Research Article

Critical Height of Unfilled Zone in Underlying Gob Piles

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To address problems associated with mining above gob piles in the Chinese midwest mining area, a mechanic model for a coal pillar was established based on the displacement variation method. Additionally, the effect of critical unfilled zone height in the underlying gob (UZHUG) on the coal pillar was investigated through a 3DEC numerical simulation; fieldwork was conducted with a borehole televiewer to measure the UZHUG in the Yuanbaowan Coal Mine. The results indicated that the shear stress value and distribution layout in the coal pillar were affected by the UZHUG. The larger the UZHUG, the greater the shear stress and the wider the distribution scope, moving from two sides to the middle zone. Moreover, the larger the UZHUG, the smaller the maximum bearing capacity of the coal pillar, and subsequently, the greater the horizontal deformation of the coal pillar and roof convergence. The critical UZHUG is 2 m considering coal pillar deformation and stress transfer characteristics. Field measurements have confirmed that the UZHUG of 2 m ensured safe mining in the No. 6 coal seam. However, a second round of filling is needed when achieving a UZHUG of 4.4 m. This study serves as a reference for safe mining above gob piles.

1. Introduction

Several gob piles are produced from room and roadway mining caused by the unreasonable planning of small coal mines and small coalpits in central and western China, and many abandoned coal seams with mining values are still buried above the gob. In recent years, with the merger and transformation of small coal mines and small coalpits, to improve the recovery rate of coal resources and the economic benefits to enterprises, several abandoned and residual coal seams have been remined; this has caused the mining of overlying coal seams in old goaf deposits to gradually become an industry hotspot [1, 2]. The main problem facing these activities is ensuring the stability of coal pillars in the old goaf deposits of the floor that are affected by the mining of the upper coal seam. The methods to address such problems include modelling and calculation of coal pillar bearings [3–5], identifying the mechanical characteristics of coal pillars under long-term bearing action [6–8], and applying function evaluation methods to analyse coal pillar stability [9] and the main factors affecting it

[10, 11]. Many theoretical systems and standards for evaluating coal pillar stability have laid the foundation for subsequent studies of the same under more complex conditions.

Many studies on the mining of coal seams under old goaf deposits have achieved fruitful results; the research topics include the instability process of the overlying coal pillar group on the working face [12, 13], the evaluation of the instability of the coal pillar group system [14–16], the mechanism of pressure frame on the working face [17, 18], and the controls of the dynamic strata pressure [19–21]. This research provides a useful guide for mining coal seams under old goaf deposits. In this context, Huang [22] determined that the key stratum of the coal floor is the key to the stability of the coal floor by analysing the stability of the mining floor above the strip goaf, and they studied the instability mechanism of the key stratum of the coal floor. Feng et al. [23, 24], based on the key stratum theory, proposed the concepts of a superimposed fracture distance for key stratum and advanced mining of coal pillars based on the problems of coal mining above a knife-pillar goaf; moreover, they

formed the theory and methodology for a feasibility determination of coal seam mining above a knife-pillar goaf. To ensure the safe mining of the upper coal seam in old knife-pillar goaf deposits, Wang [25] et al. comprehensively considered the influencing factors of the stability of the rock strata between coal seams and adopted the safety factor method to evaluate this stability. Jiang [26] et al. established a continuous deep beam mechanical model to reveal the failure and instability mechanism of the overburden in roadway goaf, and they proposed a feasible method for mining the upper coal seam in roadway goaf. In combining similar simulation experiments and numerical simulations, some scholars have researched the stress distribution law and the stability of coal pillars in upper coal seam mining in old goafs [27–31].

The abovementioned research on the feasibility of mining an upper coal seam in an old goaf deposit does not involve evaluating the influence of UZHUG on the coal pillar stability in old goaf. The disturbance of coal mining at close distances can easily cause coal pillars in the old goaf of a floor to be unstable, leading to unsafe conditions in mining above gob deposits. Grouting and filling old goaf with ground drilling is an effective method to solve this problem [1]. However, the locations of old goaf deposits are intricate; the roofs of some areas are broken and falling, and the filling process is difficult to optimize. As a result, it is difficult to connect the filling body in some positions of old goaf deposits. Therefore, it is necessary to study the critical height of whether the coal pillar is stable as per the UZHUG.

