Research Article

Research on the Redistribution Law of Lateral Mining Stress and the Bearing Characteristics of Section Coal Pillar in Extra-Thick Fully Mechanized Top-Coal Caving Mining

Qingwei Bu (1,2), Min Tu (1), and Baojie Fu (1)

1 Key Laboratory of Safety and High-Efficiency Coal Mining of Ministry of Education, Anhui University of Science and Technology, Huainan 232001, China
2 School of Mining and Coal, Inner Mongolia University of Science and Technology, Baotou 014010, China

Correspondence should be addressed to Min Tu; mtu@aust.edu.cn

Received 12 July 2021; Accepted 11 August 2021; Published 2 September 2021

Academic Editor: Gan Feng

Copyright © 2021 Qingwei Bu et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Due to the change of ground stress environment caused by underground coal mining, the intense lateral mining stress concentration is formed around the stope; so section coal pillar is generally set up to bear the mining pressure, but the different sizes of coal pillars have obvious influence on the bearing capacity of those pillars and the characteristics of mining pressure. Mastering the mechanism characteristics by which coal pillars bearing capacity and mining stress distribution is crucial to identify the reasonable coal pillar size and give full play to the bearing role of section coal pillar, given their importance for the safety and bearing stability of engineering rock mass in underground coal mining. Therefore, the bearing characteristics of section coal pillar and the redistribution of mining stress are achieved with a mechanical model analysis on the basis of the analysis of coal pillar bearing and mining influence characteristics. Moreover, applying the elastic-plastic mechanics theory revealed the mechanical equations of the effective bearing size of coal pillar and redistribution of mining stress in longwall face. Combined with the analysis of a specific engineering example, the research results are as follows. During a roadway excavation, the continuous mining stress transfer occurs "stress redistribution" and the mechanical failure of bearing coal pillar consists of lateral mining and roadway side failures. The bearing coal pillar has two critical dimensions (i.e., the critical dimension \( W_c \) of the self-bearing stability coal pillar and the critical dimension \( W_{p} \) of failure through the coal pillar). The mechanical state of the lateral mining stress redistribution and bearing coal pillar is divided into the three situations: (1) when the width of coal pillar \( W < W_{p} \), only one stress concentration area exists, the bearing capacity of the coal pillar is invalid at this stage, and the lateral mining stress concentration transfers to the roadway solid coal side; (2) when the width of the coal pillar \( W_c \geq W \geq W_{p} \) two stress concentration areas appear at this stage, and the coal pillar is in the critical state of self-bearing stability; (3) when the width of the coal pillar \( W > W_{p} \), three stress concentration areas are present, and the coal pillar at this stage is in a self-bearing stable state. Among all these factors, only the size of coal pillar is completely controllable, so the aspects of safe bearing and reserved size design of coal pillar, after estimating the critical size of coal pillar, the coal pillar size design is carried out according to the mine pressure control needs of mining engineering, and the cohesion, internal friction angle, interlayer friction coefficient, and coal seam mining height are improved by artificial technology, so as to realize the resource safe and efficient mining of all kinds of coal seam mining conditions; in the calculation of wide coal pillar size, the advance mining stress concentration at the end of the self-working face should be taken as the mining load condition, and the reserved size meets the condition of \( W > W_{c} \), thereby ensuring the stable bearing of the wide coal pillar despite the advanced mining stress concentration during the self-working face mining; in the calculation of narrow coal pillar size, the lateral mining stress concentration before mining should be taken as the mining load condition and the reserved size meets the condition \( W < W_{p} \), thereby realizing the effective transfer of mining stress concentration to the roadway solid coal side.
1. Introduction

For the mining conditions of thick and extra-thick coal seam, the longwall fully mechanized top-coal caving mining method of retaining section coal pillar is widely used in underground coal mines, which has the advantages of high efficiency and low cost. However, the continuous distribution characteristics of mining stress are changed by the mining face and its roadway layout, and the different sizes of coal pillars lead to different mining stress redistribution, which has a serious impact on the bearing stability of the coal pillars and solid coal. For example, the wide coal pillar layout can bear intense mining stress concentration so as to improve the mining influence at the end of working face, but the wider the coal pillar, the more serious the waste of resources; the narrow coal pillar layout can avoid instability induced scour through mining stress transfer, and its advantages involve improving the recovery rate, separating the gangue in goaf, and preventing water damage and air leakage, but the narrower the coal pillar is, the more unfavorable it is to the support stability of mining roadway. For different coal seam mining conditions, there are obvious differences in the size index of coal pillar and the mining influence characteristics formed by coal pillar, and how to reveal the mechanical mechanism of this scientific problem is particularly important for the safe and efficient coal mining.

For a long time, the safety and efficiency problem of coal mining has been of great concern, domestic and foreign researchers have paid special attention to the bearing stability of coal pillar and mining influence in thick coal longwall working face, and many representative research results have been obtained [1–18]. Some scholars used numerical simulation and geodesic radar to analyze the mining failure of the lateral coal and rock mass and proposed the reasonable and optimized roadway layout with a coal pillar [6]. Other scholars have analyzed the mining stress distribution of fully mechanized top-coal caving working face [7, 8]. Some scholars divided the force failure of the coal and rock mass into the elastic, plastic, and failure areas and provided the corresponding depth calculation formulas [9, 10]. In addition, many academics have taken the rectangular roadway as their research object and obtained the stress distribution equation and failure depth equation of the roadway side [11–14]. Some scholars used the limit equilibrium method to analyze the bearing characteristics of the coal pillar in the fully mechanized working face [15, 16]. Using X-ray diffraction and in situ measurement, other researchers have revealed the main factors affecting mining [17].

Nowadays, many research results reveal the mechanical characteristics of mining stress distribution, coal pillar failure, and mining roadway failure. However, certain mining dynamic problems in the long wall working face with coal pillar still need further study, such as the mechanical influence of coal pillar on the lateral mining stress redistribution, the bearing mechanical state of coal pillar with different size, and the main factors’ influence characteristics. Therefore, the lateral mining stress redistribution and section coal pillar bearing is conducted with a mechanical model analysis by using the elastic-plastic mechanics theory, which provides a mechanical calculation method and theoretical reference basis for the analysis of the mining pressure appearance and the coal pillar size.

