Numerical Simulation Study on Mining Effect of Surrounding Rock When Inclined Mining Face Passing through Empty Roadway

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Abstract: In the coal stopping process, it often happens that the mining face crossing empty roadway often causes increase of the advanced support pressure, and leads to problems such as roof fall and rib spalling, in response to which, taking a recovery mining face in Xipang Mine as the engineering background, and using software FLAC-third to establish the numerical analysis model of the mining face crossing empty roadway, the study on the influence of incline adjustment of the mining face crossing gob on the surrounding rock near the empty roadway. The result shows that with the decrease of the width of coal pillar between mining face and empty roadway, the vertical stress appears three shapes in turn: "saddle shape", "platform shape" and "solitary peak shape"; stress concentration occurs at the intersection of two roadways, and the stress concentration in acute angle area is more obvious. Adjusting the inclination of the mining face and increasing the angle between the mining face and the empty roadway are beneficial to reduce the stress concentration phenomenon of the coal pillar in the triangle area, and the maximum supporting stress is reduced from 25.3 MPa to 23.5 MPa, which is more conducive to the safe passage of the mining face through the empty roadway.

1. Introduction
In 1980s and 1990s, many small coal mines in China paid little attention to the exploitation and protection of coal, which resulted in low utilization rate of resources and serious waste. With the merger and integration of coal enterprises, small coal mines gradually withdrew from the historical stage. However, a large number of roadways left by disorderly mining in small coal mines have brought great difficulties to the subsequent mining work[1]. In the mining process, empty roadways are often encountered in the mining face. Some of these empty roadways were left over from early disorderly mining, while others were used as connecting roadway connecting track roadways and belt roadways, which played a role in transportation and temporary escape. The stopping working crossing the empty roadway has always puzzled coal mining. If the basic roof of coal seam breaks ahead of time when the mining face passes through the empty roadway or the primary rupture length of the basic roof is longer than that of the normal mining face, there will be a large area of roof weighting phenomenon, which will easily lead to safety accidents such as coal wall rib spalling, frame pressing and roof fall[2].
Therefore, it is of great significance to study the safe and rapid passage of fully mechanized mining face through empty roadway.

In recent years, many scholars have researched the technology of fully mechanized coal mining face crossing empty roadway, and have achieved outstanding results. Bai Jianbiao et al. [3] established the mechanical model of empty roadway roof stability through the hypothesis of "Key Block". Li Songqi [1] studied the stress distribution law and roof movement law of the stope when the stoping mining face passes through the inclined empty roadway. Zhang Zizheng [4] has obtained the formula for calculating the supporting resistance of backfill to keep the roof stable, and put forward the idea of using ultra-high water filling material to glue the surrounding rock of the empty roadway into a whole. Ji Yaqiang [5] took 21021 fully mechanized coal mining face in Baiping Mine as an example, and studied the influence of the inclined face crossing empty roadway on surrounding rock. Shen Guangquan [6] took 4302 mining face in Bailu Coal Mine, Shouzhou, Shanxi Province as an example, and adopted the methods of adjusting inclination and supporting in advance to ensure that the mining face passed through the empty roadway normally. Summarizing the previous research results of mining face passing through empty roadway[7], there are three main aspects: (1) strengthening the roof of empty roadway; (2) advancing rapidly; (3) adjusting inclination of mining face. Among them, adjusting inclination of mining face crossing empty roadway has been widely used in a large number of mines. However, most of the previous studies on adjusting the inclination of mining face through empty roadway only stayed in the stage of engineering experience, and both theoretical analysis and numerical simulation had some deficiencies. Therefore, on the basis of previous studies, a mining face in Xipang Mine was taken as the engineering background, and FLAC3D software was used to simulate and studied the influence degree of the inclined mining face crossing the empty roadway on the surrounding rock near the empty roadway, in order to provide reference for similar projects.

2. Analysis of roof stress state when mining face passes through empty roadway

2.1. Analysis of roof stress characteristics under the influence of vertical empty roadway

With the advance of fully mechanized coal mining face, the stress state of coal seam roof mainly depends on the distance between mining face and empty roadway, that is, the width of coal pillar between them. With the gradual reduction of the width of coal pillar, its bearing capacity also weakens, and the stress field of roof changes accordingly [8]. With the stoping on the mining face, a supporting stress area with a certain width and a plastic yield area on both sides will be formed in the coal pillar. As shown in Fig. 1, when the stoping mining face is far away from the empty roadway, the supporting stress area $W_1$ of the coal pillar on the side of the empty roadway and the supporting stress area $W_2$ of the coal pillar on the side of the mining face do not affect each other, and the original rock stress area $W_0$ also exists in the middle of the coal pillar. The width of coal pillar $W_0=0$ is called the critical width of coal pillar $W_s$; The width of coal pillar when it damages is called damaged width $W_p$ of coal pillar. With the decrease of coal pillar width $W$, the supporting stress of coal pillar can be divided into three types:

