Application of MGI Inversion Technology in Coal Seam Thickness Prediction

Pei Sun[1](✉), Xue-feng Li[2], Feng Zhang[1], Bao-quan Zhang[1], Xue-cheng Jia[1], and Hong-yu Jiang[1]

[1] BGP Geological Research Center Inc., CNPC, Beijing, China
sunpei02@cnpc.com.cn
[2] PetroChina Coalbed Methane Company Limited, Beijing, China

Abstract. The overlying strata of the No. 8 coal seam in Block XX of the Ordos Basin are Taiyuan Formation limestone, and the underlying strata are Benxi Formation sandstone and mudstone, with complex vertical lithology combinations. The impedance contrast between the target layer No. 8 coal seam and the roof wave is large and the impedance interface is easy to identify. However, the impedance contrast between the bottom plate wave is small and the impedance interface is difficult to identify. Moreover, due to strong reflection interference from the overlying limestone, seismic attributes cannot reflect the thickness distribution of the coal seam. Currently, the widely used sparse pulse inversion has limited longitudinal resolution and can only predict the approximate distribution of coal reservoirs, making it difficult to quantitatively predict the thickness of the No. 8 coal seam. MGI geological statistical inversion is based on geological information, applies random function theory and geological statistical methods, and can independently adjust low-frequency, medium-frequency, and high-frequency results during inversion, with high vertical resolution. Based on high-precision three-dimensional seismic, drilling, recording, and logging data, this paper first establishes a stratigraphic framework based on fine calibration of wells and shocks, and then interpolates and extrapolates logging data using the minimum curvature method to establish a P-wave impedance model. Then, based on spatial geological modeling, MGI geological statistical methods (rock physics feature analysis, variogram analysis, inversion parameter analysis, etc.) are applied to obtain a longitudinal high-resolution lithology inversion body, and the P-wave impedance

J. Lin (Ed.): IFEDC 2023, SSGG, pp. 124–136, 2024.
https://doi.org/10.1007/978-981-97-0268-8_11

profile is transformed into a lithology profile to analyze the distribution range of the coal seam. Finally, sensitive properties within the No. 8 coal are extracted from the high-resolution inversion body, and the spatial distribution characteristics of the No. 8 coal reservoir are quantitatively predicted. Compared with the coal thickness data drilled, the coal thickness map extracted by MGI geological statistical inversion reveals the developmental distribution range of the No. 8 coal seam more intuitively. This research result effectively improves the prediction accuracy of the No. 8 coal reservoir in Block XX and provides strong technical support for deploying high-yield wells.

Keywords: MGI geological statistical inversion · Spatial geological modeling · Variogram analysis · Sensitive properties

1 Introduction

With the application of three-dimensional seismic exploration in coalbed methane development, using seismic data to predict coal seam thickness has achieved certain results. Currently, the commonly used methods for predicting coal seam thickness are seismic attributes, sparse pulse inversion, and traditional geological statistical inversion [1–6].

Using seismic attributes to predict coal seam thickness is based on the tuning thickness method, that is, as the thickness of the coal seam changes, its amplitude and frequency also change accordingly, thereby predicting the coal seam thickness. Cheng Zengqing proposed calculating coal seam thickness based on the relationship between the amplitude of the coal seam reflection wave and the coal seam thickness [7]. Zhou Zongliang, Xiao Jianling, and others used multiple seismic attributes, selected some seismic attributes with good correlation with drilling and capable of reflecting reservoir characteristics after optimization, to predict coal seam thickness [8].

Sparse pulse inversion is based on trend-constrained pulse inversion algorithms. First, the reflection coefficients are extracted from the seismic traces based on the principle of sparsity, then the synthetic seismic data is generated by convolution with a wavelet. The difference between the synthetic and original seismic data is then used to modify the reflection coefficient sequence until the residual between the two meets the required standard. At this point, the final wave impedance data can be obtained. Peng Suping et al. used well logging-constrained seismic inversion to obtain high-resolution wave impedance profiles, and tracked coal thickness changes based on the difference in wave impedance between the coal seam and roof/floor strata [9].

Traditional geological statistical inversion is a seismic inversion method based on model-based seismic inversion techniques, which uses geological statistical analysis. Geological statistical inversion consists of two parts: random simulation and random inversion. Its basis is random seismic inversion, and the means used is random simulation [10, 11]. There are multiple equally probable outcomes of the inversion results, and appropriate outcomes are selected as predictive results based on geological knowledge.

