3D Surface-wave estimation and separation: a closed-loop approach

Tomohide Ishiyama*, Gerrit Blacquiere and Eric Verschuur, Delft University of Technology

SUMMARY

Surface-waves are often dominant in seismic data in a shallow water and land environment. Separating them out from the seismic data is of great importance for either removing them as noise for reservoir characterization, or extracting them as signal for near-surface characterization. However, their complex properties make the surface-wave separation significantly challenging in seismic processing. To address the challenges and adopt recent advances in seismic processing, we propose a methodology of surface-wave estimation and separation using a closed-loop approach. The methodology was successfully demonstrated on real 3D seismic data with mud-roll that is often dominant in a shallow water environment.

INTRODUCTION

In a shallow water and land environment, surface-waves are often dominant in seismic data. Although they are traditionally treated as prevailing coherent noise masking primaries, recently they are more and more regarded as signal for near-surface characterization. For both applications, separating them out from the seismic data is of great importance. The surface-waves, or mud-roll in a shallow water environment, are often present with higher amplitude, lower frequency and lower apparent velocity than primaries. They are dispersive, multi-modal, and these properties are spatially variable. In addition, they are usually aliased due to a large spatial sampling in seismic acquisition for economical and operational constraints. Furthermore, they are blended as well in the case of blended seismic acquisition. These complex properties make the surface-wave separation notably challenging in seismic processing.

To separate the surface-waves out from the seismic data, many approaches have been developed, such as model-based and near-surface-model-based methods (e.g. Le Meur et al., 2010; Strobbia et al., 2011). In these methods, a set of model parameters (e.g. from a near-surface model) is required to obtain the forward-modelled surface-waves, although the model parameters are usually unknown. In addition, imperfect model parameters result in a substantial residual between the forward-modeled and the existing real seismic data. This residual is not re-evaluated and the model parameters are not re-estimated based on this residual, although a data-adaption may reduce the residual and compensate for the imperfection of the model parameters. After all, non-uniqueness of the model parameters makes it uncertain to evaluate this residual.

Apart from the surface-wave separation, the so-called closed-loop approach has been developed in several stages

of seismic processing (Berkhout, 2013). In this approach, at each seismic processing stage, an optimum parameterization is used to describe the inversion problem. The closed-loop contains a forward modelling module, making it possible to evaluate the residual between the forward-modelled and the input data, estimate the model parameters, and therefore, allowing feedback between the model parameters and the input data (e.g. see Figure 1).

In addition, data reconstruction techniques have been also developed in seismic processing, based on decomposition of seismic data in a certain basis function, such as Fourier-based, Radon-based (e.g. Wang et al., 2010), curvelet-based (e.g. Herrmann and Hennenfent, 2008), and focal-based (e.g. Berkhout and Verschuur, 2006). For each basis function, the parameters are the samples in its own domain such as Fourier, Radon, curvelet and focal domain, and these parameters are solved under certain sparsity constraints such that the forward-modeled (inverse-transformed) data match the input data. The inversion problem can be solved again by the closed-loop approach, in which the residual between the forward-modeled and the input data is minimized, and the optimal parameters are selected.

THEORY AND METHOD

Forward model

According to Berkhout (1982), discrete 3D seismic data containing both subsurface signals and surface-waves can be described in the space-frequency (xy - f) domain as:

$$\mathbf{P}_{tot} = \mathbf{P} + \mathbf{N}, \quad (1)$$

where $\mathbf{P}_{tot}$ is the seismic data; $\mathbf{P}$ contains the subsurface signals; and $\mathbf{N}$ represents the surface-waves. Note that in this paper the ‘subsurface signals’ refer to all events except the surface-waves, i.e., $\mathbf{P}$ includes refractions, reflections, their surface-related and internal multiples, etc.

