Based on Immersion Study on Bearing Characteristics of Roadway Pillar Under Softening

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Abstract. In order to study the influence of coal softening on the retention of coal pillar in the working face, taking the mining of 1314 working face in Xiaoyun coal mine as the engineering background, the variation law of coal pillar lateral bearing pressure before and after water softening is analyzed by FLAC3D numerical simulation, and it is determined that platform wide coal pillar should be selected for water soaking coal pillar. Then the excavation of coal pillar roadway with different width is simulated, and the stable coal pillar range of roadway is obtained. Further simulating the mining of the working face, it is obtained that the stress change in the elastic core area in the coal pillar with different widths basically reaches a stable state at 28 M. Combined with the internal stress change of coal pillar in the mining process, the reasonable reserved width of water immersed wide coal pillar is determined to be 28 M. Through the analysis of microseismic evolution characteristics in the mining process of 1314 working face, the stability of water-soaked wide coal pillar in the mining process is verified. This paper provides a reference for the rational design of roadway pillar under the condition of water immersion and softening.

Keywords: Water immersion softening · Wide coal pillar design · Roadway pillar · Stress distribution · Microseismic

1 Introduction

The research on the bearing characteristics of coal pillar has always been an important research direction in mining science [1–7]. Zhang Jie et al. studied the stability of shallow burial-depth coal pillars and obtained the migration law of overlying stratum in the process of mining under such conditions [8]. Xu Qingyun et al. obtained the initial spatial position of coal pillar instable failure by studying the narrow coal pillar of the entry protection [9]. Zhu Weibing et al. studied the stability of room-type coal pillars and quantitatively presented the relationship between the elastic core zone and the stability of coal pillars [10]. Wu Yongping et al. studied the instable failure characteristics of the long-arm working face (large dip angles) and obtained two types of instable failure for coal pillars on the working face of large dip angles [11]. Zhang Ming et al. studied

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the stability of both the shallowly-buried thick and hard rock stratum and the coal pillar structure mode [12], providing guidance for the prevention and control of mine disasters under such conditions. Zhu Defu et al. calculated the instability probability of coal pillars based on the calculation of the plastic zone in the room-type coal pillar, and tested its reliability on the spot [13]. Zhang Xinguo et al. studied the stability of the strip coal pillar on the backfill working face through a filling body monitoring system [14]. It can be seen from the above that the research on the bearing characteristics of coal pillar has become mature at the present stage. However, very few researches focus on the bearing characteristics of the soaked coal pillar. Therefore, this paper takes the unique site conditions as the starting point, and studies the bearing characteristics of the soaked coal pillar through the numerical simulation and the field observation to ensure the safe production of the working face. Meanwhile, it also provides reference for the reasonable design of the entry protection coal pillar in the rock softening conditions after the production of water-inrush mine is resumed.

2 Engineering Background

In Xiaoyun Coal Mine, the ground elevation of the 1314 working face is +37.7–+37.9 m, and the working face elevation is −555.9––665.5 m. Strike length is 955 m, dip length is 219 m, the area is 209,145 m^2, the average coal thickness is 3.2 m, and the average dip angle is 15. The developed igneous rock wall intrudes the dike in the working face, and two scouring and thinning areas of the coal seam are developed in the working face. A water inrush accident broke out in the mine on September 10, 2018, with the maximum water inflow of 1500 m^3/h. The underground coal body is obviously softened by water immersion and the 1314 working face layout is shown in Fig. 1.

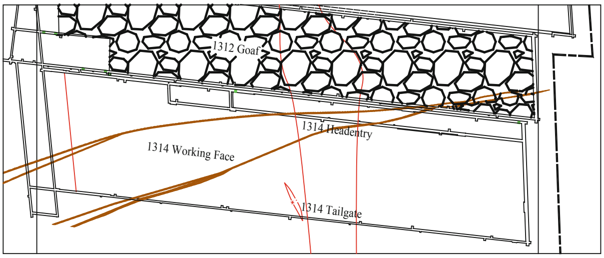


Fig. 1. Working face layout

3 Soaking Influence Analysis of the Entry Protection Coal Pillar in the Working Face

In the original design of Xiaoyun coal mine, the 6 m small coal pillar was kept for roadway excavation and the mining of 1314 working face. According to the field measurement, the water content of the coal body in the soaking side of 1314 working nquaface reached up to 11%. Based on this, it is considered that the coal body has lost its basic bearing capacity in this area. Therefore, according to the original design, the 6 m small coal pillar was kept for roadway excavation and the roadway cannot bear the pressure of the overlying stratum. Moreover, the coal pillar cannot support the working face in the process of mining. After the coal pillar is crushed, the working face is likely to be affected by unsafe factors such as residual water in the goaf.

