WAVEFIELD COMPOSITION AND DECOMPOSITION FOR THE ELECTRO-KINETIC REFLECTION

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INTRODUCTION

The electro-kinetic 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. 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.

We study the electro-kinetic effect with a simple reflection model in which there is a porous medium over a porous half-space. The free surface of the porous medium acts as the surface of the earth, while the boundary as a buried change in the properties of the subsurface. To complete the model we also include a buried source and an array of receivers at both sides of the source. Finally we present the composition and decomposition of the wavefields playing a role in the electro-kinetic effect. These wavefields can be separated providing some information about the different contribution of each wave to each measurable quantity in the field.

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.

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.

ELECTRO-KINETIC 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:

$$\frac{\partial Q_\sigma}{\partial z} = A_\sigma Q_\sigma + D_\sigma,$$

where σ={V,H} and the vectors Q_σ are

$$Q_H = [\tau^B_{yz}, H_x, E_y, \dot{u}^s_y] \text{ and}$$

$$Q_V = [\dot{u}^s_z, \dot{w}_z, \tau^B_{xz}, H_y, E_x, \tau^B_{zz}, -P, \dot{u}^s_y]$$

where τ_{yz}, τ_{xz} and τ_{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, v_y^S, v_z^S and v_x^S components of the particle velocity of the solid 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 $\boldsymbol{A}_H$ and $\boldsymbol{A}_V$ 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.

COMPOSITION AND DECOMPOSITION OPERATORS FOR THE ELECTRO-KINETIC REFLECTION.

In order to use the one-way propagation, reflection and transmission operators, two-way expressions for the source wavefield need to be converted to one-way wavefields. The relation between the two-way function and the one-way wavefield is described by the coupling coefficient *L(ω)*. Once the wavefields arrive to the receivers, they must be converted back to measurable two-way quantities via the inverse of the composition operator, $L^{-1}(\omega)$.

Source decomposition operator

The relation between the two-way expressions for the source signature and the downgoing one-way wavefield is given by the source decomposition operators that are defined as

$$\begin{pmatrix} d^+_{pf} \\ d^+_{ps} \\ d^+_{sv} \\ d^+_{tm} \end{pmatrix} = C^{-1}_{S,V}(z_B)S(\omega) \quad \text{and} \quad \begin{pmatrix} d^+_{sh} \\ d^+_{te} \end{pmatrix} = C^{-1}_{S,H}S(\omega) \ ,$$

where $S(\omega)$ is the source signature, $C^{-1}_{S,\sigma}$ is the source decomposition operator and $d^{+}_{pf\ldots tm,hs..te}$ are the downgoing wavefield at the surface.
The four elements of the source decomposition operator relate the two-way source with the four different downgoing one-way wavefields at the surface. For example the first element of C^{-1}_{s} gives the contribution of the source to the downgoing fast p wave. If this term is eliminated from the operator the model will have a seismic source that only generates slow-P, shear and electromagnetic TM waves, we can also have a source that only generates one type of waves.

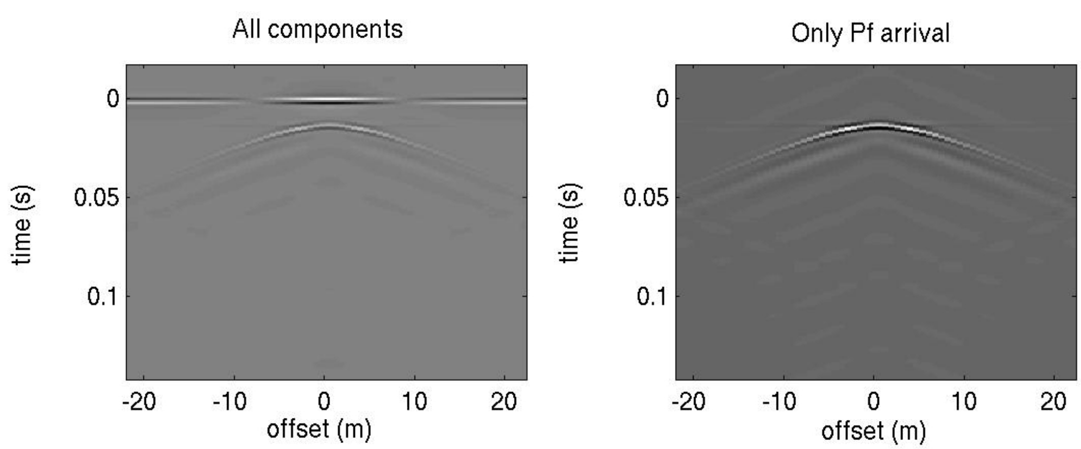
Receiver composition operator
At the receivers we need to convert the one-way wavefield to measurable two-way expressions with the receiver composition operators $C_r(z_B)$, which are defined as

