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Research and Application of Excitation Method Optimization in Areas with Low Signal-to-Noise Ratio of Seismic Data

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Abstract: In areas with a low signal-to-noise ratio of seismic data, the continuity of the seismic reflection waves in the exploration target layer is very poor, which will reduce the imaging accuracy and make it impossible to solve certain geological tasks. This article suggests an approach to address the issue of seismic acquisition by optimizing excitation parameters. It involves conducting a detailed investigation of the surface structure, enhancing the observation system, increasing the coverage appropriately, and transitioning from combined-well excitation to single-well excitation. Additionally, the use of technical tools like qualitative evaluation of the observation system and forward modeling are employed to determine the final optimized seismic acquisition plan. The effectiveness of this approach is evident from the seismic profile obtained in an exploration area in Inner Mongolia.

Keywords: Optimization; Single-well excitation; Combined-well excitation; Coverage times; Forward illumination

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1. Problem statement

Due to the complex and volatile deep seismic geological conditions in the Longwantong (LWT) exploration area in Inner Mongolia, its seismic data has a low signal-noise ratio. This makes it difficult to obtain the desired information of the target layer. The deep target layer exhibits low reflection energy, and limited continuity in seismic reflection waves, resulting in poor seismic imaging accuracy. Subsequent data processing and interpretation face significant challenges with reduced accuracy and confidence. In order to solve geological tasks, the seismic acquisition parameters in this exploration area have been continuously strengthened, and the cost of data acquisition has increased sharply [1]. Therefore, it is crucial to improve the quality of seismic data, the signal-to-noise ratio of seismic data, and the imaging accuracy at the minimum cost.

In this study, we employed various techniques, such as three-dimensional modeling, forward illumination simulation, coverage number analysis, enhanced testing, qualitative evaluation of observation systems, and more, to conduct research and analysis on the optimization of excitation parameters. It identifies the shift from combined-well configurations to single-well excitations, based on meticulous investigations of surface structures and increased excitation point density. These optimization plans were then assessed for feasibility and soundness, with the actual seismic profile outcomes used to verify their effectiveness [2].

2. Optimization scheme

2.1. The investigation of delicate surface structures provides the basis for selecting the optimal depth for well-blast stimulation

Surface structure investigation is not only the first step in seismic information collection, but also the basis for initiating optimization. To determine the optimal depth and lithology for stimulation, a thorough investigation of the three-dimensional surface structure was conducted at an enhanced density of 1/km². This process involved creating a detailed near-surface model. **Figure 1** illustrates the establishment of a three-dimensional surface model. Excitation parameters were meticulously designed point by point, ensuring that the explosions were triggered within the high-speed layer. Extensive excitation tests were performed in various media at depths ranging from 3–140 meters. These tests revealed that the best-optimized stimulation well depth was between 3–7 meters below the upper surface of the high-speed layer, and the most effective excitation lithology was water-bearing fine sand.

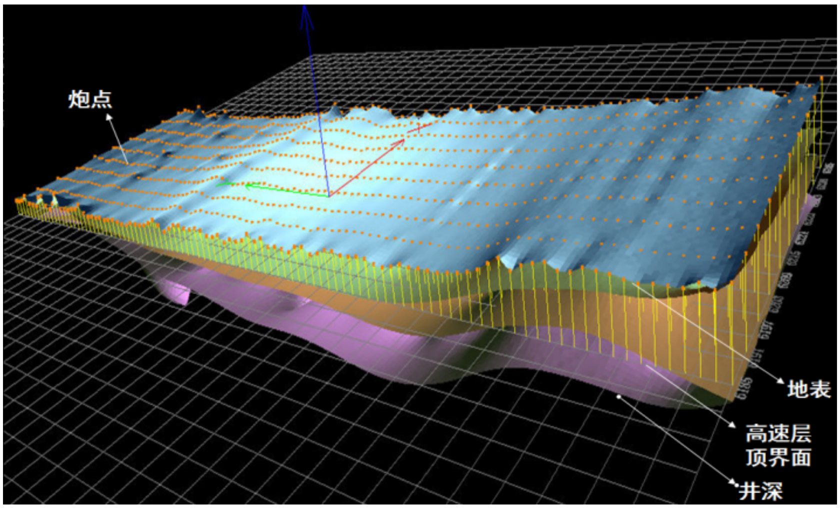

Figure 1. Accurate 3D-surface structure survey model. Translation (from left to right, from top to bottom): shot point, the surface of the earth, the top interface of high-velocity layer, well depth