In this study, a combination of theoretical analysis, numerical simulation, and field measurements is used to establish a mechanical model of coal pillars in old goaf based on the displacement variation method to analyse the shear stress distribution in the coal pillars and to simulate the coals under different UZHUG values. The characteristics of column stress, deformation, and roof subsidence of old goaf are determined to determine the critical height of UZHUG for safe mining, and these results are verified by the actual measurement results of the borehole televiewer. This information will provide a reference to ensure safe mining above gob piles.

2. Overview of Test Working Face

Yuanbaowan Coal Mine is a merged and integrated mine. After its integration, the No. 6 coal seam was first mined. There are several old goafs and old roadways of the No. 9 coal seam under the 6107 working face, as shown in Figure 1. The safety of the floor of the No. 6 coal seam is closely related to the stability of the pillar left in the seam. The instability of this pillar seriously threatens the safety of mining the working face of the upper coal seam.

The width of the 6107 working face is 240 m, the strike length is 500 m, the average mining thickness is 3 m, the inclination angle is 4–8°, and the burial depth is approximately 150 m. There is an old goaf of roadway mining in the No. 9 coal seam at 15–20 m below the 6107 working face. The measured length of the old goaf is 10–50 m, the width is 5–16 m, and the height is 5–8 m; the cumulative length of the

old roadway is approximately 4,300 m, the width is 2.5–5 m, and the height is 2.2–4 m. The width of the coal pillar in the old goaf is 3–24 m, and most of the coal pillars are larger than 8 m in width and 5–8 m in height.

The key stratum position identification results have been obtained based on the borehole column near the 6107 working face, as given in Table 1. The immediate roofs of the No. 6 and No. 9 coal seams are hard rock stratum of 7.8 m and 9.9 m, respectively; these two hard rock layers are both inferior key strata that play a leading role in the mining pressure control of the two coal seams.

3. Stability Analysis of Legacy Coal Pillar on the Floor

3.1. Construction of the Coal Pillar Based on the Floor Bearing Mechanical Model. After the coal on both sides of the floor coal pillar is mined, the coal pillar changes from a triaxial state to a uniaxial state, and its bearing capacity decreases. During the mining of the upper coal seam face, the advanced supporting stress caused by the mining face is transferred to the lower coal pillar through the coal body, as shown in Figure 2. When the advanced supporting stress value exceeds the ultimate bearing strength of the coal pillar, the coal pillar will be damaged and unstable; this will cause the coal pillar group to fail in a large area [12, 13] and negatively impact the safety of mining the working face.

The coal pillar is set as an elastic body before failure and instability, and the inferior key stratum above the coal pillar is considered a rigid body; this can simplify the advanced stress transmitted to the coal pillar as a uniform load. The bottom interface of the coal pillar is fixed, and both sides are free surfaces. The coal pillar width is set as $2a$, the height is set as b , and the coal pillar interval is L . The compression of the coal pillar under the uniform load q is considered η ; the coal pillar can thus be simplified into a rectangular thin plate of elastic mechanics on the plane, and the plane mechanics model of the coal pillar's force is shown in Figure 3. Among them, the uniform load $q = kq_0$, where k is the leading support pressure concentration coefficient and q_0 is the coal pillar overburden load.

3.2. Mechanical Model Analysis. The methodology of the mechanical model is as follows: establish the coordinate system as shown in Figure 3, adopt the elastic mechanics displacement variation method [32], and set the displacement components in the x -axis direction and y -axis direction to be u and v , respectively. Then, the displacement components u and v are calculated via the following equation:

$$\left. \begin{aligned} u &= x(A_1 + A_{2x} + A_{3y} + \cdots) \\ v &= y(B_1 + B_{2x} + B_{3y} + \cdots) \end{aligned} \right\}. \quad (1)$$

where A and B are the undetermined coefficients. Next, take the numbers of A and B in equation (1) to be 1, and the displacement components u and v in the x -axis direction and

FIGURE 1: Positional layout of gob in the No. 9 coal seam and the No. 6107 working face in the No. 6 coal seam.

TABLE 1: Thickness, burial depth, and lithology of the roof and floor.

