Research Article

Subsidence Control Design Method and Application to Backfill-Strip Mining Technology

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Intensive and massive coal mining causes a series of geological hazards and environmental problems, especially surface subsidence. At present, two major types of subsidence control technology are applied: backfilling technology and partial mining technology. However, the cost of backfill mining is high and partial mining has a low recovery ratio. Therefore, the backfill-strip mining is used to solve the problems of high cost and shortage of filling materials in coal mines at present. A subsidence control design method of backfill-strip mining was proposed in this paper based on the subsidence control effects and economic benefits. First, the stability of the composite support pillar of the filling body and coal pillars in the backfill-strip mining is analyzed, and the values of the main subsidence influencing factors that include the filling material, the size of the backfilling working face, caving mining face, and residual coal pillar are preliminarily determined. Then, the surface movement and deformation are predicted based on the equivalent superposition probability integral method (PIM). The subsidence influencing factors are optimized and determined by comparing the requirements of the safety fortification index of the antideformation ability of surface buildings, resource recovery rate, and coal mining cost. Finally, the mining scheme design parameters of the backfill-strip mining technology are determined. This method is applied in the subsidence control design of backfill-strip mining in the Ezhuang coal mine. Research results show that backfill-strip mining can ensure the safety of surface buildings, increase the resource recovery rate, and reduce coal mining costs through the reasonable design of this method. This study can provide scientific guidance for subsidence disaster control, prevention, and engineering design in backfill-strip mining.

1. Introduction

When resources are mined, a large number of goafs are produced underground, and the stress balance inside the rock is disturbed. This leads to the overburden stratum bending and breaking, resulting in surface subsidence [1, 2]. Surface subsidence caused by underground coal mining is a global problem and leads to damage to infrastructure, buildings, roads, and drainage systems [3–6]. The problems of surface subsidence have been reported in the United

States, China, Australia, Poland, Czech Republic, and other countries. In recent decades, with increased mining, the associated surface subsidence problems in China have become progressively more serious. Surface subsidence is the most common cause of disasters in mining areas. According to statistics, the surface subsidence area due to coal mining in China has reached $6 \times 10^3 \text{ km}^2$, and the area is increasing by 240 km^2 every year [7–9].

Many mining techniques were applied to control surface subsidence to achieving the coordinated and sustainable

development of coal resources exploitation and environmental protection. The backfilling mining technology based on filling body support mainly includes gob, caving zone, and separated-bed filling [10–12]. However, this technology has the disadvantages of high filling costs and backfill material shortage [13–16]. The partial mining achieves the goal of controlling surface subsidence through the support of coal pillars and reducing the mining area. However, the partial mining wastes a large amount of coal resources because its coal resource recovery rate is too low [17–19].

Backfill-strip mining is a partial backfilling technology that combines the advantages of backfill mining and partial mining, which can effectively control surface subsidence and reduce costs. In this technology, longwall partial backfill mining is conducted first. After the backfill materials achieve a certain bearing capacity, the residual coal pillar is recycled. This mining process eventually forms a combined support pillar of the filling body and the coal pillar (CSP) to support the overlying strata and achieve the goal of subsidence control. Figure 1 shows the backfill-strip mining diagram. The increase in environmental constraints has made the advantages of backfill-strip mining increasingly prominent and facilitated its application in several coal mines in China, such as Daizhuang Coal Mine, Fucun Coal Mine, Xuchang Coal Mine, Xingdong Mining, and Handan Coal Mine.

Since backfill-strip mining method was proposed, it has undergone continuous development. Backfill-strip mining uses coal gangue and other solid wastes as the main backfill material to fill the underground mine; on the one hand, it can reduce waste discharge such as gangue; on the other hand, it can be applied in coal seam extraction under building due to the subsidence control effect and achieves coal recycling economy and green mining [20]. The backfill materials commonly used in coal mine mainly include gangue, fly ash, paste, and high-water material [21]. Compared with the full backfilling of the goaf, when decreasing the backfill range of backfill-strip mining, the backfill cost is greatly reduced, and the reduction of the backfill workload also reduces the impact on the normal mining of the working face and improves the efficiency of the mining work [22, 23].