The surface-waves $\mathbf{N}$ are described as:

$$\mathbf{N} = \sum_m \mathbf{N}_m, \quad (2)$$

$$\mathbf{N}_m = \mathbf{H}_m \mathbf{S}_m, \quad (3)$$

where $\mathbf{N}$ and $\mathbf{N}_m$ are the total and the modal surface-waves, $\mathbf{H}_m$ is the modal surface-transfer operator representing the horizontal wavefield propagation; and $\mathbf{S}_m$ represents the source properties for each surface-wave mode. The subscript m is the number of the considered

Surface-wave estimation and separation

surface-wave mode, showing that the total surface-waves are described by summation of the modal surface-waves. Each element of $\mathbf{H}_m$ is provided by (after Socco and Strobba, 2004):

$$H_m(\vec{r}, \omega) = (e^{-\bar{\alpha}_m(\omega) \cdot \vec{r}} / \sqrt{|\vec{r}|}) e^{-j\omega \bar{p}_m(\omega) \cdot \vec{r}}, \quad (4)$$

where $\vec{r}$ is the receiver location relative to the source location, i.e., $|\vec{r}|$ is the offset; ω is the angular frequency;

$\bar{\alpha}_m(\omega)$ is the frequency-dependent modal attenuation factor; and $\bar{p}_m(\omega)$ is the frequency-dependent modal slowness, i.e., the dispersion surface. The term $1/\sqrt{|\vec{r}|}$ represents the cylindrical spreading, and the term $e^{-\bar{\alpha}_m(\omega) \cdot \vec{r}}$ represents the intrinsic attenuation of the amplitude. In general, the effect of the geometrical attenuation is much larger than that of the intrinsic attenuation. The term $\bar{p}_m(\omega) \cdot \vec{r}$ represents the travel-time phase shift. Equations (2) to (4) show that $\mathbf{N}$ is parameterized by $\bar{\alpha}_m$, $\bar{p}_m$ and $\mathbf{S}_m$; or by $\bar{p}_m$ and $\mathbf{S}_m$ with the assumption that $\bar{\alpha}_m$ is zero, i.e., the intrinsic attenuation is negligible compared to the geometrical attenuation.

The modal surface-waves $\mathbf{N}_m$ are also described as:

$$\mathbf{N}_m = \mathbf{B}^{-1} \mathbf{L}^H \tilde{\mathbf{N}}_m, \quad (5)$$

where $\mathbf{B}^{-1}$ and $\mathbf{L}^H$ are the inverse normalization and the inverse Radon operators, and the tilde symbol $\sim$ denotes ‘in the normalized Radon ($p_x p_y f$) domain’. The normalization enhances the phase information in the Radon domain (Park et al., 1998). Equations (2) and (5) show that $\mathbf{N}$ is also parameterized by the surface-wave samples $\tilde{\mathbf{N}}_m$ in the normalized Radon domain. This is possible because the surface-waves are well distinguished and their samples can be selected in this domain in terms of their amplitude level and areal separation from the subsurface signals.

In summary, the surface-waves are forward-modeled with each of these parameterizations.

Surface-wave estimation and separation (SWES) using a closed-loop approach

If the surface-wave model $\hat{\mathbf{N}}$ is estimated by forward modeling with the model parameters $\bar{p}_m$ and $\mathbf{S}_m$, and subtracted from the existing seismic data $(\mathbf{P} + \mathbf{N})$, the resulting signal $\hat{\mathbf{P}}$ is obtained. Here the hat symbol $\hat{}$ denotes ‘estimated’. If $\hat{\mathbf{N}}$ is not perfectly estimated, some residual $\Delta\mathbf{N} = \mathbf{N} - \hat{\mathbf{N}}$ is expected. In this case, $\hat{\mathbf{P}}$ includes

Figure 1: The closed-loop approach.

the term $\Delta\mathbf{N}$, i.e., $\hat{\mathbf{P}} = \mathbf{P} + \Delta\mathbf{N}$. To reduce this residual, an adaptive subtraction filter $\mathbf{A}_m$ for each surface-wave mode is used. This adaptive filter is supposed to compensate for the intrinsic attenuation and spatial variability of the model parameters. To further minimize this residual, an inversion scheme is used. This means that $\hat{\mathbf{N}}$ can be estimated by minimizing the following objective function $\mathbf{J}_{SWES}$:

$$\begin{aligned} \mathbf{J}_{SWES} : \mathbf{A}_m, \mathbf{H}_m, \mathbf{S}_m &\xrightarrow[\mathbf{J}_{SWES} = \min.]{s.t.} \hat{\mathbf{P}}, \\ \mathbf{J}_{SWES} &= \sum_{\omega} \left\| (\mathbf{P} + \mathbf{N}) - \hat{\mathbf{N}} \right\|^2 = \sum_{\omega} \left\| \mathbf{P} + \Delta\mathbf{N} \right\|^2 \\ &= \sum_{\omega} \left\| (\mathbf{P} + \mathbf{N}) - \sum_m \mathbf{A}_m \mathbf{H}_m \mathbf{S}_m \right\|^2, \end{aligned} \quad (6)$$

