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Research Article

Simulation Research for the Influence of Mining Sequence on Coal Pillar Stability under Highwall Mining Method

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Highwall mining, which is referred to the technique of extracting coal from the bottom of an exposed highwall, features safety, efficiency, and economy. According to existing highwall mining methods, the mining sequence has a great influence on highwall stability. Based on a highwall mining project in Australia, this study adopted the FLAC^{3D} numerical simulation method to investigate the stability of coal pillars with different mining sequences. The results show that different mining sequences of boreholes exert a great effect on highwall stability. Compared with sequential mining, the skip mining method achieves higher speed of highwall stabilization and smaller plastic zone of coal pillar with its maximum strength decreasing by 12%. By adjusting the mining sequence scientifically, the coal pillar failure and roof collapse caused by the deviation of mining angle can be avoided. The results may provide a new angle for the studies on the coal pillar layout and stability design in highwall mining.

1. Introduction

Highwall mining systems are originated in the United States in the mid-1970s and have been used for commercial mining in the United States since the early 1980s. Since 1991, highwall mining has been used in more than 30 pits at 13 coal mines in Australia [1]. Highwall mining is a remote-controlled mining method for soil slope with height between 10 m and 100 m or rock slope with height between 15 m and 100 m. Normally, a series of parallel boreholes are excavated horizontally by using remote-controlled mining methods, and coal resources are collected from a certain borehole depth [2–5]; the continuous highwall mining system is shown in Figure 1. Compared with traditional underground mines, highwall mining has the advantages of low cost, short delivery cycle, and a production of more than 1 Mt/year. In highwall mining, a large range of coal in the horizontal coal seam at the exposed part of the highwall is collected based on a series of rectangular or circular parallel boreholes. The cross-section of each stopes (boreholes) is small, but the excavation speed is fast, and the width height ratio of coal pillar is extremely small. According to the highwall mining systems and mining conditions, the penetration depth varies from 50 m to 500 m, and the mining range is stable without support [6–8].

Research on the theory and practice of highwall mining method has been widely reported [9–11]. Arrowsmith and Fiscor discussed recent developments in highwall mining techniques [12, 13]. Ross mined thick coal seams by alternating miner penetration depths to maintain highwall stability and optimize highwall production [14]. The basic equations for computing web and barrier pillar strength, applied stress, and stability factors were proposed by Amar Prakash [15, 16]. Under the highwall mining conditions, the rock mechanical properties and failure modes may be rather different from those of shallow rock and cannot be explained merely using conventional rock statics theory. Therefore, it is necessary to capture the coal pillar instability mechanism during highwall mining. Pillar stability and span stability are two major geomechanical issues for highwall mining

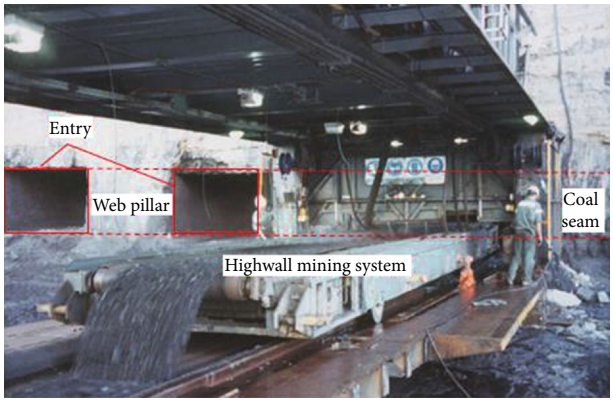


Figure 1: A continuous highwall mining system [1].

[17, 18]. During the process of highwall mining, the distance between two adjacent parallel roadways is gradually reduced in some mines, which makes the roof unstable and damaged. If the pillar collapses, it will usually cause heavy loss of mining equipment and exploitable resources. In the process of traditional mining, if sequential mining is adopted, the stability of excavation is difficult to maintain under the influence of mining stress superposition. Skip mining, especially skipping with filling mining, is more conducive to the stability of surrounding rock in fully mechanized top coal caving face.

Most of the existing research focus on the control of surface subsidence and pillar and roof stability in highwall mining. The reasonable mining sequence of highwall mining needs to be further studied. In this study, we took a coal mine in Australia as a research object; the FLAC^{3D} numerical simulation software was used to investigate its surrounding rock failure characteristics and the mechanical and stability of coal pillars in traditional sequential mining and skip mining. The theoretical analysis method and numerical simulation analysis method under highwall mining are fully evaluated, including the stress analysis of coal pillar of two different mining sequences and deformation properties. The progressive plastic zone process, stress evolution, plastic zone, and its area distribution range are described by the FLAC^{3D} simulation, which provides an improved understanding of the failure mechanism of coal pillar under different mining sequences.

