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Ocean-bottom cable data multiple suppression based on equipoise pseudo-multichannel matching filter*

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Abstract: The effect of strong reflection interfaces, such as free surface, seabed, is strong; thus, the coupling of multiples and waves reduces the quality of ocean-bottom cable seismic data. Using the different polarity response of hydrophones and geophones to downgoing wave fields, dual-sensor summation can eliminate receiver-side multiples, enhance primaries, and improve the resolution of seismic data. We present a dual-sensor summation method based on the equipoise pseudo-multichannel adaptive matching filter. Compared with traditional methods, the proposed method is totally data driven and does not depend on the reflection coefficient; moreover, good results are obtained using synthetic and real data.
Keywords: receiver-side multiple, source-side multiple, dual-sensor summation, equipoise pseudo-multichannel matching

Introduction

The dual-sensor (hydrophone and geophone) ocean-bottom cable (OBC) method is currently used to obtain high-quality seismic data in shallow seas and areas with obstacles, such as offshore drilling platforms, where traditional seismic streamers cannot be used. Because of the increased offshore oil and gas exploration in China, OBC data processing methods, especially noise suppression, have attracted attention.

Relative to conventional marine seismic streamers, the OBC method is unique in suppressing multiple reflections by matching hydrophone and geophone data. This technique is called dual-sensor summation. Loewenthal (1985) first proposed the possibility of wavelength separation based on data recorded by hydrophones and geophones. Fred et al. (1989) first suggested a robust dual-sensor summation method, which they called "reflection coefficient method" to eliminate multiples, and confirmed the matching factor $(1+K_r)/(1-K_r)$, K_r as the bottom reflection coefficient. Draggoset and Fred (1994) developed the best matching factor algorithm to directly determine the reflection data,

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and succeeded in minimizing the field processing time and cost. Fred (1997) summarized the OBC dual-sensor summation and discussed spectrum improvements and other technical advantages. In recent years, many researchers (e.g., Soubaras, 1996; Hoffe et al., 2000; Quan et al., 2005; Zhao et al., 2007; He et al., 2011; Yu et al., ,2013;) proposed improved matching algorithms for dual-sensor summation in succession. However, most of the proposed methods are based on the bottom reflection coefficient. Thus, the precision of the bottom reflection coefficient is critical to the quality of data matching, particularly in areas of complex seafloor topography and nonideal denoising.

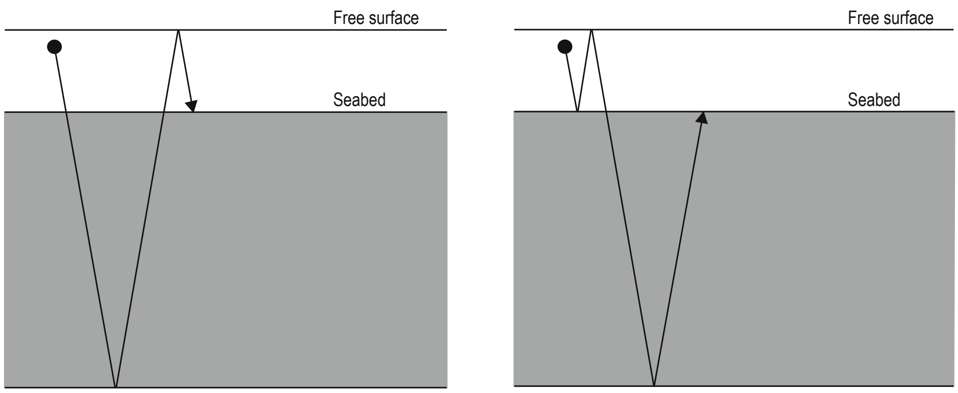
The key to the dual-sensor summation method is finding the least 2-norm matching solution. Weiner (1949) applied least squares to linear optimum filtering. Verschuur (1992) proposed the surface-related multiple elimination (SRME) method in the frequency domain using the minimum energy principle to match the predicted multiples associated with the free surface in a single channel. Subsequently, Verschuur and Berkhout (1997) used single-channel least squares adaptive matching to eliminate the predicted free-surface multiples in the time domain. However, the single-channel 2-norm solution requires orthogonality in the input data; otherwise, it introduces errors. Monk (1993) introduced the pseudo-multichannel matching method, which produces "pseudo-multichannel data" based on the phase rotation of single-channel data and somewhat improved the orthogonality of the data. Wang (2003) combined 2-norm matching and pseudo-multichannel matching, and proposed the extension multichannel matching filter. Li (2007) transformed the pseudo-multichannel matching method to a real multichannel matching method in the space domain. He succeeded in improving the orthogonality of the input data and minimizing the matching error. Riaz (2014) proposed a new processing flow of the SRME and dual-sensor summation, which eliminate multiples by using matched filtering; however, the difference between them is that the former obtains differences, whereas the latter obtains sums. Hence, the algorithms for matched filtering require improvements.

