Suppression of water-column multiples by wavefield separation techniques

Y. Yan and R. James Brown, CREWES Project,
Department of Geology and Geophysics, University of Calgary

Summary

We use wavefield separation techniques to decompose wavefields into up- and downgoing parts in order to suppress water-column multiples in ocean-bottom seismic (OBS) data. The primary reflections are contained entirely in the upgoing wavefield while the great majority of the multiple energy caused by receiver-side reflections at the free surface is contained in the downgoing wavefield. After removal of the downgoing wavefield, however, source-side multiple energy remains as part of the upgoing wavefield. In laterally homogeneous cases, source-side multiples will have raypaths that are equivalent in length to those of corresponding receiver-side multiples. So the two types of multiple are recorded simultaneously. We exploit this circumstance to devise a method, based on cross-correlation, to further attenuate the source-side multiple energy.

Introduction

Recorded wavefields in OBS data can be grouped into downgoing and upgoing wavefields, according to the direction of arrival. The downgoing wavefield contains the direct wave, receiver-side free-surface multiples and water-column reverberations, while the upgoing wavefield contains all the primaries, source-side ghosts and internal multiples. Since the primary reflections are contained only in the upgoing wavefield, extraction of the upgoing wavefield can be used to suppress the downgoing multiples, while still preserving the amplitudes of primary reflections.

Several researchers have worked on wavefield separation: (for example Amundsen and Reitan, 1995; Osen et al., 1999; Schalkwijk et al., 1999) and have combined hydrophone and geophone data in different ways to lead to different wavefield-separation formulae for various applications.

However, simply extracting the upgoing wavefield cannot eliminate the source-side water-column multiples or any multiples generated solely below the seafloor. The source-side and receiver-side water-column multiples arrive from both above and below. In cases of lateral homogeneity, source-side multiples will have raypaths that are equivalent in length to those of corresponding receiver-side multiples, so the two types of multiple are recorded simultaneously. In vertical-geophone data, these two contributions can have similar energies but opposite polarities, which attenuates the multiples by destructive interference before any wavefield separation (Brown and Yan, 1999). Then a source-side free-surface multiple would be stronger on the upgoing vertical-geophone trace after separation than on the actual recorded trace. Such strong source-side multiples in the upgoing wavefield need to be suppressed by other means.

This paper will analyze the multicomponent wavefield-separation technique for multiple attenuation and describe how the source-side multiples can be further removed from the separated upgoing wavefield. Numerical examples are provided for illustration.

Description of methods

The wave equation can be expressed in the form of a first-order ordinary differential equation in stress and velocity (Aki and Richards, 1980):

$$\frac{d}{dz}\mathbf{B} = -i\omega\mathbf{A}\mathbf{B}, \tag{1}$$

where **B** is the vector that contains the stress and velocity variables across a planar elastic/elastic interface, and

$$\mathbf{B} = (V_3, S_1, S_2, S_3, V_1, V_2)^T, \tag{2}$$

where V_1 and V_2 are horizontal components of particle velocity; V_3 is the vertical component of particle velocity; S_3 is the normal component of traction in the solid; S_1, S_2 are the tangential components of traction in the solid; z is depth, positive downward; ω is angular frequency, and **A** is the elastic-system matrix.

The wavefield separation can be obtained by eigenvalue decomposition of the matrix **A**, that is, $\mathbf{A} = \mathbf{L}^{-1}\,\boldsymbol{\Lambda}\,\mathbf{L}$, where **L** is the matrix composed of eigenvectors of matrix **A** and $\boldsymbol{\Lambda}$ is the diagonal matrix composed of the eigenvalues of **A**. Then, equation (1) can be written (Amundsen and Reitan, 1995) as:

$$\frac{d}{dz}\mathbf{B} = -i\omega\mathbf{L}^{-1}\Lambda\mathbf{L}\mathbf{B}. \tag{3}$$

It can be shown that $\mathbf{\Lambda}$ can be written as:

$$\Lambda = \text{diag}\left(q_P, q_{SV}, q_{SH}, -q_P, -q_{SV}, -q_{SH}\right). \tag{4}$$

The physical meaning of equation (4) is that eigenvalues q_P, q_{SV}, q_{SH} correspond to the upgoing waves, whereas eigenvalues $-q_P$, $-q_{SV}$, $-q_{SH}$ correspond to the downgoing waves. Therefore, equation (4) can be further decomposed into two matrices that contain either the positive or negative eigenvalues of **A**, which leads to two wave equations corresponding to up- and downgoing waves, respectively:

$$\frac{d}{dz}\mathbf{B}^U = -i\omega\mathbf{L}^{-1}\mathbf{\Lambda}_1\mathbf{L}\mathbf{B} \quad \text{and} \quad \frac{d}{dz}\mathbf{B}^D = -i\omega\mathbf{L}^{-1}\mathbf{\Lambda}_2\mathbf{L}\mathbf{B}. \tag{5}$$

