Dynamic Update Method of Working Face Geological Model Driven by Multi-Source Data

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Research

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Dynamic Update Method of Working Face Geological Model Driven by Multi-Source Data

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Abstract In order to build a high-precision dynamic geological model to serve the intelligent mining, working face is explored step by step through the comprehensive prospecting technology. A multi-source data fusion method was applied to realize mutual verification, supplement, fusion and interpretation of non-uniform heterogeneous geological data to obtain a high-precision geological data volume. Also, the dynamic update model method was proposed to update 3D geological model of working face quickly so that the accuracy of the geological model can be improved effectively. Furthermore, cutting path planning technology was developed based on the dynamic geological model. The field test showed that the cutting path planning based on the high-precision dynamic geological model can improve the coal mining efficiency and improve the fusion efficiency between geology and coal mining systems. Dynamic update of multi-attribute geological information should be studied and developed to improve the automatic level of mining driven by geological data.

Keywords comprehensive prospecting technology, data fusion, geological modeling, dynamic update, cutting path planning

1 Introduction

Intelligent mining is the key of achieving the goal of safe, efficient and green coal mining, and the direction of development of coal industry (Ralston et al. 2017; Dunn et al. 2015). China's coal industry experiences the iconic stage of manual coal mining, semi-mechanized coal mining, mechanized coal mining, integrated mechanized coal mining, and automated coal mining in past decades. Currently, it is gradually moving from the automated mining to the intelligent mining. Especially during China's twelfth Five-Year Plan (12th FYP) period (2011-2015), China's coal intelligent mine technology has made significant technical progress in coal mining machinery automation, working face alignment, autonomous follow-up of hydraulic support, remote real-time monitoring and mining techniques (Wu et al. 2008; Xie et al. 2020; Li et al. 2020b). Meanwhile, intelligent coal mining mode, which is featured with autonomous follow-up of hydraulic support, coal machinery memory cut, video monitoring and remote intervention control has been applied in the mining working face with simple geological conditions successfully (Li et al. 2021). In 2014, Shaanxi Huangling Mining Co., Ltd. cooperated with

China Coal Technology Engineering Group and other units, broke through the technology of ground control and shearer memory cutting to stabling operation in No.1 coal mine for the first time. Mining techniques such as the memorized cutting circle for autonomous cutting, autonomous navigation, were developed to realize the workerless intelligent mining in the working face (Mao et al. 2021). However, memorized cutting adopted by most of the intelligent mines failed in the complex and variable geological conditions(Hu 2013; Dong 2021; Li 2019).

Several mining experts have proposed targeted improvement in response to the shortcomings of memorized cutting (Wang et al. 2020; Shi et al. 2016). Yuan et al. (2019) put forward the definition of precise coal mining. Also, they pointed out that the transparent geological conditions based on geophysical prospecting and multi-physical field coupling is an inevitable requirement for precise mining. Wang (2019) framed eight systems for intelligent coal mine and pointed out that the 4D-GIS transparent geological model and dynamic information system are the key technologies to realize intelligent coal mine.

Still, there are many unsolved challenges in building the geological model of working faces. For example, 3D geological modeling used for exploring oil reservoirs and geological numerical simulation reveals the changes of sedimentary facies in a large area, which is established by drilling data and geostatistics. This geological model can reach meter level accuracy or even lower. However, considering the coal mining process requirements, accuracy requirement of the research object should be no less than the decimeter level. In addition, key factors affecting the accuracy of the geological model include the quantity of data types and volume besides interpolation modeling methods. It is not easy to enhance the model accuracy to centimeter-level due to the sparse ground drilling data. There are several traditional ways to improve the modeling accuracy, such as adding drilling holes or using new algorithms to improve the interpretation accuracy of seismic surveys (Zhu et al. 2019), while these methods are time-consuming or difficult to make a breakthrough in a short period.

A constructing method for a high-precision dynamic geological model used in intelligent mining is proposed, considering the drawbacks of memorized cutting and the existing prospecting and mining technology. Key technologies involve: 1) comprehensive prospecting, achieving high-precision prospecting of the coal seam conditions at the working face; 2) multi-source heterogeneous data fusion constructing high-precision 3D geological model of the working face; 3) dynamic exploration data-driven dynamic updating 3D geological model. The cutting algorithm is used to obtain the cutting curves based on the geological model. Finally, the cutting curves are sent to the coal mining machine to realize intelligent planning mining.

