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# High Resolution Multi-Modal Surface Wave Inversion for Shallow S-Wave Velocity Model Building

X. Li[1]*, Y. Chen[1], X. Miao[1], L. Li[1], F.C. Loh[1], B. Hung[1], S. Wolfarth[2], D. Priyambodo[2]

[1] CGG; [2] BP

## Summary

Shallow S-wave velocity model building is very important for land and Ocean Bottom Seismic PS data processing. Surface waves, propagating along the near surface, provide useful information for shallow S-wave velocity estimation. In this study, multi-modal surface wave inversion (MM-SWI) was used to build a high resolution shallow S-wave velocity model for a recently acquired Ocean Bottom Node survey. Super gathers were constructed to improve the signal-to-noise ratio and the spatial resolution of surface wave dispersion spectra. Auto-picking of multi-modal dispersion curves was then implemented. To overcome the strong nonlinear problem during multi-modal inversion, the combined Levenberg-Marquard and differential evolution method was used. High resolution dispersion analysis and robust auto-picking improved productivity significantly, which allowed for a high resolution shallow S-wave velocity model to be built in time. The inverted MM-SWI model correlates well with both the shallow geological structures and the seafloor map. It reveals fine layers, small faults, small channels and other lithological variations. The MM-SWI model was used for PS statics correction and also incorporated into the S-wave velocity model building process. Results from the model comparison, statics application and the PS depth image support the reliability of high resolution shallow S-wave velocity models from MM-SWI.

## Introduction

Multicomponent seismic data processing is of increasing importance due to the popularity of Ocean Bottom Seismic (OBS) surveys in recent years. PS waves, besides P waves, are recorded during OBS acquisitions. Thanks to their different impedance responses, PS waves can be used to enhance images beneath gas clouds and provide additional information for reservoir characterization.

There are usually strong statics issues in PS data due to extremely low S-wave velocity (Vs) beneath the seafloor, which make PS processing very challenging. Lack of shallow illumination from the PS reflections (due to small S-wave leg emerging angles) also compounds the difficulty of near surface Vs model building. Fortunately, surface waves and their dispersion characteristics are strongly correlated with shallow lithological heterogeneity, which can be used for near surface Vs estimation. Usually there are multiple modes (fundamental mode and higher modes) of dispersion curves for surface waves. Multi-modal surface wave inversion (MM-SWI) uses all of the modes together to invert for shallow Vs, which can provide higher resolution and better accuracy than only using the fundamental mode (Miao et al., 2016). Furthermore, surface waves propagate along the near surface resulting in wider illumination coverage, which further improves the estimation of the shallow Vs model with a high spatial resolution. The inverted Vs model can be used to correct shear wave statics during the PS signal processing, and can also be incorporated into the Vs model building for PS depth imaging. Therefore, MM-SWI plays a very important role in PS processing.

In this study, MM-SWI was applied on 3D Ocean Bottom Nodes (OBN) data from the Tangguh gas field in Indonesia. Seismic data were acquired by deploying the nodes with a 200 m node line interval and a 50 m node interval along the line, while the shot line and shot point intervals were 50 m and 25 m respectively (Stone et al. 2018). Surface waves were extracted and used for the dispersion analysis. Multi-modal dispersion curves were automatically picked from the dispersion spectra. A high resolution shallow Vs model was inverted by MM-SWI, and then used for the PS statics correction and the PS depth imaging.

## Methodology

MM-SWI includes three main steps: high resolution dispersion analysis, auto-picking of multi-modal dispersion curves and multi-modal dispersion curves inversion.

