Electroseismics for CO$_2$ storage and hydrocarbon reservoirs

Fabio I. Zyserman
Electroseismics: field experiments

- Electroseismic response in gas and oil reservoirs from about 1500 m depth.
- Signal between two and six orders of magnitude less than ambient noise.
- It is necessary to optimize the source power (∼ megawatt), the injected signal (few thousands A), and the detection equipment (digital accelerometers).
When an applied electric field acts on an electrolyte saturated porous material, besides driving $\sigma E$, it acts as a body force on the excess charge, giving rise to a net fluid filtration; this is called *electro-osmosis* ⇒ *electroseismic phenomena.* Reciprocally, an applied pressure gradient generates an electric current; this is called *electro-filtration* ⇒ *seismoelectric phenomena.*
Electroseismic modeling II

Assuming an $e^{+i\omega t}$ time dependence, Pride (1994) proposed

$$(\sigma + i\epsilon \omega)E - \nabla \times H + L(\omega)\kappa^{-1} \left[ i\omega u^f - L(\omega)E \right] = -J^\text{ext}_e,$$

$$\nabla \times E + i\omega \mu H = -J^\text{ext}_m,$$

$$-\omega^2 \rho_b u^s - \omega^2 \rho_f u^f - \nabla \cdot \tau(u) = F^{(s)},$$

$$-\omega^2 \rho_f u^s + \eta \kappa^{-1} \left[ i\omega u^f - L(\omega)E \right] + \nabla p_f = F^{(f)},$$

$$\tau_{lm}(u) = 2G \varepsilon_{lm}(u^s) + \delta_{lm} \left( \lambda_c \nabla \cdot u^s + \alpha K_{av} \nabla \cdot u^f \right),$$

$$p_f(u) = -\alpha K_{av} \nabla \cdot u^s - K_{av} \nabla \cdot u^f.$$

$\phi$: porosity, $\rho_s$, $\rho_f$: solid and fluid densities, $\rho_b = (1 - \phi)\rho_s + \phi\rho_f$, $\eta$: fluid viscosity, $\kappa(\omega)$: dynamic permeability.

In the constitutive equations $\lambda_c = K_c - 2/3G$ and $K_c = K_m + \alpha^2 K_{av}$,

$$\alpha = 1 - \frac{K_m}{K_s}, \quad K_{av} = \left[ \frac{\alpha - \phi}{K_s} + \frac{\phi}{K_f} \right]^{-1}.$$

$K_s$, $K_m$ and $K_f$: bulk moduli of the solid grains, the dry matrix and the fluid.
Electroseismic modeling III
2D Sources and Modes

- **Infinite solenoid:** $J^m_m$ generates electromagnetic fields $(E_x(x, z), E_z(x, z))$, and $H_y(x, z)$, coupled with solid displacements $(u^s_x(x, z), u^s_z(x, z))$ and fluid displacements $(u^f_x(x, z), u^f_z(x, z))$. This is the so-called PSVTM-mode, in which compressional and vertically polarized shear seismic waves (PSV-waves) are present.

- **Infinite current line:** $J^e_e$ generates electromagnetic fields $(H_x(x, z), H_z(x, z))$ and $E_y(x, z)$, coupled with solid displacements $u^s_y(x, z)$ and fluid displacements $u^f_y(x, z)$. This is known as the SHTE-mode, where only horizontally polarized seismic waves (SH-waves) are present.
Electroseismic modeling IV
Some assumptions

▶ We work in the seismic frequency range, then
\[ \text{Re}(\eta/\kappa(\omega)) \to \eta/\kappa_0 \text{ and } \frac{1}{\omega} \text{Im}(\eta/\kappa(\omega)) \to g_0 = 1.5 \frac{\rho f T}{\phi}, \]
\[ T \text{ being the tortuosity factor so that the low-frequency Biot’s equations are recovered.} \]

▶ The electroseismic coupling coefficient \( L \) is assumed to be frequency independent,
\[ L_0 = -\frac{\phi}{T} \frac{\varepsilon_0 \kappa_f \zeta}{\eta} (1 - 2 \frac{\tilde{d}}{\Lambda}), \]

▶ \( F^{(s)} = F^{(f)} = 0, \) and \( \omega \varepsilon/\sigma \ll 1 \)

▶ We consider lossy media using Liu’s model.

