Unconventional staggered distance simultaneous mining theory in extremely close and thin coal seams and its application

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Abstract

The exploitation of extremely close thin coal seams is featured of great interaction and it is hard to realize the simultaneous mining of upper and lower coal seams. This paper defines the extremely close coal seam and studies the unconventional staggered distance simultaneous mining in pressure-relief region formed by locating the lower coal mining face in the upper face. The mechanical model of unconventional staggered distance simultaneous mining is established and its theoretical formula is given. The numerical simulation analyzes the influence of staggered distance on the front abutment pressure distribution: when staggered distance increases, the degree of upper coal mining face front abutment stress concentration decreases and the degree of lower coal mining face front abutment stress concentration decreases first and increases later; when the staggered distance is larger than a certain value, the front abutment pressure in lower coal mining face is in “double peak” distribution. With theoretical analysis, the staggered distance of the left six simultaneous mining face in Zhengyang Mine is conformed to be 6 m. This research conclusion has been verified in the field and significant socio-economic benefits have been achieved, which can provide a reference for safe and efficient exploitation of extremely close coal seams.

Keywords: extremely close; thin coal seams; unconventional staggered distance; simultaneous mining; distribution of double peak values

1. Introduction

After years of high-intensity mining, the superior resources like thick coal seams in Jixi, Yima, Wuda, Datong, Lu’an and other mines are diminishing. Thus, more and more attention is paid to thin coal seam mining. The extremely close thin coal seams account for a large part of thin coal seam reserves. And how to efficiently exploit the extremely close thin coal seams is a key technical problem faced by these mines.

Usually, there are two coal seams mining models: mining seam by seam, simultaneous mining of upper and lower seams. Practice shows that the latter has obvious advantages compared to the former \cite{[1]} and is currently used. Determination of upper and lower coal seams staggered distance is the key question of simultaneous mining of coal seams, about which there are two points of view. One is that the staggered distance should ensure the lower coal...
seam is mined after the upper coal seam caving is stable. The other is that the staggered distance should ensure the lower coal mining face is located in the pressure-relief region formed by upper coal seam mining. The former is a common approach, called conventional staggered distance, and the latter is called unconventional staggered distance[2]. Conventional staggered distance is relatively safe but the roadway maintenance work in lower coal seam is great. Roadway maintenance work in unconventional staggered distance lower coal seam mining is small. So the key is to determine a reasonable staggered distance. At present, researches mainly focus on conventional staggered distance[2,3,4]; unconventional staggered distance is researched little. This paper based on Zhengyang Coal Mine’s conditions in Jixi Coal Mining Group, deeply studies the unconventional staggered distance simultaneous mining in extremely close thin coal seams, which can provide a reference for safe and efficient exploitation of coal seams with similar conditions.

2. Definition of extremely close coal seams

Definition of extremely close coal seams is more of qualitative description and lack of quantitative indicators. “Coal Mine Safety Regulations” qualitatively describes the close coal seams as those with small seam spacing and with great interaction during exploitation. It gives no definition to extremely close coal seams which are qualitatively described here as seams with very small seam spacing and with very great interaction during exploitation. The extremely close coal seams need to meet one of the following criteria.

(1) The distance between seams \( h \) is smaller than the largest thickness of upper and lower coal seams, that is, \( h \leq \text{max}\{m_u, m_l\} \), of which, \( m_u, m_l \) refer respectively to the thickness of upper and lower coal seams.

(2) The distance between seams \( h \) is smaller than the maximum floor destruction depth \( D_{s_{\text{max}}} \), impacted by upper coal seam on the floor during mining, that is, \( h \leq D_{s_{\text{max}}} \).

(3) The distance between seams \( h \) is smaller than the falling zone height \( h_{k_{\text{max}}} \) in mining lower coal seam, that is, \( h \leq h_{k_{\text{max}}} \).

