Full Waveform Inversion for Complex Near-Surface Imaging Using SEG SEAM II Synthetic Model*

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Abstract

The Earth’s complexity near the surface introduces many challenges in land seismic exploration. In arid areas such as much of the Middle East, karst features and unconsolidated sediments make the problem more difficult by introducing a complex velocity contrast, and complex anisotropy and attenuation problems, in addition to strong scattering of surface and body waves that interfere with the imaging of deeper structure. In this article, we tested and applied Full Waveform Inversion as a high-end technology in velocity model building and seismic wave migration for imaging complex near-surface structure having small-scale geological features using the Arid SEAM Phase II synthetic model.
Full waveform inversion for complex near-surface imaging using SEG SEAM II synthetic model

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Source: SEG
Motivation

Approximately 2/3 of the remaining conventional oil and gas reserves are on land.

Growing challenges of land hydrocarbon exploration place increasing demands on accurate, high resolution 3D seismic images to identify unconventional and low relief reservoirs with small extension.

Traditional geophysical tools for near-surface velocity reconstruction such as refraction and diving wave tomography have limited success for cases with near-surface velocity inversion and strong lateral heterogeneity.

Drilling optimization and efficiency decreases in karstic areas.
Outline

Problem definition & research objectives

Shallow geology of Arabian Gulf & SEG SEAM Phase II Arid Model

FWI theory, workflow & Challenges

Seismic data processing & Initial model building

Acoustic FWI on viscoelastic

Conclusions
Problem Definition

Complex near-surface geology

- Karst
- Low velocity unconsolidated sediments
- Stream channels
- Hard outcrop refractors

Problems caused by these complexities

- Scattering of seismic energy
- Distorting and degrading images of underlying structures.

Karst is an irregular limestone region with sinkholes, underground streams, and caverns largely shaped by the dissolving action of water on carbonate bedrock (usually limestone, dolomite, anhydrite or marble).
Research objectives

The primary objective is to use FWI to better characterize the near-surface zone:

1. Examine if FWI can accurately reconstruct models of small shallow geological features with strong velocity contrast

2. Assess subsurface imaging improvement
Arabia Peninsula - near-surface geology

Source: SGS
The Arid SEAM Phase II model exhibits the same reservoir and stratigraphy as the unconventional SEAM (Barret) model, but replaces the first 500 meters with complex near-surface features encountered in desert terrains like the Arabian Peninsula. In such terrains, features including karst, wadis, stream channels and low velocity unconsolidated sediments in the near-surface introduce strong velocity contrasts.
Simulation of viscoelastic data by FDM

Modeling inputs are $V_p$, $V_s$, $\rho$, $Q_p$ and $Q_s$ of the SEAM II arid model and a Klauder source wavelet.

Klauder wavelet with 3-20Hz
Correlation between seismic wavefield and the near surface velocity

1. First arrivals show complex static issues that are correlated with shallow karst locations in the velocity model.

2. Dispersion of surface waves confirms the presence of strong velocity variations.

3. All hyperbolic energies below the green line are multiples and/or S-wave reflections.

4. Scattering on seismic correlates with karst locations in the velocity model.
FWI – general workflow

- Starting model
- Forward modeling
- Synthetic Data
- Residual derivation & inversion
- Updated Model
- Iterative process
- Final Model
- Real Data
FWI - Challenges

FWI is plagued by the local non-linearity issue which depends on

- The closeness of the starting model to the true (unknown) model
- Availability of low frequency and far offset in the recorded data

Additional challenges associated with applying FWI to land data

- Strong near-surface effects such as attenuation, ground roll, and scattering due to rapid geological variations
- Elastic FWI is challenging because we have to invert for density, P-wave velocity, and S-wave velocity simultaneously as well as modeling low-velocity surface and S-waves.
- Viscoelastic FWI is even more challenging because we have to invert for density, P-wave velocity, S-wave velocity, Qp and Qs simultaneously at all frequencies of the recorded data.

Apply acoustic FWI on land seismic data which is dominated by elastic energy.
Elements of a successful acoustic FWI on land data

Before FWI

1. Use seismic data processing to eliminate non-acoustic energy.
2. Using surface wave inversion (SWI) and manual velocity picking to build an accurate initial velocity model.

During FWI workflow

1. Estimate the wavelet from the input data at each frequency band.
2. Start with the lowest frequencies and gradually increase the bandwidth of the data.
3. Start with early arrivals and include deeper ones gradually.
4. Use travel time (TT) objective function followed by least square (LS) objective function.

Jiao, 2015
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Jiao, 2015
### Viscoelastic modeling parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of forward modeling</td>
<td>Viscoelastic ($V_p$, $V_s$, $\rho$, $Q_p$, $Q_s$)</td>
</tr>
<tr>
<td>Wavelet</td>
<td>Klauder (3-20 Hz)</td>
</tr>
<tr>
<td>Free-surface multiple</td>
<td>included</td>
</tr>
<tr>
<td>Noise</td>
<td>included</td>
</tr>
<tr>
<td>Maximum frequency</td>
<td>25Hz</td>
</tr>
<tr>
<td>Acquisition geometry</td>
<td>20km 2D line with $SI=25m$ &amp; $RI=12.5m$</td>
</tr>
</tbody>
</table>
Noise attenuation to eliminate non-acoustic energy

Noise attenuation processing workflow

BPF (2-60Hz)

FX-Decon

Dip filter

(a) Non Acoustic waveforms

(b) After removing random noise

(c) After removing all noise

(d) Raw
Manually-picked velocity model

RTM using initial velocity model before SWI
Manual picked velocity model + SWI

RTM using initial velocity model after SWI
Acoustic FWI on viscoelastic synthetic data

<table>
<thead>
<tr>
<th>Peak frequency</th>
<th>Frequency band</th>
<th>Inverted energy</th>
<th>No. of iterations</th>
<th>Objective function</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>1-7</td>
<td>Refraction</td>
<td>4+6</td>
<td>TT+LS</td>
</tr>
<tr>
<td>6</td>
<td>1-11</td>
<td>Refraction</td>
<td>3+5</td>
<td>TT+LS</td>
</tr>
<tr>
<td>8</td>
<td>2-14</td>
<td>Refraction + Reflection</td>
<td>5+6</td>
<td>LS</td>
</tr>
<tr>
<td>12</td>
<td>2-21</td>
<td>Refraction + Reflection</td>
<td>6+6</td>
<td>LS</td>
</tr>
</tbody>
</table>

40 iterations, each iteration has 3 forward modeling and one migration
Initial model
Estimated model by FWI (peak freq. = 12Hz)
True model
Conclusions

- Data pre-conditioning helped in estimating a more accurate near-surface model which made using acoustic FWI on an originally viscoelastic data effective.