Seismic velocity tomography with co-located soft data

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Motivation

- soft data constrains flow simulation
Outline

- Introduction
- Seismic tomography
- Geological constraints for velocity analysis
- Cross Gradients Function
  - Accuracy in different frequency intervals
- Results
- Future work:
  - Western Geco Dataset: Seismic & Resistivity
Introduction
Schematic of seismic imaging

Model: \( v, \rho \)

Velocity Estimation

Data

Image
Tomography Problem

- Choice of constraints
  - Soft data
  - Training images
  - Smoothness
Magnetotellurics (MT) data

- Natural-source (electromagnetic method)

- Insight into the resistivity structure as the main parameter
  - Frequency: 0.001 - 1 Hz
  - Insensitive to thin resistors
Field Data

- 3D cube inverted resistivity
- Seismic Data

Courtesy of WesternGeco Co.
Seismic tomography
Tomography

- Relate travel times and slowness

\[ t = T_{nl}(s) \]

- Operator is model dependent
  - Initial guess \( s_0 \)
  - Ray paths are a function of slowness

Courtesy of Bob Clapp.
Tomography

- Relate travel times and slowness

\[ t = T_{nl}(s) \]

- Operator is model dependent
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Courtesy of Bob Clapp.
Linearization

- Linearize operator
  
  - Using Taylor’s expansion

\[
\begin{align*}
  t &\approx T_{nl}s_0 + \nabla T_{nl} \Delta s \\
  t &\approx t_0 + T_0 \Delta s \\
  \Delta t &\approx T_0 \Delta s
\end{align*}
\]

- Iteratively update approximation of \( s \mapsto s_0 \)

\[s_1 = s_0 + \Delta s.\]

- Linearize the operator around new \( s_0 \)
Tomography and null space

- shadow zones
  - lack of illumination or poor illumination
    (especially sub-salt regions)

- limited angle coverage
  - imposed by recording geometry

- resolution decreases with depth
  - velocity information is revealed with reflection angle.

- under-determined problem
  \[ Q(\Delta s) = \| \Delta t - T_0 \Delta s \|^2 + \epsilon^2 \| A \Delta s \|^2 \]
Cross-gradients function
Cross-gradients function

- Structural similarity measurement

\[ \vec{t}(x, y, z) = \nabla m_r \times \nabla m_s \]

- simplified 2-D definition

\[ t(x, z) = \left( \frac{\partial m_r}{\partial z} \frac{\partial m_s}{\partial x} \right) - \left( \frac{\partial m_r}{\partial x} \frac{\partial m_s}{\partial z} \right) \]

\( m_r \): resistivity field
\( m_s \): slowness field

- Considering the mesh below, we can linearize the cross-gradients function

\[ t \approx \frac{4}{\Delta x \Delta z} (m_{rc}(m_{sb} - m_{sr}) + m_{rr}(m_{sc} - m_{sb}) + m_{rb}(m_{sr} - n_{sc})) \]
Cross-gradients vs. Frequency range

- Accuracy for field properties in different frequency intervals:
  - Difference in frequency
  - Structural complexity?

- Velocity vs. resistivity
  - Smooth velocity as resistivity
Auto cross-gradient

Distance (m)

Cross-gradient values

Depth (m)
Cross-gradient values

Marmousi velocity (m/sec)
Velocity analysis with cross-gradient constraint

- Velocity analysis objective function

\[ Q(\Delta s) = \| \Delta t - T_0 \Delta s \|^2 + \epsilon_1^2 \| A \Delta s \|^2 \]

\[ P(\Delta s) = \| \Delta t - T L \Delta s \|^2 + \epsilon_1^2 \| A \Delta s \|^2 + \epsilon_2^2 \| G(s_0 + \Delta s) \|^2, \]

- **\( T_L \)**: linear approximation of tomography matrix
- **\( A \)**: regularization operator
- **\( G \)**: linear cross-gradients operator
- **\( g \)**: cross-gradients function
- **\( s \)**: seismic slowness
- **\( r \)**: resistivity
- **\( t \)**: travel time
Synthetic model with semi-circular fault

Velocity model

Distance (Km)

Time (s)

Velocity model

V (Km/s)
Initial velocity estimation

![Graph showing initial velocity estimation over distance and time. The graph indicates the initial velocity guess with a range from 1.6 to 2.8 Km/s.](image)
Velocity estimation without soft data

Updated velocity

Distance (Km)

Time (s)

V (Km/s)
Velocity estimation with soft data

Updated velocity with soft data
Observations

‣ Steering filters
  • Smooth and continuous velocity anomalies

‣ Cross-gradient functions
  • Sharp boundaries
  • Salt structures
  • Faults
Future work

- Improved velocity-resistivity relations
- Apply to field data
- Integrate training images as a constraint to tomography problem
- Integrate statistical uncertainty analysis
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