1.1. Calculation and Analysis of Pillar Load. The method of auxiliary area is used to calculate the coal pillar load and only considers the overburden strata of borehole, and the overburden strata within half of the borehole width were considered. After drilling, the stress of the initial overburden supported by the borehole is transferred to the adjacent coal pillar, and the coal pillar bears all the weight of the overburden. The stress analysis of coal pillar in the two mining methods is shown in Figure 2.

It is assumed that the width of the drilling hole is equal to that of the pillar, and the coal pillar stress of sequential mining is

$$\sigma_1 = \frac{\gamma H(B_P + B_Z)B_L}{B_P \cdot B_Z} = \gamma H\left(1 + \frac{B_Z}{B_P}\right). \quad (1)$$

The coal pillar stress of skip mining is

$$\sigma_2 = \frac{\gamma H(3B_P + B_Z)B_L}{3B_P \cdot B_L} = \gamma H\left(1 + \frac{B_Z}{3B_P}\right), \quad (2)$$

where B_P is the width of coal pillar, B_Z is the width of borehole, B_L is the depth of borehole, and γ is the average bulk weight of overlying strata. It is derived from theoretical formulas $\sigma_2 < \sigma_1$. The stress of skipping coal pillar is less than that of sequential coal pillar; then the rationality and reliability of the theoretical analysis were verified by numerical simulation.

2. Model Development

2.1. Introduction of Numerical Simulation Analysis Method. FLAC^{3D} (Fast Lagrangian Analysis of Continua in 3D) is a three-dimensional finite difference software based on the explicit finite difference method.

There are 12 built-in constitutive models in FLAC^{3D} which can define the model as elastic or plastic materials. In mechanical calculation, one or several calculation modes of static, dynamic, creep, seepage, and temperature can be used to simulate complex engineering problems such as joints and faults.

2.2. Mechanical Parameters of Research Object. A simplified 3D numerical model is constructed based on the coal seam geological conditions of a mine in Australia. The mechanical parameters in the numerical simulation refer to the real geological data of the mine and the basic parameters of rock mechanics measured in the laboratory, the thickness of simulated mining coal seam is 2 m, the distance between coal seam and surface is 39 m, the immediate roof is mudstone with a thickness of 4 m, and the immediate floor is mudstone with a thickness of 3 m. The numerical model specification is length × width × height = 85 m × 40 m × 50 m, and it is arranged in seven layers. The bottom of the model was restrained to move in vertical direction, and the profile was restrained to move in horizontal direction. In order to save the computational cost and speed up the calculation, the nonuniform discrete method is used to divide the elements without affecting the calculation accuracy. The model has a total of 1006400 zones and 1055943 grid points. Moreover, Mohr-Coulomb was selected as the constitutive model. Numerical simulation model is shown in Figure 3. No. 1-8 boreholes were excavated in sequence. Due to the high speed of hole excavation in the actual process of the site, the next borehole was excavated even though the coal seam was not completely stable. Therefore, the maximum unbalance coefficient 9e-4 is set to reflect the excavation conditions. Physical and mechanical parameters of coal and rock for simulation based on Hoek-Brown strength criterion are shown in Table 1 [19–22].

2.3. Simulation Schemes and Procedure. In the highwall mining method, each borehole is a stope. Two excavation sequences are designed. The first excavation sequence is from A1 to A8, and the second is interval excavation. The

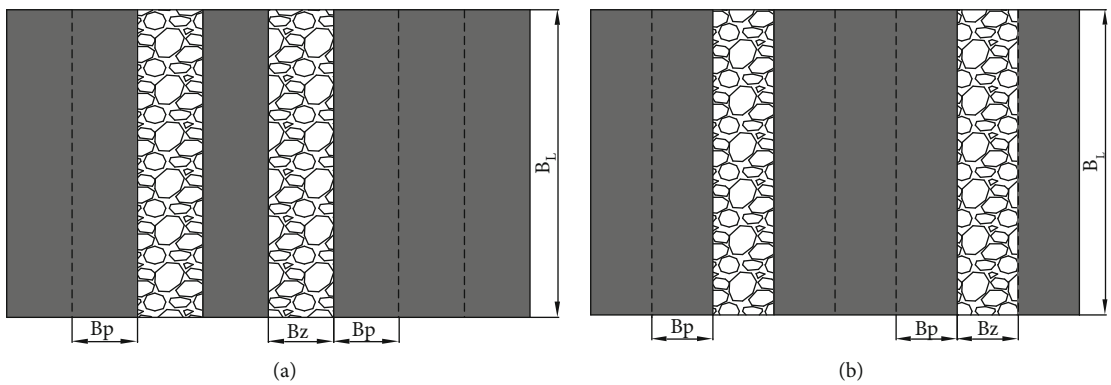


Figure 2: The stress analysis of coal pillar in the two mining methods. (a) The stress analysis of coal pillar in sequential mining. (b) The stress analysis of coal pillar in skip mining.