2. Engineering Analysis of Mining Bearing Stability in the Fully Mechanized Top-Coal Caving Mining of Extra-Thick Coal Seam

The Tangjiahui Coal Mine chiefly excavates the 6# coal seam (belonging to extra-thick coal seam). The occurrence conditions of the main coal seams are listed in Table 1.

Currently, the 61101 and 61103 working faces have been mined, thereby isolating the 61102 working face between them. The plane layout is shown in Figure 1.

Compared with the nonisolated island face, the pressure appearance at the lateral edge caused by the isolated island face mining is particularly severe, and the mining roadway of the isolated island face is affected by the lateral mining of the previous working face and by the strong advance mining in the mining process of the isolated island face [18]. In addition, the mining level belongs to full height mining of extra-thick coal seam. The mining bearing load of the coal and rock mass is also relatively serious, thereby making the safety mining of the 61102 island face more prominent. Thus, mastering the mining pressure of the isolated island face and reasonably reserve section coal pillar is vital.

The field investigation analysis revealed that the lateral mining stress distribution and coal pillar bearing characteristics are as follows:

1. Due to the roadway excavation, the continuous mining stress transfer encounters "redistribution."

2. Given the different coal pillar sizes, the "redistribution" characteristics of lateral mining stress vary, and obvious differences occur in the mining pressure appearance.

3. From the aspect of coal pillar failure evolution, the mechanical failure of the bearing coal pillar consists of lateral mining and roadway side failures, both of which show "opposite deepening and closing." If failure contact occurs, then the coal pillar will lose self-bearing stability.

4. The mining failure on two sides of the coal pillar does not have contact with each other. Thus, the coal pillar has self-stable bearing capacity and the lateral mining stress concentration will not transfer to the deep part of the solid coal. Conversely, the mining failure contact will lead to the instability of its own bearing and cause the lateral mining stress concentration to transfer to the deep part of the solid coal.

3. Mechanical Model Analysis of the Lateral Mining Stress Redistribution and Section Coal Pillar Bearing

3.1. Mechanical Model Construction of the Lateral Mining Stress Redistribution and Section Coal Pillar Bearing

Combined with the above analysis, the three situations of lateral mining stress redistribution are summarized. When
the coal pillar size is too wide, the stress concentration of the roadway coal pillar side is far away from the lateral mining stress concentration (Figure 2(a)). With the decrease of the wide coal pillar size, the stress concentration of the roadway coal pillar side is close to the lateral mining stress concentration, even if the two overlap (Figure 2(b)). When the coal pillar side is close to the lateral mining stress concentration (Figure 2(c)). With the decrease of the roadway coal pillar side is far away from the lateral mining stress concentration (Figure 2(d)). When the coal pillar side is too narrow, the coal pillar is broken through and loses its self-stable bearing capacity, thereby causing the lateral mining stress concentration to transfer to the roadway solid coal side (Figure 2(c)).

Accordingly, the mechanical model of the lateral mining stress redistribution and section pillar bearing caused by the roadway layout with the coal pillar is established. To facilitate the model solution and conform to the actual project situation, the mechanical model is simplified and the following basic assumptions are made:

(1) The coal and rock mass is considered an ideal elastic-plastic medium, and the stress failure meets the Mohr–Coulomb strength criterion.

(2) The stress concentration in the coal and rock mass is located in the boundary of the elastic zone and the failure zone.

(3) The stress redistribution of the roadway surrounding rock occurs under the mining stress environment.

(4) According to the relevant literature [19–21], the roadway excavation is a “small-scale project” compared with the work face mining, so the mining stress state is unaffected by roadway excavation.

(5) After the roadway excavation, the stress load of the roadway roof is shared equally on the surrounding rock of roadway two sides.

(6) According to the continuity of the medium, a “stress equilibrium point” exists in the coal pillar, the distance from the point to the goaf boundary is $V$, and the distance from the point to the roadway boundary is $W - V$ ($W$ is the section coal pillar size). The stress equilibrium point also meets the following requirements: $\sigma_{MX}|_{x=V} = \sigma_{LX}|_{x=W-V}$ and $\sigma_{MZ}|_{x=V} = \sigma_{LZ}|_{x=W-V}$.

(7) Given a wide coal pillar, the roadway surrounding the rock failure and the mining failure of the roadway coal pillar side have not been connected, and the coal pillar is regarded to have self-stable bearing capacity and can bear the mining load in itself area. Given a narrow coal pillar, the surrounding rock failure and mining failure have been connected, and the coal pillar is considered to bear only limited mining load, while the main mining load is transferred to the roadway solid coal side.

3.2. Mechanics Solution of the Lateral Mining Stress Redistribution and Section Pillar Bearing Capacity. According to the literature [11–14, 18–21], the section coal pillar bearing and the lateral mining stress redistribution are mechanically analyzed by using the elastic-plastic mechanics theory and limit equilibrium method. As shown in Figure 3, the stress analysis takes the boundary of the lateral coal and rock mass as the coordinate origin $O$, the horizontal direction is the $X$-axis, and the vertical direction is the $Z$-axis.

In their corresponding failure zone, the coal and rock mass are mainly affected by the vertical stress $\sigma_{Mz}$ (transmitted from the overlying strata), horizontal stress $\sigma_{Mx}$ and shear stress $\tau_M$ (generated by the dislocation of the upper and lower boundaries). Thus, the force balance equation of the micro unit body is established:

$$-m(\sigma_{Mx} + \beta \sigma_{Mz}) + m \sigma_{Mx} + 2\tau_M dx = 0,$$

where $m$ is the coal thickness.

Combined with Hypothesis (1), the force state of the coal rock mass medium meets the limit equilibrium condition, i.e., $\sigma_c = K_p \sigma_p + \sigma_s$, where $\sigma_c$ is the uniaxial compressive strength of coal and rock mass, $\sigma_p = (2C \cos \phi / 1 - \sin \phi)$; $K_p = (1 + \sin \phi / 1 - \sin \phi)$; $C$ is the cohesion; $\phi$ is the internal friction angle.