The above three methods for predicting coal seam thickness have the following problems in practical applications: ① Seismic attributes are affected by tuning frequency. Amplitude increases as coal seam thickness increases without reaching the tuning thickness, and cannot reflect the true thickness of the coal seam when the coal seam thickness exceeds the tuning thickness. ② The longitudinal lithology combination of the 8th coal seam of the target layer in XX block is complex, with the roof stratum in contact with gray rock and the floor stratum in contact with mudstone, and some coal seams contain gangue layers. Traditional single attribute prediction is limited by seismic resolution, which increases the ambiguity of coal reservoir prediction. ③ Sparse pulse inversion is completely dependent on the quality of seismic data itself. The inversion result is greatly affected by seismic noise and the complex vertical lithology combination of the coal-bearing strata in this area. The vertical resolution is limited when mudstones and coal rocks are interbedded, and can only qualitatively predict the rough distribution of coal reservoirs and unable to quantitatively predict the thickness of the 8th coal seam. ④ Traditional geological statistical inversion uses seismic data as a constraint to control the choice of simulated results within the full frequency range of well logging data. It lacks low-frequency information longitudinally, does not match the actual geological situation, and cannot improve the accuracy of predicting the thickness of the 8th coal seam.

MGI geological statistical inversion is a recently developed inversion module of Geoeast software independently developed by Orient Geophysical Company. This inversion adds low-frequency information, makes up for the shortcomings of traditional geological statistical inversion results.

2 Coal Seam Thickness Inversion Using MGI

2.1 Basic Principle of MGI Inversion

Traditional geological statistics inversion uses seismic data as a constraint to control the randomly simulated logging data in the full frequency band range. It requires a large number of iterative calculations, has low computational efficiency, and lacks low-frequency information longitudinally, which is inconsistent with actual geological conditions. MGI geological statistics inversion effectively integrates geological, logging, and seismic data for coal reservoir prediction, as shown in (Fig. 1). The spectrum of the high-resolution acoustic impedance inversion result is divided into three parts: low-frequency, medium-frequency, and high-frequency. The low-frequency part comes from the low-frequency model data, which is interpolated under the control of the logging curve filtered by low-pass at the layer position, and the low-frequency acoustic impedance data is denoted as VL. The medium-frequency part is derived from seismic data obtained by deterministic seismic inversion (sparse pulse inversion) and is denoted as VM. The high-frequency part is obtained by sequential Gaussian simulation of logging data and is denoted as VH. These three parts are combined through spectral fusion, and the final high-resolution acoustic impedance inversion result is obtained as follows: $V = VL^{\cdot}H(0, 0, f1, f2) + \alpha VMH(f1, f2, f3, f4) + BvHH\ (f1, f2, f3, f4)$, where α is used to adjust the proportion factor of the medium-frequency component, β is used to adjust the proportion factor of the high-frequency component, and is used to adjust the proportion of each frequency component.

For continuous variables, sequential Gaussian simulation is the most commonly used stochastic simulation algorithm in geostatistics. The specific implementation steps are: ① normalize the log data; ② determine a random path and access all nodes; ③ at

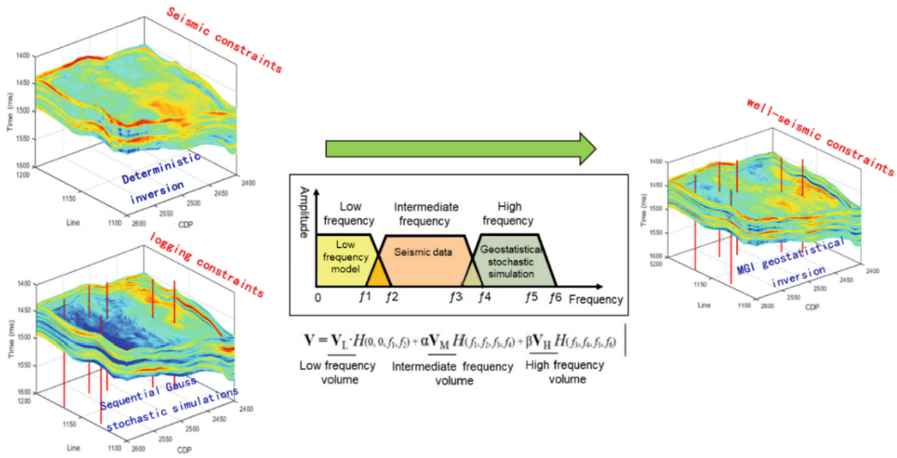

Fig. 1. MGI inversion principle diagram

each node, obtain conditional data consisting of adjacent hard data points (log data) and simulated points, calculate the conditional cumulative distribution function (ccdf) of the current node through Kriging and variogram functions; ④ randomly obtain a value from the ccdf as the value of the node and add the simulated value to the dataset; ⑤ return to step ③ until all nodes are computed; ⑥ transform the simulation results back to the original space by inverse normal transformation.