### *a. High resolution dispersion analysis and multi-modal dispersion curves auto-picking*

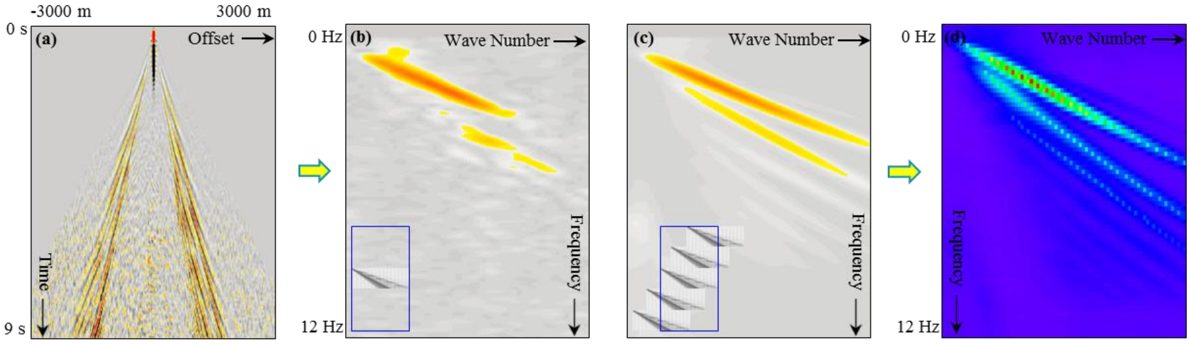

***Figure 1*** *High resolution dispersion spectrum analysis of surface wave and multi-modal dispersion curves auto-picking: (a) Extracted Surface wave; (b) dispersion spectrum of a single gather; (c) dispersion spectrum of a super gather; (d) auto-picked multi-modal dispersion curves.*

Dispersion spectral analysis and auto-picking of multi-modal dispersion curves are the first two key steps of MM-SWI. We start from the surface wave extraction which is followed by spectral analysis. Figure 1a shows an extracted surface wave. The dispersion spectrum of this single surface wave gather is shown in Figure 1b; however its signal-to-noise ratio (S/N) is too low and only the first mode of dispersion can be recognized. To enhance the S/N, a super gather is constructed by including all of the traces within a pre-defined aperture (as blue box shown in Figure 1b, 1c) for a CDP grid point, and its corresponding spectrum is depicted in Figure 1c. The super gather based dispersion analysis method does not just improve the S/N, but also makes higher modes more clear and extends the reliable frequency band. It makes auto-picking more practical and the picked dispersion curves more accurate and reliable for MM-SWI as well (Figure 1d).

