Reasonable Width of Narrow Coal Pillar of Gob-side Entry Driving in Large Mining Height

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Abstract. To determine the reasonable width of the gob-side entry driving coal pillar in Xieqiao Mine, firstly, the theoretical analysis method was applied to construct the mechanical model for limit equilibrium area of coal seam edge, and the distance obtained via analysis between the bearing pressure extremum and the coal edge was 3.34 m. Secondly, the numerical simulation method was applied to analyze the roadway rock mechanics with different coal pillar widths, and it is concluded that the width of the coal pillar was staying in a chaos area which was not conducive to the stability of the system when the peak stress position of the roof changed suddenly and the reasonable width was determined at 5 m. Finally, the high-strength, high-pre-stressed bolt and cable anchor supporting test was carried out in the roadway, with 60 mm of roof subsidence, 207 mm of two sides displacement, 305 mm of floor heave, 135 mm of lateral displacement of coal pillar, 7 d duration of strong roadway rock deformation in pressure, in which the deformation meet the safety production of mine and increased the technical and economic benefit remarkably.

1. Introduction
Reasonable width of the coal pillar is an important topic of coal mining. The small coal pillars in gob-side entry driving can not only make the roadway surrounding rocks in the low stressed state, but also can maximize the resource recovery, therefore, this method are widely adopted. Determining the coal pillar width and stability main focus on the analysis of roadway surrounding rock stress field, displacement field and plastic zone distribution, and such research methods as theoretical analysis, numerical simulation, analog simulation and engineering analogy are widely used [1-5]. Recently, scholars made a lot of researches, and the achievement has guided the engineering practice successfully. This paper is based on the No. 1232 (3) panel of Xieqiao Mine, the method of theoretical analysis and numerical simulation was used to determine the reasonable width of the coal pillar and the application was carried on in the engineering field. The research result will provide the theory and practice basis for the coal pillar width in similar engineering project.

2. Distribution rule of the gob-side coal inclining to the bearing pressure

2.1. Profile of the panel
The No.1232 (3) panel of Xieqiao Mine adopted the large mining height with fully-mechanized and full-seam mining method, and the panel was at an elevation of -463.6 m ~ 555.3 m, and average buried depth was 448 m. The average thickness of coal seam was 4.65 m with 15° of the average angle; the strike length was 3015.2 m and the inclined length was 119.0 m ~ 234.3 m. As shown in figure 1,
the No.1222 (3) panel of the upper section had finished mining. The immediate roof of the No.1232 (3) panel was mudstone and No.13-2 coal seam, with 2.05 m of average thickness, and the upper roof was fine sandstone, with 5.26 m of average thickness, and the floor was sandy mudstone, with 4.1 m of average thickness.

2.2. Limit equilibrium analysis of the gob-side coal mechanical state

Before the gob-side entry driving, the movement of the gob overlying strata tends to be stable while the gob-side coal under the remaining bearing pressure is in limit equilibrium state. The mechanical model is established as the figure 2.

\[ \begin{align*}
\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + F_x &= 0 \\
\frac{\partial \sigma_y}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + F_y &= 0 \\
\tau_{xy} &= \sigma_y \cdot \tan \varphi_0 + c_0 \\
\sigma_x &= \lambda \cdot \sigma_y
\end{align*} \]  

(1)


\[ y = \frac{m}{2}, x = x_1, \quad \sigma_y = \sigma_{y1} \cos \alpha. \] 

The solution of equation (1) was as follows:

\[ x_i = \frac{m\lambda}{2\tan \phi_0} \ln \left[ \frac{\sigma_{y1} \cos \alpha \tan \phi_0 + 2c_0 - m\gamma_0 \sin \alpha}{2c_0 - m\gamma_0 \sin \alpha + 2\frac{\rho_c}{\lambda} \sin \phi_0} \right] \] 

(2)

The bearing pressure extremum \( \sigma_{y1} \) can be calculated according to the following formula:

\[ \sigma_{y1} = 2.729(\eta \sigma_c)^{0.729} \] 

(3)

\( \sigma_c \) is the uniaxial compressive strength of the coal sample and \( \sigma_c \) is 12 MPa; the rheological coefficient \( \eta \) is 0.45; \( c_0 \), \( \phi_0 \) are the cohesive force (2 MPa) and the friction angle (25°) between the coal seam and the roof-floor respectively; \( \lambda \) is the lateral pressure coefficient; \( \lambda = 1; \gamma_0 \) is the average volume weight of the overlying strata, and \( \gamma_0 \) is 25.75 KN/m²; \( \alpha \) is the dip angle of the coal seam and \( \alpha = 15° \); the average thickness \( m \) of the coal seam is 4.65 m; coal wall lateral restriction \( p_c \) is 0.2 MPa. From integration of (2) and (3), the distance from the position of the bearing pressure extremum to the coal edge is \( x_1 = 3.34 \) m.

