The seismic physical modelling laboratory as a tool for design and appraisal of FWI methods

Sergio Romahn
Kristopher Innanen
Nov - 2017
Outline

- Introduction
  - The cycle of FWI
  - FWI vs IMMI
  - CREWES physical modelling laboratory facility
- Physical modelling data
- Data conditioning
  - Directivity correction
  - Changing-waveform correction
  - Geometrical spreading
  - Low frequency noise
- Wavelet estimation
- Inversion of physical modelling data
- Conclusions
The cycle of full waveform inversion

\[ \delta v(x, z) = \lambda \nabla_v \phi_k(x, z, w) = \lambda \int \sum_{s,r} \omega^2 \hat{\Psi}_s(x, z, \omega) \delta \hat{\Psi}_{r(s),k}^*(x, z, \omega) d\omega \]

1) Forward model through \( v_{k-1} \) to predict data \( \psi_{r,k} \)

2) Migrate “data residual” with \( v_{k-1} \) and stack

3) “Calibrate” migration and deduce velocity perturbation \( \delta v_k \)

4) Update velocity model \( v_k = v_{k-1} + \delta v_k \)

Margrave et al., 2010
The cycle of full waveform inversion

\[ \delta v(x, z) = \lambda \nabla_v \phi_k(x, z, w) = \lambda \int \sum_{s,r} \omega^2 \hat{\Psi}_s(x, z, \omega) \hat{\Psi}^*_r(s, k)(x, z, \omega) d\omega \]

1) Forward model through \( v_{k-1} \) to predict data \( \psi_{r,k} \)

2) Migrate “data residual” with \( v_{k-1} \) and stack

3) “Calibrate” migration and deduce velocity perturbation \( \delta v_k \)

\[ \delta v_k = \lambda M (\delta \psi_{r,k}) \]

4) Update velocity model \( v_k = v_{k-1} + \delta v_k \)

\[ \phi_k = \sum_{s,r} (\Psi - |\Psi|^2 \Psi_{r,k}) \]

Margrave et al., 2010
The cycle of full waveform inversion

\[ \delta v(x, z) = \lambda \nabla_r \phi_k(x, z, w) = \lambda \int \sum \omega^2 \psi_s(x, z, \omega) \delta \tilde{\psi}^*_{r(s),k}(x, z, \omega) d\omega \]

Margrave et al., 2010
The cycle of full waveform inversion

\[
\delta v(x, z) = \lambda \nabla r \phi_k(x, z, w) = \lambda \int \sum_{s,r} \omega^2 \hat{\psi}_s(x, z, \omega) \delta \hat{\psi}_{r(s),k}^*(x, z, \omega) d\omega
\]

- Standard FWI uses RTM
- IMMI proposes the use of any kind of migration: PSPI

Margrave et al., 2010
The cycle of full waveform inversion

\[ \delta v(x, z) = \nabla_x \phi_k(x, z, \omega) = \frac{\partial}{\partial \omega} \left( \sum_{s,r} \omega^2 \tilde{\Psi}_{s}(x, z, \omega) \delta \tilde{\Psi}_{r,s,k}^{*}(x, z, \omega) d\omega \right) \]

1) Forward model through \( v_{k-1} \) to predict data \( \psi_{r,k} \)

2) Migrate “data residual” with \( v_{k-1} \) and stack

3) “Calibrate” migration and deduce velocity perturbation

\[ \delta v_k = \lambda M (\delta \psi_{r,k}) \]

4) Update velocity model

\[ v_k = v_{k-1} + \delta v_k \]

Margrave et al., 2010
The cycle of full waveform inversion

\[ \delta v(x, z) = \lambda \nabla_v \phi_k(x, z, w) = \lambda \int \sum_{s, r} \omega^2 \tilde{\psi}_s(x, z, \omega) \delta \tilde{\psi}^*_{r(s), k}(x, z, \omega) d\omega \]

• FWI uses the inverse Hessian matrix or the step-length method
• IMMI incorporates well-log information to calibrate the gradient

Margrave et al., 2010
The cycle of full waveform inversion

\[ \delta v(x, z) = \lambda \nabla_v \phi_k(x, z, w) = \lambda \int \sum_{s,r} \omega^2 \hat{\Psi}_s(x, z, \omega) \delta \hat{\Psi}_{r(s),k}^*(x, z, \omega) d\omega \]

Margrave et al., 2010
• We can control and vary many acquisition parameters
• We know the subsurface model that we want to solve; therefore, we can monitor model errors almost exactly
• Physical modelling represents a potentially unique way of validating and appraising complex methods involving real measurements of seismic waveforms

