



Article The Optimization of Coal Pillars on Return Air Sides and the Reasonable Horizon Layout of Roadway Groups in Highly Gassy Mines

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Abstract: Multiple roadways are opened to solve the difficulties in gas control in the high seam working face of high gassy mines, resulting in a large width of coal pillars between roadway groups. Moreover, recovering coal pillars is challenging during stoping, which causes serious resource waste. While the size of coal pillars is optimized, the reasonable horizon layout of roadway groups is performed to ensure a fine recovery rate of coal resources, mine safety, and efficient production. Theoretical analysis was applied to calculate the stress distribution of surrounding rocks around coal pillars based on the engineering practice of the W2302 working face in the Sihe Coal Mine. The MathCAD software Prime 2.0 combined with the on-site measured stress was used to draw the stress distribution under different coal pillar widths, which can derive the stress distribution data of the floor. The vertical stress concentration factors tended to be consistent at 10 m below the coal pillars and about 12 m from the centerline of coal pillars under different coal pillar widths, this area was suitable for the layout of floor rock roadways with a stress concentration factor of about 1. Numerical simulations were used to compare the stress distributions of the roadway floor and the deformation features of surrounding rocks under different coal pillar widths. The coal pillar width was finally determined to be 45 m, which optimized the size of coal pillars. The return air roadways were arranged at 9.8 m below the coal seam combined with the strata distribution on-site. According to the industrial test on-site, the return air roadways were available during the service period, which showed reliable theoretical analysis and simulation results. A reasonable horizon layout of return air roadways can provide a scientific basis and reference for similar projects.

Keywords: high gassy mine; size optimization of coal pillars; roadway group; horizon layout; gas control

1. Introduction

China is rich in coal, poor in oil, and scarce in gas resources. According to the statistics of the Ministry of Land and Resources in 1999, China ranks ranked first in coal reserves and second in recoverable reserves in the world [1]. The mining of coal resources with the largest proportion in the energy consumption structure is not affected by the international situation. The annual output is estimated to reach 6 billion tons by the middle of the 21st century. Coal resources will remain China's main energy for a long time in the future [2,3]. Affected by the occurrence state, more than 90% of the coal resources are mined by underground mining. High seam reserves account for about 45% of the distribution of coal seam reserves. High seams are generally mined by slicing, top-coal caving, and large mining height fully mechanized mining technology. Regardless of the coal mining technology, coal pillars with a certain width are established between two working faces. More mining roadways



Citation: Ma, Q.; Zhang, Y.; Gao, L.; Li, Z.; Song, G.; Zheng, Y. The Optimization of Coal Pillars on Return Air Sides and the Reasonable Horizon Layout of Roadway Groups in Highly Gassy Mines. *Sustainability* 2022, 14, 9417. https://doi.org/ 10.3390/su14159417

Academic Editors: Cun Zhang, Fangtian Wang, Shiqi Liu and Erhu Bai

Received: 10 June 2022 Accepted: 29 July 2022 Published: 1 August 2022

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Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). are excavated by the working face to provide gas control channels, especially in high gassy mines, which reduces the temperature of the working face. However, recovering coal pillars between roadways is not easy, which causes great resource waste. China's recoverable high-quality resources are gradually exhausted with long-term high-intensity mining, which restrains the sustainable development of resources. Therefore, the recovery rate of coal resources is raised to improve the economic benefits of mines [4–11].

While the size of coal pillars is optimized, roadway groups are conducted with reasonable horizon layouts to reduce the later maintenance and improve the recovery rate of coal resources and the economic benefits of mines. Researchers have studied the optimized size of coal pillars and the reasonable horizon layout of roadway groups. Qi et al. analyzed the widths of narrow coal pillars for roadway protection within a reasonable range through numerical simulation and theoretical calculation based on the mining geological conditions of the fully mechanized 3309 caving face of certain mines in Shandong [12]. The field measurement data show that the optimized coal pillar width can control the deformation of surrounding rocks of gob-side roadways, which maintains the overall stability of fully mechanized caving roadways. Yu et al. studied the failure law of coal pillars between roadways based on field measurement taking the coal pillars between the double-roadway excavation transportation grooves and gas drainage roadways of the large mining height 204 working face in the second panel of Tingnan Mine as the engineering background [13,14]. The reasonable size of coal pillars was determined to be 10 m in a large mining height double-roadway working face after the stress evolution and elastic-plastic change law of coal pillars between roadways of different sizes were simulated. Finally, the engineering practice was used to verify the rationality of retaining coal pillars between roadways. Zhang analyzed the plastic failure width and the minimum critical elastic width for stable coal pillars based on the elastic-plastic partition of coal pillars, thus establishing the criterion for a reasonable coal pillar width [15]. Xu explored the self-stability of coal pillars left in the protective seam taking the high-gas coal seam group in Baode Coal Mine of the Shendong mining area as the engineering background [16,17]. Larger coal pillar width leads to smaller plastic zone proportion, vertical stress, horizontal deformation, and the higher stability of coal pillars. The reasonable coal pillar width is determined by the stability of coal pillars, the pressure relief effect of the protective seam, and the recovery rate of resources. Zhao proposed the roadway layout of straddled coal pillars to solve the discontinuous excavation due to coal under the village in the mining of close-distance coal seams in Qianjiaying Mine, which weakened the impact of mining [18]. Field monitoring indicates that the ascending mining roadway layout of straddled coal pillars can solve the mining problem of close-distance coal seams in the Qianjiaying Mine. Based on the entries retained for the heading stope of the multi-entry system in the Jincheng mining area, Kang [19–21] studied the characteristics of surrounding-rock deformation of the retained entry at the heading stope with a multi-entry layout. The surrounding-rock deformation of the retained entry is closely related to the roadway layout, coal pillar size, and headingstope parameters. The corresponding support technology is proposed to ensure the stability of the surrounding rocks of the roadway.