Based on dual-sensor summation, we introduce the equipoise pseudo-multichannel adaptive matched filtering to improve SRME and propose an improved dual-sensor summation that is independent of the bottom reflection coefficient. The proposed method matches geophone and hydrophone data using the polarity of the upgoing wave field and the reverse polarity of the downgoing wave field to enhance the upgoing wave (primary, source-side multiple) and suppress the downgoing wave (receiver-side multiple). The method suppresses multiples in synthetic and actual data satisfactorily.

Basic principles

According to Sheriff (1992), multiples can be classified into short- and long-path multiples. To facilitate the discussion, multiples of OBC data are classified as shown in Figure 1. Figure 1a shows receiver-side multiples (downgoing wave) and Figure 1b shows source-side multiples (upgoing wave).

Ideally, the responses of the geophones and hydrophones to the upgoing and downgoing wave fields are (Fred (1997))



(a) Receiver-side multiples (b) Source-side multiples

Fig.1 Multiple reflections model.

$$\begin{cases} \mathbf{P} = \mathbf{U} + \mathbf{D} \\ \mathbf{V}_Z = \dfrac{1}{\rho c}(\mathbf{U} - \mathbf{D}) \end{cases}, \tag{1}$$

where **P** is the P-component recorded by the hydrophones, $\mathbf{V}_Z$ is the Z-component recorded by the geophones, **U** is the upgoing wave field, **D** is the downgoing wave field, ρ is the water density, and c is the wave velocity in water. From equation (1), the geophones and hydrophones have the same polarity in the upgoing wave field and reverse in the downgoing wave field. Dual-sensor summation uses the response characteristics to enhance the upgoing wave field (primaries and source-side multiples) and suppress the downgoing wave field (receiver-side multiples). However, the dual-sensor data cannot be simply added; thus, matching is required.

Generally, geophone data have narrower bandwidth and lower signal-to-noise ratio than hydrophone data. Therefore, in this study, we match the geophone data to the hydrophone data.

Following Monk (1993), we decompose the seismic trace into four parts

$$\mathbf{d}_L = \mathbf{D}_L\mathbf{Q}_1 + \mathbf{D}'_L\mathbf{Q}_2 + \mathbf{D}_L^H\mathbf{Q}_3 + \mathbf{D}_L'^H\mathbf{Q}_4, \tag{2}$$

where for length of window n and length of filter l, the n × 1 matrix $\mathbf{d}_L$ represents the single-channel geophone data, $\mathbf{D}_L$ is the n×l Toeplitz matrix of $\mathbf{d}_L$, $\mathbf{D}'_L$ is the n×l Toeplitz matrix of the derivative of $\mathbf{d}_L$, $\mathbf{D}_L^H$ is the n×l Toeplitz matrix of the Hilbert transform of $\mathbf{d}_L$, and $\mathbf{D}_L'^H$ is the n×l Toeplitz matrix of the derivative of the Hilbert transform of $\mathbf{d}_L$. The corresponding filters to the four l×1 matrices $\mathbf{Q}_1$, $\mathbf{Q}_2$, $\mathbf{Q}_3$, and $\mathbf{Q}_4$ are related to amplitude and phase. In the following discussion, the order is $\mathbf{Q} = [\mathbf{Q}_1\ \ \mathbf{Q}_2\ \ \mathbf{Q}_3\ \ \mathbf{Q}_4]$, where **Q** is the corresponding pseudo-multichannel matching filter.

