Introduction

With the development of seismic exploration, the era of seeking oil and gas fields under complex seismic geological conditions is one of the main directions. Due to the complex acquisition condition, various types of seismic sources are used for field acquisition. Such as dynamite source, vibroseis and air gun. The application and development of vibroseis is not only a requirement of the national security, but also a requirement of the environmental protection. However, there are many new problems in the application of mixed seismic source acquisition in complex obstacles.

Affected by objective factors such as excitation methods, receiving instruments, and surface geological conditions, the seismic data acquired has great differences in energy, phase, frequency, signal-to-noise ratio and so on. For example, the wavelet of the dynamite source with the minimum phase, the energy is relatively strong, and the frequency is relatively high, but that of the vibroseis with zero-phase and low energy. These differences make it impossible for in-phase stacking by the data collected from different sources, which severely reduces the S/N ratio and resolution of the data. Conventional processing procedures will cause large differences at the splicing place of the two sources and make seismic sections with poor wave group characteristics, low S/N ratio and resolution.

In this paper, considering the S/N ratio, a high-precision matching processing technology for mixed sources is proposed. This method is applied in the complex obstacle in Sichuan Basin. Through the comprehensive application of pre-stack average amplitude spectrum matching processing, phase matching processing, and post-stack residual time correction. The inconsistencies such as amplitude, phase, frequency and time difference between mixed sources are eliminated, which greatly improves the imaging quality and S/N ratio of seismic data, while eliminating false fractures and providing high S/N ratio seismic data for seismic interpretation and inversion.

Method and/or Theory

Pre-stack average amplitude spectrum matching processing method

Conventional amplitude matching method only calculates a filter factor without considering the S/N ratio of the seismic data, and the seismic data generally includes two parts: signal and noise. When designing matching operators of mixed source seismic data, the ideal condition is Perform signal matching instead of noise, which will affect the instability of the matching operator. Assuming two traces: \(x(t)\) and \(y(t)\), composed of signal and noise respectively, after FFT can be transformed as:

\[
\begin{align*}
X(f) &= S_x(f) + N_x(f) \\
Y(f) &= S_y(f) + N_y(f)
\end{align*}
\]

If there are two sets of seismic data, the average autocorrelation of set \(x(t)\) is:

\[
E[X\overline{Y}] = E[S_xS_x] + E[N_xN_x] + E[S_yS_y] + E[N_xN_y]
\]

Defining the N/S ratio as follow:

\[
\mu_x(f) = \frac{E[N_x(f)^2]}{E[S_x(f)^2]}
\]

Supposing the noise of the data is also uncorrelated and the N/S ratio of the two sets are same, then

\[
\mu_x = \mu_y = \sqrt{\frac{E[X(f)^2]E[Y(f)^2]}{|E[X(f)\overline{Y}(f)]|}} - 1
\]

Defining the autocorrelation of the two sets: \(\gamma^2(f) = \frac{E[X\overline{Y}]}{E[X^2]E[Y^2]}\), then, \(\mu = \frac{1}{\gamma} - 1\), if \(\gamma\) is known, the signal and noise spectrum of \(x(t)\) is as follow:

\[
E[N_x(f)^2] = (1 - \gamma)E[X^2]
\]
To match $y(t)$ to $x(t)$, define the matching operator as follows:

$$M(f) = \frac{E\left[ S_x(f) \right]^2}{E\left[ S_y(f) \right]^2} \times \frac{1}{1 + \mu} \quad (6)$$

The matching operator contains two items, the former is a shaping filter, and the latter is to suppress noise. A stable matching operator can also be obtained on noisy seismic data.

Mixed source phase matching processing method

Least square pulse deconvolution and predicted deconvolution have the assumption of minimum phase wavelets, while wavelets of the vibroseis are closer to zero phase. When mixed sources of dynamite and vibroseis are jointly processed, due to phase of the acquired seismic data is not uniform, which affects the imaging effect of the profile and reduces the S/N ratio and resolution of the seismic data. Therefore, wavelets of the vibroseis need to be minimum phased.