To ensure the safety, the wide coal pillar must be set up to solve the problem that the 1314 working face cannot produce. The wide coal pillar of the working face should be designed according to site conditions. Because wide pillars waste coal resources and the mining of the working face will form a new bearing pressure zone inside the coal pillar. If the pillar is not wide enough, the bearing pressure peaks on both sides are overlaid. As a result, it will cause the high bearing pressure distribution zone of coal pillars, and the pressure in the middle of the coal pillar is always greater than the original rock stress. Because of the mining disturbance and the stress wave disturbance caused by the rotation fracture of the high stratum over the roof, rock burst accidents are easy to occur in the coal pillar. For this reason, the following section will simulate the evolution law of the coal pillar's bearing characteristics in order to determine the reasonable reserved width of coal pillars.

4 Evolution Law on the Excavation Stress of the Soaked Wide Coal Pillars

4.1 Numerical Modelling

To study the stress response of coal pillars with different widths in the mining, FLAC^{3D} numerical simulation was used, and a similar numerical model was established based on the actual geological conditions of 1314 working face in Xiaoyun coal mine. In the model, the strike-length was 1,080 m, the tendency width was 570 m and the height was 70 m. The thickness of 3 coal is 3.8 m. Physical and mechanical parameters of the rock strata were taken from the rock mechanics test report of the geological borehole in working face 1314, as shown in Table 1.

Table 1. M-C criterion mechanical parameters

Lithology	Shear modulus /(GPa)	Bulk modulus /(GPa)	Cohesion /(MPa)	Internal friction angle/(°)	Tensile strength /(MPa)	Density /(kg.m^{-3})
Fine sandstone	17.61	8.22	16.9	39	6.34	2810
Coal	1.50	0.70	0.7	24	0.53	1400
Siltstone	11.80	6.50	5.7	30	12.6	2689
Mudstone	7.60	4.70	3.8	35	2.60	1560

4.2 Simulated Result Analysis

Before simulating the excavation, the supporting pressure distribution characteristics of coal pillars on soaked sides should be determined. The simulated lateral stress distribution is shown in Fig. 2.

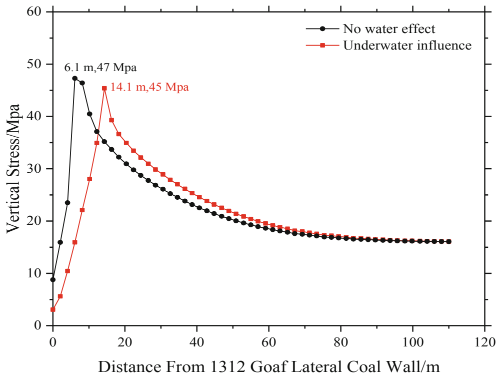


Fig. 2. Lateral stress distribution of the 1312 goaf

It can be known from Fig. 2 that the lateral stress peak before soaking was 47 MPa and the distance from the coal wall was 6.1 m. After soaking, the stress peak of the coal pillar decreased slightly to 45 MPa, about 14.1 m away from the coal wall. It shows that: the stress peak shifted to the deep after the coal strength decreased. In both cases, the influence ranges of the bearing pressure are both 80 m. According to the distribution characteristics of the lateral stress in 1312 goaf, the coal pillar width should be greater than 14 m, but the greater width of coal pillars would cause a waste of resources. Therefore, the wide coal pillar of 1314 working face was set up as the platform-type coal pillar. Therefore, when the coal pillar width was 20, 22, 24, 26, 28 and 30 m, respectively, this paper discussed in detail the distribution characteristics of both internal stress and the plastic zone inside the coal pillar after roadway excavation and the 1314 working face mining.

- Roadway excavation stability of coal pillars at different widths

With different coal pillar widths, Fig. 3 shows the internal stress distribution curve of the coal pillar after the roadway excavation.

