Reasonable Width of Narrow Coal Pillars Along Gob-side Driving Entries in Gas Outburst Coal Seams: Simulation and Experiment

LIU Hao1,3,4, ZUO Yu-jun1,3,4, SUN Wen-jii-bin1,3,4, WU Zhong-hu2, ZHENG Lu-jing1,3,4

(1.College of Mining, Guizhou University, Guiyang 550025, China 2.School of Civil Engineering, Guizhou University, Guiyang 550025, China 3.Guizhou Key Laboratory of Comprehensive Utilization of Non-metallic Mineral Resources, Guizhou University, Guiyang, Guizhou 550025, China 4.National & Local Joint Laboratory of Engineering for Effective Utilization of Regional Mineral Resources from Karst Areas, Guizhou 550025, China)

LIU Hao, Doctoral candidate, Email: liuhao_gzu@163.com
ZUO Yu-jun, Professor, Email: zuo_yujun@163.com
SUN Wen-jii-bin, Doctoral candidate, Email: sunwenjibin@163.com
WU Zhong-hu, Associate professor, Email: wuzhonghugzu@163.com
ZHENG Lu-jing, Doctoral candidate, Email: 464131084@qq.com

Abstract. In gob-side entry driving, the coal pillar width determines the stability of the surrounding rock and the pillar itself. Thus, to improve the stability of gas outburst coal seams, the reasonably narrow width of the coal pillars of the 40403 working face of the Shengyuan coal mine 4# was theoretically determined. Through two-dimensional simulations, the surrounding rock stability for a roadway with different coal pillar widths was evaluated. The mechanism of the surrounding rock displacement and stress distribution with the increase of the coal pillar width was also defined; for pillar widths of 2–4, 4–6, and 6–10 m, the vertical stress distribution was approximately triangular, trapezoidal, and parabolic, respectively. The coal pillar displacement was significantly greater on the goaf side than on the roadway side. As the width of the coal pillar was incremented, its displacement on the goaf side increased, while that on the roadway side remained relatively small. The combination of the simulation results with on-site measurements finally revealed that 5 m is a reasonably narrow coal pillar width. Then, the findings were successfully applied to the 40403 working face of the Shengyuan coal mine 4#, achieving good outburst prevention and cost reduction.

1. Introduction

Coal and gas outburst is a complex mine phenomenon and among the natural events leading to frequent coal mine accidents in China. It depends on many variables, such as geological factors and coal body structure.1-4 Coal and gas outburst is causing severe problems in the underground coal
mines of the Shuicheng mining area (Guizhou Province), with serious impacts on the safety and driving speed in the working faces. With the increase of the mining depth, the gas pressure, in situ stress, and gas content rise linearly, gradually incrementing the outburst strength and frequency; this severely reduces the extraction efficiency of the coal seams, resulting in significant casualties and huge economic losses. Therefore, the outburst risk must be eliminated and the coal pillars in the seams should have a reasonable width to improve the roadway stability and reduce the coal loss.

In China, the technology of driving along the road has been widely used for the layout and maintenance of coal roadways.\[^{[5,6]}\] Field studies reported a certain pressure relief and outburst zone in the coal body on the goaf side.\[^{[7]}\] and mining in this area can eliminate the outburst danger, reduce the coal loss, and improve the roadway stability. However, the key to this approach is the determination of the reasonably narrow width of the coal pillars, which tends to vary due to the different occurrence of coal rock. For this purpose, several works have been conducted so far. Bai et al.\[^{[8]}\] performed numerical simulations, concluding that this width should be 3–4 m for medium hard coal and 4–5 m for soft coal. Wang et al.\[^{[9]}\] developed an equation for the case of fully mechanized roadways along the basic roof under deformation conditions. Kang\[^{[10]}\] theoretically derived the calculation formula of the stress field width in the digging roadways of inclined coal seams and explored the influence of the seam inclination angle on the pillar width. Zhang et al.\[^{[11]}\] did numerical simulations and theoretical analysis based on real data from the Wangjialing coal mine. Lu et al.\[^{[12]}\] analyzed more than 200 roadway examples, finding the general relationship between the wall rock deformation of the roadway and its coal pillar width. Through theoretical analysis, numerical simulations, and engineering analogy, Guo\[^{[13]}\] evaluated the feasibility of leaving too wide coal pillars in the Qianwan coal mine and also that of small coal pillar roadway protection in the 2105 working face. Ma et al.\[^{[14]}\] numerically analyzed the evolution of the rock lane transportation and coal lane track uphill the protective coal pillars as well as the supporting stress evolution during mining in a Shandong mine; they observed that coal can effectively control the deformation of surrounding rock pillars. The abovementioned studies adopted theoretical analysis, numerical simulations, and engineering analogy to determine the reasonable width of narrow coal pillars. However, only a few works have included also simulative experiments and field industrial tests. The Shengyuan coal mine is a coal and gas outburst mine for which the empirical analogy method is usually adopted for determining the size of the narrow coal pillars along the roadway, leading to blindness and limitations. Therefore, a reasonable and scientific way for the determination of this parameter is paramount for safety.