From equation (2), we can see that the target seismic trace consists of the original seismic trace and three seismic traces. These three seismic traces are equivalent to the original seismic trace with phase correction −90°, 0°, and 90°, respectively. By using this approach, we improve the orthogonality of data and reduce the matching error.

In practice, in order to obtain the sum of the dual-sensor data instead of the difference, we need to change the polarity of the geophone data. Then, we obtain the derivative, the Hilbert transform, and the derivative of Hilbert transform of each seismic trace separately. In the original geophone seismic trace, this is equivalent to transforming one trace to four. Next, we convolute the data of these four traces and apply pseudo-multichannel matching filter. Finally, we obtain the denoising results, which are the difference from the original pressure. The process is expressed as

$$\mathbf{d} = \mathbf{d}_S - \begin{bmatrix} \mathbf{D}_L \\ \mathbf{D}'_L \\ \mathbf{D}_L^H \\ \mathbf{D}_L'^H \end{bmatrix}\mathbf{Q}, \tag{3}$$

where the n × 1 matrix **d** is the result of the dual-sensor summation and the n × 1 matrix $\mathbf{d}_S$ represents the original single-channel hydrophone data.

The suitable for dual-sensor OBC data pseudo-multichannel matching filter is based on the residuals after the dual-sensor summation and it is represented as

$$\left\|\mathbf{Q}\right\|_2 = \left\| \mathbf{d}_s - \begin{bmatrix} \mathbf{D}_L \\ \mathbf{D}'_L \\ \mathbf{D}_L^H \\ \mathbf{D}_L'^H \end{bmatrix}\mathbf{Q} \right\|_2 \to \min. \tag{4}$$

Let the partial derivative of **Q** be equal to zero; then, the least squares solution of equation (4) can be converted into solving the following linear equations

$$\begin{bmatrix} \mathbf{D}_L^T\mathbf{D}_L & \mathbf{D}_L^T\mathbf{D}'_L & \mathbf{D}_L^T\mathbf{D}_L^H & \mathbf{D}_L^T\mathbf{D}_L'^H \\ \mathbf{D}_L'^T\mathbf{D}_L & \mathbf{D}_L'^T\mathbf{D}'_L & \mathbf{D}_L'^T\mathbf{D}_L^H & \mathbf{D}_L'^T\mathbf{D}_L'^H \\ \mathbf{D}_L^{H^T}\mathbf{D}_L & \mathbf{D}_L^{H^T}\mathbf{D}'_L & \mathbf{D}_L^{H^T}\mathbf{D}_L^H & \mathbf{D}_L^{H^T}\mathbf{D}_L'^H \\ \mathbf{D}_L'^{H^T}\mathbf{D}_L & \mathbf{D}_L'^{H^T}\mathbf{D}'_L & \mathbf{D}_L'^{H^T}\mathbf{D}_L^H & \mathbf{D}_L'^{H^T}\mathbf{D}_L'^H \end{bmatrix}\mathbf{Q} = \begin{bmatrix} \mathbf{D}_L^T\mathbf{D}_S \\ \mathbf{D}_L'^T\mathbf{D}_S \\ \mathbf{D}_L^{H^T}\mathbf{D}_S \\ \mathbf{D}_L'^{H^T}\mathbf{D}_S \end{bmatrix}. \tag{5}$$

The equipoise pseudo-multichannel adaptive matching filter uses constraints on the lateral adjacent channels and thus improves the orthogonality of the input data in the space domain. Assuming K traces expressed as $\mathbf{d}_{Si}$ and $\mathbf{d}_{Li}$ ($I = 1, 2, \ldots, K$) in the hydrophone and geophone data, respectively, the equipoise pseudo-multichannel adaptive matching filter $\mathbf{Q}_0$ can be represented as

$$\left\|\mathbf{Q}_0\right\|_2 = \sum_{i=1}^{K} \left\| \mathbf{d}_{Si} - \begin{bmatrix} \mathbf{D}_{Li} \\ \mathbf{D}'_{Li} \\ \mathbf{D}_{Li}^H \\ \mathbf{D}_{Li}'^H \end{bmatrix}\mathbf{Q}_0 \right\|_2 (i = 1, 2, \cdots, K) \to \min. \tag{6}$$

