Dynamic Evolution Law of Roof Deformation in Continuous Mining and Continuous Backfilling Method

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Research Article

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DOI: https://doi.org/10.21203/rs.3.rs-563729/v1

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Dynamic evolution law of roof deformation in continuous mining and continuous backfilling method

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Abstract

To investigate the dynamic evolution law of roof deformation in the continuous mining and continuous backfilling (CMCB) method, the alternating bearing characteristics of coal and the backfilling body were obtained through statistical analysis. On the basis of two-step mining and the elastic foundation beam theory, the mechanical model of the entire stage roof deformation was established, and the dynamic change law of roof settlement was obtained. On the basis of the working face of CMCB in Haoyuan Coal Mine, the deformation rule of the two-step mining roof was analyzed. In the first stage of mining, the coal pillar is the main bearing structure, the deformation of the roof is small, and the distribution is wavy. In the second stage, the backfilling body gradually becomes the main bearing structure, and the deformation of the roof significantly increases and exhibits a U-shaped distribution. The results obtained by numerical simulations reveal that four-step mining increases the width of the coal pillars and the roof deformation is effectively controlled during the filling process. After the filling is completed, the roof remains stable under the support of the filling body under different filling modes; therefore, its final settlement remains consistent. Through field measurement, it was found that the CMCB method can effectively control the roof subsidence in Haoyuan Coal Mine.

Keywords: Continuous mining and continuous backfilling, Cemented filling, Alternating load, Dynamic evolution

1. Introduction

Although the new energy industry is rapidly and efficiently developing in China, coal resources are still the main source of the energy industry at this stage. To accelerate the industrial transformation and the harmonious coexistence of man and nature, a series of initiatives such as “green mines” and “intelligent mines” have been proposed in China. The traditional caving method has the following disadvantages: accumulation of a large number of solid waste resources, inability of recovering the remaining coal pillars, and difficulty in controlling the surface deformation (Guo et al. 2019; Dontala et al. 2015; Qian et al. 2006; Marschalko et al. 2015). Many experts have proposed coal-filling technology based on the comprehensive utilization of solid waste resources. Filling coal mining technology typically refers to the use of coal gangue, fly ash, and other solid waste resources that are directly transported to the goaf to form a solid backfill (Zhou et al. 2017;
Huang et al. 2017). Moreover, cement and other cementing materials are used to make a slurry and fill it to the working surface to form a cemented filling (Yang et al. 2015; Zhang et al. 2016). To achieve the objective of controlling the movement of overlying rock, reducing the surface subsidence, and protecting the ecological environment, problems such as difficulty in balancing the coal mining efficiency and filling efficiency must be addressed. On this basis, Lu et al. (2017; 2021) proposed the continuous mining and continuous backfilling (CMCB) method. By dividing the coal seam to be mined at the working face into several branch roads, and by adopting the method of discharging coal from the branch roads and filling and replacing them in a step-by-step manner, the coal pillars of the branch roads are skipped and filled to realize the parallel operation of coal mining and filling and improve the production efficiency.

The objective of backfill mining is to increase the recovery rate of coal resources based on controlling the overlying strata and surface deformation. Miao established an equivalent mining height model based on the characteristics of rock movement and surface subsidence (Miao et al., 2012). Zhang established an elastic foundation model and investigated the deformation laws of the roof (Zhang, 2008; Zhang et al., 2010). On the basis of the cemented filling of thick coal seams, Deng established a mechanical model for the movement and deformation of the roof of each layer and analyzed the characteristics of roof subsidence between different mining cycles (Deng, 2017; Deng et al., 2015; Deng et al., 2014). On the basis of the theory of continuous curved beams, Zuo obtained the relationship between the roof deformation curvature and fullness (Zuo et al., 2019; Liu et al., 2016). On the basis of the setting strength of the filling, Jia (2020; 2019) corrected the elastic foundation coefficient and obtained the deformation law of the roof of the cemented filling mining field. Fan et al. (2018) obtained the basic roof bending and subsidence law by modifying the elastic foundation coefficient formed by the combination of the direct roof and filling body. Yao analyzed the roof deformation rules of the filled and unfilled areas through similar model tests. The roof of the filled area only produces a curved subsidence zone, while the unfilled area undergoes obvious collapse (Yao et al., 2017). Li established a temporal and spatial evolutionary mechanical model for the appearance of rock pressure in a backfill mining field. He believes that roof stress goes through the stages of stress increase, rapid decompression, and slow pressure increase in sequence with the advancement of filling. Moreover, the stress on the backfill is much smaller than that of the original rock (Li et al., 2020). The CMCB method has similar laws as roadway cemented and filled coal mining. The roof load-bearing mechanism still goes through the three stages of coal pillar support-coal pillar and backfill cooperative support-backfill support (Gao et al. 2018). Therefore, research on the deformation law of the mining field roof should be based on the different bearing mechanisms of coal pillars and backfills at different mining stages.

