Study on the Key Factors of Terminal Mining Line Layout in Repeated Mining of Close-Distance Thick Coal Seams

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In order to master the reasonable layout basis of the terminal mining line position in the repeated mining of close-distance thick coal seams, taking Yan mine as the engineering background, we conducted theoretical analyses, numerical simulations, and field measurements to study the action mechanism of the stress arch. The results show that (1) with repeated mining, the shape of the left and right half arches of the stress arch changes in the order of time and space until it is stable; (2) the shape of the stress arch is highly related to the distribution of abutment pressure in the working face. If the shape is unchanged, the distribution of abutment pressure is unchanged; (3) in the final mining stage of repeated mining, when the shape of the right half arch is stable, the difference stagger distance of the terminal mining line has little effect on the distribution of abutment pressure of the working face where the front arch foot is located; (4) when the internal stagger distance between 3216 working face and terminal mining line of 4216 working face is greater than 22 m or the external stagger distance is greater than 30 m, 3216 working face is located in a relatively safe position. This study clarifies the key factors for the layout of terminal mining lines in close-distance thick coal seams, which can provide a scientific basis for similar projects.

1. Introduction

With the mining of the working face, a stress arch structure will be formed in the upper overburden. The front and rear arch feet are located in the nonmining body of the working face and the open cut, respectively, and the arch crown is located in the bending subsidence zone. The stress arch bears the load up to the surface rock layer and transmits it to the front and rear arch feet. The front arch foot is located in the elastic pressurization zone in front of the working face and determines its width. The layout of the terminal mining line should ensure that the main roadway is located outside the influence range of the front abutment pressure of the working face, but the repeated mining of close-distance coal seams will cause changes in the shape parameters of the stress arch, and meanwhile, when the final mining stage enters under the solid coal with the working face from the goaf, the longitudinal position of the front arch foot will be transferred to the lower coal seam. At this stage, the change law of the abutment pressure distribution of the working face is not clear, especially whether the different stagger distances of the terminal line will affect the distribution of the abutment pressure, which is related to the reasonable width of the stopping coal pillar. It is of great significance to study the mechanism of stress arch in close-distance thick coal seams.

Many scholars have widely researched on stress arch theory. Wang believed that the overburden of the working face would form a stress shell and studied the ground pressure law of the working face under the shell structure [1]. Wang established the mechanical model of the symmetrical pressure arch and studied its characteristics [2]. Wang analyzed the formation mechanism of the stress arch, established the corresponding mechanical model, and
clarified the evolution process of the stress arch [3]. Based on the pressure arch and key stratum theory, Yang established the structural model of the overburden pressure arch [4]. Based on monitoring data of ground pressure, Wang established a mechanical model of the surrounding rock to study the law of ground pressure [5]. Yue used numerical simulation to obtain the shape parameters of the stress arch in close-distance coal mining and thus obtained the distribution of additional stress in the floor roadway [6]. Some scholars have also studied this subject [7–10].

Many scholars have widely researched on ground pressure in the working face of close-distance coal seams [11–13]. Shang studied the stress environment of the stope at the end of the mining stage of the close-distance coal seams and proposed the surrounding rock control technology of the withdrawal channel [15]. Zhang studied the damage characteristics of interbedded strata in close-distance coal seams and studied the stability of gob-side entry under this condition [16]. Li studied the influence of roof stress and fracture distribution characteristics on the stability of surrounding rock in the stope under the condition of repeated mining of close-distance coal seams [17]. Liu studied the stress distribution law of the floor under the action of coal pillars in close-distance coal seams and determined the reasonable layout position of the roadway [18]. Some scholars have also studied this subject [19, 20].

To sum up, there are many studies on the location selection of mining roadways in close-distance coal seams, the law of stope ground pressure, and the stress arch structure of single coal seams. However, there is little research on the action mechanism of stress arch in close-distance, thick coal seams, and the reasonable staggering distance of the terminal mining line. The purpose of this study is to provide a scientific basis for the stopping project of close-distance thick coal seams.

2. Project Overview

4 # and 3# coal seams in Yan coal mine are close-distance, thick coal seams, with a thickness of 7.5 m and 5.5 m, respectively. The average spacing between the two coal seams is 25 m. The coal seam mining methods are downward mining and fully mechanized top coal caving longwall mining methods, as well as the roof span management method. Figure 1 shows the rock stratum histogram.

4216 working face is located above 3216 working face, as shown in Figure 2. 4216 working face has stopped mining, and the stopping coal pillar is about 110 m. 3216 working face is near the final mining, so it is necessary to determine a reasonable terminal mining line.