2.2 Rock Physics Analysis

Rock physics analysis is a feasibility analysis before inversion, mainly through the crossplot analysis of well-logging curves to determine the ability to distinguish rock types. From the intersection analysis of density curves, sonic curves and natural gamma curves of Shan 23 Formation plus Taiyuan Formation (Fig. 2), it can be seen that coal seams have characteristics of low density, low gamma, and high sonic. The intersection of P-wave impedance and gamma (Fig. 3) shows that the P-wave impedance value of coal seams is generally less than 6800 m/s*g/cm3. Therefore, coal seams can be effectively identified and coal seam thickness can be predicted through P-wave impedance inversion.

2.3 Wavelet Extraction and Synthetic Record Calibration

Fine calibration of synthetic records is the basis for high-quality impedance inversion, which can clearly define the wavelet characteristics of the marked layers and the main target layers, and then establish an accurate time-depth relationship, which is also the key to extract seismic wavelets. In theory, extracting the Ricker wavelet that is consistent with the actual seismic spectrum, the resulting synthetic seismic record can well constrain the seismic profile. In practical applications, in order to have better correspondence between logging and seismic profiles and ensure the best match between synthetic records and actual seismic traces, the wavelets of the nearby seismic traces beside wells are extracted for fine calibration of synthetic records.

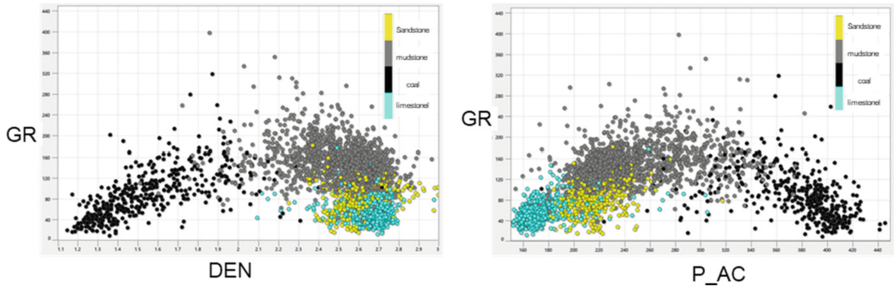

Fig. 2. Density, sonic and gamma curves at well 3-7x2 Shan23+ Taiyuan Formation intersection

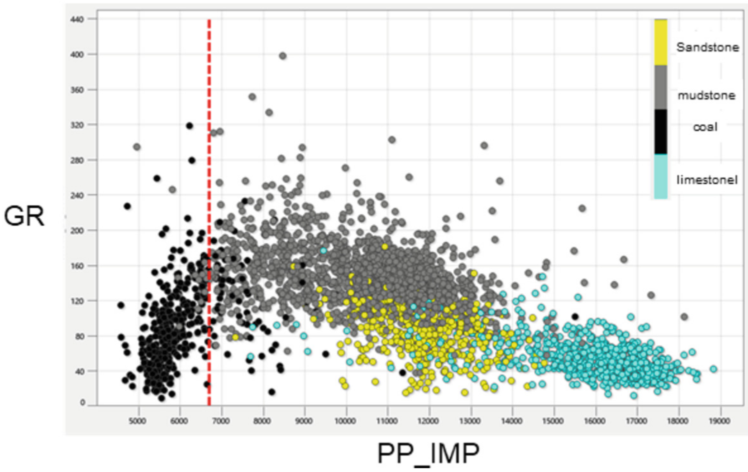

Fig. 3. Longitudinal impedance and gamma intersection diagram of Shan23+ Taiyuan formation in daji3-7x2 well area

Firstly, the near-well seismic traces of a single well are extracted to calibrate synthetic records finely and determine a reasonable time-depth relationship for each well. Then, the average wavelet used for inversion is generated using multiple near-well seismic traces from single wells (Fig. 4), and the accuracy and precision of the extracted average wavelet are analyzed to provide accurate synthetic seismic records for inversion.

Comparison of the calibration results between the synthesized record from wellhead seismic traces and the synthesized record from Rex's wavelet (Fig. 5) shows that the former matches the same-phase axis of the wellhead seismic reflection better, with a higher correlation coefficient between the synthesized seismic record and the wellhead seismic trace. From the seismic profile across the well (Fig. 6), the former composite record has better consistency among multiple wells and matches the same-phase axis of the seismic reflection better. Through the calibration of the synthesized record from wellhead seismic traces, the correlation coefficient of the composite record in the target interval reaches over 80%, which provides an accurate initial velocity model for inversion.