Let the partial derivative of $\mathbf{Q}_0$ be equal to zero; then, the least squares solution of equation (6) can be converted into solving the following linear equations

$$\sum_{i=1}^{K}\begin{bmatrix} \mathbf{D}_{Li}^{\;T}\mathbf{D}_{Li} & \mathbf{D}_{Li}^{\;T}\mathbf{D}'_{Li} & \mathbf{D}_{Li}^{\;T}\mathbf{D}_{Li}^{H} & \mathbf{D}_{Li}^{\;T}\mathbf{D}'^{H}_{Li} \\ \mathbf{D}'^{\;T}_{Li}\mathbf{D}_{Li} & \mathbf{D}'^{\;T}_{Li}\mathbf{D}'_{Li} & \mathbf{D}'^{\;T}_{Li}\mathbf{D}_{Li}^{H} & \mathbf{D}'^{\;T}_{Li}\mathbf{D}'^{H}_{Li} \\ \mathbf{D}_{Li}^{H^T}\mathbf{D}_{Li} & \mathbf{D}_{Li}^{H^T}\mathbf{D}'_{Li} & \mathbf{D}_{Li}^{H^T}\mathbf{D}_{Li}^{H} & \mathbf{D}_{Li}^{H^T}\mathbf{D}'^{H}_{Li} \\ \mathbf{D}'^{H^T}_{Li}\mathbf{D}_{Li} & \mathbf{D}'^{H^T}_{Li}\mathbf{D}'_{Li} & \mathbf{D}'^{H^T}_{Li}\mathbf{D}_{Li}^{H} & \mathbf{D}'^{H^T}_{Li}\mathbf{D}'^{H}_{Li} \end{bmatrix}\mathbf{Q}_0 = \sum_{i=1}^{K}\begin{bmatrix} \mathbf{D}_{Li}^{\;T}\mathbf{D}_{Si} \\ \mathbf{D}'^{\;T}_{Li}\mathbf{D}_{Si} \\ \mathbf{D}_{Li}^{H^T}\mathbf{D}_{Si} \\ \mathbf{D}'^{H^T}_{Li}\mathbf{D}_{Si} \end{bmatrix}\left(i=1,2,\cdots,K\right). \quad (7)$$

Equation (7) is more complex than equation (5) but the order of the Teoplitz matrix in the two equations is equal; therefore, the calculation effort is also equal. We use the successive overrelaxation method to solve the linear equations by selecting the appropriate relaxation operator ω; for $\omega = 1$, the successive overrelaxation method is equal to the Gauss–Seidel iterative method. Then, we iteratively solve the linear equations until the error satisfies the required precision.

The pseudo-multichannel adaptive matching filter method considers the problem of phase correction; thus, the phase and amplitude of the matched data are consistent with those of the hydrophone data. This means that the phase of the geophone data has changed. As a result, multiples are not only eliminated but also enhanced after dual-sensor summation. Therefore, it is necessary to add a time–space variant operator $\boldsymbol{\varphi}$ to the geophone data to maintain their phase. Finally, based on equation (6), the expression for the equipoise pseudo-multichannel adaptive matching filter for the dual-sensor summation is

$$\left\|\mathbf{Q}_0\right\|_2 = \sum_{i=1}^{K}\left\|\mathbf{d}_{Si} - \boldsymbol{\varphi}\begin{bmatrix}\mathbf{D}_{Li} \\ \mathbf{D}'_{Li} \\ \mathbf{D}^{H}_{Li} \\ \mathbf{D}'^{H}_{Li}\end{bmatrix}\mathbf{Q}_0\right\|_2 \left(i=1,2,\cdots,K\right) \rightarrow \min . \quad (8)$$

All adaptive matching filter methods that use the minimum 2-norm solution should satisfy the orthogonality of the data. Compared with the single-channel and pseudo-multichannel adaptive matching filter, the equipoise pseudo-multichannel adaptive matching filter improves the orthogonality of the data and suppresses the receiver-side multiples without harming the signal. It is noteworthy that the equipoise pseudo-multichannel matching filter is related to the seismic wavelet. In practice, the seismic wavelet varies as a function of space and time; therefore, the equipoise range does not improve when it increases. Hence, when selecting the length of the window, the wavelet length must also be considered.