3. Theoretical Analysis of Stress Arch Shape

Comprehensively clarifying the evolutionary law of stress arch shape before and after repeated mining of close-distance, thick coal seams is the premise of studying the mechanism of stress arch.

| Thickness (m) | Depth (m) | lithology         |
|--------------|-----------|-------------------|
| 12.4         | 382.6     | Coarse sandstone  |
| 6.5          | 389.1     | Fine sandstone    |
| 3.4          | 392.5     | Siltstone         |
| 7.5          | 400.0     | 1# coal seam      |
| 6.0          | 406.0     | Fine sandstone    |
| 8.0          | 414.0     | Medium-fine sandstone |
| 4.5          | 418.5     | Kaolinite rock    |
| 5.3          | 423.8     | Conglomerate      |
| 1.2          | 425.0     | Carbonaceous mudstone |
| 5.5          | 430.5     | 2# coal seam      |
| 3.2          | 433.7     | Carbonaceous mudstone |
| 3.6          | 437.3     | Kaolinite rock    |
| 5.5          | 442.8     | Medium-fine sandstone |

Figure 1: Rock stratum histogram.

Figure 2: Strike profile of working face.

3.1. Upper Coal Seam Mining

(1) The working face starts mining from the open cut, and the roof of the goaf deflects and sinks under the action of the secondary stress field. Taking the nonmining body of the open cut and working face as the fulcrum, the roof concentrated stress area is formed, and its shape is similar to the shape of the arch, that is, the stress arch, as shown in Figure 3(a).

(2) With the continuous increase of the overhead distance of the roof, the first span fall of the immediate roof and the main roof occurred successively. The position of the rear arch foot of the stress arch remains unchanged, and the front arch foot moves forward continuously, always located in the elastic pressurization zone in front of the working face, and the arch crown moves up to the complete roof, as shown in Figure 3(b).

(3) With the mining of the working face, the roof is broken repeatedly, the breaking height is increasing, and the arch height and span are also increasing. When the working face reaches full subsidence, the arch height and span of the stress arch will no longer increase, and only the horizontal extension will occur at the arch crown, and the distribution of front...
abutment pressure in the working face should no longer change, as shown in Figure 3(c).

3.2. Lower Coal Seam Mining

(1) With repeated mining, a small stress arch is formed in the interlayer, and the front and rear arch feet are located in the nonmining body of the working face and the open cut, respectively, and the stress arch shape of the upper coal seam remains unchanged, as shown in Figure 4(a).

(2) The goaf is connected to form a new stress arch. First, repeated mining affects the left half arch, and its arch height and span continue to increase until it is stable. The left and right half arches keep the stability of the stress arch under the action of horizontal restraint stress. Because the load borne by the right half arch remains unchanged, the distribution of abutment pressure in front of the working face in the upper coal seam remains unchanged, as shown in Figure 4(b).

(3) When repeated mining affects the right half arch, it has entered the final mining stage. The height and span of the right half arch continue to increase until they are the same as the left half arch, at which time a symmetrical arch structure is formed. The overlying load borne by the right half arch changes, causing the distribution of abutment pressure on the working face where the front arch foot is located to change. When the working face changes from internal stagger to external stagger at the terminal mining line, the longitudinal position of the front arch foot will change, as shown in Figures 4(c) and 4(d).

4. Numerical Simulation of Stress Arch and Abutment Pressure

4.1. Numerical Simulation Model Development. FLAC^3D numerical simulation software is used to study the change law of stress, arch shape, and abutment pressure of the working face in close-distance thick coal seams. According to the geological conditions, the model size was 600 m (X) × 10 m (Y) × 250 m (Z). The X-axis represents the strike direction of the working face. The displacements at the bottom, front, back, left, and right of the model were fixed, and a vertical stress of 4.75 MPa was applied to the upper boundary of the model to simulate the overburden pressure. Vertical and horizontal stresses were applied according to the measured in situ stress, and the side pressure coefficient was 1.2. The working face was excavated from the left side to the right side of the model.

The Mohr–Coulomb theory was adopted as the constitutive relation of the model. According to the literature [21–23], reasonable rock mechanics parameters can be obtained. Table 1 presents the rock mechanical parameters.
It is particularly important for numerical simulation to accurately reflect the compaction of gangue in goaf. We used a double yield model to replace coal seam mining and simulate the caving of gangue in the goaf. The cap pressure in the double yield model was calculated using formulas (1)–(3) [24–26]:

![Diagram](image-url)
\[ \sigma_{\text{cap}} = \frac{E_0 \varepsilon}{1 - (\varepsilon/\varepsilon_{\text{max}})} \],