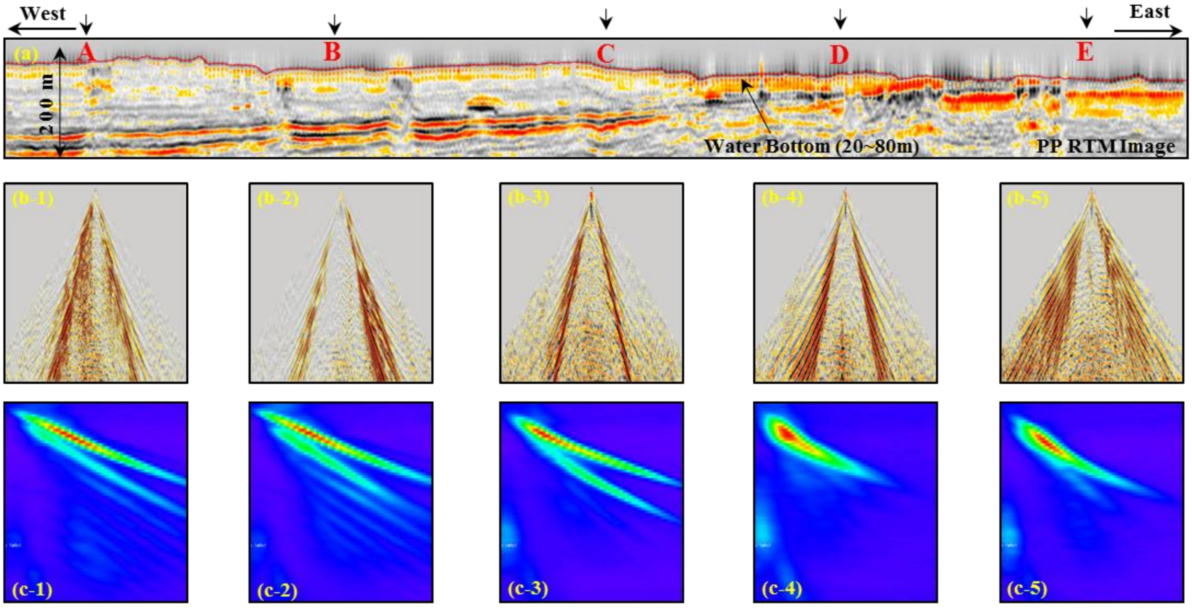

***Figure 2*** *Spatially-varying surface wave and dispersion characteristics. (a) Shallow PP RTM image; (b-1)~(b-5) Surface waves corresponding to the locations A~E in figure 2a respectively; (c-1)~(c-5) Dispersion spectra corresponding to the locations A~E in figure 2a respectively.*

To invert for the shallow Vs model, high spatial resolution dispersion curves are also needed. In this study, the size of aperture was carefully chosen (within 400 m) to obtain high spatial resolution dispersion spectra. In this survey area, the water depth is around 20 m in the western part and around 80 m in the eastern part (Figure 3c). The shallow layer pinches out from west to east and some gas pockets can be clearly seen on the P-wave reverse time migration (RTM) image (Figure 2a). Figure 2b and 2c show the spatially-varying behaviour of the surface waves and their corresponding dispersion spectra. The dispersion characteristics are strongly dependent on the water depth and the shallow geologies (Aki and Richards, 1980). Due to the shallow water depth and fine layers, the dispersion is much richer in the western part (up to 6 modes can be clearly recognized in Figure 2c-1 and c-2). The number of modes decreases as the water depth increases and when the layering structure pinches out (Figure 2c-3, 2c-4, 2c-5). Due to the shallow gas in the eastern part, the dominant energy shifts to a low frequency and hence the higher modes become much weaker (Figure 2c-4, 2c-5).

### *b. Multi-modal dispersion curve inversion*

MM-SWI, using higher-order modes together with the fundamental mode, can invert for a higher resolution Vs model. However multi-modal inversion is a strongly non-linear problem. Miao *et al* (2016) proposed a method which makes multi-modal dispersion curve inversion more robust by combining the Levenberg-Marquard (LM) and differential evolution (DE) methods. The combined method has a couple of advantages: it is able to find the global minimum solution and it is better in handling the strong non-linearity during multi-modal inversion. This combined method was used in this study. During the inversion, a high resolution shallow P-wave velocity (Vp) model (Figure 7a-1), from full waveform inversion (FWI, Wolfarth et al., 2019), was used as the initial Vp for MM-SWI.

## Results and Discussion

High spatial resolution of a shallow Vs model is important in revealing the geological structures with lateral contrast, such as small channels (as shown in Figure 3c). In order to capture these details in a Vs model, a small grid size is required. Figure 3 displays a comparison of Vs velocity (overlaid on PP image) from MM-SWI with 100X100 m versus 25X25 m spatial grid. The Vs model, inverted with 25X25 m, better matches with the PP image (Figure 3b) and the seafloor map (Figure 3c). These two models were respectively incorporated with a very smooth Vs model in the deeper section, and their corresponding PS RTM images are shown in Figure 4 (the location was indicated by yellow dashed line in Figure 3a, 3b). The PS RTM image, migrated with a high spatial resolution shallow Vs model, also provides better focusing and continuity in the image (Figure 4b). This indicates that PS images are quite sensitive to the spatial accuracy of the shallow Vs model, so a denser grid is very important to fully capture spatial variation of Vs. Usually dispersion analysis and multi-modal dispersion curves picking are time consuming. Thanks to the high resolution dispersion analysis and robust multi-modal dispersion curve auto-picking, we can significantly reduce manual picking and improve the productivity of MM-SWI. Therefore, a high spatial resolution Vs model (with 25x25 m spatial grid) can be achieved for the whole survey. Many detailed geological features can be revealed in the depth slice (100 m) of the high resolution shallow Vs model from MM-SWI (Figure 5).