Applying the boundary conditions at the seafloor to equation (5), the upgoing wavefield can finally be expressed (Amundsen and Reitan, 1995) as:

$$U_p(z_1^+) = \frac{\rho(1-2p^2\beta^2)}{q_\alpha}V_3(z_1^+) + S_3(z_1^+) - 2\rho\beta^2(p_1V_1(z_1^+) + p_2V_2(z_1^+)),$$

and

$$U_{sv}(z_1^+) = 2\mu(\rho q_\beta)^{1/2}V_3(z_1^+) + pS_3(z_1^+) + \frac{\mu(q_\beta^2 - P^2)}{p}(p_1V_1(z_1^+) + p_2V_2(z_1^+)), \tag{6}$$

where U is the upgoing wavefield; the subscripts indicate the types of wave; z_1^+ denotes a depth just below the seafloor; α and β are P-wave and S-wave velocities in the solid just below the seafloor, and q_α and q_β are the corresponding vertical slowness components.

In equation (6), the upgoing wavefields are functions of the vertical component of traction and all three components of particle velocity. In practice, not all components are always recorded or processed. In OBS data, for example, sometimes only the hydrophone and vertical-component geophone data are processed. For more practical application, equation (6) can be further derived for every component (Osen et al., 1999):

$$U^W(z_1^+) = \frac{1}{2}\{W(z_1^-) - \frac{\rho}{q_\alpha}[(1-2p^2\beta^2)^2 + 4p^2\beta^4 q_\alpha q_\beta]V_3(z_1^+)\}, \tag{7}$$

$$U^{V_1}(z_1^+) = \frac{1}{2}\{V_1(z_1^+) - \frac{p_1}{q_\alpha}[1-2\beta^2(p^2 + q_\alpha q_\beta)]V_3(z_1^+)\}, \tag{8}$$

$$U^{V_2}(z_1^+) = \frac{1}{2}\{V_2(z_1^+) - \frac{p_2}{q_\alpha}[1-2\beta^2(p^2 + q_\alpha q_\beta)]V_3(z_1^+)\}, \tag{9}$$

$$U^{V_3}(z_1^+) = \frac{1}{2}\{V_3(z_1^+) + \frac{p_1}{q_\beta}[1-2\beta^2(p^2 + q_\alpha q_\beta)]V_1(z_1^+) - \frac{p_2}{q_\beta}[1-2\beta^2(p^2 + q_\alpha q_\beta)]V_2(z_1^+) - \frac{1}{\rho q_\beta}(p^2 + q_\alpha q_\beta)W(z_1^-)\}, \tag{10}$$

where the superscripts indicates the type of components and $W(z_1^-)$ is the pressure just above seafloor. From equation (7) we can see that the pressure wavefield and the vertical particle-velocity wavefield can be represented by each other. We can also see that the upgoing wavefield for pressure can be obtained just by combining the pressure and scaled vertical particle-velocity components, which is the basic idea of the dual-sensor method.

By applying the equations given above, the upgoing wavefield can be separated from the downgoing, effectively suppressing the latter, which contains such arrivals as the direct wave and receiver-side water-column reverberations. However, a lot of source-side multiple energy, arriving as upgoing waves, still remains. This kind of multiple energy needs to be suppressed, especially any free-surface-related multiples that have energy comparable to that of the primaries.

Fortunately, there are receiver-side multiples whose raypaths are equivalent to those of corresponding source-side multiples. The two types of multiples are of comparable energy but opposite polarities on the vertical-component geophone records, and this can be used to further attenuate these multiples. A simple way toward this end is to cross-correlate the upgoing- and downgoing-wavefield data, U and D, respectively, using, in a moving window, the following expression:

$$\psi_{UD}(j) = \frac{\sum_{i=1}^{L} U_{i+j}D_i}{\sqrt{\sum_{i=1}^{L} U_{i+j}^2 \sum_{i=1}^{L} D_i^2}}, \tag{11}$$

where $\psi_{UD}(j)$ is the cross-correlation of U and D in a particular window for a lag of j samples and L is the length of the window.