Stratum number	Thickness (m)	Buried depth (m)	Lithology	Remarks
7	5.8	138.3	Mudstone	
6	2.8	141.1	Sandy mudstone	
5	7.8	148.9	Medium sandstone	KS
4	3.5	152.4	No.6 coal seam	
3	4.0	156.4	Sandy mudstone	
2	9.9	166.3	Fine sandstone	KS
1	8.4	174.7	No. 9 coal seam

FIGURE 2: Coal pillar stress analysis in mining above gob piles.

y -axis direction of the mechanical model are obtained via the following equation:

$$\left. \begin{aligned} u &= A \times \frac{x}{a} \times \frac{y}{b} \times \left(1 - \frac{y}{b}\right) \\ v &= -\eta \frac{y}{b} + B \frac{y}{b} \left(1 - \frac{y}{b}\right) \end{aligned} \right\}. \quad (2)$$

Solve the displacement variational equation of undetermined coefficients A and B in equation (2) as the following equation:

$$\left. \begin{aligned} \frac{\partial U}{\partial A} &= \iint_A f_x u \, dx \, dy + \int_{so} \bar{f}_x u \, ds \\ \frac{\partial U}{\partial B} &= \iint_A f_y v \, dx \, dy + \int_{so} \bar{f}_y v \, ds \end{aligned} \right\}. \quad (3)$$

FIGURE 3: Stress analysis in coal pillar.

In equation (3), because physical strength is not included, $f_x = 0$ and $f_y = 0$. Then, equation (3) can be simplified as the following equation:

$$\left. \begin{aligned} \frac{\partial U}{\partial A} &= 0 \\ \frac{\partial U}{\partial B} &= 0 \end{aligned} \right\}. \quad (4)$$

The relationship between the deformation potential energy U and the displacement component in this model is shown in the following equation:

$$U = \frac{E}{2(1+\mu)} 2 \int_0^a \int_0^b \frac{\mu}{1-2\mu} \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right)^2 + \left(\frac{\partial u}{\partial x} \right)^2 + \left(\frac{\partial v}{\partial y} \right)^2 + \frac{1}{2} \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right)^2 dx dy. \quad (5)$$

In equation (5), E is the modulus of elasticity and μ is Poisson's ratio. Calculate the partial derivative of the displacement component according to equation (2) and integrate it into equation (5); then, substitute the expression of U into equation (4) to obtain two linear equations of A and B , and finally substitute the equations of A and B into equation (2). The displacement component is obtained as the following equation:

$$\left. \begin{aligned} u &= \left(-\frac{15ab\eta\mu}{-5a^2 - 3b^2 + 10a^2\mu + 3b^2\mu} \right) \times \frac{xy}{ab} \times \left(1 - \frac{y}{b} \right) \\ v &= -\eta \frac{y}{b} \end{aligned} \right\}. \quad (6)$$

According to the plane strain problem, the result of solving the corresponding transverse strain ε_x and

longitudinal strain ε_y through equation (6) is shown in the following equation:

$$\left. \begin{aligned} \varepsilon_x &= \frac{15y\eta\mu}{-5a^2 - 3b^2 + 10a^2\mu + 3b^2\mu} \times \left(1 - \frac{y}{b} \right) \\ \varepsilon_y &= -\frac{\eta}{b} \\ \gamma_{xy} &= -\frac{15x(b-2y)\eta\mu}{3b^3(-1+\mu) + 5a^2b(-1+2\mu)} \end{aligned} \right\}. \quad (7)$$

Incorporating equation (7) into geometric and physical equations, the stresses in the x and y directions can be obtained via the following equation:

$$\left. \begin{aligned} \sigma_x &= \frac{E}{(1-2\mu)(1+\mu)} \left[(1-\mu)\varepsilon_x + \mu\varepsilon_y \right] \\ \sigma_y &= \frac{E}{(1-2\mu)(1+\mu)} \left[(1-\mu)\varepsilon_x + \mu\varepsilon_y \right] \\ \tau_{xy} &= \gamma_{xy} \frac{E}{2(1+\mu)} \end{aligned} \right\}. \quad (8)$$

A brief analysis of the amount of subsidence at the top of the coal pillars is made from equations (7) and (8). If $y = b$ at the top of the coal pillar, then the lateral deformation $\varepsilon_x = 0$, and the y -direction stress σ_y can be expressed by the abovementioned uniform load q . Then, the amount of subsidence at the top of the coal pillar can be obtained between the overlying load and the height of the coal pillar. This relationship is shown in the following equation:

$$q = -\frac{E(1-\mu)}{(1-2\mu)(1+\mu)} \times \frac{\eta}{b}. \quad (9)$$

According to equation (9), both E and μ are the constants. Under the condition of a certain overlying load on the coal pillar, the sinking amount of the coal pillar is proportional to the height of the coal pillar. The higher the height of the coal pillar, the greater the pillar's sinking amount. Conversely, the smaller the height of the coal pillar, the smaller the amount of pillar sinking.