**Figure 1** Comparison of dynamite source and vibroseis at the same location. (1-a) dynamite source (1-b) vibroseis before matching (1-c) vibroseis after matching. All three shots are displayed with the same energy level. It can be seen that the energy level of the vibroseis source before the match is $10^{14}$ stronger than that of the dynamite source. After amplitude matching, the vibroseis source and the dynamite source are at the same energy level.

**Figure 2** Comparison of vibroseis shot before minimum phased (2-a), after minimum phased (2-b), dynamite source (2-c). It can be seen that the vibroseis minimum phase processing can better solve the problem of inconsistency with the dynamite source wavelet. After phase matching, both source wavelet are minimum phase; on the other hand, first-break of the shot is smoother and more stable, which is useful for accurate picking, laying good foundation for subsequent inversion of near-surface velocity model and statics calculation.
Figure 2 is the shot comparison chart of the vibroseis wavelet before and after the minimum phase. The workflow of minimum phased of vibroseis is as follows: The first, the scan signal of the vibroseis can be obtained through the parameters such as the scan frequency, scan length, slope and so on; Second, Make the scanning signal of the vibroseis autocorrelation to obtain the zero-phase wavelet; Third, Use the zero-phase wavelet of the vibroseis to extract the minimum phase conversion operator; Finally the conversion operator is applied to the pre-stack vibroseis shot, that is, the phase matching is completed and the seismic data with the zero-phase wavelet is converted into the seismic data with the minimum phase wavelet.

**Post-stack residual time correction method**

For large time differences, the average amplitude spectrum matching processing and mixed sources phase matching processing method can better eliminate the differences, but the residual time can’t be solved, which will affect the accuracy of velocity analysis and in-phase stacking. The post-stack residual time correction is mainly to solve remaining time on the seismic profile after processed by the above method. Because the overlapping part is the same reflection information of the underground area, and has the same structural morphology, the two seismic records should have good correlation. Figure 3 is the comparison of stack sections before and after residual time correction.

**Figure 3** Comparison of stack section before and after residual time correction. The cross-correlation result can quantitatively describe the time delay of the two signals. Through cross-correlation analysis, the residual time between the vibroseis and the dynamite source can be quantitatively determined. The residual time is about 18ms. Based on the statistics of the residual time after stacking, this time is corrected to all the pre-stack data of the vibroseis, which better solves the residual time of the mixed source systems.

**Examples (Optional)**

The work area is located in the Sichuan Basin in Western China. Figure 4 shows the surface elevation map of the work area and the distribution of complex obstacles. It is dominated by mountainous and hilly landforms, and rivers are relatively developed including the M River (300-1000m in width), the Z River (80-500m in width) and its tributaries. Because they are mostly local first-class drinking water sources, it is forbidden to install underwater geophones and dynamite source. Then, there are also several obstacles such as, S and Y county and towns, F and Y water systems, natural gas pipelines and canals and other ground and underground facilities. The complex obstacle area in the work area has a large area and a wide range, which has a great impact on the design of the geometry and the uniform layout of physical points. So, vibroseis and dynamite source are used for acquisition. Figure 5 shows the comparison of the stack section before and after high-precision matching processing, the amplitude energy tends to be consistent, the discontinuity in the marker layer is significantly eliminated, and the S/N ratio is significantly improved.
Figure 4 (4-a) the surface elevation map of the work area, (4-b) obstacle distribution in work area

Figure 5 Comparison of the stack section before and after high-precision matching processing. It can be seen that the amplitude energy of the vibroseis before matching is significantly stronger than the dynamite source data, and there is a system time difference between the two mixed sources and obvious discontinuity in the marker layer (5-a). After processing by the high-precision matching method (5-b), the amplitude energy tends to be consistent, the discontinuity in the marker layer is significantly eliminated, and the S/N ratio is significantly improved.

Conclusions

The high-precision matching processing method of mixed sources proposed in this paper achieves consistent processing of mixed source data, and solves inconsistencies such as amplitude, frequency, phase, and time difference through the comprehensive application of pre-stack average amplitude spectrum matching processing, mixed source phase matching processing, and post-stack residual time correction. This technology has a good application prospect. It is not only suitable for onshore and offshore mixed source acquisition data, but also can be used to process merging of seismic data acquired at different times and with different acquisition factors, and improve the S/N ratio of the profile.

References
