SUMMARY

In several domains of applied geophysics, surface and guided waves are considered a source of information that can be exploited by a variety of well-established geophysical solutions for characterizing the near surface, which in a marine environment includes the seabed. In contrast, in exploration seismic surveys, these waves have traditionally been regarded as coherent noise that should be quickly filtered out. With proper analysis and inversion they can be used to characterize the near surface with a surprisingly high resolution, and can provide valuable information for tasks such as velocity and geological modelling. Here, we discuss a workflow for the analysis and joint inversion of surface and guided waves in ocean-bottom cable and shallow streamer seismic data and we list cases where the retrieved shallow velocity models can enhance conventional processing in shallow marine environments.
Introduction

Seismic data acquired in shallow waters often display well-defined dispersion patterns related to surface and guided waves. Figure 1 shows minimally preprocessed hydrophone component data acquired in shallow water from ocean-bottom cables (OBC) and towed streamers. The waves propagating as normal modes are represented by a low-velocity, low-frequency wavetrain identified with Scholte waves (events A and B). The high-frequency part of Scholte waves consists mainly of Stoneley waves localized in the vicinity of the liquid/solid interface; whereas, at lower frequencies, they consist of Rayleigh waves propagating in the layers below the seabed (Shtivelman 2004). Because the interface waves decay rapidly with increasing distance to the liquid/solid interface, sources and receivers must be close to the seabed. Hence, Scholte waves can be recorded by OBC and, in very shallow water, by towed streamers. Numerous examples obtained in areas with various geological conditions using different acquisition geometries show that most of the energy of the waves is localized within a narrow range of low frequencies between 2 and 20 Hz. The phase velocities of Scholte waves are related to the S-wave velocities \( V_S \) below the water bottom and can be inverted to estimate them in the subwater layers (Shtivelman, 2004; Boiero et al., 2013).

The guided waves propagating as leaking modes are composed mostly of multiply reflected P-waves; whereas, their resonant character is due to S-waves leaking outwards from the upper layers (events C and D in Figure 1). They usually display a number of characteristic features: 1) their dispersion patterns have a resonant frequency-tuned appearance; 2) they have relatively high cut-off frequencies; and 3) their phase velocities exceed the velocity of the water (Shtivelman, 2004). When the subwater layers are composed of relatively soft saturated rocks with high Poisson’s ratio, the leaking modes can be approximated by guided acoustic waves. By inverting the guided-wave dispersion curves, the vertical distribution of the P-wave velocity \( V_P \) in the shallow subwater layers can be estimated (Shtivelman, 2004; Boiero et al., 2013).

A surface-wave analysis and inversion method exploits all the different modes described above to obtain a near-surface model that can be used for near-surface perturbation corrections, for velocity model building, and for geotechnical applications.

![Figure 1](image.png)

**Figure 1** a) example shallow-water OBC receiver gather with Scholte waves (A) and guided P-waves (C); b) example shallow-water towed-streamer shot gather with Scholte waves (B) and guided P-waves (D).

**Surface wave analysis and inversion**

Different Scholte and guided P- wave modes can be analyzed together to build a reliable near-surface velocity model in two steps:

- Obtain a high-resolution spatial distribution of the modes’ properties.
- Invert the modes’ properties to a near-surface model.
The common physical principle of different surface-wave methods is related to the fact that their propagation depends on their wavelengths, which in turn is responsible for the geometric dispersion (different frequencies have different phase velocities). The dispersion is strictly related to the earth properties and can be inverted to obtain a near-surface velocity model (Strobbia et al., 2011).

For this reason we analyze surface waves by looking at their main property: geometric dispersion. The objective of the analysis is extracting the local wavenumber as a function of frequency, $k(f)$, for the different modes. Phase velocity estimation can be done by following the approach of Strobbia et al. (2011), which is based on the use of high-resolution, unevenly spaced F-K transforms to estimate the local properties of surface waves within a patch of receivers. The analysis workflow extracts the local properties of the linear event of interest (Scholte or guided-wave modes) and, by using the redundancy in the data, it removes the effect of the propagation path from the source to the analysis point by extracting the local average phase gradient. The analysis can be run on both source and receiver lines for typical 3D acquisition geometries, where the results can be merged into a volume (Figure 2a) representing the surface-wave properties (at a certain frequency) within a survey.