Application and analysis of deghosting

Synthetic data example

To verify the proposed method, we use forward modeling and consider a horizontally layered homogeneous medium (Figure 2). In Figure 2, H_i (i = 0, 1, …, 4) denotes the thickness of each layer and V_i (i = 0, 1, …, 4) is the P-wave velocity of each layer. The first layer is seawater. We use a 50 Hz Ricker wavelet, a group interval of 12.5 m, a minimum offset if 0 m, and sampling intervals of 2 ms.

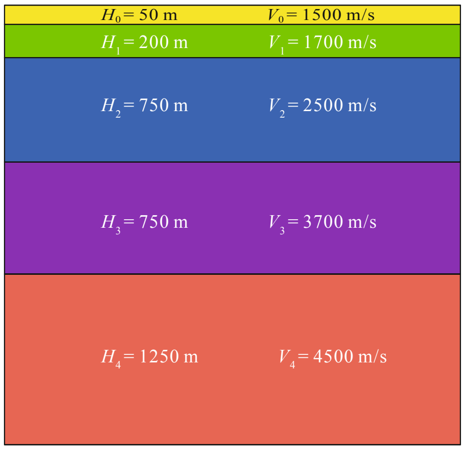


Fig.2 Geological model used in the forward modeling of the dual-sensor data.

Based on the model shown in Figure 2, we obtain synthetic hydrophone and geophone data, as shown in Figures 3a and 3b, where the arrows point to the primary reflection of each layer below the seafloor. The primary reflections in the synthetic hydrophone and geophone data have the same polarity, whereas the near-offset direct waves and part of the multiples have reverse polarity. Figure 3c shows the results of the reflection coefficient method; the arrows point to the residual multiples. Figure 3d shows the results of the dual-sensor summation method based on the equipoise pseudo-multichannel adaptive matching filter. Compared with Figures 3a and 3b, the energy of the primaries and source-side multiples (upgoing wave) has obviously strengthened. The receiver-side multiples, shown by the dotted line, are clearly suppressed with almost no residuals, especially in the area of the near offset; furthermore, the direct waves have somewhat weakened. Overall, the signal-to-noise ratio of the synthetic data has improved significantly, the effective waves are strengthened, and the receiver-side multiples are suppressed. Clearly, the proposed method improves the deep reflection energy, which improves data imaging.

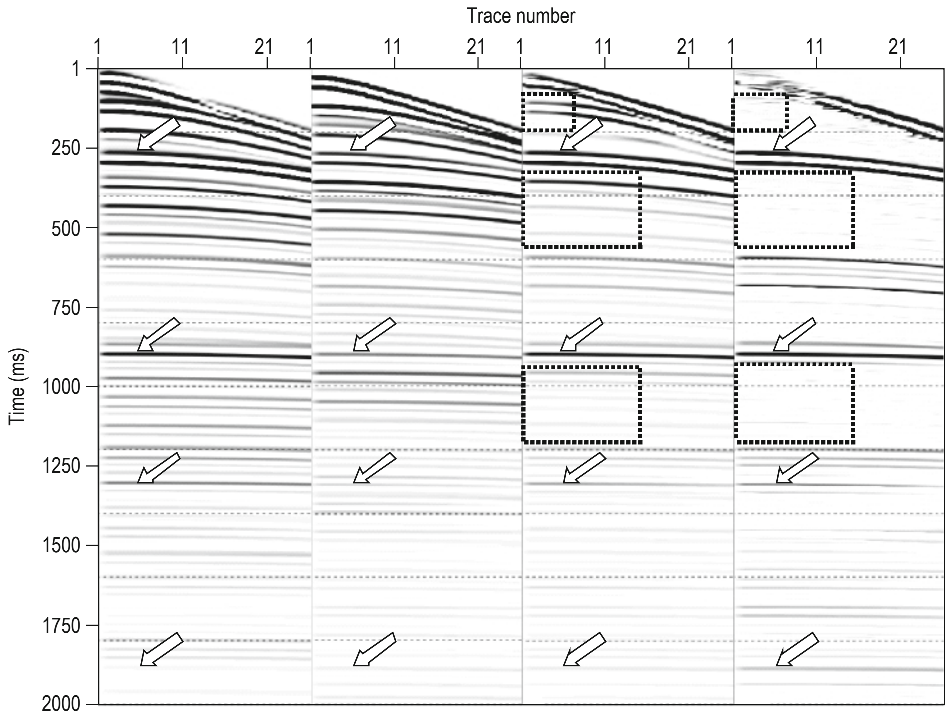
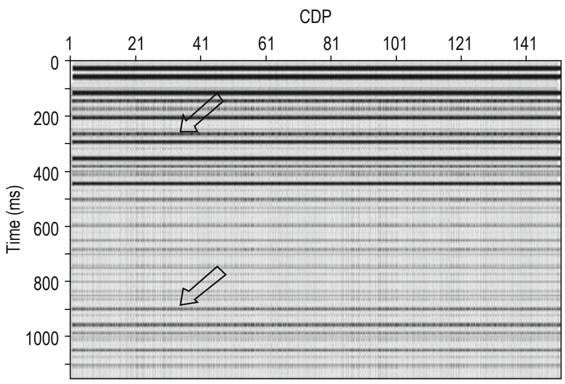
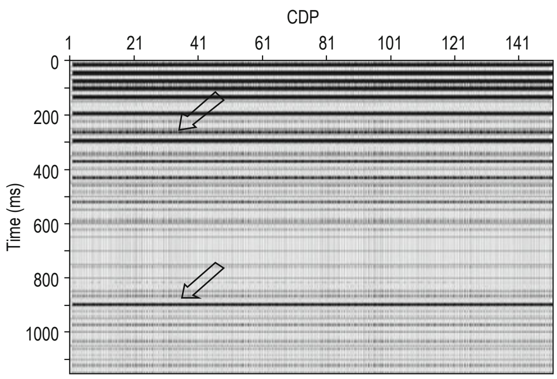


