Study on Reasonable Coal Pillar Width of Goaf-side Roadway Driving in Deep Island Working Face with Fully Mechanized Caving Mining

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Abstract: Goaf-side roadway driving with narrow coal pillars could obviously improve the coal recovery rates compared to traditional wide pillars of 15–40 m. However, it is difficult to control the stability of goaf-side roadway driving, especially in the deep island coal working face. To control the stability using fully mechanized caving, working face 4206 in Jianxin Coal Mine in the Shaanxi Province of China, field investigation, theoretical analysis, and numerical simulation were performed to obtain the main influencing factors of the surrounding rock deformation and reveal the characteristics of stress distribution, plastic zones, and deformations of the surrounding rock of roadways with coal pillars of different widths. Results show that the main influencing factors of surrounding rock deformation of roadways in the island working face 4206 in Jianxin Coal Mine include large, buried depth, thick coal seam, large coal pillars, and island working face with high stress concentration. Moreover, the reasonable coal pillar width is 8 m. The stress concentration and the damage of the 8-m-wide coal pillar are smaller, and the corresponding deformation is lower than that of the other pillars, which is beneficial to the stability of the Goaf-side roadway driving.
Keywords: Island working face; Coal pillar; Goaf-side roadway driving; Stress; Deformation; Stability

1 Introduction

In the process of coal mining, the island working face often occurs due to the influence of geological conditions, unbalanced mining and excavation, and management methods [1-3]. Compared with the ordinary working face, the stress concentration of the island working face is higher, the surrounding rock of the roadway is seriously damaged, and the stability control is difficult [4-7]. In the recent years, experts and scholars have conducted several studies on the lateral stress distribution of the island working face, the stress state of coal and roof closing to the goaf, and the failure mechanism of roadways.

Zhao et al. [8] studied the asymmetric deformation of the surrounding rock for roadways during the mining of the island working face and proposed that the principal stress deflection led to the ‘diagonal’ development of the plastic zone of roadway surrounding rock under the influence of island coal pillar, and the asymmetric floor heaving. Xu et al. [9] experimentally studied the advanced abutment pressure of the fully mechanized caving face with soft coal by using the self-developed mining stress monitoring system and found that the advanced mining influence distance of the fully mechanized caving face with soft coal was greater than that of the ordinary island working face; the influence range caused by the relaxation of the two roadways became larger with the advancement of the working face. Chen et al. [10] analyzed the mechanism of the large deformation in the process of “inward movement” of the two sides in the transportation roadway tunneling in the island working face. By using the deformation mechanism transforming principle, the support idea of ‘Relying on the top and bottom, controlling the two sides’ was proposed, so that the surrounding rock of the roadway was effectively controlled [10]. Some experts and scholars found that compared with ordinary working face, the occurrence frequency of rock burst accidents is higher, and the harm greater when the island working face is mined [11,12]. Li et al. [13] proposed a method for the prediction of the rock-burst-threatened areas in an island coal working face with weak rock-burst propensity. Feng et al. [14] analyzed the stress propagation mechanism of different roof structures, established the abutment pressure estimation model of island working face, proposed the abutment pressure estimation method, and constructed an evaluation method of rock burst hazard induced by overall instability of island coal face based on the existence of the elastic loading zone.

To ensure the safe mining of the island working face, the roadways with wide pillars of 15–40 m are usually excavated along the adjacent goafs. However, with the increase in the mining speed and height, the strata pressure is becoming more intense, the deformation of the surrounding rock of roadways is serious and the roadways are increasingly difficult to support [15-17]. In the recent years, some scholars have proposed the method of goaf-side entry driving, which fundamentally avoids high stress concentration in the island working face and reduces the support difficulty of roadways [18-20]. However, coal occurrence and mining conditions are different, and the choice of coal pillar width is also different when driving on the roadway along goaf. Based on the engineering background of the island working face 4206 of Jianxin Mine in Binhuang Mining Area of Shaanxi Province in China, this paper analyzes the influencing factors of the surrounding rock deformation of roadways and proposes the reasonable width of coal pillar using FLAC$^{3D}$ numerical simulation software, which
provides a reference for the layout of mining roadway in the island working face with similar mining geological conditions.

2 Engineering Background

The working face 4206 is located in the eastern part of the panel 42, and mining coal seam 4-2# with weak rock-burst propensity. The working face is arranged in the southwest-northeast direction. The west is the goaf of the working face 4204 (the fourth working face abstracted), and the east is the goaf of the working face 4208 (the eighth working face abstracted), the north is the boundary of panel 42, and the south is the protection coal pillar of auxiliary transportation roadway in panel 42. The mining roadway depth of the island working face 4206 is 500–600 m, with an average depth of 550 m. The strike length of the working face is 2132.93 m, and the dip length is 197 m. And the average thickness of the coal seam is 8.5 m, and the average dip angle is 3°. The width of coal pillars on either side of the island working face 4206 is 15 m. The width and height of roadway are 5.2 m and 4.4 m, respectively. The layout of working face 4206 and mining roadway is shown in Figure 1.