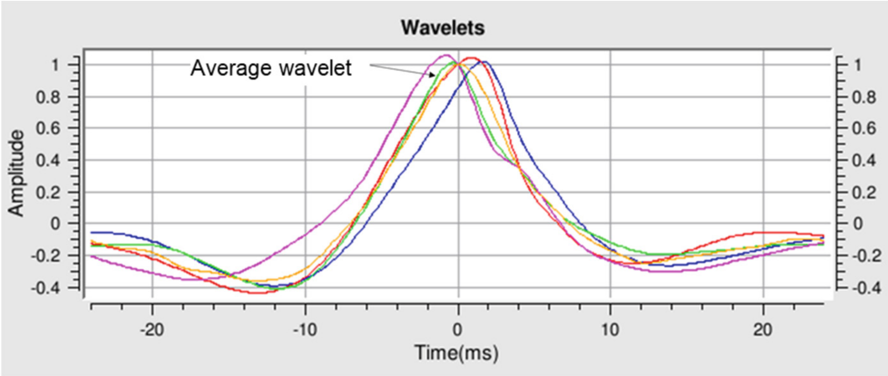

Fig. 4. Average Subwave of Wellside Seismic

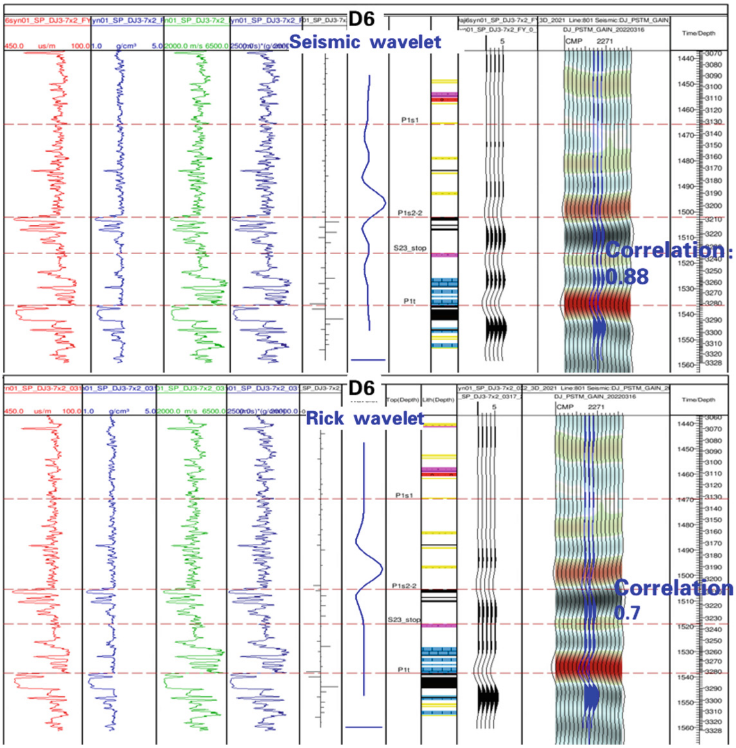

Fig. 5. Comparison of Synthetic Record Calibration

2.4 Establishment of Initial Geological Model

The establishment of the initial geological model is mainly achieved by horizontally interpolating well curves in the time domain along the interpreted stratigraphic positions. Constrained by well properties, the range of inversion results is controlled and seismic

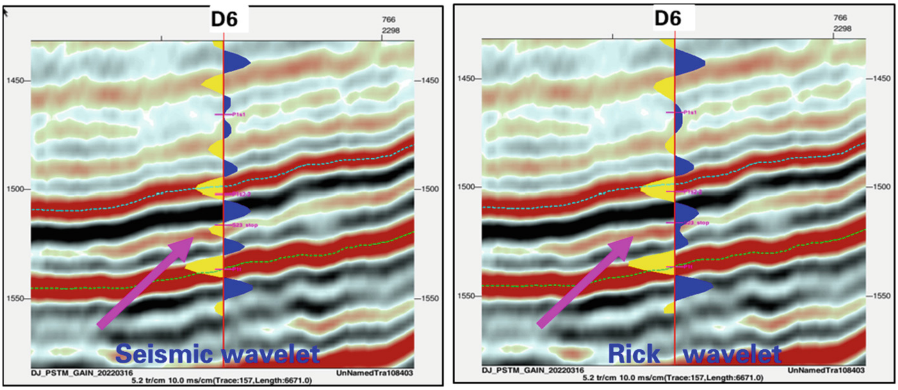

Fig. 6. Comparison of well-seismic calibration profile

low-frequency content is supplemented. The model effectively improves the resolution of seismic inversion and plays a crucial role in interpreting inversion results.