Scholars have studied the optimized sizes of coal pillars and the layout of roadway groups. However, most optimization methods are applied based on a single coal pillar. The studies on the layout of roadway groups mostly aim at the cross-sectional shapes of roadways, support patterns, and distances between two roadways on the same horizon. Shanxi Sihe Coal Mine was studied with a field investigation and sampling in the work. Combined with theoretical analysis and numerical simulation, the coal pillars on the return air side were optimized to explore the reasonable layout of roadway groups in high gassy mines. The application of research results improved the recovery rate of coal resources to reduce the later maintenance cost of roadways. Social and economic benefits were guaranteed, which provides a scientific basis and guidance for similar projects.

2. Background

The W2302 working face of Sihe Mine was used as the research site to exploit coal seam 3# in the work. The overall coal seam was flat, with a slope of $1-7^{\circ}$ (average 4°), a buried depth of 400–500 m, a thickness of 4.45–8.75 m (average 6.08 m), a strike length of 920 m, and an inclination length of 220 m. The W2303 working face is to the north of the W2302 working face. Figure 1 shows the roadway layout of the W2302 working face.





There are air-intake roadways 1, 2, and 3# and ventilation roadways 1 and 2# (I_1 , I_2 , I_3 , V_1 , and V_2) from bottom to top. The roadways of coal seam groups are I_1 , I_2 , and I_3 , where a 35 m coal pillar is left between roadways I_3 and V_1 ; a 20 m coal pillar is left between roadways V_1 and V_2 .

Fresh airflow enters the working face from roadway I_1 , I_2 , and I_3 in the stoping process of the W2302 working face, and the dirty air is discharged from roadways V_1 and V_2 . After the stoping process, roadways V_1 and V_2 are used as the air intake roadways of W2303. Draining gases at a slow driving speed is challenging when the working face is arranged to excavate the coal seam roadways. The coal pillars cannot be easily recovered after mining, which causes huge resource waste. The following layout scheme is proposed to reduce resource waste and facilitate the pre-drainage of coal seam gas, which can optimize the coal pillar size and solve gas pre-drainage. Figure 2 shows the roadway layout of the new scheme.



Figure 2. Roadway layout of the new scheme.

Roadway V_1 was firstly excavated in the floor stratum to drain gases existing in the coal seam in advance in the roadway layout. Roadway I_3 and V_2 , and cut holes are excavated when the gas drainage in the coal seam complies with the standard. The original two protective coal pillars were reduced to optimize size. The width of the optimized coal pillar is B, with the unchanged application of roadways. The layout of the W2302 working face is completed after roadways I3, V1, and V2 are excavated. Roadway are the intake airway; roadways V_1 and V_2 are the return airways. After the stoping of the W2302 working face, roadway I_3 was scrapped; roadways V_1 and V_2 became the intake airways of the W2303 working face.

In the roadway layout, h is the distance between roadway V_1 and the coal seam floor; d the horizontal distance between roadway V_1 and V_2 . Too large h and d are not conducive to gas extraction. Moreover, roadway excavation requires a large work amount. If h and d are too small, then *B* is small, and the stability of roadways cannot be easily controlled. When the roadway group on the return air side of the W2302 working face is arranged, B, h, and b (the horizontal distance between roadways V_1 and V_2) are of great significance to reducing coal pillar loss and roadway maintenance costs and improving the drainage effect. Figure 3 shows the comprehensive geological histogram of coal seams in the mine. According to the classification standard of stope strata in Refs [22,23], the mudstone and sandy mudstone in the coal seam roof are the immediate roof; the medium-grained sandstone and the sandy mudstone in the upper layer are the basic roof, the mudstone in the floor of the coal seam is the immediate floor, and the sandy mudstone is the basic floor. Medium-grained sandstone and sandy mudstone in the lower layer are basic floor underlying rock layers. According to the comprehensive geological histogram of coal seams, holes in the roadway I_1 of the W2302 working face were drilled to take the core of the roof and floor, and coal samples were taken in the W2301 working face.

