Seismic to Electric Conversion: a Tool for Earth Subsurface Characterization

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Overview

- Seismoelectric effects – why?
- Seismoelectric effects – what kind of structural sensitivity?
- Governing equations
- Assessing seismoelectric effects for carbon storage monitoring
Where is the fluid (oil, gas, water)?

- Currently, subsurface fluid recovery is blind below 1km
- What if we could map fracture network and track leakage at relevant depth

Creating optimal fracture networks
- To optimize reservoir performance
- To increase production

Seismoelectric conversion enables a probing of subsurface at greater depth than EM & improve sensitivity to fluid compared to seismic techniques

Seismic techniques alone: do not capture fluid properties and fluid related mechanism

EM techniques alone: do not constrain rock properties, have shallow penetration in ground

Store CO2 in sealed reservoir/risk management
- To monitor leakage
Seismoelectric effects (SEE): pore scale phenomena

(1) A seismic source triggers a seismic wave, which propagates in a porous medium
    => Charges are put in relative motion between grain surfaces and pores, generating an electric dipole

(2) Electric dipole triggers an electromagnetic field

Field test of seismic to electric conversion (Thompson & Gist, 1993)
    => They detected gas-water interface due to seismoelectric effects (~500m).
SEE seismograms vs. radargrams records: different information

[after Haines, 2004]

Seismoelectric conversion generates direct field, coseismic signal, and interface response
SEE governing equations

schematic view

In-house new software to model SEE implemented in SPECFEM

[Electromagnetic module]

[Seismic-to-electric coupling]

[Fluid pressure gradient and solid phase acceleration drive a Darcy flow]

[An electric current creates a magnetic field and Darcy flow create an electric current]

[A magnetic field creates an electric field]

[Electric-to-seismic coupling]

[Darcy flow, relative acceleration between fluid & solid phases and electroosmotic effect define a drag force]

[Subject to a drag force, shear, in-phase and out-of-phase fluid & solid displacements are observed]

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SEE governing equations

\[ \rho \partial_t^2 \mathbf{u}_s + \rho_f \partial_t^2 \mathbf{w} = \nabla \cdot \mathbf{T} + \mathbf{F} \]
\[ \eta k^{-1} \partial_t \mathbf{w} + \frac{\rho_f c}{\phi} \partial_t^2 \mathbf{w} + \rho_f \partial_t^2 \mathbf{u}_s = \nabla \cdot \mathbf{T}_f + \mathbf{F} + Q_v \mathbf{E} \]
\[ \mathbf{T} = (B \nabla \cdot \mathbf{u}_s + C \nabla \cdot \mathbf{w}) \mathbf{I} + 2\mu_f r \mathbf{D}_s \]
\[ \mathbf{T}_f = -p_f \mathbf{I} = (C \nabla \cdot \mathbf{u}_s + M \nabla \cdot \mathbf{w}) \mathbf{I} \]

\[ \epsilon \partial_t^2 \mathbf{E} = \nabla \cdot (\partial_t \tilde{\mathbf{H}}) - \sigma \partial_t \mathbf{E} - \partial_t \mathbf{j}_s \]
\[ \partial_t \tilde{\mathbf{H}} = \tilde{\mu}^{-1} : \nabla \mathbf{E} \]
\[ \mathbf{j}_s = Q_v \partial_t \mathbf{w} \]

Qv is the moveable charge density, which acts as a coupling factor (Revil et al., 2015)

In-house new software to model SEE implemented in SPECFEM

[funded under LDRD 17-LW-029]
Carbon storage monitoring

Cross-wells monitoring setup

Solid seismic displacement

Triggered coseismic electric field

Coseismic signal accurately modeled

[funded under LLNL Carbon Storage Program]
Carbon storage monitoring

Our in-house software accurately detects 3 types of seismic-to-electric conversions:

1. coseismic electric signal,
2. quasi-instantaneous electric signal generated when the seismic source occurs, and
3. quasi-instantaneous seismo-to-electric conversion at material discontinuity.

[funded under LLNL Carbon Storage Program]
Conclusion

- Coupling between Biot-poroelastic and Maxwell-EM wave equations was implemented in a spectral-element code.

- Seismic-to-electric conversion can be assessed to monitor CO$_2$.

- Instantaneous seismic-to-electric conversion when the seismic source occurs can be used to provide the exact time an event happens but can also be used to determine source mechanism information.
Next: SEE adjoint capability

Finite frequency sensitive kernels have been derived for:

• pure Biot poroelastic seismic parameters (Morency et al, 2009)
• pure electromagnetic parameters (Mukherjee & Morency, 2018 in preparation)

➢ We are now working on deriving finite frequency sensitivity kernels for the coupled system.
➢ These kernels will be the first step towards new full waveform inversion for SEE parameters and SEE imaging.