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A Fault-Constrained Partitioned 3D Modeling Method for Coal Seams in a Working Face

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Abstract: Traditional coal seam geological models often fail to represent the complex spatial distribution of coal seams in a working face, particularly in fault-affected areas where structural discontinuities tend to reduce model continuity and prediction accuracy. To address this issue, this study develops a fault-constrained partitioned 3D modeling workflow by integrating data quality inspection, spatial partitioning, local surface reconstruction, and model fusion. Gas-drainage borehole records are first checked through roof-floor elevation comparison and geometric consistency screening. Fault control points are then used to delineate partition boundaries, and coal seam points are assigned to different modeling units using a ray-casting-based point-in-polygon procedure. Guided by the partitioning logic and the density-evaluation idea described in the workflow, local surfaces are reconstructed using alternative interpolation strategies, including inverse distance weighting (IDW), ordinary kriging, and radial basis function (RBF) interpolation, together with regular-grid and TIN-based mesh generation. The resulting partition-level models are fused into a unified 3D representation of the working face. The workflow clarifies the spatial relationship between faults and coal seams and provides a practical technical route for transparent underground geology and safe mining in structurally complex areas.

Keywords: 3D geological modeling, coal seam modeling, fault constraint, partitioned modeling, working face.

1. Introduction

Three-dimensional geological modeling is a key technical foundation for transparent geology, digital mine construction, and safe working-face design [1-3]. In underground coal mining, the geometric expression of coal seams directly affects geological interpretation, roadway deployment, gas control, and local hazard prevention [6, 7]. Because borehole information, engineering drawings, and structural data are often collected from different stages and sources, the resulting dataset is spatially heterogeneous and structurally discontinuous. These characteristics make accurate coal seam reconstruction difficult when only a conventional global modeling strategy is adopted [3, 6].

Traditional coal seam models are commonly built by directly interpolating seam roof and floor elevations over the entire working face. Although this strategy is simple, it tends to smooth structural discontinuities and weaken the expression of local offsets caused by faults [4, 14]. In fault-affected areas, such undifferentiated interpolation may connect geologically separated coal blocks into an apparently continuous surface, thereby reducing interpretability and potentially misleading engineering judgment [4, 6]. Therefore, a modeling framework that explicitly incorporates structural boundaries is required for working faces with complex geological conditions [4, 5].

Partition-based modeling provides a practical way to improve structural consistency. The central idea is to divide the working face into multiple modeling units according to structural boundaries and then reconstruct local coal seam surfaces within each unit separately [4, 5]. By limiting interpolation to structurally coherent blocks, the method reduces cross-fault interference and preserves local geometry more faithfully. When such a strategy is combined with data-quality inspection and flexible interpolation methods, the resulting model can better reflect the actual occurrence characteristics of the coal seam [7, 10].

The present study develops an engineering-oriented workflow for fault-constrained partitioned 3D coal seam modeling. The manuscript is written by combining the study abstract with the uploaded data-processing and model-construction programs. The implemented workflow covers four main stages: (1) borehole data checking and preprocessing, (2) fault-bounded spatial partitioning and regional data export, (3) local surface reconstruction using alternative interpolation and mesh-generation methods, and (4) model fusion and interactive visualization. The main contribution of the study is not merely the use of one interpolation algorithm, but the integration of structural partitioning, reproducible data handling, and flexible surface construction into one coherent modeling chain, which is consistent with the development direction of multi-source 3D geological modeling [1, 3, 6].

2. Data Basis and Workflow

The workflow is oriented toward a fault-affected coal working face represented by borehole-based seam data and structural boundary data. The uploaded programs indicate that the modeling dataset contains roof and floor elevations, borehole identifiers, planar coordinates, terminal-hole coordinates, and polygonal boundary information derived from fault control points or interpreted structural boundaries. The case data also include partition files and intermediate spreadsheets prepared for the 4103 working-face modeling task. Similar multi-source data structures have been widely emphasized in practical 3D geological modeling workflows [1, 3, 6].

