# Robust multi-modal surface wave inversion for shallow velocity and shear statics

*Xiaogui Miao*, Dong Zheng, Libo Zi, Zhenyu Zhou and Meng Gao, CGG*




## Summary

A robust surface wave inversion (SWI) has been developed to estimate near-surface shear velocity for depth model building and shear statics correction. The algorithm minimizes the dispersion curve distance for simpler cases, or directly solves the Eigen-determinant of surface wave secular functions for more complex cases.

The SWI algorithm has been applied to 3D ocean-bottom cable (OBC) data from offshore Vietnam, where the near surface geology changes from rapidly depth-varying reef structures to floodplain alluvial fans. Surface waves, Scholte waves in our case, demonstrate a variety of dispersion patterns, which are used in the inversion to reveal complex subsurface velocity structure underneath the sea floor. Receiver-side shear statics have been calculated for PS-wave time imaging based on the Vs model from SWI. This method reduces manual processing intervention compared with a conventional, horizon-based, shear statics method. Furthermore, it also provides a more accurate statics solution, improving event continuity and producing geologically interpretable horizons after time imaging. In addition, the SWI has supplied a shallow Vs model that is closely correlated with seabed geology for PS wave depth imaging.


## Introduction

Shallow S-wave velocity is notoriously difficult to estimate from conventional ocean-bottom seismic datasets. This is because near-surface illumination is very poor for PS-wave reflections, which provide information from the region almost directly below the receivers but not in-between receivers. To overcome this problem, surface waves have been considered as an alternative resource to invert near surface shear wave velocity structure for depth imaging and statics correction (Socco et al., 2010).

In shallow water environments, Scholte waves, a special type of surface wave, have been observed worldwide in ocean bottom seismic surveys. Similar to Rayleigh waves in land acquisition, Scholte waves carry rich information about shallow velocity structures and also illuminate the region in-between receivers (Socco et al., 2010; Foti et al., 2015). Scholte-wave inversion, to obtain shallow S-wave velocity (Scholte wave inversion is not sensitive to P velocity), is thus of interest to the seismic imaging industry. In this paper, we present recent developments in Scholte-wave inversion and its application to PS-wave data processing and imaging using the Vietnam OBC data.

## Theory and Method

The wave types included in surface wave inversion are Rayleigh waves for land data, Scholte waves for ocean-bottom data, and guided waves for both land and ocean-bottom. The inversion is based on measured phase-velocity dispersion, which varies with frequency and location, and is strongly dependent on near surface velocities. Usually, dispersion curves consist of several branches, with the slowest referred to as the fundamental mode. Multi-modal (the fundamental plus higher-order modes) inversion reduces uncertainty in the estimated velocities and provides higher resolution in depth compared with inversion of the fundamental mode only. However, multi-mode inversion is a more strongly non-linear problem than fundamental-mode inversion, and requires an inversion strategy with increased sophistication.

The surface wave inversion method we developed consists of three steps: (1) multi-offset dispersion analysis, (2) automatic dispersion-curve picking, and (3) surface wave inversion (Figure 1).

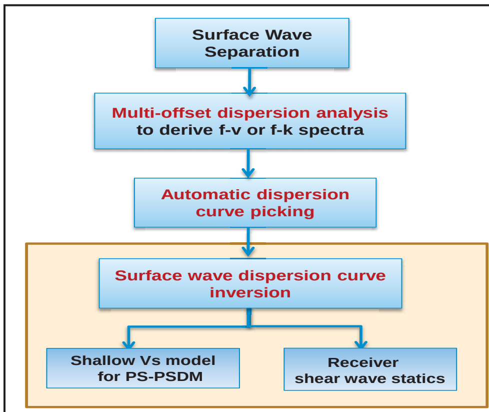



Figure 1. Surface wave inversion work flow.

### a. Multi-offset dispersion curve analysis

Dispersion analysis sounds like a simple procedure which establishes frequency-velocity relationships in the frequency-phase velocity or frequency-wavenumber domain. However, the success of inversion is critically dependent on the accuracy of dispersion curve characterization, and this step requires considerable effort and attention to detail in the algorithms performing the dispersion analysis. To facilitate auto-picking, we generate spectral super gathers with both high S/N ratio and good lateral resolution through superposition of dispersion spectra after careful selection of offset and aperture ranges.