▶ Electro-filtration feedback negligible; this decouples the EM fields from the poroviscoelastic response. (This makes calculations easier)
Scheme of the Finite Element Procedure

- Create a partition of the domain (elements).
- Transform original equations into a "weak form".
- Choose appropriate polynomial functions to approximate the solution in each element, (dofs).
- Transform the weak form into a linear sistem, and solve it. ($\sim 4 - 7 \times 10^7$ unknowns)
### Single horizontal layer

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Medium 1</th>
<th>Medium 2 (layer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$ (S/m)</td>
<td>0.1</td>
<td>0.01</td>
</tr>
<tr>
<td>$\phi$ (—)</td>
<td>0.2</td>
<td>0.33</td>
</tr>
<tr>
<td>$K_s$ (Pa)</td>
<td>$4.5 \times 10^{10}$</td>
<td>$6 \times 10^{10}$</td>
</tr>
<tr>
<td>$v_p$ (m/s)</td>
<td>3900</td>
<td>4800</td>
</tr>
<tr>
<td>$v_s$ (m/s)</td>
<td>2130</td>
<td>2800</td>
</tr>
<tr>
<td>$\rho_s$ (kg/m$^3$)</td>
<td>2600</td>
<td>2600</td>
</tr>
<tr>
<td>$k_0$ (m$^2$)</td>
<td>$10^{-16}$</td>
<td>$10^{-11}$</td>
</tr>
<tr>
<td>$L_0$</td>
<td>$10^{-14}$</td>
<td>8.16 $\times 10^{-9}$</td>
</tr>
<tr>
<td>$Q$ (—)</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>$\rho_f$ (kg/m$^3$)</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>$\eta$ (kg/(m s))</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>$K_f$ (Pa)</td>
<td>$2.25 \times 10^9$</td>
<td>$2.25 \times 10^9$</td>
</tr>
<tr>
<td>$S_f$ (—)</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
Single horizontal layer
SHTE-mode

$t=0.1$ s

$t=0.2$ s

$t=0.3$ s

$t=0.4$ s

F. I. Zyserman

EOST, March 12th, 2013
Single horizontal layer

Different layer widths, SHTE-mode

F. I. Zyserman

EOST, March 12th, 2013
Single horizontal layer
PSTVM-mode
Single horizontal layer

PSTVM-mode

Div and Curl of an acceleration trace

-2.5e-14
-2e-14
-1.5e-14
-1e-14
-5e-15
0
5e-15
1e-14
1.5e-14
2e-14
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

Div and Curl of an acceleration trace

F. I. Zyserman
EOST, March 12th, 2013
Wedge

<table>
<thead>
<tr>
<th></th>
<th>First Layer</th>
<th>Second layer</th>
<th>Third layer</th>
<th>Wedge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_c$ (S/m)</td>
<td>0.01</td>
<td>0.1</td>
<td>0.01</td>
<td>0.001</td>
</tr>
<tr>
<td>$\phi$ (—)</td>
<td>0.2</td>
<td>0.25</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>$K_s$ (Pa)</td>
<td>$3.7 \times 10^{10}$</td>
<td>$2.5 \times 10^{10}$</td>
<td>$3.7 \times 10^{10}$</td>
<td>$3.7 \times 10^{10}$</td>
</tr>
<tr>
<td>$v_p$ (m/s)</td>
<td>2500</td>
<td>2600</td>
<td>3000</td>
<td>3000</td>
</tr>
<tr>
<td>$v_s$ (m/s)</td>
<td>1400</td>
<td>1450</td>
<td>1800</td>
<td>1800</td>
</tr>
<tr>
<td>$\rho_s$ (kg/m$^3$)</td>
<td>2650</td>
<td>2650</td>
<td>2650</td>
<td>2650</td>
</tr>
<tr>
<td>$k_0$ (m$^2$)</td>
<td>$10^{-13}$</td>
<td>$10^{-16}$</td>
<td>$10^{-13}$</td>
<td>$10^{-13}$</td>
</tr>
<tr>
<td>$L_0$</td>
<td>$3.2 \times 10^{-15}$</td>
<td>$1.5 \times 10^{-9}$</td>
<td>$3.3 \times 10^{-9}$</td>
<td>$3.3 \times 10^{-9}$</td>
</tr>
<tr>
<td>$Q$ (—)</td>
<td>30</td>
<td>50</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>$\rho_f$ (kg/m$^3$)</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>0.88</td>
</tr>
<tr>
<td>$\eta$ (kg/(m s))</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>1.10$^{-5}$</td>
</tr>
<tr>
<td>$K_f$ (Pa)</td>
<td>$2.25 \times 10^9$</td>
<td>$2.25 \times 10^9$</td>
<td>$0.1 \times 10^9$</td>
<td>$0.1 \times 10^9$</td>
</tr>
<tr>
<td>$S_f$ (—)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.75</td>
</tr>
</tbody>
</table>

F. I. Zyserman
EOSS, March 12th, 2013
Surface gather

x-component acceleration
Surface gather

z-component acceleration
Methane hydrates (GH) ...

