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Research Article

Study on Deformation Response Law of Surrounding Rock in Solid Backfill Mining Stope

Xingping Lai, Longquan Wu, Jiantao Cao, and Yuhang Tu

Xi'an University of Science and Technology, Xi'an 710054, China

Correspondence should be addressed to Longquan Wu; 21203077019@stu.xust.edu.cn

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To fully control the roof and surface and reduce the ecological damage caused by mining, it is necessary to understand the deformation response law of the surrounding rock in solid backfill mining. The similarities and differences of overburden movement characteristics between natural caving method and solid backfill method are analyzed and compared by means of on-site investigation and monitoring, theoretical derivation and analysis, numerical simulation and effect verification. The control mechanism of backfill mining on the roof is clarified, and the relationship between stope roof displacement and support pressure of backfill body is established. Furthermore, the mechanical conditions of immediate roof in equilibrium state during backfill mining are established. The FLAC^{3D} simulation indicates that the solid backfill mining face has a concentrated stress peak located 15 m ahead of the coal wall. Within the range from 0 to 5 m, the abutment pressure is reduced gradually. However, within the range from 5 to 15 m, the abutment pressure is increased evidently. The stress concentration is located 35 m behind the working face. With continuous backfilling of the goaf, the maximum displacement occurs in the backfill body near the working face. The total deformation of the surrounding rock in the goaf is reduced by 58%. The total deformation of coal wall is reduced by ~37.5%. The subsidence coefficient is reduced from 0.59 to 0.013 by using the backfill mining technology. The research results provide theoretical guidance and reference for roof control and ecological protection of backfill mining.

1. Introduction

The development and utilization of coal resources provide effective support for the economic development of our country, but the long-term development of coal resources has led to increasingly prominent ecological problems such as water damage, land desertification, land subsidence, and surface accumulation of solid waste, seriously damaging the ecological environment on which human survival depends [1]. At the same time, with the further expansion of coal production scale, ecological environment problems will become more serious. The destruction of underground water bodies and ecological environment pollution caused by mining are the main culprits threatening human health [2–4]. Under the principles of "safety, economy, and environmental protection" and "safe, efficient, and green" mining has become the national development concept; therefore, the research of eco-friendly mining methods is the theme of current and future resource development. In recent years, with the large-scale mining of coal resources in China, the mining conditions are deteriorating, and the trend of coal resources under "three-body" is increasing year by year; therefore, it has a very broad application prospect to promote and develop the effective method of coal mining under "three-body" [5, 6].

Backfill mining is based on deepening the sustainable development strategy of coal resources, and effectively solves the problem of ecological environment damage caused by underground resource development. Backfill mining is an important measure to promote the secondary utilization of coal gangue and other underground waste. It is a green mining technology to liberate the coal resources under "three-body" and protect the surface subsidence [7, 8]. Solid backfill mining is a kind of mining technology of "replacing coal with gangue." In other words, filling coal gangue and other mixed solids in the gob, which plays a supporting and buffering role in the overburden, effectively controls the migration and destruction of the roof, and makes the movement and deformation law and the structure of the overburden in the

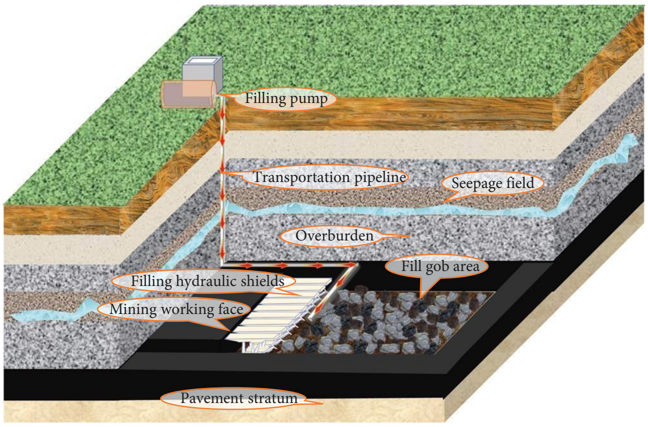

Figure 1: Schematic diagram of solid backfill mining.

backfill mining greatly different from the traditional natural caving mining [9, 10]. In recent years, the application and development of backfill technology has become a trend. With the help of numerical simulation, Huang et al. [11] studied the control effect of backfill body compaction rate on overburden. Zha et al. [12] designed a new method of intelligent backfill, and obtained the intelligent principle of solid automatic backfill system. Zhao et al. [13] applied rock mechanics test to reveal the influence of mass concentration on damage characteristics of backfill body. The majority of scholars have made a lot of practical results on the research of solid backfill mining, but the solid backfill mining technology still needs further development and improvement.