2.2. Reasonably increasing the density of excitation points to increase the number of coverages

Choosing a reasonable number of coverages is the key to optimizing the excitation scheme. Superpositions have a suppressive effect on waves and random interference. Reasonably increasing the density of excitation points to increase the number of coverages can improve the signal-to-noise ratio of seismic data, thereby improving the quality of seismic processing profiles [1].

A theoretical curve can be obtained based on the relationship between the signal-to-noise ratio and the number of coverages [2] (**Figure 2**). **Figure 2** shows that before the number of coverages reached 36 times, the signal-to-noise ratio increased rapidly as the number of coverages increased. When the number of coverages was between 36 and 140 times, the signal-to-noise ratio increased rapidly and then slowly. In other words, the increase in the number of coverages will not result in significant effects after a certain number is reached.

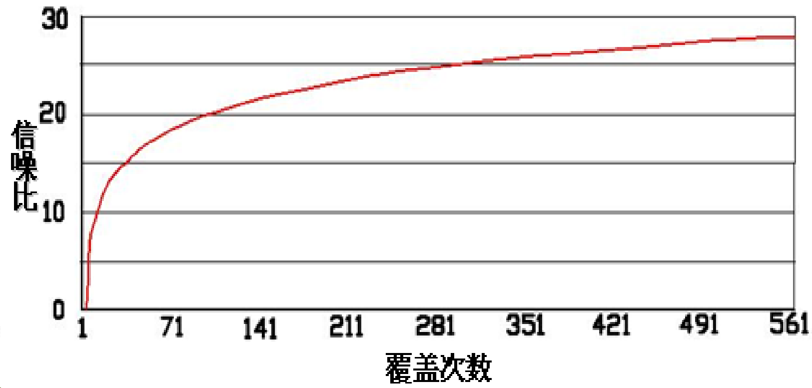

Figure 2. The theoretical curve between the fold and SNR. Note: The *x*-axis represents the number of coverages; *y*-axis represents the signal-to-noise ratio

We established a geophysical model of the area based on the geological data of the area, as shown in **Figure 3**, and conducted an analysis through a comparison of observation systems with different coverage times to determine reasonable optimization factors [1]. Observation systems of 25 m and 50 m away from the shot point were used for forward lighting simulation. The corresponding times of coverage of these two observation systems were 160 and 80 times, respectively. Other acquisition parameters were the same; the final acquisition parameters were determined based on the simulation results.

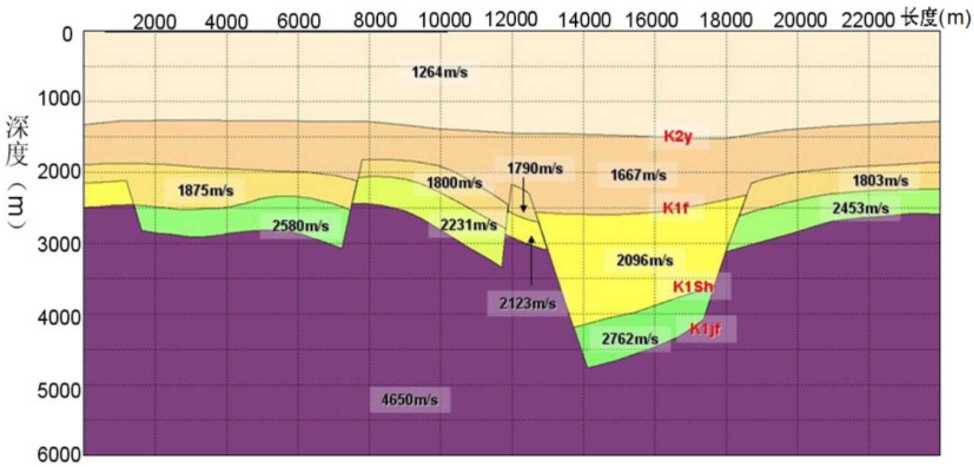

Figure 3. Geophysical model through well ZC3. Note: the *x*-axis represents length; the *y*-axis represents depth