3. Research on the reasonable width of the entry protection coal-pillar

3.1. Process of research and analysis

After excavating, the distribution of the bearing pressure in gob coal changes further with a new unloading loose zone and plastic zone in the roadway edge, while the bearing pressure moves to the deep coal part. Meanwhile, the different width of coal pillar also leads to the corresponding changes in mine pressure distribution of the coal pillar and the roadway roof. Based on the surrounding rock mechanics of gob-side entry driving, the 2D finite-difference calculation program FLAC²D was applied to simulate the mechanics form of the coal pillar and roof after excavating. According to the geological conditions of No.1232 (3) panel, the simulation adopted Mohr coulomb constitutive model with 230 m wide and 192 m high and the vertical load of upper model was in accordance with the mining depth of 448 m. The coal rock mechanics calculation parameters are shown in table 1. Based on the limit equilibrium analysis of the gob coal, the simulating width of the narrow coal pillar is 3 m, 5 m, 7 m respectively, while the comparison stands at 10 m, 15 m, 20 m.

| Lithology  | Volume weight /\( \text{kg/m}^3 \) | Tensile strength /MPa | Cohesive force /MPa | Friction angle (/°) | Bulk modulus /MPa | Shear modulus /MPa |
|-----------|-----------------------------------|----------------------|---------------------|-------------------|------------------|------------------|
| Fine sandstone | 2620                             | 2.14                 | 3.98                | 41                | 6964             | 5223             |
| Siltstone  | 2610                             | 1.82                 | 3.2                 | 39                | 7039             | 4846             |
| Sandy mudstone | 2560                            | 1.56                 | 1.5                 | 37                | 5355             | 3526             |
| Mudstone   | 2540                             | 0.92                 | 1.6                 | 29                | 4792             | 1716             |
| Coal       | 1350                             | 0.67                 | 1.3                 | 30                | 2149             | 935              |

3.2. Stress distribution of the coal seam roof with different coal pillar widths

Figure 3 represents the vertical stress distribution curve of the roadway roof in different coal pillar widths. The figure shows that the vertical stress above the roadway roof is small, and there is a vertical stress peak in the two coal walls (pillar) of the roadway roof. When the coal pillar width stands at 3 m, 5 m and 7 m, the peak stress of coal pillar roof is less than that of coal wall roof; when the coal pillar width stands at 10 m, 15 m and 20 m, it goes to the opposite direction.
When the coal pillar width increases from 3 m to 10 m, the peak stress of the coal pillar roof increases quickly from 6 MPa to 35 MPa; when the coal pillar width increases from 10 m to 20 m, the peak stress of the coal pillar roof changes little and remains stable in high stress level; the peak stress in the coal wall roof decreases slowly with the increase of the coal pillar width, and the peak stress gradually closes to the roadway coal wall with the increase of the coal pillar width. When the coal pillar width changes from 7 m to 10 m, in which the roof peak stress transit to the upper coal pillar from the coal wall.

![Figure 3. The roof stress distribution curves of different coal pillar widths.](image)

### 3.3. Characteristics of wall rock deformation with different coal pillar widths

While the width of coal pillar changes, the deformation distribution characteristic of the coal seam and roadway floor also changes. As shown in figure 4, when the coal pillar width stands at 3 m, the roadway is affected by the mining drastically, and the shear failure occurs in the two coal walls and the floor of the roadway, and the failure zone covers throughout coal pillars which are in loose and broken state; when the coal pillar width stands at 5 m, the range of shear failure shrinks. Because the coal pillar is in low stress state, the failure zone covers small, and the appropriate supporting measures should be adopted so that the roadway remains stable; when the coal pillar width stands at 7 m, the coal pillar is in high stress, and the failure zone covers throughout the coal pillar, so the coal pillar stability is poor and it is hard to maintain. When the coal pillar width stands at 10 m, the shear failure inordinately and a small scale of tensile failure appeared in the roof-floor of the roadway and two sides of the coal pillar, but the failure zone in the coal pillar is not well covered. When the appropriate supporting measures are adopted, the roadway can remain stable. When the coal pillar width reaches 15 m and 20 m, the failure zone around the roadway shrinks apparently and the tunnel can remain stable well in mining.
3.4. Comprehensive analysis of the reasonable coal pillar width

When the coal pillar width is 3m, 5m and 7m, the roof vertical stress peak located in the coal wall side, and when the coal pillar width is 3m, 5m, the values of maximum principal stress in the coal pillar is low. The coal pillar has suffered from the peak pressure during mining, leading to the plastic yielding and its failure zone running throughout, but the peak stress transferred to the inner of the coal wall side quickly with little high vertical pressure on the upper coal pillar and rocks remaining the residual strength after the peak stress. So for the coal pillar of 3 m, 5 m and 7 m wide, with little high vertical stress in the upper zone, they can keep itself stable through the residual strength of coal when adopting a certain reinforcement constraints on both sides of the coal pillar to keep the integrity of the yielded coal pillar. In addition, when the coal pillar width is 3 m, it cannot keep stability of itself even adopting a certain reinforcement constraints on both sides of the coal pillar. Consequently, the coal pillar will be deformed severely, and tends to cause air leakage for spontaneous combustion in the gob. Therefore, it is not conducive to make the roadway stable when the coal pillar width is 3 m.