In this paper, the deformation response characteristics of surrounding rock in solid backfill mining are analyzed theoretically. With the help of FLAC^{3D} software, the movement law of overburden in solid backfill mining is accurately simulated. The surface control effect of backfill mining is evaluated by means of in situ measurement. The study on the deformation response law of surrounding rock in solid backfill mining is helpful to the further promotion and application of backfill mining technology, and has a positive impact on the green development of coal resources.

2. Engineering Background Overview

A mine in northern Shaanxi is located in the ecologically fragile area of the Ordos Basin. The mining area is located at the junction of the Loess Plateau and the Mu Us Desert. The surface of the mining area is mainly desert beaches and loess ridges. The terrain in the desert area is gentle, the terrain in the plateau area is undulating, and the surface elevation is between 1270 and 1330 m. The region is rich in coal resources, and the occurrence conditions are simple. In the early stage of the mine, the traditional natural caving mining technology was used for large-scale mining, which caused serious damage to the surface ecological environment. Therefore, it is urgent to adopt new green mining technology to achieve the purpose of protecting nature and restoring ecology. The solid backfill mining is shown in Figure 1.

The 2^{-2}# coal seam in the mine field is the main minable coal seam, the buried depth is close to 400 m, and the average coal thickness is 5.8 m. The pseudo-roof is carbonaceous mudstone, the direct roof is fine-grained sandstone, containing a small amount of muscovite debris, locally containing siltstone interlayers, and the basic roof is mainly sandstone locally containing calcareous cementation, massive bedding, and carbonaceous laminating. The direct bottom is mainly composed of sandy mudstone and siltstone. The horizontal and wavy bedding is relatively developed, argillaceous cementation, and fine-grained sandstone thin layer. The basic bottom is mainly siltstone and fine-grained sandstone, containing a small amount of debris.

3. Response Analysis of Surrounding Rock Deformation in Solid Backfill Stope

3.1. Stope Surrounding Rock Migration Characteristics Analysis. Solid backfill mining has the same coal mining process as traditional collapse method coal mining, the only difference is that solid backfill mining fills solid backfill material into the void area in time after coal seam mining, and forms the roof support system in the void area together with surrounding rock and coal pillars, thus achieving the purpose of controlling the sinking and movement of overburden and preventing surface subsidence and damage [14–16]. The traditional natural caving mining method is to manage the roof of gob by adopting the method of free caving of overburden rock. With the advancement of mining, the scope of gob is steadily expanding, and the unsupported roof is suspended in a large area and exposed to the gob. When the overburden abutment stress exceeds the support capacity of the direct roof, the direct roof completely collapses, and then the main roof is exposed in the gob. After the main roof loses support, it forms its own masonry beam structure, which further plays the role of controlling the overlying rock layer rotation and slippage [17]. Working face mining advancement leads to the expansion of the area of exposed roof in the face area, the original stress balance of the roof is constantly disturbed by mining and disrupted, which leads to the emergence of the roof “bending and sinking–overburden fractures development–rotation and sliding” of the ground pressure behavior. After each occurrence of ground pressure, the strong strata above the roof of the face area will spontaneously form a macrostructure with certain support for the overburden, which will plays a controlling role on the overburden in a certain range until the surface subsidence occurs. Using the traditional natural caving mining technology, after the roof of the gob is deformed by “stabilization-destabilization-subsidence,” it will form the broken form of overburden rock in the face area as shown in Figure 2, which is most typically characterized by the formation of obvious “three horizontal zones and three vertical belts” in the face area and overburden rock. That is, in the horizontal direction, the supporting area, the separation area and the recompaction area are successively formed (corresponding to A, B, and C in Figure 2, respectively, a–b is the supporting area, b–c is the separation area, and c–d is the

