

A method for P-P and P-S mode separation in the presence of statics

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Summary

A method to separate P-P and P-S wave modes in the presence of near-surface P and S statics is applied to synthetic and real 2-D land data. The method uses the free surface response and information about statics to separate the wavefields in the ω - p domain. More continuity can be observed in stacked sections of real data after mode separation. We believe that the method could contribute to velocity analysis and stacking, and hence to better seismic sections.

Introduction

A basic aim of the converted-wave method is to obtain two independent seismic sections, one with P-P waves and the other with P-S waves. It is usual to assume that the vertical component records the data of P-P waves and the horizontal component records P-S waves. However real data shows that there is mode leakage between the two components. The free surface effect explains the leakage: the free surface is a reflector; thus, reflected and converted modes are generated and both P-P and P-S events are detected by the vertical and horizontal components (depending on the elastic properties of the near-surface, and the incidence angle).

From the free surface effect can be defined coefficients of the relative amplitude response for vertical and horizontal components as a function of the V_p and V_s velocities and the incidence angle.

Methods have been proposed to separate wave modes using the free surface effect (or "geophone response") equations. For example, Dankbaar, (1985) uses the free surface response equations in the f - k domain, and Donati (1996) performs a similar type of separation in the τ - p domain. Both of these methods assume that a constant-velocity layer exists just below the surface.

However, land surface data is usually strongly affected by statics due to heterogeneous near-surface layers. Moreover, the receiver statics for P-waves and S-waves are very different from each other, so it is impossible to apply one set of statics to simultaneously remove the effect of the heterogeneous layers for both wave types.

Receiver gathers on land data usually suffer from data aliasing so shot gathers (with variable receiver statics) must be analyzed. A method is required which takes account of the statics problem on shot gathers while separating modes.

The theory for such an algorithm has been proposed by Cary (1998). It makes use of the free surface response and the horizontal variation in velocities of the near surface layer. Thus, in principle, this method can be applied advantageously to land data in the shot domain.

Theoretical background

The free surface reflection coefficients, when multiplied by the amplitude of the incident wave, allow the calculation of the resultant either in the vertical or horizontal direction. Therefore, the vertical and horizontal displacements can be defined as a "forward problem" represented by

$$D_V = R_{PV} U_P + R_{SV} U_S \quad (1a)$$

$$D_H = R_{PH} U_P + R_{SH} U_S \quad (1b)$$

where R_{PV} , R_{SV} , R_{PH} , R_{SH} are the reflection coefficients of the free surface, P and S identify the wave modes, V and H the vertical and horizontal components, U_P , U_S are the incident P and S wave fields, and D_V , D_H are the recorded vertical and horizontal data.

These equations can be defined in terms of the ray parameter p . Therefore equations (1a) and (1b) can be represented in the τ - p domain. The propagation of plane waves through the heterogeneous near-surface layer, interaction with the near-surface, and plane-wave synthesis (Cary, 1998) can be represented for each frequency as

$$\mathbf{D} = \mathbf{B} \mathbf{U} \quad (2)$$

where \mathbf{D} is a $2NX$ -length vector with the horizontal and vertical input data in the ω - x domain (NX is the number of receivers), \mathbf{B} is a matrix whose elements are the product of the appropriate free-surface response, R , a P-wave or S-wave static delay, $\exp(i\omega\Delta\tau_{p,s})$, and a plane-wave delay, $\exp(i\omega p x)$, and \mathbf{U} is a $2NP$ -length vector with the separated P and S wavefields in the ω - p domain (NP is the number of p values).

Thus the separated wavefields in the ω - p domain below the near-surface layer can be found by applying generalized linear inversion to equation (2):

$$\mathbf{U} = (\mathbf{B}^H \mathbf{B})^{-1} \mathbf{B}^H \mathbf{D}, \quad (3)$$

which constitutes the basic procedure of the algorithm.

Synthetic data separation

A simple two-layer geological model was used to test the method with synthetic data. The near-surface layer has $V_p = 1000$ m/s and $V_s = 500$ m/s, and the second layer has $V_p = 1850$ m/s and $V_s = 925$ m/s. The interface is 400 m below the surface. For convenience, only the right half of the spread was calculated and the interfering effects of direct waves and ground roll were eliminated. A simple time shift was assumed, to simulate the statics effect, which varies horizontally along the line in three segments. The near surface velocities were calculated from the statics, assuming a constant thickness of 20 m. The original shot gathers are illustrated in Figure 1.

The results of the application of the method are shown in Figure 2. In Figure 2a the separated P-wave reflection and the S-P converted wave are visible. In Figure 2b the separated P-S converted wave and the pure S wave are visible.

