Fwi on land seismic datasets with topography variations: Do we still need to pick first arrivals?

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Summary

Building accurate depth migrated seismic images in on-shore environments is very challenging, especially for data acquired in areas of strong topography changes and complex shallow velocities variations like in foothills context.

The examples presented in this abstract show how incorporating first break picks information during the full waveform inversion (FWI) process, facilitated the convergence of the iterative process to produce an improved near surface velocity model.

Three different real case applications of FWI on land seismic datasets are presented in this paper.

Introduction

Processing and imaging in complex on-shore environment is a very challenging task. The main problems that are often encountered are strong topography changes and near surface heterogeneities, generating complex elastic wave propagations (surface waves, acoustic and elastic mode conversion, surface to body waves conversions, …) and an often under sampled recording of these complex wave fronts with the current seismic acquisitions designs (set of 2D seismic lines or sparse 3D acquisition).

We have developed specific tools and workflows to improve the seismic images of these type of datasets. In particular, the velocity model building workflow that we propose is mainly focused on near-surface model update, and based on the use of a specific time acoustic FWI approach. This FWI implementation requires seismic first arrivals, refractions and diving waves, from raw shot gathers.

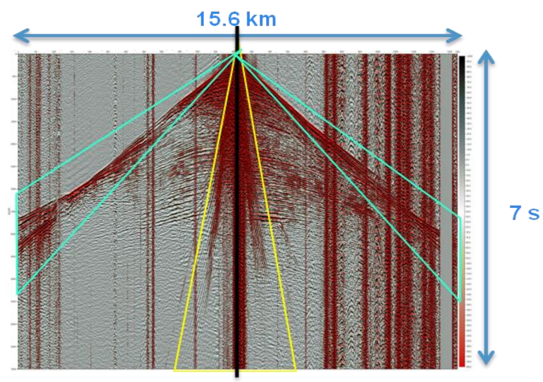
Motivation

When using land seismic dataset, the source is located at the elevation surface for vibrator cases, or at bottom of a borehole for dynamite cases.

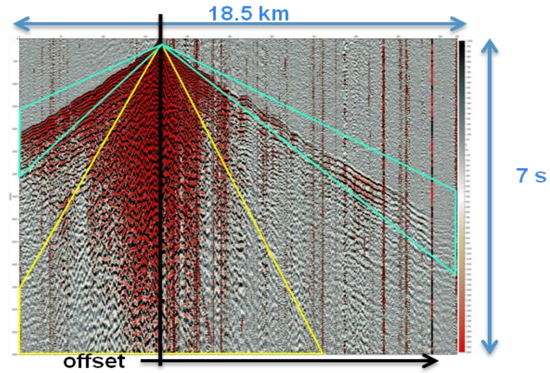
In both cases, one need to face two main challenges:

- The first one is the shallow velocities heterogeneities in near-surface, with quick changes from low-velocity soil and weathered zones to relatively higher velocity harder rock layers, with potentially steep dips. This is the main subject of the current abstract.
- The second one is the spatial sampling of topography (air-ground interface): It is commonly observed that rough topography is often linked to large elevation variations. One of the foothills dataset shown later in this paper exhibits very rough topography with large elevations changes up to 900 meters. This topic is not developed in this paper.

These near-surface heterogeneities can generate surfaces waves with strong amplitudes and elastic effects on short offsets, known as ground roll. Yellow triangles in figure 1.a and 1.b illustrate various ground roll contaminations on two shot gathers from two different land datasets: One from mild topography (fig 1.a), the second one from foothills area (fig 1.b). In addition, rapid changes in shallow velocities and elevation produce local time delays, known as statics. Those affect adjacent seismic traces, inducing, if not carefully corrected, a drastic reduction in data quality during the stacking process.



(a) Land shot record (from mild topography)



(b) Land shot record (foothills topography)

Figure 1: Different ground roll strength illustrated from two shot gathers from different land seismic survey

Land conventional depth processing sequence

A conventional approach to solve the previously described challenges is summarized below:

1. Time pre–processing steps:
   - Edit/ Noise Attenuation and Amplitude Corrections
   - First break picking (FB)
   - Diving Ray/Refraction first break Tomography to build a shallow velocity model and calculate field statics.