Therefore, based on the CMCB working face of Haoyuan Coal Mine in Wuhai City, Inner Mongolia Autonomous Region, this paper introduces the filling mining technology of this working face. The roof bearing mechanism during the filling mining process was investigated, and the dynamic evolution law of roof deformation was obtained. On the basis of different mining modes, the dynamic migration law of roof deformation under the alternate bearing of coal pillars and backfills was analyzed through numerical simulation. Additionally, through on-site monitoring, the effect of the coal filling technology in controlling the roof deformation was verified.

2. Study Location

Haoyuan Coal Mine is located in Hainan District, Wuhai City, Inner Mongolia, China. The
mine has an annual design production capacity of 0.6 Mt/a, and mainly mines No. 9 coal and No. 16 coal. To further increase the recovery rate, the CMCB method is used to mine No. 16 coal. A combination of local waste resources, gangue, and cement are used as the main filling materials. The inclination angle of the No. 16 coal seam is 8°–14°, and the average coal thickness is 5 m. According to the drilling histogram, the roof of the coal seam is dominated by sandy mudstone and mudstone, and the bottom is mainly sandy mudstone (Fig. 1).

![Fig. 1. Haoyuan Coal Mine and its drilling histogram: (a) location of Haoyuan Coal Mine; (b) drilling histogram.](image)

The 1602 working face of Haoyuan Coal Mine has a strike length of 690 m and a face length of 52 m, and is divided into several branch lanes at an interval of 5 m along the strike. The slurry is prepared on the well and mixed with the gangue underground. The cement slurry is mixed with the gangue when filling the roadway exit at the filling working face. The gravity potential energy and the fluidity of the cement slurry are used to carry the gangue for self-flow filling. The cement slurry is mixed at the surface filling station and transported through the return air shaft to the return air lane of the 1602 working face, and then reaches the roadway to be filled. The gangue enters the underground gangue buffer silo through the gangue hole on the surface, and enters the roadway to be filled through the 1602 return airway and the transportation belt (Fig. 2).

![Fig. 2. Schematic diagram of filling of 1602 working face.](image)

3. Roof bearing characteristics of backfill mining field

Haoyuan Coal Mine adopts two-step mining. The odd-numbered lanes are mined first, and the even-numbered lanes are recovered after the filling body of the first lane of the odd-numbered lanes
reaches the initial strength. The mining field is divided into several branch lanes along the strike and the lanes are numbered in sequence. For the ease of analysis, \( O_i \) is the odd number, and \( E_j \) is the even number; \( i \) and \( j \) represent the design branch lanes of the odd-numbered lanes and even-numbered lanes, respectively. In the first stage, the odd-numbered lanes are skipped and filled (Fig. 3). Step 1: Mining \( O_1 \) odd roadways; Step 2: Mining \( O_2 \) odd-numbered lanes and filling \( O_1 \) odd-numbered lanes; Step 3: Repeat Step 2, mine \( O_3 \) odd-numbered lanes and fill \( O_2 \) odd-numbered lanes. The above steps are repeated until the mining reaches the \( O_i \) odd roadway.

![Fig. 3. Alternate distribution of roof bearing structures in first stage mining.](image)

In the first stage, the odd roadway mining is analyzed, the coal pillars are successively mined at intervals, and the backfilling body gradually fills the goaf. Thereby, the characteristics of the backfilling body-coal pillar interval distribution are formed. For the convenience of analysis, \( M \) represents the coal on both sides, \( A \) represents the coal pillar roadway, \( B \) represents the goaf area, and \( C \) represents the backfill roadway. By analyzing the mining process of odd roadways as shown in Figure 3, the roof support structure remains stable through the continuous circulation of the backfilling body and coal pillar, and the following laws can be obtained:

