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Guided Waves - Inversion and Attenuation
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SUMMARY

Guided waves contain significant information about the near surface in seismic data, but prove difficult to remove through conventional velocity discrimination methods. Here, we analyse guided waves jointly with ground roll to characterise the near-surface properties and then we remove them by modelling methods.

We begin by retrieving guided wave and ground-roll phase velocities. Then, we jointly invert them to build S- and P-wave velocity models using a robust multimodal inversion algorithm. Finally, we use the inferred guided wave and ground-roll properties to model the dispersive coherent noise and subtract it while preserving the signal.
Introduction

Guided waves are reflected multiples that travel in layers separated from the surrounding medium by high-impedance contrasts and, therefore, are a common phenomenon of wave propagation in layered media (Ernst and Herman 2000). In exploration seismology, guided elastic or acoustic waves are often observed in surface seismic data (Muyzert 2007). For example, the shallow marine environment supports guided pseudo-acoustic waves in the water layer. Guided elastic waves are generated in land seismic acquisition. Figure 1a shows a characteristic land shot record. The complexity of the wavefield is due to the interference of reflected and refracted multiples of P- and S-waves and of converted waves. Guided P-waves are dispersive events that appear with relatively high phase velocities, which can approach the moveout of reflections at large offsets. Guided S-waves have slower phase velocities than guided P-waves and overlap the ground-roll cone; they are usually called higher-order Rayleigh modes on vertical component data. From a theoretical point of view, Roth et al. (1998) showed that the Rayleigh waves are the superposition of normal modes and that shingled guided waves are the superposition of leaking modes.

The P- and S-velocities of the near surface determine the range of phase velocities in the seismic data. Guided waves can, therefore, cover large parts of seismic records and mask the target reflections (even at far offsets) such as in Figure 1a. The guided waves are then considered as shot-generated noise, such as ground roll.

Figure 1 a) example of shot gather where the ground-roll cone (zone A) and the guided waves (zone B) are indicated; b) example of F-K spectrum along the line. Event 1 is a Rayleigh wave mode, while event 2 is a guided wave mode.

Summarising, the motivation to study guided waves is two-fold:

1. P- and S-velocities for near-surface characterisation: guided waves and ground roll can be used to obtain a near-surface velocity model for P- and S-waves (Muyzert 2007; Boiero et al. 2009) to complement or replace refraction seismic data when appropriate. In particular, guided P-waves can provide constraints on the P-velocities. Guided S-waves appear as higher Rayleigh modes and are included in our analysis.

2. Shot-generated noise attenuation: the amplitudes of the guided waves are much higher than those of the target reflections. In the case of guided P-waves, the phase velocities approach the linear moveout of reflections at far offset, which make their attenuation challenging.

We show in the following how the guided waves can be analysed together with the ground roll to build a reliable near-surface velocity model and then to be removed.
Coherent noise analysis

We analyse guided waves by looking at their main property: dispersion. The estimation of phase velocities is done following the approach proposed by Strobbia et al. (2010), which is based on the use of high-resolution, unevenly spaced F-K transforms (Figure 1b) to estimate the local properties of the guided waves within a patch of receivers.

An example of continuous profiling along a 12-km receiver line is shown in Figure 2. The main two modes identified in Figure 1b (numbered 1 and 2) are extracted along the seismic line and shown in Figures 2a and 2b, respectively. In this representation, each vertical line represents the dispersion curve for that location. In Figure 2b, the black contour line at 2000 m/s indicates the separation between guided P- and S-waves (higher-order Rayleigh modes). The highest S-wave velocity (2000 m/s) is inferred from the Rayleigh wave phase velocity panel (Figure 2a).

![Figure 2](image)

Figure 2 a) Rayleigh-wave phase velocity distribution along the line (event 1 in Figure 1b); b) Guided-wave phase velocity distribution along the line. The black contour line indicates the separation between guided P-waves (below) and guided S-waves (above).

Near-surface characterisation

The inversion of phase velocities gives us access to the medium velocities. There are two challenges with dispersion curve inversion:

1. Curve inversion needs identification of the order 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 Rayleigh mode for S-waves.