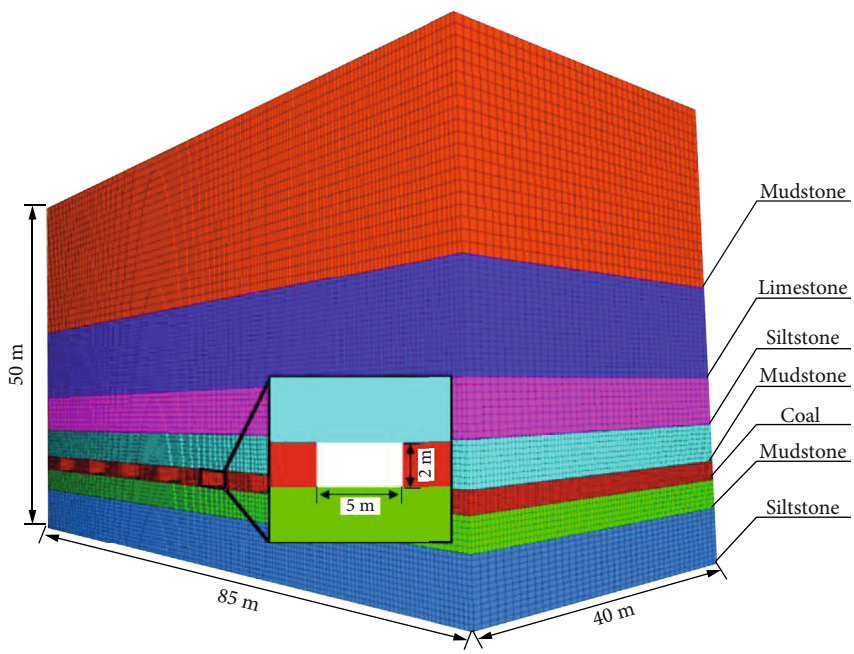


Figure 3: Calculation model of numerical simulation.

excavation sequence is A1-A3-A5-A7-A2-A4-A6-A8. The typical geometry of highwall mining panel is shown in Figure 4.

3. Analysis

3.1. Stress and Displacement Analysis of Different Mining Sequences

3.1.1. Excavation of the First Borehole. The first borehole is excavated by two mining methods. Since all geological factors are similar, the stress in the borehole is assumed to be the same. *ZZ*-stress nephogram and *Z*-displacement nephogram are shown in Figures 5(a) and 5(b). The radial stress of the surrounding rock around the borehole is released, and the in situ stress balance is destroyed. The stress in the surrounding rock of the stope roof is transferred to the coal pillars on both sides, which increases the stress on the coal pillar. The roof, floor, and two sides of the borehole are subjected to compressive stress, and the maximum compressive stress appears in the middle of the two sides, about 1.4 MPa. The borehole began to deform and the borehole deformation mainly concentrated in the middle of the roof and floor. The roof subsidence was about 6 mm, and the floor heave was about 7 mm. Therefore, the middle part of the top and bottom plate of the drilling hole should be mainly supported during the excavation.

3.1.2. Excavation of the Second Borehole. When the second borehole is excavated, the sequence of two excavation methods begins to change. The first excavation method is to excavate the adjacent A2 borehole after excavating the A1 borehole, while the second excavation method is to excavate the A3 borehole. The interval between A1 and A2 boreholes is 5 m, and 15 m between A1 and A3. The stress of *ZZ* direction of two methods is shown in Figures 5(c) and 5(d). It

Table 1: The mechanical parameters of coal and rock.

Lithology	Bulk modulus (GPa)	Shear modulus (GPa)	Cohesion (MPa)	Friction (°)	Tensile strength (MPa)	Thickness (m)
Mudstone	1.19	1.26	2.0	30	1.5	20.0
Limestone	1.79	1.89	4.2	38	3.0	10.0
Siltstone	2.90	2.27	2.3	32	1.7	5.0
Mudstone	1.19	1.26	2.0	30	1.5	4.0
Coal	0.09	0.08	1.5	25	0.3	2.0
Mudstone	1.19	1.26	2.0	30	1.5	3.0
Siltstone	2.90	2.27	2.3	32	1.7	6.0

