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Multi-modal Surface Wave Inversion and Application to North Sea OBN Data

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SUMMARY

Surface-wave inversion (SWI) for S-wave velocity plays an important role in near surface characterization and PS-wave velocity model building for depth migration. The inversion requires dispersion curves picked from the spectrum of surface waves. Robust f-k spectral analysis is achieved by superposition of surface-wave spectra, with a careful balance struck between larger transform apertures that provide higher spectral resolution, and smaller apertures that provide higher spatial resolution. A hybrid cost function is used in the inversion to reduce non-linearity for a multi-modal inversion without a-priori identification of higher order modes. This method is applied to a North Sea ocean bottom node (OBN) survey to produce a shallow Vs model that penetrates 120 m depth below the seabed. It has similar spatial resolution to the Vp model from Full Waveform Inversion while highlighting shallow structures that are not visible in the Vp model. The Vp/Vs ratio from these inversions provides a powerful tool for near-surface characterization. Furthermore, the high-resolution shallow Vs model from SWI complements the use of PS-wave tomography in illuminating the near surface, and is shown to improve the PS image at both shallow and deep targets.

Introduction

The importance of near surface characterization has been recognized by the oil and gas industry. Shallow elastic properties are important for drilling operations and shallow gas detection, and also for static corrections and velocity model building for depth migration. Although the reservoir is usually away from the near surface, velocity errors in the shallow will propagate to deeper targets through the velocity model building workflow, and in the imaging itself as the wavefield is propagated downwards from the acquisition surface.

Lack of shallow shear-wave illumination from reflections in sparse aquisition hinders the application of reflection tomography in the near surface. Fortunately, surface-wave inversion (SWI) can extract high-resolution shallow shear velocity models from the dispersion curves of surface waves (Xia *et al*., 1999; Socco *et al*., 2010). The bandwidth of surface waves limits the depth that SWI can resolve, which is generally within one wavelength of the surface (e.g. 50 m-100 m in land and 100 m or more in marine, depending on the lowest frequency the surface wave contains). Nevertheless, the shallowest layers are the hardest to account for during velocity-model building, and SWI has an important role to play in this process.

Surface-wave inversion consists of two main steps: 1. dispersion curve picking after spectral analysis of the surface waves; 2. dispersion curve inversion for near surface shear velocity (Xia *et al*., 1999). In this paper, we address some practical issues in these stages. A hybrid inversion scheme is used to overcome difficulty in surface-wave mode identification and to reduce the range of non-unique solutions of the inversion problem. This approach is applied to ocean bottom node (OBN) data from the North Sea to demonstrate the application of SWI in PS-wave velocity model building.

Method

The method is split into two components, first the spectral dispersion analysis and then the dispersion-curve inversion to estimate S-wave velocity.

High-resolution spectral analysis of surface waves
Surface waves are commonly recorded and are usually very strong, at least at low frequencies (roughly 1 Hz – 5 Hz in marine data and 4 Hz – 15 Hz in land data). The surface-wave arrivals are known as Rayleigh waves or ground roll on land, and Scholte waves or mud roll on the seabed. The surface wave itself has many modes and is dispersive in each mode (Socco and Strobbia, 2004). To extract the modal dispersion curves, we use a spectral analysis technique based on the superposition of surface waves (Neducza, 2007). The spectrum is enhanced by stacking *f-k* amplitude spectra at the same location (Zheng and Miao, 2014). Generally, larger analysis apertures in the transform and superposition produce higher spectral resolution. However, in practice, the aperture must be small to localize the measurements in space and achieve reasonable spatial resolution.
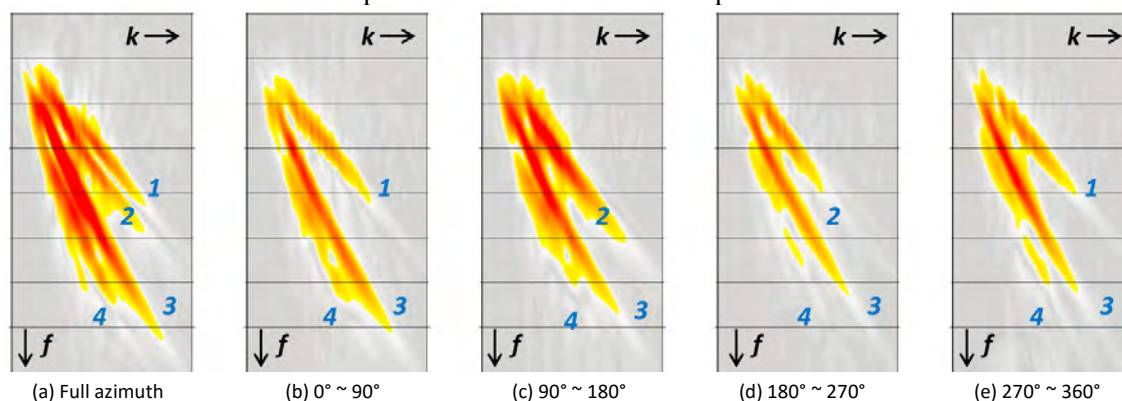