\[
S_1 : M \rightarrow B \rightarrow A \rightarrow A \rightarrow A \rightarrow A \rightarrow A \rightarrow A \rightarrow L \rightarrow A \rightarrow A \rightarrow A \rightarrow A \rightarrow A \rightarrow M \\
S_2 : M \rightarrow C \rightarrow A \rightarrow B \rightarrow A \rightarrow A \rightarrow A \rightarrow A \rightarrow L \rightarrow A \rightarrow A \rightarrow A \rightarrow A \rightarrow A \rightarrow M \\
S_3 : M \rightarrow C \rightarrow A \rightarrow C \rightarrow A \rightarrow B \rightarrow A \rightarrow L \rightarrow A \rightarrow A \rightarrow A \rightarrow A \rightarrow A \rightarrow M \\
S_{i-1} : M \rightarrow C \rightarrow A \rightarrow C \rightarrow A \rightarrow C \rightarrow A \rightarrow L \rightarrow B \rightarrow A \rightarrow A \rightarrow A \rightarrow M \\
S_i : M \rightarrow C \rightarrow A \rightarrow C \rightarrow A \rightarrow C \rightarrow A \rightarrow L \rightarrow C \rightarrow A \rightarrow B \rightarrow A \rightarrow M
\]  

(1)

According to the statistical analysis of Eq. (1), during the first stage of mining, the roof bearing structure continuously changes, the coal pillar support is converted into coal pillar-backfilling body joint support, and the coal pillar is still the main bearing structure. The number of the roadway to be mined is denoted as \( m \), and the change law is expressed as follows:

\[
S_m : M \rightarrow (C \rightarrow A)^{m-1} \rightarrow B \rightarrow A_{2l+1} \rightarrow M
\]  

(2)

The above-mentioned process completes the first-stage odd roadway mining and then moves the equipment, and the second-stage even roadways are recovered (Fig. 4). Step 1: Mining the first lane \( E_1 \) of even roadways and filling the end lanes of odd roadways; Step 2: Mining \( E_2 \) even roadways and filling \( E_1 \) even roadways. The even roadway mining is completed in turn. Step \( j+1 \): After all of the even roadways have been mined, the tail lanes of the even roadways are filled to complete the filling of all branch lanes.
During the second stage of mining, the coal pillars are gradually mined, the filling lanes are connected into pieces, and the main bearing structure of the roof is transformed from the joint bearing of the coal pillars and the backfilling body to being mainly carried by the backfilling body. Analysis revealed that the roof support structure undergoes the following changes:

\[
\begin{align*}
S_1 : & \quad M \rightarrow C \rightarrow B \rightarrow C \rightarrow A \rightarrow C \rightarrow A \rightarrow L \rightarrow C \rightarrow A \rightarrow C \rightarrow A \rightarrow M \\
S_2 : & \quad M \rightarrow C \rightarrow C \rightarrow C \rightarrow B \rightarrow C \rightarrow A \rightarrow L \rightarrow C \rightarrow A \rightarrow C \rightarrow A \rightarrow M \\
S_3 : & \quad M \rightarrow C \rightarrow C \rightarrow C \rightarrow C \rightarrow B \rightarrow L \rightarrow C \rightarrow A \rightarrow C \rightarrow A \rightarrow M \\
S_{n-1} : & \quad M \rightarrow C \rightarrow C \rightarrow C \rightarrow C \rightarrow L \rightarrow C \rightarrow B \rightarrow C \rightarrow A \rightarrow M \\
S_n : & \quad M \rightarrow C \rightarrow C \rightarrow C \rightarrow C \rightarrow L \rightarrow C \rightarrow C \rightarrow B \rightarrow M \\
S_{n+1} : & \quad M \rightarrow C \rightarrow C \rightarrow C \rightarrow C \rightarrow L \rightarrow C \rightarrow C \rightarrow C \rightarrow A \rightarrow M
\end{align*}
\]  (3)

According to the statistical induction of Eq. (3), during the second stage of mining, the change rule of the roof’s load-bearing structure mainly changes in three stages. First, before the even roadways are mined, the rear roof of the mined branch roadway is completely supported by the backfilling body, and the front roof is still jointly borne by the coal pillar and backfilling body. Secondly, after the even roadways are mined, all roofs of the mining field are supported by backfills except for the tail lanes. Finally, after the even roadways are filled, the coal pillar roadways are all replaced by the backfilling bodies, and the mining field roof is completely supported by the backfilling bodies. Therefore, the roof-bearing structure transformation obeys Eq. (4).

\[
\begin{align*}
S_n : & \quad M \rightarrow (C)_{2(n-1)} \rightarrow (C \rightarrow B) \rightarrow (C \rightarrow A)_{j-1, n-1} \rightarrow C \rightarrow M \\
S_n : & \quad M \rightarrow (C)_{2n} \rightarrow (C \rightarrow B) \rightarrow M \quad (n = j) \\
S_n : & \quad M \rightarrow (C)_{2n} \rightarrow M \quad (n = j + 1)
\end{align*}
\]  (4)