Firstly, the inversion framework model is defined to control the morphology of the target layer through parameters such as unconformable contact relationships (normal sedimentation or erosion) and sedimentary patterns of stratigraphic units (parallel top surface, parallel bottom surface, proportional). An automatic layer intersecting framework model is established, and small layer models are divided according to the sedimentary pattern. Then, the longitudinal wave impedance model is spatially interpolated. Under the constraint of the stratigraphic model, converted well data is inputted, and the minimum curvature interpolation method is used for interpolation and extrapolation of log data and TV data. A high-resolution longitudinal impedance model (Fig. 7) is generated by spatial interpolation.

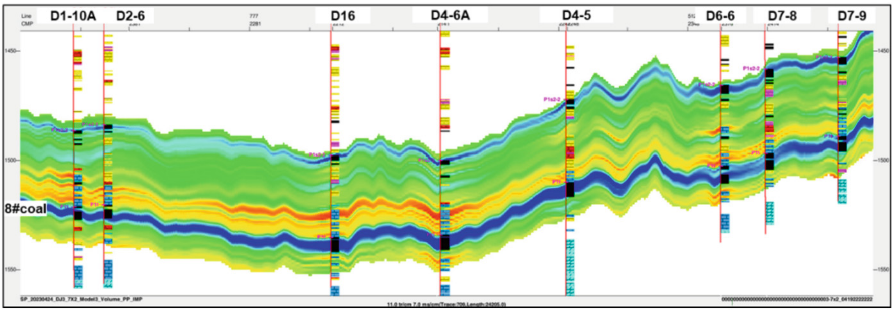

Fig. 7. Profile of longitudinal impedance model

2.5 Inversion Parameter Analysis

The low-frequency body of the inversion parameters comes from the model data body, and the frequency filtering range (f1, f2) of the low-frequency body is used to adjust the low-frequency component of the inversion result. The mid-frequency body comes from the seismic data inversion result, and the frequency components (f1, f2, f3, f4) are jointly determined by the low-frequency body and high-frequency body filtering parameters. The high-frequency body comes from MGI geological statistical random simulation, and the filtering range (f3, f4, f5, f6) controls the high-frequency component of the inversion result. Alpha is used to adjust the proportion of mid-frequency components, mainly from seismic data, and beta is used to adjust the proportion of high-frequency components, mainly from random simulation (Fig. 8). In the analysis of the misfit function, the main deformation and secondary deformation control the speed of changes in the random simulation results on the plane. The larger the value, the more continuous the formation, and the smaller the value, the faster the formation changes. The vertical deformation controls the change of the formation thickness in the longitudinal direction. The larger the value, the thicker the formation in the random simulation results, and the smaller the value indicates that the formation is thinner.

Among these parameters, the high-frequency range supplemented by the model, the mid-frequency proportion factor, the high-frequency proportion factor, and the variance function have a greater impact on the inversion results. The high-frequency range supplemented by the model mainly controls the frequency band range that participates in the frequency domain fusion. If the high-frequency band is too low, the gangue layer between coal seams will be identified as coal-rock, and the coal-rock containing gangue layers will not show obvious impedance changes in the inversion profile. If the high-frequency band is too high, although the resolution of thin coal seams is improved in the vertical direction, the inversion result modeling is seriously affected horizontally. The high-frequency proportion factor mainly increases the amplitude value of the high-frequency band, and the mid-frequency proportion factor mainly reduces the amplitude value of the mid-frequency band. These two parameters are mainly used to highlight the amplitude information of the high-frequency band. When selecting inversion parameters, while complying with geological rules, it is also necessary to modify the inversion parameters appropriately based on the desired thickness of the target layer of coal seams.