In recent years, some subsidence control design methods were proposed according to the corresponding mining subsidence control techniques. The regulation [24] promulgated by China Coal research institute describes the subsidence control design method of strip mining, and the stability of coal pillar, the influence of surface subsidence, and recovery rate are considered in this method. Wang [25] proposed the subsidence control design method of backfill mining, and the filling quality, the influence of surface subsidence, and economic benefits are considered in this method. Backfill-strip mining combines the advantages of backfill mining and partial mining, but the control mechanisms of the strata subsidence between backfill mining, strip mining, and backfill-strip mining are not the same. The subsidence effect of backfill-strip mining is influenced by many factors, among which the stability of the CSP is the key to the success of backfill-strip mining. The CSP in the backfill-strip mining is affected by the filling material and the

size of the backfilling working face, caving mining face, and residual coal pillar [21, 26]. However, CSP is different from coal pillar or fulling body because of different material properties and structure. Therefore, the subsidence control design method of backfill-strip mining cannot completely copy those of strip mining and backfill mining. A new subsidence control design method of backfill-strip mining was proposed in this paper based on the subsidence control effects and economic benefits.

The rest of the paper is organized as follows. The subsidence control design method of backfill-strip mining is introduced in detail to determine the size of the backfilling working face, caving mining face, and residual coal pillar in Section 2. An engineering case of the subsidence control design of backfill-strip mining is shown in Section 3. The subsidence control effect and economic benefit of backfill mining, strip mining, and caving mining methods are contrastively analyzed in Section 4. Section 5 presents the conclusions.

2. Subsidence Control Design Method of Backfill-Strip Mining

2.1. Subsidence Control Design Principles of Backfill-Strip Mining. The subsidence control design of backfill-strip mining is determined by three aspects to meet the requirements of subsidence control and cost reduction: the stability of composite support, the surface movement and deformation value, and the economic benefit. Therefore, the following principles should be followed in the design process:

- (1) The primary principle in the subsidence control design of backfill-strip mining is to ensure that the surface subsidence is controlled within the safety fortification index of the surface building. This is the most important principle of subsidence control in backfill-strip mining.
- (2) The second principle is to ensure the stability of the CSP. The CSP is the main support of the overlying strata. The stability of the CSP is the core of backfill-strip mining, and it is also the premise of using the equivalent superposition PIM to predict the surface subsidence. Therefore, the subsidence control design of backfill-strip mining must ensure the stability of CSP.
- (3) On the premise of ensuring the above two principles, the width of the residual coal pillars and the backfill working face are reduced, and that of the caving mining working face is increased to improve the recovery rate of coal resources, minimize the mining cost, and achieve better economic benefits.

2.2. Subsidence Control Design Flow of Backfill-Strip Mining. In Figure 2, the subsidence control design method of backfill-strip mining is divided into 6 steps as follows:

- (1) First, the fortification index of surface movement and deformation is determined according to the

FIGURE 1: Diagram of backfill-strip mining.

FIGURE 2: Subsidence control design flow of backfill-strip mining.

antideformation ability of buildings and surrounding environment, with determining the mining area of backfill-strip mining with the protection target as the center. The subsidence control fortification index is generally the critical deformation value of the building grade damage, and different environments may require additional fortification indexes. The values of tilt, curvature, horizontal movement, and horizontal deformation are used as the fortification index for the safety of surface building. The maximum surface subsidence is also used as a fortification index to prevent the house from being submerged due to surface subsidence in areas with high phreatic levels.

- (2) The influencing factor values of subsidence control in backfill-strip mining are preliminarily determined, and

the influencing factors of subsidence control include the filling material, the size of the backfilling working face, caving mining face, and residual coal pillar.

- (3) The type of composite support is determined based on the mining technology and filling material ratio. According to the elastic-plastic analysis of the CSP, the widths of the filling body and residual coal pillar in the different types of CSP are calculated to adjust the width of the backfilling working face, caving mining face, and residual coal pillar. Then, the stability of the CSP is analyzed.
- (4) Based on the initial values of working face size, the surface movement deformation value of backfill-strip mining is predicted based on the equivalent superposition PIM.