Geological histogram	Rock name	Thick- ness (m)	Buried depth (m)	Description of rock properties
	Medium grained sandstone	9.55	376.85	light gray, thick bedded, mainly composed of quartz and feldspar,with argillaceous angular grains in some parts.
	Sandy mudstone	11.80	388.65	Grayish black, medium thick layered, flat end, with more argillaceous in local area.
	Medium grained sandstone	3.40	392.05	Dark gray, thick bedded, locally intercalated with thin sandy mudstone, mainly composed of quartz feldspar.
	Sandy mudstone	2.45	394.50	Gray black, medium thick bedded, complete core, containing plant fossils, and 0.2m mudstone at the bottom.
	Mudstone	1.71	396.21	Black gray, thin layer, containing mica.
	No. 3 coal seam	6.08	402.29	Black, uniform structure, metallic luster, hard coal quality, complete coal core, coal contains a thin layer of gangue.
	Mudstone	2.28	404.57	Black gray, thin layer, containing mica.
	Sandy mudstone	7.51	412.08	Gray black, medium thick bedded, containing plant fossils, high sandpaper content in some parts, and complete core.
	Medium grained sandstone	1.95	414.03	Dark gray, high hardness, locally intercalated with thin sandy mudstone.
	No. 5 coal seam	0.5	414.53	light gray, thick bedded, mainly composed of quartz and feldspar,with argillaceous angular grains in some parts.
	Sandy mudstone	6.2	420.73	Black, metallic luster, thin layer of gangue in coal seam.
	Fine grained sandstone	3.7	424.43	Gray, medium thick bedded, with small cross bedding.

Figure 3. Comprehensive geological column.

Physical and mechanical properties of surrounding rocks in the stope were explored to solve B, h, and d. Therefore, coal-rock masses were taken on-site in the W2302 working face and processed to prepare samples for physical and mechanical experiments. Figure 4 and Table 1 show the experimental process and results, respectively.



Figure 4. Experimental process.

 Table 1. Experimental results.

Stratum	Lithology	CS/MPa	TS/MPa	M/GPa	Р	C/MPa	F/(°)
Main roof	Medium-grained sandstone	46.70	6.81	31.40	0.23	7.78	34.26
Immediate roof	Sandy mudstone	16.64	2.73	18.90	0.18	2.78	27.62
Immediate roof	Mudstone	10.33	1.47	18.60	0.25	2.34	25.31
Coal 3#	Coal	6.21	0.57	9.77	0.31	2.12	22.44
Immediate floor	Mudstone	10.89	1.42	17.56	0.24	2.26	24.22
Basic floor	Sandy mudstone	11.89	1.59	21.58	0.22	2.46	23.58
Underlying strata	Medium-grained sandstone	50.36	2.86	31.67	0.21	9.74	38.12
Underlying strata	Sandy mudstone	24.51	1.73	29.48	0.17	2.57	27.69

Note: CS: compressive strength; TS: tensile strength; M: modulus of elasticity; P: Poisson's ratio; C: cohesion; F: friction.

According to the laboratory test results, the immediate roof and floor mudstone and sandy mudstone of the working face have low compressive strength. According to the rock classification standard of the coal industry, the immediate roof belongs to the unstable rock stratum. Basic roof medium-grained sandstone and the basic floor medium- grained sandstone underlying rock layers have high hardness and belong to the rock layer with good stability. The strength of sandy mudstone in the basic floor underlying rock- layers is higher than that of the basic floor, which belongs to a medium stable rock layer. It is easy to control the stability of surrounding rocks after excavating the roadway in the sandy mudstone and medium-grained sandstone of the basic floor underlying rock layer.

3. Size Optimization of Coal Pillars and Horizon Layout of the Roadway Group

3.1. Force Analysis of Section Coal Pillars

The vertical stress distribution of the floor strata under the coal pillars on the return air side of the working face is important to the location of floor rock roadways. Therefore, it is necessary to analyze the vertical stress transfer law of the floor strata. The floor rock roadways are arranged in the floor strata with small vertical stress. Coal pillars are more impacted by the spatiotemporal effect of the latest mining of the W2302 working face than the W2303 working face. Support pressures of coal pillars are asymmetrically distributed. Moreover, the coal pillar width should be greater than the sum of the peak ranges of lateral support pressures after mining the two working faces. The section size of the floor stone drift is smaller than the coal pillar width. Therefore, its influence on the coal pillar can be ignored. The above conditions are used to establish a mechanical model combined with mining science and multi-directional mechanics [22,24–26] (see Figure 5).



Figure 5. Physico-mechanical model.

The distribution of the lateral support pressures above the coal pillar in the W2302 working face can be described by two curves, $f_1(\varepsilon)$ and $f_2(\varepsilon)$ are vertical stress above the coal pillar within and without the lateral support pressure peak, respectively.