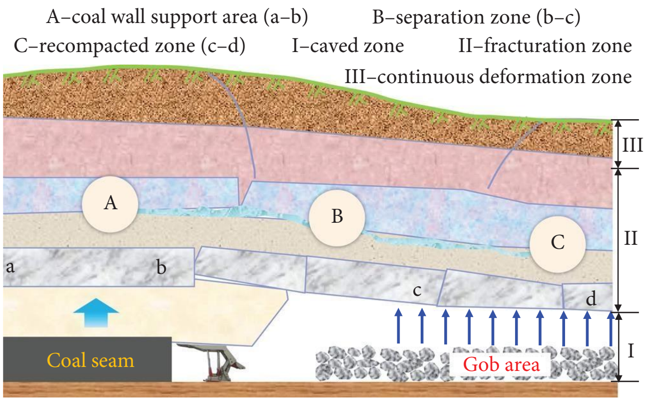

FIGURE 2: Overburden movement characteristics of natural caving method mining.

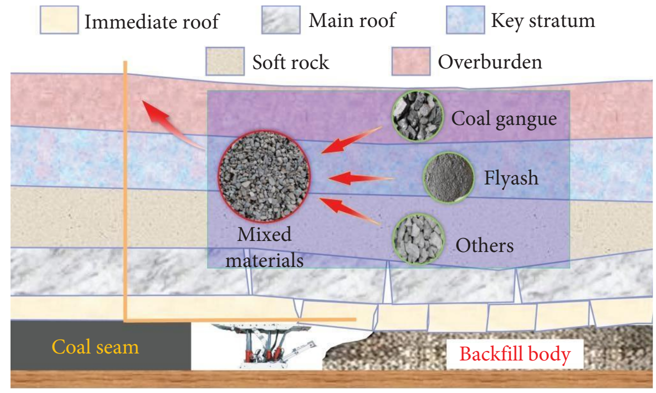

FIGURE 3: Overburden movement characteristics of backfill mining.

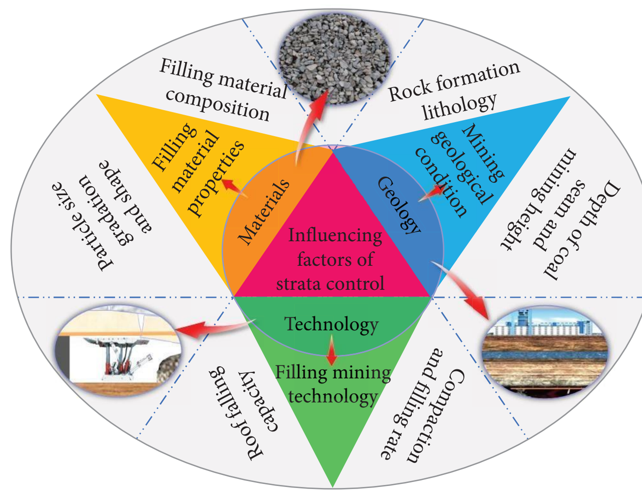

FIGURE 4: Influencing factors of solid backfill mining rock control.

recompaction area), and in the vertical direction, the caved zone, the fracturation zone, and the continuous deformation zone are successively formed (corresponding to I, II and III in Figure 2).

Through the above analysis of the movement characteristics of surrounding rock in traditional natural caving mining, caving mining has caused great environmental problems (such as farmland destruction, gangue accumulation, road damage, house cracking, etc.). In order to solve such environmental problems caused by mining without restricting the normal production of coal resources, and then achieve the purpose of protecting surface damage and realizing the reuse of gangue and the green development of coal resources, the backfill mining technology came into being [18–21]. Solid backfill technology is a mixture of coal gangue and flyash and other backfill materials, through the shaft and transport equipment to the face area and then filled and compacted, to control the role of the overburden movement deformation of the face area. The overburden of solid backfill mining is supported and buffered by the solid backfill material, which leads to the movement and deformation law of the roof and the structural form of the overburden is fundamentally different from the traditional caving mining [22].