- (5) The values of surface movement and deformation are compared with the fortification index, and the resource recovery rate and economic benefits are analyzed. If the extreme values of surface movement and deformation exceed the fortification index, or the resource recovery rate and economic benefits are inappropriate, then the value of the influencing factors of backfill-strip subsidence control is readjusted and optimized. Step (3) is reconducted until the extreme values of surface movement and deformation are less than the fortification index. Within the fortification index, the resource recovery rate and economic benefits are coordinated, and the backfill-strip mining subsidence process and design parameters are finally determined.
- (6) The surface movement and deformation observation station are established according to the backfill-strip mining subsidence technology and design parameters. The regular observations are implemented during the mining impact period for ensuring the safety of surface buildings.

2.3. The Stability Assessment of the CSP. The key to the subsidence control design of backfill-strip mining is to ensure the stability of the CSP and the movement and deformation of the surface structures within the fortification index. These two key steps are affected by the width of the residual coal pillar and working face, so the parameter design of the width of residual coal pillars, the backfilling working face, and the caving mining working face are the core of the subsidence control design of the backfill-strip mining, and the specific calculation method is as follows.

2.3.1. Safety Width Calculation of the Residual Coal Pillar and Backfilling Working Face in Backfill-Strip Mining. The wider the width of the backfilling working face and the residual coal pillars, the lower the coal resource recovery rate and the greater the filling mining cost, which directly affect the stability of the CSP. Therefore, the width of the backfilling working face and the residual coal pillar should be reduced as much as possible under the premise of ensuring the stability of the CSP.

The width of filling working face and coal pillar is also different according to the different filling materials. Zhu [27] divides the stable CSP into three types, namely, Type I, Type II, and Type III CSP, and using the elastic-plastic theory, the calculation method of the minimum residual coal pillar and the width of the backfilling working face under the stable condition of different types of CSP is presented. The residual coal pillars in Type I CSP are wide (Figure 3). The residual coal pillar plays the role of a retaining wall by providing the lateral stress of the filling body to ensure its triaxial stress state and improve the stability of the CSP. The widths of the broken and plastic zones of Type I CSP are small, and its elastic zone, including partial coal pillars and all backfill bodies, is large. The residual coal pillars in Type II CSP are relatively narrow (Figure 4). The widths of the broken and plastic zones of Type II CSP are larger than those of Type I CSP. The residual coal pillars in Type III CSP completely collapse (Figure 5). The filling body is partially destroyed, but the CSP is intact.

The solid filling material of backfilling mining is the bulk material, which needs lateral restraint to obtain a certain supporting capacity. Therefore, when solid backfilling mining is implemented, the stability of the residual coal pillars must be ensured to construct Type I CSP. According to the elastic-plastic analysis method of the CSP, the width of the residual coal pillars on both sides should be at least

$$L_C \geq \frac{n \cdot m}{2 \tan \varphi_0} \left[\ln \left(\frac{k_1 \gamma H + C_0 \cot \varphi_0}{P_x / \beta + C_0 \cot \varphi_0} \right)^\beta + \ln \left(\frac{k_2 \gamma H + C_0 \cot \varphi_0}{P_x / \beta + C_0 \cot \varphi_0} \right)^\beta + 2 \tan^2 \varphi_0 \right], \quad (1)$$

where L_C is the reserved coal pillar width, m is the average mining thickness of the coal seam, n is the safety factor, taking 1.5, φ_0 is the internal friction angle of the coal seam interface, k_1 and k_2 are the stress concentration coefficients, γ is the average rock mass density, H is the average mining depth of the coal seam, C_0 is the cohesive force of the coal seam, β is the lateral pressure coefficient, p_x is the lateral pressure of the gangue and support on the coal pillar in the caving area, and p_b is the lateral pressure of the backfill on the coal pillar.

The width of the solid backfilling working face should be determined in combination with the predicted results of surface subsidence and the filling process.

Paste filling mining is based on coal gangue as aggregate, mixed with a certain amount of cementing material and water as the filling material. After a period of solidification, the filling material has a certain strength and can be used alone as a support pillar for the overlying strata. Therefore, it can be designed as Type II or Type III CSP when the filling material is paste material, and the coal pillars are completely recovered or a small amount of coal pillars are reserved as the support body to protect the roadway, and the overlying rock strata are supported by the filling body. According to the elastic-plastic analysis of the CSP, the width of the filling face is at least

FIGURE 3: Diagram of Type I CSP.

FIGURE 4: Diagram of Type II CSP.