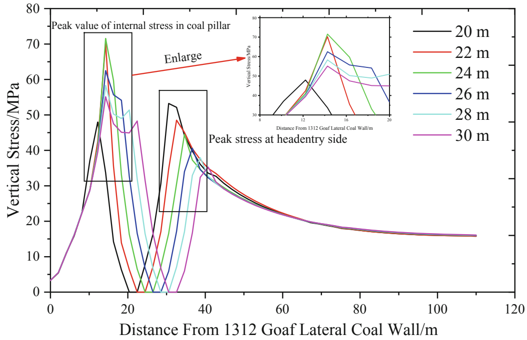


Fig. 3. Internal stress distribution of the coal pillar at different widths after roadway excavation

It could be known from Fig. 3 that: as the coal pillar width gradually increased from 20 m to 30 m, the stress peak of the coal pillar increased first and then decreased. When the coal pillar was 20 m, the minimum stress peak was 47 MPa. The stress peak reached the maximum 72 MPa when the coal pillar was 24 m.

As the coal pillar width continued to increase, the stress peak began to decrease, that is, when the width was 26 m, 28 m and 30 m, the stress peak was 62 MPa, 58 MPa and 55 MPa respectively. Meanwhile, the stress peak value in the coal pillar in the figure was magnified to compare the variation trend of each curve. It could be known from the comparison that: when the coal pillar width was 20 m, 22 m, 24 m and 26 m, the stress curve presented a single peak state, indicating that the bearing pressure of the 1312 goaf side and the roadway side was overlaid to form a high stress area. When the coal pillar width was 28 m and 30 m, the internal stress curve of the coal pillar presented a double peak state, indicating that the lateral stress superposition of both the 1312 goaf and the roadway was relatively small. Therefore, the width of 20 m, 28 m and 30 m were suitable given that the relatively low value of the internal coal pillar stress were selected after roadway formation.

Besides avoiding the accumulated high stress in the coal pillar, the stability of roadways and coal pillars should be combined with the plastic zone for comprehensive analysis.

In the $FLAC^{3D}$ numerical model, the coal body in the plastic zone can be considered to have been destroyed and the cracks are relatively developed. Therefore, the overall plastic state of the coal pillar should be avoided and the middle should retain a certain elastic core. The internal plastic zone distribution of coal pillars with different widths was shown in Fig. 4.

(a) coal pillar width 20m

(b) coal pillar width 28m

(c) coal pillar width 30m

Fig. 4. Plastic zone distribution of the coal pillar at different widths

It can be seen from Fig. 4 that: when the width was 20 m, plastic failure happened to the whole coal pillar. Considering that the coal body had been soaked in water, the whole plastic coal pillar was likely to cause deformation and the overall instability. When the coal pillar width was greater than 28 m, the elastic zone appeared inside the coal pillar. Therefore, considering the stability of the coal pillar, the coal pillar width should be greater than 28 m. The comprehensive stress analysis results showed that: the pillar width of 28 m and 30 m were more suitable.

- Internal stress distribution of coal pillars at different widths during mining

The monitoring line layout is shown in Fig. 5. Figure 6 shows the internal stress variation curves of coal pillars at different widths after the mining of the 1314 working face is finished.

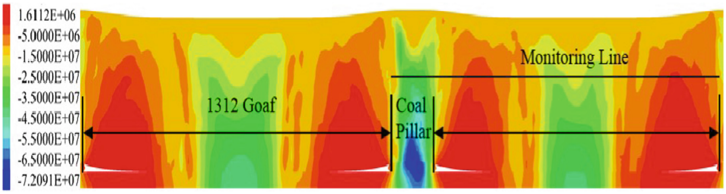


Fig. 5. Monitoring line layout of coal pillar stress during mining

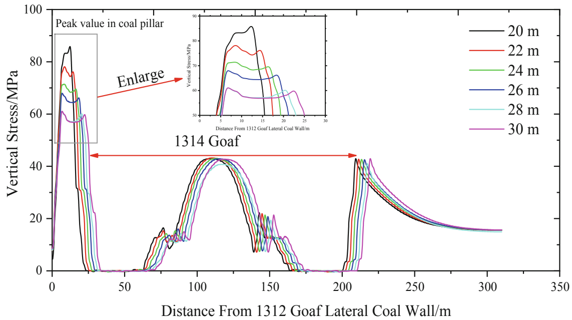


Fig. 6. Internal stress distribution of coal pillars at different widths after the mining of the 1314 working face is finished

It can be seen from Fig. 6 that: as the reserved width increased, the stress distribution in the coal pillar gradually changed from the single peak state to the double peak distribution. Meanwhile, the stress peak value in the coal pillar gradually decreased, but this decrease was not infinite and a stable value existed. Namely, when the pillar width was 28 m, the stress peak was about 60.95 MPa. When the width continued to increase to 30 m, the stress peak was about 60.76 MPa. The results showed that: when the pillar width exceeded 28 m, the increase of the pillar width had no obvious effect on reducing the internal stress concentration of the pillar. Therefore, the reserved width of coal pillar should be 28 m when considering the mining of the 1314 working face.