Fig.3 Synthetic OBC seismic data computed using the model in Figure 2.
(a) synthetic geophone data; (b) synthetic hydrophone data; (c) Dual-sensor summation based on the reflection coefficient method; (d) Dual-sensor summation based on equipoise pseudo-multichannel adaptive matched filtering.

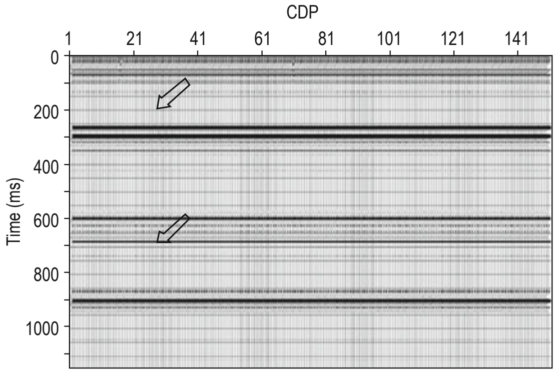
Figures 4a, 4b, and 4c show the direct stack sections corresponding to Figures 3a, 3b, and 3d. After dual-sensor summation, it is clearly seen in the stack sections that receiver-side multiples are significantly suppressed, whereas the primaries and source-side multiples are enhanced, the number of reflection events is reduced, and the continuity of reflection events improves. This helps data processing and interpretation.



(a) Stack from the geophone data



(b) Stack from the hydrophone data



(c) Stack from Figure 3d

Fig.4 Comparison of stacks from the synthetic seismic data in Figure 3.

Real data example

We used dual-sensor OBC data from the SLX survey area with group interval of 12.5 m and sampling interval of 2 ms. The OBC data were collected and provided by SINOPEC Geophysical Corporation Shengli Branch. We selected the interval from 0 to 1750 ms to apply the equipoise pseudo-multichannel adaptive matching filter and the dual-sensor summation.

Prior to the dual-sensor summation, we pretreated the data without changing the phase, especially the geophone data, because the noise-to-signal ratio is not high and the noise of the strong surface waves cover the reflections. Without effective separation, **φ** is not real and the accuracy of the results is affected.