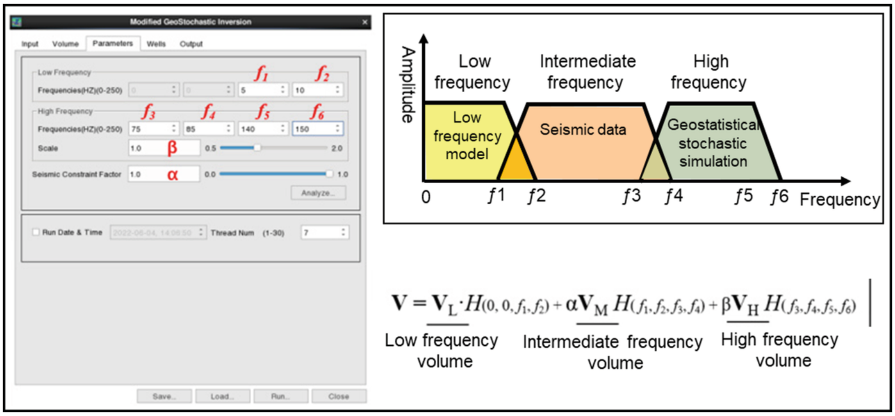

Fig. 8. Schematic diagram of inversion parameter description

3 Effect of MGI Inversion Application

The results of MGI geostatistical inversion are shown in (Fig. 9). The 8# coal seam in the figure is represented by a blue low impedance value. The longitudinal resolution of MGI geostatistical inversion is significantly improved compared to the sparse pulse impedance inversion in (Fig. 10), while the lateral resolution retains the characteristics of seismic data. The inversion results show a good correspondence with actual drilling, and not only can identify the lithological boundaries of the top and bottom plates of large coal seams, but also have a clear response on the profiles of coal seams with gangue,indicating reliable inversion results.

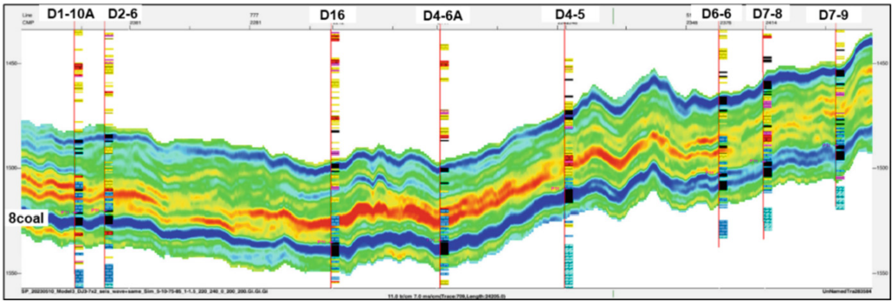

Fig. 9. MGI geological statistics rice evolution profile

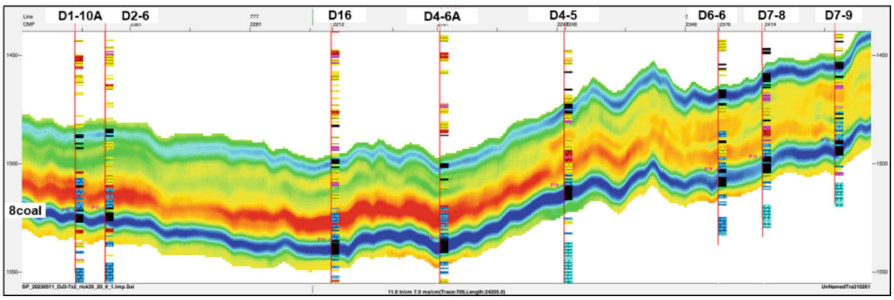

Fig. 10. Sparse pulse inversion profile

The process of obtaining seismic reflection profiles from inversion profiles is called seismic wave impedance forward modeling. By using the MGI inversion results for forward modeling, synthetic seismic profiles can be calculated and compared with actual seismic profiles (Fig. 11). It can be seen that the seismic reflection characteristics of coal layer 8# in the two have a good corresponding relationship, which further confirms the reliability of the inversion results.

Based on the inversion results and the low impedance characteristics of coal seams, the minimum wave impedance attribute map of coal seams was extracted. (Fig. 12) shows a comparison between the predicted coal seam thickness by three methods and the