(1)

\[ \varepsilon_{\text{max}} = \frac{Kp - 1}{Kp} \],

(2)

\[ E_0 = \frac{10.39 \sigma_c^{0.1042}}{Kp^{0.7}} \],

(3)

where \( \sigma_{\text{cap}} \) is the pressure on the gangue in the goaf; \( \varepsilon \) is the volume strain of gangue in goaf under the action of \( \sigma_{\text{cap}} \); \( \varepsilon_{\text{max}} \) is the maximum volumetric strain that can be produced by gangue in goaf; \( E_0 \) is the initial elastic modulus of gangue in goaf; \( Kp \) is the coefficient of dilatancy of caving rock mass, and 1.25; \( \sigma_c \) is the compressive strength of rock mass, 23.7 MPa. Then, formula (1) can get \( \sigma_{\text{cap}} \), as shown in Table 2.

| Strain  | 0.00 | 0.01 | 0.03 | 0.05 | 0.07 | 0.09 | 0.11 | 0.13 | 0.15 | 0.17 |
|---------|------|------|------|------|------|------|------|------|------|------|
| Stress (MPa) | 0.00 | 0.53 | 1.78 | 3.37 | 5.44 | 8.26 | 12.34 | 18.76 | 30.30 | 57.23 |

4.2.4216 Working Face Mining. A 70 m boundary was set on the left side of the model for excavating the 4216 working face, and the excavation is carried out step by step to 210 m. The evolution of the stress arch shape is shown in Figure 5.

At the same time, stress monitoring points are arranged at an interval of 1 m in the front along the strike during the mining process of the working face, and the evolution of abutment pressure distribution with the mining of the working face is analyzed.

It can be seen from the analysis of Figures 5 and 6:

1. When the 4216 working face is mined for 50 m–160 m, the shape of the stress arch changes constantly, and the peak value and influence range of abutment pressure also increase continuously. The peak value increased from 21 MPa to 30.5 MPa, and the influence range increased from 23 m to 75 m.
Figure 6: Abutment pressure of 4216 working face.

Figure 7: Evolution process of stress arch shape in repeated mining: (a) internal stagger 180 m, (b) internal stagger 90 m, (c) internal stagger 50 m, (d) internal stagger 20 m, (e) external stagger 20 m, and (f) external stagger 50 m.
(2) Mining to 160 m, reaching full subsidence, the shape of the stress arch remains unchanged, and the distribution of abutment pressure does not change.

(3) The numerical simulation results show that the shape of the stress arch is highly related to the distribution of abutment pressure, which is consistent with the theoretical analysis in Section 3.1.

4.3. 3216 Working Face Mining. Connected to 4216 working face mining 210 m, a 50 m boundary was set on the left side of the model for excavating 3216 working face, and the excavation is carried out step by step to 280 m. The relative position of 3216 working face and 4216 working face is described by the horizontal distance between them.
Similarly, stress monitoring points are arranged at an interval of 1m along the mining direction of the two working faces, and the evolution of abutment pressure distribution with repeated mining is analyzed. It can be seen from the analysis of Figures 7 and 8 that

1. In the case of an internal stagger, the front arch foot is located at 4216 working face, and in the case of an external stagger, the arch foot moves down to 3216 working face.

2. As shown in Figure 7(a), when the internal stagger is 180 m, the shape of the left half arch changes, while the shape of the right half arch remains unchanged. This stage corresponds to Figure 4x(d). The front arch foot is located in the 4216 working face, and its abutment pressure distribution is basically unchanged. 3216 working face belongs to pressure relief mining;

3. As shown in Figure 7(b), when the internal stagger is 90 m, the shape of the right half arch begins to change, and the peak value and influence range of the abutment pressure of the 4216 working face increase to 32.6 MPa and 85 m;

4. As shown in Figures 7(c) and 7(d), when the internal stagger is 50 m, the peak value and influence range of abutment pressure of 4216 working face continue to increase to 35 MPa and 95 m. Continue mining to an internal stagger of 20 m, the shape of the right half arch remains stable, and its abutment pressure distribution remains unchanged. This stage corresponds to Figure 4(c);

5. When the external stagger is 20–50 m, the shape of the stress arch is stable, the front arch foot is transferred to the 3216 working face, and the peak value and influence range of the abutment pressure of the 4216 working face are greatly reduced. The peak value and influence range of the abutment pressure of 3216 working face were increased to 36.5 MPa and 95 m and remained unchanged. This stage corresponds to Figure 4(d).

6. When the external stagger is 150 m, the peak value and influence range of abutment pressure of 3216 working face are significantly reduced, which is similar to the mining of 4216 working face.

7. The numerical simulation results show that the shape of the stress arch is highly related to the distribution of abutment pressure, which is consistent with the theoretical analysis in Section 3.2.