To further obtain the relationship between the amount of coal pillar subsidence and the key parameters of coal pillar instability, the values of two principal stresses at any point in the coal pillar can be obtained from equation (7), as shown in the following equation:

$$\frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_y}{2} \right)^2 + \tau_{xy}^2} = \begin{matrix} \sigma_1 \\ \sigma_3 \end{matrix}. \quad (10)$$

The mechanical model constructed by the coal pillar conforms to the Tresca [32] yield criterion to determine whether the coal pillar is damaged or not. The Tresca yield condition is shown in the following equation:

$$f(\sigma) = \frac{\sigma_1 - \sigma_3}{2} - k_1 = 0. \quad (11)$$

In equation (11), k_1 represents the material constant. Under this condition, the coal pillar's failure is compression-shear failure. Therefore, k_1 is the shear strength of the coal pillar. The shear stress at any point in the plane mechanics model can be obtained when combined with equation (10). The expression can be used as the judgment condition for coal pillar failure.

Combined with the actual mine conditions, assign values to the undetermined parameters of the expression and analyse the stability of the coal pillar under specific conditions. After filling, the coal pillars are retransformed into a three-axis stress state, which can simplify the height of the coal pillars in the old goaf to represent the UZHUG; the width of the coal pillars represents the width wherein most of the remaining coal pillars of No. 9 coal seam are generally present. The coal pillar height b is 2 m, 4 m, 6 m, and 8 m, the coal pillar width $2a$ is 8 m, the elastic modulus E is 1 GPa, and Poisson's ratio μ is 0.3. After analysing and calculating using the Matlab software, the shear stress values at any point in the plane of the coal pillar are obtained. The shear stress distribution in the coal pillar under different height conditions is shown in Figure 4.

When the coal pillar width and load are the same, the distribution state and peak area of the shear stress in the coal pillar are related to the height of the coal pillar. The greater the height of the coal pillar, the greater the shear stress values concentrated in the middle of the coal pillar, which poses a greater risk of coal pillar instability and damage; the lower the height of the coal pillar, the lower the shear stress value in the coal pillar, and the concentration tends to be gentle. When the height of the coal pillar is lower than a certain value, the peak value of the shear stress in the coal pillar continues to decrease, gradually shifting from the centre of the coal pillar to both sides, and finally approaches the four corners of the coal pillar. The smaller the shear stress, the more stable the coal pillar.

4. Influence of UZHUG on Coal Pillar Stability

Theoretical analysis shows that there is a hidden danger of failure and instability of the coal pillars in the old goaf of the No. 9 coal seam when mining the 6107 working face. For this reason, the old goaf on the floor must be filled before mining. Owing to the complexity of the old goaf and the severely broken and collapsed parts of the roof area, it is difficult to connect the filling body in some positions of the old goaf, which inevitably affects the safety of the overlying 6107 working face. Therefore, the numerical simulation method is used to study the influence of the UZHUG on the stability of the coal pillars in the working face floor.

4.1. Numerical Simulation Scheme. The methodology of this scheme is as follows: establish a 3DEC three-dimensional numerical model with a size of $300\text{ m} \times 260\text{ m} \times 85\text{ m}$. We used the maximum height and width of the old goaf and the minimum width and the maximum height of the coal pillars

based on the most unsafe site conditions. The height and width of the No. 9 coal seam pillar are both 8 m, and the height and width of the old goaf are 8 m and 16 m, respectively. A uniform load of 2.5 MPa is applied to the top of the model according to the burial depth, the horizontal displacement is restricted around the model, and the vertical displacement is restricted at the bottom using the Mohr Coulomb criterion. Four old goaf deposits are designed with different filling heights, and the numerical simulation scheme is given in Table 2.