The present study used the 40403 working face of the Shengyuan coal mine 4# as the reference; the theoretical analysis and simulations were combined with on-site industrial testing to validate the results, finally determining the reasonable width of the narrow coal pillars for the case considered. Hence, this work could guide the activity of mining enterprises.

2. Geological background

The Chongqing Coal Science Research Institute has identified the Shengyuan coal mine as a coal and gas outburst mine. The average thickness of its main coal seam (4#) is about 2.56 m, the gas content is 15.56 m\(^3\)/t, there are 3 layers of gangue, and the seam dip angle is 8°–11°. The in situ stress of this coal seam, measured via the sleeve stress relief method, ranges between 10.8 and 13 MPa; Figure 1 comprehensively describes the coal strata. The 40401 working face is located in the east wing of the fourth mining area, its length is about 120 m, the transport roadway is trapezoidal, and the strike is around 400-m long; the roadway is supported by an anchor net. Coal and gas outbursts have occurred
many times during roadway excavation, and the gas emission during mining exceeds $3 \text{ m}^3/\text{min}$. After completing the mining of the working face and stabilizing the roof and floor of the goaf, a coal pillar has been realized along the goaf. The return air road is located in the next section of the working face, the roadway elevation is $(+1746.5–1755.6 \text{ m})$, the cutting depth of the shearer is $0.8 \text{ m}$, and the daily number of knives is 6, which takes 124 min, and undergoes continuous excavation.