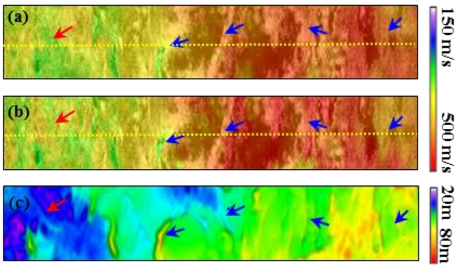

***Figure 3** Depth slice (130 m) of SWI Vs (a) 100X100 m grid; (b) 25X25 m grid; and (c) Water depth map.*

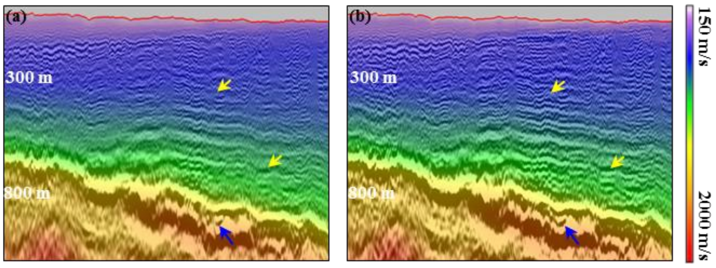

***Figure 4** PS RTM images: Migration with a smooth Vs model by incorporating a near water bottom MM-SWI Vs model with (a) 100X100 m grid; (b) 25X25 m grid.*

The inverted shallow S-wave velocity model was used to compute receiver-side shear statics, which were applied to the PS data prior to time imaging. Figure 6 shows a comparison of the PS receiver stack image with and without the statics correction. Structural distortions due to shear wave statics were observed (Figure 6a). After the shear wave statics correction, the lateral continuity of PS reflections was improved significantly and the events became more focused from shallow to deep (Figure 6b). Successful application of PS statics corrections was strong evidence to support the reliability and accuracy of the high resolution shallow S-wave velocity model from MM-SWI.