Phase velocity inversion at each location provides the medium velocities (Figure 2b). Three challenges can be identified with dispersion curve inversion, especially when looking at guided waves:

- Curve inversion traditionally requires identification of the order (nature) of the modes. Mode identification is mainly limited by the bandwidth of recorded data, in particular at low frequencies. Furthermore, guided P-waves do not have a characteristic reference mode like the fundamental Scholte mode for S-waves.
- Guided P-waves can interfere with converted-wave modes and higher Scholte modes, in particular, in the presence of hard sea bottoms.
- Scholte waves propagate as normal modes defined by the real-valued roots of the dispersion equation whereas guided waves (especially P-guided waves) in many conditions propagate as leaking modes defined by the complex-valued roots of the dispersion equation, which is difficult to deal with.

The approach described by Boiero et al. (2013) can be used to address these challenges. It involves minimizing an implicit function whose zeros are the solution of the secular function and correspond to modal curves. The inversion algorithm modifies S- and P-wave velocities to match the estimated dispersive events with the secular function solutions. This misfit function allows inverting Scholte and

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**Figure 2** a) map of phase velocity for guided P-waves along source and receiver lines at 8 Hz; b) seabottom model vertical section obtained inverting Scholte and P-guided phase velocities along a receiver line.
P-guided modes without the need to associate experimental data points to a specific mode, thus avoiding mode misidentification errors in the retrieved velocity profiles. The advantage of this approach is that it does not have to describe leaking modes as acoustic or pseudo-acoustic modes (Shtivelman 2004), which is a reasonable approximation when dealing with soft saturated rocks with high Poisson’s ratio but may not be appropriate in other cases (Roth and Holliger 1999).

Next, we show two examples from OBC and towed-streamer data acquired in shallow marine environments.

**Near-surface modelling examples**

Figure 3 shows the S- and P-wave beneath an OBC survey. The two sections are inferred by inverting the phase velocities estimated along source and receiver lines (Figure 2). These sections highlight the laterally variant complexities within this layer which would be difficult to appreciate using alternative methods applied on deep prospection acquisition geometry. In this specific case, we observed a maximum penetration depth for surface-wave inversion of about 200 m from sea level.

![Figure 3](image_url)  
*Figure 3 a) map of S-wave velocity at 110 m of depth; b) map of P-wave velocity at 110 m of depth.*

Figure 4 shows an example of velocity models retrieved from towed-streamer data (measuring phase velocities along sailing lines) following the same approach described for OBC data.

**Applications**

Beside static estimation and correction, surface- and guided-wave inversion has the ability to enhance conventional shallow velocity model building, depth imaging, and full waveform inversion (FWI) efficiency and results. The assumptions that typically underpin current acoustic FWI methods are generally not justified in the elastic near-surface environment, and surface-wave inversion may provide P-wave velocity models that can be incorporated into the FWI initial model. Obtaining both P- and S-wave velocity models in the near surface through guided- and Scholte-wave inversion, respectively, may provide essential constraints on the wet bulk density of unconsolidated sediments.

For multicomponent data, a further benefit of accurate near-surface P- and S-wave velocity models is their potential contribution to improved PP-PS matching, imaging and (joint) inversion. Generating an accurate near-surface model enables imaging processes to more accurately account for differences in traveltimes and paths rather that reliance on 1D time statics. This will result in more accurate depth images from both PS and PP data, better amplitude handling in offset/angle gathers, and therefore
greater confidence in matching PS-PP events in migrated stacks and joint inversion using the results of amplitude-versus-offset gather analysis.

The inferred near-surface properties can also be used to design and optimize the coherent noise filtering workflow, and can be used for local adaptive filters. Model-based noise generation can be used to predict the coherent noise even beyond aliasing. Finally, interpreting the inversion results can provide a robust geological, structural, and lithological model of the near surface from which geotechnical parameters and drilling hazards may be identified.

![Figure 4](image_url)

**Figure 4** a) map of S-wave velocity at 80 m of depth; b) map of P-wave velocity at 80 m of depth.

**Conclusions**

In exploration seismic surveys, surface and guided waves can be analyzed and inverted to model the near surface. The size and quality of modern seismic datasets enable implementing robust workflows for processing surface waves, providing accurate estimates of their propagation properties with high lateral and vertical resolution which can be adapted to the characterization objectives. A proper inversion scheme can then infer S- and P-wave velocities from the propagation properties of different type of surface and guided waves that can be found in shallow marine environments, whether recorded by OBC, ocean-bottom nodes or towed streamers. The retrieved shallow velocity models can then enhance conventional processing in shallow marine environments.

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**References**