4. Distribution characteristics of roof subsidence in backfill mining field

The roof-bearing structure of the backfill mining field changes with the backfill mining process. In the first stage of mining, the coal pillar and the backfilling body are jointly supported, but the
strength of the coal pillar is much higher than the strength of the backfilling body. Therefore, the coal pillar is the main bearing structure. With the mining of odd roadways, the coal pillars are distributed at intervals, and the main bearing bodies of the roof jump and distribute. In the second stage of mining, the back of the mining branch roadway is completely carried by the backfilling body, and the coal pillar in front of the branch roadway remains the main bearing structure. To simplify the calculation, the following assumptions are made:

1. The coal pillar, backfilling body, and roof are simplified as vertical bearing structures, and the interaction between the structures is ignored.
2. The backfilling process is consistent, and the stress release of the surrounding rock caused by factors such as the interruption of backfilling is ignored.
3. Each structure is an elastic member, regardless of the roof breakage and the plastic deformation of the coal and backfilling body.
4. It is assumed that the overburden load is the maximum load generated after mining on the working face; the load changes generated during the filling process are not considered.

Therefore, on the basis of the key stratum theory (Qian et al., 1996), the overburdened load of the working face after the full filling can be obtained as follows:

\[
(q_u)_i = \frac{E_i h_i^3 (\gamma_i h_i + \gamma_2 h_2 + L + \gamma_3 h_3)}{E_1 h_1^3 + E_2 h_2^3 + L + E_3 h_3^3}
\]

where \( E_i \) is the elastic modulus of each layer of the overlying rock; \( \gamma_i \) is the bulk density of each layer of the overlying rock; \( h_i \) is the thickness of each layer of the overlying rock.

Therefore, the roof is assumed to support the elastic foundation beams on the coal pillar and backfilling body. According to the evolution characteristics of the roof bearing mechanism, a mechanical model is established in stages to analyze the evolution of roof deformation.

### 4.1 Mechanical model of roof subsidence in first stage mining

In the first stage of mining, the coal pillars behind the mining branch roadways are spaced apart from the backfilling bodies, and the coal pillars are in front of them. The roof-bearing structure of the back support roadway in front of the working face is different. Based on the distribution characteristics of the coal pillars and backfilling bodies, \( k_1 \) and \( k_2 \) are used to represent the elastic coefficients of the coal and backfilling body, respectively, and foundation beam models with different elastic coefficients can be established (Fig. 5).

![Fig. 5. Elastic foundation model of roof bearing in first stage mining.](image)

The foundation reaction coefficients \( k_1 \) and \( k_2 \) are related to the elastic modulus, Poisson’s ratio, and thickness of the elastic foundation; therefore, the foundation reaction coefficient can be obtained (Jiang 2016).

\[
\begin{align*}
k_1 &= \frac{E_1}{(1-\nu_1^2)} h_1 \\
k_2 &= \frac{E_2}{(1-\nu_2^2)} h_2
\end{align*}
\]
where \( E_m, \nu_m, \) and \( h_m \) are the elastic modulus, Poisson’s ratio, and thickness of the coal pillar, respectively; \( E_e, \nu_e, \) and \( h_e \) are the elastic modulus, Poisson’s ratio, and thickness of the filling body respectively; when fully filled, \( h_m = h_e. \)

By analyzing the above-mentioned foundation beam model, it was found that the rock layer above the coal pillar is less disturbed and the original rock stress state is maintained. At the backfilling body, because its strength is less than that of coal, the rock layer causes bending and sinking at the upper side, and the load increases. Above the mined-out area, the surrounding rock stress is not fully released, and only slight deformation occurs when the goaf occurs. Therefore, a mechanical model is established on the basis of the different loads and elastic coefficients of the coal and backfilling body (Fig. 6). Here, \( p_1, p_2, \) and \( p_3 \) denote the original rock load, disturbed load after filling, and load in the empty roof area, and \( \nu \) denotes the roof deflection.