According to the synthetic column map of the left six simultaneous mining faces in Zhengyang mine: 27 upper coal thickness is 0.9 m, 27 lower coal thickness is 1.23 m, and seam spacing is 0.8 m. Based on criterion (1), 27 upper coal seam and 27 lower coal seam are typical extremely close coal seams. Present development of top-coal caving is using fully mechanized mining technology in thick coal seams.

3. Theoretical research on unconventional staggered distance

3.1. Establishment of theoretical model

In accordance with mine pressure theory[5], the in-situ rock stress of surrounding-rock is redistributed after coal seam mining. According to the vertical stress value, it can be divided into stress-decreasing zone \( b \) (pressure-relief zone), stress-increasing zone \( a \) (pressurized zone) and stable stress zone \( c \) (pressure-regulated zone). From pilot support pressure peak to coal wall is the ultimate balance area; to the coal inside is the elastic zone, as shown in Fig.1. During unconventional staggered distance simultaneous mining, i.e. the lower coal mining face is located in the pressure-relief region formed by upper coal seam mining, the maximum unconventional staggered distance \( T_{\text{max}} \) should not exceed the pressure-relief range. Its mathematical expression is:

\[
T_{\text{max}} \leq b - L_s \quad (1)
\]

Here: \( L_s \) is the maximum roof control distance, m.

To avoid the mining face production interaction between upper and lower coal seams, the minimum unconventional staggered distance \( T_{\text{min}} \) should meet formula (2):

\[
T_{\text{min}} \geq L_s + h \cot \theta + x_n \quad (2)
\]

Here: \( L_s \) is the maximum roof control distance of upper coal seam mining face, m; \( h \) is the seam spacing between upper and lower coal seams, m; \( \theta \) is the strata movement angle; \( x_n \) is the width of ultimate balance zone in lower
coal seam mining face, m.

Fig. 1. Mechanical model of unconventional staggered distance simultaneous mining in coal seams

3.2. Analysis of theoretical model

In the solution to unconventional staggered distance theoretical model formula (1), the key is to determine $b$, the width of mining face pressure-relief zone in upper coal seam. According to the foundation calculation in soil mechanics and plasticity theory\[^{[5,6]}\], the mining-induced floor limit equilibrium area can be divided into three zones. As is shown in Fig.1, zone I is the active stress zone, in which:

\[ \angle CBA = \angle CAB = \frac{\pi}{4} + \frac{\varphi}{2} \tag{3} \]

Here: $\varphi$ is the internal friction angle of floor rock strata.

Zone II is the transition zone; CD curve is the logarithmic spiral lines, its starting point is $B$, its equation is:

\[ r = r_0 \cdot e^{\alpha \tan \varphi} \tag{4} \]

Here: $r$ is the spiral radius, forming the angle $\alpha$ with $r_0$ and with $B$ as the starting point; $r_0$ is the length of $AC$; $\alpha$ is the angle between $r$ and $r_0$.

Zone III is the passive stress zone, in which:

\[ \angle DBE = \angle DEB = \frac{\pi}{4} - \frac{\varphi}{2} \tag{5} \]

Since, $\angle CBD = \frac{\pi}{2}$, so from equation (4), we can get:

\[ r_{BD} = r_0 \cdot e^{\frac{\varphi}{2}} \tag{6} \]

In $\triangle ABC$, there is the following equation:

\[ r_0 = \frac{x_{ub}}{\cos\left(\frac{\pi}{4} + \frac{\varphi}{2}\right)} \tag{7} \]

In $\triangle BED$, there is the following equation:

\[ b = 2r_{BD} \cdot \cos\left(\frac{\pi}{4} - \frac{\varphi}{2}\right) \tag{8} \]

So from equations (6), (7), (8) together, we can get:

\[ b = 2r \cdot e^{\frac{\varphi}{2}} \cdot \tan\left(\frac{\pi}{4} + \frac{\varphi}{2}\right) \tag{9} \]

