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3D Modeling and Quantitative Analysis of Remediation Engineering for Coal Field Fire Zones by Integrating Multi-Source Data

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Abstract This research focuses on a steeply inclined coal seam fire zone in Xinjiang, proposing a novel 3D geological modeling and analysis approach that integrates multi-source data, including drilling and geothermal monitoring. Utilizing a software platform, a high-precision 3D model integrating topography, coal seams, fire zone boundaries, and the temperature field was constructed. This model enables the 3D visualization and precise delineation of the combustion extent and temperature distribution within the fire zone. Building upon this foundation, a new quantitative calculation method was developed based on the 3D block model. This method facilitates the classification of fire zone reserves, demarcation of remediation areas, and quantification of water injection volume, loess coverage volume, as well as excavation and leveling quantities. The results demonstrate that, compared to traditional two-dimensional methods, the proposed 3D quantitative analysis approach enhances the accuracy of remediation engineering quantity calculations by over 20%, significantly reducing project uncertainty. This research provides a robust technical framework for transitioning coal field fire zone remediation from "empirical judgment" to "3D precise quantification" in decision-making, holding significant theoretical importance and substantial engineering application value.

Key words Coal field fire zone, 3D geological modeling, Integrated exploration, Engineering quantity optimization

0 Introduction

In recent years, with the rapid advancement of digital mine technology, 3D geological modeling has been playing an increasingly vital role in coal mine exploration, development, and disaster management[1-3]. As a typical geological hazard, coal field fire zones, characterized by temperature anomalies and coal seam spontaneous combustion, pose a severe threat to coal mine safety production and the ecological environment[4-5]. Traditional fire zone remediation primarily relies on two-dimensional drawing analysis, limited cross-section inference, and empirical formula estimation. This approach struggles to intuitively represent the three-dimensional spatial structure and heterogeneous temperature field of fire zones, leading to inaccuracies in delineating remediation areas and significant deviations in engineering quantity estimates. These limitations severely constrain the scientific rigor and economic efficiency of remediation projects.

Although existing research has explored the application of 3D modeling in coal mines, systematic studies specifically addressing steeply inclined coal seams, integrating temperature field attributes, and directly enabling precise quantification for remediation engineering remain relatively scarce[6-7]. This paper takes a steeply inclined coal seam fire zone as a case study. Based on a software platform, it comprehensively integrates multi-source data including borehole logs, geophysical exploration results, and surface/borehole temperature measurements to construct a multi-attribute 3D geological model encompassing topography, coal seams, fire zone boundaries, and the temperature field. This model not only facilitates the visualization of the fire zone's spatial morphology and temperature distribution but, more importantly, this research has developed a set of precise calculation methods based on the 3D model for reserve estimation and quantifying remediation engineering quantities (water, soil, rock volume).

This represents a paradigm shift from two-dimensional empirical estimation to 3D precise quantitative analysis. It provides novel solutions and a technical foundation for the comprehensive remediation of coal field fire zones under similar complex geological conditions.

1 Overview of the coal field fire zone

The formation and expansion of the coal field fire zone primarily stem from historical open-pit mining activities. During the mining process, large areas of the coal seam were exposed to the atmosphere. Coupled with the inherent high susceptibility of the coal seam in this region to spontaneous combustion, the lack of effective sealing or covering measures made it highly prone to initiating and sustaining the spread of coal seam fires. Furthermore, the local arid climate with low rainfall and significant wind action further accelerated the combustion process within the fire zone and the expansion of the thermal hazard area.

Field investigations revealed that the fire pit extends in an east-west direction, with a length of approximately 1 550 m and a width ranging from 40 to 240 m, covering a total area of about 74 200 m^2. The geological conditions on both sides of the pit are complex, characterized by fractured rock masses and strata dips generally ranging from 60° to 85°, resulting in poor overall stability. Large-scale collapses have occurred on the southern slope of the pit, and distinct signs of roasting and combustion are visible on the rock walls to the east and west. The focus of this study is the currently identified fire zone extent, primarily concentrated within the pit area formed by the open-pit excavation of the A61 and A62 coal seams.