In the failure zone, the shear stress is caused by the displacement of upper and lower boundaries, i.e.,

$$\tau_M = f \sigma_{Mz},$$

where $f$ is the friction coefficient of the upper and lower interface.

A horizontal resistance $P_{Mi}$ occurs at the boundary of the goaf side (i.e., $x = 0$), $\sigma_{Mx}|_{x=0} = P_{Mi}$. Then, the lateral mining stress distribution equation in the failure zone is as follows:

$$\sigma_{Mx} = \left( P_{Mi} + \frac{\sigma_s}{K_p} \right) e^{\beta x} - \frac{\sigma_s}{K_p},$$

$$\sigma_{Mz} = K_p \left( P_{Mi} + \frac{\sigma_s}{K_p} \right) e^{\beta x},$$

where $\beta = 2K_p f/m$.

Combined with Hypothesis (2), the peak value of lateral mining stress is taken as $KP$ in the deep boundary of the failure zone (i.e., $x = x_M$), that is, $\sigma_{Mx}|_{x=x_M} = KP$, where $P$ is the original rock stress, MPa, and $K$ is the lateral mining stress concentration coefficient.

By substituting the above formula into equation (3), the lateral mining failure equation is obtained as follows:

$$x_M = \frac{1}{\beta p_M} \ln \left[ \frac{KP}{K_p p_M + \sigma_s} \right].$$
Figure 1: Schematic diagram of the 61102 isolated island face layout and rock occurrence structure.

Figure 2: Continued.
In the deep boundary of the lateral mining failure zone (i.e., \( x = x_M \)), boundary conditions arise: 
\[ \sigma_{Mx}^{p} \bigg|_{x = x_M} = \sigma_{Mx}^{p} \bigg|_{x = x_M} = \sigma_{Mx}^{p} \bigg|_{x = x_M}. \]

Then, the lateral mining stress distribution equation in the elastic zone of the coal and rock mass is constructed as follows:

\[
\begin{align*}
\sigma_{Mx}^{p} &= P + \left( \frac{KP - \sigma_c}{K_p} \right) \frac{x_M^2}{x^2}, \\
\sigma_{Mz}^{p} &= P + (KP - P) \frac{x_M^2}{x^2},
\end{align*}
\]

where \( P_M \) is the undetermined coefficient, before the roadway layout with coal pillar, \( P_M = P \).

To arrange roadways with the coal pillar, the lateral mining stress transfer of coal and rock mass is no longer continuous after the excavation of the roadway. Moreover, the roof load transfers to the roadway two sides. The lateral mining stress environment presents a nonuniform stress field (the vertical stress is higher than the horizontal stress), so the stress concentration at the roadway side can be calculated by the K. B. Pytlíček equation. According to Hypothesis (5), the corresponding mining stress environment at the two sides of the outer circle roadway (its center position is \( W + a \)) is taken, respectively, i.e., \( x = W \) and \( x = W + 2a \). The surrounding rock stress concentration formula at the roadway two sides is derived from the K. B. Pytlíček Equation [19–21], i.e.,

\[
\begin{align*}
\sigma_{Lx}^{p} \bigg|_{x = x_L} &= 3\sigma_{M0x}^{p} \bigg|_{x = W} - \sigma_{M0z}^{p} \bigg|_{x = W} + \sigma_{R2x}^{p} \bigg|_{x = x_L} = 3\sigma_{M0x}^{p} \bigg|_{x = W + 2a} - \sigma_{M0z}^{p} \bigg|_{x = W + 2a},
\end{align*}
\]

where \( x_L \) is the deep boundary of failure zone of the roadway coal pillar side; \( x_T \) is the deep boundary of the failure zone of the roadway solid coal side; \( \sigma_{M0x}^{p} \) and \( \sigma_{M0z}^{p} \) are, before the roadway is excavated with coal pillar, the lateral mining horizontal stress and vertical stress of the coal and rock mass in the elastic area, which can be solved by equation (5); \( 2a \) is the roadway outer circle size, \( 2a = \sqrt{(2b)^2 + h^2} \); the width of the rectangular roadway is \( 2l \), and the height is \( h \).

According to the mechanical model analysis of the coal and rock mass presented above, the equations of stress distribution and failure depth are similarly solved at the coal pillar side and roadway solid coal side. Taking the boundary of the roadway coal pillar side as the coordinate origin \( O \), the horizontal direction from the boundary to the deep part of the coal pillar is the \( X \)-axis, and the vertical direction is the \( Z \)-axis. A horizontal support resistance \( P_L \) occurs at the boundary of the roadway coal pillar side, i.e., \( \sigma_{Lx}^{p} \bigg|_{x = 0} = P_L \).

The stress distribution equation of the surrounding rock in the failure zone of the roadway coal pillar side is as follows:

\[
\begin{align*}
\sigma_{Lx}^{p} &= \left( P_L + \sigma_cK_p \right) e^{\beta_L x} - \sigma_cK_p, \\
\sigma_{Lz}^{p} &= \left( P_L + \sigma_cK_p \right) e^{\beta_L x},
\end{align*}
\]

where \( \beta_L = 2K_p f/h \);

\[
x_L = \frac{\ln \left( \left( 3\sigma_{M0x}^{p} \bigg|_{x = W} - \sigma_{M0z}^{p} \bigg|_{x = W} \right)/\left( K_p + \sigma_c \right) \right)}{\beta_L}.
\]

In the deep boundary of the failure zone of the roadway coal pillar side, boundary conditions exist: \( \sigma_{Lx}^{p} \bigg|_{x = x_T} = \sigma_{Lx}^{p} \bigg|_{x = x_T} \) and \( \sigma_{Lz}^{p} \bigg|_{x = x_T} = \sigma_{Lz}^{p} \bigg|_{x = x_T} \). Then, the stress distribution equation of the surrounding rock in the elastic zone of the roadway coal pillar side is as follows:
\[
\begin{align*}
\sigma_{\text{Lx}}^e &= P_L \left[ \frac{\left(3\sigma_{M0x}^{\epsilon}|_{x=W} - \sigma_{M0x}^{\epsilon}|_{x=-W} \right) - \sigma_e}{K_p} \right] \frac{x_2^2}{x^2} \quad (x_L \leq x), \\
\sigma_{\text{Lz}}^e &= P_L \left[ \frac{\left(3\sigma_{M0z}^{\epsilon}|_{x=W} - \sigma_{M0z}^{\epsilon}|_{x=-W} \right) - \sigma_e}{K_p} \right] \frac{x_2^2}{x^2},
\end{align*}
\]
(8)

where \( P_L \) is the undetermined coefficient.