Based on the model, forward illumination was used to generate single-shot records, and the superimposed profile was then obtained through further processing, as shown in **Figure 4**. Based on **Figure 4**, it is clear that the imaging of the main target layer of the stacked profile with 160 coverage times was more accurate and detailed than those of the pre-stack time migration profile with 80 coverage times.

The illumination analysis results were also consistent with the above-mentioned results. **Figure 5** shows the total illumination effects of 80 and 160 coverage times. The 160 coverage times had apparent advantages in terms of illumination intensity of the main target layer, especially in the deep layer. This shows that the excitation optimization scheme with a reasonable increase in coverage times effectively improves the signal-to-noise ratio and imaging accuracy of the exploration target layer in this area [3-7].

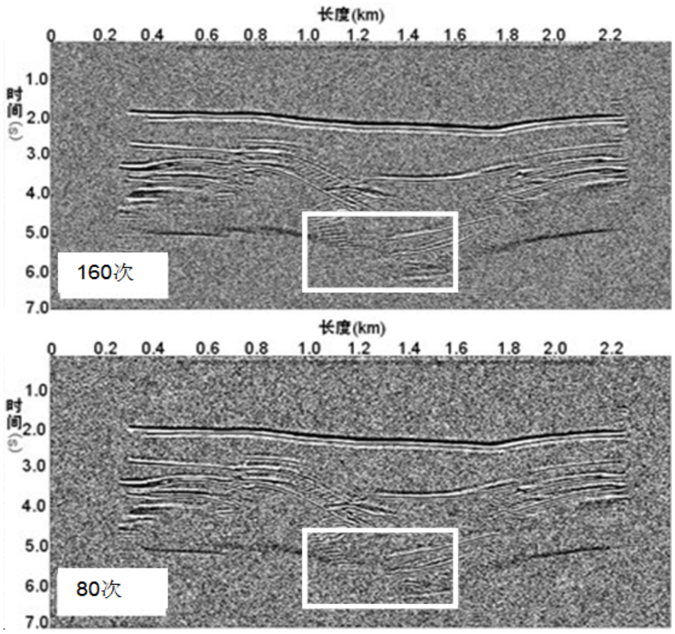

Figure 4. Forward section comparison of different folds. Note: The *x*-axis represents length; the *y*-axis represents time. The number of times in the upper part of the figure is 160 times, and the number of times in the lower part of the figure is 80 times

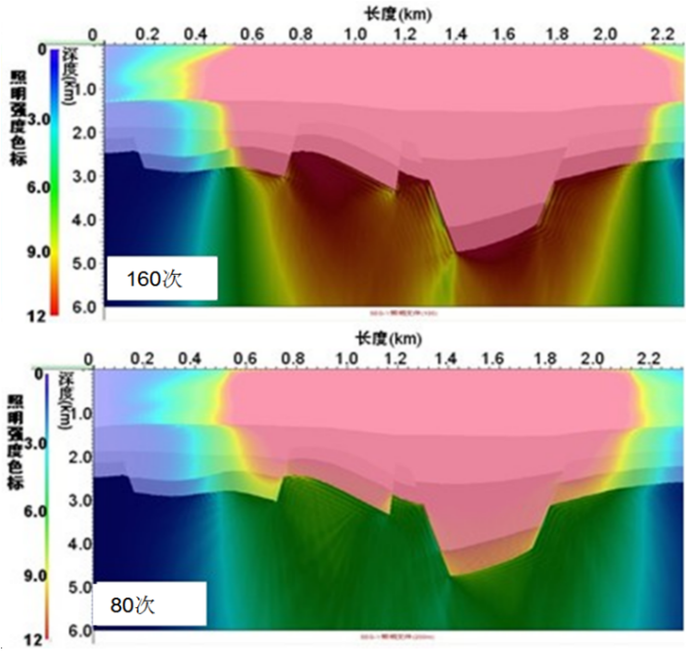

Figure 5. Illumination comparison of different folds. Note: The *x*-axis represents the length; the *y*-axis represents the color code of strength of illumination (left), depth (right)