where the model parameters $\bar{p}_m$ and $\mathbf{S}_m$ as well as the adaptive filter $\mathbf{A}_m$ are solved in such a way that the residual $(\mathbf{P} + \Delta\mathbf{N})$ between the forward-modeled surface-waves $\hat{\mathbf{N}}$ and the existing seismic data $(\mathbf{P} + \mathbf{N})$ is minimized. Note that this minimization scheme is supposed to work on $\hat{\mathbf{N}}$ only, i.e., the term $\Delta\mathbf{N}$ is minimized only, and $\mathbf{P}$, therefore, remains untouched by a signal-protecting scheme. The signal-protecting scheme is controlled by data-adaption parameters, i.e., aggressive parameters lead to an adaptive filter predicting more energy of $\Delta\mathbf{N}$ but attacking $\mathbf{P}$, and conservative parameters lead to an adaptive filter protecting $\mathbf{P}$ but predicting less energy of $\Delta\mathbf{N}$. This is the trade-off between conservative signal protection and aggressive surface-wave estimation. As a consequence, the resulting residual $(\mathbf{P} + \Delta\mathbf{N})$ closely corresponds to $\mathbf{P}$. To solve the inversion problem, the closed-loop approach is used (Figure 1). The closed-loop consists of three modules: parameter estimation/selection; forward modelling; and adaptive subtraction. For each loop (i), from the residual update $(\mathbf{P} + \Delta\mathbf{N})^{(i)}$, the model parameters are estimated; the surface-wave model $\hat{\mathbf{N}}^{(i)}$ is built; then this model is subtracted from the existing seismic data $(\mathbf{P} + \mathbf{N})$ to obtain the signal $\hat{\mathbf{P}}^{(i)}$ (referred as

Surface-wave estimation and separation

SWES in this paper). In fact, each i -loop contains inner m -loops for each surface-wave mode. For each inner loop (i, m), the model parameters and/or their updates are estimated. The procedure is iterated until it has reached a stopping criterion.

Post-SWES processing

SWES estimates most of the surface-wave energy including the aliased energy (e.g. see Figure 2). However, a residual still exists, which is present as remaining surface-wave samples in the normalized Radon domain. Optionally, to further minimize this residual, $\Delta\hat{\mathbf{N}}$, the residual of the output $(\mathbf{P} + \Delta\mathbf{N})$ from SWES, can be estimated by minimizing the following objective function $\mathbf{J}_{SWESSI}$:

$$\begin{aligned} \mathbf{J}_{SWESSI} : \Delta\tilde{\mathbf{N}}_m &\xrightarrow[\mathbf{J}_{SWESSI} = \min.]{s.t.} \hat{\mathbf{P}}, \\ \mathbf{J}_{SWESSI} &= \sum_{\omega} \left\| (\mathbf{P} + \Delta\mathbf{N}) - \Delta\hat{\mathbf{N}} \right\|^2 = \sum_{\omega} \left\| \mathbf{P} + \Delta\mathbf{N} \right\|^2 \\ &= \sum_{\omega} \left\| (\mathbf{P} + \Delta\mathbf{N}) - \sum_m \mathbf{B}^{-1} \mathbf{L}^H \Delta\tilde{\mathbf{N}}_m \right\|^2 \\ &= \sum_{\omega} \left\| (\mathbf{P} + \Delta\mathbf{N}) - \sum_m \mathbf{B}^{-1} \mathbf{L}^H \mathbf{C}_{N_m} \mathbf{L} \mathbf{B} (\mathbf{P} + \Delta\mathbf{N}) \right\|^2, \end{aligned} \quad (7)$$

where $\mathbf{B}$ and $\mathbf{L}$ are the normalization and the Radon operators, and $\mathbf{C}_{N_m}$ is sparsity constraints implemented as amplitude thresholding and areal windowing to extract the surface-waves in the normalized Radon domain. Again, using the closed-loop approach similar to SWES, the surface-wave samples $\Delta\tilde{\mathbf{N}}_m$ in the normalized Radon domain are solved such that the residual is minimized (referred as SWESSI in this paper). This minimization scheme is supposed to work on $\Delta\hat{\mathbf{N}}$ only by a signal-protecting scheme, or by using sparsity constraints.