Taking the boundary of the roadway solid coal side as the coordinate origin \( O \), the horizontal direction from the boundary to the interior of the solid coal is the \( X \)-axis, and the vertical direction is the \( Z \)-axis. A horizontal support resistance \( P_R \) exists at the boundary of the roadway solid coal side, i.e., \( \sigma_{\text{Rx}}^e|_{x=0} = P_R \). Similarly, the stress distribution equation of the surrounding rock in the failure zone of the roadway solid coal side is as follows:

\[
\begin{align*}
\sigma_{\text{Rx}}^e &= P_R + \left[ \frac{\left(3\sigma_{M0x}^{\epsilon}|_{x=W} - \sigma_{M0x}^{\epsilon}|_{x=-W} \right) - \sigma_e}{K_p} \right] \frac{x_2^2}{x^2} \quad (x_R \leq x), \\
\sigma_{\text{Rz}}^e &= P_R + \left[ \frac{\left(3\sigma_{M0z}^{\epsilon}|_{x=W} - \sigma_{M0z}^{\epsilon}|_{x=-W} \right) - \sigma_e}{K_p} \right] \frac{x_2^2}{x^2},
\end{align*}
\]
(11)

where \( P_R \) is the in the deep boundary of the failure zone of the roadway solid coal side, \( P_R = P \).

When the coal pillar size is wide enough, the surrounding rock failure of the roadway coal pillar side is not connected with the mining failure. According to Hypothesis (7), the “stress balance point” is located in the elastic zone of the coal and rock mass, i.e., \( \sigma_{Mx}^{\epsilon}|_{x=W} = \sigma_{Mx}^{\epsilon}|_{x=-W} \).

Combining equations (6) and (8) generates

\[
P_M \left( 1 - \frac{x_2^2}{V^2} \right) - P_L \left( 1 - \frac{x_1^2}{(W - V)^2} \right) = \sigma_{Lx}^e|_{x=x_L} \frac{x_2^2}{(W - V)^2} - K \sigma_{Mx}^{2M} \frac{x_2^2}{V^2} \quad (x_M \sim W + a)
\]
(12)

According to Hypothesis (7), the wide coal pillar has self-stable bearing capacity and can bear the mining load in the range \((0 - W + a)\), including half the span load of the excavation roadway. Hypothesis (4) indicates that the mining stress state in the lateral mining failure area is unaffected by roadway excavation. Therefore, only the bearing range

\[
\Delta F_M = \Delta F_L,
\]
(14)

where \( \Delta F_M = \int_{x_M}^{W} (\sigma_{Mx}^{\epsilon} - P) \, dx \)

\[
\Delta F_L = \int_{x_M}^{W} (\sigma_{Lx}^{\epsilon} - P) \, dx + \left( \int_{0}^{x_2} \sigma_{Lx}^{\epsilon} \, dx + \int_{x_1}^{W-V} \sigma_{Lx}^{\epsilon} \, dx \right) - \int_{0}^{W-V} P \, dx.
\]
(15)

The results are as follows:
\[
\frac{(V - x_M)^2}{V} P_M + \frac{(W - V - x_L)^2}{W - V} P_L = \left(\frac{W + a - x_M}{W + a}\right)^2 P + \left[\frac{(W + a - x_M)x_M}{W + a} - \frac{(V - x_M)x_M}{V}\right] K_P \\
- \left[\frac{\sigma_L^c|_{x=x_L}}{\beta_L} - \left(K_P P_L + \sigma_c\right)\right] + \frac{\sigma_L^c|_{x=x_L}}{W - V} \left(W - V - x_L\right) x_L
\]

Equation (16) is combined with equation (12), and the result is as follows:

\[
\begin{align*}
PM & = \frac{(IE + JB)}{(AE + DB)} \\
PL & = \frac{(JA - ID)}{(AE + DB)}
\end{align*}
\]  

(17)

\[
\sigma_L^c|_{x=x_L} = 3\sigma_M^c|_{x=(W+l-a)} - \sigma_M^c|_{x=(W+l-a)}
\]

\[
J = \frac{(W + a - x_M)^2}{W + a} P + \left[\frac{(W + a - x_M)x_M}{W + a} - \frac{(V - x_M)x_M}{V}\right] K_P \\
- \left[\frac{\sigma_L^c|_{x=x_L}}{\beta_L} - \left(K_P P_L + \sigma_c\right)\right] + \frac{\sigma_L^c|_{x=x_L}}{W - V} \left(W - V - x_L\right) x_L
\]

\[
I = \sigma_L^c|_{x=x_L} \frac{x_L^2}{(W - V)^2} - K_P x_M^2 \frac{V^2}{V^2}
\]

\[
A = 1 - \frac{x_M^2}{V^2}
\]

\[
B = 1 - \frac{x_L^2}{(W - V)^2}
\]

\[
D = \frac{(V - x_M)^2}{V}
\]

\[
E = \frac{(W - V - x_L)^2}{W - V}
\]

(18)

Substituting the solved \(P_M\) and \(P_L\) into equations (5) and (8) obtains the stress distribution in the elastic zone of the wide coal pillar. Conversely, the stress distribution of the roadway solid coal side is obtained by equations (9) and (11).