2.3. Using single-well stimulation instead of combined-well stimulation to achieve cost optimization without compromising the quality of data acquisition

While the shot density increases with the optimization of the number of coverages, the cost of data acquisition also increases. Therefore, it is important to control the cost while ensuring the quality of data acquisition. Therefore, we propose to use single-well excitation instead of combined-well excitation. However, the efficacy of this method needs to be verified through a few tests. With this method, a single-point test is far from enough, and systematic line tests are needed to compare the profile effects of single-well and combined-well stimulation to determine whether such stimulation optimization is feasible [8].

In terms of single-shot quality, the excitation effect of combined wells is better than that of single wells, but the final geological interpretation is carried out on the final seismic stacked profile. This optimization involves doubling the coverage. The question we need to answer is whether increasing the coverage can compensate for, or even outperform, the difference between single well and combined-well single shots. This emphasizes the importance of enhancing line testing [9].

We carried out single-well and combined-well excitation comparison tests on a two-dimensional line, using a 2-line and 2-shot observation system, with the two excitation lines located within the two receiving lines. One of the excitation lines used an excitation factor of 10 kg for a single well, and the other excitation line used an excitation factor of 6 kg for 4 wells. The other acquisition factors were identical for both lines [10].

Judging from the final processed migration profile (**Figure 6**), the signal-to-noise ratio and imaging effect of the target layer of the two-factor profiles were equivalent, so the cost optimization plan of using single-well stimulation is feasible. In this way, data quality is improved by increasing the number, while the cost is controlled.

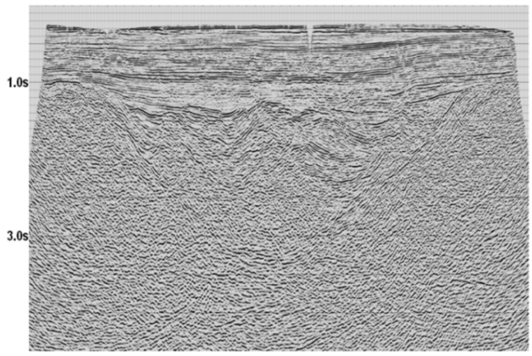

Figure 6a. Migration section of 100-fold (1 × 10 kg).

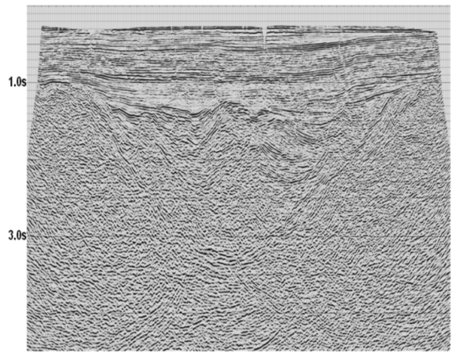

Figure 6b. Migration section of 100-fold (4 × 6 kg).

2.4. Strengthen the observation system to ensure the quality of the collection

There is no doubt that the design of the observation system is an important aspect of seismic data acquisition. In order to ensure the acquisition quality and fulfill the requirements of pre-stack migration processing, the concepts of sufficient sampling, uniform sampling, and symmetric sampling are followed in the parameter design of the seismic acquisition and observation system in the LWT exploration area.

Through acquisition parameter analysis, forward illumination simulation, and observation system evaluation, the 24L3S192R acquisition template was finally adopted. This observation system was greatly enhanced, both in terms of the number of single-line receiving channels and the total number of receiving lines. The size of the panel grids was 12.5 m × 12.5 m. **Figure 7** shows the dip-moveout (DMO) impulse response waveform of the 12.5 m. The uniform distribution of offset and azimuth angles within the grids prevented the collection of footprints [11]. Moreover, from the corresponding F-K spectrum recorded by a single shot (**Figure 8**), it was found that the track distance of 25 m, and the 12.5 m × 12.5 m panel grids prevented the folding frequency of the refracted wave and ground roll wave from aliasing the effective wave frequency. This proved that the panel grid size selected for this seismic acquisition was suitable.