(1) When the width of the coal pillar is greater than or equal to the critical width $W \geq W_s$, except the plastic failure areas on both sides, the coal pillar appears as elastic deformation area. The elastic deformation area in the middle of coal pillar can be divided into three parts: stress increasing area, stress decreasing area and original rock stress area $W_0$. The supporting stress is distributed as a shape similar to an asymmetric saddle, as shown in Fig. 1. Because the exposed area of stope side roof is larger than that of empty roadway roof, the stress peak value of the stope side is larger and the stress distribution range is wider. When $W > W_s$, the original rock stress area exists in the stress field, namely $W_0 > 0$; when $W = W_s$, the original rock stress area in the stress field is just zero, that is $W_0 = 0$, the supporting stress on the stope side and the supporting stress on the empty roadway side begin to intersect.
Figure 1. Supporting stress distribution in coal pillar elastic deformation stage

(2) When the width of coal pillar is less than the critical width of coal pillar and greater than the damaged width of coal pillar \(W < W < W_p\), the supporting stress \(W_1\) of coal pillar at the side of empty roadway and the supporting stress \(W_2\) of coal pillar at the side of stope begin to overlap. The supporting stress area in the middle of coal pillar begins to develop from elastic deformation to plastic deformation, and the stress distribution begins to develop from saddle type to platform type, as shown in Fig. 2.

Figure 2. Distribution of supporting stress during coal plastic deformation

(3) When the width of the coal pillar is less than or equal to the damaged width of the coal pillar \(W \leq W_p\), the stress value of the supporting stress area in the middle of the coal pillar reaches the ultimate strength of the coal pillar, which leads to instability and damage of the coal pillar, greatly reduces the bearing capacity, redistributes the advance supporting stress of the stope above the empty roadway, and the coal to be mined is in the peak area of supporting stress. The stress distribution is transformed into an asymmetric "isolated peak type", as shown in Fig. 3.

Figure 3. Supporting stress distribution in the failure stage of coal pillar

2.2. Analysis of Stress Characteristics in Triangle Area of Inclined Intersection Empty Roadway

Ping Shoukang [10] once deduced the approximate expression of stress concentration factor at the intersection of circular roadway in elastic state, as shown in Formula 1:

\[
K = \frac{1+\lambda}{2} \left[ 1 + \frac{r_1^2}{(\rho \sin \theta + r_2)^2} \right] + \frac{1-\lambda}{2} \left[ 1 + \frac{3}{(\rho \sin \theta + r_2)^4} \right] + \frac{1+\lambda}{2} \left[ 1 + \frac{r_2^2}{[\rho \sin(\alpha-\theta)+r_1]^2} \right] + \frac{1-\lambda}{2} \left[ 1 + \frac{3}{[\rho \sin(\alpha-\theta)+r_1]^4} \right]
\]

Where, \(\sigma_1\) and \(\sigma_2\) are respectively the vertical and horizontal stress of original rock, MPa; \(\alpha\) is the angle of two crossing roadways, (°); \(r_1\) is the distance (radius) from the center of roadway at intersection point to the boundary of plastic deformation circle, m; \(\lambda\) is the lateral pressure factor \((\lambda = \sigma_2 / \sigma_1)\); \(\rho\) and \(\theta\) are the polar coordinate of stress at a certain point.
According to Formula (1), the contour map of stress concentration factor near the empty roadway can be drawn out, as shown in Fig. 4. It can be seen from the contour map that the smaller the intersection angles between the empty roadway and the main roadway, the greater the stress concentration factor. The stress concentration degree in the triangle area of inclined roadway is much higher than the advanced supporting pressure, so when the mining face passes through the empty roadway, the coal pillar in the triangle area is often be destroyed first.

Figure 4. Contour map of stress concentration coefficient near abandoned roadway

From the above analysis, it can be seen that when the empty roadway is arranged perpendicular to the track roadway, that is, when the empty roadway is parallel to the stopping mining face, if the coal pillar between the empty roadway and the mining face is less than or equal to the damage width of the coal pillar, the coal pillar will be unstable and damaged, resulting in the rapid increase of the hanging exposed size of the roof, which is prone to roof fall and other safety accidents. When the empty roadway and track roadway are arranged at an acute angle, the triangle area will be damaged first because of the increase of stress concentration factor in the triangle area. Therefore, whether it is vertical or inclined empty roadway, before the mining face passes through the empty roadway, the inclination of the mining face is to be adjusted at the appropriate position in advance, which will increase the included angle between the mining face and the empty roadway, and will be more conducive to the passage of the mining face.

