Modelling of Seismoelectric Effects

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Electrical double layer / Electrokinetic phenomena

Description of seismoelectric effects
  - Direct field, coseismic field and interface response

Theoretical fundamentals
  - Governing equations ("u-p formulation")

Numerical simulation
  - Model setup
  - Physical responses of the system
  - Anatomy of the interface response

Conclusion & Outlook
Motivation

Why numerical modelling of seismoelectric effects?

- **Seismoelectrics** is an energy transfer between seismic and electromagnetic wavefields occurring at the electrical double layer.

- Generation of seismoelectric signals in porous media is connected with properties such as *hydraulic permeability* and *porosity*.

- Seismoelectric method could be used in *hydrogeophysics* for determining these parameters *directly*.

- Numerical modelling in COMSOL with a view to an improved understanding of the *interactive processes* associated with seismoelectric effects.
The electrical double layer in a porous media – „Stern model“

The electrical double layer in a porous media – „Stern model“
The electrokinetic phenomena

Effects caused by electrical gradient

- Electric current induces water flow
  - Electroosmosis -
  - Imposed: electric potential gradient $\Delta \varphi$
  - Measured: fluid flux $Q$

Effects caused by mechanical movement

- Water flow induces electrical gradient
  - Streaming potential -
  - Imposed: pressure gradient $\Delta h$
  - Measured: electric potential gradient $\Delta \varphi$
Generation of seismoelectric effects

Electric and magnetic fields caused by deformation processes

I.) Direct field

II.) Seismic wave

II.) Coseismic wave

Source

Receivers

Surface

Interface

$E$

EM wave

Induced E-field

Fluid flow

Fluid flow

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Generation of seismoelectric effects – interface response

I.) Seismic Wave

II.) Electrokinetics

III.) Wave conversion

IV.) Measurements
Dynamic poroelasticity equations

Coupled processes of elastic deformation and pore fluid diffusion

- **Constitutive equations for linear poroelasticity (stress-strain relationship)**

\[
\sigma_{ij} = 2G\varepsilon_{ij} + 2G\left(\nu / (1-2\nu)\right)\varepsilon_{kk} \delta_{ij} - \alpha p \delta_{ij}
\]

Variation in the pore pressure

- **Dynamic equilibrium for the mixture ("Biot formulation")**

\[
\sigma_{ij,j} = \rho \ddot{u}_i + \rho_f \ddot{w}_i \quad \text{with} \quad w_i := \phi \left(u^f_i - u^s_i\right)
\]

Relative displacement

- **Balance law for the solid equilibrium ("dynamical behaviour of the system")**

\[
\left( G \nabla^2 u + G/(1-2\nu) \nabla (\nabla \cdot u) \right) = \alpha \nabla p + \rho \ddot{u} + \rho_f \ddot{w}
\]

- **Fluid mass balance equation, i.e. continuity equation**

\[
\dot{\zeta} = -\nabla \cdot q \quad \text{with} \quad q = \phi w \quad \land \quad \zeta = \alpha \nabla \cdot u + S_\alpha p
\]

Increment of fluid content := kind of volumetric strain

\[\text{fluid flux}\]
Maxwell equations – electrokinetic coupling equations

Maxwell's electromagnetic field equations

- **Faraday's law**
  \[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{H}}{\partial t} \]

- **Ampère's law**
  \[ \nabla \times \mathbf{H} = \mathbf{J} = \sigma \mathbf{E} + \nabla p \]

The electrokinetic coupling equations

- **Fluid transport modeled with generalized Darcy's law**
  \[ \nabla \cdot \mathbf{q} = \frac{k_f}{\eta} (-\nabla p + \rho_f \mathbf{\ddot{u}}) + \nabla (\mathbf{L} \cdot \mathbf{E}) \]
  Electroosmosis

- **Electric balance modeled with generalized Ohm's law (no external sources!)**
  \[ \nabla \cdot \mathbf{J} = \nabla \cdot \left( \nabla (-\nabla p + \rho_f \mathbf{\ddot{u}}) + \sigma \mathbf{E} \right) = 0 \]
  Streaming electric current

- **Coupling coefficient**
  \[ L := -\varepsilon_0 \varepsilon_r \tilde{\xi} / F_0 \eta \approx 10^{-9} \text{ [m}^2 / \text{Vs]} \]
Set of equations for all responses of the system