In view of the identical arrival times (assuming lateral homogeneity) we focus our attention at zero lag. Then the cross-correlation coefficients at samples where the source side multiples appear should approach –1, depending on how close to equality the amplitudes are of the upgoing and downgoing contributions to the multiple. Such large negative values can be used as indicators of source-side multiple energy. The indicated sample positions of source-side multiples can in turn be used to eliminate the multiples in the upgoing wavefields of all the components.

Numerical examples

To test the performance of these methods, we use synthetic seismograms modelled in a plane-layered medium. We use a 2D model with a 500-m water layer and two further reflectors at depth 750 m and 900 m. P-wave velocities are 1500 m/s, 1900 m/s and 2400 m/s, in layers 1, 2 and 3, respectively. The synthetic data are generated by ELMO, an elastic modelling program based on phase-shift cascade method (Silawongsawat and Margrave, 1998). The synthetic pressure, vertical component of particle velocity, and horizontal components of particle velocity are shown in Figures 1, 2 and 3, respectively. Note that primaries are present for events at approximately 0.59 and 0.72 s. The downgoing direct arrival and its reverberations are present for events at approximately 0.33, 1.01 and 1.67 s, respectively. Also notice that source-side multiples arrive both from above and below, at approximately 1.27 s.

After applying wavefield separation techniques, the upgoing wavefields for every component are shown in Figures 4, 5 and 6. Comparing these with Figures 1, 2 and 3, we can see that the multiples belonging to downgoing waves are successfully suppressed. However, the source-side multiple is still present in the upgoing wavefields. After applying the cross-correlation method, this multiple is significantly suppressed. The final upgoing wavefields are shown in Figures 7, 8 and 9, respectively, where only the primaries are well preserved.

Conclusions

The suppression of multiples can be realized by wavefield-separation techniques. Generally, the wavefield separation technique combines the pressure (hydrophone) with horizontal and vertical velocity (geophone) components in proper proportions to gain the upgoing wavefield. However, as a simplification, this technique also can be realized on two data components.

After application of wavefield decomposition techniques, there are still the source-side multiples left in the upgoing wavefield. With cross-correlation of up- and downgoing vertical-geophone wavefields, the source-side multiples can be identified and eliminated.

Acknowledgements

We would like to thank the sponsors of the CREWES project for their support.

References

Aki, K. and Richards, P. G., 1980, Quantitative seismology: W.H. Freeman and Co.

Amundsen, L., 1993, Wavenumber-based filtering of marine point-source data: Geophysics, **58**, 1335-1348.

Amundsen, L. and Reitan, A., 1994, Decomposition of multicomponent sea-floor data into upgoing and downgoing P- and S-waves: Geophysics, **60**, 563-572.

Amundsen, L. and Reitan, A., 1995, Extraction of P- and S-waves from the vertical component of the particle velocity at the seafloor: Geophysics, **60**, 231-240.

Barr, F.J. and Sanders, J.I., 1989, Attenuation of water-column reverberations using pressure and velocity detectors in a water-bottom cable: 59th Annual International Meeting, SEG, Expanded Abstracts, 653-656.

Brown, R. J. and Yan, Y., 1999, Suppression of water-column multiples in multicomponent seafloor data: Preliminary results and proposal: CREWES Research Report **11**, 311-321.

Osen, A., Amundsen, L. and Reitan, A., 1999, Removal of water-layer multiples from multicomponent sea-bottom data: Geophysics, **64**, 838-851.

Schalkwijk, K. M., Wapenaar, C.P.A. and Verschuur, D.J., 1999, Application of two-step decomposition to multicomponent ocean-bottom data: Theory and case study: Journal of Seismic Exploration **8**, 261-278.

Silawongsawat, C. and Margrave, G. F., 1998, The phase-shift cascade method of elastic wavefield modeling: 68th Annual International Meeting, SEG, Expanded Abstracts, 1807-1810.

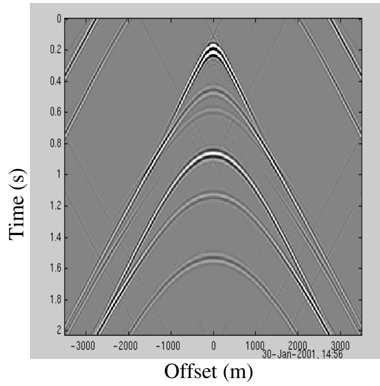

Figure 1. Hydrophone.