Real data mode separation

The method was applied to real data from the seismic survey Blackfoot III (Hoffe et al, 1998). This was an experimental 3C-2D seismic line acquired over an oil field belonging to Pan Canadian, 60 km SE of Calgary, Canada.

The length of the line was 3 km, with shots and receivers located every 20 m. Thus there are 151 receivers. A subset of the data, 29 shots separated by 100 m, were used to test the method. Thus the spread is more typical of standard land multicomponent surveys, where the distance between sources is larger than the distance between receivers. The nominal charge depth was 18 m. The total record length was 2.5 s. To reduce the computational cost, the original data, with 1 ms sampling interval, was resampled to 4 ms. The original nominal fold of 100 was reduced to 20. As an initial step, the rotation of the data to get the optimum radial component was performed (shear-wave splitting was not observed). An example of the raw data for the vertical and radial components is illustrated in Fig. 4.

Application to prestack data

Near-surface velocities were estimated from the receiver statics, assuming a near-surface layer of 20 m. The resulting velocities are shown in Fig. 3. Taking into account the uncertainties of the method, these velocities were compared with the results of two other sources of information, the near-surface work of Cieslewicz (1999) on the same line and the drilling information reported by the acquisition crew, with reasonable agreement (Fig. 3).

The result of the application of the method to the shot in Figure 4 is illustrated in Figure 5. The filtering effect of the tau- p transform, related to the chosen range of slowness, is

very noticeable. In order to see the effect of the tau- p transform and statics only, the algorithm was applied without the effect of the conversion coefficients R . To do that, constant coefficients were assumed:

$$R_{PV} = R_{SH} = 1, \text{ and } R_{PH} = R_{SV} = 0.$$

The observed differences between the results were subtle, which is not surprising with noisy prestack data. The test did show, however, that the impact of the free-surface coefficients is relatively small in the inversion procedure.

Results on poststack data

A simplified version of the processing flows used at the CREWES Project for research purposes (Lu et al, 1999) was applied in order to see the effects of the mode separation on stacked data.

The S-wave processing results are compared in Figure 6, which is a close-up of the complete line. Figure 6a shows the result without mode separation and Figure 6b shows the result with mode separation. Although the quality of the data is not homogeneous along the section, more continuity can be observed on some reflections after separation, as illustrated by the arrows. The difference between the two sections can be attributed only to the free-surface coefficients.

Conclusions and future work

These tests show that the algorithm proposed by Cary (1998) works well for mode separation of synthetic data affected by statics. The effect of mode separation is hard to determine on real prestack data; however, increased continuity on some events does appear on poststack data.

The speed of computation is determined by the inversion of matrix \mathbf{B} , which is slow because it does not have many symmetry properties. More work is needed to improve the efficiency of the algorithm. The method can be explored to increase the information content of the P- and S-wave sections including the statics corrections.

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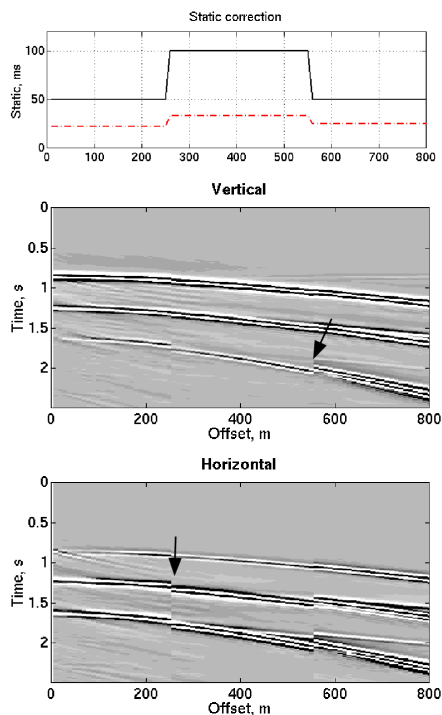


Figure 1. Synthetic data with statics applied. The upper figure illustrates the statics shift, a continuous line for P-S wave and a dashed line for P wave. The arrows indicate the shifting.