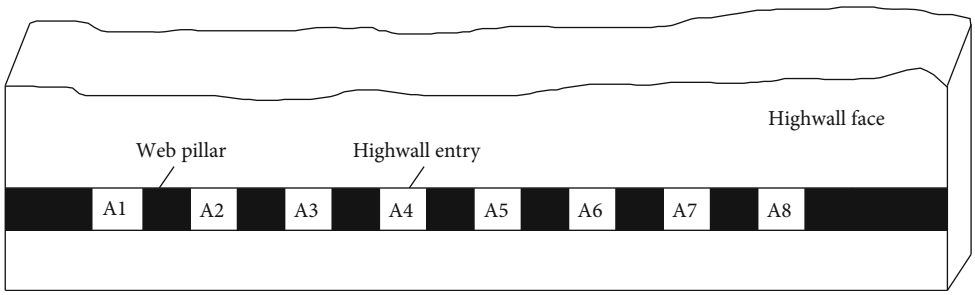


Figure 4: Typical geometry of highwall mining pane.

can be that the vertical stress of coal pillar side after excavation of adjacent A1 and A2 boreholes is about 1.4 MPa, while that of A1 and A3 boreholes after excavation interval is about 1.2 MPa. According to the nephogram, when the adjacent boreholes are excavated, the stress of surrounding rock is redistributed due to the excavation of two boreholes. The weight of overlying strata is carried by the coal pillar between the boreholes and the outer coal seam. However, the vertical stress of the 5 m coal pillar between A1 and A2 is much higher than that of the 15 m coal pillar between A1 and A3 boreholes. According to the plastic failure diagram, plastic failure occurs in the middle of both sides of hole A1 after the excavation of hole A2 under the sequential excavation mode, with the damage range of 0~0.26 m. Under the skip mining mode, plastic damage occurs on both sides of A1, with the damage range of 0~0.24 m.

3.1.3. Excavation of the Third Borehole. When the third borehole is excavated, shear failure occurs on both sides of A1 and A2 boreholes under sequential mining mode. The vertical stress of two methods are shown in Figures 5(e) and 5(f). However, under the skip mining mode, only the left and right sides of borehole A1 and the left side of A2 have shear failure, and the failure range is 0~0.8 m. At this time, the stress distribution of coal pillar between boreholes presents significant difference. In the first mining method, the stress is concentrated on the coal pillar between the boreholes, which leads to the serious deformation and damage of the coal pillar. In the second mining method, the weight of overlying strata is mainly supported on the floor rock under the coal pillar. The action way is that the load of overlying strata is transferred to the floor through the wide coal pillar, which weakens the rheological effect of coal pillar subjected to long-term high static stress.

3.1.4. Excavation of the Fifth Borehole. As shown in Figures 5(g) and 5(h), when the fifth borehole is excavated, the compressive stress of coal pillars between boreholes in the first mining method is about 1.4 MPa, ranging from 0 to 2.6 m. In the second mining method, the stress situation of coal pillar between A3, A5, and A7 boreholes is quite different. The maximum compressive stress of the two sides of the borehole is about 1.4 MPa. The wide coal pillar gives full play to its own stress transfer function and transfers the stress to the floor. The compressive stress of the coal pillar is about 1.0 MPa. According to Figures 5(i) and 5(j), the roof subsidence above A3, A5, and A7 pillars is about 0.5 mm. The closer to A1 and A2 boreholes, the larger the roof subsidence. The maximum displacement grid point is located on the roof of A1 borehole, about 1.6 mm.

3.1.5. Excavation of the Seventh Borehole. When the seventh borehole is excavated, the stress state of coal pillar under the two excavation methods tends to be consistent again. The stress range of the roof plates is basically the same as the floor. This is because the coal pillars between the boreholes are narrow. At this time, it is difficult for the coal pillars to exert their own stress transfer function, resulting in the stress concentration in the coal pillars. At this time, most of the coal pillars are plastically damaged.

Generally speaking, the adoption of skip mining technology can effectively reduce the vertical stress of coal pillar in the excavation process, improve the stress state of coal pillar, and reduce the damage scope of plastic zone. It is believed

