Rayleigh-wave filtering through phase-velocity dispersion inversion and modeling: application to north Kuwait 3D seismic field data

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SUMMARY

Land seismic data are often plagued with substantial amounts of coherent surface-related noise that blurs the reflection signals needed for imaging of the deeper lying targets. Such waves typically consist of a combination of Rayleigh-waves, Love waves, and guided P and S waves. Here we present a method that uses the phase-velocity dispersion of un-scattered Rayleigh waves to first invert for the near-surface (shear-wave) velocity. Once a model is obtained that accurately fits the locally observed phase-velocity dispersion, the resulting modeled dispersion can be used to calculate the travel-times and amplitudes of Rayleigh-waves as a function of frequency and mode number. In this way the un-scattered Rayleigh waves can be modeled in a laterally and vertically varying medium. This then allows an adaptive subtraction procedure to remove the undesired Rayleigh wave signal. The benefit of this method is that it is not affected by aliasing of the signal and as such allows removal of aliased Rayleigh waves.

INTRODUCTION

Land seismic data are usually of a lesser quality than such marine data. A substantial contributing factor to this difference in quality is usually the presence of a complex near-surface earth structure filled with often highly heterogeneous unconsolidated rock. Therefore it becomes important to try and estimate the near-surface velocity structure, such that the hampered imaging of the deeper lying targets can be improved by correcting for the near-surface velocity structure. Recently Jones (2012) presented an overview of the current industrial practice for building complex near-surface models.

Surface waves sample the near surface well and they can be used to estimate the near-surface properties. It is well known that the phase-velocity of Rayleigh waves is predominantly sensitive to the shear-wave velocity and can thus be inverted to obtain a near-surface shear-wave velocity model. This model can, for example, be used to calculate receiver statics in converted wave surveys (e.g., Haney & Douma (2012)). At the same time, the phase-velocity of guided P-waves can be inverted to obtain the P-wave velocity (e.g., Boiero et al. (2013)).

From a conventional imaging perspective, however, surface waves are still considered undesirable noise. Once the surface waves have been used to obtain a near-surface model, this model can be used to predict the surface waves. This allows a model-based (adaptive) subtraction of the surface waves, both for fundamental and higher modes (e.g., Strobbia et al. (2010) and Strobbia et al. (2011)). Knowing that the fundamental mode is often aliased given typical acquisition geometries, this approach benefits from the possibility to model and subtract even the aliased part of the surface waves.

RAYLEIGH-WAVE PHASE VELOCITY DISPERSION INVERSION

We first invert the phase-velocity dispersion curves for a near surface shear-wave velocity model. The phase-velocity spectra are obtained using beam forming (e.g., van der Kruk et al. (2007)). Figure 1 shows the obtained spectra for several shots along a line of shots in a North Kuwait 3D seismic survey. The data were recorded without any in-field array forming and using point receivers. The acquisition geometry for this particular survey had relatively small in-line receiver and shot spacing of 10 m. The spectra clearly show the presence of the fundamental mode Rayleigh wave over a bandwidth of 4-28Hz. The picked phase velocities here range from about 350-700 m/s. Some higher modes can also be observed.

Figure 2 shows the picked phase-velocity dispersion curves as a function of the shot location along the line. The frequencies are plotted on the vertical axis from high on the top, to low on the bottom. Since the penetration depth of surface waves is proportional to the frequency, such plots are usually referred to as pseudo-depth sections. On top of the pseudo-depth section a QC measure is plotted that provides a quality control on the automatic picking of the dispersion curves. There are two areas where the quality of the dispersion curves is not very good as indicated in Figure 2. Poor quality of the picked dispersion curves can
usually be attributed to scattering of the surface waves, attenuation, or mode jumping. An anomalous area with much lower phase-velocities can be observed between shot locations 100 and 150. The QC measures don’t indicate a significant problem with the picking. These lower phase-velocities are caused by the presence of a near-surface channel running across the shot line.

Figure 3a) shows $\chi^2/N = 1/N \sum_{i=1}^{N} (v_{i}^{ob}_i - v_{i}^{mod}_i)^2 / \sigma_i^2$ where $N$ is the number of frequencies, $v_{i}^{ob}_i$ and $v_{i}^{mod}_i$ are the observed (i.e. picked) and modeled phase velocities for the $i$-th shot location, and $\sigma_i$ the associated standard deviation. This provides a measure of the misfit of the modeled and observed phase velocities. If $\chi^2/N < 1$ all data are fit within one standard deviation. Figure 3b) shows the inverted shear-wave velocity model. Since there are several shot locations where the inversion could not fit the data, as evident from the locations with high $\chi^2/N$ values in Figure 3a), we reject all inverted models from shot locations where $\chi^2/N > 1.5$ as shown in Figure 3c). Subsequently, we