**Governing equations – „u-p formulation“** *

(i) \[ \frac{E}{2(1+\nu)} \left( \nabla^2 u + \frac{1}{1-2\nu} \nabla(\nabla \cdot u) \right) = \rho \frac{\partial^2 u}{\partial t^2} + \frac{\partial^2}{\partial t^2} \rho_f w + \alpha \nabla p \]

Neglecting acceleration of relative displacement *

(ii) \[ \nabla \cdot \left( \frac{k_f}{\eta} (\nabla p + \rho_f \frac{\partial^2 u}{\partial t^2}) + LE \right) = -\alpha \frac{\partial}{\partial t} \nabla \cdot u - S_a \frac{\partial}{\partial t} p \]

(iii) \[ \nabla \cdot \left( L (\nabla p + \rho_f \frac{\partial^2 u}{\partial t^2}) \right) = -\sigma \nabla \cdot E \]

(iv) \[ \nabla \times \left( \frac{1}{\sigma} \nabla \times H - L \nabla p \right) = -\frac{\partial}{\partial t} \mu H \]

• Valid for a low-frequency range! – Modelling is performed by **COMSOL Multiphysics**.

*Zienkiewicz et al. Computational Geomechanics, 1999*
The model features a thin clay lens in a sand background.

Responses illustrated as (i) snapshots at different times and (ii) magnetograms recorded by a surface receiver line.

Signal input is a Ricker wavelet with a centre frequency of 380 Hz.
Snapshots at different times - seismoelectric responses

**Direct field**
Surface: $u_x$, Contour: Electric potential [V]

*Electric field due to charge distribution at impact source with reversed polarity on opposite sides of the shotpoint*

**Interface response**
Surface: $v_y$, Contour: Magnetic field, z-component [A/m]

*Conversion from seismic-to-electromagnetic waves at the interface – SV-wave generates a transversal polarized magnetic (TM-) wave*

**Coseismic field**
Surface: Mises stress, Contour: Electric potential [V]

*Electric field travelling with seismic wave because of charge accumulations due to streaming currents*
Seismoelectrogram – the different responses collected

„Direct field“ and „interface response“:
- The waves reach all receivers at virtually the same time due to the high EM-velocity!
  - Signals change sign on opposite side of shotpoints

„Coseismic field“:
- Coseismic wave with the same waveform as seismic wave (hyperbolic structure)
  - Signals change on opposite side of shotpoints
Generation of electromagnetic TM – mode caused by SV - wave

Figures from different views at the same time (t = 1.07 ms)

Overall view

Surface: Electric potential [V]  Contour: Mises Stress
Heigth: Magnetic Field, z-component [A/m]

Topview x–y plane

View from the front in x–z plane
Snapshots - magnetic dipoles at the interface caused by SV-waves

Surface: Magnetic field, z-component (Hz) [A/m]  Contour: Vertical displacement SV-wave (vy)

- Peak of the wave at 1st interface
- Peak at 2nd interface and trough at 1st interface
- Multipole generation
- Trough of the wave at 2nd interface

Left figures: Full waveform - Right figures: Zoom at the interfaces
Magnetogram for z-component – correlation at different times

- Magnetic dipoles are generated by vertical displacement of SV-wave
- Highest amplitudes of dipoles are correlated with peaks and troughs of the wavelet (SV-wave: Displacements perpendicular to direction of wave propagation!)

Wavelet

Magnetogram Snapshots

1.07 [ms]
1.20 [ms]
1.29 [ms]
1.39 [ms]
Summary

What did we learn?

- Our finite-element algorithm („u-p formulation“) provides a reasonable method for understanding the seismoelectric coupling.

- Synthetic time sections of wave propagation show the interaction of the different responses in the system.

- The direction of the streaming potential gradient induced by the seismic wave corresponds with the direction of the generated dipole response.

- Our modelling results indicate the capability of the seismoelectric method to detect thin layers (thickness smaller than wavelength).
Outlook

What comes next?

- Investigation of new geometries: *downhole and crosswell surveys*.
- *Quantitative analysis* of seismoelectric effects in 2.5D and 3D.
- *Validation* of the „u-p formulation“ with existing algorithms.
- Development of a *seismoelectric inversion* algorithm.
- *Application of the seismoelectric method* to determine permeabilities.
References


Thank you for your attention!