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2 3D geological modeling

2.1 Construction of the terrain model The terrain surface model serves as the foundational framework for the 3D geological model of the coal field fire zone, and its accuracy directly impacts the reliability of subsequent analyses. This research employed two data sources and methods to construct a high-precision Digital Terrain Model (DTM) surface:

2.1.1 Based on topographic survey point data. Scattered point data acquired from field surveys (*e. g.*, using total stations and GPS) were imported into the software. After unifying coordinates and removing outliers, the initial terrain surface was generated using the [Surface] →[Generate DTM Surface] function by setting reasonable triangulation parameters (such as a maximum triangle edge length ≤50 m). The model was subsequently refined using the [Clean Redundant Points] and [Smooth Triangulated Network] functions to ensure the terrain representation was realistic, natural, and free from topological errors.

2.1.2 Based on contour data. If high-precision digital topographic maps are available, contour data in DWG format are imported directly. The [Assign Elevation to Lines] function is utilized to batch assign elevation values to these contours. Subsequently, the contours are used as the data source to generate a triangulated network surface. For areas enclosed by closed contours, the [Generate DTM within Closed Lines] function is employed for local refinement. Finally, the [Generate Contours] function is used to back-generate contours from the model surface, which are then compared with the original data to verify the model's accuracy (Fig. 1).

2.2 Construction of the coal seam and combustion zone models Model construction commenced with the spatial registration of the fundamental geological cross-sections. The specific steps involved: importing the comprehensive cross-section drawings along the fire zone survey lines (in CAD format) into the software platform. Using the software's "Plane Two-Point Coordinate Transformation" tool, each cross-section drawing was precisely registered to its true geodetic coordinate position. This ensured that all sections possessed the correct spatial orientation and elevation relationships. Building upon this foundation, the coal seam roof and floor lines, as well as the combustion boundary lines, were accurately extracted from each section. These lines were then converted into 3D line data embedded with elevation information, thereby completing the transformation from 2D to 3D representation.

Subsequently, a discrete point/line triangulation algorithm was applied. Utilizing the [Generate DTM Surface] function, the 3D line data representing the coal seam roof and floor from all survey lines were used to generate continuous roof and floor surfaces, respectively. Finally, the two surfaces were connected using solid modeling tools to construct a 3D solid model that accurately reflects the spatial morphology of the coal seam and the extent of the combustion zone (Fig. 2). This model clearly reveals the complex spatial morphological characteristics of the fire zone within the steeply inclined coal seam.

2.3 Construction of the fire zone temperature field model The 3D visualization of the temperature field within a coal field fire zone serves as the fundamental basis for precisely delineating the fire extent, identifying combustion centers, assessing fire development trends, and formulating fire suppression strategies[8-12]. Building upon the previously constructed high-precision terrain model and coal seam solid model, this research combined geological attributes with temperature measurement data by establishing a 3D block model. This approach enabled the 3D spatial interpolation and representation of the temperature field across the study area within the software environment.

2.3.1 Block model creation and temperature field assignment. Within the established coal seam solid model, a block model with dimensions of 5 m×5 m×2 m was created to serve as the medium for temperature interpolation. To accurately constrain the interpolation range, the "coal seam" solid model was converted into a boundary constraint. This ensured that temperature attributes were calculated exclusively within the calibrated combustion zone.

A floating-point attribute named "Temperature" was created within the block model. Temperature data were sourced from borehole temperature logging and surface infrared thermometry. All data were organized into a set of 3D scatter points in the format (X, Y, Z, Temperature). Temperature interpolation employed the Inverse Distance Weighting (IDW) method with a power function. The formula is:

$$T(\mu) = \frac{\sum_{i=1}^{n} \lambda_i T_i}{\sum_{i=1}^{n} \lambda_i}, \ \lambda_i = \frac{1}{d(\mu, \mu_i)^p} \tag{1}$$

where $T(\mu)$ is the estimated block temperature, T_i is the temperature of a known measurement point, $d(\mu, \mu_i)$ is the distance between the block to be estimated and the known point, p is the power exponent (taken as 2 in this study), and n is the number of known points within the search radius.

Within the advanced options, the previously created "coal seam" or "combustion zone" coded attributes were selected as constraint conditions. This restricted the interpolation operation to the target geological body only, preventing the erroneous assignment of high-temperature anomalies to the surrounding rock. After executing the interpolation calculation, the software assigned a calculated temperature value to each block that satisfied the geological constraints based on the algorithm. This resulted in the generation of a continuous 3D temperature field model (Fig. 3).