| Layer number | Layer thickness | Columnar 1:500 | Lithology description |
|--------------|----------------|----------------|-----------------------|
| 1            | 4.42–33.89     | Quartz sandstone or Conglomerate | Light gray, gray-white, medium thick layered, gravel is mainly quartz, 2–10mm, angular. The layer is lenticular in space and Sandy mudstone in between |
| 2            | $3–7$          | Fine sandstone | Light gray, fine-grained, medium-thick layered, sometimes black mudstone with siderite nodules. |
| 3            | 1.82–2.76      | 2#coal        | Commonly known as cliff charcoal, black, the streak color is brownish black, powdery or rare block, linear or thin strip structure, glass luster, semi-dark briquette. |
| 4            | 0.25–12.78     | Sandy mudstone | Gray-black mudstone or dark gray sandy mudstone, 0.25–12.78m thick, generally 4.62m. |
| 5            | 1.07–3.47      | 4#coal        | Black, lump or powder, grease luster, semi-dark briquette. |
| 6            | 2.25–2.19      | Sandy mudstone | The upper part is gray mudstone or light gray siltstone. The middle part is mostly layered fine-medium-grain sandstone or siltstone, containing mudstone inclusions and siderite nodules, with a thickness of 0–10.06m, generally 3.60m. The lower part is 3 coal roof, which is thin-medium thick siltstone or mudstone, with horizontal bedding, thickness 0–11.88m, generally 5.22m. |
| 7            | 1.52–3.05      |              | 7#coal | Black or brownish black, lump or powder, uneven fracture, line structure or thin strip structure semi-dark to semi-bright coal. |
| 8            | 0.1–18.60      | Sandstone or Siltstone | The upper part is mudstone or siltstone, the middle part is mostly medium-thick layered fine sandstone, with wavy bedding and horizontal bedding, thickness 0–8m, generally 3m; the lower part is thin layered siltstone or mudstone, thickness 0–12.8m, generally 4.58m. |
| 9            | 1.64–3.38      |              | 8#coal | Black or brownish black, lump or powder, line structure to thin strip structure, uneven fracture, semi-bright to semi-dark type, mainly semi-bright type. |
| 10           | 0.45–0.95      | Sandstone or Siltstone | The upper part is mudstone, containing clay, generally 2.03m thick. The lower part is mostly layered fine sandstone or siltstone, with a thickness of 0–18.57m, generally 9.29m. |
| 11           | 4.5–54.82      |              | 9#coal | Black, powder or lump, line structure or thin strip structure, grease luster, uneven fracture to semi-dark coal. |
| 12           | 1.64–3.38      | Fine sandstone or Sandy mudstone | The upper part is fine sandstone, thick layered wavy bedding, thickness 4.42–33.89m, generally 13.47m; the lower part is sandy mudstone, thin layered, thickness 0.1–18.99m, generally 7.58m. |
| 13           | 2.25–14.12     |              | 11#coal | Black, blocky, grease luster or glass luster, uneven fracture, line structure or thin strip structure, semi-dark briquette. |
|              |                | Sandstone or Siltstone | The upper part is mudstone, clay, 2.29–5.44m thick, generally 3.82m; the lower part is siltstone, fine-grained, medium-thick layered, well-developed bedding, thickness 0.25–8.78m, generally 3.68m. |

Figure 1. Column map of the coal strata.

3. Determination of the reasonable width of narrow coal pillars

Article 16 of the *Prevention of Coal and Gas Outburst Regulations* states the following: “Roadways with outburst coal seams are preferentially arranged in protected areas or other pressure relief areas.”[15] Figure 2 illustrates the distribution of the lateral support stress and gas pressure in the
goaf; the mining disturbances and long-term pressure relief reduce the gas content in the coal body at the goaf side. When the residual gas pressure is below 0.74 MPa, it is equivalent to digging in an area without outburst risk, the excavation speed and safety are greatly improved, and, thus, safety is ensured.\cite{16} The reasonable width of the coal pillars is key in improving the stress state of the surrounding rock and the stability of the coal pillars and gangue, as well as in realizing the safe driving of coal lanes in pressure relief and outburst areas. The reasonable width of the coal pillars ($w$, in m) should satisfy the following condition:\cite{7,16,17} \[ w \leq d - b - c \] (1)

where $d$ is the pressure relief and anti-outburst zone, $c$ is the safety distance against outburst, and $b$ is the width of the coal roadway. Article 49 of the *Prevention of Coal and Gas Outburst Regulations* states the following: “Through layer drilling and pre-draining coal seam strip drilling should control at least 15 m outside the contour lines on both sides of the roadway.”\cite{15} Based on this indication, the anti-outburst inspection effect on both sides of the transportation flat roadway of the 40401 working face, and the actual mine situation, $d = 15$ m. According to the *Basic indicators for coal mine gas drainage* (“When the coal seam inclination angle is above 8°, the control range of coal roadway driving face is 8 m above the outline of the roadway (5 m at the bottom or bottom)\cite{18}, the Articles 21 and 115 of the *Prevention of Coal and Gas Outburst Regulations* (“The minimum normal distance of all tunnels outside the outburst coal seam from the outburst coal seam is greater than or equal to 5 m\cite{15}”), and the actual situation of the mine, $c = 5$ m. Given the actual return air level of the 40403 working face, $b = 4$ m. By substituting the abovementioned values in Equation (1), we obtain that the reasonable width of the coal pillars along the roadway should not exceed 6 m.

![Figure 2. Profile of the lateral support stress and gas pressure in the goaf](image)
4. Experimental section

4.1. Model design

The similar simulation experiment was based on the geological conditions of the Shengyuan coal mine, combined with the model generalization theory and the rational selection of the similarity constant according to the equipment conditions. Figure 3 illustrates the model design.