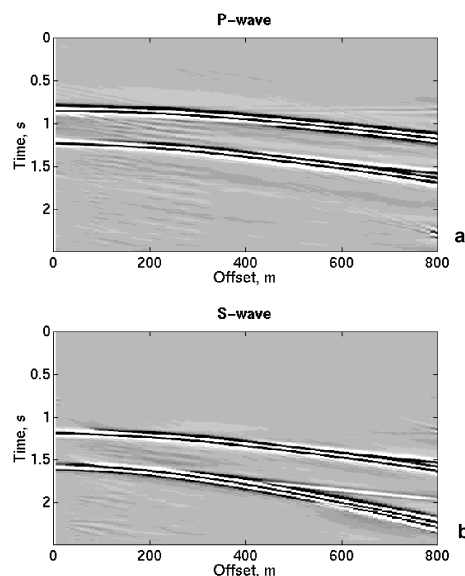
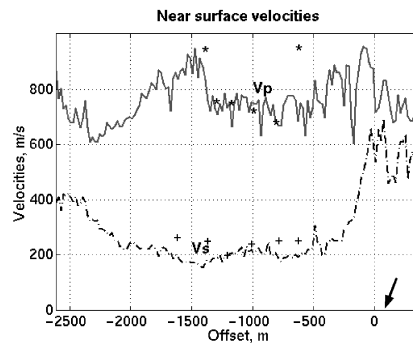


Figure 2. Results of separation on synthetic data. (a) is the P wave and (b) the P-S wave

Figure 3. Near surface velocities in Blackfoot III, based on statics corrections. The offsets correspond to the shot used as an example in Figs. 4 and 5. Information of velocities from Cieslewitz (1999) is illustrated by plus symbols (Vs) and asterisks (Vp). The arrow indicates a sandstone outcrop.



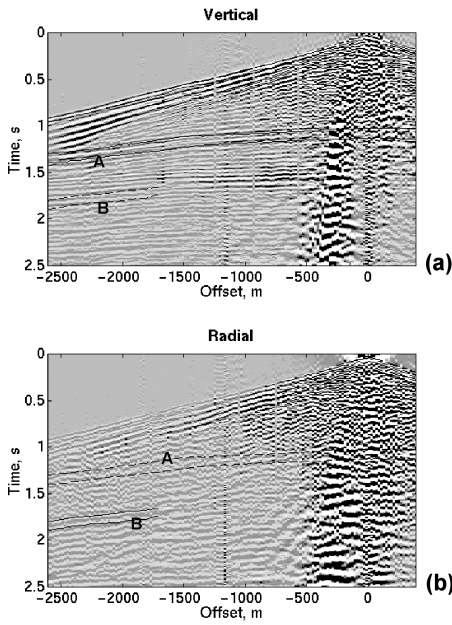


Figure 4. Real data, shot gather from Blackfoot III. Two reference events are labelled A and B.

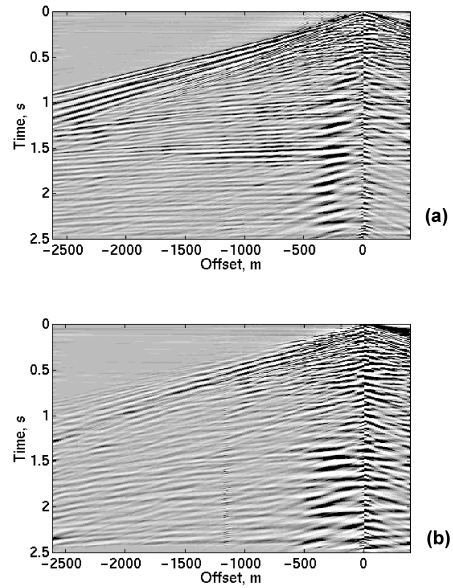


Figure 5. Real data after mode separation. (a) P wave, (b) S wave.

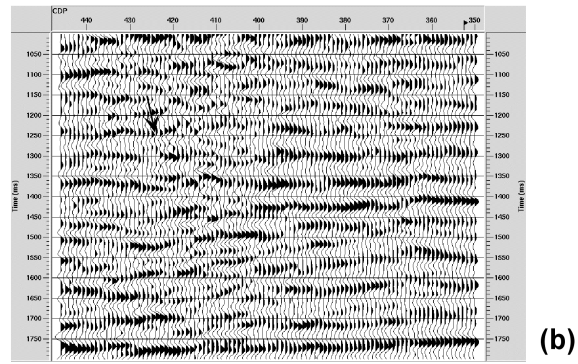
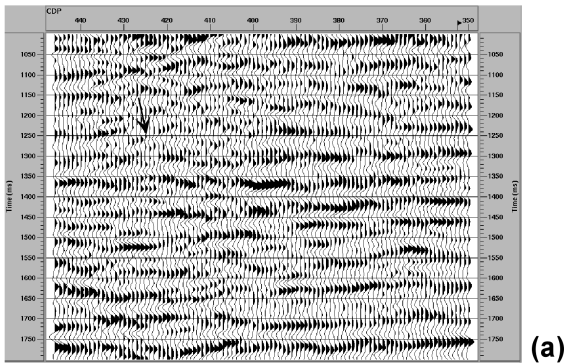


Figure 6. Close-up of the S wave stacked section, (a) without mode separation and (b) with mode separation. The arrow indicates an example of improvement in the continuity of the data.