Vertical stress above the coal pillar within the lateral support pressure peak is in a limited equilibrium state. $f_1(\varepsilon)$ is calculated by Equation (1).

$$f_1(\varepsilon) = \left(\frac{C_0}{\tan\varphi} + \frac{p_i}{\lambda}\right) e^{\frac{2\tan\varphi}{m\lambda}(\varepsilon + \frac{B}{2})} - \frac{C_0}{\tan\varphi}, \varepsilon \in \left[-\frac{B}{2}, x_1 - \frac{B}{2}\right]$$
(1)

where C_0 is the cohesion of the coal–seam interface, MPa; φ is the internal friction angle of the coal–seam interface; p_i is the bolt support strength, MPa; λ is the lateral pressure coefficient of coal pillar internal stress ($\lambda = \mu/(1-\mu)$); *m* is the roadway height (m); *B* is the coal pillar width, m; and x_1 is the peak range of lateral support pressure by the W2302 working face, m.

Vertical stress above the coal pillar beyond the lateral support pressure peak accords with Weibull distribution, which can be expressed as:

$$w(x) = w e \frac{x}{x_w} e^{-\frac{x}{x_w}}$$
(2)

The relevant parameters of Equation (1) are substituted in Equation (2) to obtain:

$$f_2(\varepsilon) = k_1 \gamma H \frac{\varepsilon + x_f + \frac{B}{2} - x_1}{x_f} e^{1 - (\frac{\varepsilon + x_f + \frac{B}{2} - x_1}{x_f})}, \varepsilon \in \left[x_1 - \frac{B}{2}, \frac{B}{2}\right]$$
(3)

where γ is the bulk density, kN/m³; *H* is the buried depth of roadways m; *k*₁ is the mining influence coefficient of the W2302 working face; and *x*_f is the parameter for adjusting the urgency degree of the function.

In Equation (3), $f_2(\varepsilon)$ is a unimodal function. When $\varepsilon = x_1 - \frac{B}{2}$, $f_2(\varepsilon) = k_1\gamma H$. Larger k_1 leads to a greater stress peak. Therefore, the stress peak can be adjusted by changing k_1 to reflect the influence of working face stoping on the support pressure peak above the coal pillar. There is an inflection point after the peak of $f_2(\varepsilon)$. When $\varepsilon \rightarrow \frac{B}{2}$, $f_2(\frac{B}{2}) \approx 0$. Therefore, the urgency degree of $f_2(\varepsilon)$ is adjusted by increasing or decreasing x_f in the process of $f_2(\varepsilon) \rightarrow 0$ when $\varepsilon \rightarrow \frac{B}{2}$.

According to the above analysis, the influence of W2302 working face stoping on stress above the coal pillar is expressed as:

$$F(\varepsilon) = f_1(\varepsilon) + f_2(\varepsilon) = \begin{cases} \left(\frac{C_0}{\tan\varphi} + \frac{p_i}{\lambda}\right) e^{\frac{2\tan\varphi}{m\lambda}(\varepsilon + \frac{B}{2})} - \frac{C_0}{\tan\varphi}, \varepsilon \in \left[-\frac{B}{2}, x_1 - \frac{B}{2}\right] \\ k_1\gamma H \frac{\varepsilon + x_f + \frac{B}{2} - x_f}{x_f} e^{1 - \left(\frac{\varepsilon + x_f + \frac{B}{2} - x_1}{x_f}\right)}, \varepsilon \in \left[x_1 - \frac{B}{2}, \frac{B}{2}\right] \end{cases}$$
(4)

Similarly, the influence of W2303 working face stoping on stress above the coal pillar is expressed as:

$$G(\varepsilon) = g_1(\varepsilon) + g_2(\varepsilon) = \begin{cases} k_2 \gamma H \frac{x_g - \varepsilon + \frac{B}{2} - x_2}{x_g} e^{1 - (\frac{x_g - \varepsilon + \frac{B}{2} - x_2}{x_g})}, \varepsilon \in \left[-\frac{B}{2}, \frac{B}{2} - x_2\right] \\ \left(\frac{C_0}{\tan \varphi} + \frac{p_i}{\lambda}\right) e^{\frac{2\tan \varphi}{m\lambda}(-\varepsilon + \frac{B}{2})} - \frac{C_0}{\tan \varphi}, \varepsilon \in \left[\frac{B}{2} - x_2, \frac{B}{2}\right] \end{cases}$$
(5)

where k_2 is the mining influence coefficient of the W2303 working face; x_g is the parameter for adjusting the urgency degree of the function; and x_2 is the peak range of lateral support pressure by the W2303 working face, m.