2 Multi-source geological exploration data of working face

The complex geological conditions have become a challenging factor limiting intelligent coal mining. Cheng et al. (2019) proposed the idea of constructing a multi-level, progressive, high-precision geological model based on different prospecting techniques. In order to provide accurate geological navigation to coal machinery, a high-precision 3D geological model of the working face should be constructed. The geological model collects comprehensive geological data, including the high-precision data body obtained from geological exploration before and during the mining period. Comprehensive prospecting system is applied to fully explore the primary geological conditions based on occurrence feature in coal strata, as shown in Fig.1.

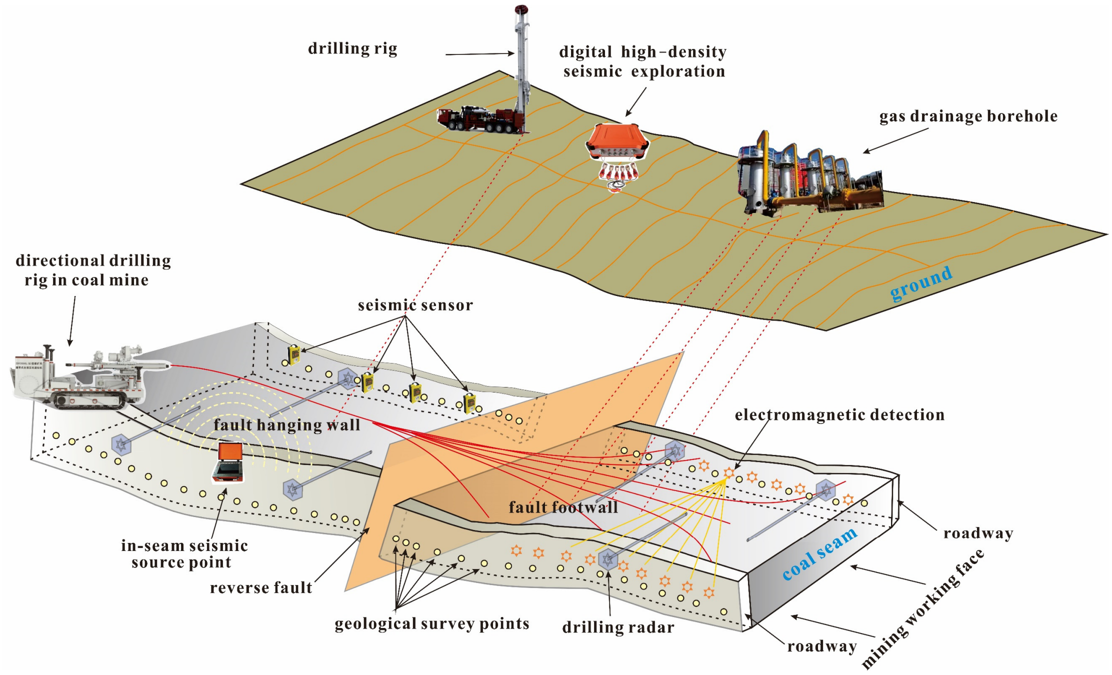

Fig.1 Comprehensive exploration technology system for working face

Before the excavation period, ground prospecting such as 3D seismic surveys, electromagnetic prospecting, and ground drilling is implemented. Before mining period, further prospecting of inside and near the working-face such as in-seam seismic survey, drilling logging, electromagnetic prospecting etc. is implemented. During mining period, detailed prospecting in the mining area such as seismic surveys, resistivity monitoring, geological cataloguing, dynamic image identification, etc.is implemented.