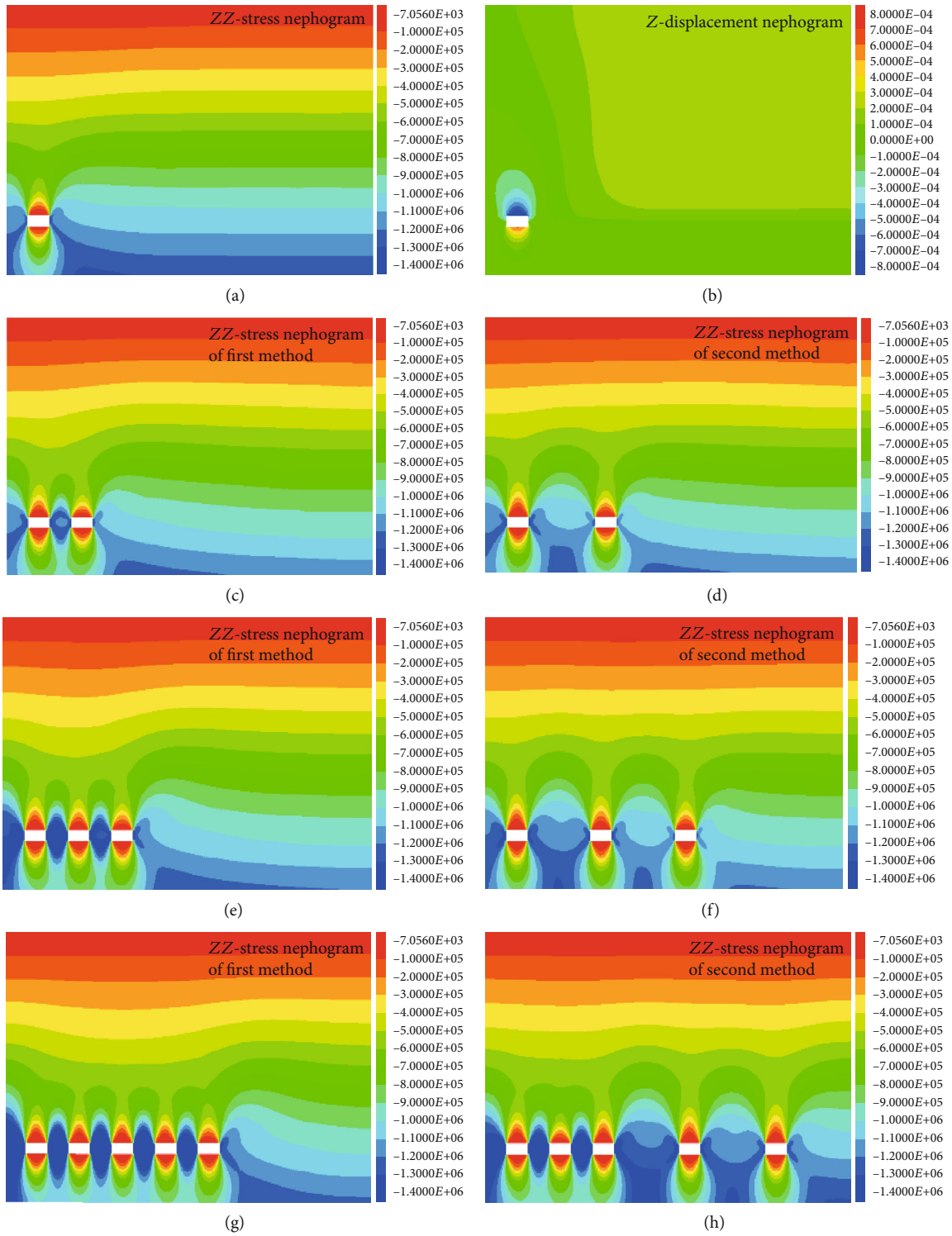


Figure 5: Continued.

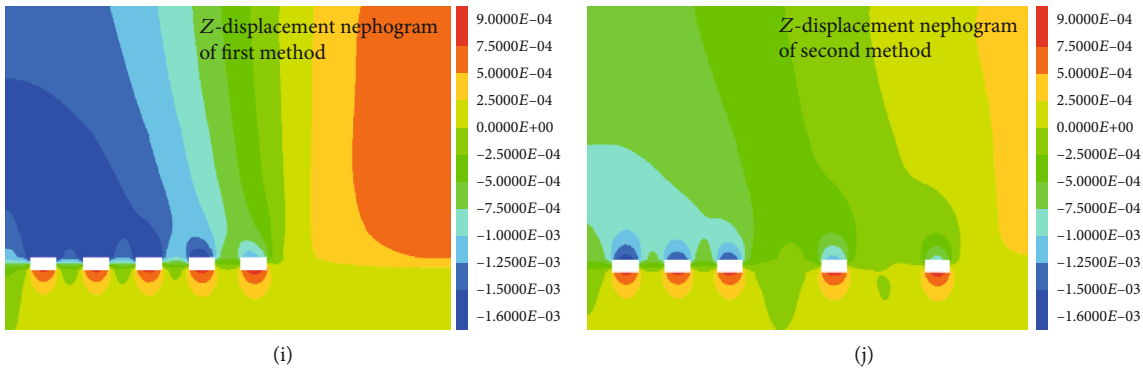


Figure 5: Stress nephogram and displacement nephogram of two methods. (a) Vertical stress nephogram of the first borehole. (b) Displacement nephogram of the first borehole. (c) Vertical stress nephogram of the second borehole. (d) Vertical stress nephogram of the second borehole. (e) Vertical stress nephogram of the third borehole. (f) Vertical stress nephogram of the third borehole. (g) Vertical stress nephogram of the third borehole. (h) Vertical stress nephogram of the third borehole. (i) Displacement nephogram of the fifth borehole. (j) Displacement nephogram of the fifth borehole.