$$x_{1} = \frac{m\lambda}{2\tan\varphi}\ln\left(\frac{k_{1}\gamma H + \frac{C_{0}}{\tan\varphi}}{\frac{C_{0}}{\tan\varphi} + \frac{p_{i}}{\lambda}}\right); x_{2} = \frac{m\lambda}{2\tan\varphi}\ln\left(\frac{k_{2}\gamma H + \frac{C_{0}}{\tan\varphi}}{\frac{C_{0}}{\tan\varphi} + \frac{p_{i}}{\lambda}}\right)$$

 $F_1(\varepsilon)$ and $F_2(\varepsilon)$ are combined to obtain the stress distribution above the coal pillar.

$$q(\varepsilon) = \begin{cases} \left(\frac{C_0}{\tan\varphi} + \frac{p_i}{\lambda}\right) e^{\frac{2\tan\varphi}{m\lambda}(\varepsilon + \frac{B}{2})} - \frac{C_0}{\tan\varphi} + k_2\gamma Hte^{1-t}, \varepsilon \in \left[-\frac{B}{2}, x_1 - \frac{B}{2}\right) \\ k_1\gamma Hse^{1-s} + k_2\gamma Hte^{1-t}, \varepsilon \in \left[x_1 - \frac{B}{2}, \frac{B}{2} - x_2\right) \\ \left(\frac{C_0}{\tan\varphi} + \frac{p_i}{\lambda}\right) e^{\frac{2\tan\varphi}{m\lambda}(-\varepsilon + \frac{B}{2})} - \frac{C_0}{\tan\varphi} + k_1\gamma Hse^{1-s}, \varepsilon \in \left[\frac{B}{2} - x_2, \frac{B}{2}\right) \end{cases}$$
(6)

where $s = \frac{\varepsilon + x_f + B/2 - x_1}{x_f}$; $t = \frac{-\varepsilon + x_g + B/2 - x_2}{x_g}$.

When the coal pillar width is large, there must be an original rock stress area in the coal pillar. The external stress of the limit equilibrium area is greater than the original rock stress in the coal pillar. After calculation:

$$k_1 s e^{1-s} + k_2 t e^{1-t} \ge 1 \tag{7}$$

Equation (7) is a transcendental inequality. It is difficult to obtain the critical width of the coal pillar where there is no original rock stress area by the analytical method. Therefore, the graphical method is used to solve the problem combined with elastic mechanics. There is an original rock stress area, correspondingly, k_1 and k_2 are the on-site measured values.

3.2. Measured Influence Coefficient of Mining Activities

 k_1 and k_2 in Equation (7) are lateral pressure concentration factors, which need to be obtained through field measurement. The borehole stress meter was selected to measure pressure distribution in the W2301 working face and the coal pillar of the return air side. YHY60 mining intrinsically safe pressure gauge and PZY-60 expansion pressure converter are used for drilling stress gauges. Figure 6 shows the intrinsically safe pressure gauge and pressure converter. Forty-two expansion pressure converters were installed in the coal pillar at the air return side of the W2301 working face. Thirty-seven borehole stress meters were installed in the coal pillar and thirty-two were installed in the coal pillar whit depths of 2, 3, 4, and 17 and a width of 35 m between roadways I_3 and V_1 of the W2301 working face. Moreover, 5 borehole stress meters were installed in the coal pillar with depths of 3, 5, 9, 12, and 15 m and a width of 20 m between roadways V_1 and V_2 . Five borehole stress gauges with depths of 3, 5, 9, 12, and 15 m were installed in the solid coal slope of W2301 working face. Figure 7 shows the specific installation. The monitoring station was arranged about 150 m away from the working face, which was monitored for 2 months. The drilling stress data were monitored once in the morning and evening shifts each, during the advancement of the working face. Combined with the daily report of the advancement of the working face, Figure 8 presents the changed internal stress of the coal body and coal pillar in front of the working face with the advancement of the working face.



Figure 6. Physical drawing of a borehole stress gauge.



Figure 7. Stress monitoring location of the borehole.



(**b**)

Figure 8. Lines of measured borehole stress. (a) Lines of advance support pressure. (b) Lines of lateral support pressure.

The support pressure increment on the working face side first increases and then decreases with the decreased distance from the working face. The influence range of advance support pressure is about 100 m; the peak value of support stress increment is about 15 m in front of the coal wall of the working face; the maximum stress increment is about 16 MPa. The internal stress in the coal pillar increases first and then decreases in roadway I₃ of the W2301 working face with the decreased distance from the working face. The peak value of the supporting stress increment is about 12 m away from the side of roadway I₃, and the maximum stress increment is about 12 MPa. However, the pressure increment in the coal pillar between the two air return roadways changes slightly, and the pressure increment is generally within 2 MPa.

