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Estimation of the P-wave Velocity Profile of Elastic Real Data Based on Surface Wave Inversion

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SUMMARY

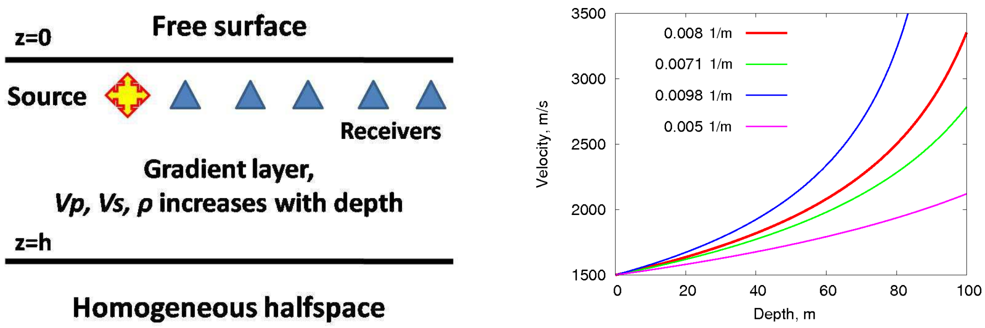
Recently, we proposed an analytical approach to invert for a smoothly varying near-surface P-wave velocity profile that has a squared slowness linearly decreasing with depth. The exact solution for such a velocity profile in the acoustic approximation can be expressed in terms of Airy functions and leads to a dispersion equation. The method was successfully applied to synthetic elastic data with small Vs/Vp-ratio. Here, we apply the method to land data. The result agrees with that of multi-layered inversion, confirming its potential to provide an initial P-wave velocity model for acoustic full waveform inversion. Compared to multi-layered inversion, the method is simpler to use and produces a smooth model characterized by three parameters. In some cases, having a smooth rather than a blocky initial model for full waveform inversion is more appropriate.

Introduction

Recently, we proposed an analytical approach to invert for a smoothly varying near-surface P-wave velocity profile that can serve as a starting model for full waveform inversion (Ponomarenko et al., 2013), together with the usual S-wave profile that can be estimated from the Rayleigh waves. We used a vertical velocity profile that has a squared slowness linear with depth together with a free-surface boundary condition and approximated the elastic equations by an acoustic one, because if the V_s/V_p-ratio in the near surface is small, the P-waves can be distinguished from the Rayleigh waves. For such a velocity profile, the exact solution in the acoustic case can be expressed in terms of Airy functions (Brekhovskikh, 1980). Using this representation, we obtained a dispersion relation similar to the multi-layered case (Socco et al., 2010) and inverted it for the gradient parameter of the squared P-wave slowness by direct minimization, which doesn't depend on modal number (Maraschini et al., 2010). The method was illustrated by inverting 2-D synthetic elastic data with small V_s/V_p-ratio to obtain the P-wave velocity profile. Here, we apply the method to real land data of unspecified origin.

Review of the method

Ponomarenko et al. (2013) derived the dispersion relation for surface P-waves in a 2-D acoustic model with a layer that has a linear vertical decrease of the squared slowness on top of a homogeneous halfspace. A free-surface boundary condition was imposed. The velocity in the layer was $v_1(z) = v_0[1-az]^{-1/2}$. The halfspace below started at a depth h and had a constant velocity $v_2 = v_1(h)$, so there is no velocity jump. Also, there is no density jump. The elastic version of this model is sketched in Figure 1(a). Figure 1(b) shows the V_p velocity profiles for the different values of the gradient parameter.



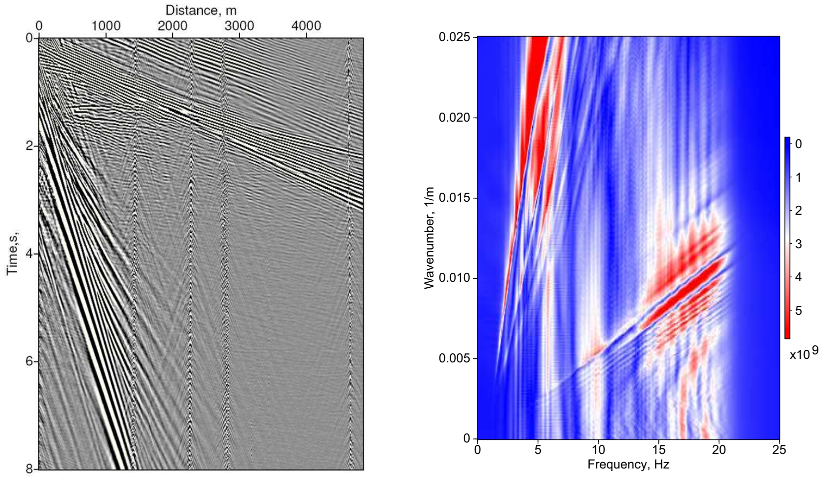
(a) (b)