Finally, a conventional Radon filtering can be applied to $\hat{\mathbf{P}}$ for further separating it to the signal part $\hat{\mathbf{P}}_s$ and the unexplained noise part $\hat{\mathbf{P}}_N$.

Consequently, after cascading SWES, SWESSI and Radon filtering (referred as SWES+ in this paper), the surface-waves $\hat{\mathbf{N}}$ and the subsurface signals $\hat{\mathbf{P}}_s$ are estimated, and separated out from the existing seismic data $(\mathbf{P} + \mathbf{N})$.

REAL DATA EXAMPLES

We applied the proposed methodology to 3D OBC hydrophone data in a shallow water environment offshore Abu Dhabi. For the first example, a cross-spread gather is considered, consisting of a receiver line in the x direction and a source line in the y direction, each with a length of 3200 m and a spatial sampling interval of 50 m. This makes

Figure 2: The results for the aliased data example (a) in the xy - t , and (b) in the $k_x k_y$ - f domain, with a vertical section at the top and a time/frequency slice at the bottom. $(\mathbf{P} + \mathbf{N})$ is the input seismic data; $\hat{\mathbf{N}}$ is the estimated surface-waves by SWES; and the resulting $\hat{\mathbf{P}}$ is separated into $\hat{\mathbf{P}}_s$ by Radon filtering. Red, magenta, green and blue arrows indicate the surface-wave fundamental mode, a surface-wave higher mode, refractions and reflections, respectively. A filled arrow indicates the true energy, and a whitish arrow indicates the aliased energy. Notice that the surface-waves are dispersive, multi-modal and aliased here.

a 3D cube, where surface-waves are clearly observed for the fundamental mode and one higher mode, each in a cone shape with a slowness larger than that of subsurface signals. The severe aliasing can be observed especially in the Fourier $(k_x k_y$ - $f)$ domain. Bad traces have been edited here. Figure 2 shows the results after SWES+ (SWES and Radon filtering in this example), demonstrating that it estimates most of the surface-wave energy including the aliased energy.

For the second example, the seismic data are synthesized into a *blended* source gather consisting of three blended sources and a receiver spread with a width of 3200 m and a

Surface-wave estimation and separation

Figure 3: The results for the aliased/blended data example (a) in the $xy-t$, and (b) in the $k_x k_y f$ domain, with a vertical section at the top and a time/frequency slice at the bottom. $(\mathbf{P} + \mathbf{N})$ is the input seismic data; $\hat{\mathbf{N}}$ is the estimated surface-waves by SWES; $\Delta\hat{\mathbf{N}}$ is the estimated surface-wave residual by SWESSI; $\hat{\mathbf{N}} + \Delta\hat{\mathbf{N}}$ is summation of these estimates; and the resulting $\hat{\mathbf{P}}$ is separated to $\hat{\mathbf{P}}_N$ and $\hat{\mathbf{P}}_S$ by Radon filtering. Notice that aliased/blended surface-waves are handled here.

spatial sampling interval of 50 m both in the x and y directions. Again, this makes a 3D cube. Blending for all events is seen in the $xy-t$ domain, and the corresponding decimation-like effect is found in the $k_x k_y f$ domain. Figure 3 shows the results after SWES+ (SWES, SWESSI and Radon filtering in this example), demonstrating that it further estimates the residual, and thus estimates even the blended surface-waves. Note that it was applied to a single blended source gather without using other source gathers simultaneously. Note also that in these examples conservative signal-protecting schemes were used in order to avoid distorting the subsurface signals.

Figure 3: Continued.

CONCLUSIONS AND REMARKS

The essential properties of the proposed methodology of surface-wave estimation and separation are:

- It addresses the surface-wave properties: dispersion and multi-modes.
- It is fully data-driven and data-adaptive. This automatically takes into account physical phenomena such as anisotropy, attenuation, spatial variation, etc.
- It can be applied in any geometry domain such as 3D common shot, 3D common receiver, and cross-spread gathers. Furthermore, it can handle irregularly sampled, aliased, and blended seismic data. This suggests the possibility of relaxing the spatial sampling, encourages blending, and therefore, offers flexibility with respect to the seismic acquisition geometry.

ACKNOWLEDGMENTS

We thank ADNOC for their permission to use the data offshore Abu Dhabi and publish this paper.