<table>
<thead>
<tr>
<th></th>
<th>Distance</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>From laboratory to</td>
<td>1 : 10000</td>
<td>10000 : 1</td>
</tr>
<tr>
<td>real world scale</td>
<td>1 mm = 10 m</td>
<td>10 kHz =  1 Hz</td>
</tr>
</tbody>
</table>

Photographs courtesy of Kevin Bertram.
- **Introduction**
  - The cycle of FWI
  - FWI vs IMMI
  - CREWES physical modelling laboratory facility

- **Physical modelling data**

- **Data conditioning**
  - Directivity correction
  - Changing-waveform correction
  - Geometrical spreading
  - Low frequency noise

- **Wavelet estimation**

- **Inversion of physical modelling data**

- **Conclusions**
Physical model

1485 m/s Water
2350 m/s PVC
1485 m/s Water
2745 m/s PLX

Physical modelling data

Physical modelling shot

Well B

Distance (m)

Depth (m)

Velocity (m/s)

Time (s)

Offset (m)
Introduction
- The cycle of FWI
- FWI vs IMMI
- CREWES physical modelling laboratory facility

Physical modelling data

Data conditioning
- Directivity correction
- Changing-waveform correction
- Geometrical spreading
- Low frequency noise

Wavelet estimation

Inversion of physical modelling data

Conclusions
Directivity correction

\[ \lambda = \frac{\nu}{f} \]

\( p(p_0, D, \lambda, z, \gamma) = 4p_0 \frac{J_1(X)}{X} \sin \left( \frac{\pi D}{8\lambda z} \right) \)

\[ X = \frac{\pi D}{\lambda} \sin \gamma, \]

\[ J_1(x) = \frac{x}{2} - \frac{x^3}{2^2 4^2} + \frac{x^5}{2^2 4^2 6^2} - \frac{x^7}{2^2 4^2 6^2 8^2} \cdots \]

Amplitude abruptly decays with offset

Buddensiek et al., 2009

Data conditioning

<table>
<thead>
<tr>
<th>S</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>S</td>
</tr>
</tbody>
</table>

\( D = 13 \text{ m} \)
\( \nu = 1500 \text{ m/s} \)
\( f_{\text{dom}} = 150 \text{ Hz} \)
Directivity correction

Data conditioning

\[ \lambda = \frac{1500 \text{ m/s}}{50 \text{ Hz}} = 30 \text{ m} \]

\[ v = 1500 \text{ m/s} \]

\[ f_{\text{dom}} = 50 \text{ Hz} \]
Introduction
- The cycle of FWI
- FWI vs IMMI
- CREWES physical modelling laboratory facility

Physical modelling data

Data conditioning
- Directivity correction
- Changing-waveform correction
- Geometrical spreading
- Low frequency noise

Wavelet estimation

Inversion of physical modelling data

Conclusions
Changing waveform correction

Data conditioning

N = 3 points
\(N^2 = 3^2 = 9\) traces

9 traces with different arrival times are summed to build the final trace

Loss of high frequencies and amplitude
Changing waveform correction

Laboratory case $\lambda > D$

- $D = 13\,\text{m}$, Vel. = $1500\,\text{m/s}$, $f = 50\,\text{Hz}$, $\lambda = 30\,\text{m}$

![Graph showing time, offset, and frequency for laboratory case $\lambda > D$.]

Stronger effect when $\lambda < D$

- $D = 13\,\text{m}$, Vel. = $1500\,\text{m/s}$, $f = 150\,\text{Hz}$, $\lambda = 10\,\text{m}$

![Graph showing time, offset, and frequency for stronger effect when $\lambda < D$.]

Reference wavelet
- 1-point transducer

Wavelet for a
- N-point transducer
- Introduction
  - The cycle of FWI
  - FWI vs IMMI
  - CREWES physical modelling laboratory facility
- Physical modelling data
- Data conditioning
  - Directivity correction
  - Changing-waveform correction
  - Geometrical spreading
  - Low frequency noise
- Wavelet estimation
- Inversion of physical modelling data
- Conclusions
Geometrical spreading from 3D to 2D

Multiplying by $\sqrt{t}$ and convolving by $1/\sqrt{t}$
(Bleistein, 1986; Pratt, 1999)

From 3D ($1/r$) to 2D ($1/\sqrt{r}$)

Data conditioning

Geometrical spreading correction
Introduction
- The cycle of FWI
- FWI vs IMMI
- CREWES physical modelling laboratory facility

Physical modelling data

Data conditioning
- Directivity correction
- Changing-waveform correction
- Geometrical spreading
- Low frequency noise

Wavelet estimation

Inversion of physical modelling data

Conclusions
Low frequency picks

Data conditioning

Amplitude spectrum

Shot number

Frequency (Hz)

Amplitude spectrum for shots 6, 16, 26, and 43.