**b. Automatic dispersion curve picking**

Without automatic dispersion curve picking, surface wave inversion is virtually impossible for modern 3D datasets. Automatic picking finds frequency-phase velocity pairs along each frequency slice, or along a dip direction for each dispersion mode. It initially picks all the local maxima in dispersion spectra, and then evaluates the picked values based on the mode order, continuity of dispersion curves and some other criteria to filter out the real dispersion curve data points from others. One difficulty in picking is that sometimes it cannot distinguish the mode order of dispersion curves correctly, which can cause some problems in inversion. However, our surface wave inversion copes with this uncertainty using an Eigen-determinant misfit function that does not need mode order information, as described in the next section.

**c. Surface wave inversion (SWI)**

To make the dispersion-curve inversion robust and suitable for all kinds of scenarios, we introduce two types of misfit functions. The most common one (e.g. Gabriels et al., 1987) is the dispersion-mode based phase-velocity misfit function, also called curve distance misfit, defined as

$$s(m) = \sum_{i=1}^{N} w_i \left| v_i^{real} - v_i^{syn}(m, f_i^{real}) \right|,$$

where $(f_i, v_i)$ is a frequency-phase velocity pair on a dispersion curve, $w_i$ is a data point weight, $m$ represents Vp, Vs and density models, and there are N dispersion-curve picks. Although this misfit function is physically intuitive, it does require a-priori identification of dispersion-curve modes to avoid non-linearity in the inversion. In many cases this a-priori identification is unrealistic, especially when the subsurface structures are complex. Maraschini et al. (2010) proposed use of the Eigen-determinant as a misfit function, whose roots are found to describe dispersion-curve data points. Then the misfit function is

$$s(m) = \sum_{i=1}^{N} w_i \left| T( f_i^{real}, v_i^{real}, m) \right|,$$

where $T$ is a surface wave dispersion function. Only the correct parameter $m$ generating $(f_i^{real}, v_i^{real})$ satisfies $T(f_i^{real}, v_i^{real}, m) = 0$. By introducing this new misfit function the mode recognition and numbering are avoided.

Different kinds of optimization methods were tried in the inversion (Zheng and Miao, 2014). The most effective two are the Levenberg-Marquardt method (LM), a non-linear least squares method, and the differential evolution method (DE). The former uses gradient descent or quasi-Newton methods to find the local minimum. It converges fast, but could be trapped in local minima. The DE method, a global optimization engine, is capable of jumping out of local minima. It intrinsically deals with continuous real-number optimization problems, making it suitable for searching in a multi-dimensional space. However, it usually has weaker local search ability than the LM method and results in a less accurate final model. Combination of these two makes the inversion more robust as it is able to find the global minimum with a high degree of precision in the solution. In the inversion process, we use a generalized reflection/transmission coefficient method to produce a model response (Chen, 1993). Lateral constraints are also introduced in the inversion so that the result is laterally continuous.

**Data application example**

Our surface wave inversion workflow has been applied to a number of projects successfully (e.g. Hou et al., 2016). In this paper we present a case study with 3D ocean-bottom cable data acquired in Cuu Long Basin, offshore Vietnam. The total size of the survey is about 852 $km^2$ with water depth varying from 12-66 m, which reflects geological variation from rapid depth varying reef structures, as shallow as 12 m, to floodplain alluvial fans in the south of the survey. The observed Scholte wave dispersion patterns and dominant mode change with location. In the areas with gentle sea-floor variation, up to four Scholte wave dispersion modes can be traced (rightmost spectra in Figure 2). Near the reef areas, with sharp water depth variation, higher modes gradually disappear and the fundamental mode dispersion curves become shorter and more strongly curved (leftmost spectra in Figure 2), imposing serious challenges for automatic dispersion curve picking and inversion.

To enhance the signal to noise ratio for the dispersion spectra, the offset and aperture ranges to generate the spectra were carefully selected and adjusted from area to area, so the stacked multi-offset spectra were good enough to facilitate automatic dispersion-curve picking. In most of

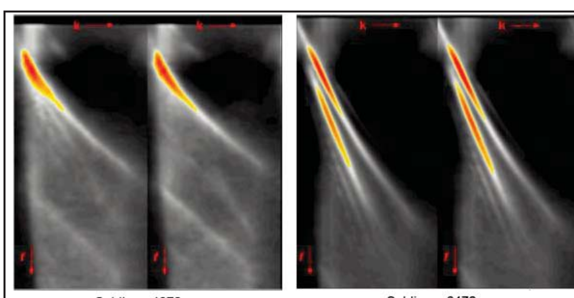



Figure 2. Scholte wave dispersion f-k spectra at subline 4872 (left) and subline 6472(right).