When using solid backfill technology for underground coal mining, filling the goaf with solid backfill material effectively reduces the space for overlying strata to deform and collapse. At the same time, the solid backfill material in the gob plays a certain buffering role in the movement and deformation of the roof strata, resulting in a significant weakening of the strata deformation and pressure manifestation in the gob. As a result, there is no occurrence of roof strata fracture or collapse, and the solid backfill mining working face roof experiences no significant initial and periodic pressure. The movement characteristics of overlying strata during solid backfill mining are shown in Figure 3. The use of solid backfill mining is equivalent to greatly reducing the mining thickness based on the caving method, thereby reducing the degree of damage to the overlying strata and the surface. The development height of the roof cracks in solid backfill mining is related to the geological conditions of the coal seam occurrence. Due to the filling effect on the goaf, the development of cracks is inhibited. With the advance of the fully mechanized mining face, when the immediate roof reaches its caving step distance and collapses, it directly contacts the fractured solid backfill. The overlying strata supported by the immediate roof also experience subsidence and delamination with the main roof. The main roof undergoes bending deformation under the load of the overlying strata, but due to the small space for the subsidence of the backfilled mining roof, the main roof and its support directly act on the softer rock strata below it due to the limited delamination space. As the deformation of the main roof increases, the support force provided by the lower rock strata strengthens, thus limiting the bending deformation of the main roof and greatly protecting the ground surface.

In fact, solid backfill mining mainly consists of two stages, the first stage is coal seam mining at the working face and the second stage is void backfill. In the whole solid backfill mining process, “backfill” always lags behind “mining,” and the roof strata will sink earlier during the period of face mining and void backfill, plus the backfill body cannot guarantee the complete contact with the roof and the solid backfill body has certain compressibility. As a result, solid backfill mining cannot fully play the role of controlling roof transport. Figure 4 shows the influencing factors of solid

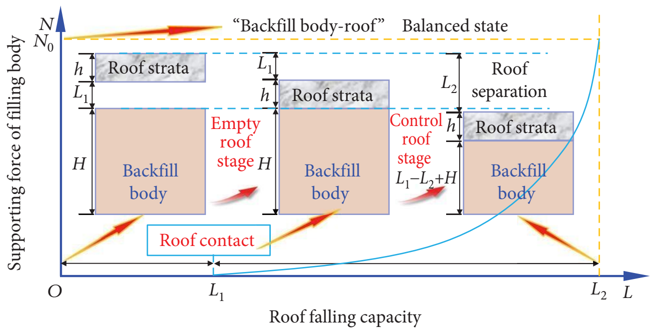

FIGURE 5: Relationship between the amount of top slab sinking and the support force of the backfill body.

backfill mining, and it can be seen that the process of roof control by solid backfill mining is restricted by the backfill technology, nature of backfill material and mining geological conditions. The roof formation in the backfill gob will be controlled to a great extent, but the backfill body cannot completely inhibit the deformation and movement of the roof [23]. Therefore, the more mature the backfill technology, the higher the backfill rate, and the more superior the mining conditions, the better the effect on the control of the deformation of the roof and surface movement.

3.2. Mechanical Analysis of Surrounding Rock Migration in Stope. The essence of solid backfill mining is to replace the coal seam with solid backfill body, which fills the void area, and the backfill material occupies the space for the roof to rotate, deform, and fall, resulting in only a small-scale rotation and deformation of the roof, but no breakage or even caving. During the process of roof rotation and deformation, the roof strata will show weak fracture development in vertical direction and produce a small range of delamination in horizontal direction. By adopting solid backfill mining technology, the roof strata will generate smaller fracturation zone and continuous deformation zone, but no caved zone. Therefore, the ground pressure behavior is reduced and the surface settlement is protected [24]. Throughout the integrated mechanized solid backfill mining process, the roof strata always maintains its continuity, so the roof can be considered as a four-sided solid support thin plate bearing the overburden load at the top and supported by the elastic backfill at the bottom.