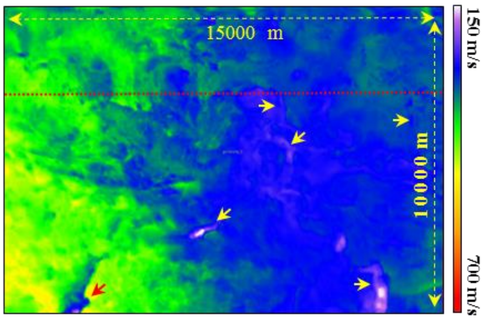

***Figure 5** Depth slice (100 m) of high resolution Vs model from MM-SWI*

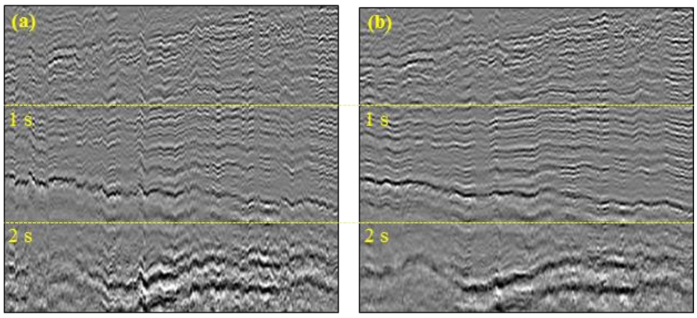

***Figure 6** PS Receiver stack image. (a) Before statics correction; (b) After shear statics correction.*

The inverted high resolution shallow S-wave velocity was also used to build a Vs model for PS depth imaging. A series of PS RTM experiments were carried out. It is well known that PS data contains P waves at the source side and S waves at the receiver side. Therefore, the Vp model from FWI and the Vs model, incorporating the shallow Vs model from MM-SWI, were used for the PS RTM imaging. Figure 7 shows a vertical section comparison of the shallow Vp model inverted by FWI with the Vs model inverted by MM-SWI, and comparison of the PP RTM image with the PS RTM image. The PP RTM image is overlaid on both of the models (figure 7a-1, 7a-2). From the comparison we can notice both FWI and SWI models are of high resolution. P-wave velocity is more sensitive to shallow gas, hence many low velocity anomalies can be observed in the FWI model (Figure 7a-1). However, S-wave velocity is not at all affected by shallow gas. The SWI model is able to reveal fine layers and small faults (figure 7a-2) as well as small channels and other kinds of lithological variations (figure 3b). The inverted Vs model correlates well with the shallow structures (figure 7a-2) and the seafloor map (figure 3c), indicating the reliability of the high resolution MM-SWI. As figure 7b shows, all of the major events in the PS image match well to those in the PP image, which again validates the reliability of the high resolution Vs model from MM-SWI. As indicated by the blue circles, the image beneath the shallow gas is significantly improved in the PS image. Some events in the PS RTM image (highlighted by arrows) are inconsistent with those in the PP image. This suggests impedance differences between the PP and PS wave propagation. This information is useful for interpretation studies.

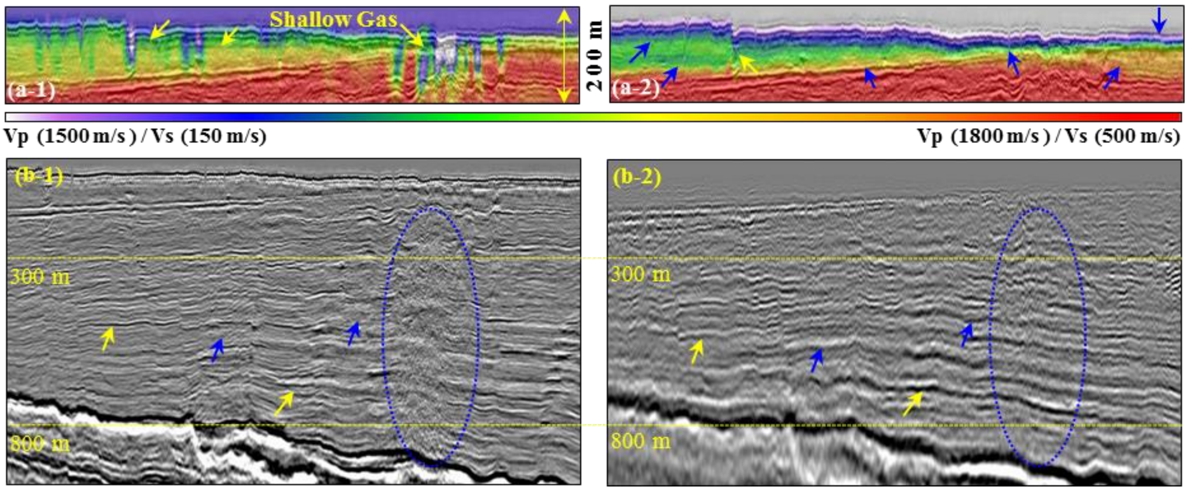

***Figure 7*** *High resolution (a-1) Vp from FWI; (a-2) Vs from MM-SWI overlaid on PP RTM image. Comparison of seismic image above 1000 m. (b-1) PP RTM image. (b-2) PS RTM image.*

## Conclusions

High resolution dispersion analysis and robust multi-modal dispersion curves auto-picking have shown their capability to make MM-SWI applicable to build a high resolution shallow S-wave velocity model for a large OBN project. The inverted Vs model correlates well with the shallow structures and the bathymetry. MM-SWI model-based PS statics correction improves the continuity and coherency of the PS image significantly. The shallow Vs model was also successfully incorporated into the S-wave velocity model building for PS depth imaging. All of these evidences support the usefulness of the MM-SWI to build high resolution shallow S-wave velocity models.

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