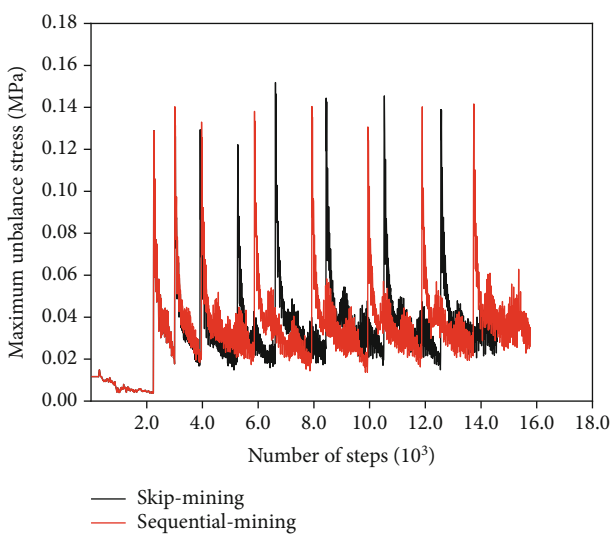


Figure 6: Maximum unbalance stress curve of two excavation methods.

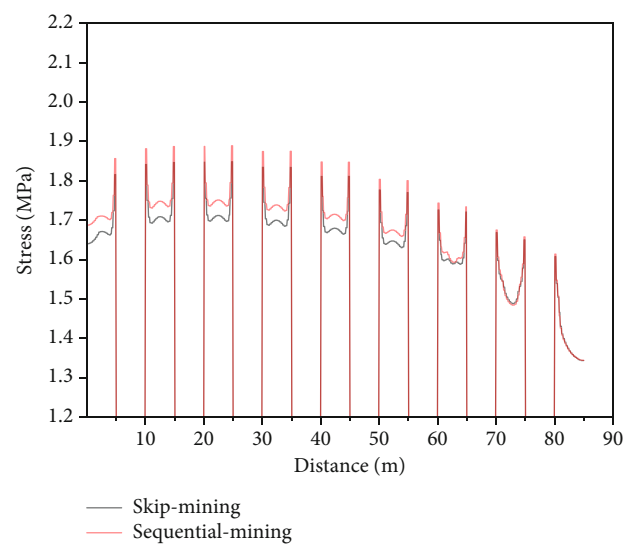


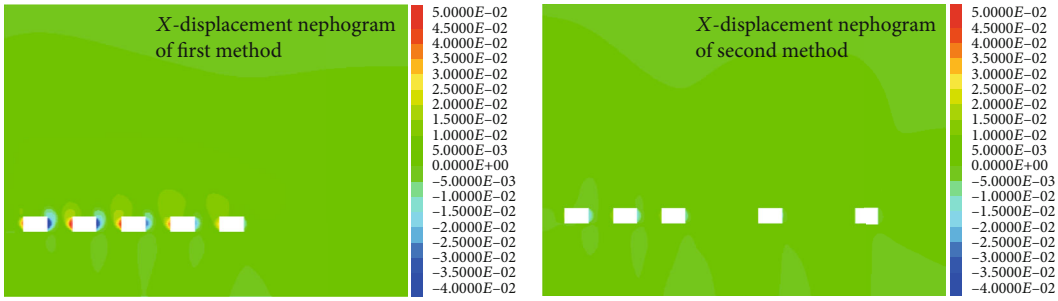
Figure 7: Distance-stress curve of two excavation methods.

that the skip mining has better stability than sequential mining.

During numerical simulation, the difference between the internal and external forces of the grid point system is called the maximum unbalanced force. When the maximum unbalanced force is close to zero or equal to zero, the model is in a stable state; on the contrary, when the maximum unbalanced force jumps from the initial change to a nonzero constant value, the model enters the plastic flow state and tends to be destroyed. According to the change of unbalanced force, the roof pressure is fully released, and the stress is redistributed due to the change of mining sequence, which makes the borehole stability increase and the maximum unbalanced force decrease.

The fourth excavation under skip mining mode is between position 1 and position 3. Due to the influence of multiple mining disturbance at this position, the stress concentration is relatively high, and the maximum unbalanced force increases; the maximum unbalance stress curve of two excavation methods is shown in Figure 6. However, as the mining process continues, the maximum unbalanced force gradually decreased. To a certain extent, it indicates that different mining sequences should be set. It is necessary to consider the appropriate length of working face by arranging the mining sequence reasonably and avoiding the aggravation of approximate "island" effect caused by long working face interval.

Different excavation sequences lead to a different stress state and a different degree of damage in coal pillar. Therefore, the stability of coal pillar not only depends on the mechanical parameters of coal and rock mass but is also closely related to the excavation sequence. At the same time, according to the map of the maximum unbalanced force, adjusting the mining sequence reasonably can speed up the stability of borehole, reduce the time of borehole self-stabilization, and increase the stability of surrounding rock.