Amplitude

Frequency (Hz)

www.crewes.org
Low frequency picks

Data conditioning

Amplitude spectrum

Shot number

Frequency (Hz)

Amplitude

Frequency (Hz)
Low frequency picks

Data conditioning

Amplitude spectrum

Shot number

Frequency (Hz)

0 5 10 15 20

0 1 2 3 4 5 6 7 8 9 10

1 Hz 10 Hz

HPB

Shot 6

Shot 16

Shot 26

Shot 43

Amplitude

Frequency (Hz)

0 50 100

0 20 40 60 80

0 20 40 60 80

0 20 40 60 80

0 20 40 60 80

0 50 100

0 50 100

0 50 100

0 50 100

www.crewes.org

CREWES

UNIVERSITY OF CALGARY

NSERC CRENSG

Faculty of Science

Department of Geoscience
Introduction
• The cycle of FWI
• FWI vs IMMI
• CREWES physical modelling laboratory facility

Physical modelling data

Data conditioning
• Directivity correction
• Changing-waveform correction
• Geometrical spreading
• Low frequency noise

Wavelet estimation

Inversion of physical modelling data

Conclusions
Wavelet estimation

[Diagram showing wavelet analysis options and parameters]

- **Spline**
  - Percentage of Points: 2
  - Fit to Amplitude
  - Fit to Decibels
- **Polynomial**
  - Order: 7
  - Fit to Amplitude
  - Flat before Min f
  - Flat after Max f
  - Fit to Decibels
- **Polynomial with Log10(f)**
  - Order: 8
  - Fit to Amplitude
  - Flat before Min f
  - Flat after Max f
- **Phase Options**
  - Minimum Phase
  - Zero Phase
  - Constant Phase: 10

[Graphs showing amplitude spectra and wavelet in time]

Wavelet calibration

Correlation coefficient: 0.7678

Normalized wavelets

Amplitude spectrum

www.crewes.org
Introduction
- The cycle of FWI
- FWI vs IMMI
- CREWES physical modelling laboratory facility

Physical modelling data

Data conditioning
- Directivity correction
- Changing-waveform correction
- Geometrical spreading
- Low frequency noise

Wavelet estimation

Inversion of physical modelling data

Conclusions
Initial velocity model

1st iteration

Inversion process
Gradient

1st iteration

Spatial multi-scale approach
1) Migrate residuals with full-frequency band
2) Apply Gaussian smoother with a half-width of 160 m for the first iteration

Gradient (1 - 70 Hz)

Smoothed gradient, half-width = 160 m
1st iteration

Well-calibration technique

Nonstationary matched filter

Well B       Well C

m/s

0

500

400

300

200

100

0

-100

0

500

1000

1500

Distance (m)

Depth (m)

1000

1500

2000

2500

3000

3500

m/s
New velocity model

Inversion process

1st iteration

Velocity update + Initial model = Inverted model
Inversion process

- Observed shot
- Modelled shot
- Blind well
- Calibration well
- Velocity model, \( t_{l=0} \)

- Time (s)
- Offset (m)
- Distance (m)
- Error in shot
- Error in blind
- Error in call
- Error in model

- Half-width (m)
- Iteration

www.crewes.org
Inversion process

Well B  Well C
Inversion process

Well B

Well C

Velocity model, it=10

www.crewes.org
Inversion process

- Observed shot
- Modelled shot
- Blind well
- Calibration well
- Velocity model, It=25

- Well B
- Well C

Half-width (m) vs Iteration
Error in shot vs Iteration
Error in blind vs Iteration
Error in call vs Iteration
Error in model vs Iteration

www.crewes.org

UNIVERSITY OF CALGARY
FACULTY OF SCIENCE
Department of Geoscience
The CREWES seismic physical modelling laboratory facility is a valuable tool for evaluating new seismic processing and interpretation techniques outside the synthetic environment.

Physical modelling data have to be conditioned in order to be treated as real seismic data.

We evaluated a nonstandard FWI approach that is referred as iterative modelling, migration and inversion:

1) PSPI migration to obtain the gradient (instead of RTM).
2) Non-stationary matched filters from well-log velocity to calibrate the gradient (instead of the step length method).
3) Spatial multi-scale approach. Iterative application of Gaussian smoothers to frequency-band fixed migrated data residuals (instead of the frequency multi-scale technique).

The strategy showed great potential to recover long-wavelength information from reflection seismic data.
Acknowledgements

Thanks

Kevin Bertram and Joe Wong

Sponsors of CREWES for their support

NSERC through the grant CRDPJ 461179-13

PEMEX and the government of Mexico for funding this research
Questions?