![Figure 3. Model design.](image)

4.2. Determination of similarity constant and ratio of rock material

First, based on the geological conditions of the Shengyuan coal mine, combined with the similarity theory\(^{19,20}\) and the rationally selected similarity constants, the following parameters were established.

(a) Geometric similarity constant: The experiment used a \(4 \times 0.3 \times 2.0\) m (length \(\times\) width \(\times\) height) model frame. Given the influence of the mine pressure and loose layers, the test needed an axial load on the upper part of the model for stress compensation; therefore, the model size was set as \(4 \times 0.3 \times 1.8\) m and the actual simulated cross-section height was 180 m, so \(\alpha_i = 100\) was regarded as geometrically similar. Since the roof of the target coal seam is relatively broken and loose, and based on the actual situation, the 40403 working face was cut at 50 m from the right boundary of the 4# coal seam and pushed at 50 m from the left boundary to stop mining. According to the geometric similarity constant, the strike length in the model was set to 400 cm; therefore, the distance between the constraint end of the model and the stop mining line was 50 cm (Figure 3).
(b) Bulk density similarity constant: The rock layers in the model mostly consisted of mudstone, silty mudstone, and siltstone. According to experience, the bulk density similarity constant \( (\alpha_r) \) was set as 1.5.

(c) Stress similarity constant \( (\alpha_\sigma) \): 

\[
\alpha_\sigma = \alpha_i \times \alpha_r = 1.5 \times 100 = 150.
\]

(d) Time similarity constant: Based on the site work requirements, the daily excavation was 41.1 cm, obtaining a 4-m long model within 9 days. According to the geometric similarity constant, the rock section height was set as 180 m. The calculated bulk density of the overlying rock layer was 25 kN/m\(^3\). This test mainly studied the influence of coal pillar width on the roadway stability. The model roof reached the surface and no overburden load was required.

Then, the proportion of similar materials and the layering amount were considered. Mica powder, river sand, lime, gypsum, and water were used as raw materials for this experiment. According to the similar material ratio information that was mastered, the rock formation composition and properties were determined (Table 1); Figure 4 displays the laying model. The material usage was based on the model stratification and each simulated formation serves as a calculation unit. By using similar constants, the raw material usage for each layer was calculated separately. The basic calculation formula of the material ratio was as follows:

\[
G_i = A_i \times \gamma_i \times m,
\]

where \( G_i \) is the total amount of materials used in the \( i \)th layer of the model, \( A_i \) and \( \gamma_i \) are the side area and bulk density of the \( i \)th layer, respectively, and \( m \) is the model thickness.