2.3.2 Model validation. To assess the model's reliability, a cross-validation approach was employed: 10% of the temperature measurement points were randomly withheld as a validation set, while the remaining 90% were used for model construction. The actual measured values of the validation set were then compared against the corresponding model-predicted values. The calculated Mean Absolute Error (MAE) was 12.7 ℃, and the Root Mean Square Error (RMSE) was 15.3 ℃. Considering the inherent variability of subsurface temperature fields, these error levels were deemed acceptable. This demonstrates that the constructed temperature field model possesses high accuracy and reliability. It is capable of meeting the requirements for engineering analysis and quantitative calculations.

3 Application of the 3D geological model in fire zone remediation

3.1 Reserve estimation Leveraging the 3D coal seam and temperature field models, this research achieved precise classification and reserve estimation of resources within the fire zone. First, using the coal seam solid model as the boundary, the block model was utilized to classify resources[13-14]. Combusted Coal (Fire-Altered Coal): Blocks with temperature >300 ℃; Threatened Reserves: Blocks with temperature between 100 and 300 ℃, or located within a 50 m buffer zone outside the fire boundary; Normal Coal: Blocks with temperature < 100 ℃ and situated away from the fire zone.

Building upon the established 3D geological and temperature field models, this research employed numerical modeling software to perform integrated reserve estimation and classification assessment for the combusted coal (fire-altered coal), threatened coal reserves, and normal coal resources within the study area. Initially, a block model was created using the coal seam solid model as the boundary. Based on the temperature field model and geological exploration results, a resource status attribute was defined for each block. By setting temperature thresholds (*e.g.*, >300 ℃), the extent of the already combusted coal (fire-altered coal) was precisely delineated. Utilizing buffer analysis or temperature gradient models, the extent of threatened reserves (areas immediately adjacent to the fire zone, subjected to high-temperature baking and under threat but not yet combusted) was delineated. The remaining portions constituted the normal coal resources. Subsequently, differentiated calculation parameters were assigned to resources based on their status: For combusted coal and partially threatened reserves, modified apparent relative density values and coal quality indicators corresponding to their degree of metamorphism were applied; for the normal coal seam, the average raw coal density obtained during the exploration phase was used. Finally, utilizing the software's reporting functionality, the formula calculation "Tonnes = Volume × Density" was executed. The automatic statistical summary of reserves for the three resource categories was simultaneously completed using conditional filtering. This process enabled the comprehensive assessment within a unified 3D model of the precise spatial distribution of both resource losses due to the fire and the remaining resources. It provides precise data support for evaluating the benefits of fire suppression engineering and resource recovery planning.

3.2 Determination of remediation scope Based on the established 3D geological model and temperature field model, this research constructed a comprehensive fire zone remediation decision-making model through multi-source information fusion[15-17]. Building upon this, differentiated remediation scopes and methods were scientifically determined according to the disaster-causing mechanisms and risk levels of different zones. For high-temperature active zones, thorough remediation primarily involving grout injection for cooling and excavation-backfilling was employed. For hazardous slope areas, the excavation-soil covering method was applied. For hazard belts within goaf areas, filling and reinforcement were implemented to prevent further collapse and air leakage that could fuel combustion. The aforementioned process facilitated the translation from 3D model analysis to the formulation of precise remediation plans. It provided a scientific basis for decision-making in the design and construction of fire suppression engineering.

3.3 Estimation of fire suppression water demand Building upon the established 3D geological model and temperature field model, this research overcame the limitations of traditional methods reliant on 2D cross-sections and empirical coefficients for estimating water demand in fire zone remediation. A novel method for estimating fire suppression water demand based on precise 3D spatial calculations was proposed. Traditional methods typically estimate the average cross-sectional area and volume of temperature anomaly bodies by setting up a limited number of cross-sections, subsequently calculating water injection, grout injection, and drilling water consumption. The calculation process is simplified and struggles to accurately reflect the heterogeneity of temperature and porosity within the fire zone interior. This research innovatively utilized the high-precision 3D block model to discretize the entire fire zone into millions of individual unit blocks. Each block contains precise attributes for its temperature, lithology, porosity, and combustion state. For water injection volume calculation, instead of using uniform average temperatures and cross-sectional areas, the method treats each high-temperature block as an individual unit. Based on the heat that needs to be removed to reduce its own temperature to the target temperature, the required water absorption for each block is precisely calculated. These values are then automatically summed to obtain the total water injection volume. For grout injection volume calculation, differentiated porosity values are assigned to different zones based on the spatial distribution model of the combustion-altered rock (burned rock).