![Fig. 6. Mechanical model of roof bearing capacity in one-stage mining.](image)

When the first stage of mining reaches the Om lane, it is divided according to the different roof support structures. Let \( a \) represent the number of the odd roadway. When \( a < m \), the branch roadway has been filled and its roof is supported by the backfilling body; therefore, the roof deformation can be obtained as follows (Huang, 2005):

\[
\nu_1^{(a)} + 4 \lambda_2^a \nu_1^{(a)} = \frac{P_2}{EI} \tag{7}
\]

where \( E \) and \( I \) are the elastic modulus and section distance of the roof rock layer, respectively, and \( k_2 = 4EI \lambda_2^a. \)

When \( a = m \), the branch roadway has been mined but not filled, and is considered as an empty top area. The roof of this area slightly deforms under the action of its own structure.

\[
\nu_m^{(a)} = \frac{P_3}{EI} \tag{8}
\]

When \( a > m \), the branch roadway is not mined, and its roof remains stable under the action of the coal pillars.

\[
\nu_1^{(a)} + 4 \lambda_4^a \nu_1^{(a)} = \frac{P_1}{EI} \tag{9}
\]

where \( k_4 = 4EI \lambda_4^a. \)

During the first stage of mining, the even roadways are not mined because they are the main load-bearing structure maintaining the stability of the roof. Under this condition, the roof is deformed.

\[
\nu_1^{(j)} + 4 \lambda_4^j \nu_1^{(j)} = \frac{P_1}{EI} \tag{10}
\]

On the basis of the statistical analysis result (2), the above equations are combined to establish the roof deflection distribution equation set during the first stage of mining. The equations are solved in accordance with the continuity condition between the coal pillar and the backfill, and the boundary conditions of the coal on both sides.

### 4.2 Mechanical model of roof subsidence in two-stage mining

According to the statistical analysis result (4), filling can be divided into three stages according to the change of the supporting structure of even roadways. When \( n < j \), all of the fillings before
the $E_n$ lane are filled, and the backfilling bodies and coal pillars are distributed after the $E_n$ lane. This stage is considered as second stage filling (I). When $n = j$, all backfilling bodies are before the $E_n$ lane, and the coal is after the $E_n$ lane. This stage is considered as second stage filling (II). When $n = j + 1$, the roof of the stope remains stable under the action of the backfilling body, which is considered as second stage filling (III). On the basis of the above analysis, three-stage elastic foundation beam models are established and simplified into mechanical models for analysis (Fig. 7).

Let $b$ represent the even roadways mined. In the second stage of mining (I), when $b < n$, the roof at this location is supported by the backfilling body, and the roof deformation at this place can be obtained.

$$w_{(b)}^{(4)} + 4z^4w_{(b)} = \frac{P_2}{EI}$$ (11)

When $b = n$, the roof of the mining branch roadway is in the empty top area, and the upper load is borne by the roof structure itself, which results in slight deformation; therefore, the roof deformation at this place can be obtained.

$$w_{n}^{(4)} = \frac{P_1}{EI}$$ (12)

When $b > n$, the backfilling body and the coal pillar are spaced apart; therefore, the roof deformation of the coal pillar roadway can be obtained.

$$w_{(b)}^{(4)} + 4z^4w_{(b)} = \frac{P_1}{EI}$$ (13)

The roof deformation of the backfilling body roadway can be expressed as follows:

$$w_{(b)}^{(4)} + 4z^4w_{(b)} = \frac{P_2}{EI}$$ (14)

According to the statistical analysis result (4), the above equations are combined and the
continuity conditions and boundary conditions are substituted to obtain the deformation distribution of the roof at this stage.

In the second stage of mining (II), after the mining of the jth branch roadway, the back of the working face is completely supported by the backfilling body, and there is no pillar roadway in front of it (Fig. 7b); thus, the following model can be established:

\[
\begin{align*}
  w_1^{(4)} + 4\lambda_1^4 w_1 &= \frac{p_1}{EI} \\
  w_2^{(4)} + 4\lambda_2^4 w_2 &= \frac{p_2}{EI} \\
  w_3^{(4)} &= \frac{p_1}{EI} \\
  w_4^{(4)} + 4\lambda_4^4 w_4 &= \frac{p_1}{EI}
\end{align*}
\]

(15)

In the second stage of mining (III), all branches within the stope are filled with fillings, and the roof remains stable under the combined action of the backfilling bodies and coal. The following model is established:

\[
\begin{align*}
  w_1^{(4)} + 4\lambda_1^4 w_1 &= \frac{p_1}{EI} \\
  w_2^{(4)} + 4\lambda_2^4 w_2 &= \frac{p_2}{EI} \\
  w_3^{(4)} + 4\lambda_3^4 w_3 &= \frac{p_1}{EI}
\end{align*}
\]

(16)

Through the integral solution of each equation, and by substituting the continuity conditions between the coal and the backfilling body and the boundary conditions at both ends of the coal, the unknown variables can be calculated using MATLAB, and the relevant deflection distribution law can be quickly and conveniently obtained.