- Floating Datum (FD) calculation
- Long, mid and short wavelength statics calculation

2. Application of short wavelength component of statics to seismic traces
3. PSTM (Pre-Stack Time Migration from FD) migration step,
4. PSDM (Pre-Stack Depth Migration from FD) migration step starting from depth converted PSTM velocity field,
5. Model update by tomography,
6. Post-migration processing and final depth stack.

Schematically, in the classic workflow, short wavelength component of the shallow velocities and part of the roughness of the topography are compensated by a static correction applied to seismic traces that hence need to be excluded from the shallow velocity model by smoothing.
This methodology allows migrations (either time or depth) to run from a floating datum using a shallow smooth velocity model but this approach relies on local 1D correction.
The standard approach for the depth velocity model update, such as reflection tomography, relies on the capability to pick move-out reflections in the migrated common image gathers. Unfortunately, as it was shown on Figure 1, near offsets from land seismic records can be extremely noisy, especially in shallow areas where useful information for model building update is scarce.

However, acceptable results can be achieved with such approaches, providing that elevation variations are smooth. Figure 2 illustrates results from a conventional land seismic processing approach. Note that datum plane is above mean sea level at 600 m and that floating datum represented by the yellow horizon is relatively mild in this case.

Advanced workflow
The main benefit of land datasets is often very long offset acquisitions (see blue triangles in figure 1) and low rich frequencies for dynamite acquisition. The proposed advanced workflow, using FWI, is designed to take advantage of these long offsets and low frequencies information; not only using direct arrival picks but also the full waveform of these first arrivals.
It is well known that FWI is an-iterative process where data residuals are used to update the subsurface model (Tarantola, 1984). This implies that the FWI can be divided in three steps scheme: a forward modeling, to generate shots records, a mismatch evaluation between these records versus acquired records and finally the use of this mismatch to the gradient computation and update of the model.

We have applied our multi-parameter acoustic FWI method on different land seismic datasets to recover long and intermediate spatial wavelength of the near surface velocity model (see table 1).

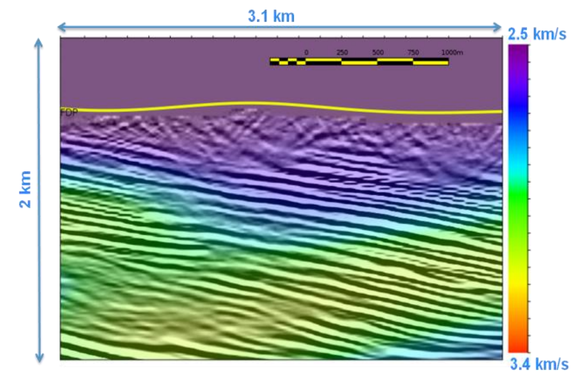


Figure 2: Conventional Kirchhoff land PSDM from Floating Datum on set 01 (Depth section with velocity overlay).

Table 1

Land dataset		Maximum Elevation differences	Signal/noise Ratio
Set 01	2D	mild: up to 170m	S/N high
Set 02	2D	medium: up to 280m	S/N acceptable
Set 03	3D	foothills: up to 850 m	S/N Low

First positive results were achieved using our iterative acoustic time FWI (finite differences formulation) updating for both P-wave velocity and density.
Starting after conventional step 1, the following workflow was implemented:

2. Build a new starting velocity model using near-surface shallow velocities from “statics” model,
3. Data preconditioning for FWI (High amplitude and Noise removal),
4. Multi scale strategy FWI iterations increasing progressively the frequency band and the maximum offset,
5. Deep model update using reflection-based tomography (optional),
6. PSDM with final velocity model,
7. Post-migration processing.

A basic time-domain pre-processing (noise and high amplitude removal) was applied on raw shot gathers in order to preserve refractions and diving waves. Shots were processed at acquisition datum. Several iterations of FWI using only first arrivals were performed, using increasing frequencies from 2Hz (when possible) up to 10Hz and by incorporating long offsets progressively.
Including reflections information, located just below first arrivals, into our FWI allowed running FWI to higher frequencies (up to 15 Hz), however this remains data quality dependent.

Use of first break picks

During these studies we faced the following classical problems related to FWI: Lack of low frequencies, starting velocity model (and associated cycle skipping effects) and elevation sampling.