FIGURE 5: Diagram of Type III CSP.

$$L_F \geq n \cdot \frac{k_3 m \gamma H / 2 \tan \varphi_0 \left[\ln (k_3 \gamma H + C_0 \cot \varphi_0 / P_x / \beta + C_0 \cot \varphi_0)^\beta + \tan^2 \varphi_0 \right] + \gamma H (2L_C + L_M) - \gamma L_M^2 \cot \delta / 4}{k_3 \gamma H - \gamma H} \quad (2)$$

In the formula, if all coal pillars are recovered, $L_C = 0$, L_F is the width of the filling body, k_3 is the factor of stress concentration, L_M is the width of the caving mining face, and δ is the overburden strata fall angle of the goaf.

2.3.2. Safety Width Calculation of the Caving Mining Working Face. As the size of the caving mining face becomes larger, the coal resource recovery rate will increase and the economic benefits will be better. However, the size of

the caving mining working face has the greatest impact on the subsidence control of backfill-strip mining. Therefore, the width of the caving mining face should be as large as possible under the premise of satisfying the subsidence control requirement.

Consider the following aspects in the design process of caving mining face width:

- Referring to the experience of strip mining, the width of the caving mining face should be limited to prevent surface wave subsidence basin, and the ratio of the caving mining working face width to the average mining depth is generally less than 1/3.
- From the perspective of insufficient mining, the width of caving mining working face should be limited to the extremely subcritical mining, and the ratio of the width of the caving mining face to the average mining depth is generally less than 1/3.
- Finally, the prediction values of surface movement deformation are less than the fortification index. Section 2.4 describes the prediction method of surface subsidence in backfill-strip mining.

2.4. The Surface Subsidence Prediction Method in the Backfill-Strip Mining. Zhu [20] proposed a detailed prediction method of surface subsidence in the backfill-strip mining. The prediction method of surface subsidence in backfill-strip mining can be adopted as the superposition of the surface subsidence results of strip mining and backfilling mining.

The superposition surface subsidence prediction method for backfill-strip mining is developed on the basis of the PIM (Figure 6). PIM is a mining subsidence prediction method based on stochastic media theory. In China, PIM is the most used function for coal mine subsidence prediction and plays an important role in reducing the influence of mining subsidence. According to the principles of mining subsidence prediction by the PIM, the formula of surface subsidence caused by a small unit is as follows:

$$W_e(x, y) = \frac{1}{r} e^{-\pi(x^2+y^2/r^2)}, \quad (3)$$

where $W_e(x, y)$ is surface subsidence caused by a small unit mining, (x, y) are coordinate of the surface point, r is major influence radius given by $r = H/\tan\beta$, H is mining depth, and $\tan\beta$ is tangent of major influence angle.

Integral is carried out on the whole working face, and the subsidence value of any point caused by the mining of working face could be calculated as follows:

$$\begin{aligned} W(x, y) &= \iint_D W_0 W_e(x, y) ds dt, \\ &= \iint_D \frac{W_0}{r^2} e^{-\pi((x-s)^2+(y-t)^2/r^2)} ds dt, \end{aligned} \quad (4)$$

where $W(x, y)$ is the subsidence of working face mining, W_0 is the maximum ground subsidence, $W_0 = mq\cos\alpha$, m is the mining thickness, q is the subsidence factor, α is the dip angle of coal seam, D is the calculation mining area of the working face, the length of the area D along the strike is D_3 , l is the calculated length of the working face along the strike and can be calculated by $l = D_3 - 2S$, S is the inflection point offset, the length of the area D along inclination is D_1 , L is the calculated length of the working face along the strike and can be calculated by $L = (D_1 - 2S)\sin(\theta + \alpha)/\sin(\theta)$, θ is the main propagation angle, and $ds dt$ is the integration variable of double integral of area D .

2.4.1. Surface Subsidence Prediction of the Backfill Mining.

The actual mining thickness of backfilling mining is not the thickness of the coal seam. The traditional caving mining PIM model cannot be applied to backfilling mining. The concept of equivalent mining height is proposed to solve this problem (Figure 7). The equivalent mining height is the difference between the actual mining height of the filling face and the filling height, that is, the mining height of the working face minus the height of the compaction filling.