(a) (b)

Figure 8: X-displacement nephogram of the fifth borehole. (a) Displacement nephogram of the first method. (b) Displacement nephogram of the second method.

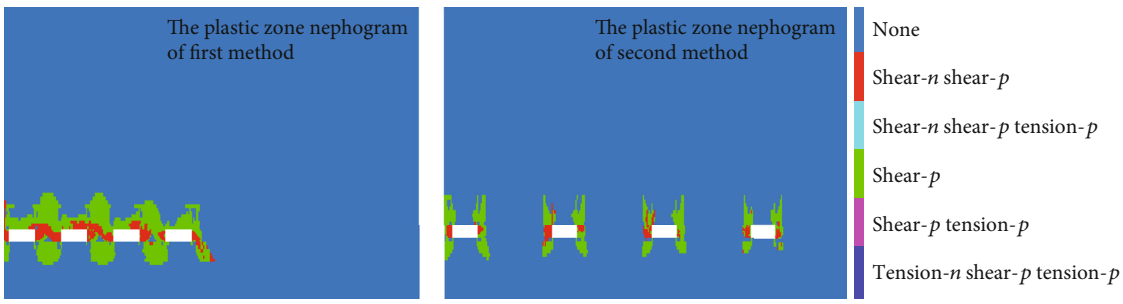


Figure 9: The plastic zone nephogram of the coal pillar of the fourth borehole.

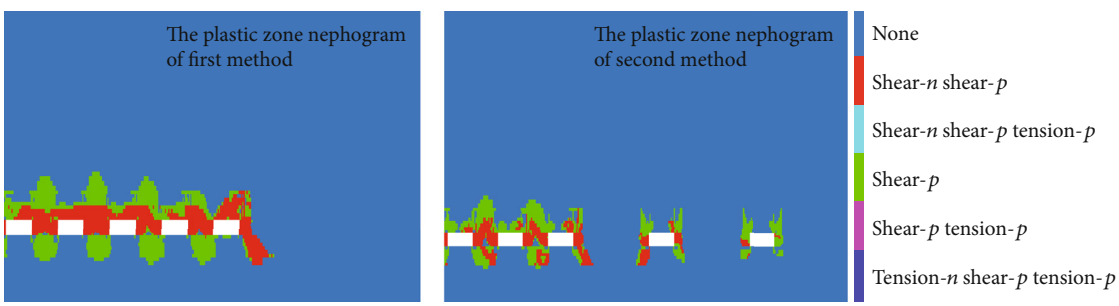


Figure 10: The plastic zone nephogram of the coal pillar of the fifth borehole.

3.2. Stress Analysis of Coal Pillar. The stress situation of coal pillar is shown in Figure 7. It can be seen from the analysis that the stress of coal pillar in the middle of stope is the largest without considering the condition of boundary coal pillar, and the stress of coal pillar on both sides of stope is relatively less. The X-displacement of coal pillar is shown in Figure 8. It is obvious that the horizontal deformation of sequential mining is larger than that of skip mining, and the maximum horizontal displacement of the borehole of sequential mining is 5 mm compared with skip mining borehole which is only 1.5 mm. It shows that compared with sequential mining, skip mining can effectively reduce the horizontal deformation of borehole.

The analysis of the two mining methods shows that after changing the mining sequence, the stress value of coal pillar is significantly reduced, and the stability of coal pillar is improved. Therefore, changing the mining sequence can reduce the stress of coal pillar to a certain extent, which helps increase the stability of coal pillar. At the same time, it can reduce the instability disaster of the large-area hanging roof caused by the wrong mining direction.

3.3. Plastic Zone Analysis of Coal Pillar. The plastic zone nephogram of the coal pillar is shown in Figures 9 and 10. Under the first mining method, due to the unreasonable selection of the coal pillar width, a large area of coal pillar shear failure occurred after the first borehole excavation. Only a small part of coal pillar still has residual strength, and the plastic zone is mainly concentrated on the corner of borehole, the roof and floor of borehole have almost no plastic failure. The failure range of plastic zone is about 0~5.92 m. The curve of plastic zone ratio is shown in Figure 11. The ratio of plastic zone of coal pillar excavated by the first borehole of first method is about 90%. Under the skip mining mode, the ratio of plastic zone increased significantly after the fourth borehole was excavated, the ratio of

