A Three-Dimensional Modeling Method for The Caving Zone of Goaf

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Abstract. The research on the three-dimensional simulation of caving zone in goaf is relatively few, so a three-dimensional modeling algorithm for the caving zone in goaf is proposed in this paper. The method firstly estimates the height of the caving zone based on empirical formulas and forms the filling zone; secondly generates original spherical fall-off blocks of different particle sizes; then uses the principle of spherical tangent to fill the caving zone randomly. This method avoids the impractical drawbacks of the filling problem and makes the three-dimensional simulation of the caving zone faster.

1. Introduction

After coal mining, the mined-out area was formed, which caused the original stress balance of overlying strata to be broken[1-2]. The destruction of the original stratum structure will trigger a series of irreversible damage to the ecological environment. In recent years, the use of three-dimensional geological modeling[3-5] to simulate the stratum after mining has become an urgent problem to be solved. The simulation of the emergence of falling blocks in the caving zone after mining has traditionally been a knotty point in 3D geological modeling. Existing simulation such as deformation and fracture of the formation after mining in FLAC3D numerical software is calculated based on the rectangular model. The modeling process is overly complex for those who do not need to accurately calculate the caving data, such as virtual roaming or the need to roughly demonstrate the caving three-dimensional effects. In fact, the formation and filling of the falling blocks in the caving zone is similar to the placement of aggregates in the concrete, compared to the slightly altered manner of filling. In the latter half of the 20th century, an algorithm for the placement of concrete aggregates began[6]. In recent years, with the further development of technology, many scholars have elaborated on the three-dimensional simulation of aggregate placement. Liu Guangyan[7], Du Chengbin[8], Kuang Weiping[9], Song Xiaogang[10] and so on, based on the establishment of spatial polyhedron intrusion criteria, the aggregate generation model, derived random distribution of irregular aggregates algorithm. There is a certain similarity between the falling block formed after coal mining and aggregate, but according to the practical significance, the distribution of concrete aggregate is different from that of the broken rock in the caving zone. Aggregate suspended in cement mortar, the placement of concrete aggregates only needs to consider the unreasonable conflict between aggregates. However, to simulate the positional relationship between fractured rocks in the caving area after mining, it is necessary not only to consider the problem of non-conflict between a single falling block and other falling blocks, but more importantly, to ensure the existence of supporting points between adjacent caving blocks. Therefore, in this paper, based on the algorithm of aggregate delivery, the spheres are
used to approximate the scattered blocks in the goaf, the adjacent caving blocks can be generated by using the two-ball tangent rule, and the borders are determined to ensure that the generated caving blocks are falling inside the area. Then, the falling block is cyclically generated and judged until the entire falling area is filled. Finally, a three-dimensional model of the caving zone after mining is created.

2. The 3D modeling process of the caving zone
First, drilling data and working face information in the mining area are analyzed and sorted. Secondly, the relevant data are substituted into the caving zone calculation formula to predict the height reached by the caving zone after coal mining, and to generate the caving zone. Then the primitive spherical caving blocks with different particle sizes are generated, and then the caving blocks are filled to the falling area according to the tangent rule. The final loop checks whether the current nth occurrence of the caving block conflicts with the generated n-1, and detects whether the current caving block is filled inside the caving zone. When neither the conflict detection nor the boundary detection generates an error, the padding of this caving block is allowed; otherwise, it is refilled. According to the above algorithm steps, the three-dimensional modeling flowchart of the caving zone is illustrated in Figure 1.

![Fig.1. Three-Dimensional Modeling Flowchart of Caving Zone in Goaf](image)

3. Determination of falling height
During the coal mining process, due to mechanical and other factors, the strata on the goaf will undergo more complex movement and deformation, which is formed by caving zone, fault zone and bend zone from top to bottom\cite{11}. At this stage, the height of the caving zone in real-time survey has a certain degree of complexity. Xu Yanchun\cite{12} and other people based on the results of actual measurement of the two belts and the two-band height data of more than 40 different types of hardness overburden collected in China, then adopted the method of regression analysis, and finally obtained the empirical formula for calculating the caving height of different types of strata in fully mechanized caving face, as shown in Table 1.
### Table 1. Empirical Formulas for Calculating Height of Caving Zone

| Overlying lithology | Application of stratified fully mechanized mining and conventional mining calculation formula/m | Application of fully mechanized mining calculation formula/m |
|---------------------|------------------------------------------------------------------------------------------------|----------------------------------------------------------|
| Hard                | $H_m = \frac{100 \sum M}{2.5 \sum M + 1.25}$                                               | $/                                                  |
| Medium hard         | $H_m = \frac{100 \sum M}{4.3 \sum M + 2.2}$                                              | $H_m = \frac{100M}{0.49M + 19.12}$ = 4.71            |
| Weak                | $H_m = \frac{100 \sum M}{6.5 \sum M + 1.5}$                                              | $H_m = \frac{100M}{-1.19M + 28.57}$ = 4.76          |

Note: $\sum M$ is the cumulative mining height; $H_m$ is the height of the caving zone.

### 4. Filling algorithm for caving block

The sphere is a relatively simple geometric structure. It can be readily expressed by using the coordinates of the sphere center and radius in the three-dimensional coordinate system. Because of gravity and other factors, there are different degrees of contact between adjacent different sizes of caving blocks after mining. Therefore, spheres with different radii are used to replace the falling blocks of different grain sizes. Through the two-ball tangential method, it is determined whether there are intersections between the falling blocks and there is no collision. Therefore, the three-dimensional caving zone formed by caving block accumulation after coal mining is simulated simply and efficiently.