When the internal stagger is 50 m to the external stagger, 50 m, the abutment pressure distribution of the working face where the front arch foot is located is extracted, as shown in Figure 9. Analysis shows that:

1. When the working face changes from an internal stagger of 50 m to an external stagger of 50 m, the shape of the stress arch remains unchanged, only the front arch foot moves down, and the load borne by the stress arch does not change, so the abutment pressure distribution of the working face where the front arch foot is located does not change;

2. Under the action of the stress arch structure, the layout of the terminal mining line only needs to consider the influence range of the front abutment pressure of the working face where the front arch foot is located and the stagger distance of the terminal mining line only needs to ensure the safety of the working face.

5. Numerical Simulation of Reasonable Stagger Distance of Terminal Mining Line

5.1. Numerical Simulation Model Development. In this section, UDEC numerical simulation software is used to study the reasonable stagger distance of the terminal mining line. According to geological conditions, the model size was 200 m ($X \times 105$ m ($Y$). The displacement at the bottom, left, and right of the model were fixed, and a vertical stress of 9.01 MPa was applied to the upper boundary of the model to simulate the overburden pressure. Vertical and horizontal stresses were applied according to the measured in situ
Figure 10: Continued.
stress, and the side pressure coefficient was 1.2. The Mohr–Coulomb theory was adopted as the constitutive relation of the model. Table 3 presents the rock mechanical parameters.

5.2. Model Excavation. First, we excavate the 4216 working face of 120 m. Then, we excavate 3216 working face to 90 m, 100 m, 110 m, 120 m, 130 m, 140 m, 150 m, and 160 m. The working face was excavated from the left side to the right side of the model. The relative position of 3216 working face and 4216 working face is described by the horizontal distance between them.

It can be seen from the analysis of Figure 10 that

(1) When the internal stagger is greater than 20 m, the main roof of the interlayer is well spliced, and the high stress range of the main roof is not large, as shown in Figures 10(a) and 10(b);

(2) When the internal stagger is 10 m to the external stagger, 10–20 m, the stress range of the main roof of the interlayer is large, and sliding and rotary

Figure 10: Ground pressure of working face in different stagger distance: (a) internal stagger 30 m, (b) internal stagger 20 m, (c) internal stagger 10 m, (d) overlap, (e) external stagger 10 m, (f) external stagger 20 m, (g) external stagger 30 m, and (h) external stagger 40 m.
instability of the main roof are shown in Figures 10(c)–10(f);

(3) When the external stagger is greater than 30m, the main roof splicing is good, the roof subsidence is small, and the surrounding rock of 3216 working face is relatively complete, as shown in Figures 10(g) and 10(h).

To sum up, the 3216 working face should be staggered at least 20m internally or 30m externally at the terminal mining line of the 4216 working face.

6. Field Measurement

In order to determine the reasonable internal and external stagger distance of the terminal mining line, install the support working resistance monitoring station at the 40#, 70#, 100#, and 130# supports of 3216 working face to monitor the roof pressure in the final mining stage in real time, as shown in Figure 11.

It can be seen from the analysis of Figure 12 that

(1) A total of five times of periodic weighting is monitored at a distance of 80 m. When the internal stagger is about 33 m, the main roof is weighted, and the periodic weighting strength is not large;

(2) When the internal stagger is 22 m to the external stagger, 26 m, the pressure of the supports increases significantly;

(3) When the external stagger is more than 26 m, the pressure of the supports begins to decrease.

Comprehensive numerical simulation and field measurement results: 3216 working face should be staggered at least 22 m internally or 30 m externally at the terminal mining line of 4216 working faces.

7. Conclusions

(1) During the mining of 4216 working face, the peak value and influence range of abutment pressure continue to increase until the shape of the stress arch is stable. With repeated mining, the shape of the left and right half arches of the stress arch changes in order of time and space until it is stable. When the shape of the right half arch changes, the distribution of abutment pressure on the working face where the arch foot is located also changes until the shape is stable.

(2) Under the action of the stress arch structure, the layout of the terminal mining line in close-distance thick coal seams only needs to consider the influence range of the front abutment pressure of the working face where the front arch foot is located, and the stagger distance of the terminal mining line only needs to ensure the safety of the working face in the lower coal seam.

(3) When the internal stagger distance between 3216 working face and the terminal mining line of 4216 working face is greater than 22 m or the external stagger distance is greater than 30 m, the left stopping coal pillar has little impact on 3216 working face, and 3216 working face is located in a relatively safe position, which can be regarded as the minimum safe stagger distance.

Data Availability

The data used to support the findings of this research are included within the paper.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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