromagnetic wave source. The porous-porous boundary at z_r has a contrast in the ion concentration and porosity. In the upper medium the concentration and porosity are $C_u = 10^{-6}$ and $\phi_u = 0.2$. In the lower medium $C_l = 10^{-3}$ and $\phi_l = 0.4$*

In Figure 3 we see the recording at an array of geophones measuring the y component of the particle velocity of the response of a TE mode electromagnetic wave generated at z_s and reflected at the porous-porous boundary at z_r. As in the reciprocal case we find here three arrivals labeled A, B and C. Arrival A is the electromagnetic wave generated at the source that travel very fast compared with the seismic velocities, therefore its arrival time is zero in this graph. The arrival B is the conversion at the interface of an incoming TE mode electromagnetic wave to horizontal shear wave. Finally arrival C is a shear wave generated when an electromagnetic wave from the source hits the surface and is reflected as a shear wave from the boundary z_r to the receivers.

Note the travel time for arrival B is in both cases half the arrival time of C. This is because in the reflection B one way is seismic and the other electromagnetic travel time while in C both are seismic.

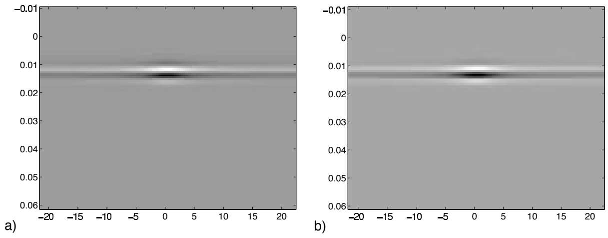

Fig. 4: *a) Arrival at electric receivers (E_x) of a TM mode electromagnetic wave converted at the boundary z_o from a fast-p wave. b) Arrival at geophones ($\dot{u}_z^S$) of a fast-p compressional wave converted at the boundary z_o from a TM mode electromagnetic wave. The contrast at the z_r boundary is the same as in the SHTE case.*

In Figure 4a) we see the arrival at electric receivers of a TM mode electromagnetic wave converted at the boundary z_o from a fast-P wave, and the reciprocal effect in Figure 4b) as a TM electromagnetic wave is generated at the source and partially converted to fast-P at the z_o boundary. Note the similarities between both graphs.

Fieldwork results

Here we present our fieldwork results which have many similarities with the results of the model. The following is our interpretation of the measurements. In the first place we find the AA' arrival that is a seismic wave converted to an electromagnetic wave right above the source and from there travels as an air wave to the detectors. In this AA' arrival could also be included the seismo-electric response from a first interface, just like events A and B in the model. The arrivals BB' and CC' are the electric fields confined inside a fast-p wave, and therefore travel with the velocity of a seismic wave, similar to event B in the model graph. In the bottom of the graph we see arrivals DD' and EE' that are the seismo-electric conversions of interfaces at depths of aproximately 120 m and 140 m respectively. These could be events like event B in the model graph, but from deeper interfaces.

Concluding remarks

In this paper we introduced our point of view in the electro-kinetic effects. We presented parts of the electro-kinetic effect not well known in a general scheme that includes both seismo-electric and electro-seismic 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. Finally we derived and included in the model different sources and receivers through the composition and decomposition operators, which gives a better insight in the use of electro-kinetic effect as a prospecting tool.

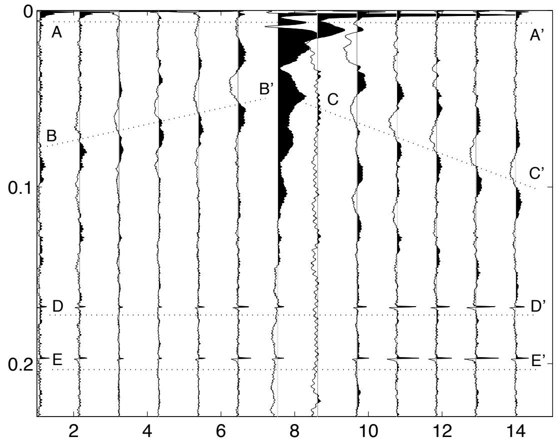

Fig. 5: *Fieldwork results: Split-dip with shotgun as seismic source between traces 8 and 9, and electric receivers spaced 2m.*

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