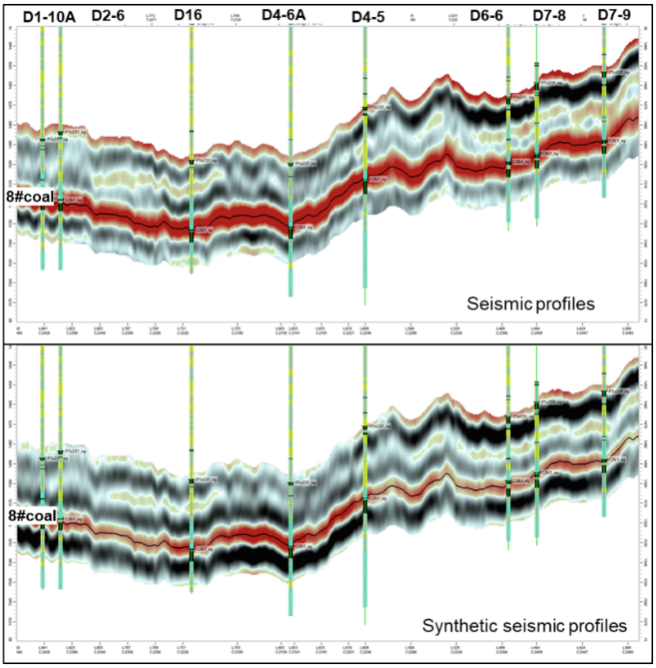

Fig. 11. Comparison of seismic profile and synthetic seismic profile

actual drilling-exposed thickness. It can be seen from the figure that geological statistical inversion predicts coal thickness more accurately and is closer to the coal seam thickness exposed by drilling, with an average accuracy of over 85%. The prediction effect of MGI geological statistical inversion on thin coal seams in this area is good.

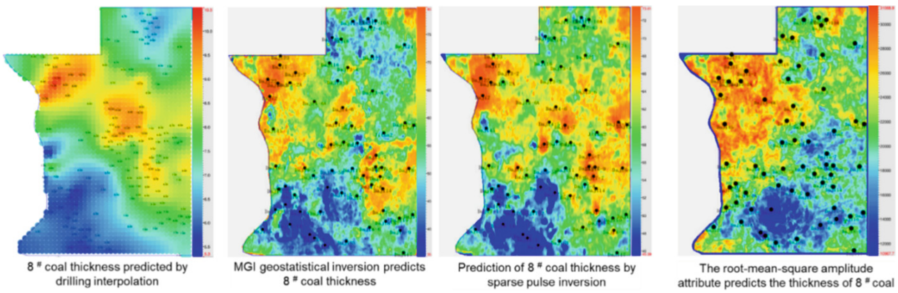

Fig. 12. Comparison of coal seam thickness prediction by three methods with actual drilling exposed thickness

According to the inversion results of MGI geological statistics, combined with drilling and logging data, the thickness variation of coal seam No. 8 in well area 3–7 towards 2 was analyzed and predicted. From the thickness map of coal seam No. 8

(Fig. 13), it can be seen that coal seam No. 8 exhibits a large area of continuous distribution and has a relatively thick overall thickness, with a main thickness of 8–10 m mainly distributed in the northwest-southeast part of the study area.

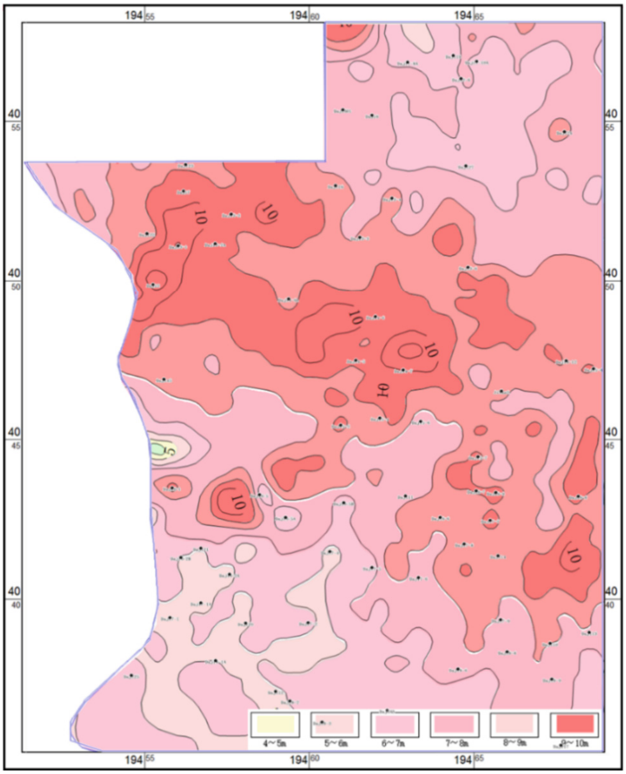

Fig. 13. Contour map of thickness of coal seam No. 8

By studying the error statistics of the predicted thickness and actual thickness of coal seams in 66 boreholes within the area, it can be seen that the accuracy of predicting the thickness of coal seam #8 is higher. The absolute error value of the thickness is less than 0.2 m, and the prediction accuracy is reliable. MGI geological statistical inversion has a good prediction effect on thin coal seams in this area. The thickness errors are shown below (Fig. 14).