According to the existing limit equilibrium zone width formula $x_0\,^{[7]}$ ahead the mining face:
\[ x_n = \frac{m}{2} \left( \frac{K \cdot H + c \cdot \cot \phi}{\xi - c \cdot \cot \phi} \right) \ln \frac{1 + \sin \phi}{1 - \sin \phi} \]  

Here: \( K \) is the stress concentration factor; \( \gamma \) is the average density of overlying rocks, kN/m\(^3\); \( H \) is the coal buried depth, m; \( f \) is the friction coefficient between coal seams; \( m \) is mining face height, m; \( c \) is the coal cohesive force, MPa; \( \xi \) is the triaxial stress factor, \( \xi = \frac{1 + \sin \phi}{1 - \sin \phi} \).

From formulas (1), (2), (9), (10), we can get the distinguish criterion for unconventional staggered distance \( T \) as follows:

\[
\begin{align*}
T_{\text{min}} & \geq L + h \cot \theta + \frac{m}{2} \frac{K \cdot \gamma \cdot H + c \cdot \cot \phi}{\xi - c \cdot \cot \phi} \\
T_{\text{max}} & \leq \frac{m}{2} \frac{1 + \tan(\frac{\pi}{4} - \frac{\phi}{2})}{2} \ln \frac{K \cdot \gamma \cdot H + c \cdot \cot \phi}{\xi - c \cdot \cot \phi} - L_n.
\end{align*}
\]

Here: the subscripts \( s \) and \( x \) respectively refer to upper and lower coal seam mining face.

By checking the simultaneous mining face conditions in 27# mining seam of Zhengyang mine and taking \( L_s = 4.2 \) m, \( h = 0.8 \) m, \( \theta = 70^\circ \), \( L_s = 4.1 \) m, \( m_s = 1.2 \) m, \( f_s = 0.4 \), \( m_x = 0.9 \) m, \( H_s = 500 \) m, \( H_x = 501.7 \) m, \( \gamma_s = \gamma_x = 25000 \) kN/m\(^3\), \( K_s = 2.2 \), \( K_x = 1.2 \), \( c_s = 20 \) MPa, \( c_x = 15 \) MPa, \( \phi_s = 35^\circ \), \( \phi_x = 43^\circ \) into the formula, we can get \( T_{\text{min}} \geq 5.96 \) m, \( T_{\text{max}} \leq 11.2 \) m. That is, the reasonable staggered distance for unconventional simultaneous mining of the left six mining face in Zhengyang mine is 5.96–11.2m.

4. Research on different staggered distances’ pilot support pressure distribution

Based on 27# coal seam synthetic column map, the discrete element modeling software UDEC simulation is used to analyze the front abutment pressure distribution feature with different staggered distances of 0m, 6m, 12m, 18m, to more accurately determine the reasonable staggered distance of the left six simultaneous mining face in Zhengyang Coal Mine.

As is shown in Fig.2, when the staggered distance changes from 0m to 18m, the front abutment pressure distribution of 27\text{upper} coal seam mining face is similar to general mining face, along the mining face advancing direction, both increasing first and then decreasing; the distance between the front abutment pressure peak and coal wall is about 8m, affecting a range of 35m. In the 27\text{lower} coal seam mining face, as the staggered distance increases, the front abutment pressure peak moves away from the coal wall; when the staggered distance is 12m and 18m, affected by the 27\text{upper} coal seam mining face rear abutment pressure and the 27\text{lower} coal seam mining face stress coupling effects, the front abutment pressure of 27\text{lower} coal seam mining face is in “double peak” distribution, i.e. the front abutment pressure decreases first and then increases and decreases later, with two peaks. The “double peak” distribution of 27\text{lower} coal seam mining face pilot support pressure has a great impact on its safe mining.