![Figure 1. Roadway layout in island working face 4206](image)

The direct roof, basic roof, and direct floor of the coal seam consist of siltstone, grit sandstone, and fine sandstone, respectively. The physical and mechanical parameters of the roof and floor in the working face 4206 are shown in Table 1. The bolt-mesh-cable support technology is adopted for the support of the mining roadway in the working face 4206. The mine pressure control method is hydraulic fracturing for the roof fracture but its support effect is not obvious. Although the roadway support is dense, as shown in Figure 2a, the roof of the roadway dramatically sank during the advanced mining, the deformation of the two sidewalls were severe, making the maintenance difficult, which seriously affects the safety of production, as shown in Figure 2b.
a. Intensive support for the roof  
b. Surrounding rock deformation

*Figure 2. Damage of roadway in the working face 4206*

*Table 1. Roof and floor lithology and physical and mechanical parameters of rock strata in the working face 4206*

| Lithology       | Thickness (m) | Bulk modulus (GPa) | Shear modulus (GPa) | Friction Angle (°) | Cohesion (MPa) | Density (kg/m$^3$) |
|-----------------|---------------|--------------------|---------------------|--------------------|----------------|-------------------|
| Silty sandstone | 5.3           | 2.22               | 1.81                | 28                 | 0.8            | 2314              |
| Grit sandstone  | 6.6           | 2.42               | 2.15                | 38                 | 1.8            | 2593              |
| Siltstone       | 5.7           | 2.10               | 1.76                | 36                 | 1.7            | 2395              |
| Coal            | 8.5           | 1.97               | 1.5                 | 27                 | 0.6            | 2214              |
| Fine sandstone  | 7.1           | 2.10               | 1.76                | 36                 | 1.7            | 2395              |

3 Analysis of the Influencing Factors of Surrounding Rock Deformation

(1) Large buried depth of the coal seam

The buried depth of roadway in the island working face 4206 is 500–600 m, with an average of 550 m. The buried depth is large, and the ground stress is high. Combined with the rock mechanics parameters obtained from the coal mine, the vertical ground stress of roadway surrounding rock in the island working face 4206 is about 13.8 MPa. The roadway is in a high stress environment due to the large buried depth and the superposition of the mining lateral abutment pressure. The surrounding rock deformation shows obvious characteristics of brittle-plastic transformation, rheology, and expansion. The large deformation of the deep roadway with fast speed brings great difficulties to control the roadway stability.

(2) Large thickness of the coal seam

The thick coal seam determines the mode of fully mechanized caving mining in the working face 4206. The high mining height causes the height of the basic roof fracture to increase. The rotary subsidence of the key block to the edge of the coal pillar increases the stress concentration of the coal side, which aggravates the development of the surrounding rock fracture, and converts from shallow to deep to form a large deformation in the surrounding rock. At the same time, the roadway is excavated along the floor. The top coal thickness of the roadway is large, the coal body is soft, and the expansion characteristics are strong. The plastic zone of thick top coal in the roof expands and the deformation increases due to the residual abutment pressure of goaf on both sides. The stress zone of the original rock in the coal pillar disappears, the damage degree intensifies, and gradually becomes the plastic
state of complete damage. Only the residual strength is retained and the bearing capacity decreases sharply, thus making the roadway support difficult.

(3) Stress concentration in the island working face

The mining roadway in the island working face 4206 is affected by the superposition of the abutment pressure of those goafs and the stress concentration of the surrounding rock of the roadway is high when the working face is mined. As shown in Figure 3, the width of the coal pillar on both sides of the island working face 4206 is 15 m, and the roadway is located in the areas with the high lateral abutment pressure. The 15 m wide coal pillar is difficult to bear such high stress, which is prone to deformation and failure.

![Figure 3. Stress distribution nephogram of wide coal pillar of 15 m](image)

In summary, retaining wide coal pillar of 15 m increases the support difficulty of the roadway. Therefore, it is recommended that such working face should be mined using r Goaf-side roadway driving with narrow coal pillars along the adjacent goaf. The coal pillar should be arranged in the stress reduction zone to avoid the stress concentration and fundamentally solve the problem of serious deformation of the roadway and improve the coal recovery rates.

4 Numerical Simulation Analysis of Coal Pillar Widths

4.1 The numerical simulation model

According to the geological condition of the island working face 4206, the numerical model is established, as shown in Figure 4. The model sizes are 200 m wide, 100 m long, and 40 m high. The vertical stress in the upper boundary of the numerical model is determined according to the buried depth of the coal seam. The bulk density of the upper strata is calculated according to 25 kN/m³. The stress and deformation characteristics of the coal seam and each rock layer meet the Mohr-Coulomb yield criterion. The corresponding physical and mechanical indices of coal and rock layers are consistent with the results of the laboratory test. The horizontal direction and bottom boundary of the model are set to a fixed boundary while the top boundary of the model is set to a stress boundary. Combined with the actual situation, the coal pillar width is set to 4–10 m, and a calculation model is established with an interval of 1 m. Seven groups of numerical simulation schemes are designed to analyze the stress, plastic zone distribution, and the deformation of the roadway under different widths of the coal pillar.
4.2 Results and Discussion

(1) Stress distribution characteristics of the coal pillar with different widths

The stress distribution of coal pillar under different widths is shown in figure 5. The peak stress of the narrow coal pillar is significantly reduced compared with the wide coal pillar of 15m, but the peak stress of the solid coal side becomes larger, which is the result of the transfer of the roof pressure to the solid coal side using the narrow coal pillar scheme. It is beneficial for the support of the narrow coal pillar but it increases the support difficulty of the solid coal side, thus the width of the narrow coal pillar should not be too small.