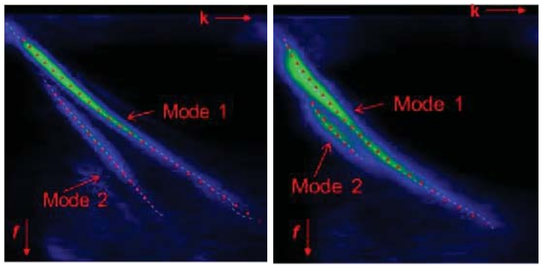



Figure 3. SWI inversion QC. Synthetic f-k dispersion curves in red dots overlaid on the observed f-k dispersion curves.

the survey area the first two modes were relatively stable and were used in the inversion. In areas with good dispersion spectra, the LM inversion with curve distance misfit function was able to produce reliable results with fast convergence. In the neighborhood of reef areas, a combination of curve distance and Eigen-determinant was used to avoid mis-interpreted mode orders. In this case the differential evolution method with lateral constraints was able to get good initial estimations, which was followed by LM optimization to refine the accuracy of the inversion.

To QC the inverted shear velocity, the first two modes of Scholte wave dispersion curves were synthesized. They are overlaid on the auto-picked dispersion curves from the recorded data and displayed in Figure 3. The red dots in Figure 3 are the synthetic dispersion curves while the observed dispersion curves are shown in white dashed lines overlaid on the dispersion spectra. The leftmost figure in Figure 3 is from an area with gentle sea floor variation, and the rightmost figure is from an area close to a reef. In both cases the synthetic curves match the observed ones well.

**Results and discussion**

The final inversion has produced a robust result in which the inverted S-wave velocity correlates well with the sea floor geology (Figure 4c and 4d). The estimated Vs is compared with a Vp model from diving wave tomography (Figure 4a and 4b). The Vs model penetrates up to 160 m below seafloor, with average water depth of 50 m. The color bars have been clipped at 735 m/s for Vs and 1900 m/s for Vp. There are many similarities between the two models: three larger reefs 1, 2, and 3 with high velocity anomalies as indicated by red arrows and the low velocity alluvial fans indicated by a blue arrow. For reef 4, the uplifted high-velocity anomaly in both models matches well with reef location in the sea floor map (see Figure 4b and 4d). In general, because the S wavelength is shorter in the shallow, the Vs model demonstrates higher resolution than the Vp model. From depth slices at 95 m (Figure 4a and 4c) the presence of channels can be detected in the Vs model but can be hardly traced in the Vp model. We also notice small reef no.5 (see Figure 4b and 4d), which is clearly delineated as a high velocity anomaly in the Vs model, but can hardly be seen in the Vp model.

The inverted S velocity model was used to compute receiver-side shear statics, which were applied to the data prior to time imaging. Figure 5 shows a comparison of the stacks (Figure 4c shows location of the section). The Vp/Vs ratio is shown in the top left and right of Figure 5 with the inverted Vs model in the middle. The stack with only