- Coal pillar stability in the whole process of the working face mining

During the mining of the working face, when the coal pillar width is 28 m, rock burst accidents are likely to happen under the cumulated influence from the lateral supporting pressure of the elastic core zone in the coal pillar. In order to study in detail the variation trend of coal pillars' internal stress in different mining stages and test the safety of coal pillars, the monitoring line is set along the coal pillar length, where the starting point of the monitoring is A (the coal pillar length is 0) and the finishing point is B, as shown in Fig. 7. When the extracted distance of the working face is different, the stress distribution law of coal pillars along the length direction is also obtained. Moreover, the stress peak change law of both coal pillars at different distances and the working face at different distances is also obtained, as shown in Fig. 8 and 9.

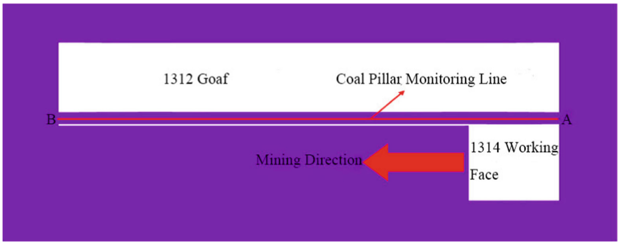


Fig. 7. 1314 working face mining and the monitoring line layout of the coal pillar

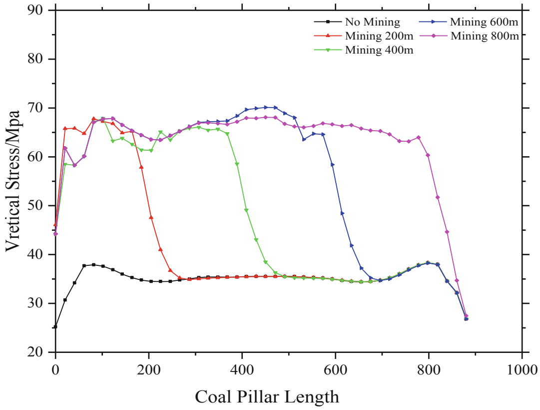


Fig. 8. Stress distribution law of coal pillar along the length at different mining lengths

It can be seen from Fig. 8 that: the peak value of internal stress in the coal pillar can reach 37 MPa before mining. The peak value of the coal pillar's internal stress changed slightly and was basically 67–70 MPa when different distances were extracted on the working face. However, the stress varied greatly in different positions of the coal pillar. The coal pillar with high stress was located on the 1314 goaf side mainly due to the rock caving in the goaf of the 1314 working face. Another reason was that the lateral bearing pressure caused the stress to increase in the coal pillar. For the non-extracted part of the working face, the stress of the adjacent coal pillar section was relatively small.

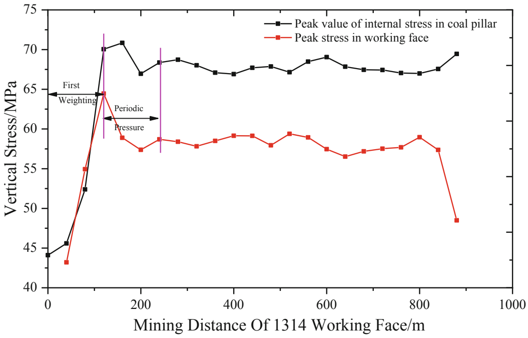


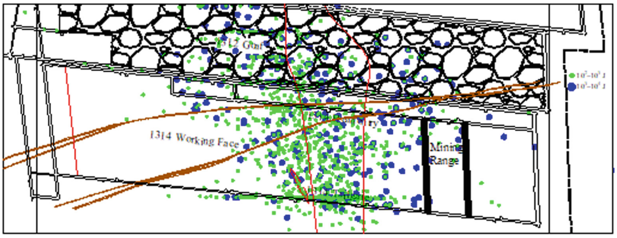
Fig. 9. Peak value change law of the working face stress and the coal pillars at different mining lengths

It can be seen from Fig. 9 that: when the working face advanced to 0–120 m, the stress peaks in the working face and the coal pillar increased significantly, and then began to decrease. This indicated that: the initial pressure obviously influenced the working face and the coal pillar stress. When the working face continued to advance 140–880 m, the peak values of the coal pillar and the working face showed a periodic fluctuation, which is caused by the periodical pressure of the working face, but the stress didn't fluctuate greatly. Namely, the influence of the incoming pressure is not obvious.