To monitor the internal stress state of the coal pillar and the movement of the coal pillar roof in real time, stress and displacement measuring points are set at different positions in the model and on the same plane in each coal pillar. The average stress value is obtained to replace that of the coal pillar to reduce the data error. A measuring point is set on the same plane directly above each coal pillar to ensure that the values from the displacement measuring points are close to that of the coal pillar roof. The layout of the measuring points is shown in Figure 5. After the initial balance of the model, the No. 9 coal seam old goaf is first mined. After the iterative balance is completed, the No. 9 coal seam's old goaf is filled to different heights, and then, the overlying No. 6 coal seam is mined. The deformation, stress, and subsidence of the coal pillars of the old goaf floor under different UZHUG values are analysed based on the increase of the No. 6 coal seam mining area.

4.2. Dynamic Deformation and the Instability Process of Coal Pillars. The remaining coal pillars in the old goaf are numbered 1, 2, 3, and 4 from left to right. During the mining of the No. 6 coal seam, the deformation and instability process of the No. 9 coal seam pillar in the old goaf is shown in Figure 6 (taking plan 2 as an example).

Before the working face enters the old goaf, the floor coal pillar is kept stable. When the working face enters the old goaf, the instantaneous deformation of the coal pillar is exceedingly large. As the working face is mined, the coal pillar's deformation increases, although this rate of increase later slows down. When the working face is not pushed into the underlying coal pillar area, the deformations of the coal pillars are exceedingly small below 0.5 m, and most pillars undergo no deformation; when the working face is pushed into the underlying coal pillar area, the deformation of coal pillars 1, 2, and 3 are suddenly increased by 1.5–2 m. With the continuous mining of the working face, the deformation of coal pillars 1, 2, and 3 gradually increases by 2–2.5 m; later, after completely pushing through the underlying coal pillar area on the working face, the deformation of each coal pillar increases to the maximum. Specifically, the deformations of coal pillars 1, 2, and 3 all exceed 2.5 m, of which the largest deformation occurs in coal pillar 2, reaching 2.89 m, and all coal pillars fail. This shows that with an insufficient filling rate, the coal pillars in the old goaf will be damaged and unstable during the mining process of the upper working face, which will seriously affect the safety of mining in the upper working face.

FIGURE 4: Shear stress distribution in different heights of coal pillars.

TABLE 2: Numerical simulation schemes.

Scheme	Old goaf width (m)	Coal pillar width (m)	Whether to fill	Filling height (m)	UZHUG (m)
1	16	8	No	0	8
2	16	8	Yes	2	6
3	16	8	Yes	4	4
4	16	8	Yes	6	2

FIGURE 5: Layout of the measuring points.

FIGURE 6: Failure process of coal pillars.

4.3. Influence of UZHUG on Coal Pillar Stability. To study the influence of the UZHUG on the stability of the coal pillars, the critical UZHUG of the No. 9 coal goaf was determined, and the coal pillars under the conditions of 8 m, 6 m, 4 m, and 2 m were filled according to the simulation plan. The results are shown in Figure 7 (taking the No. 2 coal pillar as an example).

Figure 7 shows that the UZHUG directly affects the stability of the coal pillar. The greater the UZHUG, the greater the deformation and the deformation area of the coal pillar and the lower the stability. Under the unfilled condition (the UZHUG is 8 m), the maximum deformation of the coal pillar is 3.5 m during mining, and this deformation is 3 m with an UZHUG of 6 m. If UZHUG is 4 m, the deformation is 2.5 m. The coal pillars are all found along the “zero displacement surface” from the upper left corner to the lower right corner; the amount of deformation generated in the opposite direction increases sequentially, and the coal pillars are damaged and unstable. However, if UZHUG is 2 m, the maximum lateral deformation of the coal pillar is only 0.5 m, the deformation of most areas is 0, and the coal pillar can remain stable.

4.4. Change Law of Coal Pillar Disturbance Stress. To verify the correctness of the above results, it is necessary to understand the law of stress transfer before and after the deformation and instability of the coal pillar during working face mining under different filling heights. Multiple measuring points are set in the same horizontal plane of each coal pillar to monitor the stress value of each coal pillar during the working face mining. From there, the average stress value of the measured points in each coal pillar and the stress of the pillar itself during the mining process are calculated. These values are compared with the initial stress values of the coal pillar before mining, and the concentration stress change law of each coal pillar is obtained, as shown in Figure 8 (taking options 3 and 4 as examples). The stress

transfer law of the coal pillars under different filling heights is shown in Figure 9 (taking the No. 1 and No. 2 coal pillars as examples).