The dual-sensor summation is shown in Figure 5 and is compared with the reflection coefficient method. Figure 5a shows the geophone data, Figure 5b shows the hydrophone data, Figure 5c shows the dual-sensor summation results based on the reflection coefficient method, and Figure 5d shows the dual-sensor summation results based on the equipoise pseudo-multichannel matching filter. The geophone data were pretreated to eliminate noise bursts and surface waves but the data quality is not the same as in the hydrophone data. The geophone data need to be matched with the hydrophone data that have lower signal-to-noise ratio. Both methods suppress the multiples but the equipoise pseudo-multichannel dual-sensor matching filter offers more advantages. The arrows in Figure 5 show that there are clearly residuals in the suppression results of the reflection coefficient method and that the signal-to-noise ratio is lower; moreover, the wave energy after the dual-sensor summation is also significantly lower than that of the equipoise pseudo-multichannel matching filter.

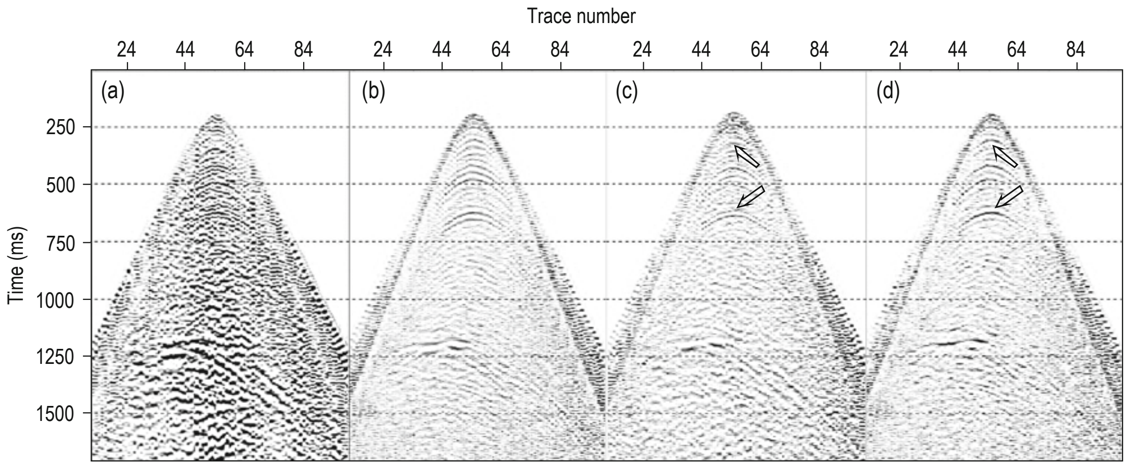


Fig.5 OBC seismic data from the Shengli Oilfield.

(a) Geophone data; (b) Hydrophone data; (c) Dual-sensor summation based on the reflection coefficient method; (d) Dual-sensor summation based on equipoise pseudo-multichannel adaptive matched filtering.

Figure 6 shows the normalized spectra that correspond to Figures 5a, 5b, and 5d. The red line represents the spectrum of the real geophone data, the green line is the spectrum of the real hydrophone data, and the blue line is the spectrum of the data after dual-sensor summation. In the real geophone data, we see that the low-frequency data dominate, the high-frequency data decay fast, and there is a notch at 120 Hz. In the real hydrophone data, the effective bandwidth is wider, the high-frequency data dominate, and there is a notch at 70 Hz. The real hydrophone and geophone data complement each other at the notches, the low- and high-frequency spectra after dual-sensor summation are consistent, and the effect of the notches is removed owing to the water column, thus maximizing the bandwidth.

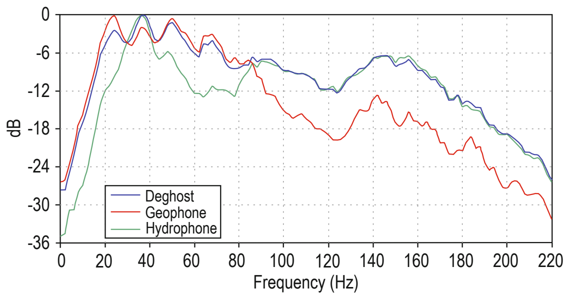
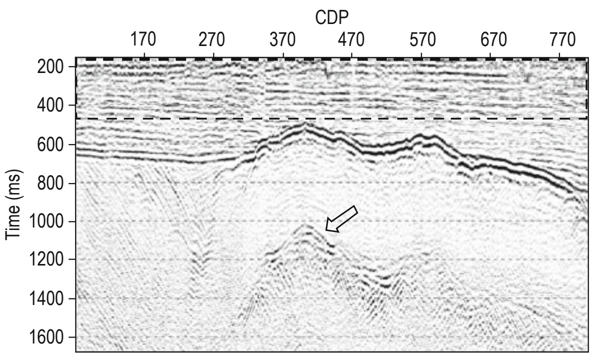