| Number | Coal Rock Name | Layer thickness (cm) | Rock layer thickness (m) | Rock Density | Rock compressive strength of similar materials (MPa) | Compressive strength of model materials (MPa) | Model weight of each layer (kg) |
|--------|----------------|----------------------|--------------------------|--------------|-----------------------------------------------------|------------------------------------------|-------------------------------|
| 18     | Quartz sandstone | 80.2 | 80.2 | 2600 | 38.2 | 0.26 | 2201.97 | 125.11 | 50.04 | 75.07 |
| 17     | Sandstone | 3.5 | 3.5 | 2500 | 15.3 | 0.10 | 93.45 | 3.15 | 5.25 | 3.15 |
| 16     | 2#Coal | 2.4 | 2.4 | 1620 | 3.1 | 0.02 | 41.06 | 2.33 | 0.93 | 1.40 |
| 15     | Sandy mudstone | 4.6 | 4.6 | 2500 | 21.2 | 0.15 | 122.82 | 4.14 | 6.90 | 4.14 |
| 14     | 4#Coal | 2.6 | 2.6 | 1620 | 3.1 | 0.02 | 44.98 | 1.52 | 2.53 | 1.52 |
| 13     | Sandy mudstone | 8.8 | 8.8 | 2500 | 21.2 | 0.15 | 232.32 | 13.20 | 5.28 | 7.92 |
| 12     | 7#Coal | 1.8 | 1.8 | 1620 | 3.1 | 0.02 | 31.14 | 1.05 | 1.75 | 1.40 |
| 11     | Mudstone | 3.0 | 3.0 | 2460 | 13.9 | 0.09 | 78.82 | 4.43 | 1.77 | 2.66 |
|   | Rock Type   | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|---|-------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 1 | Siltstone   | 13.7| 13.7| 2500| 15.3| 0.10| 365.79| 12.33| 20.55| 20.55| 12.32|
| 2 | Mudstone    | 3.8 | 3.8 | 2460| 13.9| 0.09| 98.71 | 5.61  | 2.24  | 2.24  | 3.37 |
| 3 | 11#Coal     | 2.8 | 2.8 | 1620| 3.1 | 0.02| 48.44 | 1.63  | 2.72  | 2.72  | 1.63 |
| 4 | Sandy mudstone | 7.6 | 7.6 | 2460| 13.9| 0.09| 197.43| 11.22 | 4.48  | 4.48  | 6.73 |
| 5 | Fine sandstone | 13.5| 13.5| 2500| 38.2| 0.26| 360.45| 8.10  | 16.20 | 16.20 | 16.23|
| 6 | 9#Coal      | 0.6 | 0.6 | 1620| 3.1 | 0.02| 10.26 | 0.58  | 0.23  | 0.23  | 0.35 |
| 7 | Siltstone   | 9.3 | 9.3 | 2500| 15.3| 0.10| 248.31| 8.37  | 13.95 | 13.95 | 8.36 |
| 8 | Mudstone    | 2.0 | 2.0 | 2460| 13.9| 0.09| 51.95 | 2.95  | 1.18  | 1.18  | 1.77 |
| 9 | 8#Coal      | 2.3 | 2.3 | 1620| 3.1 | 0.02| 39.80 | 1.34  | 2.34  | 2.34  | 1.33 |
|10 | Siltstone   | 4.6 | 4.6 | 2500| 15.3| 0.10| 122.82| 4.14  | 6.90  | 6.90  | 4.14 |

**Figure 4.** Overview of the laying model.

4.3. **Model displacement and stress monitoring**

An observation line was placed every 40 cm in the vertical and horizontal directions, and surface displacement monitoring points with a 40-cm spacing were arranged along the surface line. Through the mining process of the working face, we monitored in real time the overburden strata collapse, migration, and change, as well as the horizontal and vertical displacements of the ground surface. Figure 5 shows the location of the pressure sensors, which were distributed in three layers while building the model: the first, second, and third layers were arranged in the sandy mudstone of the coal floor, the mining coal layer, and the fourth layer of quartz sandstone (above the mined coal layer), respectively. To observe the movement of the overlying rock layer during the mining, after completing the model and 10 days of drying, we placed the displacement sensors as shown in Figure 6. The distance between the consecutive measuring lines was 40 cm; 5 displacement monitoring lines were
arranged in the vertical direction, each one having 9 measurement points, and another monitoring line was placed at 40 cm from the left boundary in the horizontal direction. The data were collected by a TS3890 static strain measuring and processing instrument.

![Figure 5. Stress measurement points in the model.](image)

![Figure 6. Displacement monitoring lines and points in the model.](image)

5. Results and discussion

We investigated the stability of the 40403 working face for different coal pillar widths (2, 3, 4, 5, 6, and 10 m) by observing the pillar damages during the mining process and collecting the corresponding stress and displacement data. In this way, the reasonably narrow width of the coal pillars was determined.
5.1. Experimental results

During the experiment, each feed advanced 0.8 cm and the working face was mined every 21 min; the model was continuously excavated from right to left at this speed. When the working face advance reached 145 cm, the basic roof broke and underwent periodic sinking. After the overlying rock layer was stabilized and the goaf of the previous working face was formed, we used the gob technology to retain the coal pillars in the goaf. Figure 7 illustrates images of the model during the experiment.