(a) Full azimuth   (b) 0° ~ 90°   (c) 90° ~ 180°   (d) 180° ~ 270°   (e) 270° ~ 360°

Figure 1 F-k spectra from a single gather split into azimuth sectors with different events representing the modes identified by numbers.

Due to strong lateral heterogeneity at the near surface, a large analysis aperture might lead to two or more modes with the same order being included in one spectrum, which further complicates the subsequent inversion problem. Additionally, the dispersion-curve inversion is based on a 1D Earth model, which is appropriate for small spatial areas in the analysis aperture.

The *f-k* spectrum of a full-azimuth gather is plotted in Figure 1(a). From this spectrum, we might identify four modes of surface wave and recognize event-1 as the fundamental mode, and event-2 as the first higher-order mode. However, when we split the gather into four azimuthal sectors and analyse their spectra separately, we find that event-2 is actually the fundamental mode of azimuth 90° - 270° (Figures 1(c) and (d)) rather than the first higher order mode. This is due to the rapid spatial velocity veriation of surface waves and the relatively low lateral resolution of the *f-k* spectrum. Since the dispersion-curve inversion can only invert one dispersion curve at each order of mode, spectrum (a) is not suitable for SWI. To sum up, a trade-off needs to be made between spectral resolution (controlled by aperture in the surface-wave superposition) and the lateral resolution of velocity estimated by SWI.

Hybrid scheme of dispersion-curve inversion
The misfit function used to invert measured dispersion-curves is crucial to the inversion process due to the strong non-linearity of the problem. Gabriels *et al.* (1987) proposed a misfit function based on measuring the distance between the picked dispersion curves and the calculated dispersion curves. This reduces the number of local minima of the inversion problem. This approach requires a-priori identification of the dispersion-curve modes which, in practice, is often challenging, particularly for higher order modes. To overcome this drawback, Maraschini *et al.* (2010) proposed a misfit function based on the Haskell-Thomson matrix method. Comparing with the former, this misfit function allows a multi-mode inversion without modal identification in exchange for an increase in the number of local minima in the problem as described by Zheng and Miao (2014). For example, the inversion might match the picked fundamental curve as the first higher order mode and end up with a velocity profile much faster than reality. Combining the merits of two misfit functions, a hybrid approach is used that builds an initial velocity profile by minimizing the curve distance of the first one or two modes, then further updates the velocity by minimizing the Maraschini *et al.* (2010) misfit function using a differential evolution inversion scheme.

Results

In shallow marine environments, Scholte waves propagate in the vicinity of seabed and appear as strong, low frequency, arrivals in OBN data. Figure 2 shows Scholte waves that are well recorded by the vertical and the radial components of an OBN survey in the North Sea. We highlight the fundamental modes and the first higher order modes as A and B on the gathers, respectively. Comparing with the radial component, the vertical component records a stronger fundamental mode, which can be clearly observed on the spectrum. As the fundamental mode is essential to the dispersion curve inversion, our subsequent inversion is based on the dispersion curves picked from the vertical component.
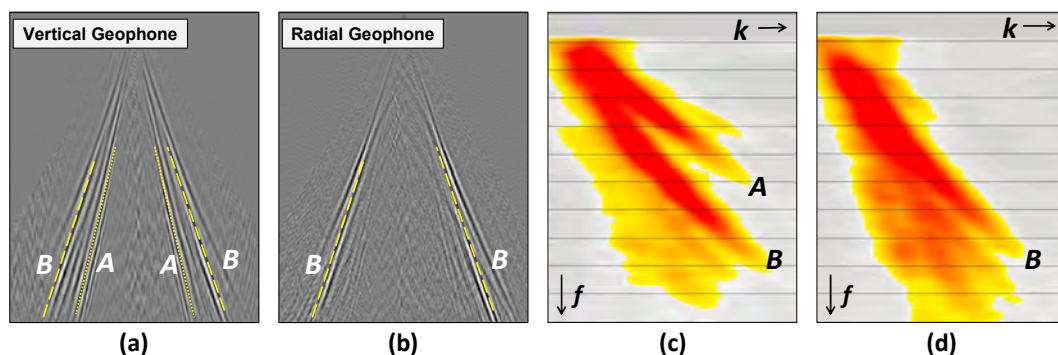