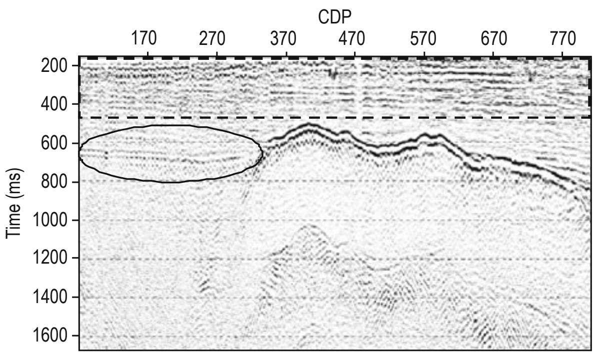
Fig.6 Spectra of the dual-sensor OBC data in Figure 5.

Figures 7a, 7b, and 7c show the stack sections that correspond to Figures 5b, 5c, and 5d. Figure 7a is the stack section for the real hydrophone data. Figure 7b is the stack section for the dual-sensor summation. Figure 7c is the stack section for the dual-sensor summation based on the equipoise pseudo-multichannel matching filter. We can see that the noise in the shallow section (dotted lines in Figure 7c) is significantly suppressed and the reflections are highlighted. This improves the continuity of events and the resolution. It also provides high-quality seismic data for subsequent processing and interpretation. There are many residuals in the shallow section in Figure 7b and even some damaged reflections (ellipse).

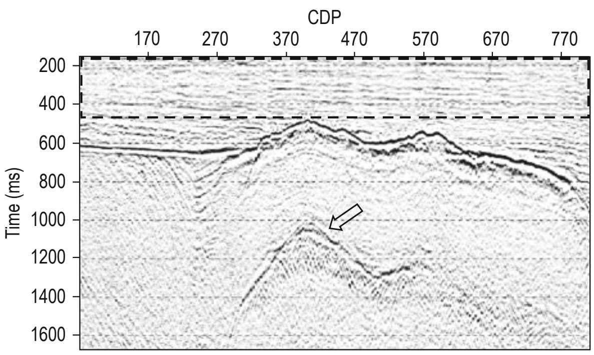
The dual-sensor summation suppresses the receiver-side multiples and highlights the reflections and source-side multiples. For the residuals of the receiver-side and source-side multiples, we can apply several postprocessing techniques, such as predictive deconvolution and high-resolution Radon transform, which are not within the scope of this study.



(a) Stack from Figure 5b



(b) Stack from Figure 5c



(c) Stack from Figure 5d

Fig.7 Stacks from the OBC seismic data in Figure 5.

Conclusions

Dual-sensor matching summation is an important part of OBC data processing and essentially separates the upgoing and downgoing wave fields. The key to this method is the matching of the hydrophone and geophone data. We discuss a dual-sensor summation method based on the equipoise pseudo-multichannel adaptive matching filter. The latter is an improvement of the pseudo-multichannel adaptive matching filter in SRME and does not depend on the traditional reflection coefficient method. The proposed method suppresses the receiver-side multiples by optimizing the 2-norm solution for matched hydrophone and geophone data. The method is totally data driven, avoids errors owing to the inaccurate reflection coefficient, improves the matching results while suppressing the multiples, and maintains the amplitude and phase information of the waves. The proposed method was successfully tested using synthetic and real data processing.

Dual-sensor summation can effectively expand the bandwidth, eliminate notches in the frequency spectrum caused by noise, and maintains the frequency information; therefore, we can produce realistic underground images while suppressing the downgoing and upgoing waves and enhancing the source-side multiples. Therefore, processing is needed to eliminate this type of interference before imaging.

Upgoing waves can be obtained after the dual-sensor summation. Conversely, downgoing waves, which can be used for imaging multiples, can also be retained. This method shows promise in imaging the seafloor with a wide range of lighting.

Acknowledgments

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