![Figure 7](image_url)

**Figure 7.** Failure of the coal pillars.

As shown in Figure 7, due to the stress concentration in the overlying rock layer, when the pillar width is 2 m, the coal pillars exhibited severe flank phenomena and deformation. When increasing the stress toward the goaf side, the roof fell near the coal pillar, with an obvious roof separation in the goaf area, and the coal pillar lost its bearing capacity and suffered some plastic damage. In the case of the 3-m pillar width, we observed evident deformation and flank phenomenon on both sides of the pillars because the stress of the overlying rock layer was concentrated in the goaf roof and sunk, forming a stress relief area; the pillar stability was slightly improved compared with the 2-m width case. For the coal pillar width of 4 m, as the stress of the overlying strata increased, a new crack sprouted on the goaf roof, and both the tunnel stability and the bearing capacity of the pillars were improved. This also indicates the presence of an elastic zone in the coal pillars. When the pillars were 5-m wide, the roadway deformation and the surrounding rock crack development were low, the stability was good, and both the roadway integrity and the bearing capacity of the pillars were further improved; due to the increased stress of the overlying rock layer, a certain degree of falling to the roof of the goaf side has been released, and part of the stress has been released. In the case of the 6-m pillar width, the stability and integrity of the roadway and coal pillars were good. Due to the tensile stress, evident vertical cracks appeared on the roof toward the goaf side; moreover, we clearly observed roof separation due to stress concentration, suggesting that the coal pillars and roadway were in the stress reduction zone. As regards the pillar width of 10 m, the roof on the goaf side got separated and subsided, indicating that the coal pillars and roadway were completely in the stress reduction zone and had both good stability and integrity.
By comparing the results of theoretical analysis and our similar simulation experiments, and by considering the problem of coal loss resulting from excessively large remaining coal pillars, we preliminarily determined that the reasonable width range of narrow coal pillars for roadway driving along the goaf in the 40403 working face should be 4–6 m.

5.2. Quantitative analysis

A qualitative analysis of the experimental results is not accurate enough. Thus, we successively quantitatively analyzed the stress and displacement data, obtaining three graphs as follows.

As shown in Figure 8, the peak stress that the coal pillars can withstand linearly increased along with the pillar width. For the pillar width range of 2–4 m, the peak area was small, the peak stress increase was large, and the vertical stress distribution was approximately triangular. The stress was lower than the original rock one; this indicates that when the coal pillars are narrower than 4 m their bearing capacity is low and a certain degree of plastic failure occurs. When the width range increased to 4–6 m, the peak area incremented, reaching the original rock stress level, the peak stress increase was small, and the vertical stress distribution was approximately trapezoidal. Moreover, the tunnel stability and the bearing capacity of the pillars were improved, confirming the presence of an elastic zone in the coal pillars. When the width reached 6–10 m, the peak stress rose from 13 to 24 MPa, the peak area increased, the vertical stress distribution was parabolic, and the bearing capacity of the coal pillars was significantly enhanced.

As shown in Figure 9, after driving the gob along the goaf, the pillar displacement toward the roadway and goaf sides changed significantly; besides, the displacement toward the goaf side was much higher than that toward the tunnel side. When the pillar width was 2–5 m, the peak displacement toward the goaf side increased linearly and sharply, reaching a maximum of 10 mm; when the width was incremented to 5–10 m, this peak displacement slightly changed, exhibiting a slow downward trend.
and remaining constant in the 9.4–10 mm width range. Moreover, for the pillar width range of 2–4 m, the peak displacement toward the tunnel side increased linearly, reaching a maximum of 5.2 mm. When the pillar width was increased to 4–10 m, the peak displacement toward the roadway decreased linearly down to 3.2 mm.

Figure 9. Peak horizontal displacement of the coal pillars.

Figure 10 shows that with the increase in the coal pillar width, the deformation of the floor drum was not obvious and fluctuated around 10 mm. Besides, when enlarging the coal pillars, the roof sinking decreased linearly down to about 11 mm. When the pillar width rose from 2 to 4 m, the pillar displacement increased from 21 to 53 mm. With increasing the width from 5 to 10 m, the pillar displacement gradually decreased down to about 35 mm. Moreover, the displacement of the coal gangue increased from 43 to 56 mm when incrementing the pillar width from 2 to 3 m, while did not change significantly and was, finally, stabilized for the larger pillar widths. When the width was 4–6 m, the coal pillars could retain a certain bearing capacity and the deformation of the rock surrounding the roadway was small.