3.3. Location of Intake Airway

According to the geological conditions and relevant test results in Sihe Mine, buried depth of roadway H = 400 m; stratum density $\rho = 2500$ kg/m³; roadway height m = 3.8 m; bolt support strength $p_i = 0.1$ MPa; lateral pressure coefficient = 1; coal–seam interface cohesion $C_0 = 0.26$ MPa; internal friction angle = 19°, and relevant parameters $x_f = 4$ and $x_g = 4$, combined with the change law of the internal stress of the coal pillar, lateral support pressure increasing coefficient $k_2 = 2.5$ in W2302 working face stoping, the other side is mainly affected by roadway excavation ($k_2 = 1.5$). According to Equation (7),

$$M(\varepsilon) = k_1 s e^{1-s} + k_2 t e^{1-t} - 1$$

The above relevant parameters are substituted in Equation (7). The mathematical software MathCAD was used to draw the relationship between ε and *B* (see Figure 7). The horizontal axis represents the distance from the centerline of the coal pillar; the vertical axis represents the coal pillar width. When $M(\varepsilon) > 0$, there is no original rock stress area in the coal pillar. Figure 9 shows that the critical width of the coal pillar without the original rock stress area is 57.2 m after W2302 working face stoping.



Figure 9. Stress-change nephogram.

MathCAD was used to calculate the vertical, horizontal, and shear stress concentration factors of the floor strata under different coal pillar widths (see Figures 10–12).



Figure 10. Vertical stress concentration factor at 10 and 15 m below the pillaring of the W2302 working face. (**a**) 10 m below the coal pillar. (**b**) 15 m below the coal pillar.



Figure 11. Horizontal stress concentration factor at 10 and 15 m below the pillaring of the W2302 working face. (a) 10 m below the coal pillar. (b) 15 m below the coal pillar.



Figure 12. Shear stress concentration factor at 10 and 15 m below the pillaring of the W2302 working face. (a) 10 m below the coal pillar. (b) 15 m below the coal pillar.

When the coal pillar width ranges from 40 to 55 m, the vertical stress changes greatly at 10–15 m below the coal pillar, with small changes in horizontal and shear stress. Therefore, vertical stress is the most important for the location of the floor rock roadways. The vertical stress concentration factor tends to be equal under different coal pillar widths, about 1 at 10 m below the coal pillar and 12 m from the centerline of the coal pillar. Stress concentration coefficient curves to the left of the point are quite different under different coal pillar widths. When the coal pillar width is small, the stress concentration factor increases rapidly. When the coal pillar width is large, the stress concentration factor increases slowly. Stress curves to the right of this point under different coal pillar widths decrease rapidly, with few differences. The vertical stress concentration factor tends to be equal at different

coal pillar widths, about 0.8 at 15 m below the coal pillar and 15 m from the centerline of the coal pillar. The stress concentration coefficient curves to the left of the point are quite different under different coal pillar widths. When the coal pillar width is small, the stress concentration factor increases rapidly. When the coal pillar width is large, the stress concentration factor increases slowly. Stress curves to the right of this point under different coal pillar widths decrease rapidly, with few differences.

From top to bottom, there are 9.8 m sandy mudstone, 2 m medium-grained sandstone, 0.5 m coal seam, and 4.2 m sandy mudstone according to the floor stratum thickness and lithology of coal seam 3# in the comprehensive histogram. The coal seam thickness < 0.3 m in the drilling process near the W2302 working face can be ignored. According to the test results of the mechanical properties of rock, 9.8 m sandy mudstone has a small strength (11.89 MPa); and 2 m medium-grained sandstone has a large strength (50.86 MPa). Medium-grained sandstone is suitable as the roof or both sides of floor rock roadways. Meanwhile, the vertical distance between the floor rock roadway and coal seam is considered to be reduced. Therefore, medium-grained sandstone was used for both sides of the floor rock roadway. Then, the vertical distance between the floor rock roadway and coal seam is 9.8 m.

The floor rock roadway is arranged in the floor area where the vertical-stress concentration factor is less than 1 to avoid the influence of working face stoping on the floor rock roadway, which ensures the stability of the floor rock roadway. According to the stress distribution of floor strata under different coal pillar widths after W2302 working face stoping, the floor rock roadway is not affected by mining of the W2302 working face. Table 2 shows the horizontal distances between the floor rock roadway and roadway 4 under different coal pillar widths.

Table 2. Technical plan.

Coal pillar width/m	40	45	50	55
Distance from roadway 4/m	8	10	13	15

4. Stone Drift Location and Simulation Analysis

4.1. Construction of the Numerical Model

Section 3 determines the distance between the return air roadway and the centerline of the coal pillar, the horizon of the roadway, four coal pillar sizes, and roadway layout schemes. Deformations of roadways' surrounding rocks and stress changes in coal pillars were accurately graphed under different coal pillar widths and roadway layouts to study the optimal coal pillar size and reasonable layouts of roadway groups. In this section, the FLAC^{3D} 6.0 finite difference numerical simulation software was used to simulate the actual engineering geological conditions of the W2302 working face in Sihe Coal Mine.