- form stable ice-like crystals in permafrost regions and beneath the ocean floor along continental margins.

- are considered as a potentially huge energy resource.
- have the highest energy density of any naturally occurring form of methane (about 160 times that of methane gas)
- decrease the electrical conductivity of the medium.

Ellis, 2008
Composite Media

We use an extended Biot theory for composite matrix rocks with non uniform porosity distributions.

- The solid matrix can be formed by mixtures of different mineral grains.
- A fraction of the GH (ice) is assumed to form a second matrix occupying the pore space, and the rest of it is assumed to cement the mineral grains.
- Letting $V = (V_{gh}^c + V_{gh}^{nc}) + V_{mg} + V_f$, $V_p = V - V_{mg}$, $\phi_a = V_p / V$; and $C_{gh} = V_{gh}^c / V_{gh}$, cementation coefficient, $S_{gh} = V_{gh} / V_p$ GH saturation, all (Biot) model parameters are obtained in terms of $C_{gh}$, $S_{gh}$, $\phi_a$, $K_{mg}^j$ and $\mu_{mg}^j$ forming the solid matrix; and $K_{gh}$, $\mu_{gh}$. 
The Model

<table>
<thead>
<tr>
<th></th>
<th>Permafrost</th>
<th>Sandstone</th>
<th>Slab ($S_{gh} = 0.1$)</th>
<th>Slab ($S_{gh} = 0.8$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi$</td>
<td>0.025</td>
<td>0.25</td>
<td>0.225</td>
<td>0.05</td>
</tr>
<tr>
<td>$V_p$ m/s</td>
<td>4100</td>
<td>2250</td>
<td>2930</td>
<td>4080</td>
</tr>
<tr>
<td>$V_s$ m/s</td>
<td>2150</td>
<td>690</td>
<td>1580</td>
<td>2180</td>
</tr>
<tr>
<td>$\sigma$ S/m</td>
<td>$8 \cdot 10^{-3}$</td>
<td>0.025</td>
<td>$8 \cdot 10^{-3}$</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>$L_0$ A/(Pa m)</td>
<td>$10^{-16}$</td>
<td>$4.6 \cdot 10^{-9}$</td>
<td>$4.15 \cdot 10^{-9}$</td>
<td>$9.4 \cdot 10^{-10}$</td>
</tr>
</tbody>
</table>
SHTE-mode
Acceleration surface gather

Without hydrate

With hydrate

F. I. Zyserman
EOST, March 12th, 2013
SHTE-mode
Acceleration well gather

Without hydrate

With hydrate

F. I. Zyserman
EOST, March 12th, 2013
SHTE-mode

Acceleration surface trace for $S_{gh} = .1$ and $S_{gh} = .8$

---

F. I. Zyserman
EOST, March 12th, 2013
PSVTM-mode

Acceleration (x-component) well gather

Without hydrate vs. With hydrate
PSVTM-mode

Acceleration well traces for $S_{gh} = .1$ and $S_{gh} = .8$
CO₂ storage monitoring

The Model
CO₂ storage monitoring
PSVTM mode, acceleration traces

F. I. Zyserman
EOST, March 12th, 2013
CO$_2$ storage monitoring
PSVTM mode, acceleration traces

F. I. Zyserman
EOST, March 12th, 2013
We have developed a numerical tool to simulate electroseismic (and seismoelectric) phenomena.

It was observed that the response is sensitive to changes in fluid conductivities (mixtures of gas and brine).

We have shown that methane hydrates can be detected by means of electroseismics on land in permafrost regions.

We have observed that the seismic response is sensitive to methane hydrate concentration.

Preliminary results indicate that it could be very interesting to consider electroseismics/seismoelectrics as a monitoring tools for CO\(_2\) storage sites.

Heaps of work ahead!