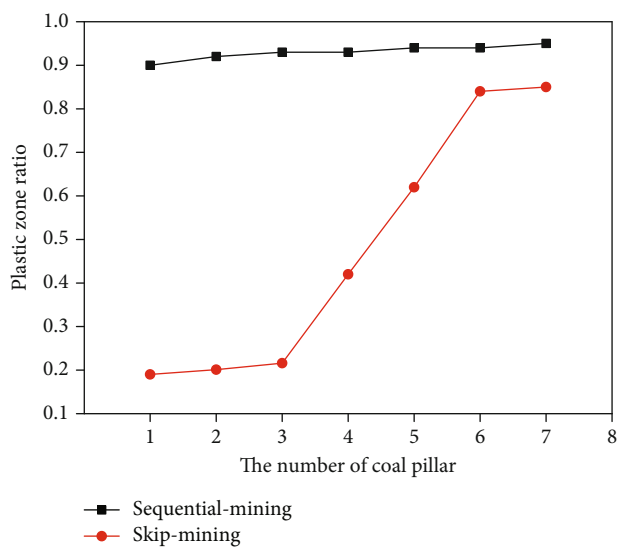


Figure 11: The curves of plastic zone ratio.

plastic zone after excavation of the fourth borehole increased significantly, the ratio of plastic zone after the seventh drilling excavation finally increased to 80%, and the ratio of plastic zone has been below sequential mining.

Under the second mining mode, plastic shear failure dramatically occurs at the surrounding rock of A7 borehole. The plastic failure range is about 0~1.75 m; during the subsequent excavation of A1, A3, A5, and A7 boreholes, the plastic failure zone expanded slowly. Until the excavation of A7 borehole, the plastic deformation range of A1, A2, and A3 boreholes extended rapidly, and the failure range was about 0~4.80 m. Although the range of plastic zone increases significantly, the ratio of plastic zone in skip mining is smaller than that of sequential mining overall.

4. Discussion

After years of development and improvement, the backfill mining method has become an important way of mineral development and has been widely used in mine development engineering. Backfilling mining poses little damage to the ecological environment and can achieve a high recovery rate. Backfilling has been reported in a highwall mining system to stabilize the stopes [21]. It also contributes to the protection of the environment around the mines of highwall mining. In this paper, only one layer of borehole mining is carried out, and there may be multiple boreholes in the actual high-slope mining process. Due to the space limit, the multilayer and filling mining methods are not considered in the analysis. Therefore, a detailed analysis on different mining arrangements of filling mining and multilayer drilling is necessary in the follow-up study.

The complexity of filling mining is increased, but the stress of coal pillars can be further reduced. At the same time, it can replace the coal pillar and improve the recovery and utilization of mineral resources. The settlement of overlying strata is further reduced or even avoided, which greatly improves lope stability. As a part of green mining, urban construction solid waste should be used as filling material as much as possible. In the next step, laboratory test and engineering practice of the borehole and filling mining situation will be analyzed and improved, and the theoretical feasibility and reliability of high-slope mining and filling mining will be discussed.

5. Conclusions

In the shallow underground, coal pillars are often subjected to stress concentration due to the effect of borehole mining and the structural surfaces in rock mass. Understanding the failure mechanism of coal pillar under different mining sequences is thus critical for construction safety in shallow underground engineering projects. In this study, based on field practice, the theoretical analysis method and FLAC simulation software with different mining sequences were used to reveal the stability of coal pillar and the progressive plastic zone process. The simulation results reproduce the influence of mining sequence on the stability of coal pillar and reflect the stability of coal pillar under traditional sequential mining and interval mining. Compared with the traditional mining method, highwall mining can improve the production and recovery rate, without additional cost, only by adjusting change the mining sequence and with different mining depths, and achieve good results.

The following main conclusions can be drawn:

(1) The theoretical calculations show that the coal pillar stress of sequential mining is $\sigma_1 = \gamma H(1 + (B_Z/B_P))$, the coal pillar stress of skip mining is $\sigma_2 = \gamma H(1 + (B_Z/3B_P))$, and the stress of skipping coal pillar is less than that of sequential coal pillar

(2) Changing the mining sequence can reduce the stress of coal pillar, and the maximum reduction value of coal pillar stress is 12%. The results show that the plastic zone of coal pillar is obviously reduced, and the proportion of plastic zone in sequential mining has been kept at 90%, indicating that coal pillars are insufficient to support the overburden weight. However, the proportion of plastic zone of skip mining began to maintain at 20% and increased from the fifth borehole, indicating that the width of coal pillar has a great influence on the stress distribution of the borehole. The overall stability time of stope is shortened, the stability speed of stope is accelerated, and the roof collapse caused by mining angle deviation can be avoided

(3) In this paper, the influence of different mining sequence on the stability of coal pillar is studied by means of simulation, and it is found that the stability of skip mining pillar is better than that of sequential mining. The traditional sequential mining technology is simple, but the interval mining method can obviously improve the stope and working face conditions. Therefore, the excavation sequence should be reasonably arranged if the site conditions permit

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

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