3-D Surface-Wave Estimation and Separation Using an Iterative Closed-Loop Approach*

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Abstract

Surface waves in seismic data are often dominant and mask primaries in land or shallow-water environments. Separating them from the primaries is of great importance either for removing them as noise for reservoir imaging and characterization, or for considering them as signal for near-surface characterization. However, their complex properties, such as dispersion, multi-modality and spatial variability, make the surface-wave separation significantly challenging in processing. To address the challenges, we introduced a method of 3-D surface-wave estimation and separation using an iterative closed-loop approach.

The closed loop contains a relatively simple forward model of surface waves and adaptive subtraction of the forward-modelled surface waves from the observed surface waves, making it possible to evaluate the residual between them. In this approach, the surface-wave model is parameterized by the frequency-dependent slowness and source properties for each surface-wave mode. The optimal model parameters are estimated in an iterative way such that the residual is minimized and, consequently, the approach solves the inverse problem.

We applied this method to several data sets to demonstrate its virtues, such as real 3D geophone/hydrophone seismic data onshore/offshore Abu Dhabi where ground-roll/mud-roll is significantly dominant in land/shallow-water environments. Through the examples, we observed that the method successfully estimates and separates out the surface waves from the seismic data to consequently obtain the subsurface signals. The method provides a better result than a conventional slowness/velocity-based filtering method which cannot handle both surface waves and subsurface signals overlapping each other. We also observed its wide range of applicability to under-sampled, asymmetrically sampled, irregularly sampled and blended seismic data. This suggests the possibility of relaxing requirements for seismic survey parameters in terms of surface-wave separation and, therefore, offers flexibility as well as potential effort reduction with respect to seismic surveys. It should be noted that recent advances in acquisition, such as point receivers and a large amount of stations, make the method more effective because of the improved spatial sampling of surface waves without negative array effects.
References Cited


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Outline

• Introduction
• Theory and method
• Real data examples
• Conclusions and remarks
Outline

• Introduction
• Theory and method
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• Conclusions and remarks
Surface-wave characteristics

- Surface-wave characteristics in seismic data
  - Higher amplitude
  - Lower frequency
  - Lower velocity

![Graphs and diagrams showing surface-wave characteristics](image-url)
Surface-wave properties

- Dispersive
  - Different frequencies propagate with different velocities.
Surface-wave properties

- **Dispersive**
  - Different frequencies propagate with different velocities.

A lower frequency has a smaller slowness.
Surface-wave properties

- Dispersive
- Multi-modal
  - Each frequency propagates with several velocities simultaneously.
Surface-wave properties

- Dispersive
- Multi-modal
  - Each frequency propagates with several velocities simultaneously.

A lower mode has a larger slowness.
Surface-wave properties

- Dispersive
- Multi-modal
- Spatially variable
  - These properties change spatially in a shot record, and one shot to another.
Surface-wave properties

- Dispersive
- Multi-modal
- Spatially variable
- Under sampled
Surface-wave properties

- Dispersive
- Multi-modal
- Spatially variable
- Under sampled
Surface-wave properties

- Dispersive
- Multi-modal
- Spatially variable
- Under sampled
Surface-wave properties

Dispersion surface

Dispersion curve

Dispersion vector
Surface-wave properties

- Dispersive
- Multi-modal
- Spatially variable
- Under sampled
- Irregularly sampled
Surface-wave properties

- Dispersive
- Multi-modal
- Spatially variable
- Under sampled
- Irregularly sampled
- Blended

\[ (P + N) \]

\[ \tau_s = 0 \text{ s} \]
\[ \tau_s = 0.5 \text{ s} \]
\[ \tau_s = 1 \text{ s} \]

\[ \begin{align*}
\text{Time (s)} & : -1 \quad 0 \quad 1 \\
\text{Frequency (Hz)} & : -5 \quad 0 \quad 5 \\
\end{align*} \]
Surface-wave separation

Surface waves
- traditionally treated as noise, masking primaries.
- today regarded as signal, for near-surface characterization.