Figure 2 *Scholte waves in (a) the vertical component, (b) the radial component. (c) and (d) show f-k spectra of (a) and (b). Label A denotes the fundamental, and B the first higher order mode.*
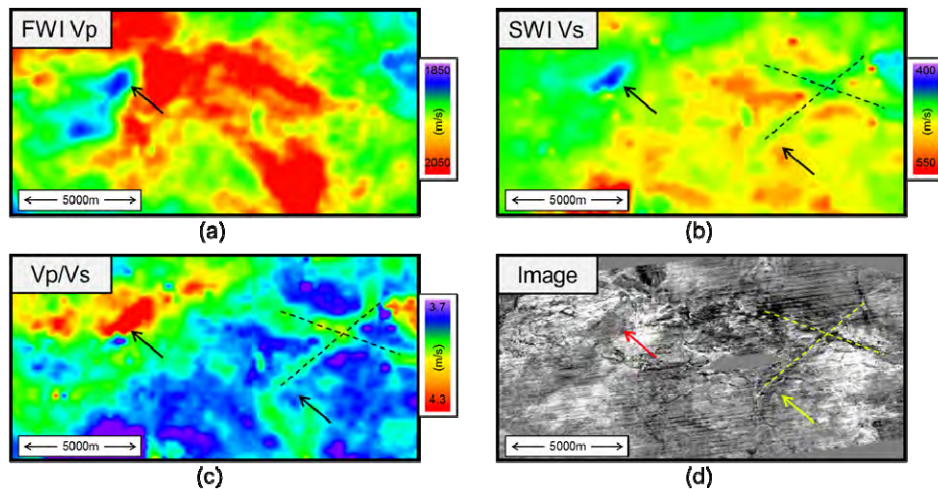
Figure 3 *(a) Shallow depth-slice of Vp from FWI; (b) Same depth-slice of Vs from SWI; (c) Calculated Vp/Vs Ratio; (d) Depth-slice from shallow towed-streamer PP image.*

The spectra were produced from CMP gathers with a 500 m aperture, which achieved a good compromise between spectral and spatial resolution levels.

Inversion of the dispersion curves at each location gives a spatial volume of 1D shear velocity profiles, which combine to make a shallow Vs model in 3D. It is difficult to get reliable Vp from SWI because surface waves are not sensitive to P-wave velocity. Therefore, we use a full-waveform inversion (FWI; Warner *et al*., 2013) for shallow Vp estimation. Figure 3 illustrates the inverted Vs model from SWI with comparisons to the inverted Vp from FWI and a shallow depth-slice from a towed-streamer PP image. The depth-slice of Vs has similar spatial resolution to the depth-slice of Vp, and has many shared features. The Vs volume does show structure not evident in the Vp volume, particularly the shallow-channel features. This is clear from the spatial variability of the Vp/Vs ratio. For example, we can observe a mini-basin in both the Vp and the Vs depth-slices (arrow on left), while the semicircle structure (arrow on right) and two intersecting channels (dashed lines) are visible in Vs only. The towed-streamer image confirms the existence of these features. In interpretation terms, the high Vp/Vs ratios in Figure 3(c) might result from softer sediments, while low Vp/Vs ratios could be an indicator of shallow gas.

The estimated Vs from SWI can also be used to build a velocity model for PS-wave depth migration. This is useful since PS-wave reflection tomography has limited capability in the near-surface due to poor reflection illumination (e.g. shallow PS reflection events are absent or difficult to pick at wide angles). If shallow horizons are identifiable on both PP and PS images, the effective Vp/Vs ratio can be calculated from a horizon registration process to initialise the velocity model. However, this provides a low-resolution model (Figure 4a), and since shallow velocity errors occur in the slowest parts of the velocity model they have a disproportionately large effect on the wavefield, distorting and degrading the PS image from near surface to deeper targets. The SWI model populates the near surface with a high resolution measurement of Vs (Figure 4b), which improves the image of both shallow and deep structures. In Figure 4, panels (c) and (e) were imaged using a Vs model with shallow features depicted in panel (a). The Vs model used to make the images in panels (d) and (f) has had the top 120 m below water bottom replaced by the SWI model. Changing only the top 120 m of velocity model improves the image at both shallow (1 km, panel d) and deep (3 km, panel e) levels.