3 High-precision geological modeling method for working face

3.1 Multi-source data fusion

The multi-source heterogeneous data is featured with different sources and structures. In order to construct a high-precision geological model, the multi-source heterogeneous data must be effectively fused and unified into a same spatial coordinate system. Since the single geological exploring data source is insufficient in prospecting accuracy and interpretation reliability, cross-validation method of geological exploration data based on the spatial fusion of multi-source heterogeneous geophysical data is proposed to improve exploration's overall accuracy and reliability. Liu et al. (2020) proposed the spatial location of coal seams and the internal geological structure can be predicted by mutual cross-validation method of geophysical survey data, drilling data and mining exposing data. When seismic data is available, the multi-source data fusion based on seismic dynamic interpretation can be applied. The dynamic interpretation of geological and seismic data is used to achieve the goal of predicting the geology structures and the coal seam surface of the working face. In static interpretation stage, layers are labeled. Also, coal seam floor and structures are interpreted according to high-quality seismic superposition or migration data set. Meanwhile, coal seam thickness and lithology of roof and floor are predicted, according to wave impedance data volume, Quasi-natural gamma body, etc. The geological information revealed by excavation roadway, including roof and floor, coal seam thickness and structures, is collected using measurement technology. Then, the spatial form and structure of the coal seam floor are updated with the constraints of the new geological information. The primary task of dynamic interpretation is to determine the basic geological condition of the working face, build the basic geological framework of transparent working face, detect the main geological anomalies, and provide a high-precision data volume for the geological modeling of the working face.

3.2 High-accuracy dynamic geological modeling

3.2.1 Dynamic model updates

A high accuracy coal seam model which meets the requirements of autonomous coal mining is the key of cutting path planning. The accuracy of the static coal seam model constructed with static geological data is not sufficient to provide geological navigation for cutting path planning. Therefore, a working process is proposed to update the prediction of coal seam spatial form and dynamic coal seam model using multi-level, progressive, and high-precision coal seam geological exploration technology. The dynamic geological model of coal mining working face is a high-precision geological model constructed by fusing the static geological data before mining and the dynamic geological data during the mining process. In conclusion, the dynamic update of the model is a process of collecting the roof/floor revealing data and estimating coal seam surface with interpolation methods. The model updating process is shown in Fig.2.

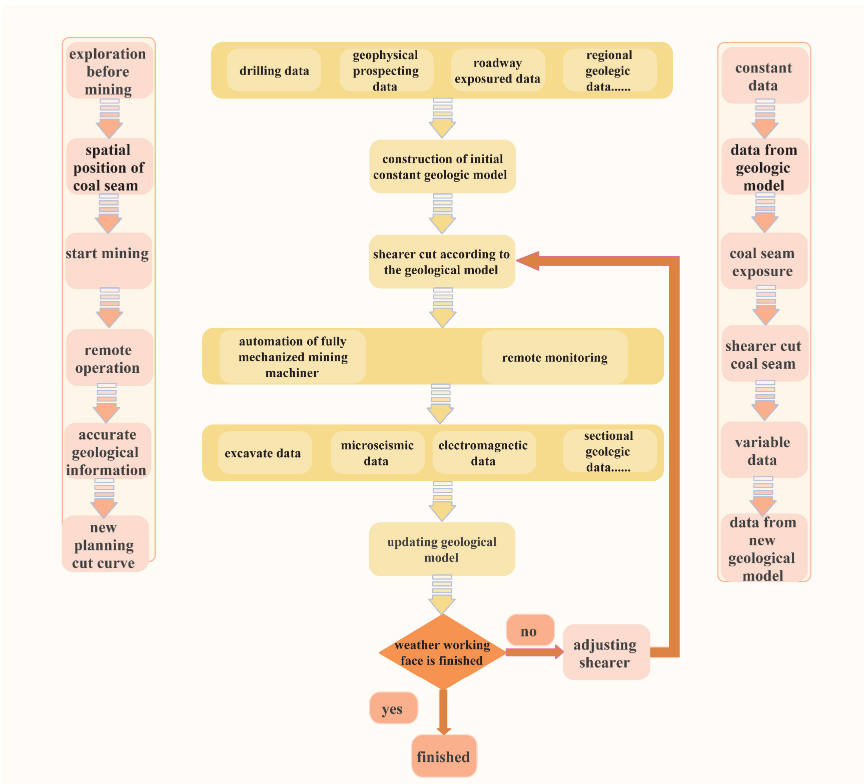

Fig.2 Flow chart of dynamic update process of geological model

3.2.2 Model interpolation algorithm

Constrained interpolation is applied with non-uniform discrete geological data points to construct a high-precision geological model(Le et al. 2014; MacCormack et al. 2018). The discrete smooth interpolation (DSI) algorithm creates a grid of interconnected nodes by constructing a discretized natural body model. If the nodes in the grid satisfy some constraints (known node data, geological structure and etc.), the values of the location grid points can be obtained by solving linear equations (Ming et al. 2010; Song et al. 2019).