The calculation formula of the equivalent mining height M_e is as follows:

$$M_e = (M - \delta - \Delta)\eta + \delta + \Delta, \quad (5)$$

where M_e is the equivalent mining height for backfilling mining, δ is the amount of top plate moving, Δ is the unfilled height, and η is the compression rate of the filling body.

The surface subsidence calculation formula for backfilling mining is obtained by substituting the equivalent mining height formulas (5) into (4):

$$W_b(x, y) = [(M - \delta - \Delta)\eta + \delta + \Delta] \frac{q_b \cos \alpha}{r_b^2} \iint_D e^{-\pi((x-s)^2+(y-t)^2/r_b^2)} dt ds, \quad (6)$$

2.4.2. Surface Subsidence Prediction in Strip Mining. The mining thickness of strip mining is the mining thickness of the coal seam minus the roof subsidence after the mining is stabilized. The following formula can be used to calculate the thickness M_s of strip mining:

$$\begin{aligned} M_s &= M - M_e, \\ &= (M - \delta - \Delta)(1 - \eta). \end{aligned} \quad (7)$$

Substituting the thickness calculation formula of strip mining into formula (4) yields the calculation formula of the surface subsidence in strip mining:

FIGURE 6: A diagram of surfer movement calculated by PIM.

FIGURE 7: Diagram of the equivalent height mining.

$$W_s(x, y) = [(M - \delta - \Delta)(1 - \eta)] \frac{q_s \cos \alpha}{r_s^2} \cdot \iint_D e^{-\pi((x-s)^2 + (y-t)^2/r_s^2)} dt ds. \quad (8)$$

2.4.3. Surface Subsidence Superposition Prediction of Backfill-Strip Mining. Surface subsidence of backfill-strip mining can be regarded as the sum of the surface subsidence of backfilling and strip mining. This model is referred to as a superposition prediction method based on the PIM, and its surface subsidence value includes two parts:

$$W = W_b + W_s$$

$$= [(M - \delta - \Delta)\eta + \delta + \Delta] \frac{q_b \cos \alpha}{r_b^2} \iint_D e^{-\pi((x-s)^2 + (y-t)^2/r_b^2)} dt ds + [(M - \delta - \Delta)(1 - \eta)] \frac{q_s \cos \alpha}{r_s^2} \iint_D e^{-\pi((x-s)^2 + (y-t)^2/r_s^2)} dt ds. \quad (9)$$

According to equation (9), the surface movement and deformation values of backfill-strip mining are predicted, and the surface movement and deformation values are compared with the fortification index. If the extreme value of surface movement and deformation exceeds the fortification index, then the values of the

influencing factors of subsidence control in backfill-strip mining are readjusted and returned to Step (3) until the extreme value of surface movement and deformation is less than the fortification index; then, the subsidence process and design parameters of backfill-strip mining are finally determined.

3. Engineering Case Study

3.1. Study Area. Ezhuang coal mine is located in Shandong Province, China. The resources of the Ezhuang coal mine are nearly exhausted, and most residual coal reserves are covered by village buildings (Figure 8), which has seriously affected the normal continuity of the mine and shortened the service life. The surface houses in the coal mine are dense. Hence, the caving mining method is not suitable to use for mining because it will easily cause severe surface subsidence, which will have a greater impact on the life of residents. Moreover, the caving mining method is not conducive to the long-term stability and sustainable development of enterprises. Therefore, an effective subsidence control of coal mining technology must be established.

The designed mining area is the 15th coal seam in the west wing of the first mining area. The 15th coal seam in the west wing of the first mining area is located in the middle of the coal mine. The average strike length of the mining area is 750 m, the average incline width is 850 m, and the mining height is 1.2 m. The direct roof of the coal seam is siltstone with a thickness of 8 m.

According to the regulation [20] promulgated by China Coal research institute, the impact of coal mining on the buildings should be less than the Level I damage. The movement deformation values of the building with the Class I damage are as follows: the horizontal deformation, curvature, and tilt value do not exceed 2.0 mm/m, 0.2 mm/m², and 3 mm/m. Therefore, the safety fortification index of the surface building are as follows: the horizontal deformation, curvature, and tilt values are 2.0 mm/m, 0.2 mm/m², and 3 mm/m, respectively.