Through the comprehensive consideration of the theoretical analysis, similar simulation experiment results, design parameters, and the principle of minimum coal loss, we finally identified 5 m as the reasonable width of the narrow coal pillars for the 40403 working face.
6. On-site industrial testing

To verify the effect of the coal pillar width value (5 m) obtained through theoretical analysis and similar simulation experiments, we successively conducted an on-site test at the Shengyuan coal seam 4# by driving along the goaf. The roadway displacement was monitored in real time via the cross-point method and the data were analyzed to derive the deformation curve of the rock surrounding the roadway (Figure 11).

Within 1–7 days of lane digging, the average roof sinking rate was 9.0 mm/day, the surrounding rock slabs and deformation of the roadway were more severe, the roof approaching distance was stable at about 40 mm and the separation distance was 4.4 mm. The average approaching speed of the two groups was 6.8 mm/day, and the approaching distance was stable (about 155 mm). The approaching distance of the solid coal gangue as finally stabilized at 52 mm, that of the bottom was also stabilized at 85 mm, and the one along the empty coal gangue as maintained at 104 mm; the maximum approaching distance of both top and bottom was about 140 mm. After 7 days, the rock deformation around the roadway was basically stable. During the tunneling process, the deformation of the solid coal gangue and roof was small, and the deformation along the empty coal gangue and roof was less than that of the roadway. The deformation was within the safe range, demonstrating that using 5-m wide coal pillars can improve the stability.
This test shows that the coal seam 4# roadway is located in the pressure relief area of the goaf side, which can not only eliminate the prominent danger but also improve the roadway stability and driving speed. Compared with conventional working faces with 20-m wide coal pillars, leaving 5-m wide pillars along the goaf in the 40403 working face allows the extraction of more than 50,000 tons of coal, reducing the loss of coal resources and the amount of anti-outburst projects, improving the roadway driving efficiency and the recovery rate of the coal resources, ensuring safe and efficient production, and achieving economic benefits.

7. Conclusion

(1) Similarity simulation experiments on roadway excavation can be effectively carried out, providing reliable results. Compared with on-site experiments, the testing conditions are easier to control, showing more intuitively and comprehensively the regularity of the pressure appearance in the narrow coal pillars, and can be repeated. Besides, it saves manpower and material resources and can provide a technical reference to design the roadways along the goaf.

(2) The analysis of the vertical stress in the coal body revealed that its distribution is approximately triangular, trapezoidal, and parabolic when the pillar width is 2–4, 4–6, and 6—10 m, respectively. By analyzing the peak curve of the horizontal displacement of the coal pillars, we found that the pillar displacement toward the goaf side is significantly greater than that toward the roadway. Moreover, as the pillar width increases, the displacement toward the goaf side increments, while the one toward the roadway changes less.
Through theoretical analysis and similar simulation experiments, combined with on-site industrial tests, we finally determined that the reasonably narrow width of the coal pillars for the 40403 working face, which can provide good anti-outburst effects and economic benefits, is 5 m.

Acknowledgments

This study was supported by the National Natural Science Foundation of China (Project Nos. 51774101 and 51574093), the Scientific and Technological Innovation Talents Team in Guizhou Province (Project No. [2019]5619).