5. Deformation law of roof settlement

A model for calculating the roof subsidence in each mining process was established on the basis of the geomechanical parameters of Haoyuan Coal Mine and its mining technology. To facilitate the analysis and reduce the stope area, the stope was divided into eight roadways with an interval of 5 m. The odd roadways were mined first, and the even roadways were mined next. By combining the above-mentioned mechanical model, the law of roof subsidence at each stage was obtained using MATLAB.

5.1 Settlement of roof in first stage

During the first stage of mining, the coal pillars and the backfilling body bear the load in a coordinated manner. However, the strength of the backfilling body is much smaller than that of the coal pillar; therefore, the coal pillar is the main bearing structure at this stage. After the roadway is mined, the stress release is small; therefore, the roof always produces a large settlement above the backfilling body (Fig. 8). In Step 1, the odd roadway O1 is mined, the roof emptying time is short, the stress release is small, and the roof undergoes slight subsidence. In Step 2, while the odd roadway O2 is being mined, the odd roadway O1 is filled, and the upper surrounding rock load is completely released. Therefore, under the action of the backfilling body, the deformation of the roof increases. Under the action of the coal pillar to isolate the stress transmission, the roof deformation center is
still at O1 in the odd roadway. In Step 3, the roof deformation is similar to that in Step 2, and because O3 in the odd roadway is not filled, the center of the roof deformation is at O2 in the odd roadway. As the mining progresses, the roof deformation is gradually distributed in a wave shape. As shown in Step 4, the extreme value of roof subsidence appears at O2 in odd roadways. As can be seen from the law of roof subsidence in the first stage, after the roadway is mined, timely filling can significantly reduce the stress release of the surrounding rock and thereby control the subsidence of the roof in the empty roof area. The roof subsidence deforms less at this stage. Additionally, the roof subsidence is distributed in a symmetrical wave shape at the filled branch roadway, and its extreme value appears at the center of the filled branch roadway.

![Fig. 8. Distribution of roof subsidence in first stage of mining.](image)

### 5.2 Settlement of roof in second-stage mining

After the completion of the first stage of mining, the coal pillar-backfilling body interval distribution appears in the stope. In the second stage of mining, the coal pillars are gradually replaced by the backfilling body, which becomes the main bearing structure and results in greater roof settlement (Fig. 9). In the second stage of mining Step 1, the coal pillars of the E1 branch of the even roadway are mined, and the O4 branch of the odd roadway is filled to complete the filling of all odd roadways. In Step 2 of mining the even roadway E2 branch, the stress transmission isolation of the coal pillar is lost between the backfilling bodies, the roof deformation further increases and concentrates in the O2 branch, and the roof deformation is V-shaped. In Step 3 of mining the E3 branch road, the roof deformation law is similar to that in Step 2. However, when mining the E4 branch road in Step 4, after the stope reaches a certain range, the roof subsidence expands from a V shape to a U shape. The roof maintains a relatively gentle deformation within a certain range. In Step 5, the E4 branch is filled, all coal pillars in the stope are replaced by the backfilling bodies, and the roof subsidence further increases. At this stage, the roof deformation is symmetrically distributed, and a gentle curve exists within a certain range in the middle. Compared with the previous stage, the deformation is still U-shaped. During the second-stage mining, the roof deformation is first distributed from a wave-shape to a V-shaped distribution. As the coal pillars are gradually replaced by backfills, the deformation of the roof becomes U-shaped. Subsequently, the further mining of the even roadway causes the roof deformation to increase further and continue to expand in a U shape.
6. Roof Settlement Laws in Different Mining Modes

Haoyuan Coal Mine adopts a two-stage stoping mode. To further verify the control effect of this mode on roof deformation, and to investigate the roof settlement laws under different mining modes, numerical analysis models were established under different filling modes, and the expansion laws of roof deformation were analyzed. On the basis of the geomechanical parameters of Haoyuan Coal Mine (Table 1), two-step mining, three-step mining, and four-step mining models were established, and the roof deformation laws in each mode were analyzed in stages.