From a geological perspective, the input information can be grouped into three categories. The first category is borehole seam data, including coal seam roof and floor elevations and related borehole coordinates. The second category is structural boundary data, represented by control points used to form fault-bounded polygons. The third category is derived intermediate datasets created during preprocessing and regional export. These derived datasets are essential because they allow each structural block to be modeled independently rather than forcing all observations into a single global interpolation space [3, 4, 14].

Based on the uploaded scripts, the complete workflow may be summarized as follows. First, roof-floor elevation relationships are checked to identify potentially abnormal boreholes. Second, fault-bounded polygon files are loaded and used to classify seam points into different regions. Third, classified points are exported into separate files for block-by-block modeling. Fourth, local surfaces are reconstructed through alternative interpolation methods and mesh structures. Finally, partition-level models are visualized and fused into a complete 3D representation of the working face. This sequence follows the general logic of constructing structurally consistent geological models from sparse and heterogeneous observations [4, 5].

3. Methodology

The methodology combines implemented code logic with the partitioned modeling concept described in the study abstract. To avoid overstatement, the manuscript distinguishes between steps that are explicitly implemented in the uploaded scripts and density-evaluation logic that is part of the proposed workflow but not yet fully automated in the current code package.

(1) Borehole data inspection and preprocessing

The first preprocessing task is consistency checking of seam roof and floor elevations. In the uploaded quality-check program, borehole records from the roof and floor datasets are merged by borehole identifier, and the elevation difference between the seam roof and seam floor is calculated for each matched borehole. The difference values are sorted by absolute magnitude so that anomalous records can be reviewed first. This step provides a direct way to identify possible data-entry errors, seam-thickness inconsistencies, or mismatched borehole records before surface modeling begins.

In engineering practice, this check is important because interpolation is highly sensitive to a small number of abnormal elevations, especially in datasets with uneven sampling density. When unrealistic roof-floor differences are not removed or corrected, the resulting coal seam model may contain artificial bulges, depressions, or discontinuities unrelated to actual geology. Therefore, quality inspection is treated here as a mandatory prerequisite for structural partitioning and model generation, especially because interpolation performance is strongly affected by sampling density, spatial arrangement, and data quality [10].

In addition to vertical consistency checking, the preprocessing scripts also assume that borehole coordinates and partition polygons have been brought into one consistent spatial reference framework. This common-coordinate requirement is essential because subsequent point-in-polygon classification and local interpolation both depend on geometric comparability among seam points, structural boundaries, and grid nodes [1, 5].

(2) Fault-constrained partitioning

The core of the proposed method is fault-constrained partitioning. In the uploaded partition-processing scripts, regional boundary files are read from Excel tables containing X-Y control points. These points are organized into polygons representing structural blocks bounded by faults or other interpreted partition lines. Coal seam points are then assigned to these polygons through a ray-casting point-in-polygon algorithm. For a point with planar coordinates (x, y), a horizontal ray is cast from the point, and the point is judged to be inside or outside a polygon according to the odd-even crossing rule. Such explicit structural partitioning is consistent with surface-based fault and horizon modeling principles [4, 5].

This implementation provides a reproducible and geologically meaningful way to classify seam observations into separate modeling units. Instead of allowing points from different structural blocks to influence one another across faults, the method enforces a prior structural segmentation before interpolation. Such segmentation is especially useful when fault throws or abrupt local morphology changes would otherwise be smoothed by global interpolation [4, 6, 14].

After regional classification, the seam dataset is exported by partition. The uploaded regional-export program writes each region into a separate spreadsheet, such as block-specific floor-coordinate files. This export step is not merely clerical. It creates independent modeling subsets that can be checked, supplemented, and reconstructed separately, thereby improving both workflow transparency and engineering operability [1, 3].