Figure 1 *(a) Geometry of the model and (b) V_p velocity profiles for different values of the gradient parameter.*

The easiest way to obtain a P-wave velocity profile is to estimate the gradient parameter, a. We look for the minima of misfit functionals of the form

$$F_j(a) = \sqrt{\sum_i D_{ij}^2(f_{ij}, V_{ij}, a)}. \quad (1)$$

Here, D_{ij} is the value of the dispersion equation, computed for a frequency f_{ij} and dispersion velocity V_{ij}; i is the index of a point on the dispersion curve and j is the number of the picked dispersion curve or mode. The misfit functional, $F_j(a)$, can be minimized with Newton's method. In the synthetic example analyzed earlier (Ponomarenko et al., 2013), $D_{ij} = 0$ for the true value of the gradient parameter, assuming that the true values of V_0 and h are known, and the global minimum could be readily found. In the present case with real data, there are several local minima and the global minimum will not have a zero value. We will therefore search for the value of gradient, a, for which the local minima of the functionals for each picked curve lie close to each other.



(a) (b)

Figure 2 *Real-data seismogram in the (a) x,t-domain and (b) f,k-domain.*

Real data example

We applied the method to the pre-processed vibroseis data shown in Figures 2(a) and 2(b). The geophone data represent the vertical particle velocity. Their P-wave component can be approximated by an acoustic model with a pressure source just below the free surface and with receivers at the same depth. It is clear from the seismogram that the V_s/V_p-ratio is small. The P-waves can be easily distinguished from the Rayleigh waves. In the synthetic example considered earlier (Ponomarenko et al., 2013), there were two sets of spectral maxima, one corresponding to the dispersion curves of the Rayleigh-waves and one related to the P-waves. These two groups are also visible in the real data. We will focus on the second set of curves. These dispersion curves show up as nearly straight lines, which is also the case in the chosen analytical model over a wide range of parameters. We picked the main dispersion curves as straight lines, drawn in Figure 3.

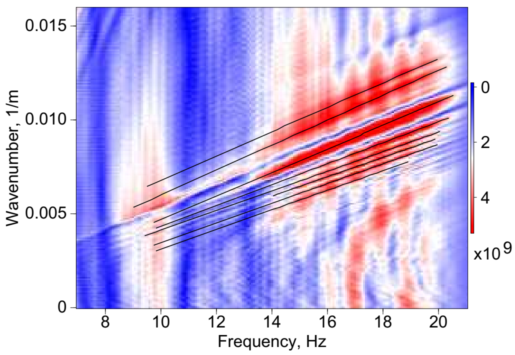


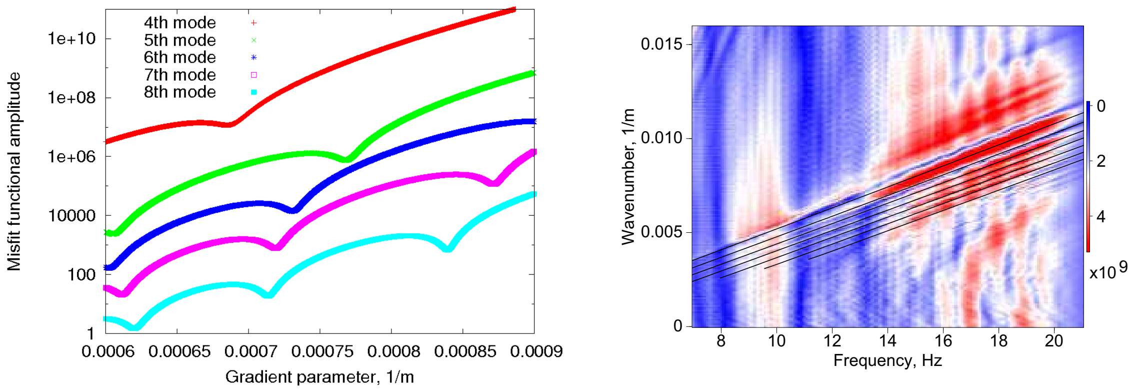
Figure 3 *Maxima of the real-data seismogram in the f,k-domain with picked dispersion events. The three events at the higher wavenumbers will be referred to as the 'high' modes and the closely spaced events at the lower wavenumbers as the 'low' modes.*

The picked events, a total of eight curves, are marked from high wavenumbers to low wavenumbers. The curves can be split into two groups that can be explained by different set of parameters. One group, corresponding to the higher wavenumbers or shorter wavelengths, will be referred to as the 'high' modes and consist of modes 1, 2 and 3. The others are the 'low' modes. Mode nr. 3 corresponds to the broad and pronounced dispersion curve and might also belong to the 'low' modes. The analytical model can explain each group with a different set of parameters, but not both simultaneously. The low modes have seen a deeper part of the model and correspond to higher velocities than the high modes. We can make separate data fits with our model to these two groups of modes.