During the upper coal seam working face mining, the coal pillars demonstrate successive concentrated stress peak areas, and the UZHUG affects the distribution characteristics of the concentrated stress peak size of each coal pillar and the “second rise” phenomenon. The UZHUG affects the bearing capacity of the coal pillar. The greater the UZHUG, the smaller the concentrated stress of the coal pillar and the smaller the bearing capacity. Because the working face is approximately 50 m away from the coal pillar area, there are concentrated stress peak areas from coal pillar 1 to coal pillar 4, and the sudden increases in the concentrated stress values of coal pillars 1, 2, 3, and 4 gradually decrease. When the UZHUG is 4 m, 6 m, and 8 m, the peaks of the concentrated stress values of the coal pillars are different, and the stress concentration factor is 2-3. After the coal pillar is pushed through the working face, the concentrated stress decreases sharply, and the stress is concentrated. The coefficients are all below 0.5, which is lower than the initial concentrated stress and tends to be gentle. When the UZHUG is 2 m, the peak values of the concentrated stress of each coal pillar tend to be the same, and after the coal pillar is pushed through the working face, these values sharply decrease and then increase. The stress concentration factor of some coal pillars reaches 2, which exceeds the original concentrated stress of the coal pillars. Under different UZHUG values, the peak of the concentrated stress increases as the filling height decreases. The unfilled zone height in the underlying gob is reduced from 8 m to 2 m, and the stress concentration factor is increased from 1.5 to 3.

These results show that the mining of the upper coal face causes a sudden increase in the concentrated stress values of the coal pillars. The closer the coal pillars are to the working face, the greater the stress concentration increases, and the risk of the working face entering the coal pillar area is high. The UZHUG affects the size distribution of the peak

FIGURE 7: Deformation of No. 2 coal pillar in different schemes.

FIGURE 8: Stress evolution in coal pillars with different UZHUG.

concentrated stress and the bearing capacity of the coal pillar. The smaller the UZHUG, the more uniform the peak concentrated stress distribution. The stress values of the coal pillars with UZHUG values of 4 m, 6 m, and 8 m are much lower than the initial stress, and the coal pillars almost lose their bearing capacity. However, the stress value of the coal pillar with an UZHUG of 2 m above the roof rises sharply, which indicates that most of the coal pillars are stable and undamaged, and they still maintain a high bearing capacity.

4.5. Deformation Law of Coal Pillar Roof Strata. To determine the mining safety of the No. 6 coal seam working face

under different UZHUG values, the coal pillar roof deformation is used for evaluation. The roof subsidence of the No. 1, 2, 3, and 4 coal pillars are monitored with UZHUG values of 8 m, 6 m, 4 m, and 2 m, as shown in Figure 10.

During the mining process of the working face, the subsidence value of the roof of each coal pillar will increase sharply, which occurs when the working face just enters the position above the coal pillar area in the old goaf. The greater the height of the UZHUG, the greater the amount of roof subsidence and the greater the instantaneous sinking increment. When the distances between coal pillars 1, 2, 3, and 4 and the working face are approximately -25 m, -50 m, -75 m, and -100 m, the working face is located above the

FIGURE 9: Stress evolution in different coal pillars affected by mining activities.

FIGURE 10: Roof convergence above the studied coal pillars using different UZHUG values.

area pushed into the coal pillar, and the roof displacement of each coal pillar is equal. At this point, sudden increases of varying degrees have occurred. In the comparison of the subsidence of various coal pillars, sudden and large increases in coal pillars 1, 2, and 3 can obviously be observed, whereas coal pillar 4 is relatively flat. With UZHUG values of 2 m, 4 m, 6 m, and 8 m, the amount of roof subsidence increases successively, and the maximum values are 0.5 m, 1.3 m,

2.3 m, and 3.1 m, respectively. With an UZHUG of 2 m, the amount of roof subsidence is small, and after the working face is pushed past the coal pillar (0 m position), a small amount of rebound will occur in the subsidence of the coal pillar. Under this condition, the coal pillar is an elastic body, and the compressed amount is released after pressure relief. This shows that with UZHUG values of 8 m, 6 m, and 4 m, the coal pillars are unstable and damaged, causing the roof

FIGURE 11: Field measurement indication and equipment operation.

rock layer of the coal pillar to sink significantly; the coal pillar is almost undamaged with an UZHUG of 2 m without the roof. The settlement is exceedingly small and can remain stable, which is consistent with the conclusion that the concentrated stress of the coal pillar rises sharply.