When the “stress equilibrium point” comes close to the mining failure boundary, the coal pillar enters the critical state of self-bearing stability, so \(V = x_M\) is substituted into equation (13) as follows:

\[
\left[\left(K_P - 1\right)\left(3\sigma_M^c|_{x=(W+l-a)} - \sigma_M^c|_{x=(W+l-a)}\right) + \sigma_c\right] x_L^2 = (W - x_M)^2 \left[(K_P - 1) K_P + \sigma_c\right].
\]

(19)

Combining equations (5), (8), and (19) reveals the calculation equation for the critical size of the self-stable coal pillar \(W_e\), i.e.,
\[
(K_p - 1) \left[ 2P + \left( 2P + 3KP - \frac{KP - \sigma_c}{K_p} \right) \left( \frac{\ln [KP/(K_p + \sigma_c)]/\beta_M}{W_c + l - a} \right)^2 \right] + \sigma_c \\
= \left[ (K_p - 1)KP + \sigma_c \right] \left( \frac{W_c}{\ln [KP/(K_p + \sigma_c)]/\beta_M} - 1 \right)^2.
\]

Equation (20) is a complex fourth-order polynomial, and the critical size \(W_c\) of the self-stable coal pillar can be obtained by an interpolating solution. To sum up, \(x_M, x_L, \) and \(x_R\) can be identified through equations (4), (6), and (9); \(V\) can be obtained from equation (11); \(P_M\) and \(P_L\) can be obtained from equation (17), and the lateral mining stress redistribution with a wide coal pillar (the failures on two sides of the coal pillar are unconnected) is obtained from equation (3), (5), (6), (8), (9), and (11).

In addition, if the narrow coal pillar is reserved for the roadway layout, that is, if the failure of the roadway coal pillar side is connected with the lateral mining failure, the force state of the coal pillar consists of the lateral mining stress in the failure area of the goaf side and the surrounding rock stress in the failure area of the roadway side. At this time, the intersection point of the two vertical stresses is the stress balance point under the condition that the failure of the roadway coal pillar side is connected with the mining failure. At the stress equilibrium point of failure through the coal pillar, \(\sigma_{M0}\vert_{x=V} = \sigma_{L0}\vert_{x=V}, \) \(\sigma_{M0}\vert_{x=V} = \sigma_{L0}\vert_{x=W-V}. \) The solution of the latter conditional simultaneous equations (3) and (6) is as follows:

\[
F_W = \frac{K_p}{\beta_M} \left( P_M + \frac{\sigma_c}{K_p} \right) (e^{\delta_0V} - 1) + \frac{K_p}{\beta_M} \left( P_M + \frac{\sigma_c}{K_p} \right) (e^{\delta_0(W-V)} - 1).
\]

The roadway layout with the coal pillar belongs to the internal medium excavation of the coal rock bearing body and does not affect the mechanical state of the outer and deep boundaries. So, the integral equation of the force balance is

\[
\Delta F_M = \Delta F_R,
\]

where

\[
\Delta F_M = \int_0^{x_M} \sigma_{M0z} \, dx + \int_{x_M}^{\infty} \sigma_{M0z} \, dx - \int_0^{\infty} P \, dx;
\]

\[
\Delta F_R = \int_0^{x_R} \sigma_{R0z} \, dx + \int_{x_R}^{\infty} \sigma_{R0z} \, dx + F_W - \int_{-(W+2a)}^{0} P \, dx - \int_0^{\infty} P \, dx.
\]

\[
\left( \frac{1}{\beta_M} + x_M \right) KP - \frac{KP}{\beta_M} (P_M - P_{Ri}) + P(W + 2a - 2x_M) - F_M = \left( \frac{1}{\beta_M} + x_M \right) K_p \left( P_{Ri} + \frac{\sigma_c}{K_p} \right) e^{\delta_0x_M}.
\]
According to the above analysis, the characteristics of the lateral mining stress redistribution and coal pillar bearing caused by different sizes of the coal pillar are obtained. When the width of coal pillar $W > W_p$, three stress concentration areas are present, and the coal pillar is in self-bearing stable state at this stage. When the width of the coal pillar $W < W_p$, only one stress concentration area is present, and the bearing capacity of the coal pillar is invalid at this stage. Moreover, the lateral mining stress concentration transfers to the roadway solid coal side. When the width of coal pillar $W_c \geq W \geq W_p$, two stress concentration areas occur at this stage, and the coal pillar is in the critical state of self-bearing stability. Considering the advance mining influence in the mining process of the self-working face, when the wide coal pillar is reserved and to ensure that the advanced mining stress at two ends of working face is controlled in the bearing coal pillar, the mining stress concentration at the end of the working face is substituted into equation (20), and the coal pillar size meets $W > W_c$. When the narrow coal pillar is reserved, the mining stress concentration before mining is effectively transferred to the roadway solid coal side, so the lateral mining stress concentration before self-working face mining is substituted into equation (21). Furthermore, the coal pillar size meets $W < W_p$, but the roadway coal pillar side entered the failure yield stage too early or the coal pillar is too narrow. Those features will increase the difficulty and cost of roadway support.

4. Analysis on the Influence Factors of the Lateral Mining Stress Redistribution and Section Coal Pillar Bearing

Taking the 61102 isolated island face with fully mechanized top-caving as the engineering background, the initial conditions are set: $m = 18.3$ m; $P = 14$ MPa (burial depth 520 m, rock weight $27000$ N/m$^3$); $P_{Mi} = 0$ MPa; $K = 2.0$; $2a = 6.85$ m (i.e., the external circle size of the roadway, transportation roadway size of the 61102 isolated island face is $2l = 5.7$ m and $h = 3.8$ m); $C = 1.3$ MPa; $\varphi = 28^\circ$; and $f = 0.53$. The characteristics of the lateral mining stress redistribution and section coal pillar bearing are calculated and analyzed for the wide ($W = 50$ m) and narrow ($W = 5$ m) coal pillars. The results are shown in Figures 4–10.

As shown in Figure 4, for setting the wide coal pillar, the smaller the wide coal pillar size, the stronger the superposition effect of the lateral mining stress and surrounding rock stress of roadway coal pillar side, and the greater the bearing stress accumulation in the coal pillar. Moreover, the main effect of mining stress on the roadway failure is gradually protruding. On the contrary, the wider the coal pillar size is, the weaker the superposition effect of the lateral mining stress and surrounding rock stress of the roadway coal pillar side, and the closer the failure degree of the roadway surrounding rock is to the original rock stress condition influence characteristics. For setting the narrow coal pillar, the narrow coal pillar has been broken through, a situation which results in the transfer of the mining stress to the solid coal roadway side and the surrounding rock failure of the roadway solid coal side being covered by the mining failure. At this time, the smaller the narrow coal pillar size is, the lower the bearing capacity of the coal pillar. Furthermore, too narrow coal pillar is not conducive to support stability, but the influence of the lateral mining stress on the size of the broken-through narrow coal pillar is not obvious.