The total pore volume requiring filling is precisely calculated, from which the grout volume and associated water demand are derived. Drilling water consumption can also be optimized by considering the actual length of the designed borehole trajectory within the 3D model and the lithology of the strata encountered. This method elevates water demand estimation from reliance on 2D empirical formulas to a stage of 3D precise quantification. It significantly enhances the scientific rigor and reliability of the calculation results. It provides a more precise basis for decision-making in resource allocation for fire suppression engineering.

3.4 Estimation of loess demand for fire suppression Building upon the established 3D geological and temperature field models, this research developed a novel method for precisely calculating the loess demand for fire suppression based on 3D spatial com-

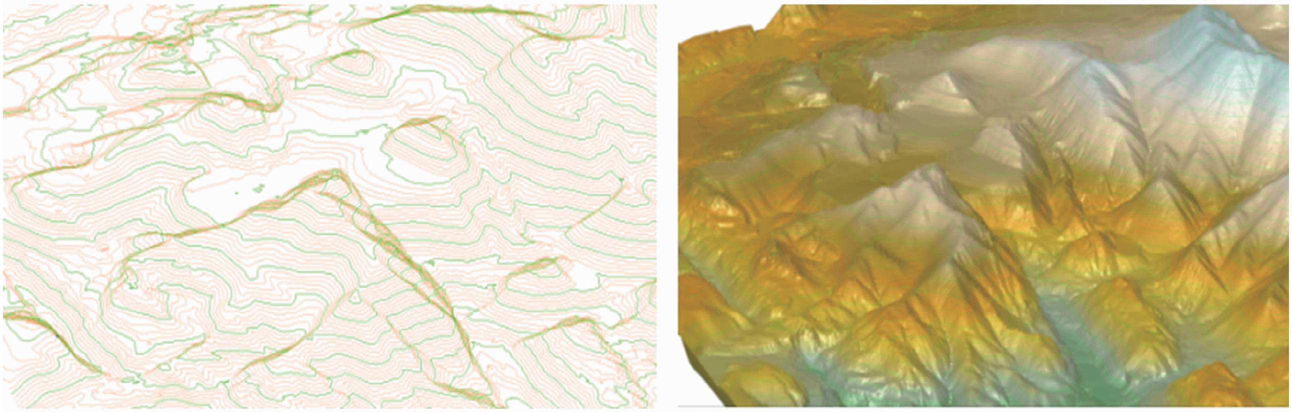

Fig. 1 Conversion of contour or topographic survey point data into a surface model