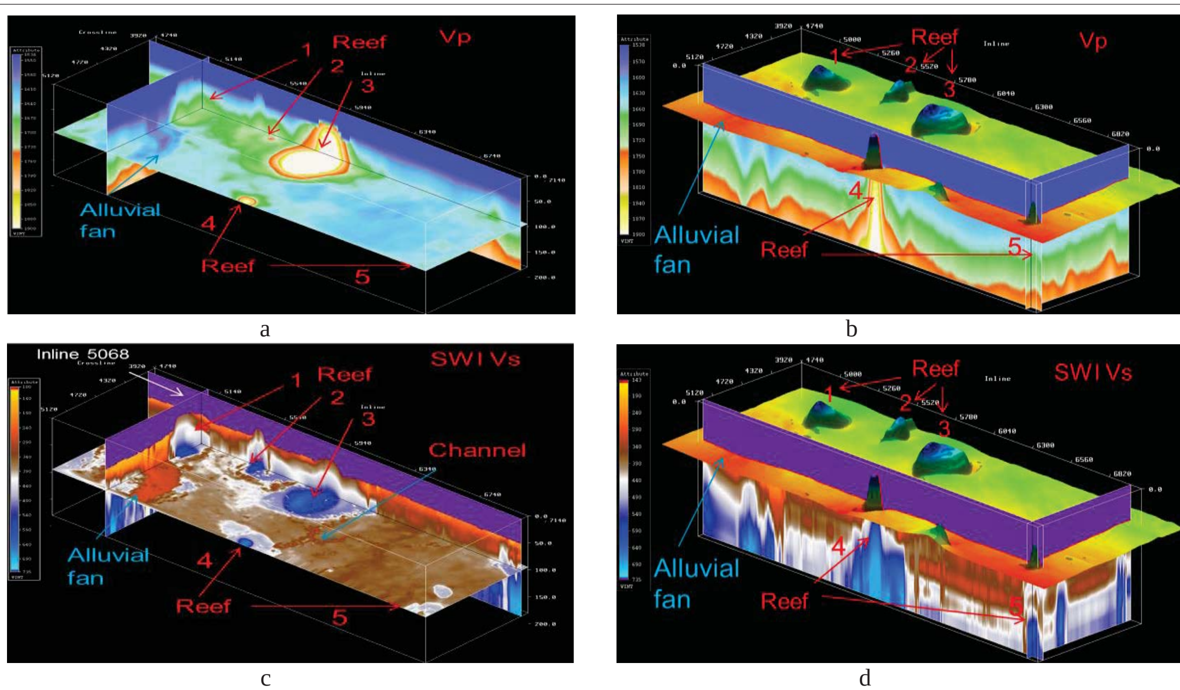



Figure 4. a) and b) is the Vp model from diving wave tomography. c) and d) is the Vs model from SWI inversion. a) and c) show depth slices at 95 m below sea-surface for Vp and Vs respectively.

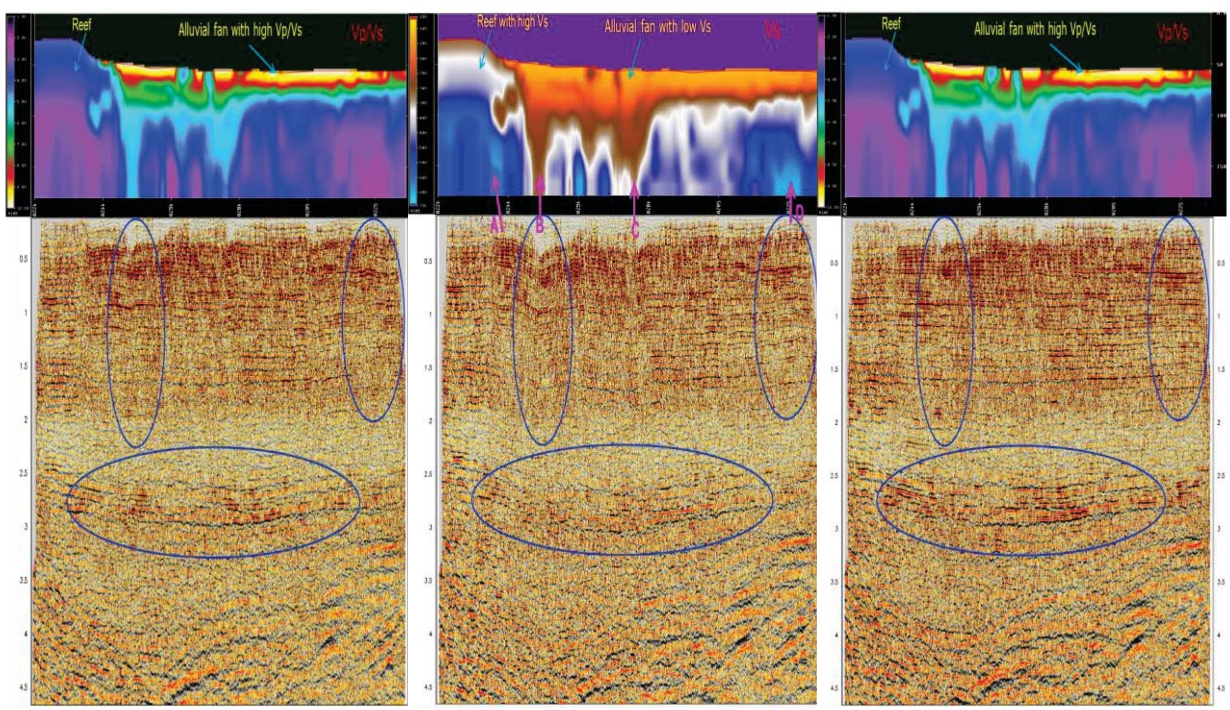
source side P wave statics is shown in Figure 5b. The high Vs anomalies cause an uplift effect in travel times as highlighted by arrows A and D, and the low Vs alluvial fans push the seismic section down as highlighted by arrows B and C. The travel time distortion in the seismic section correlates well with the inverted Vs model. Figure 5c shows the stack with both source side P wave statics and receiver side SWI statics applied. After SWI shear statics application, the travel time distortions are successfully corrected by this long wavelength statics compensation. With only one statics value for each receiver, SWI not only improves event continuity in the shallow, but also makes the deep events significantly more coherent. The remaining short wavelength statics can be corrected by stack-power residual statics methods. For comparison, the stack after conventional receiver statics correction is shown in Figure 5a. It requires picking both PP and PS horizons, and then correlating them to get statics values. The difficulty caused by large receiver line spacing (400 m) and human picking errors have resulted in some long wavelength statics being left uncorrected by conventional horizon-registration method.