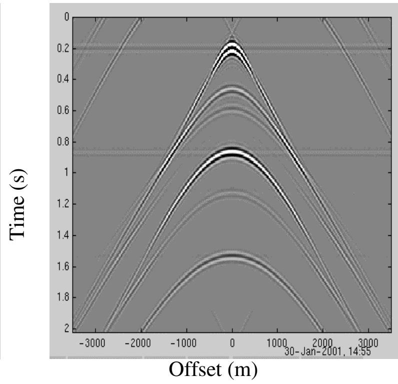

Figure 2. Vertical geophone.

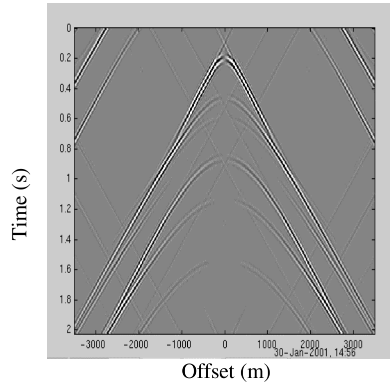

Figure 3. Horizontal inline geophone.

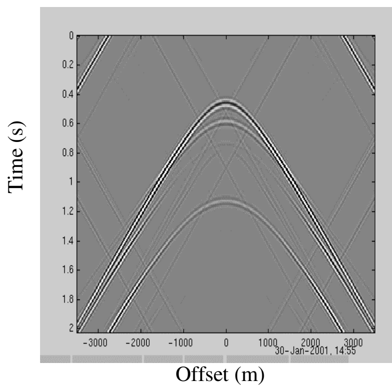

Figure 4. Separated upgoing wavefield: hydrophone.

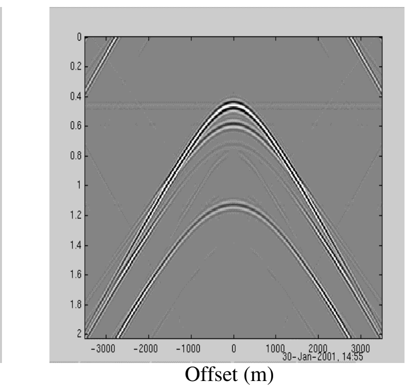

Figure 5. Separated upgoing wavefield: vertical geophone.

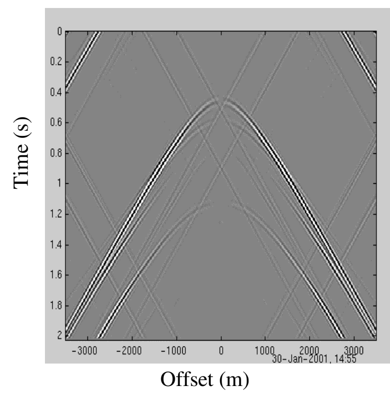

Figure 6. Separated upgoing wavefield: horizontal geophone.

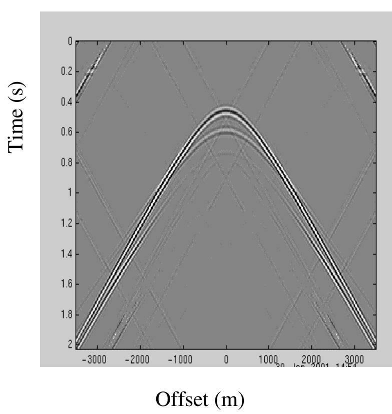

Figure 7. Upgoing wavefield after eliminating source-side multiple: hydrophone.

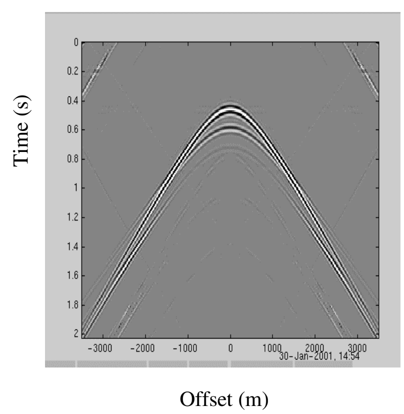

Figure 8. Upgoing wavefield after eliminating source-side multiple: vertical geophone.

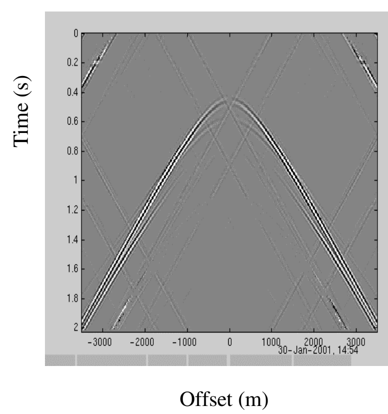

Figure 9. Upgoing wavefield after eliminating source-side multiple: horizontal geophone.