For the low modes, we found that $V_0 = 1.75\,\text{km/s}$, $h = 0.95\,\text{km}$ and $a = 0.000723\,\text{m}^{-1}$ provided a reasonable data fit. Figure 4(a) plots the value of the functional for the five picked low modes as a function of the gradient parameter a for fixed $V_0 = 1.75\,\text{km/s}$ and $h = 0.95\,\text{km}$. The mode numbers in the figure legend correspond to the picked modes. Each curve has local minima at different values of the gradient parameter. For the average $a = 0.000723\,\text{m}^{-1}$, these local minima are sharp and close to each other, which is not true for other values of a. Figure 4(b) displays the seismogram in the f,k-domain. The drawn dispersion curves are solutions of the dispersion equation for the estimated parameters.

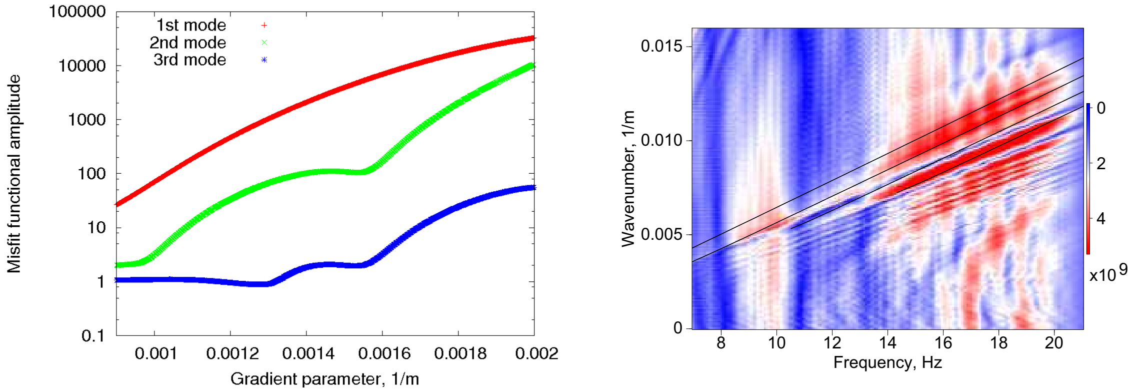
We analyzed the high modes in the same way. Figure 5(a) shows the misfit functionals, similar to Figure 4(a), and Figure 5(b) the dispersion curves obtained for $V_0 = 1.35\,\text{km/s}$, $h = 0.35\,\text{km}$ and $a = 0.00153\,\text{m}^{-1}$.

Finally, Figure 6 compares the resulting V_p-velocity profiles for the two groups. The red line represents the result of multi-layered inversion. The results of our method agree well with the reconstructed multi-layer model, with the high modes being more accurate in the shallower and the low modes in the deeper part.



(a) (b)

Figure 4 *(a) Misfit functionals for the low modes and (b) predicted modal structure with the estimated parameters.*



(a) (b)

Figure 5 *(a) Misfit functionals for the high modes and (b) predicted modal structure with the estimated parameters.*

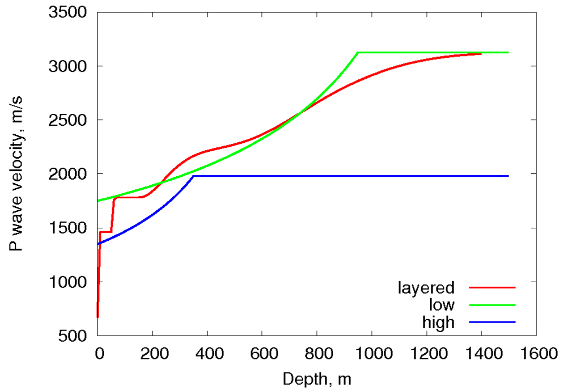


Figure 6 *Estimated V_p velocity profiles for the high (blue) and low (green) modes, together with the multi-layered inverted profile (red).*

Conclusions

We have used an analytical acoustic model with a gradient in the squared slowness to estimate the P-wave velocity profile from land data. Dispersion curves were picked in the f,k-domain. These curves could be explained by two different profiles, one corresponding to the shorter wavelengths and shallower part, the other to the longer wavelengths and deeper part. Both profiles agree with a more detailed multi-layered inversion result in their respective depth ranges. This demonstrates that out method has the potential to provide a P-wave initial model for more advanced model inversion schemes, such as acoustic full waveform inversion. The method is simpler than a multi-layered inversion algorithm and produces a smooth model characterized by three parameters. In some cases, it is a better to start full waveform inversion from a smooth rather than a blocky initial model.

Acknowledgements

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