#### 4.1 Sphere data structure representation

In a three-dimensional coordinate system, a sphere can be uniquely identified by the center coordinates and radius values. Simulate the falling block with a sphere, and its data structure is shown in Table 2:

| Element       | Data structure                               |
|---------------|----------------------------------------------|
| Sphere        | struct Sphere{                               |
|               | long id; /Sphere identifier                  |
|               | float x,y,z; /Center coordinates             |
|               | float r; /Sphere radius                      |
|               | }                                            |

#### 4.2 Fill algorithm

Step1 Placement area determination

According to a definite grading standard, three spheres with different particle diameters are generated randomly, and the radii are respectively expressed as $r_1$, $r_2$, and $r_3$. Assume that the length and width of the original filling area are $l$ and $w$, and the function $H(x,y)$ represents the falling height...
value corresponding to the point \((x,y)\). The maximum radius \(R_{\text{max}}\) in the three types of spheres is taken as the interval between each surface of the placement area and the corresponding surface of the original filling area, so the length, width and height of the placement area are \((l-2R_{\text{max}})\), \((w-2R_{\text{max}})\), \((H(x,y)-2R_{\text{max}})\). As shown in Figure 2, the outer surface body represents the original filling area, and the inner surface body represents the placement area.

![Fig.2. Falling Block Placement Area and Original Filling Area](image)

Step2 Initial Falling Block Fill

A point is randomly selected in the placement area determined in Step 1 as the geometric center of the initial caving block, and one of the three particle sizes is selected as the initial falling block for filling. The center of the initial caving block is set \((x_0,y_0,z_0)\), and the \(R_0\) is its particle diameter.

Step3 Cyclic generation of caving block

Select the radius of the generated block to be \(R_1\) (where \(R_1\) belongs to \(\{r_1, r_2, r_3\}\)), and stipulate that the center coordinates \((x_1, y_1, z_1)\) of the caving block meet specified constraints, see Equation 1-3.

\[
x_1 \in \left[ x_0 - (R_0 + R_1), x_0 + (R_0 + R_1) \right]
\]

\[
y_1 \in \left[ y_0 - \sqrt{(R_0 + R_1)^2 - (x_1 - x_0)^2}, y_0 + \sqrt{(R_0 + R_1)^2 - (x_1 - x_0)^2} \right]
\]

\[
z_1 \in \left[ z_0 - \sqrt{(R_0 + R_1)^2 - (x_1 - x_0)^2 - (y_1 - y_0)^2}, z_0 + \sqrt{(R_0 + R_1)^2 - (x_1 - x_0)^2 - (y_1 - y_0)^2} \right]
\]

The limit of the coordinates ensures that the two falling blocks are tangent to each other. According to this rule, multiple consecutive tangential spheres can be generated from the relative position between two falling blocks (as shown in Figure 3). If \(\sum V_i > V_{\text{max}}\) is satisfied (where \(V_i\) represents the volume of the \(i\)th falling block and \(V_{\text{max}}\) represents a given volume limit), generation stops.

![Fig.3. Cyclic Generation of Caving Block](image)

Step4 Intersection decision

Since Step 3 does not guarantee that there is no intersection between the newly generated one and other falling blocks from which the previous caving block was removed, the rationality of the newly generated dropout block must be detected. The method is to detect whether the distance between its geometric center and the geometric center of the rest of the falling blocks is greater than or equal to the sum of the particle sizes of the two falling blocks immediately after each new block is generated. If the condition is met, the falling block is valid and allowed to be generated; otherwise, the falling block is invalid and is generated again.

Step5 Boundary determination

The newly generated caving block must be inside the filling area, otherwise it is invalid. In this case, it is necessary to make boundary judgment on the generated falling block. Suppose that the coordinates of the geometric center of the falling block is \((x_i, y_i, z_i)\) and the particle size is \(R_i\). The method is to determine whether each property of the caving block satisfies the constraints as shown in Equation 4-6. If yes, the generation of the falling block is permitted; otherwise, the falling block is deleted.
5. Experimental verification

In order to verify the validity and rationality of the filling algorithm proposed in this paper in actual engineering, a three-dimensional simulation of the caving belt in the goaf was conducted by selecting the measurement data from a certain working face in the Hongliulin coal mine in northern Shaanxi. This example is implemented in the Visual Studio environment and is based on the Directx graphical interface and Win32 technology. The working face is 305 meters long and the average height is 5.87 meters. Mining height data are substituted into the empirical formula of hard strata height calculation in fully mechanized mining. The final height of the caving zone after mining is 31.396 meters. On this basis, the placement area is established. Then select three spheres with a particle size ratio of 1:2:3 (the maximum particle size is 6 meters) to circularly fill the falling area. Finally, the simulation of the three-dimensional model of the caving zone is illustrated in Figure 4.

![Fig.4. Three-Dimensional Model of Caving Zone in Goaf](image)

6. Summary

This paper presents a three-dimensional modeling algorithm of caving zone based on sphere. Compared with other modeling methods which require complex mechanical calculations or numerical simulation, the algorithm uses the sphere to simulate the caving block, and then quickly completes the three-dimensional modeling of the caving zone. The tangent criterion ensures the rationality of the simulation of the caving belt in the goaf after coal mining; the three-dimensional modeling of the caving zone in the goaf allows researchers to understand the caving area more intuitively; this paper only proposes the filling of spheres. However, in actual projects, the occurrence of the falling block is more irregular and convex polyhedral. Therefore, it is the next research direction to explore the distribution of multiple irregular convex polytopes coexisting in caving zone and more in line with the actual situation.

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