3. Numerical simulation

3.1. Building model

Taking a mining face in Xipang Mine, Hebei Province as the engineering background, the numerical analysis model of the mining face crossing the inclined empty roadway was established by the analysis software FLAC3D to study the surrounding rock mining effect when the stoping mining face passes through the empty roadway normally (without inclination adjustment), and compare with the surrounding rock mining effect when the mining face passes through the empty roadway with inclination adjustment of 5° and 10° respectively, and analyze the influence of the mining face inclination adjustment on the surrounding rock stress state and plastic area. The physical and mechanical parameters of coal seam and rock formation are simplified as shown in Table 1.

| Rock formation name | Bulk modulus /Gpa | Shear modulus /Gpa | Cohesion /Mpa | Internal friction angle/(°) | Tensile strength /Mpa | Bulk density /(N/m³) | Thickness /m |
|---------------------|-------------------|--------------------|---------------|-----------------------------|----------------------|----------------------|-------------|
| Siltstone           | 10.4              | 6.0                | 2.4           | 29                          | 0.8                  | 2460                 | 22          |
| Daqing limestone    | 11.6              | 7.1                | 4.8           | 33                          | 2.8                  | 2650                 | 4           |
The three-dimensional analysis software FLAC3D was used to build the model, as shown in Fig. 5. The model size was length × width × height =138 m×200 m×62 m, the mining face length were 90 m, and the cross-section dimensions of track roadway, haulage roadway and empty roadway were 4 m×3 m. Considering the lateral support stress of stope, coal pillars with a thickness of 20 m were reserved on both sides of track roadway and haulage roadway, and the included angle between empty roadway and track roadway was 53°, the distance between the stope mining face and the first contact points of the empty roadway was 100 m. According to the measured values in the field, the roof has collapsed for the first time, and the periodic weighting interval was 20 m. Therefore, the mine goaf area was backfilled every 20 m of mining progress. Normally, the coal gangue after 40 m from the fully mechanized mining face is gradually compacted, so the mechanical parameters of backfill gangue are divided into two kinds of materials with 40 m behind the mining face as the dividing line. Comprehensively considering the physical and mechanical characteristics of the gangue falling from mine goaf and combining with the rock formation of Xipang Mine, the mechanical parameters of the gangue falling from the mine goaf are taken as shown in Table 2. The bottom of the model is fixed, and the displacement of four sides has been limited. The upper boundary of the model is 280 m away from the ground, and 2500 N/m³ of the average body force of the overlying formation is taken, that is, a uniform load of 7.0 MPa is applied to the upper surface of the model.

Table 2. Physical and mechanical parameters of coal gangue formation

| Distance from mining face /m | factor of crushing expansion | Bulk modulus /Mpa | Shear modulus /Mpa | Density |
|-----------------------------|------------------------------|-------------------|-------------------|---------|
| <40                         | 1.4                          | 1.8               | 2.2               | 2400    |
| >40                         | 1.25                         | 8.8               | 10                | 2400    |

Figure 5. Three-dimensional numerical model
3.2. Analysis of simulation results

3.2.1. Analysis of stress evolution law of normal advancing coal pillar in mining face.
Mining face inclination adjustment can usually be divided into real center inclination adjustment and virtual center inclination adjustment. In this simulation, the real center inclination adjustment method was adopted, and the inclination adjustment of the mining face was carried out 20 m before the mining face first contacts the empty roadway. In order to better study the influence of the inclined angle of the mining face on the mining effect of surrounding rock when the mining face passes through the empty roadway, the simulation was carried out by adjusting the inclined angle by 5° and 10°, and the normal advance was taken as the control group.

The analysis was carried out based on that the working face passes through the empty roadway normally. The vertical stress profile of the model at x=40 m with its unit of Pa was selected as shown in Fig. 6. It can be seen from Fig. 6 that with the decrease of the width of coal pillar between the mining face and the empty roadway, three shapes of the vertical stress appeared in turn: "saddle type", "platform type" and "isolated peak type".

![Diagram](image)

(a) The mining face 100m away from the empty roadway
(b) The mining face 60m away from the empty roadway
(c) The mining face 10m away from the empty roadway

Figure 6. Longitudinal profile of vertical stress when mining face crosses abandoned roadway normally

It can be seen from Fig. 6(a) that when the distance between the mining face and the empty roadway is 100 m, the vertical stress of the coal pillar presents an asymmetric saddle shape, and the peak stress of the coal pillar on the mining face is larger and the distribution range is wider, with the maximum stress being 12.2MPa. The original rock stress area exists in the middle part of the coal pillar, which indicates that the supporting stress of the coal pillar on the mining face has not affected the supporting stress of the coal pillar in the empty roadway.