$$\begin{pmatrix} H_y \\ E_x \\ u_z^s \\ u_x^s \end{pmatrix} = C_{r,V}(z_B)\begin{pmatrix} d_{pf}^- \\ d_{ps}^- \\ d_{sv}^- \\ d_{tm}^- \end{pmatrix} \quad \text{and} \quad \begin{pmatrix} E_y \\ u_y^s \end{pmatrix} = C_{r,H}(z_B)\begin{pmatrix} d_{sh}^- \\ d_{te}^- \end{pmatrix}$$

Where the quantities in the left hand side of the equations have been chosen from the two-way wavefield Q_σ as measurable quantities in the field. $C_{r,\sigma}(z_B)$ is the receiver composition operator and $d^{-}_{pf\ldots tm,sh..te}$ are the upgoing one-way wavefields that arrive to the receivers.
The receiver composition operator relates the measurable quantities with the upgoing wavefields, therefore we can check precisely what wavefield is contributing to what quantity. For example the element $C_{r,V}(1,4)$ gives the contribution of the upgoing electromagnetic TM wave to the *y* component of the magnetic field H_y. Eliminating a column of the receiver composition operator eliminates the contribution of the correspondent wavefield, i.e. first column affects to the fast-P wavefield.

THEORETICAL RESULTS

To illustrate the theoretical results obtained we use a simple WRW reflection model in which there is a contrast at the 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, $k_u=1.6\ 10^{-13}$ D and $\phi_u=0.2$. In the lower medium $C_l=10^{-3}$ mol/l, $k_l=1.28\ 10^{-13}$ D and $\phi_l=0.4$.



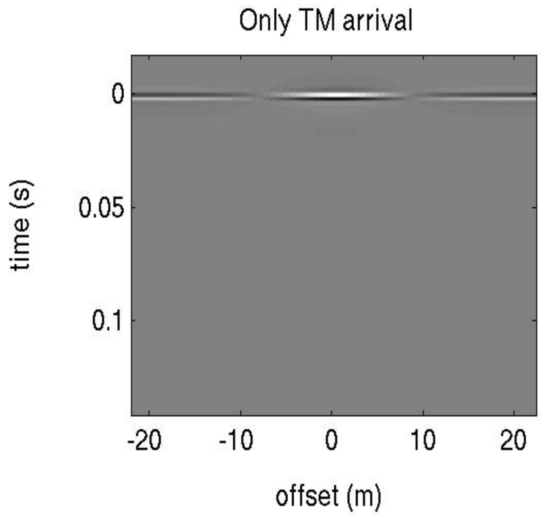


Figure 1: First figure is the arrival from a seismic source to an array of electric receivers (E_x). The second figure is just the contribution of the fast-P wave to the electromagnetic signal received at the electrodes. Note that at zero time there is no electromagnetic arrival from the source blast.

Figure 2: Electromagnetic contribution to the arrival from a seismic source to an array of electric receivers (E_x). The arrival at zero time is the electromagnetic blast from a seismic source that travels at the speed of light and reflects back from the interface to the receivers in the surface.

CONCLUDING REMARKS

In this paper we present the composition and decomposition of two-way wavefields via the source and receiver operators. The use of these operators gives us the possibility of separating the different wavefields contributing to the signal recorded in the receivers. This is especially interesting in the field of electro-kinetics where the combination of different types of waves is complicated and not all the arrivals contain the information we need since not all the arrivals come from the same electro-kinetic conversion.

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