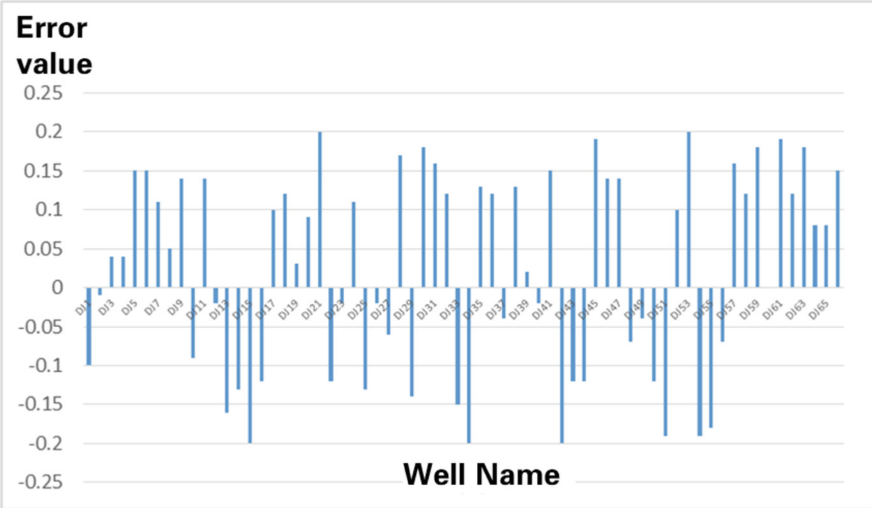

Fig. 14. Thickness error between pre-drilling prediction and actual drilling result

4 Conclusion

(1) Compared to traditional geostatistical inversion, MGI inversion is more flexible, decoupling the results of each frequency component and allowing separate adjustments of low-frequency, medium-frequency, and high-frequency results. By combining geological statistical simulation with seismic inversion, it can further improve the efficiency and accuracy of inversion.

(2) In this area, MGI impedance geostatistical inversion technology was applied to predict the thickness of coal reservoirs, greatly improving the vertical resolution of seismic data, maintaining consistency with lateral extrapolation trends and seismic information, and achieving a prediction error of less than 1 m. The accuracy of reservoir prediction is high, providing guidance for later-scale production planning.

References

1. Sun, X., Zhang, F., Zhang, B., et al.: Seismic prediction method for tight gas thin reservoir in coal measure strata: Taking Daning-Jixian block in Ordos Basin as an example.Nat. Gas Geosci. **33**(7), 1165–1174 (2022)
2. Zhang, F., Jia, X., Zhang, X., et al.: Application of thin reservoir prediction technology based on facies-controlled inversion at eastern margin of ordos basin. OGP, **57**(S1), 215–220 (2022)
3. Diao, W., Tong, J., Zhang, B., et al.: Fcaies-controlled inversion prediction for tight thin sand layers dis-tribution. OGP, **57**(S1), 172–176 (2022)
4. Jia, X., Zhang, F., Li, X., Yang, X., et al.: Prediction technique of thin sandstone reservoir affected by dual coal seam. Open J. Yangtze Oil Gas **7**(4), 231–239 (2022)
5. Zhang, F., Zhang, M., Li W., et al.: Identification of low sequence faults and microstructures in tight reservoirs. In: 2021 SPG, pp. 1305–1307 (2021)

6. Zhang, X., Zhang, F., Hu, X., et al.: Fine interpretation method and quality control of sand formation in Fuyu Reservoir, Qian'an oilfield, Songliao basin. In: 2022 SPG, pp. 1112–1114 (2022)
7. Cheng Zengqing, W., Yifeng, Z.Z., et al.: Method for quantitative interpretation of coal seam thickness by seismic reflection waves. Chinese. J. Geophys. **1**, 657–662 (1990)
8. Zongliang, Z., Jianling, X.: Optimization processing of seismic attributes and quantitative interpretation of reservoir thickness. Xinjiang Geol. **20**(3), 262–266 (2002)
9. Yansheng, G., Zhaoping, M., Ruizhao, Y., et al.: Application of seismic attributes in coal seam thickness prediction. J. China Univ. Min. Technol. **33**(5), 557–562 (2004)
10. Yameng, Z., Shoujun, G.: Random seismic inversion method based on sequential Gaussian simulation. In: CJ/China Geophysics 2013 - Proceedings of the 20th Session (2013)
11. Yuecheng, S., Guangke, M., Fang, L., et al.: Study and application of seismic inversion, geological modeling and reservoir simulation based on geostatistics inversion. In: CJ/SPG/SEG 2014 International Geophysical Conference (2014)