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Review of Double-Focusing Imaging Technology in Seismic Exploration

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Abstract

This paper systematically summarizes the research progress of double-focusing imaging methods in seismic exploration. As an observation system evaluation method based on wave theory, the double-focusing imaging method can directly reflect the prestack migration imaging effect and provide a scientific basis for the design of observation systems in seismic exploration. It systematically sorts out the theoretical basis, development history, algorithm improvement, application examples and future trends of the double-focusing imaging method, focuses on expounding the evolution process of the double-focusing method from homogeneous media to complex media and from sparse acquisition to "two-wide and one-high" acquisition, and analyzes the influence law of key parameters of the observation system on imaging quality, providing theoretical guidance and practical reference for the design of observation systems in seismic exploration.

Keywords

Double-focusing Imaging; Observation System Design; Seismic Exploration; Resolution Analysis; "Two-Wide and One-High" Acquisition.

1. Introduction

Seismic exploration is an important means for the exploration and development of oil and gas resources. The design of the observation system is a key link in seismic exploration, which directly affects the quality of seismic data and the effect of subsequent interpretation. Traditional observation system evaluation methods are mainly based on common midpoint analysis, evaluating through indicators such as coverage times, offset distribution and azimuth distribution. However, these methods cannot directly reflect the prestack migration imaging effect, especially when facing complex geological targets, the reliability of the evaluation results is insufficient.

The double-focusing imaging method originated from the confocal point (CFP) imaging theory proposed by Berkhout in 1997[1], which is an observation system resolution analysis method based on wave equation continuation. By separately performing focusing analysis on geophones and seismic sources for target points to calculate the confocal beam, this method can be directly used for seismic acquisition design, and the resolution results it provides are equivalent to those of migration imaging. The double-focusing imaging method can be applied to homogeneous media, horizontal layered media or complex media, and can consider the influence of surface waves and multiple waves, providing a more scientific evaluation tool for the design of observation systems.

With the gradual shift of oil and gas exploration targets to deep or ultra-deep complex geological targets, higher requirements have been put forward for the quality of seismic data, and the "two-wide and one-high" acquisition technology, namely wide frequency band, wide azimuth and high density, has emerged as the times require. However, the "two-wide and one-high" acquisition technology requires high economic investment. How to select appropriate

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acquisition parameters according to the geological and geophysical conditions of the specific work area under the existing cost constraints and equipment conditions has become a key issue in current seismic exploration. As an important tool for observation system design, the double-focusing imaging method has important guiding significance for the optimal design of "two-wide and one-high" acquisition technology.

2. Research Progress of Double-Focusing Imaging Method

2.1. Theoretical Basis of Double-Focusing Imaging Method

The double-focusing imaging method originates from the confocal migration theory, and its core idea is: for the target point, separately perform focusing analysis on the geophone and the seismic source to obtain the focused wavefield, and then multiply the two focused wavefields to obtain the confocal beam. The main lobe width and main lobe energy ratio of the confocal beam reflect the imaging resolution of the observation system.

Berkhout[1] first proposed the double-focusing method, applying the confocal point imaging theory to the evaluation of seismic observation systems. By extrapolating the forward and reverse wavefields of geophones and shot points to obtain the confocal beam, it evaluates the seismic acquisition observation system according to spatial resolution function, illumination intensity distribution and angle-ray parameter function. This method focuses on underground complex geological targets and establishes the connection between observation system attributes and target imaging effects.

The double-focusing imaging method is based on wave equation theory, and its basic expression is:

$$F\left(x_{B'}x_A\right) = \int_S \left(x_{B'}x'\omega\right) \cdot G^*\left(x_{A'}x'\omega\right) dx \tag{1}$$

Among them, $F(x_{B'}\, x_A)$ is the double-focusing beam, $G(x_{B'}\, x'\, \omega)$ is the Green's function from x to x_B, $G^*(x_{A'}\, x'\, \omega)$ is the conjugate of the Green's function from x to x_A, and S is the boundary of the observation system.

This expression shows that the double-focusing beam is the product of the geophone focusing beam and the seismic source focusing beam, and its size is related to the spatial resolution of the observation system. The smaller the main lobe width of the double-focusing beam, the higher the resolution; the larger the main lobe energy ratio, the better the imaging quality.