As shown in Figures 5–7, the larger the original rock pressure (i.e., the depth of coal seam), the mining stress concentration degree, and the mining height are, the more obvious the mining pressure is and the stronger the superposition effect of the lateral mining stress and surrounding rock stress of roadway coal pillar side, thereby leading to a more serious bearing force and failure degree of the coal pillar. The more severe the mining pressure appearance is, the larger the reserved safe size should be for the wide coal pillar. By contrast, the narrow coal pillar can more effectively transfer the lateral mining stress to the deep part of the solid coal for the condition of strong mining pressure behavior or thick coal mining. Although the narrow coal pillar can effectively realize the mining stress transfer to prevent the induced scour disaster, controlling the stability of the coal pillar support is difficult. By contrast, the wide coal pillar needs to set a wider safety size to bear the strong mining stress concentration and ensure the safety of mining.

As shown in Figures 8–10, the better the bearing condition of coal rock (i.e., the greater the interface friction coefficient, cohesion, and internal friction angle of the coal rock), the faster the lateral mining stress convergence rate, and the smaller the lateral mining failure degree and the superposition effect of the lateral mining stress and surrounding rock stress of the roadway coal pillar side, a condition which is more beneficial to the bearing stability of the coal pillar and roadway surrounding rock. Therefore, engineering technical measures (such as strong active support, grouting, and reinforcement of the coal and rock mass) are adopted to improve the mechanical properties of the coal and rock media, thereby achieving a significant gain effect on the mining bearing stability of the section coal pillar and roadway surrounding rock.

It is further concluded that from the mining stress redistribution characteristics of coal pillar in the failure area, the cohesion, internal friction angle, interlayer friction coefficient, and mining height of coal seam are the key indicators to determine the bearing capacity of coal pillar, while the buried depth of coal seam, mining stress concentration coefficient, and coal pillar size have no influence on them, but these factors mainly determine the mechanical environment of mining stress distribution, the bearing state of lateral coal pillar and solid coal; the key factor for determining the critical size of the broken-through narrow coal pillar ($W_p$) is cohesion, internal friction angle, interlayer friction coefficient, and mining height, but for the determination of the critical size of wide coal pillar with bearing function ($W_c$), it is necessary to further consider the buried depth of coal seam and mining stress concentration coefficient.

In addition, it should be noted that on the influence of lateral mining stress redistribution of coal pillar, the buried depth of coal seam and mining stress concentration
Figure 4: Lateral mining stress redistribution and section coal pillar bearing with different coal pillar sizes ($W$). (a) Wide coal pillar setup. (b) Narrow coal pillar setup.

Figure 5: Lateral mining stress redistribution and section coal pillar bearing with original rock stress of different coal seam depths ($H$). (a) Wide coal pillar setup. (b) Narrow coal pillar setup.

Figure 6: Lateral mining stress redistribution and section coal pillar bearing with different stress concentration coefficients of lateral mining ($K$). (a) Wide coal pillar setup. (b) Narrow coal pillar setup.
Figure 7: Lateral mining stress redistribution and section coal pillar bearing with different mining heights (m). (a) Wide coal pillar setup. (b) Narrow coal pillar setup.

Figure 8: Lateral mining stress redistribution and section coal pillar bearing with different interface friction coefficients of the coal and rock mass ($f$). (a) Wide coal pillar setup. (b) Narrow coal pillar setup.

Figure 9: Lateral mining stress redistribution and section coal pillar bearing with different cohesions of the coal and rock mass ($C$). (a) Wide coal pillar setup. (b) Narrow coal pillar setup.
coefficient are uncontrollable geological condition factors, while the cohesion of coal body, internal friction angle, interlayer friction coefficient, and mining height of coal seam are also factors of geological conditions, but they can be adjusted to a certain extent through artificial technology and engineering design. Only the size of coal pillar is completely controllable, so the aspects of safe bearing and reserved size design of coal pillar, after estimating the critical size of coal pillar, the coal pillar size design is carried out according to the mining pressure control needs, and the cohesion, internal friction angle, interlayer friction coefficient, and coal seam mining height are improved by artificial technology, so as to realize the resource safe and efficient mining of all kinds of coal seam mining conditions.

5. Analysis of the Bearing Stability of the Section Coal Pillar in the 61102 Isolated Island Face in Extra-Thick Fully Mechanized Top-Coal Caving Mining

5.1. Theoretical Calculation of the Bearing Coal Pillar Size. Regarding the problem of coal pillar setting in the 61102 isolated island face of fully mechanized top-coal caving in the Tangjiahui Coal Mine and according to the mining influence analysis of the said island face, the lateral mining stress concentration before the isolated island working mining is $KP = 40$ MPa, the deep stress environment is $P = 14$ MPa, the stress concentration in the mining process of the isolated island face is $KP = 62$ MPa, and the advance mining stress environment in the middle part of the working face is generally $P = 48$ MPa.

With the 61102 isolated island face as the engineering background, the above parameters are substituted into the corresponding equation in Section 2.2. Thus, under the stress environment before the mining of the isolated island face, the critical size of the coal pillar with self-bearing stability is $W_c = 20$ m, and the critical size of the coal pillar breaking through is $W_p = 16$ m. Under the advance mining stress environment at the end of the isolated island face, the critical size of the coal pillar with self-bearing stability is $W_c = 22$ m, and the critical size of the coal pillar breaking through is $W_p = 21$ m. As the advanced mining influence of isolated island face is particularly strong, the narrow coal pillar of failure through is not conducive to the bearing stability of the working face overlying strata and the support stability of the mining roadway. However, setting wide coal pillar can control the intense mining stress in the coal pillar itself, thereby avoiding serious mining pressure appearance of the isolated island face. Therefore, the 25 m wide coal pillar should be reserved for the 61102 isolated island face mining of extra-thick coal pillar, so as to ensure the self-bearing stability of the coal pillar in each mining influence stage.