Estimating them and separating them out from seismic data is important for both applications.

\[ P_{tot} = P + N \]

- \( N \): Surface waves
- \( P \): Subsurface signals
- \( (P+N) \): Seismic data
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Forward model

\[ P_{tot} = P + N \]

- \( N \): Surface waves
- \( P \): Subsurface signals
- \((P+N)\): Seismic data
Forward model

\[ N = \sum_{m} N_{m} \]
\[ N_{m} = H_{m} S_{m} \]
\[ H_{m}(\vec{r}, \omega) = \left( e^{-\lambda_{m}(\omega)\vec{r}} \right) e^{-j\omega p_{m}(\omega)\vec{r}} \]

\( S \): Source properties
\( H \): Horizontal propagation operator
\( X \): Earth propagation operator
Forward model:

**S**: Source properties
**H**: Horizontal propagation operator
**X**: Earth propagation operator

$$N = \sum_{m} N_m$$

**Multi-modes**

$$m$$: the number of a surface-wave mode.

$$N_m$$: dispersion vector

$$H_m(\vec{r}, \omega) = \left( e^{-\vec{\lambda}_m(\omega)\cdot\vec{r}} \right) e^{-j\omega p_m(\omega)\cdot\vec{r}}$$

Travel-time phase shift

Sources

Receivers
Forward model

Sources

Receivers

Multi-modes

\( m \): the number of a surface-wave mode.

\[
N = \sum_{m} N_m
\]

Intrinsic attenuation

\[
H_m (\vec{r}, \omega) = \left( e^{-\lambda_m (\omega) \vec{r}} \right) e^{-j\omega p_m (\omega) \vec{r}}
\]

Cylindrical spreading

\( S \): Source properties

\( H \): Horizontal propagation operator

\( X \): Earth propagation operator
Multi-modes

\( m \): the number of a surface-wave mode.

\[ N = \sum_{m} N_m \]

\[ H_m(\vec{r}, \omega) = (e^{-\lambda_m(\omega) \cdot \vec{r}}) e^{-j\omega \vec{p}_m(\omega) \cdot \vec{r}} \]

Sources

Receivers

Intrinsic attenuation

Cylindrical spreading

Travel-time phase shift

- \( N \) is parameterized by \( \lambda_m, \vec{p}_m \) and \( S_m \);
  - or \( \vec{p}_m \) and \( S_m \) with the assumption that \( \lambda_m \) is zero.

The geometrical spreading effect is much larger than the intrinsic attenuation effect.
Inversion

\[ J : A_m ; H_m , S_m \xrightarrow{\text{s.t.} J = \text{min.}} < P > \]

\[ J = \sum_\omega \| P + \Delta N \|^2 \]

\[ = \sum_\omega \| (P + N) - < N > \|^2 \]

\[ = \sum_\omega \left\| (P + N) - \sum_m A_m H_m S_m \right\|^2 \]

- The parameters as well as the adaptive filter are solved such that the residual \( P + \Delta N \) is minimized.

- The minimization scheme works on \(< N >\) only, and \( P \) remains untouched by a signal-protecting scheme.

- In the ideal situation, the resulting residual \( P + \Delta N \) closely corresponds to \( P \).

\(<N> : \text{Surface-wave estimate} \]

\(<P> : \text{Subsurface-signal estimate} \]

\[ <N> : \text{Surface-wave estimate} \]

\[ <P> : \text{Subsurface-signal estimate} \]
Inversion

\[ J : A_m : H_m : S_m \xrightarrow{\text{s.t. } J = \min.} \langle P \rangle \]

\[ J = \sum_\omega \| P + \Delta N \|^2 \]

\[ = \sum_\omega \| (P + N) - \langle N \rangle \|^2 \]

\[ = \sum_\omega \| (P + N) - \sum_m A_m H_m S_m \|^2 \]

- The parameters as well as the adaptive filter are solved such that the residual \( P + \Delta N \) is minimized.

- The minimization scheme works on \( \langle N \rangle \) only, and \( P \) remains untouched by a protecting scheme.

- In the ideal situation, the resulting residual \( P + \Delta N \) closely corresponds to \( P \).
Closed loop

- For each loop, the modal parameters $\hat{p}^{(i)}_m, \Delta S^{(i)}_m$ as well as the modal adaptive filter $A^{(i)}_m (m = 1, 2, \ldots)$ are estimated.
Closed loop
Closed loop

\[(P + N)\]

Adaptive Subtraction Parameter Estimation Parameter Selection Forward Modeling

\[\langle N(0) \rangle \quad \langle P(0) \rangle\]

\[H^{(1)} \Delta S^{(0)}\]

Update the \(\hat{p}_m^{(i)}\).
Closed loop

\[ (P + N) \]

Adaptive Subtraction  Parameter Estimation  Parameter Selection  Forward Modeling

\[ \langle N^{(0)} \rangle \quad \langle P^{(0)} \rangle \]

\[ (P + N)^{(i)} \]

\[ \Delta S^{(n)} \]