Ultimately, picks of first break were used in different manners in this modified workflow:

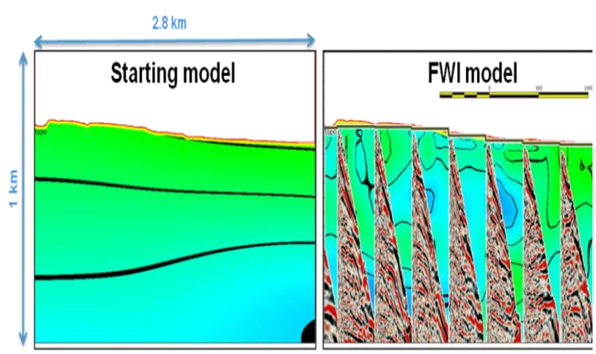
- From refraction tomography velocity model :
  - Trough static corrections applied to seismic traces prior FWI or
  - Directly using the shallow refraction velocity model as near-surface starting model of FWI.
- From first break picks in combination with Laplace-Fourier FWI (Shin and Cha, 2009; Rivera et al., 2015).

It is well known that for FWI the starting velocity model is an essential point, especially when very low frequencies are not present in the recorded data. Figure 3 shows two results of FWI 4.7Hz – 6.3 Hz using a starting model with and without shallow refraction velocity model. Depth migrated gathers obtained from FWI using the shallow refraction velocity model are clearly flatter (Fig 3.b) and produce a much better depth migrated stack.

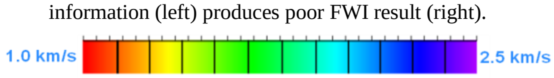
In order to tackle possible cycle skipping effect during FWI process, we use Laplace-Fourier FWI formulation. Laplace-Fourier FWI consists in using time damping which localizes early arrivals in time. Figure 4 clearly shows that result out of 4Hz FWI using Laplace-Fourier approach produces a better lateral continuity of the depth migrated stack, than the one without this constraint.

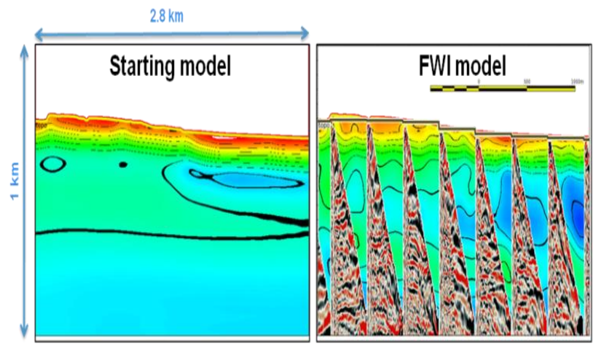
Results and Discussion

Figures 5 and 6 exhibit results of advanced FWI land PSDM workflow on different datasets. It is clear that the use of standard finite differences FWI engine provide valuable velocity model update.



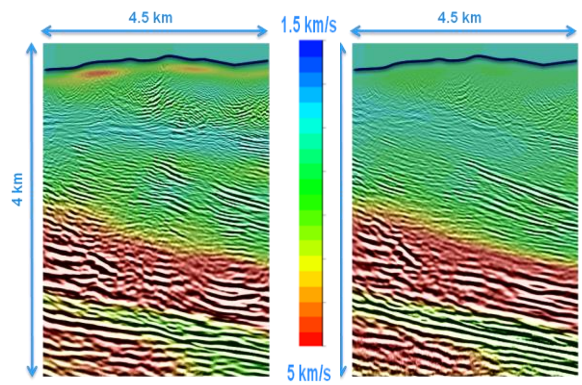
(a) Initial velocity model without shallow refraction information (left) produces poor FWI result (right).





(b) Initial velocity model including shallow refraction information (left) produces better FWI result (right).

Figure 3: Shallow land Kirchhoff PSDM gathers (with velocity overlay) showing the impact of incorporating refraction model information in the initial velocity model for FWI

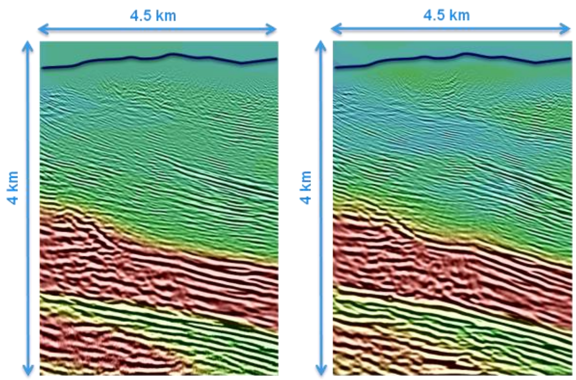


(a) Velocity from standard time FWI.