The Rhino modeling software was used to build the model where the grids are divided by Griddle. The model constrained the surrounding and bottom displacements. The stress of 11.2 MPa was set above the model to simulate the bulk density of the overlying rocks. Then, a DXF file was exported after setting the ratio of coal pillars and roadways (1:1), and the supports of bolts and anchor cables adopted Rhino. Before the calculation, The DXF file was imported to the model, where the parameters were assigned to the anchor bolt and cable. The working faces on two sides with a width of 100 m were not completely established in the model. The length and height of the model were 600 and 57.5 m, respectively; the width varied with the coal pillar. Figure 13 and Table 1 show the numerical simulation model and modeling parameters, respectively.



Figure 13. Numerical simulation model.

4.2. Simulated Results and Analysis

The main simulation content is divided into two parts. The first is stress changes in the coal pillar after the stoping of two sides of the working face under different coal pillar widths (see Table 2); the second is the displacement changes in the intake airway under different roadway layouts. Figure 14 shows stress accumulation in the coal pillar after two sides of the working face are excavated.



Figure 14. Floor stress changes under different coal pillar widths.

Stress accumulation in the coal pillar presents a single peak curve with a coal pillar width of 40 m, the peak stress of 34.62 MPa, and a stress concentration factor of 3.09. When the coal pillar width increased to 45 m, peak stress decreased. Stress presents a distribution of a single peak on the left of the coal pillar with the maximum peak stress of 29.74 MPa and a concentration factor of 2.66. Peak stress decreased with the increased coal pillar

width. When the coal pillar width increased to 50 and 55 m, vertical stress distribution was saddle-shaped with peak stress on the right of the coal pillar centerline. Stress in the surrounding rocks of V₂ was decreased to keep peak stress of coal pillars away from V₂, which maintained the stability of V₂ in the stoping process. Therefore, the 40 and 45 m coal pillars were more appropriate. Five schemes were set to simulate the deformation of roadways surrounding rock under different roadway layouts. The intake airways were arranged in the coal seam, and the coal pillars with widths of 35 and 20 m were on two sides of the roadway. The roadways Were arranged in medium-grained sandstone at 9.8 m below the coal seam in the last four schemes. In scheme *b*, the coal pillar width was 40 m; the horizontal distance *d* from V₂ was 8 m. In scheme c, the coal pillar width was 45 m; d = 10 m. In scheme d, the coal pillar width was 50 m; d = 13 m. In scheme e, the coal pillar width was 55 m; d = 15 m. After the W2302 working face stoping under different numerical simulation schemes, the deformations of V₂ and V₁ had a large difference. Figure 15 indicates the deformation nephogram and statistics of surrounding rocks.



Figure 15. Histogram of roadway deformations under different schemes.

When the stoping of two working faces was simulated, the roadways surrounding rocks were weak in the coal seams based on the original roadway layout scheme. The maximum roof subsidence was 683 mm; the maximum floor bulge was 165 mm; the maximum convergence of the left side was 467 mm; the maximum convergence of the right side was 452 mm. The coal pillar with a width of 40 m had a high-stress concentration in the surrounding area. Therefore, the roadway deformation was larger than the original scheme. The maximum convergence between roof and floor was 1067 mm; the maximum convergence between two sides was 952 mm. When the coal pillar width increased to 45 m, the maximum convergence between roof and floor was 846 mm and that between two sides was 870 mm due to a weak coal seam on two sides. The roadway deformation gradually weakened with the increased coal pillar width. Table 3 shows the statistics of roadway deformations under different schemes.

Deformation Scheme	Original Scheme	40 m	45 m	50 m	55 m
Roof subsidence/mm	683	816	687	657	599
Floor bulge/mm	165	251	159	147	131
Left side deformation/mm	467	513	468	450	432
Right side deformation/mm	452	439	402	389	369
Convergence between roof and floor/mm	848	1067	846	804	730
Convergence between two sides/mm	909	952	870	839	801

Table 3. Simulated deformations under different coal pillar widths.

Table 3 and Figure 14 show that the roadway is arranged in the coal seam in the original scheme. Serious surrounding rock deformation and large coal pillar width cause resource a waste. The roadway has a certain deformation under small coal pillar widths after the optimization of coal pillars and roadway layouts. The roadway deformation is improved with the increased coal pillar width. When the coal pillar width is 40 m, the roadway deformation is most serious due to the influence of strong mining. The maximum deformation is larger than that of the original scheme. When the coal pillar width rises from 45 to 55 m, the deformation of the roadway's surrounding rocks gradually decreases in a small amplitude. However, for every 5 m increase in the coal pillar width, there is great resource. Therefore, the coal pillar width is determined to be 45 m based on the above analysis of surrounding rock stress and roadway deformation. Roadway V_1 roadway is arranged in the floor rock stratum after the optimization of coal pillar sizes. After the mining of the two working faces, the roof and floor displacement of roadway V_1 is slightly reduced, and the approach of the two sides is reduced by 4%. However, compared with the original scheme, the coal pillar size is reduced by 10 m, and the recovery rate of coal resources is greatly improved.

