Time-lapse poroelastic modelling for a carbon capture and storage (CCS) project in Alberta

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Outline

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• Quest project
• Numerical examples
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• Time-lapse modelling of the Quest project
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Goals

• To develop a finite difference program for modeling the wave propagation in the fluid saturated media based on the Biot’s theory of poroelasticity.

• To investigate the theoretical detectability of the CO₂ for the Quest carbon capture and storage project using a poroelastic approach.
Biot’s Theory of poroelasticity (1962)

- Useful in geophysical applications in which the fluid content of the rock is of interest.
- Poroelastic medium is composed of two phases: the porous rock frame and the viscous fluid within the pore space.
- The poroelastic theory (Biot) predicts a slow P-wave generated due to the relative movement of the fluid with respect to the rock frame.

(Russell et al., 2003)
Partial differential equations for isotropic porous media saturated with viscous fluid (Biot, 1962):

Stress-strain relations:

\[
\frac{\partial \tau_{ij}}{\partial t} = 2\mu \frac{\partial e_{ij}}{\partial t} + \left( \lambda_c \frac{\partial e_{kk}}{\partial t} + \alpha M \frac{\partial \varepsilon_{kk}}{\partial t} \right) \delta_{ij}
\]

Velocity-stress relations:

\[
\begin{align*}
\frac{\partial W_i}{\partial t} &= A \frac{\partial \tau_{ij}}{\partial x_j} + B \frac{\partial P}{\partial x_i} + CW_i \\
\frac{\partial V_i}{\partial t} &= D \frac{\partial \tau_{ij}}{\partial x_j} + E \frac{\partial P}{\partial x_i} + FW_i
\end{align*}
\]

Coupling Modulus
\[
M = \left[ \frac{\phi}{K_{\text{Fluid}}} + \frac{\alpha - \phi}{K_{\text{Solid}}} \right]
\]

Value of \(\alpha\):
\[
\alpha = 1 - \frac{K_{\text{Dry}}}{K_{\text{Solid}}}
\]

\(W\) : Solid Particle Displacement

\(U\) : Fluid Particle Displacement

\(A, B, C\) : Density dependant coefficients

\(D, E, F\) : Density dependant coefficients
QUEST Project

- CO₂ storage in Basal Cambrian Sands or BCS, which is a saline aquifer within Western Canadian Sedimentary Basin (WCSB)

Modified after Bachu et al. 2000.
Logs from well
SCL-8-19-59-20W4
2D Staggered-grid velocity-stress finite difference scheme.

Fourth order in space and second order in time.

The stability condition is the same as the one in the elastic case (Zhu:1991)

\[ \Delta t \leq \frac{\Delta x}{(V_p^2 - V_s^2)^{1/2}} \]

\[ \Delta x = 2m \quad \Delta t = 0.2 \text{ ms} \]

Explosive buried source: Ricker wavelet with dominant frequency 40 Hz
Single layer model

Vertical particle velocity of the solid:
**Two layer model**

<table>
<thead>
<tr>
<th></th>
<th>Top Layer</th>
<th>Bottom Layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho_f )</td>
<td>1070 (kg/m(^3))</td>
<td>937 (kg/m(^3))</td>
</tr>
<tr>
<td>( \rho )</td>
<td>2400 (kg/m(^3))</td>
<td>2370 (kg/m(^3))</td>
</tr>
<tr>
<td>( V_p )</td>
<td>4100 (m/s)</td>
<td>3800 (m/s)</td>
</tr>
<tr>
<td>( V_s )</td>
<td>2390 (m/s)</td>
<td>2400 (m/s)</td>
</tr>
<tr>
<td>( \phi )</td>
<td>16%</td>
<td>16%</td>
</tr>
<tr>
<td>( \eta )</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

![Diagram showing two layers with different compositions]
Two layer model

Poroelastic

Elastic

100% brine

40% CO2 + 60% brine
Perfectly matched layer (PML):

- Berenger, 1994: Electromagnetic waves
- Chew and Liu, 1996: Elastic waves

\[ a_x = \log \left( \frac{1}{R} \left( \frac{3V_F}{2} \right) \left( \frac{x^2}{L_{PML}^3} \right) \right) \]

- \( R \): Theoretical reflection coefficient
- \( L_{PML} \): Thickness of the PML region
- \( x \): distance from the PML boundary
No PML

PML: 15 grid-points

PML: 20 grid-points

PML: 25 grid-points
Time-lapse modelling

Baseline

Monitor

CO2 plume:
- 1.2 million tonnes CO₂
- CO₂ saturation 40%
- Porosity 16%
Shot gathers: Poroelastic
Zero offset sections: Poroelastic

Baseline zero offset section

Monitor zero offset section
Time-lapse difference: Poroelastic
Time-lapse differences
Conclusions

- We showed that the fluid induced flow even in cases of low viscosity effects the seismic response of the fluid saturated medium.
- Perfectly matched layers were used as boundary condition that effectively absorbed the reflections from the computational boundaries.
- This means that the CO\textsubscript{2} plume could be detected in the seismic data providing the data have good bandwidth and a high signal to noise ratio.
- The difference between the elastic and poroelastic algorithms are considerable and we need to take the poroelastic effects into account.
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- David Aldridge from Sandia national laboratories
- Juan Santos from Purdue University
Absorbing boundary condition (ABC)

In 2D case:

\[
\frac{\partial V_z}{\partial t} = A \left( \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{zz}}{\partial z} \right) + B \frac{\partial S}{\partial z} + CW_z
\]

\[
\left( \frac{\partial}{\partial t} + a_x \right) V_x^z = A \left( \frac{\partial \tau_{xz}}{\partial x} \right) + C \left( W_x^z + a_x \int_{-\infty}^{t} W_x^z \, dt \right)
\]

\[
\left( \frac{\partial}{\partial t} + a_z \right) V_z^z = A \left( \frac{\partial \tau_{zz}}{\partial z} \right) + B \frac{\partial S}{\partial z} + C \left( W_z^z + a_z \int_{-\infty}^{t} W_z^z \, dt \right)
\]

\[
V_z = V_x^z + V_z^z
\]
Biot’s Theory (1962)

Assumptions:

- Elastic rock frame
- Connected pores
- Seismic wavelength $\gg$ average pore size
- Small deformations
- Statistically isotropic medium
Staggered-grid finite difference

Levander (1988)

\[ X : \tau_{xx}, \tau_{zz} \text{ and } P \]

\[ Y : V_x \text{ and } W_x \]

\[ Z : V_z \text{ and } W_z \]

\[ O : \tau_{xz} \]