(b) Velocity model from Laplace-Fourier FWI.

Figure 4: Land Kirchhoff PSDM stacks (with velocity overlay) showing the impact using FWI or Laplace-Fourier FWI (4Hz) on set 02.

Even with complex topography (Figure 6), from foothills environment, the complex geological features from the structural geological sections and measured surface dips seem to be retrieved through FWI velocity model update. (Fig 6.b and 6.c). However we believe that more advanced modeling engines such as Spectral Element Method (SEM) or curvilinear Finite differences should better handle the topography variations and the free surface condition, and should therefore provide improved near surface models and seismic image. It is the subject of ongoing tests.



(a) Kirchhoff PSDM section from starting velocity model including shallow refraction information.

(b) Kirchhoff PSDM section from Final velocity model after Laplace FWI and extra tomography.

Figure 5: Result of new FWI land PSDM workflow (from Floating datum level) on set 02

Conclusions

A new velocity model building approach using FWI in complex land seismic environment has been presented on several datasets. It showed imaging improvements and uplifts of the velocity model produced.

The convergence of the iterative process was facilitated by incorporating extra first break picks information in combination with Laplace-Fourier FWI, leading to better shallow velocity models update.

Next steps will be to use, more advanced FWI seismic modeling engines such as elastic curvilinear finite differences or elastic spectral element methods.

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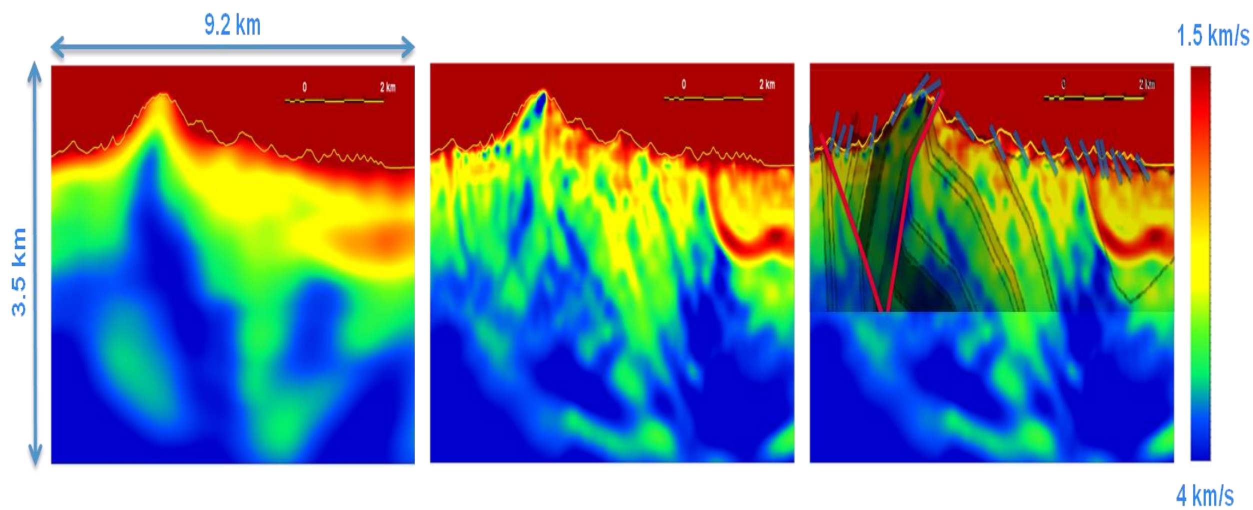

(a) PSDM Velocity (Vp) section : starting model

(b) PSDM Velocity (Vp) section : FWI model (1-2-10-15 Hz)

(c) PSDM Velocity (Vp) section from FWI with overlay of topographic dips and projected shallow structural interpretation.

Figure 6: Result of new FWI land PSDM workflow (from elevation surface) on foothills set 03

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