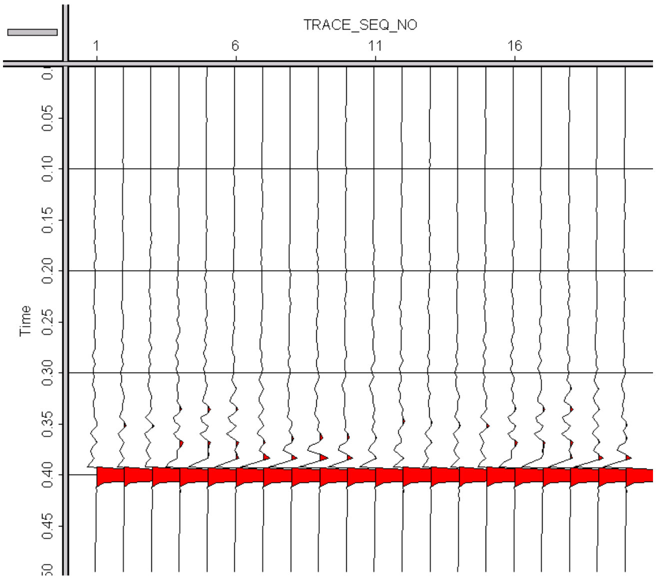

Figure 7. The waveform of impulse response wavelet

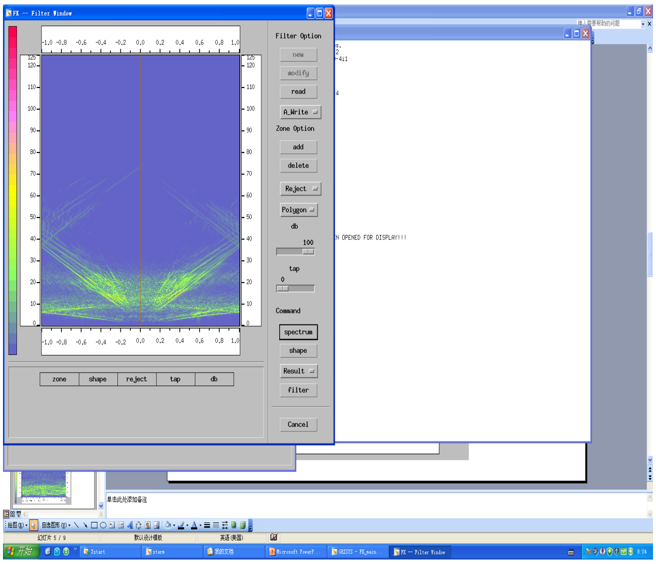

Figure 8. FK spectrum of single shot record

3. Optimization effect analysis: Profile analysis

In short, the excitation optimization plan mentioned above is to use single-well excitation instead of combined-well excitation to reduce cost. The observation system was also optimized by increasing the density of excitation points, the number of single-line receiving channels, and the total number of receiving lines to increase the number of coverages. Besides, small panel grids were used to avoid collecting footprints.

The comparison of the old and new migration profiles of the survey lines at the same position is shown in **Figure 9**. A new seismic profile (top of **Figure 9**) was acquired after executing the excitation optimization plan. Regardless of the signal-to-noise ratio and resolution, or interlayer information and deep imaging, the data quality was greatly improved compared to the old profile collected in 2004 (bottom of **Figure 9**). The quantitative analysis results of the profile spectrum can also be supported. The bandwidth of the deep layers in the new profile (the frame area in Figure 9) is 20 Hz wider than that of the old profile.