(3) Density evaluation and partition-specific modeling strategy

The study abstract specifies that nearest neighbor analysis is used to evaluate borehole distribution density within each modeling unit. This idea is retained in the methodological framework because density differences among partitions strongly affect the suitability of interpolation methods [10]. However, the currently uploaded scripts do not yet contain a standalone nearest-neighbor-analysis module. Accordingly, this step is described here as a partition-specific evaluation principle embedded in the workflow rather than as a fully automated coded routine in the present package.

From a modeling standpoint, density evaluation serves two purposes. First, it helps determine whether a partition contains enough points to support smooth surface interpolation or whether a geometry-preserving approach should be preferred. Second, it provides a rational basis for selecting among interpolation methods. Dense and relatively uniform partitions may support statistically smoother methods, whereas sparse or geometrically irregular partitions may benefit from methods with stronger local control or direct triangulation support [10, 12].

(4) Local surface reconstruction

The uploaded model-construction program supports both regular-grid interpolation and TIN-based surface generation. For regular-grid modeling, the program first creates a rectangular grid covering the borehole extent and expands the domain by a small buffer so that edge data are not clipped. Three interpolation options are available: inverse distance weighting (IDW), ordinary kriging, and radial basis function (RBF) interpolation, which are commonly discussed in spatial interpolation and surface reconstruction studies [8-11].

For IDW, the estimated elevation at an unsampled grid node is calculated as a weighted average of surrounding sample values, with weights inversely related to the distance raised to a power. This method is simple, intuitive, and effective when local geometric control is more important than global statistical assumptions [10]. Ordinary kriging estimates grid values from the spatial covariance structure of the sample set. In the current code, a linear variogram model is adopted, and kriging is used as a statistically informed alternative when spatial continuity is adequate [8, 9]. RBF interpolation reconstructs the surface by fitting a radial basis function to the sample points, allowing smoother expression of nonlinear local undulations [11].

For TIN-based modeling, Delaunay triangulation is constructed directly from the planar sample points, and seam elevations are attached to the triangle vertices [12]. Compared with regular-grid interpolation, TIN surfaces preserve the original sample geometry more explicitly and are often more suitable for partitions with sparse or irregular point distributions. The coexistence of regular-grid and TIN options therefore gives the modeling workflow methodological flexibility rather than forcing one model form on all partitions [4, 13].

(5) Model fusion and interactive implementation

In the implemented workflow, roof, floor, and terminal-hole surfaces can be reconstructed separately and displayed in the same 3D environment. Once the partition-level surfaces are generated, they can be assembled into a full working-face model through model fusion. In geological terms, this fusion step allows the final model to retain local partition characteristics while still presenting an overall interpretation of coal seam occurrence across the target working face [4, 5, 13].

The uploaded model-construction code further encapsulates the process in a graphical user interface. Users can load data files, select interpolation methods, switch between regular-grid and TIN meshes, specify grid resolution, generate 3D models, and compare alternative methods interactively. This software-oriented design enhances the practical value of the method because it turns a sequence of isolated scripts into an operational prototype for engineering use, which accords with the broader trend toward interactive geoscience information systems and geological visualization [1, 2].

4. Results and Discussion

Because the uploaded material consists mainly of processing and modeling programs rather than a full set of final numerical outputs and figures, the discussion below focuses on the methodological results that can be directly supported by the implemented workflow and the case-oriented conclusions that logically follow from it. Quantitative error metrics and final figure numbering can be inserted directly once the finished case outputs are exported.

(1) Effects of preprocessing and structural partitioning

The preprocessing stage improves the reliability of subsequent surface reconstruction by identifying boreholes with unusual roof-floor relationships before interpolation. In structurally complex coal seams, this step is particularly valuable because a small number of abnormal records may distort surface trends within an entire partition. The code-based quality-check strategy therefore serves as a first filter for controlling model error propagation, which is consistent with the recognized influence of data quality on interpolation results [10].

The partitioning stage provides the most important structural improvement over conventional global modeling. By classifying seam points into fault-bounded blocks through polygon containment judgment, the workflow prevents points on opposite sides of a fault from directly influencing the same interpolated surface. This structural separation is essential for preserving the geometric meaning of fault offsets and discontinuities [4, 6, 14]. In practical terms, the approach makes the resulting model easier to interpret for transparent geology and local engineering decision-making.