5.2. Numerical Simulation Analysis on the Bearing Coal Pillar Stability. FLAC3D simulation modeling (1 186 m ($X$) × 12 m ($Y$) × 504 m ($Z$), 52 6118 zones), as shown in Figure 11, indicates that the original rock stress is 14 MPa (burial depth 520 m, rock weight 27000 N/m$^3$), the lateral stress coefficient is 1.0, gravity acceleration is 9.8 m/s$^2$, and the width of the 61102 isolated island face is 235 m. Moreover, the widths of the 61103 and 61101 goafs on its two sides are 220 m and 240 m, respectively. The Mohr–Coulomb model is adopted, and according to the rock mechanics test of geological drilling coring in Tangjiahui Coal Mine, the mechanical parameters of coal and rock are obtained, as shown in Table 2. The lateral and bottom boundaries are set by displacement, and the top boundary is set as the vertical stress loading. First, the compaction of the 61103 and 61101 goafs is simulated (mining step distance 18 m), according to references [22–24], the double-yield model is employed to simulate goaf compaction, and the medium parameters of the goaf are shown in Table 3. The stress-strain relationship is indicated in Table 4. After balancing, the 25 m coal pillar is set and the 61102 transport roadway (5.7 m × 3.8 m) is excavated. The mining of the 61102 isolated island face after...
balance is simulated (mining step distance of 12 m). The simulation results on the coal pillar bearing and the mining stress redistribution are depicted in Figures 12 and 13.

Under the lateral mining influence before isolated island face mining (Figure 12(a)), the failure depth of the roadway solid coal side is approximately 3 m, and that of the roadway coal pillar side is nearly 4 m and is still 7 m away from the lateral mining failure, and the lateral mining and surrounding rock stress concentrations of the roadway coal pillar side are clearly shown in the bearing coal pillar. At this time, the coal pillar has stable bearing capacity and low safety risk. During the advance mining influence of the isolated island face (Figure 12(b)), the failure depth of roadway solid coal side increases to 5 m, and that of the roadway coal pillar side increases to 6 m. Although the top and bottom of the coal pillar have failure contact, a 5 m wide undamaged zone still appears in the coal pillar itself. Moreover, the lateral mining stress concentration overlaps close with the stress concentration of the roadway coal pillar side, thereby forming a high stress elastic energy accumulation which is similar to the “mining stress concentration core structure” in the coal pillar. Furthermore, the self-bearing of the coal pillar is stable at this time.

In the process of island face mining, the advanced mining aggravates the lateral mining stress concentration. The numerical simulation shows that the mining stress concentration of the advanced mining part of the section coal pillar increases from 46 MPa to 72 MPa. The lateral mining of the roadway coal pillar and the stress concentration of the surrounding rock are closely overlapped. The strong influence of the advanced mining leads to the relatively close failure of the roadway coal pillar and the lateral goaf. At this time, the strong elastic stress can accumulate, leading to a relatively high safety risk of coal pillar bearing stability. In general, the current section coal pillar bearing state is still safe and stable. The numerical

### Table 2: Mechanical parameters of the coal and rock.

<table>
<thead>
<tr>
<th>Medium name</th>
<th>Shear modulus (GPa)</th>
<th>Bulk modulus (GPa)</th>
<th>Cohesion (MPa)</th>
<th>Friction angle (°)</th>
<th>Tensile strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium fine sandstone</td>
<td>1.62</td>
<td>1.71</td>
<td>2.6</td>
<td>35</td>
<td>0.62</td>
</tr>
<tr>
<td>Bedrock</td>
<td>1.04</td>
<td>1.14</td>
<td>3.3</td>
<td>33</td>
<td>0.82</td>
</tr>
<tr>
<td>Sandy mudstone</td>
<td>0.91</td>
<td>0.86</td>
<td>3.3</td>
<td>37.5</td>
<td>2.25</td>
</tr>
<tr>
<td>Coal seam</td>
<td>0.67</td>
<td>0.50</td>
<td>1.3</td>
<td>28</td>
<td>0.54</td>
</tr>
<tr>
<td>Fine sandstone</td>
<td>1.04</td>
<td>1.14</td>
<td>3.3</td>
<td>33</td>
<td>0.82</td>
</tr>
<tr>
<td>Coarse sandstone</td>
<td>1.54</td>
<td>1.68</td>
<td>3.3</td>
<td>35</td>
<td>0.40</td>
</tr>
<tr>
<td>Mudstone</td>
<td>2.04</td>
<td>2.15</td>
<td>1.6</td>
<td>37.4</td>
<td>0.41</td>
</tr>
</tbody>
</table>

### Table 3: Mechanical parameters of the goaf medium of the double-yield model.

<table>
<thead>
<tr>
<th>Goaf medium</th>
<th>Shear modulus (GPa)</th>
<th>Bulk modulus (GPa)</th>
<th>Friction angle (°)</th>
<th>Dilatancy angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7.78</td>
<td>5.83</td>
<td>12</td>
<td>8</td>
</tr>
</tbody>
</table>

### Table 4: Stress-strain relationship of the goaf medium of the double-yield model.

<table>
<thead>
<tr>
<th>Strain</th>
<th>Stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>0.003</td>
</tr>
<tr>
<td>0.04</td>
<td>0.015</td>
</tr>
<tr>
<td>0.07</td>
<td>0.028</td>
</tr>
<tr>
<td>0.1</td>
<td>0.042</td>
</tr>
<tr>
<td>0.13</td>
<td>0.059</td>
</tr>
<tr>
<td>0.16</td>
<td>0.079</td>
</tr>
<tr>
<td>0.19</td>
<td>0.103</td>
</tr>
<tr>
<td>0.22</td>
<td>0.131</td>
</tr>
<tr>
<td>0.25</td>
<td>0.166</td>
</tr>
<tr>
<td>0.28</td>
<td>0.210</td>
</tr>
<tr>
<td>0.31</td>
<td>0.267</td>
</tr>
<tr>
<td>0.34</td>
<td>0.343</td>
</tr>
<tr>
<td>0.37</td>
<td>0.452</td>
</tr>
<tr>
<td>0.40</td>
<td>0.620</td>
</tr>
<tr>
<td>0.43</td>
<td>0.910</td>
</tr>
<tr>
<td>0.46</td>
<td>1.533</td>
</tr>
<tr>
<td>0.49</td>
<td>3.842</td>
</tr>
<tr>
<td>0.50</td>
<td>7.122</td>
</tr>
</tbody>
</table>
Simulation results show that the 25 m wide coal pillar calculated by the mechanical theory can meet the safe bearing requirements of mining pressure of 61102 island working face.