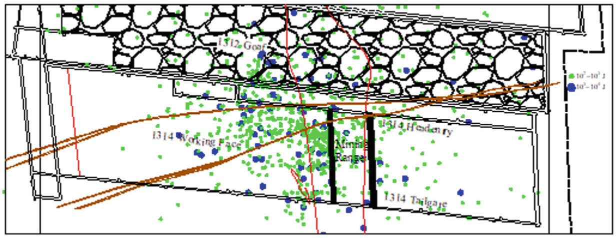
It can be known from the above simulation analysis that: when the coal pillar width is 28 m, the vertical stress of the coal pillar is always at a low level, and no stress concentration is shown in the coal pillar, which can realize the safe mining in the working face and save coal resources.

5 Microseismic Evolution Characteristics During the Working Face Mining in Large Soaked Coal Pillars

According to the production experience, the internal stress of the coal pillar is prone to present the high value instability of the stage and it is risky during the initial square and the second square. Therefore, the microseismic data were analyzed by taking the square as the research node. Figure 10 is the microseismic location plan in the dangerous stage of the working face mining.



(a) microseismic location plan near the initial square of the mining (1.9-2.27)



(b) microseismic location plan near the second square of the mining (5.13-4.13)

Fig. 10. Microseismic location plan of the dangerous stage during the working face mining

Around 40 m was selected from the square dangerous zone. Figure 10(a) shows that: microseismic events are mainly minimal energy events in the microseismic location of the initial square stage. Microseismic events are distributed and concentrated near geological structures. It can be seen that the coal pillar is in a stable state in the initial square stage. It could be known from Fig. 10(b) that: microseismic events further decreased in the second square stage of the working face. The roadway on both sides of the coal pillar was excluded, and no cubic events occurred inside the coal pillar. It can be seen that there is no instability failure of the coal pillar in this dangerous stage.

It could be known from Fig. 10 that: in the two possible dangerous stages of the coal pillar, the number of events didn't accumulate inside the coal pillar in the microseismic event plan. It shows that the stability of coal pillar is in good condition and the designed width of the coal pillar is reasonable.

6 Conclusions

- According to the actual situation, it is concluded that: in order to ensure the coal pillar stability during the working face mining, the reserved wide coal pillar design should be selected. By studying the lateral bearing pressure distribution of the coal pillar, the selected platform shape of the wide coal pillar was initially determined based on the comprehensive analysis of the soaking influence and the economic benefits in the coal pillar.
- By comparing the lateral stress distribution law of the goaf before and after soaking, it can be seen that: the peak value of the lateral stress decreased from 47 MPa to 45 MPa

after soaking, and the distance from coal wall shifted from 6.1 m to 14.1 m. Therefore, the reserved coal pillar width should be ensured to be greater than 14 m at least.

- By comparing the stress peak values and the plastic zone evolution of coal pillars at different widths throughout the 1314 transportation tunneling, it can be seen that: the inner stress of 20-m-wide coal pillars was relatively low, but the overall plastic state may destroy the instability. When the width was 28 m and 30 m, it could ensure the low stress of the coal pillar. Meanwhile, a certain elastic zone existed inside the coal pillar. It is conducive to the coal pillar stability as a whole.
- By simulating the 1314 working face mining and reserving coal pillars at different widths, it could be known from the stress changes of the coal pillars that: The peak value of stress in coal pillars decreased gradually with the increase of the width. However, when the width was greater than 28 m, the stress value became stable along with the increase of the coal pillar width. Therefore, the reasonable reserved width of coal pillars should be 28 m, and the coal pillar stability got verified again by simulating different mining stages.
- By analyzing the microseismic evolution characteristics of the working face when mining to the initial square and the second square, it could be known that: there were relatively few cubic events in the coal pillar during the working face mining. No abnormality was found during the working face mining, and no instability sign was found in the coal pillar. The designed width of the coal pillar was reasonable.

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