Time (s)  Amplitude  Frequency (Hz)  Phase (rad)

\[ x \text{ (km)} \]

-1 0 1

0 0.5 1 1.5 2 2.5 3

0 0.5 1 1.5 2 2.5 3

0 5 10 15 20 25 30

0 5 10 15 20 25 30

Amplitude  Amplitude
Closed loop
Closed loop

\( (P + N) \)

\( <N^{(i)} > \)  \( <P^{(i)} > \)

Adaptive Subtraction \rightarrow Parameter Estimation \rightarrow Parameter Selection

\( (P + N)^{(i)} \)

Forward Modeling

\( A^{(i)} H^{(i)} \Delta S^{(i)} \)

Update the \( A_m^{(i)} \).
Closed loop

Go to the next loop, etc., etc...
\begin{align*}
\langle N^{(i)} \rangle &= A^{(i)} H^{(i)} \Delta S^{(i)} \\
\langle P^{(i)} \rangle &= (P + N) - A^{(i)} H^{(i)} \Delta S^{(i)}
\end{align*}
After several iterations.
Methods of surface-wave separation

- Slowness/velocity-based filtering methods (e.g. Yilmaz, 2001)
- Data-driven, data-adaptive and model-based method (AROGA; Le Meur et al., 2008, 2010)
- Data-driven, data-adaptive and model-based method using an iterative closed loop (SWES+; Ishiyama et al., 2014, 2015)
- Near-surface model-based method (SWAMI; Strobbia et al., 2010, 2011)
- FWI-based methods (e.g. Ernst, 2013)
Methods of surface-wave separation

- **SWES+**
  - Simple (and robust) model
  - Parameterized by surface-wave properties: few parameters
  - Data-adaptive
  - Computationally affordable

- **FWI**
  - Complex (and sensitive) model
  - Parameterized by near-surface properties: many parameters
  - Computationally expensive
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Real data examples

- 3D land data acquired onshore Abu Dhabi
  1. Less-aliased vertical geophone data
  2. More-aliased vertical geophone data

\[ \Delta x_b = \Delta y_b = 25 \text{ (m)} \]

\[ \Delta x_b = \Delta y_b = 50 \text{ (m)} \]

Receiver:
Arrayed geophones

Source:
Vibroseis with 6 Hz to 80 Hz linear sweep
Some aliased energy exists even around small wavenumbers.

\[ \Delta x_b = \Delta y_b = 25 \ (m) \]
Less-aliased

\[ (P + N) \]

\[ <N> \]

\[ <P> \]
Even the aliased surface waves are estimated.
Only aliased energy exists in the whole range of useful frequencies.

\[ \Delta x_b = \Delta y_b = 50 \ (m) \]
Even the aliased surface waves are estimated.
Real data examples

- 3D OBC data acquired offshore Abu Dhabi
  1. Un-aliased hydrophone data
  2. Aliased hydrophone data
  2' The above data with a conventional filtering method

\[
\Delta x_b = \Delta y_b = 25 \ (m)
\]

\[
\Delta x_b = \Delta y_b = 50 \ (m)
\]

Receiver:
Single point hydrophone

Source:
Arrayed air-guns
(P + N)

Aliased

< N >

< P >

1.25 s

1.25 s

1.25 s
Even the aliased surface waves are estimated.
Delphi

(P + N)

(SWES)

< N >

< P >

1.25 s

1.25 s

1.25 s

(P + N) + < N > + < P >

SWES +
The aliased energy is not properly contained. The aliased energy is thrust into the subsurface signals.
Real data examples

- 3D OBC data acquired offshore Abu Dhabi
  1. Irregularly sampled hydrophone data
  2. Blended hydrophone data
Irregularly sampled

\( (P+N) \)

\( <N> \)

\( <P> \)

10 Hz

\(<br>\)
Random noise due to the irregularly sampling.
Even the randomly sampled surface waves are estimated.
Notch effect due to the blending.
Even the blended surface waves are estimated.
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Conclusions and remarks

• The proposed method addresses the surface-wave properties, i.e., dispersion and multi-modes.

• The method is data-driven and data-adaptive, automatically taking into account physical phenomena such as spatial variation, attenuation, anisotropy, etc.

• The method can be applied in any geometry domain, i.e., in any gathers. It can be applied to under-sampled, asymmetrically sampled, irregularly sampled and blended seismic data.
Conclusions and remarks

• This suggests the possibility of relaxing the spatial sampling interval, encourages random sampling / blending, and offers flexibility with respect to acquisition geometry.
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