3.2. The Width Design of the Residual Coal Pillar and Working Face in the Study Area. Since the backfilling working face adopts the solid filling material as the filling body, the filling body itself has poor supporting ability and needs lateral restraint to obtain a certain supporting capacity and ensure the stability of the residual coal pillars. Type I CSP should be designed to support the load of overlying strata for ensuring the safety of surface buildings and the subsidence control effect of the overlying strata. The designed mining thickness of the 15th coal is 1.2 m, and the factor of stress concentration k_1 is 1.4 and of k_2 is 1.3. The average unit weight γ of the rock formation is 25kN/m³, the average mining depth H of the coal seam is 630 m, and the lateral pressure coefficient $\beta = 0.34$. The internal friction angle φ_0 of the coal seam interface is set to 24°, and the cohesive force C_0 of the coal seam interface is set to 2.9MPa. If the collapsed gangue and anchor rods in the goaf have no binding force on the horizontal direction of the coal wall, then $p_x = 0$. The side pressure of the backfill on the coal pillar is calculated by the passive earth pressure formula; then, $p_b = 37.4$ MPa. The width of the plastic zone at the junction of the coal pillar and the backing body is zero because the side pressure of the backing body on the coal pillar is large. Substituting formulas (1) and (2), the residual coal pillar size can be obtained as follows:

$$L_C \geq 9.94\text{m}. \quad (10)$$

To meet the needs of engineering construction, the width of residual coal pillar L_C is 10 m.

Since the CSP is Type I, the stability of the CSP depends on the residual coal pillar, and the size of the backfilling working face is not limited.

According to the design principle, the ratio of the width of the caving mining working face to the average mining depth should be controlled within 1/3 to prevent the surface from wave subsidence. The average mining depth of the 15th coal seam in the design area is 630 m, so the width of the caving mining working face should be less than 210 m.

3.3. Layout of the Working Surface in the Study Area. The layout of the backfill-strip mining face in the study area is as follows: the working faces of 11501, 11503, and 11505 are filled by solid backfilling method, and the gangue filling rate of the designed goaf is 75%. Then, the working faces of 11502, 11504, and 11506 are mined by caving mining method. The design mining thickness is 1.2 m, the layout plan of the working face is shown in Figure 9, and the sizes of each working face are illustrated in Table 1. The design scheme can mine approximately 531,000 tons of coal.

3.4. Surface Movement and Deformation Prediction in the Study Area

3.4.1. Prediction Parameters of Surface Movement and Deformation

(1) *Analysis of the Observation Data of Surface Subsidence.* The surface movement and deformation calculation parameters for caving mining in the 15th coal seam are comprehensively determined according to the data of the strata movement analysis and the strata movement parameters of nearby coal mines with similar geological mining conditions. The strata movement calculation parameters of the PIM are shown in Tables 2 and 3 under the conditions of the first mining and repeated mining of the coal seam in the coal mine.

(2) *Predicted Parameters of PIM in the Backfill Mining.* The geological and mining conditions of Ezhuang coal mine and the solid backfilling mining technology are considered; then, the designed goaf gangue filling rate is 75%, and the equivalent mining height of each backfilling working face is

$$\begin{aligned} M_e &= M - M_g, \\ &= 1200 - 1200 \times 0.75, \\ &= 300\text{mm}. \end{aligned} \quad (11)$$

According to the equivalent mining height theory, the surface subsidence of solid backfilling mining can be predicted by the prediction formulas of caving mining method and the parameters under the same geological mining conditions. The prediction parameters of backfilling mining for the 15th coal seam is approximately equal to the predicted parameters of PIM in the case of repeated mining (Table 4).

FIGURE 8: Ground and underground contrast map.

(3) *Predicted Parameters of PIM in Strip Mining.* The number of mining strips in the design area is small, and the superposition prediction method of multiple small working faces can be used to predict the surface subsidence affected by strip mining.

The surface subsidence parameters of PIM for small working face mining are mainly related to the area recovery rate and width-depth ratio of the mining area of the working face and can be obtained according to the conversion relationship with caving mining method. The predicted parameters of the strip mining in the case of the first mining area adopt the PIM of small face mining under the condition of extremely insufficient mining. The predicted parameters of each working face in the study area are determined (Table 5).