2.2. Development History and Application Optimization of Double-Focusing Imaging Method

The development of the double-focusing imaging method has experienced an evolution process from homogeneous media to complex media and from theoretical research to practical application. Berkhout and Volker et al.[2] first completed the research on the double-focusing algorithm for homogeneous media, laying a theoretical foundation for the double-focusing method; Volker and Blaequier further expanded its practical application and gave practical engineering cases. On the basis of the above research, Di Bangrang et al.[3] developed an industrialized double-focusing analysis software for homogeneous media that can be applied to actual production, successfully promoting the method from theory to practical application.

With the in-depth seismic exploration in complex structural areas, the double-focusing method has gradually developed towards adaptation to complex media. Di Bangrang et al.[4] proposed a double-focusing calculation method for different media models, effectively expanding the application scope of the method; Wei Wei et al.[5] adopted a combination of Fourier finite

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difference large-step wavefield continuation and Born-Kirchhoff small-step wavefield interpolation recursion to perform double-focusing analysis on complex structural models, significantly improving the calculation efficiency; Yao Gang et al.[6] used Rayleigh integral to realize the calculation of the focusing beam of the 3D observation system for layered media models, adapting to the exploration needs of layered homogeneous media with relatively gentle interfaces; Yang Mengmeng et al. simplified the calculation process of the double-focusing beam resolution through ray theory, which, although having errors caused by high-frequency approximation, provides a convenient way for rapid resolution estimation.

In response to the application needs of the "two-wide and one-high" acquisition technology, the double-focusing method has been further optimized and upgraded. Chang Zijuan et al.[7] studied the focusing resolution of the "wide frequency band, wide azimuth and high density" onshore 3D seismic observation system, systematically analyzed the influence law of parameters such as array length, array width, bin size and wavelet spectrum on horizontal resolution, and gave the theoretical limit value of horizontal resolution under different conditions; Hou Hailong et al.[8] proposed an improved double-focusing imaging analysis method, which obtains imaging gathers through Gaussian ray beam forward modeling using the finite-frequency Snell's law based on the viscoelastic media model, taking into account the influence of Fresnel zone and formation absorption attenuation, and is suitable for deep and ultra-deep seismic exploration needs; Zhao Hu et al.[9] focused on the key parameters of the 3D observation system, analyzed the influence of array length, trace spacing, receiver line spacing, etc. on focusing, providing a reference for the design of observation system parameters; Wang Chaoyue et al.[10] carried out uniformity evaluation research on the offset distribution of high-density acquisition, supplementing the reference basis for the design of high-density observation systems.

In terms of application optimization, the double-focusing imaging method mainly focuses on the evaluation of observation system parameters and the improvement of calculation efficiency. This method can quantitatively analyze the influence of key parameters such as array length, trace spacing, receiver line spacing and shot spacing on imaging quality, providing a scientific basis for parameter optimization-an increase in array length can improve horizontal resolution but will increase the calculation amount; a decrease in trace spacing and receiver line spacing can improve resolution but will increase acquisition costs; a decrease in shot spacing can improve azimuth coverage but will increase data volume. Liu Bin et al. proposed to use the ratio of the main lobe to the maximum side lobe of double-focusing as a quantitative evaluation index for the observation system, which has high effectiveness verified by geological models and examples; Di Zhixin et al. calculated the focusing degree through double-focusing analysis, clarifying the order of sensitive parameters of the observation system affecting imaging accuracy, and providing support for the optimization of observation systems in complex structural areas.

To solve the problem of large calculation amount of the double-focusing method, researchers have proposed various optimization strategies: Wei Wei et al. proposed a multi-frequency fast focusing analysis algorithm in the frequency-wavenumber domain, which can obtain full-band focusing analysis results through a small number of single-frequency calculations combined with interpolation; Wu Sihai realized parallel optimization using CUDA technology based on wave theory combined with acoustic wave equation and Fourier finite difference method, greatly improving the calculation efficiency; the simplified double-focusing calculation method proposed by Hou Hailong et al. simplifies the wavefield forward modeling and prestack migration processes while taking into account both calculation efficiency and imaging accuracy.

3. Summary

As an observation system evaluation tool based on wave theory, the double-focusing imaging method can directly reflect the prestack migration imaging effect, effectively solving the problem of insufficient reliability of traditional evaluation methods under complex geological targets, and providing a scientific basis for the design of seismic observation systems and the optimization of "two-wide and one-high" acquisition parameters.

The double-focusing method has completed the leap from homogeneous media to complex media and from theory to practice, with continuous improvement in calculation efficiency and imaging accuracy, adapting to the needs of different exploration scenarios. In the future, this method will develop towards integration with artificial intelligence technology, integration into full-waveform inversion, and adaptation to multi-scale seismic exploration, providing stronger technical support for the exploration and development of oil and gas resources.

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