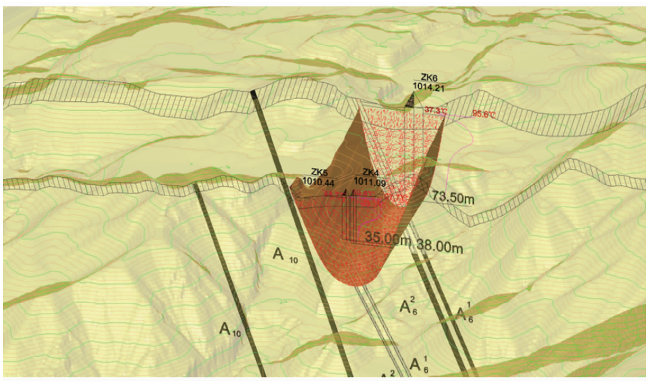

Fig. 2 3D solid model showing the spatial morphology of the combustion zone

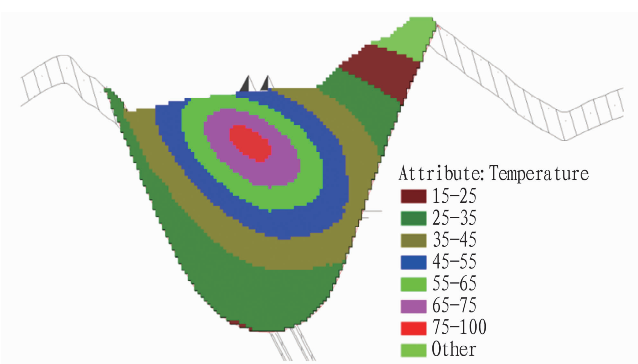

Fig. 3 Temperature field model of the combustion zone

putation, overcoming the inherent limitations of traditional 2D cross-section empirical estimation methods. Traditional methods rely on limited cross-sectional lines to estimate an average cross-sectional area for calculating the required soil cover volume, a process fraught with significant approximation. This research precisely integrates the 3D surface model with the remediation scope. Utilizing solid Boolean operations technology, it directly determines the exact volume of earthwork requiring coverage, thereby completely circumventing the calculation errors inherent in 2D cross-section methods. This innovation elevates earthwork volume estimation from traditional 2D empirical approximation to a stage of 3D precise measurement. It significantly enhances the credibility of calculation results and the accuracy of engineering budgets. It provides crucial technical assurance for the optimal allocation of loess resources and cost management within fire suppression projects (Fig. 4).

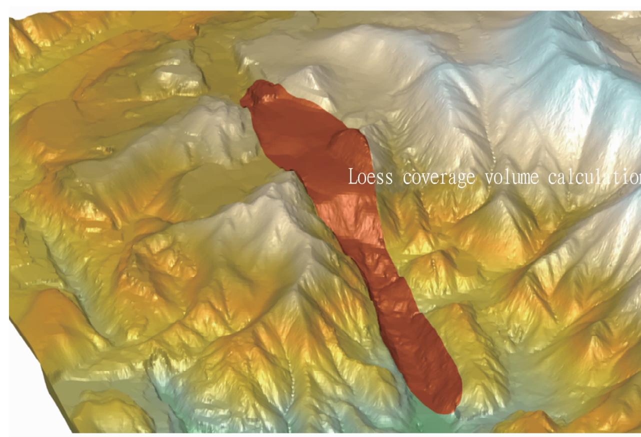

Fig. 4 Estimation of loess demand for fire suppression

3.5 Excavation and leveling quantities Leveraging the constructed high-precision 3D surface model and coal seam solid model, this research achieved precise calculation of engineering quantities for areas remediated using the excavation method. Traditional methods reliant on 2D drawings and limited cross-sections struggle to accurately reflect the variations in earthwork volume caused by complex topography and irregular remediation boundaries. This research utilizes the 3D model to directly generate a closed solid representing the excavation scope within the remediation area. Using the [Volume Calculation] function, the excavation volume between this solid and the original topographic surface is precisely calculated. Simultaneously, based on the designed leveling elevation, the fill area can be rapidly generated and the fill volume calculated. This method not only outputs the total cut and fill volumes but also facilitates earthwork balance analysis. It optimizes construction plans and significantly enhances the accuracy and efficiency of calculating excavation and leveling quantities. It provides a reliable basis for construction organization and cost control.

4 Conclusions

4.1 3D modeling effectively integrates multi-source data, accurately characterizing fire zone spatial features The 3D geological model integrating topography, coal seams, fire zone boundaries, and the temperature field, constructed based on the software platform, achieved high-precision visualization of the complex geological conditions and combustion status within the steeply inclined coal seam fire zone. It significantly enhanced the accuracy and intuitiveness of fire zone extent delineation and combustion mechanism analysis.

4.2 The model supports precise calculation of fire zone resources and remediation quantities Through the 3D block model and attribute constraints, automatic classification and statistics of coal reserves in the combusted zone, threatened zone, and normal zone were achieved. Simultaneously, based on 3D solid Boolean operations and dual constraints of temperature and lithology, the calculation accuracy of remediation engineering quantities (such as water injection, grout injection, loess coverage, and excavation-leveling) was significantly improved. This overcame the errors inherent in traditional 2D cross-section empirical estimation methods.

4.3 The model provides a reliable basis for differentiated remediation and scientific decision-making The 3D model supports the systematic zoning of the fire area by integrating multi-dimensional factors such as lithology, temperature, and goaf distribution. This enables the scientific formulation of differentiated remediation scopes and methods. It promotes a shift in remediation work from empirical judgment towards 3D quantitative and refined decision-making.

4.4 The model possesses significant value for technology promotion and engineering application The 3D modeling methodology established in this research exhibits strong versatility. It demonstrates significant value in enhancing the efficiency of fire suppression engineering, optimizing resource allocation, and controlling costs. It can serve as a reference paradigm for the comprehensive remediation of coal field fire zones under similar conditions.

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