In summary, when the working face is being mined into the coal pillar area, the deformation and stress of the coal pillar will increase sharply. At this time, the risk of the working face is high, whereas the coal pillar is relatively smooth and has a small risk. The UZHUG is an important factor affecting the safety of the working face. The smaller the UZHUG, the higher the bearing capacity of the coal pillar, the smaller the lateral deformation and the roof convergence, and the higher the safety of the working face. The coal pillars are damaged when the UZHUG is 8 m, 6 m, and 4 m, and it is difficult to ensure the safe mining of the working face. When the UZHUG is 2 m, the coal pillar can be kept stable to ensure the safe mining of the working face. This determines that the critical UZHUG is 2 m.

5. Field Measurement Research on Floor Grouting Filling

5.1. Field Measurement Equipment and Schemes. The equipment used for the field measurement is a SYKJ-18 downhole camera provided by the State Key Laboratory of Coal Resource and Safe Mining, China University of Mining and Technology, Xuzhou, Jiangsu, China. The operation of the field measurement equipment is shown in Figure 11. The drilling scheme is formulated based on the drilling location and plane distribution, as given in Table 3.

5.2. Analysis of Field Measurement Results. To reveal the filling effect of the old goaf on the floor of the 6107 working face, a borehole televiewer was used to observe the unclosed grouting filling holes 1, 2, 5, 6, and 13 to detect whether the old goaf of the floor was filled; the UZHUG, ground grouting hole layout, and peek results are shown in Figure 12.

Observation results show that water accumulated in boreholes 1, 2, and 6, and the water level was significantly higher than the buried depth of the No. 9 coal roof and remained unchanged for a long period. This indicates that the old goaf was thoroughly filled, thus reflecting that the filling body was roof-contacted. During the peeping process of the 5 and 10 boreholes, a cavity area was observed at the borehole bottom. The depths of the bottom of the borehole (the top interface of UZHUG) are -160.5 m and -163.4 m, the depths at the water surface (the bottom interface of UZHUG) are -162.5 m and -167.8 m, and the height difference is 2.0 m and 4.4 m, respectively. This demonstrates the distance between the filling body and roof, which shows that the filling effect of the old goaf near the two boreholes is not acceptable.

The UZHUG is large, and the coal pillars in the old goaf will fail during mining, which will likely impact miner safety in the upper coal seam. In the real-world mining process of the working face, when the working face mining used an UZHUG value of 2 m in borehole 5, the working face was mined normally without any safety problems. When the working face mining to the edge of the old goaf was filled by the No. 13 borehole, the floor in front of the scraper conveyor contained a collapsed area. Therefore, the floating coal and falling coal lump of the working face and cement were

TABLE 3: Drilling measurement schemes.

Sequence	Drilling number	Time interval (d)	Monitoring site	Monitoring purposes
1	1	1~2	Surface	Whether the filling body is connected to the roof
2	2			
3	3			
4	5			
5	6			
6	10			
7	13

FIGURE 12: Borehole layout and observation results from televiewer.

used to fill the cavity in the front floor of the working face in time. After the filling was completed, safe mining of the 6107 working face was subsequently ensured.

6. Conclusion

The findings of this study are as follows:

- (1) The UZHUG affects the size and distribution characteristics of the shear stress in the coal pillar. The greater the UZHUG, the greater the peak shear stress of the coal pillar and the more concentrated the stress is in the middle of the pillar. Conversely, the peak of the shear stress in the coal pillar decreases and gradually shifts from the middle to both sides.
- (2) In combining coal pillar deformation and pillar stress transfer characteristics, the coal pillars failed when the UZHUG was 4 m, 6 m, and 8 m; by contrast, the coal pillar remained stable when the UZHUG was 2 m, thus demonstrating that this is the critical value.
- (3) Field measurements of the 6107 working face showed that the UZHUG value of borehole 5 was 2 m and

that of borehole 13 was 4.4 m. When the working face is mined to the vicinity of borehole 5, it can be safely recovered. When the working face is pushed to the vicinity of borehole 13, the old goaf must undergo a 2nd round of filling work before mining can continue. We have verified that the critical height of the unfilled zone needed to ensure safe mining above underlying gob deposits is 2 m.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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