5.3. Industrial Practice Analysis on the Bearing Coal Pillar Stability. In the Tangjiahui Coal Mine, the 25 m width bearing coal pillar is reserved for the 61102 isolated island face safe mining, and analysis of the roadway deformation monitoring and hydraulic support pressure monitoring was carried out. Through the evaluation of the roadway deformation and hydraulic support pressure, the stability effect of the bearing coal pillar was evaluated indirectly. As shown in Figure 13, the roadway deformation monitoring was performed on the roof and floor of the 61102 transport roadway and its two sides (the initial distance is 100 m from the coal wall of the isolated island face, and data were collected once every 3–4 m of the coal wall). The hydraulic support pressure near the end of the isolated island face was also monitored (the pressure monitoring sensor was used to record real-time, and the pressure data were automatically generated into the pressure distribution curve).

As shown in Figure 14, the deformation monitoring of the 61102 transport roadway revealed that in the range of 40–86 m away from the coal wall of the isolated island face, the surrounding rock deformation increases with the mining load increase, the displacement of the roof and floor is stable at 100 mm, and the displacement of two sides is stable at 240 mm. In the range of 20–40 m away from the coal wall of the isolated island face, the advance mining stress concentration approaches the measuring point of the roadway and causes the surrounding rock deformation to increase rapidly, the displacement of roof and floor is 400 mm, and the displacement of two sides is 750 mm. Subsequently, the advance support is reinforced promptly to control the roadway stability. As shown in Figure 15, the 22-day pressure monitoring of the hydraulic support near the end of the 61102 isolated island face confirmed that the minimum working resistance is 24 MPa, the maximum working resistance is 42 MPa, the utilization rate of the support working load is 80%, and no serious mining pressure instability and support accidents arose. Therefore, the mining pressure of the isolated island face and the bearing of the end coal pillar are stable. The roadway deformation monitoring and the bearing pressure monitoring of the hydraulic support proved that the 25 m wide section coal pillar is reserved to realize the mining pressure stable bearing and safe production of the 61102 isolated island face.
6. Conclusions

(1) After roadway excavation, continuous mining stress transfer occurs “stress redistribution,” the lateral mining stress redistribution will present 1–3 stress concentration areas, and the mechanical failure of the bearing coal pillar consists of lateral mining and roadway side failures; by using the elastic-plastic mechanics theory, a mechanical model on the lateral mining stress redistribution and section coal pillar bearing was established, and the mechanical equations of the lateral mining stress redistribution and coal pillar critical size were obtained.

(2) Two critical dimensions exist for the bearing coal pillar (i.e., the critical dimension $W_c$ of self-bearing stability coal pillar and the critical dimension $W_p$ of failure through coal pillar). Moreover, the mechanical state of the lateral mining stress redistribution and section coal pillar bearing is divided into the three situations. When the width of the coal pillar $W < W_p$, only one stress concentration area exists, the bearing capacity of the coal pillar is invalid at this stage, and the lateral mining stress concentration transfers to the roadway solid coal side. When the width of the coal pillar $W_c \geq W \geq W_p$, two stress concentration areas exist at this stage, and the coal pillar is in the critical state of self-bearing stability. When the width of the coal pillar $W > W_c$, three stress concentration areas exist, and the coal pillar is in self-bearing stable state at this stage.

(3) The lateral mining stress redistribution and section coal pillar bearing become increasingly serious with the increase of the original rock pressure, mining stress concentration degree, and mining thickness, whereas the situation becomes increasingly favorable with the increase of the coal cohesion, internal friction angle, and rock mass interface friction coefficient; among all these factors, only the size of coal pillar is completely controllable, so the aspects of safe bearing and reserved size design of coal pillar, after estimating the critical size of coal pillar, the coal pillar size design is carried out according to the mine pressure control needs of mining engineering, and the cohesion, internal friction angle, interlayer...
friction coefficient, and coal seam mining height are improved by artificial technology, so as to realize the resource safe and efficient mining of all kinds of coal seam mining conditions.

(4) In the calculation of wide coal pillar size, the advance mining stress concentration at the end of the self-working face should be taken as the mining load condition, and the reserved size meets the condition of $W > W_p$, thereby ensuring the stable bearing of the wide coal pillar despite the advanced mining stress concentration during the self-working face mining; in the calculation of narrow coal pillar size, the lateral mining stress concentration before mining should be taken as the mining load condition and the reserved size meets the condition $W < W_p$, thereby realizing the effective transfer of mining stress concentration to the roadway solid coal side.

**Data Availability**

The known data in this paper come from practical engineering case data, which are reliable and available.

**Conflicts of Interest**

The authors declare that they have no conflicts of interest.

**Acknowledgments**

NSFC project (52074008, 51674007), Inner Mongolia Natural Science Foundation project (2019MS05055), open research fund project of Key Laboratory of Safety and High-Efficiency Coal Mining of Ministry of Education (JYBSYS2019208).

**References**


[12] K. Wen, *Study on deformation of narrow pillar of roadway driving along next goaf of full caving face and its control in deep coal mine*, Xi’an University of Science and Technology, Xi’an, China, 2009.


[22] Z. Zhang, J. Bai, Y. Chen, and S. Yan, “An innovative approach for gob-side entry retaining in highly gassy fully-

[23] X. Wu, Evolutionary Regularity of Plastic Zone and Stability Control in Repetitive Mining Roadway in Shendong Mining Area, China University of Mining and Technology, Beijing, China, 2018.