![Figure 4. Numerical calculation model](image)

![Figure 5. Stress distribution of the narrow coal pillar with different widths](image)

A stress measuring line is arranged in the middle of the narrow coal pillar to obtain the stress distribution law in the coal pillar under different coal pillar widths, as shown in Figure 6. Through the analysis, the following results can be obtained:

(a) The stress in the coal pillar presents a single peak distribution, the peak is continuously far away from the goaf, and the peak position is roughly located at 1/2 of the width of the coal pillar.

(b) The peak stress of coal pillars with different widths changes, as shown in Figure 7. The corresponding peak abutment pressure quickly increases with the increase in the coal pillar width almost linearly, when the width of the coal pillar is less than 9 m. The abutment pressure almost does...
not change when the width of the coal pillar increases to 9 m. Therefore, the reasonable width of the coal pillar should be less than or equal to 9 m.

(c) The peak stress is less than the original rock stress when the width of the coal pillar is less than 8 m.

(d) In order to reduce the support difficulty of the coal pillar, the width of the coal pillar should be less than 9 m. Considering the economic benefits and the support difficulty of the solid coal side, the reasonable width of the coal pillar determined by stress distribution is 7–8 m.

**Figure 6.** Vertical stress in the coal pillars with different widths

- **Figure 7.** Peak stress of the coal pillars with different widths

The distribution of plastic zone in the coal pillars with different widths is shown in Figure 8. In the figure, red and pink represent the shear failure zone, and dark blue and light blue represent the plastic zone. The analysis results are listed below.

(a) Almost the entire coal pillar becomes the shear failure zone when the width of coal pillar is 4 m (Figure 8a). (b) The failure zone gradually decreases and the plastic zone gradually increases with the increase of the coal pillar width, (Figure 8b, c and d). (c) The width of the plastic zone exceeds that of the shear failure zone when the width of coal pillar reaches 8 m, (Figure 8e). Considering the support strength, the coal pillar has been able to maintain stability. (d) Compared with Figure 8f and Figure 8g, the failure zone has a trend of increasing when the width of coal pillar is greater than 9 m. (e) Through
the analysis of the plastic zone, the reasonable width of the coal pillar is 8.9 m.

![Distribution of the plastic zone of the coal pillars with different widths](image)

Figure 8. Distribution of the plastic zone of the coal pillars with different widths

(3) Analysis of surrounding rock deformation of the coal pillars with different widths

To further determine the reasonable width of coal pillar, the correlation between the coal pillar width and surrounding rock deformation was studied. Based on the analysis of the deformation of roadway surrounding rock under different coal pillars of 4–10 m, the relationship between the deformation of the roadway and the width of the coal pillar is obtained as shown in Figure 9.
Figure 9. Deformation curve of the roadway with different coal pillar widths

Figure 9 shows the deformation of roadway surrounding rock in the state of no support and the deformation is generally large. The change of roadway deformation with different coal pillars shows the following characteristics: (a) With the change of the coal pillar width, the roof subsidence of roadway fluctuates but the overall change is small, and the roof subsidence is the smallest (457 mm) when the coal pillar width is 8 m. (b) With the change of the coal pillar width, although the deformation of the narrow coal pillar side fluctuates, it decreases in general. When the coal pillar width is 4 m, the deformation is the largest (433 mm). When the coal pillar width is 8 m or 10 m, the deformation of the roadway is relatively small. The corresponding deformations are 231 mm and 226 mm, respectively. (c) The floor heave and the deformation of the solid coal sidewall change negligibly with the different coal pillar widths, indicating that the change of the coal pillar width has little effect on the floor heave and the deformation of the solid coal sidewall.

In summary, when the width of the coal pillar is 8 m, the overall deformation of the surrounding rock for the roadway is small. Combined with the stress distribution and plastic zone distribution in the coal pillar and the economic benefits, the reasonable width of the coal pillar is finally determined to be 8 m.

5 Conclusions

(1) The main influencing factors for the deformation and stability of the surrounding rock island working face 4206 in Jianxin Coal Mine include large buried depth, the thick coal seam, large coal pillar, and the island working face with the high stress concentration.

(2) This research shows that 15 m wide coal pillar increases the support difficulty. And the scheme of Goaf-side Roadway Driving with the narrow coal pillar is proposed to control the stability of the roadway in the island working face.

(3) According to the distribution law of stress, plastic zones, and deformations around the roadway under different coal pillar widths, the reasonable width of the narrow coal pillar is finally determined to be 8 m in the island working face 4206 in Jianxin Coal Mine which is beneficial to the stability of the Goaf-side roadway driving.

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