### Table 1. Geological model parameters.

|                  | Thickness (m) | Density (kg·m⁻³) | Bulk modulus (GPa) | Shear modulus (GPa) | Internal friction angle (°) | Cohesion (MPa) | Tensile strength (MPa) |
|------------------|---------------|------------------|--------------------|---------------------|----------------------------|----------------|-----------------------|
| Topsoil layer    | 24            | 2615             | 1.87               | 1.12                | 30                         | 2              | 0.9                   |
| Sandy mudstone   | 5             | 2450             | 1.09               | 1.6                 | 18                         | 3.8            | 4.7                   |
| Siltstone        | 5             | 2615             | 1.87               | 1.12                | 30                         | 2              | 0.9                   |
| Sandy mudstone   | 17            | 2450             | 1.09               | 1.6                 | 18                         | 3.8            | 4.7                   |
| Mudstone         | 3             | 2370             | 2.1                | 1.41                | 25                         | 3.8            | 3.7                   |
| Sandy mudstone   | 2             | 2450             | 1.09               | 1.6                 | 18                         | 3.8            | 4.7                   |
| Mudstone         | 3             | 2370             | 2.1                | 1.41                | 25                         | 3.8            | 3.7                   |
| Sandy mudstone   | 6             | 2450             | 1.09               | 1.6                 | 18                         | 3.8            | 4.7                   |
| Coal             | 5             | 2400             | 1.69               | 0.56                | 40                         | 2.83           | 2.5                   |
| (Filling body)   | 5             | 1700             | 0.98               | 0.375               | 12                         | 0.5            | 0.5                   |
| Sandy mudstone   | 3             | 2450             | 1.09               | 1.6                 | 18                         | 3.8            | 4.7                   |
| Coal             | 1.5           | 2400             | 1.69               | 0.56                | 40                         | 2.83           | 2.5                   |
| Sandy mudstone   | 35.5          | 2450             | 1.09               | 1.6                 | 18                         | 3.8            | 4.7                   |

6.1 Deformation law of roof in first stage of mining

At this stage, the roof deformation is distributed in a wave shape, and the deformation is relatively large in the filling area. Small deformation occurs above the coal pillar and in the empty roof area. In two-step mining, the coal pillar spacing is small, the mining area is large, and the coal pillar bears a large load, which results in compression deformation (Fig. 10a). In three-step mining, the mining area is reduced, the overlying load is significantly reduced, the width of the coal pillar increases and its supporting effect becomes obvious, and the roof above the coal pillar exhibits an obvious smooth transition section (Fig. 10b). In four-step mining, the width of the coal pillars further
increases, and the smooth transition section is further extended (Fig. 10c). The increase of the mining stage leads to an increase in the width of the coal pillar, a reduction in the area of recovery, and a weakening of the load on the overlying strata. This reduces the roof deformation at the coal pillar and further extends the smooth transition section, which enhances the control of roof deformation.

6.2 Deformation law of roof in final stage

At this stage, all of the coal bodies in the stope have been mined, and only the last mining branch is left unfilled. At this stage, the roof of the stope is completely borne by the backfilling body, and with the stress release of the surrounding rock of the roof, the deformation of the previous filling area becomes relatively large. In the two-step mining mode, the mining proceeds from left to right, which results in the significantly greater deformation of the roof on the left side (Fig. 11a). In the three-step mining mode, the coal pillars are mined three times, and the roof deformation clearly exhibits three stages on the left side of the model. The first stage has the largest deformation, the second stage has the second largest deformation, and the third stage has the smallest deformation (Fig. 11b). In the four-step mining mode, the roof deformations at different stages have greater differences (Fig. 11c). In different mining modes, the control of roof deformation becomes better as the mining stage increases. In two-step mining, the roof deformation has little difference at each stage and maintains a large settlement. In three-step mining, the roof deformation greatly fluctuates, and the roof deformation becomes smaller in the subsequent mining stage.
6.3 Settlement law of stope roof after mining

After the stope is filled and calculated to be stable, the roof settlement deformation is the same in all modes. In two-step mining, the roof deformation is relatively smooth (Fig. 12a). In four-step mining, the roof deformation has certain volatility (Fig. 12c). From the above analysis, if the surrounding rock properties are the same, the different filling modes only have a minor effect on the final settlement of roof deformation, which helps stabilize the roof during the filling process. Compared with two-step mining, four-step mining can significantly reduce the roof deformation during the filling process and give full play to the supporting role of the coal pillar. Therefore, in mining areas with poor roof conditions, multi-step mining is preferred to increase the width of the coal pillars during mining and strengthen the control of roof deformation during the mining process.

Fig. 12. Roof settlement distribution after mining: (a) two-step mining; (b) three-step mining; (c) four-step mining.

7. Engineering practice

To further verify the control effect of backfill mining on roof deformation, a roof subsidence monitoring station was established in the 1602 working face of Haoyuan Coal Mine. The CMCB work face divides the stope into several branch lanes with an interval of 5 m and adopts two-step mining. The odd roadways are mined first, and the even roadways are mined next. When the backfill body of the first branch roadway reaches the strength of seven days, the even roadway is switched and the even roadway is mined. Therefore, every 14 branch lanes are a filling cycle unit; hence, a monitoring station is established in a filling cycle unit at the 1602 working face. A measuring station is installed on the roof at 25 m of each branch lane to monitor the entire filling process (Fig. 13).