Conclusions

In this paper, we proposed a new approach to dispersion-curve inversion for deriving a shallow Vs model based on a hybrid misfit function. The main benefit of this hybrid method is to reduce the non-linearity of simultaneous inversion of multi-modal dispersion curves without a-priori identification of their modes. The method is verified using OBN data from the North Sea. The SWI velocity model has similar spatial resolution to FWI and correlates well to the seismic image. The SWI Vs model brings appreciable benefit to PS-wave velocity-model building and depth imaging.
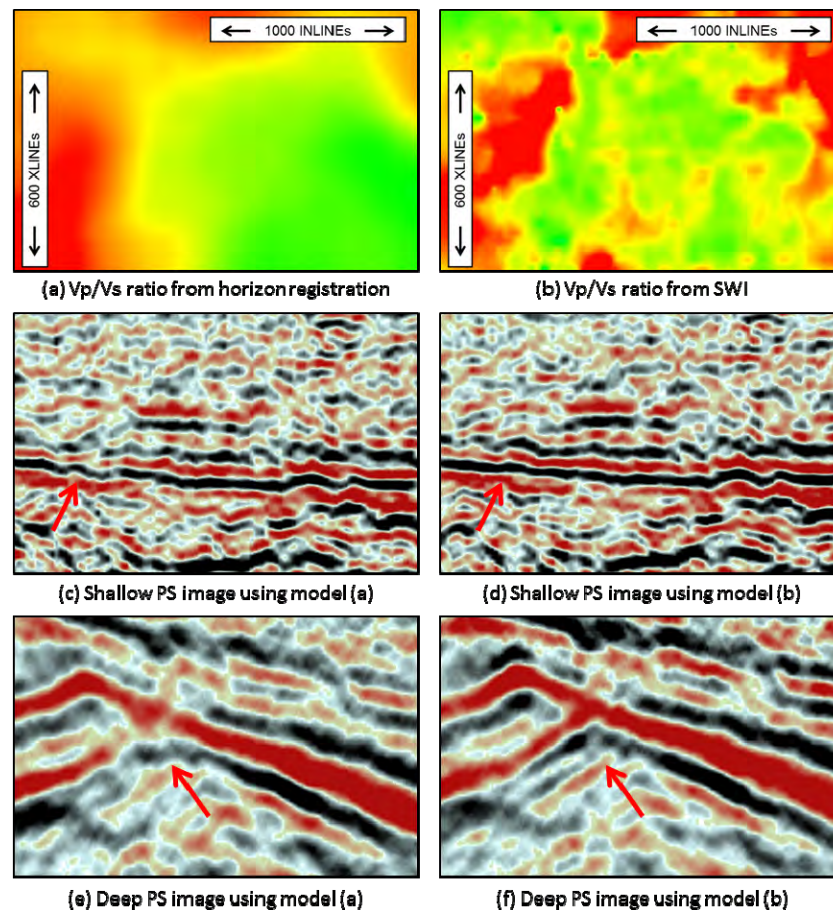
Figure 4 *(a) Shallow depth-slice of Vp/Vs from horizon registration; (b) From FWI and SWI velocities; (c) Shallow section (1km depth) from PS image using model (a); (d) Using model (b); (e) Deep section (3km depth) from PS image using model (a); (f) Using model (b).*

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References

Boiero, D., Wiarda, E., and Vermeer, P. [2013] Surface-and guided-wave inversion for near-surface modeling in land and shallow marine seismic data. *The Leading Edge,* **32**(6), 638-646.

Gabriels, P., Snieder, R. and Nolet, G. [1987] In situ measurements of shearwave velocity in sediments with higher-mode Rayleigh waves: *Geophysical Prospecting*, **35**, 187-196.

Maraschini, M., Ernst, F., Foti, S. and Socco, L.V. [2010] A new misfit function for multimodal inversion of surface waves. *Geophysics*, **75**(4), G31-G43.

Neducza, B. [2007] Stacking of surface waves. *Geophysics,* **72**(2), V51-V58.

Socco, L.V., Foti, S. and Boiero, D. [2010] Surface wave analysis for building near surface velocity models: established approaches and new perspectives. *Geophysics*, **75**(5), 75A83-102.

Socco, L.V. and Strobbia, C. [2004] Surface wave methods for near-surface characterisation: A tutorial. *Near Surface Geophysics*, **2**(4), 165-185.

Warner, M. *et al.* [2013] Anisotropic 3D full-wave form inversion. *Geophysics,* **78**(2), R59-R80.

Xia, J., Miller, R. and Park, C. [1999] Estimation of near-surface shear-wave velocity by inversion of Rayleigh waves. *Geophysics*, **64**(3), 691-700.

Zheng, D. and Miao, X. [2014] Multimodal Rayleigh wave dispersion curve picking and inversion to build near surface shear wave velocity models. *76th EAGE Conference & Exhibition*, Amsterdam.