5. Actual Measurement Analysis of Roadway Deformation

The coal pillar at the return air side of the W2302 working face in Sihe coal mine was optimized to verify the reliability of the research results and the feasibility of the roadway layout scheme. The width of the coal pillar was set to 45 m, and the roadway V_2 was arranged in the coal seam floor. When the W2302 working face was arranged, roadways I_1 and I_2 were the air return roadways of the W2301 working face. Rock roadway V_1 was excavated first, after excavation, and drill holes in the roadway were drilled to drain the gases in the coal seam, which ensure the safe excavation of roadways I_3 and V_2 . After W2302 working face was mined completed, the area with large deformations of roadways V1 and V2 was repaired, and used as roadways I_1 and I_2 of W2303 working face. As the deformation of roadways V1 and V2 were relatively slight during the mining process of the W2302 working face, deformation monitoring was not carried out. Surrounding rock deformation of roadway I2 (the roadway V2 of W2302 working face) of the W2303 working face was monitored during the mining of the W2303 working face. According to Section 3, the affected area of advanced stress is 100 m; the accumulation area is about 40 m. Therefore, the first and second stations are 40 and 100 m away from the working face, respectively. Figure 2 shows the roadway deformation and specific monitoring results.

In Figure 16, the first and second stations are 40 and 100 m away from the working face, with 26 and 66 observation days, respectively. The monitoring results show that the overall deformation of roadways' surrounding rocks is not large (about 50 mm) at 40–100 m from the front of the working face. When the distance between the measuring point and the working face is less than 40 m, the roadway is greatly affected by advanced stress, which causes severe deformations. The maximum convergence between two sides is 185 mm; the maximum deformation rate is 6.8 mm/d; the maximum convergence between roof and floor is 594 mm; and the maximum deformation rate is 27.5 mm/d. Surrounding rocks of the roadway (intake airway) with certain deformations are available during the service

period. The field application results show that the theoretical analysis and numerical simulation results in the work are accurate and reliable, which verifies the feasibility of the proposed coal pillar optimization and roadway horizon layout scheme. The optimized coal pillar can meet the requirements of ventilation, pedestrian, material transportation, and other aspects of roadway surrounding rocks in the service period, which provides a useful reference for similar projects.



Figure 16. Deformation monitoring lines of the surrounding rocks of the roadway.

6. Conclusions

Based on the engineering geological conditions of the W2302 working face in Sihe Coal Mine, the coal pillar size on the return air side was optimized by theoretical analysis, numerical simulation, field test, and actual measurement. The following conclusions were obtained after discussing the reasonable horizon arrangement of roadway groups.

- (1) An original rock stress area in the coal pillar with a width larger than 57.2 m after working face stoping. When the coal pillar width ranged from 40 to 55 m, the vertical stress changed greatly at 10–15 m below the coal pillar, with small changes in horizontal stress. The vertical stress concentration factors tended to be consistent at 10 m below the coal pillars and about 12 m from the centerline of coal pillars under different coal pillar widths. The area with a stress concentration factor of about 1 was suitable for the arrangement of floor rock roadways on the return-air side;
- (2) Peak stress of coal pillars was kept away from V_2 to maintain stability in working face stoping. The coal pillar widths of 40 and 45 m were more appropriate by simulating the stress distributions of the floor under different coal pillar widths. The optimal coal pillar width was 45 m by simulating the deformations of roadways' surrounding rocks under different coal pillar widths;
- (3) Based on specific strata distribution, there were medium-grained sandstone, thin coal 5#, and sandy mudstone at 9.8 m below coal 3#. Medium-grained sandstone was suitable for the roof of arched roadways. Coal 5# and sandy mudstone existed on the two sides. Coal 5# with small thickness had little effect on the stability of the surrounding rock of the roadway. The floor was comprised of sandy mudstone. V1 was arranged at 9.8 m below the coal seam and 12 m from the centerline of the coal pillar, which optimized the sizes of the coal pillar. The on-site measurement proved the stability of V1 in the service period, which provides a reference for similar projects.

Author Contributions: Conceptualization, Q.M. and Y.Z. (Yidong Zhang); methodology, Z.L.; software, Z.L. and Y.Z. (Yu Zheng); validation, G.S. and L.G.; formal analysis, Q.M.; writing—original draft preparation, Q.M.; writing—review and editing, Y.Z. (Yidong Zhang) and Q.M.; project administration, Y.Z. (Yu Zheng). All authors have read and agreed to the published version of the manuscript.

Funding: The work was funded by the Key Project of Joint Funds of the National Natural Science Foundation of China (Grant No. U1903209); the National Natural Science Foundation of China (Grant No. 52174111).

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Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank the engineering technicians in Shaping Coal Mine for their enthusiastic assistance and suggestions.

Conflicts of Interest: The authors declare no conflict of interest.

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