Based on the analysis above, the coal pillar width can be divided into four regions to evaluate the stability of the roadway (figure 5). I zone and III zone embrace poor stability, otherwise II zone and IV zone are better stable. For the gob-side entry driving system of No.1232 (3) panel, I zone is below about 5 m; II zone is about 5 m to 10 m; III zone is about 10 m to 20 m; IV zone is over 20 m. Point A in Figure 5 represents a tipping point for leaping of the peak stress in the roof. When the coal pillar width is smaller than that in point A, the roof peak stress is in the coal wall side and gradually closes to the roadway with the increase of the coal pillar width, and this process is a gradual process; when the coal pillar width approaches point A, the roof peak stress transfers to the upper coal pillar from the entity coal seam, and this process is a mutation process; when the coal pillar width is larger than that in point A, the roof peak stress gradually stay away from the roadway, which is also a gradual process. Corresponding to the process above, the stability of the gob-side entry driving system also changes and its stability is poor when the coal pillar width near the roof peak stress mutation area, while the areas a certain distance from both sides of the mutation point are well stable. The coal pillar transits to a less stable region on the far area of the left mutation point because the width is too narrow. In this study, point A lies between 7 m to 10 m.

When choosing the reasonable width of the chain pillar of the gob-side entry driving system, not the wider coal pillar makes more stability. Because before and after mutation of the roof peak stress, the coal pillar width is in a chaotic region which is not conducive to the stability of the system. The coal pillar width in the range must be avoided in the production [7]. Outside of the chaotic area, the increase of the coal pillar width will make the gob-side entry driving system more stable. However, this is not conducive to improve the recovery rate of coal resources. Therefore, the reasonable width of chain pillars should choose II zone in Figure 5, and the reasonable pillar width should be 5 m.
Figure 5. The stable area division of the rock mechanics system in gob-side entry driving.

4. Engineering Practice

4.1. The roadway support design

Given the complex situation of the coal seam, the weak roof layers formed, the joint grew well, and the regional tectonic stress was obvious. The soft and broken coal seam tended to form coal sliding and roof falling in the mining, and the two sides displacement was large and severe deformation of the surrounding rock took place. In order to solve the supporting problem, high-strength and high pre-stressed bolt and cable were applied for support experiment and research. The roof was equipped with M5 steel belt and bolt supporting for cable reinforcement. The bolt featuring BHRB500 L-nonlongitudinal reinforced rebar, with 22 mm of diameter and 2.6 m of length, was anchored by total lengthened prestress, with 800 mm * 800 mm in row spacing. 6-hole M5 steel belt, with the length of 5.0 m and metal mesh canopy guard were applied. Anchor cable was 20 mm of diameter, 7.4 m of length, resin extended anchorage, with 1.8 m of length and 1200 x 800 mm in row spacing. Two-anchor bolt was with 2.0 m of length, while other forms were equal to the roof, and the metal mesh applied the diamond graticules woven with 8 # galvanized iron wires, with 1500 mm of web width, 30 * 30 mm in mesh specification and less than 100 mm of overlap length.

4.2. Roadway supporting performance

Figure 6 shows the displacement curves of the surface of the roadway surrounding rock. The roof subsidence was 60 mm, two sides of the roadway displacement was 207 mm and the floor heave was 305 mm. Among them, the lateral displacement of the coal pillar was 135 mm, and the strong deformation persists 7 d in pressure. Preserving 5 m of the chain pillar meet the safe production of mine and improved the recovery rate of coal resources greatly.

Figure 6. The displacement curves of surrounding rock of roadway.
5. Conclusions
(1) The control system was divided into 4 areas to evaluate the stability of the roadway. The tipping point A for leaping of the peak stress in the roof was located in zone II with poor stability and the point A was between 7 m and 10 m.
(2) When choosing the reasonable width of the chain pillar of the gob-side entry driving system, not the wider coal pillar made the roadway more stable. Because before and after mutation of the peak stress in the roof, the coal pillar width was in a chaotic region which was not conducive to the stability of the system.
(3) After preserving the narrow coal pillar, the displacement of the surrounding rock around roadway was monitored, with 135 mm of the lateral displacement of coal pillar. The strong deformation persisted about 7 d during the pressure. After preserving 5 m of the coal pillar width, the mine has made significant technical and economic benefits.

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