Fig. 13. Displacement measuring station of 1602 working face.

The roof deformation is not obvious during coal mining and filling (Fig. 14a and Fig. 14b), and remains stable under the action of the backfilling body (Fig. 14c). After the filling is completed, the roof is connected to the backfilling body, which does not only support the roof at the working face, but also effectively controls the roof at the return airway and transportation roadway (Fig. 14d). By
sorting the on-site monitoring data, the roof settlement approximately conforms to the Gaussian curve (Fig. 15). The roof subsidence at the middle of the stope is more obvious, which is similar to the theoretical analysis results and numerical simulation results. Through data fitting, it was found that the roof deformation of the odd roadway is slightly larger than that of the even roadway, and the roof subsidence in the first mining area is larger than that in the next mining area. The overall deformation is small, and the sudden change of the roof sink is not observed, which effectively avoids problems such as roof breakage. According to the on-site monitoring results, the 1602 working face of Haoyuan Coal Mine adopts the CMCB method, which can effectively control the movement and deformation of the overlying strata and ensure the safety of the working face.

![Fig. 14. Roof deformation: (a) roof during mining; (b) roof during filling; (c) filling body; (d) roof of transportation roadway after filling.](image)

![Fig. 15. Monitoring results for 1602 working face.](image)

8. Conclusion

On the basis of the CMCB face of Haoyuan Coal Mine, this study investigated the roof bearing mechanism and settlement evolution law, and analyzed the dynamic transformation law of roof deformation under alternate loading and coal pillar loading. The following detailed conclusions were drawn:

1. The CMCB method realizes the parallel operation of continuous coal mining and continuous filling. In the first stage of mining, the coal pillar and the backfilling body support the roof in a coordinated manner, and the coal pillar is the main bearing structure. In the second stage of mining, the backfilling body gradually becomes the main bearing structure.

2. On the basis of the alternate bearing characteristics of the backfilling body and the coal pillar, a mechanical model of roof deformation at each stage of backfill mining was established, and
the distribution law of roof settlement at each stage was obtained. In the first stage of mining, the roof subsidence is distributed in a wave shape and its deformation is relatively small. In the second stage of mining, the roof deformation gradually expands into a U-shaped distribution and the roof deformation significantly increases as the coal pillars are mined.

(3) The numerical models of different filling modes were established. The results reveal that four-step mining effectively reduces the roof deformation during the coal mining process, which is beneficial to roof control during the mining process. Through monitoring, it was found that in a single filling cycle unit of Haoyuan Coal Mine, the roof deformation approximately conforms to the Gaussian curve. Finally, the roof sink is small, which satisfies the requirements for deformation control.

Data Availability

The data used to support the findings of this study are included within this article.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

Acknowledgments

The authors sincerely appreciate the financial support from the National Natural Science Foundation of China (No. 51804310).

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Figures

Figure 1

Haoyuan Coal Mine and its drilling histogram: (a) location of Haoyuan Coal Mine; (b) drilling histogram. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

Schematic diagram of filling of 1602 working face.
Figure 3
Alternate distribution of roof bearing structures in first stage mining.

Figure 4
Alternate distribution of roof bearing structures in second-stage mining.
Figure 5

Elastic foundation model of roof bearing in first stage mining.

Figure 6

Mechanical model of roof bearing capacity in one-stage mining.
Figure 7

Roof bearing elastic foundation model and mechanical model in second stage mining: (a) second stage mining (I); (b) second stage mining (II); (c) second stage mining (III).
Figure 8

Distribution of roof subsidence in first stage of mining.
Figure 9

Distribution of roof subsidence in second-stage mining.

Figure 10

Settlement distribution of roof in first stage mining: (a) two-step mining; (b) three-step mining; (c) four-step mining.
Figure 11
Settlement distribution of roof in final stage: (a) two-step mining; (b) three-step mining; (c) four-step mining.

Figure 12
Roof settlement distribution after mining: (a) two-step mining; (b) three-step mining; (c) four-step mining.
Figure 13

Displacement measuring station of 1602 working face.

(a)  (b)  (c)  (d)

Figure 14

Roof deformation: (a) roof during mining; (b) roof during filling; (c) filling body; (d) roof of transportation roadway after filling.
Figure 15

Monitoring results for 1602 working face.