The effective thickness of strip mining is as follows:

$$\begin{aligned} M_s &= M - M_e, \\ &= 1200 - 300, \\ &= 900\text{mm}. \end{aligned} \quad (12)$$

(4) *Prediction Analysis of Surface Movement and Deformation.* The surface movement and deformation of backfill-strip mining should be predicted by the prediction model of the equivalent superposition PIM.

Before the 15th coal seam was mined, the surface buildings had been affected by the 7th coal seam, so the superposition influence of the 7th and 15th coal seam was predicted in the final surface subsidence. Table 6 is a statistical table of the maximum value of surface movement and deformation in the backfill-strip mining in the study area. The surface curvature is less than 0.01 mm/m^2 ; hence, it is not listed. Figure 10 shows the predicted contour map of the surface subsidence in backfill-strip mining.

Table 6 illustrates that the maximum surface subsidence in backfill-strip mining is 754 mm. The maximum tilt value is 2.9 mm/m, the maximum horizontal movement value is 232 mm, the maximum tensile deformation value is 1.2 mm/m, and the maximum compression deformation value is 1.8 mm/m. The above prediction and analytical results demonstrate that the buildings on the surface are only damaged by level I and can be normally used after backfill-strip mining at each working face. After backfill-strip mining is carried out, the length of the road section affected by mining subsidence of the Tailai Expressway is approximately 944 m. The maximum subsidence of the affected section is 370 mm, the maximum tilt deformation is approximately 2.7 mm/m, the maximum tensile deformation is 1.2 mm/m, the maximum compression deformation is 0.9 mm/m, and the maximum horizontal movement is 210 m.

FIGURE 9: The layout of the backfill-strip mining working face.

TABLE 1: Size of each working surface.

Working face	Strike length (m)	Incline length (m)	Width of the residual coal pillar (m)
11501 backfilling working face	371	80	10
11502 caving mining working face	444/621	99	10
11503 backfilling working face	621/808	103	10
11504 caving mining working face	700/808	118	10
11505 backfilling working face	574/700	96	10
11506 caving mining working face	416/574	100	10

TABLE 2: Predicted parameters of PIM in the case of the first mining.

Mining depth (m)	Q	b	$\tan \beta$	$\theta (^{\circ})$	S (H)
300–500	0.62	0.3	1.8	85.2	0.08
550–1000	0.58	0.3	1.74		

TABLE 3: Predicted parameters of PIM in the case of repeated mining.

Mining depth (m)	Q	b	$\tan \beta$	$\theta (^{\circ})$	S (H)
300–500	0.68	0.3	2.4	87	0.06
550–1000	0.60	0.3	2.2		

TABLE 4: Subsidence prediction parameters of backfilling mining.

Prediction parameters	q	b	Tan β	S	θ_0 (°)
	0.60	0.3	2.2	0	$90^\circ-0.5\alpha$

α is the inclination angle of the coal seam.

TABLE 5: Subsidence predicted parameters of the 15th coal seams' strip mining.

Prediction parameters	q	b	Tan β	S (H)	θ_0 (°)
	0.40	0.28	1.85	0.05	$90^\circ-0.5\alpha$

TABLE 6: Extremum statistics of surface movement and deformation in backfill-strip mining.

Subsidence (mm)	Tilt deformation (mm/m)		Horizontal movement (mm)		Horizontal deformation (mm/m)	
	North and south	East and west	North and south	East and west	North and south	East and west
754	2.9	2.5	232	184	-1.8, 1.2	-1.3, 1.3

FIGURE 10: Contour map of surface subsidence.

FIGURE 11: Working face layout of different mining methods. (a) Layout of backfilling mining working face. (b) Layout of caving mining working face. (c) Layout of strip mining working face.

In combination with the predicted results of surface movement and deformation, the selected size of the residual coal pillar and working face meets the fortification index.

4. Comparison of Subsidence Control Effect and Economic Benefit of Different Mining Methods

The surface subsidence values of backfill mining, strip mining, and caving mining methods are predicted by PIM to assess the subsidence control effect. The working face layouts of different mining methods are shown in Figure 11. The maximum values of surface subsidence of each mining

method are shown in Table 7. The comparison and analysis of the resource recovery rate, economic benefits, mining technology issues, and social issues are shown in Table 8.