(2) Local model reconstruction characteristics

The regular-grid models generated by IDW, ordinary kriging, and RBF interpolation are well suited to continuous visualization of roof and floor morphology within each partition. Among these methods, IDW provides stable local responsiveness, kriging offers a statistically informed smoothing mechanism, and RBF is more flexible for representing nonlinear local curvature [8-11]. Their coexistence in one workflow allows the user to compare reconstruction behavior under different local data conditions rather than relying on a single predetermined method [7, 10].

TIN-based modeling provides an alternative representation that directly preserves the sample distribution and local geometric variability [12]. This is valuable in partitions where boreholes are sparse, unevenly distributed, or controlled by irregular boundaries. Instead of forcing the data into a regular grid that may introduce unnecessary smoothing, the TIN option maintains closer geometric contact with the original observations. Therefore, the proposed workflow is best understood as a flexible partitioned modeling framework rather than one fixed interpolation formula [4, 13].

(3) Geological expression and engineering significance

A key advantage of the proposed method is its clear expression of the spatial relationship between faults and coal seams. In undifferentiated interpolation, fault-affected seam surfaces may appear artificially continuous, making it difficult to distinguish true structural segmentation from interpolation artifacts. In contrast, the fault-constrained partitioning strategy preserves geological discontinuity before interpolation occurs, so the final model better reflects the actual structural organization of the working face [4, 6, 14].

From an engineering perspective, the resulting 3D model supports transparent underground geology, seam-occurrence interpretation, and safer mining deployment. The method is also useful for local verification of coal seam geometry against production geological maps and borehole termination information. Because it integrates data checking, structural partitioning, local modeling, and visualization, the workflow offers a practical and extensible technical route for working faces characterized by faults and uneven borehole layouts [2, 3, 6, 7].

(4) Limitations and prospects

The present study has two main limitations. First, although the manuscript framework includes nearest-neighbor-based density evaluation, that module is not yet separately automated in the currently uploaded scripts. Second, the present version of the manuscript does not include final quantitative validation statistics such as cross-validation error, root mean square error, or mean absolute error because those case outputs were not provided together with the code package.

Future work should therefore proceed in three directions. The first is to integrate an explicit density-analysis module so that partition statistics can directly guide interpolation recommendation. The second is to perform quantitative validation for roof and floor surfaces in each partition and compare the predictive behavior of IDW, kriging, and RBF methods [10]. The third is to expand solid-model generation and export functions so that the workflow can support downstream geological simulation, engineering design, and model sharing in a wider range of software environments [1, 2, 5].

5. Conclusion

This study developed a fault-constrained partitioned 3D modeling workflow for coal seams in a working face by combining borehole data inspection, fault-bounded spatial partitioning, partition-level data export, flexible local surface reconstruction, and model fusion. The workflow was summarized from the study abstract and explicitly implemented code modules, thereby forming an engineering-oriented technical route for structurally complex coal seam modeling [3, 4, 6, 7].

The results show that introducing structural partitioning before interpolation is an effective way to reduce cross-fault interference and improve geological interpretability. The ray-casting-based point-in-polygon classification and partition export procedures provide a reproducible data-handling mechanism for block-by-block modeling. The surface-construction module further supports multiple interpolation methods and mesh forms, including IDW, ordinary kriging, RBF, regular grids, and TINs, which gives the workflow flexibility under different local data conditions [8-13].

Overall, the proposed method can clarify the spatial relationship between faults and coal seams and provides a practical basis for transparent geology and safe mining in fault-affected working faces [2, 6]. Further improvement should focus on quantitative accuracy evaluation, explicit density-analysis automation, and richer solid-model export and integration capabilities [1, 5, 10].

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The manuscript text in this draft was prepared by integrating the study abstract with the uploaded data-processing and model-construction scripts. Numerical validation tables, partition statistics, and final figure plates can be added directly after the case-specific outputs are finalized.

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