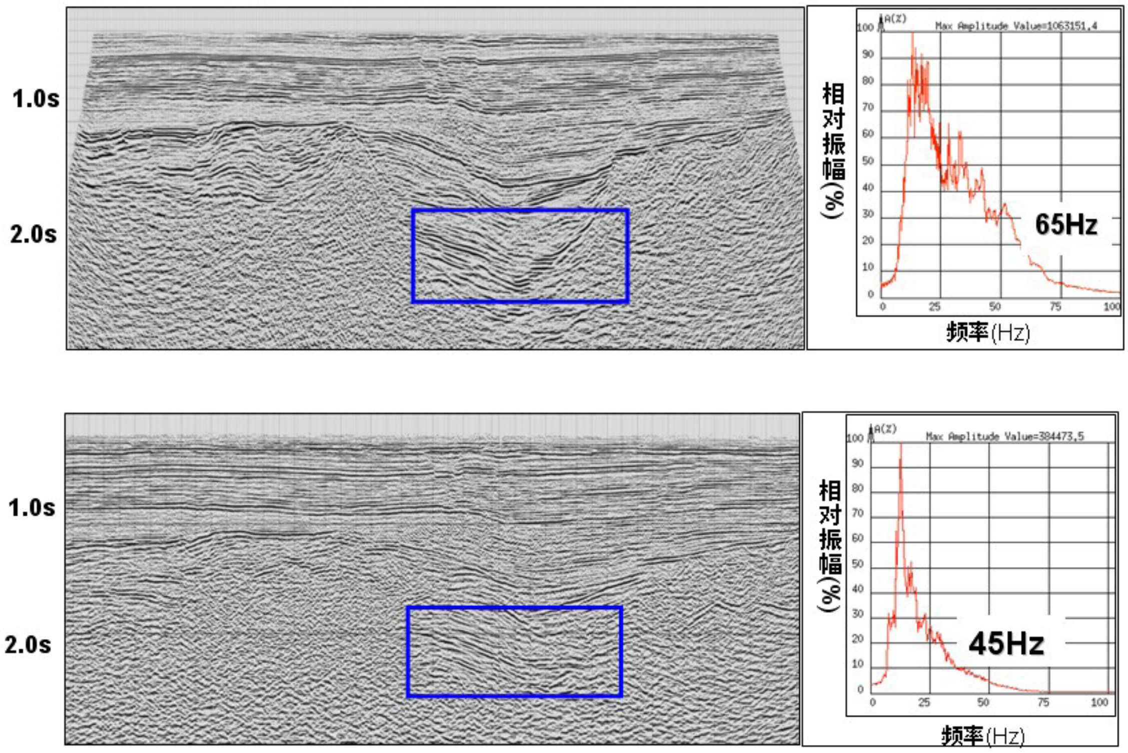

Figure 9 Analysis of optimization effect comparison of new and old sections. Note: The *x*-axis represents the frequency; the *y*-axis represents the relative amplitude

The higher data frequency has greatly improved resolution, enriched information in shallow layers, ensured good continuity for mid-layer events, increased the visibility of microstructural features, strengthened deep reflection energy, clarified structural boundaries, and significantly enhanced imaging quality. This clearly demonstrates the effectiveness of the stimulation optimization scheme described in this article.

4. Conclusion

Through the single-well and combination-well point test, line test, and the application of single-well for the three-dimensional seismic profile in the LWT exploration area in Inner Mongolia, several conclusions can be made.

(1) The signal-to-noise ratio of the target layer stimulated by a single shot fired by a combined well is higher than that of a single shot fired by a single well, and the continuity of the event axis is better. However, the effect of the combined well on noise suppression is greatly weakened after superposition. The stimulation effect of combined wells is basically the same as that of single well stimulation.

(2) By changing the combined well to single-well excitation, the observation system can be optimized, such as increasing the number of single-line receiving channels and the total number of receiving lines, and increasing the number of coverages, all without increasing the cost of data acquisition. These measures improve the data signal-to-noise in areas with low signal-to-noise ratio.

(3) Both combined-well stimulation and single-well stimulation have achieved good results in the LWT exploration area in Inner Mongolia, these methods can be applied in other areas with sufficient testing.

Disclosure statement

The author declares no conflict of interest.

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