Build discreet model of mining working face: $M^n\left(\Omega, N(a), \varphi(a), C\right)$, where Ω is the set of all points in the working face, including unknown and known points; $\varphi(a)$ is n-dimensional vector function on set Ω; C is the constraints for interpolation of the working face; $N(a)$ is neighborhood of point a.

For constraints for interpolation of the working face C, consider the roughness as main constraints, neglecting the soft constraints. According to the definition of smooth discrete interpolation, the global roughness is calculated as follows:

$$R(\varphi) = \sum_{\mathrm{a} \in \Omega_C} \mu(a) \cdot R(\varphi|a) \qquad (1)$$

In Equation(1), $\mu(a)$ is Non-negative weighting function which could indicate the magnitude of the contribution for different points within the working surface to the global roughness, $R(\varphi|a)$ is the local roughness that is calculated as follows:

$$R(\varphi|a) = \left\{ \sum_{\beta \in N(\mathrm{a})} v^v(\alpha, \beta) \cdot \varphi^v(\beta) \right\}^2 \qquad (2)$$

where $v^v(\alpha, \beta)$ is the weight on node a, v is different dimension, $\varphi^v(\beta)$ is vector function of the known points.

After obtaining the global and local roughness, the implicit function in the working face can be built. While neglecting soft constraints, the whole constrains function shows as follows:

$$R^*(\varphi) = R(\varphi) + \rho(\varphi) = R(\varphi) = \sum_{a \in \Omega} \mu(a) R(\varphi|a) \qquad (3)$$

$$R(\varphi|a) = \left\{ \sum_{\beta \in N(\mathrm{a})} v^v(\alpha, \beta) \cdot \varphi^v(\beta) \right\}^2 = \varphi^T v(\alpha, \beta) v(\alpha, \beta)^T \varphi \qquad (4)$$

where $\rho(a)$ is the soft constrains.

Then find the first-order partial derivative of the constraint equation with respect to $\varphi(a)$ and let the derivation function equals to 0. $\varphi(a)$ is calculated as follows:

$$\varphi(a) = -\frac{1}{M(a)} \left\{ \sum_{a \in \mathrm{N}(a)} \left[v(\alpha, \beta) \sum_{\substack{\beta \in \mathrm{N}(a) \\ \beta \neq \alpha}} v_\beta(k) \varphi(\beta) \right] \right\} \qquad (5)$$

$$M(a) = \sum_{a \in \mathrm{N}(a)} \varphi(a) v(\alpha, \beta)^2 \qquad (6)$$

Finally, the objective function is solved by equation (5), getting $\varphi(a)$.

3.3 Geological model correction based on mining data

Intelligent cutting technology based on a geological model is the processing of constructing a dynamic geological model of working face and cutting path planning by comprehensive prospecting, mining status, and measurement data (Li et al. 2020a; Li et al. 2014). In order to apply model cutting, the coordinate is transformed based on an absolute reference point so that the geological model and the mining system achieve real-time joint under the unified real coordinates.

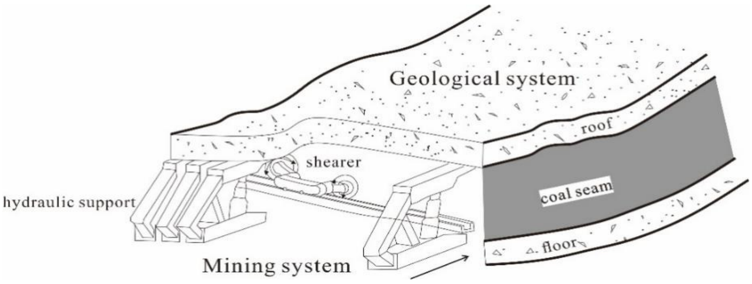

Fig.3 Transparent working face mining model construction based on geological model

Model CT cutting algorithm is developed and applied on 3D geological body of the working face. The algorithm can divide into several steps:

(1) Setting the grid steps in both directions of width and length of coal mining face, and meshing the digital model of the coal seam in both directions, after which the grid is projected to the 2D horizontal plane;

(2) Transforming the cutting path planning of the coal mining machinery into the plane projection of the grid and then, approximately dividing the planning cutting path into a finite number of straight-line segments;

(3) Transforming the coal seam roof and floor surfaces into the two-dimensional horizontal plane. Firstly, calculate the line equation for each straight line segment between the start point and endpoint of the cutting path sequence. Secondly, calculate the plane coordinate of the intersection point between the straight line segment and elevation height of that point. Then, connect the control points on coal seam roof and floor surfaces according to the direction of the straight line segment and finally get the roof and floor surfaces curve.