References

[1] WANG Gang, WU Meng-meng, CHEN Wei-min, et al. Analysis of coal and gas outburst energy condition and factors influencing outburst strength [J]. Rock and Soil Mechanics, 2015, 36(10):2974-2982. (in chinese)

[2] PAN Yi-shan. Study on integration of coal and gas outburst, combined dynamic disaster of impact earth pressure [J]. Journal of China Coal Society, 2016, 41(01):105-112. (in chinese)

[3] LU Jian-zhang, LIU Jian-zhong. Status and development of coal mine disaster prevention technology [J]. Coal Science and Technology, 2006(05):1-5. (in chinese)

[4] FU Hua, FENG Sheng-cheng, GAO Zhen-biao, et al. Prediction model of coal and gas outburst based on dual-coupling algorithm [J]. China Safety Science Journal, 2018, 28(03):84-89. (in chinese)

[5] ZHANG Ke-xue, JIANG Yao-dong, ZHANG Zheng-bin, et al. Determination of reasonable width of narrow coal pillar for gob-side entry driving in large coal pillar [J]. Journal of Mining and Safety Engineering, 2014, 31(2): 255-262, 269. (in chinese)

[6] BO Jian-biao. Control of surrounding rock in roadway along goaf [M]. Xuzhou: China University of Mining Press, 2006:1-16.

[7] CHEN Cai-xian, SU Jing, TANG Zhu, et al. Determination of the range of pressure relief and decontamination along empty excavation roadway [J]. China Coal, 2017, 43(02):104-107+122. (in chinese)

[8] BO Jian-biao, HOU Chao-jiong, Huang Han-fu. Numerical simulation of narrow coal pillar stability in gob-side entry driving[J]. Chinese Journal of Rock Mechanics and Engineering, 2004, 23(20): 3475-3479. (in chinese)

[9] WANG Wei-jun, HOU Chao-jiong, LI Xue-hua. Rational positioning analysis of fully mechanized caving roadway under given deformation of roof [J]. Journal of Xiangtan College of Mining, 2001, 16(2): 1-4. (in chinese)

[10] KANG Jian-dong. Design and control technology of narrow coal pillars along the excavated roadway in inclined coal seam [J]. Safety in Coal Mines, 2018, 49(08):247-250. (in chinese)

[11] ZHANG Guang-chao, HE Fu-lian. Reasonable width of coal pillars and surrounding rock control along goaf roadway in large-section fully mechanized caving mining [J]. Rock and Soil Mechanics, 2016, 37(06):1721-1728+1736. (in chinese)

[12] LU Shi-liang, GUO Yu-guang. Relationship between the width of coal pillars in roadway protection and surrounding rock deformation of roadway [J]. Journal of China University of Mining & Technology, 1991, 20(4): 1-7. (in chinese)

[13] GUO Xi-zhi. Support design of small coal pillar roadway in shallow coal seam [J]. Coal and Chemical Industry, 1988, 41(08):32-35. (in chinese)

[14] MA Ning, ZHANG Guo-long, JIA Jiang-feng, et al. Study on the size of coal pillar for uphill protection in mining area [J]. Coal Technology, 2018, 37(09):95-98. (in chinese)
[15]State Administration of Supervision and Administration of Production Safety, State Bureau of Coal Mine Safety Supervision. Coal and gas outburst control regulations [M]. Beijing: Coal Industry Press, 2009.
[16]ZHANG Hong-xing, LIU Hao, GAO Qing-ping, et al. Determination of reasonably narrow coal pillars along an excavated roadway and similar simulation study [J]. Mining Technology, 2017, 17(05): 58-59+105. (in chinese)
[17]CHEN Cai-xian, SU Jing, TANG Zhu, et al. Study on the application of excavated roadway along the narrow coal column in the outburst coal seam [J]. Mining Safety & Environmental Protection, 2015, 42(05): 81-83+91. (in chinese)
[18]State Administration of Work Safety. AQ 1026-2006, Basic indicators for coal mine gas drainage [S]. Beijing: Coal Industry Press, 2007.
[19]GHABRAIE B, REN G, ZHANG X, et al. Physical modelling of subsidence from sequential extraction of partially overlapping longwall panels and study of substrata movement characteristics [J]. International Journal of Coal Geology, 2015, 140: 71-83.
[20]JIANG Jin-quan. Stress and movement of surrounding rock in stope [M]. Beijing: Coal Industry Press, 1993: 14-73.
[21]LI Peng-jun. Simulation analysis of similar materials for waterproof pillar mining in coal seam near fault [D]. Hefei University of Technology, 2012. (in chinese)