![Fig. 2. The front abutment pressure distribution of the left six simultaneous mining faces (a) 27\text{upper} coal seam mining face (b) 27\text{lower} coal seam mining face](image)
As is shown in Fig. 3, under the condition of different staggered distances, as the staggered distance increases, the front abutment pressure concentration of $27_{\text{upper}}$ coal seam mining face decreases; when the staggered distance is 0 m, the degree of stress concentration is the highest and the stress concentration factor is 2.41. As the staggered distance increases, the front abutment pressure concentration of $27_{\text{lower}}$ coal seam mining face decreases first and then increases. And when the staggered distance is 6m, the $27_{\text{lower}}$ coal seam mining face is affected least by the $27_{\text{upper}}$ coal seam mining face.

![Fig. 3. Different staggered distances' stress concentration factor in the left six simultaneous mining faces](image)

5. Engineering application

The $27\#$ coal seam in the left six simultaneous mining faces in Zhengyang mine, is mined. This coal seam is divided into upper and lower seams. The coal seam thickness of $27_{\text{lower}}$ is 1.2m with the seam inclination angle of 7°~11°, the average being 9°. The coal seam thickness of $27_{\text{upper}}$ is 0.9m with the upper and lower seams spacing of 0.8m. Exploitation of the lower mining face is 6m behind the upper mining face, with the staggered distance of 6m. $27_{\text{upper}}$ and $27_{\text{lower}}$ mining faces are both supported by single props.

During the mining face advancing period, observation of mine pressure in the left six simultaneous mining faces is carried on, shown in Fig. 4. In $27_{\text{upper}}$ coal seam mining face, the first weighting interval is 12m, periodic weighting interval is 4m, the central load is larger than that at both ends, the maximum load of upper support is 18MPa and its minimum is 1.5MPa, with larger changes, and the changes of middle and lower support load is relatively stable compared to the upper support. In $27_{\text{lower}}$ coal seam mining face, the first weighting interval is 6m, periodic weighting interval is 3m, the pressure of lower mining face is affected by upper simultaneous mining face, the maximum support load is 16MPa and its minimum load is 6MPa, and mining face load is evenly distributed along the inclination direction because the lower mining face is mainly affected by static load.

![Fig. 4. The pillar loading distribution of the left six simultaneous mining faces (a) $27_{\text{upper}}$ coal seam mining face; (b) $27_{\text{lower}}$ coal seam mining face](image)

The successful practice of the left six simultaneous mining faces in Zhengyang Coal Mine verifies the feasibility of coal seams unconventional simultaneous mining. During the recovery period, the roadway excavation cost is saved by 2.09 yuan per ton, the unit yield has been increased 1.5 fold, the roof maintenance cost is saved by 200 Yuan per m, and the direct economic benefit reaches 23,975,200 Yuan, with significant economic benefits.
6. Conclusions

(1) As the high-quality reserves in medium-thick and thick coal seams have decreased, thin coal seams exploitation attracts more and more attention. The extremely close coal seams are defined through occurrence spatial structure of coal seams and mining-induced coupling effect. Thus, the 27# coal seams in Zhengyang Coal Mine can be determined to be the typical extremely close thin coal seams.

(2) For reducing the roadway maintenance work of lower coal seam mining face, the mechanical model for unconventional staggered distance simultaneous mining in coal seams is established. With reference to the soil mechanics theory, the reasonable staggered distance mathematical expression is derived. The reasonable staggered distance in the left six simultaneous mining face of Zhengyang mine is 6–11m.

(3) The numerical simulation reveals the “double peak” feature of lower coal seam mining face front abutment pressure distribution in the extremely close coal seams unconventional staggered distance simultaneous mining. When the staggered distance is 6m, the lower coal seam front abutment pressure concentration in left six simultaneous mining faces of Zhengyang Coal Mine is the minimum. Combined with theoretical analysis, the reasonable staggered distance for left six simultaneous mining faces is 6m.

(4) The field exploitation shows that it not only is feasible to adopt unconventional staggered distance simultaneous mining in exploiting the extremely close thin coal seams but also makes significant social and economic benefits.

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