The optimal planning cutting curve of the mining working face in a specific range is calculated based on coal mining requirements. Intelligent cutting is implemented based on the unified data integration platform, using the data integration process between the central control system and the cutting curves model formed by multiple surface curves. Shearer cuts coal seam automatically on the basis of high-precision 3D geological model and the information of shearer location and machinery operating conditions. The model updates dynamically by comparing the actual cutting information and planning cutting path in the next cutting circle.

4 Field test

4.1 Working face overview

In order to verify the application effect of intelligent coal mining cutting path algorithm based on the high-precision dynamic geological model, a field test was carried out at a mining working face. This working face is located in the west wing of No.8 Minefield Area, with a strike length of 950 m and a face width of 261 m. The coal seam thickness varies from1.3 to 3.0 m, with an average of 2.72 m. Two folds are located at the working face, and the coal seam rises gradually from the stopping line towards the open-off cut. The first fold is located 600m~650m from the stopping line; the second one is near the open-off cut, at the range of 20m-100m in the direction from the intake roadway to return roadway.

4.2 Comprehensive geological exploration data

Comprehensive geological exploration was carried out in the working face in order to find out the occurrence feature and structure distribution of coal and rock strata in the working face.

(1) High-precision geological cataloguing

The scope of the geological cataloguing is the intake roadway, return roadway and open-off cut of the working face. The roadway spatial information including roadway marker points, roadway slope, bottom elevation height, top elevation height, coal seam thickness, coal seam production, and the drilling hole's coordinate are measured using high-precision electronic total station. The geological cataloguing reached the fine measurement requirements of centimeter level.

(2) In-seam borehole measuring and logging

There are 31 drilling sites (319 gas drilling holes) distributed in the intake and return roadways. According to the distribution of holes, In-seam borehole measuring and logging were implemented in 54 effective drilling holes, of which 41 holes with completion of trajectory measurement, in-hole video, and natural gamma logging and 13 holes with completion of trajectory measurement and in-hole video.

(3) In-seam seismic surveys

Based on the geological condition, transmission and reflection in-seam seismic surveys were carried out at the working face. An abnormal structural belt was detected based on the interpretation result of transmission and reflection in-seam seismic surveys, as shown in Fig.4.

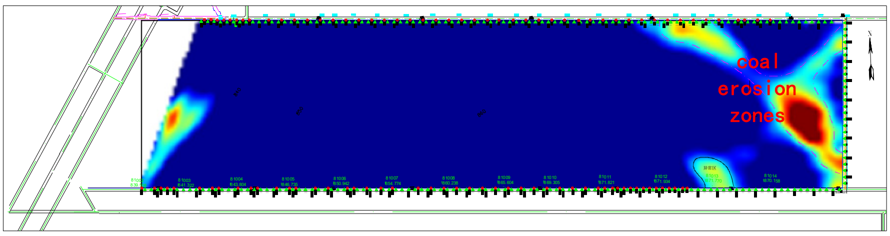

Fig.4 In-seam seismic surveys imaging map of the working face

(4) Comprehensive geological analysis

According to the interpretation results and geological conditions, the conclusion is that there was a large coal erosion zones in the working face near the open-off cut. The extension range of the coal erosion zones in the working face has been accurately defined, which provided geological guidance for the rational planning of working face.

4.3 Multi-source geological data fusion analysis

Multi-source heterogeneous data were fused and unified into a same spatial coordinate system due to the different sources and structures of data. For the prospecting data in time domain, time-depth conversion is essential in spatial fusion. For the targeted intelligent working face, the geological anomaly was predicted to be a coal erosion zone by cross-verification between sandstone zone revealed by roadway and in-seam seismic survey. The coal erosion zone was verified by in-seam borehole logging. In addition, the cross points between in-seam boreholes and coal seam surface were determined comprehensively according to roof and floor lithology revealed by roadways, surface drilling, in-seam seismic survey, and logging.