It can be seen from Fig. 6(b) that when the mining face is 60 m away from the empty roadway, the vertical stress of the coal pillar presents an asymmetric "platform type", with the advancement of the mining face, the supporting stress of the coal pillar increases, and the maximum stress is 18.8 MPa. The supporting stress area of the coal pillar at the side of the mining face has affected the supporting stress area of the coal pillar at the side of the empty roadway, and the two areas overlap each other, and the original rock stress area in the middle part of the coal pillar no longer exists.

It can be seen from Fig. 6(c) that when the distance between the mining face and the empty roadway is 10 m, the vertical stress of the coal pillar between them presents an asymmetric "isolated peak type".
and the maximum stress is 21.8 MPa. At this moment, the peak stress in the supporting stress area in the middle of the coal pillar approaches the ultimate failure strength of the coal pillar, and the supporting stress area in the middle coal pillar has already affected the supporting stress area behind the empty roadway.

When the mining face normally advances through the empty roadway, the vertical stress profile at 0.5 m(z=30.5) of the empty roadway roof is selected for analysis, as shown in Fig. 7. Fig. 7(a) shows the vertical stress diagram of the roof of the empty roadway after roadway excavation. Because the empty roadway intersects with the track roadway and belt roadway obliquely, there is a large stress concentration phenomenon in the triangle area (including acute angle area and obtuse angle area), and the stress concentration in the acute angle area is more obvious, which is more prone to damage. It can be seen from Fig. 7(b) that when the mining face first contacts the empty roadway, the coal wall supporting stress is biased towards the track roadway due to the influence of the empty roadway, the track roadway and the mining face, and the maximum supporting stress is 23.9 MPa. It can be seen from Fig. 7(c) that under the condition that the mining face normally passes through the empty roadway, when the roof of the mine goaf has not collapsed, due to the large exposed area of the stope roof, the supporting stress of the coal pillar in the triangle area reaches the maximum of 25.3 MPa, and the roof of the empty roadway is the most dangerous at this moment. It can be seen from Fig. 7(d) that the supporting stress in front of the mining face is 22.4 MPa after the mining face completely passes through the empty roadway.

Figure 7. Cross-sectional view of vertical stress when mining face crosses abandoned roadway normally
3.2.2. Stress evolution law and plastic area distribution of inclined coal pillar in mining face.
From the analysis of Fig. (7), it can be seen that when the mining face passes through the empty roadway and the roof of the rear mine goaf does not collapse, the supporting stress of the coal pillar in the front triangle area reaches the maximum, and the surrounding rock of the empty roadway is most prone to problems such as rib spalling and roof fall. Therefore, the vertical stress nephogram of the mining face passing through the empty roadway under both normal condition and inclined condition is selected for comparative analysis, as shown in Fig. 8.

![Figure 8. Vertical stress transverse section of abandoned roadway roof](image)

It can be seen from Fig. (8) that the maximum supporting stress of coal pillar appears in the triangle area under every condition of normal passage, 5° inclination adjustment and 10° inclination adjustment of the mining face, which are 25.3 MPa, 25.1 MPa and 23.5 MPa respectively. With the increase of the inclined angle of the mining face, the supporting stress gradually decreases. It can be seen from Fig. 8(a) that when the mining face passes through the empty roadway normally, the red stress area at the roof of the empty roadway is not continuous, and large yellow areas and green areas appear, which indicates that the stress of the roof of the empty roadway is too large, and it is easy to cause rib spalling and roof fall. It can be seen from Fig. 8(b) that when the mining face passes through the empty roadway with an inclination of 5°, the red area of the empty roadway roof increases, indicating that the stress of the empty roadway roof decreases. It can be seen from Fig. 8(c) that when the mining face passes through the empty roadway with an inclination of 10°, the red area of the empty roadway roof is the largest, which is in a continuous state, indicating that the stress of the empty roadway roof is reduced, the side wall and roof of the empty roadway are more stable, and it is not easy to cause rib spalling and roof fall.

4. Conclusions
(1) The distribution law of roof vertical stress under different coal pillar widths has been analyzed. With the decrease of coal pillar width, three shapes of the vertical stress have appeared in turn: "saddle shape", "platform shape" and "solitary peak shape".
(2) Stress concentration occurs at the intersection of empty roadway and two roadways (track roadway and belt roadway), and the stress concentration degree of coal wall in acute angle area is greater than that in obtuse angle area.
(3) For the first time, the numerical simulation study on the inclined mining face crossing the empty roadway was carried out, and the vertical stress distribution law of the coal pillar in the triangle area under the inclined and non-inclined state of the mining face has been compared. The results show that the coal pillar stress concentration phenomenon in the triangle area is reduced by adjusting the inclination of the mining face, and the maximum supporting stress is reduced from 25.3 MPa to 23.5 MPa, which reduces the risk of rib spalling and roof fall in the empty roadway and is more conducive to the safe passage of the mining face passing through the empty roadway.
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