## Conclusion

A robust surface wave inversion has been developed and successfully used to invert shallow S wave velocity model and calculate shear statics for Cuu Long Basin 3D4C OBC data. The inverted Vs model correlates very well with the geology underneath the sea floor, and the imaging results with receiver shear statics correction also show much better event coherence and horizon continuity from shallow to deep.

## Acknowledgments

The authors appreciate VietSovPetro, Petropartner and CGG for their permission to publish the paper. Authors would also like to thank Changhai Jiao of CGG for his diligent work to extract mud rolls; Vishal Kumar of CGG for his help in PS data processing; Joe Zhou and Fongcheen Loh of CGG for their technical advice and discussions on the project; and Zhonghuan Chen and Ye Zhou of CGG for their technical supports to the project.




a b c

Figure 5. The shear statics comparison in time stacks. Top middle: S wave velocity profile from SWI inversion; Top left & right: The Vp/Vs ratio derived from the SWI inverted Vs and the Vp of diving wave tomography. In the bottom: a) stack with the source side P statics and the receiver side conventional statics applied; b) stack with only the source side P statics applied; c): stack with the source side P statics and the receiver side SWI shear statics applied.

**EDITED REFERENCES**

Note: This reference list is a copyedited version of the reference list submitted by the author. Reference lists for the 2016 SEG Technical Program Expanded Abstracts have been copyedited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

**REFERENCES**

Chen, X., 1993, A systematic and efficient method of computing normal modes for multilayered half-space: Geophysical Journal International, **115**, 391–409, http://dx.doi.org/10.1111/j.1365-246X.1993.tb01194.x.

Gabriels, P., R. Snieder, and G. Nolet, 1987, In situ measurements of shear wave velocity in sediments with higher-mode Rayleigh waves: Geophysical Prospecting, **35**, 187–196, http://dx.doi.org/10.1111/j.1365-2478.1987.tb00812.x.

Foti, S., C. Lai, G. Rix, and C. Strobbia, 2015, Surface wave methods for near surface site characterization. CRC Press, Taylor & Francis Group.

Hou, S., D. Zheng, X. Miao, and R. Haacke, 2016, Multi-modal surface wave inversion and application to North Sea OBN data: 78th Annual International Conference and Exhibition, EAGE, Extended Abstracts.

Maraschini, M., F. Ernst, S. Foti, and L. V. Socco, 2010, A new misfit function for multimodal inversion of surface waves: Geophysics, **75**, no. 4, G31–G43, http://dx.doi.org/10.1190/1.3436539.

Socco, L.V., S. Foti, and D. Boiero, 2010, Surface-wave analysis for building near-surface velocity models — Established approaches and new perspectives: Geophysics, **75**, no. 5, 75A83–75A102, http://dx.doi.org/10.1190/1.3479491.

Zheng, D., and X. Miao, 2014, Multimodal Rayleigh wave dispersion curve picking and inversion to build near surface shear wave velocity models. 78th Annual International Conference and Exhibition, EAGE, Extended Abstracts, http://dx.doi.org/10.3997/2214-4609.20140538.