4.4 High-precision dynamic geological modeling

The multi-source heterogeneous geological data were processed using space-time fusion technology. Then, discrete smooth interpolation (DSI) algorithm was applied to construct high-precision geological model of the mining working face. The geological data collected before mining, including surface drilling data, roadway refinement measurement, in-seam boreholes logging, were used to build static model. With the measured cutting profiles, the model was refined using a dynamic update algorithm. The updating duration is less than 100ms. In order to verify the accuracy of working face model, the model was updated dynamically with mining data when the working face was mined at 540 m. The statistic shows that the prediction error of coal seam thickness in the areas of 8 m and 15m in front of working face are lower than 0.15m and 0.3m respectively.

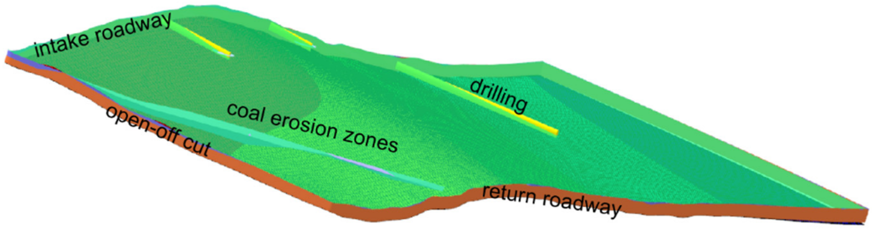

Fig.5 Geological model construction of the working face

4.5 Cutting path planning based on the geological model

The roof and floor cutting profile is generated by cutting high-precision geological model vertically in the direction of mining, shown in Figure 6. Then, the cutting path planning of the geological model is implemented to attain the spatial curve of the coal seam roof and floor at the current cutting circle, which refers as planning cutting curve. Finally, following the step above, the multiple planning cutting curves of the whole working face can be subsequently obtained. The drum height and shearer path can be set according to this spatial coordinate curves. Meanwhile, the correction amount of current position can be calculated based on the sensing data information such as posture positioning. Using the correction data, intelligent planning cutting driven by geological model navigation could be applied integrated with automatic mining machinery.

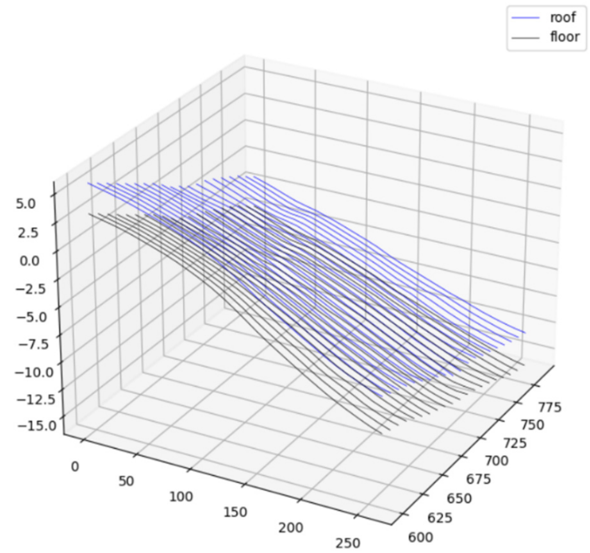

Fig.6 Planning truncation based on geological model

Shearer accomplishes multiple cutting circles automatically on the basis of planning cutting curves. Field test shows that the actual cutting curve of a cutting cycle matches the planned cutting curve in a relative high level. Almost all the cutting circles are completely accomplished under the unmanned automatic mining mode, expect for cutting triangle coal stage at the start and the end of the working face involved remote manual intervention. As a result, the intelligent mining mode based on a high-precision dynamic geological model successfully implemented in the field test.

5 Conclusions

(1) Before the mining period, the high-precision geological prospecting method could be applied to obtain the geological conditions accurately. Also, according to alignment, cross-validation, and fusion analysis of the geological data using multi-source data fusion method, the high-precision geological model of the working face could be constructed.

(2) During the mining period, the high-precision dynamic geological model for intelligent mining could be refined using dynamic update method on the basis of geological data revealed in the working face.

(3) The field test shows that the cutting curve planned by high-precision dynamic geological model in the mining period can be sent to the shearer through the central control center for automatic mining.

At present, the intelligent and automatic coal mining can be applied based on the high-precision geological model. In future research, dynamic update of multi-attribute geological information, mining disturbance effect analysis and automatic prospecting should be studied and developed to improve the automatic level of mining driven by geological data.

Declarations

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