2. Guided P-waves can interfere with converted-wave modes. In this case, mode identification is difficult because the dispersion curves split into short pieces.

To address these challenges, we follow the approach proposed by Ernst (2007), which involves minimising the determinant of the stiffness matrix (an implicit function whose zeros are solution of the secular function and correspond to modal curves). In particular, we consider the misfit function proposed by Maraschini et al. (2010) based on the Haskell-Thomson matrix method adapted to take into account leaking modes (Boiero et al. 2009).

This misfit function allows Rayleigh and guided modes to be inverted without the need to associate experimental data points to a specific mode, thus avoiding mode misidentification errors in the retrieved velocity profiles. In Figure 3, we show the S-wave (Figure 3a) and the P-wave (Figure 3b) velocity model along the receiver line. The two sections are inferred from the phase velocities (Rayleigh and guided waves) estimated at each location in Figure 2.
Modelling and coherent-noise attenuation

Once the spatial distribution of the coherent noise properties is known, it is possible to generate a noise model. Ernst and Herman (2000) showed that the propagation of a guided wave $\rho$ for a given frequency $\omega$ can be written as a sum of laterally propagating modes:

$$\rho(x, \omega, s) = \sum_m \phi_m(z, \omega, x_h) A_m(x_h, \omega, s_h) \exp[-i\omega\tau_m(x_h, \omega, s_h)] \phi_m(s_z, \omega, s_h)$$

(1)

where $x$ and $s$ are spatial coordinates, $x_h$ and $s_h$ are horizontal coordinates, and $z$ and $s_z$ are depths of receivers and sources, respectively. The kinematic aspects of guided-wave propagation follow from the traveltimes $\tau_m$, which can be computed from the phase velocity fields (Figure 2). The geometrical spreading, the intrinsic attenuation and the leakage are accounted for in the amplitudes $A_m$. The local structure of the medium beneath source and receivers (Figure 3) follows from the modal amplitudes $\phi_m$.

The predicted noise model can be then (adaptively) subtracted from the data. The current example is a 2D data set, but the propagation of guided waves in 3D can be simulated using horizontal ray tracing of the phase and amplitude term. The local amplitude perturbations $\phi_m$ are predicted via matching. The coherent noise is modelled considering each dispersive event (Figure 1b), and in the following example, both Rayleigh and guided waves are considered. Figure 4 shows the input data, the filtered data, and the noise model. The subtraction effectively removes the modelled noise, preserving the signal, as shown in Figure 4b. Non-direct events (side scattering and back scattering) are not modelled. This approach makes it possible to model spatially aliased noise (Strobbia et al. 2011).

In Figure 5, we show how this approach can be used to attenuate the shingled guided waves that mask reflections at far offsets. Both events have a similar linear velocity and conventional velocity discrimination methods do not work properly in these cases. The white arrow indicates the reflected event before (Figure 5a) and after (Figure 5b) the subtraction of the modelled guided waves (Figure 5c). In Figure 5a and Figure 5b, the noise crossing the seismic gather is due to the air wave coming from another shot and its removal is outside the scope of this work.

Conclusions

We analyse guided waves jointly with ground roll to characterise near-surface properties. In particular, by extracting guided wave and ground roll phase velocities and inverting them, we can build consistent S- and P-wave velocity models. The results can be used to complement or substitute refraction methodologies for near-surface characterisation.

The inferred guided wave properties are then used to design and optimize the filtering workflow. We show how the dispersive coherent noise is modelled and filtered by subtraction while preserving the signal, even when velocity discrimination methods do not work properly. This can improve AVO analysis because it attenuates the coherent noise that masks reflection events at far offsets.

Figure 3 Near-surface model obtained from phase velocities in Figure 2: a) S-wave and b) P-wave velocities.
**Figure 4** Example of attenuation for Rayleigh and guided waves: a) input; b) output; c) noise modelled.

**Figure 5** Example of attenuation of guided waves at far offset: a) input; b) output; c) noise modelled. The noise crossing the seismic gather is due to the air wave coming from another shot.

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**References**