- (1) Backfill mining, backfill-strip mining, and strip mining and caving mining are contrasted, and the subsidence control effect and economic benefit are analyzed in this study. The surface movement and deformation values caused by backfill mining, strip mining, and backfill-strip mining methods are small, and the damage to surface buildings is less than level I damage, which does not affect the normal use of the buildings, and only simple maintenance is required. However, the surface movement deformation values

TABLE 7: The extreme values of surface movement and deformation after mining in each scheme.

Mining scheme	Subsidence (mm)	Tilt deformation (mm/m)	Curvature deformation (mm/m ²)	Horizontal movement (mm)	Horizontal deformation (mm/m)
Backfilling mining	653	2.5	0.02	184	-1.8/1.1
Backfill-strip mining	754	2.5	0.03	232	-1.8/1.3
Strip mining	667	2.6	0.02	207	-1.8/1.2
Caving mining	1573	5.3	0.03	450	-2.5/2.3

TABLE 8: Benefit comparison of different coal mining schemes under buildings.

Mining scheme	Damage level of surface buildings	Village treatment scheme	Mineable coal volume (10,000 tons)	Filling cost (ten thousand yuan)	Mining technical issues	Social issues
Backfilling mining	Level I damage	Repair compensation	54	2160	Low coal mining efficiency, and high filling costs	The surface subsidence is small, and the buildings are effectively protected.
Backfill-strip mining	Level I damage	Repair compensation	54	1200	High resource recovery rate and low filling costs	The surface subsidence is small, and the buildings are effectively protected.
Strip mining	Level I damage	Repair compensation	23	—	Low resource recovery rate	The surface subsidence is small, and the buildings are effectively protected.
Caving mining	Level II damage	Village relocation	54	—	The mining technology is mature.	The surface subsidence is large, a large number of buildings need to be relocated, the relocation cost is high, and the surface ecological environment has been destroyed.

caused by the caving mining method are large, and the damage to surface buildings exceeds level II damage. A large number of buildings need to be relocated, the relocation cost is high, and the surface ecological environment has been destroyed.

- (2) The recoverable coal reserve is 230,000 tons when strip mining is implemented. Meanwhile, the recoverable coal reserve is 540,000 tons when backfill mining, backfill-strip mining, and caving mining methods are implemented, greatly increasing the recovery rate of coal resources.
- (3) The backfilling mining and backfill-strip mining adopt backfill mining technology, which increases the filling cost. The added cost of backfilling mining is 21.6 million yuan. Meanwhile, backfill-strip mining belongs to partial filling mining, and the cost has only increased by 12 million yuan. The economic benefit of backfill-strip mining is better than that of backfilling mining.
- (4) From the analysis of the surface movement deformation value and economic benefit, it is shown that the surface movement deformation values are small in backfill-strip mining, the surface buildings were not damaged, the resource recovery rate is high, and the filling cost is low. There, the backfill-strip mining can meet the requirements of surface subsidence control and achieve good economic benefits. This backfill-strip mining is the best choice for coal mining under buildings in Ezhuang coal mine.

5. Conclusion

The following conclusions are drawn:

- (1) A subsidence control design method of backfill-strip mining was proposed in this paper based on the subsidence control effects and economic benefits. First, the stability of CSP in the backfill-strip mining is analyzed and the values of the main subsidence influencing factors that include the filling material, the size of the backfilling working face, caving mining face, and residual coal pillar are preliminarily determined. Then, the surface movement and deformation are predicted based on the equivalent superposition PIM. The subsidence influencing factors are optimized and determined by comparing the requirements of the safety fortification index of the antideformation ability of surface buildings, resource recovery rate, and coal mining cost. Finally, the mining scheme design parameters of the backfill-strip mining technology are determined.
- (2) This method is applied in the subsidence control design of backfill-strip mining in the Ezhuang coal mine. Research results show that backfill-strip mining can ensure the safety of surface buildings, increase the resource recovery rate, and reduce coal mining costs through the reasonable design of this method.
- (3) The subsidence control effect and economic benefit of backfill-strip mining, backfilling mining, strip

mining, and caving mining method are contrastively analyzed. Analysis shows that the surface movement deformation values are small in backfill-strip mining, the surface buildings were not damaged, the resource recovery rate is high, and the filling cost is low. There, the backfill-strip mining can meet the requirements of surface subsidence control and achieve good economic benefits.

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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