![Figure 2](image2.png)  
*Figure 2. Pseudo-depth section, i.e. the picked phase-velocity dispersion curve plotted along the shot line. On top a QC measure is displayed that indicates a level of confidence associated with the picked dispersion curves. The area of low phase velocity between source location 100 and 150 can be traced back to the presence of a surface channel.*

![Figure 3a](image3a.png)  
*Figure 3a. $\chi^2/N$ as a function of source location number indicating the goodness of fit of the modeled dispersion curves (resulting from the inversion) and the measured dispersion curves.*

![Figure 3b](image3b.png)  
*Figure 3b. Near-surface shear-wave velocity model resulting straight from the inversion.*

![Figure 3c](image3c.png)  
*Figure 3c. Near-surface shear-wave velocity model with the source locations with $\chi^2/N > 1.5$ omitted (see red area in subfigure a).*  
*Figure 3d. Resulting shear-wave velocity model with lateral linear interpolation to interpolate the gaps. A lateral smoothing filter of 30m was applied.*
interpolate the missing locations using a horizontal interpolation and apply a 30m-wide running mean filter to obtain the final shear-wave velocity model shown in Figure 3d).

**RAYLEIGH-WAVE FORM WAVE MODELING**

Once a shear-wave velocity model has been obtained the modeled phase-velocity dispersion curves can be used to make maps of the lateral phase-velocity variation for each frequency and each mode. An example of such a map is shown for one frequency and for the fundamental mode in Figure 4. Then, using an eikonal solver and ray tracing, the frequency dependent travel-times and geometrical spreading can be estimated; Figure 4 shows an example with several isochrons of the travel-times for a given mode and frequency, as well as several associated rays from the source to the receiver locations. These in essence determine the lateral propagation part of the Green function of the Rayleigh waves. Once the travel-times and geometrical spreading are obtained, they can be used together with the mode-shapes and an estimate of the source time function to model the Rayleigh waves. An alternative to using the modeled dispersion obtained from the inverted shear-wave velocity model, one can also directly use the measured phase-velocity dispersion to calculate the travel-times and geometrical spreading as just outlined. Finally, we mention that recently Ernst (2013) showed that the lateral propagation part of the Green function can also be calculated using a finite difference solution to the Helmholtz equation with the dispersive phase-velocity maps as the velocity field.

**RAYLEIGH-WAVE FILTERING**

Figure 5a) shows one shot-gather from a North Kuwait 3D seismic dataset. The data have been trace-balanced and gained for display purposes. The fundamental mode Rayleigh-wave dominates the gather and is aliased due to the relatively low group- and phase velocities in relation to the spatial sampling of the receivers (10m). A higher mode Rayleigh wave can also be observed. Figure 5b) shows the modeled fundamental mode Rayleigh wave, while Figure 5c) shows the result from the adaptive subtraction. The fundamental mode Rayleigh wave has been successfully

![Figure 4. Example phase-velocity map (as a function of spatial horizontal grid locations) for the fundamental mode at a frequency of 3Hz with superposed several isochrons of travel-times as well as several rays traced from a source to 4 receiver lines. Even though this phase-velocity map was created from a near-surface P-wave velocity model for a field dataset not related to the dataset used throughout the remainder of this abstract, it suffices to illustrate the method. The final model shows a very low shear-wave velocity near the surface of about 200 m/s. Furthermore, there appears to be a high shear-wave velocity layer at elevations between 20 and 50 m. And the near-surface channel previously observed in the pseudo-depth section is evident by a thicker low shear wave velocity near the surface between shot locations 100 and 150.](image)

![Figure 5. a) Shot-gather showing aliased fundamental mode Rayleigh waves and at least one higher mode. b) Modeled fundamental mode Rayleigh wave. c) Result of adaptive subtraction of modeled Rayleigh wave. The aliased fundamental mode Rayleigh has been completely removed and some coherent energy underneath it has been recovered. All data are plotted using trace-balancing.](image)
removed and some underlying coherent energy has been recovered. As a next step, the higher mode Rayleigh wave could be modeled and subsequently removed from the data. We are currently processing the whole 3D survey in this manner to estimate the impact of the method on the final stacked image.

When the Rayleigh waves are largely scattered and the unscattered part has a poor signal-to-noise ratio, it is difficult to estimate the phase-velocity dispersion reliably. In that case the method breaks down. As such the method relies on the presence of un-scattered Rayleigh waves with a high signal-to noise ratio that allow reliable picking of the dispersion curves.

CONCLUSION

Using the shear-wave velocity model obtained from phase velocity dispersion curve inversion, the modeled dispersion can be used to calculate the travel-times and amplitudes necessary to model Rayleigh waves in (smoothly) laterally varying media. The modeled Rayleigh waves can be used in an adaptive subtraction procedure to attenuate these waves in the field data. The method allows filtering of aliased Rayleigh waves as opposed to velocity-based filtering methods.

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