The control model of solid backfill body on the roof is equivalent to the supporting effect of spring. With the gradual increase of the sinking amount of the roof, the backfill body is further compacted, resulting in the increase of the density of the backfill body and the increase of the support force of the backfill body. According to Figure 5, when the working face along the direction of the advancement of the amount is small, the overhanging area of the roof of the gob is small, at this time the roof strata of the gob relies on its own bearing capacity, so that the roof and the backfill body of the gob to maintain a certain distance, the backfill body of the gob on the roof lack of support, this state is the empty roof state. With the further enlargement of the gob, the roof rock strata gradually bends and sinks, when the sinking amount of the roof reaches L_1, the roof contacts with the

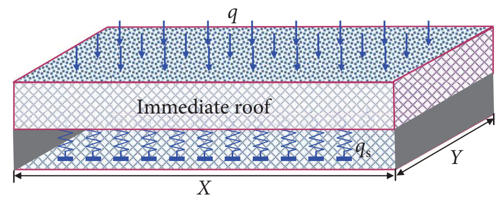

FIGURE 6: Schematic diagram of the solid backfill mining roof model.

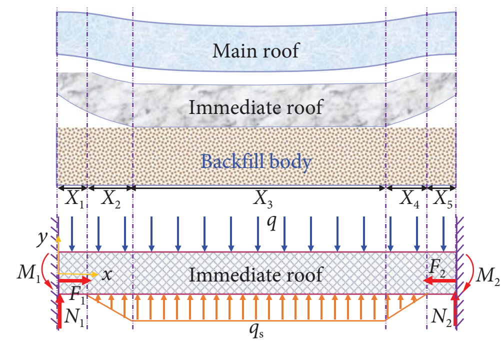

FIGURE 7: Roof deformation morphology and mechanical model of solid backfill mining.

backfill body, but the shape and volume of the backfill body does not deform, this state is the roof joint state, the top joint state lasts for a very short time, the backfill body does not form support for the roof. When the sinkage of the roof is greater than L_1, as the roof sinks, the support of the backfill body to the roof becomes more and more obvious, and the backfill body plays a controlling role to the roof, which is the state of controlling the top. When the sinking amount of the roof reaches L_2, the roof no longer sinks and the roof is in equilibrium with the backfill body, and the height of the backfill body is compressed to $(H+L_1-L_2)$ in this state. The size of L_2 is used as the basis for judging the backfill effect, and the smaller the L_2, the better the backfill effect.

The 3D model, deformation morphology and mechanical model of the solid backfill mining roof are shown in Figures 6 and 7. The two ends of the direct roof are embedded within the rock body and are restrained and supported by the rock body, and in the middle section of the direct roof (X_3 in the figure) has sunk to the lowest position, and the height of the backfill body is compressed to the minimum. The direct roof only shows rotary deformation in the interval between X_2 and X_4 as shown in the Figure 7, and does not move down completely, resulting in uneven distribution of the support force of the backfill body in this area. In the interval near the two ends of the coal and rock (X_1 and X_5 as shown in the Figure 7), a "triangular" gap is formed between the top and the backfill body, and the top is not supported by the backfill body. Usually $X_1 \neq X_5$ and $X_2 \neq X_4$, with the advancement of working face recovery, the phenomenon that the direct roof and the main roof will be separated from each other first and then overlap, when the direct roof and the main roof are separated from each other, the load above the direct roof

Table 1: Simulated physical and mechanical parameters of coal seams.

Rocks name	Weight density d (N/m^3)	Young's modulus E (GPa)	Poisson ratio (v)	Cohesion (MPa)	Friction (°)	Tensile strength (MPa)
Siltstone	24,600	19.5	0.2	2.75	38	1.84
Argillaceous sandstone	25,200	5.425	0.147	2.16	36	0.75
Mudstone	24,610	8.75	0.26	1.2	30	0.605
Coal	13,800	5.3	0.32	0.15	32	1.25
Solid backfill body	13,500	2.0	0.2	0.015	20	0.7

$q = 0$, and the solid backfill body only bears its own gravity above the direct roof. The direct roof is equivalent to a thin plate fixed on both sides, and in the equilibrium state of "roof-backfill body," the $F_x = 0$, $F_y = 0$, and $M_s = 0$ equilibrium conditions are satisfied, that is:

$$F_1 - F_2 = 0, \tag{1}$$

$$N_1 + N_2 + q_s\left(\frac{1}{2}X_2 + X_3 + \frac{1}{2}X_4\right)Y - \gamma XYh - qXY = 0, \tag{2}$$

$$M_1 - M_2 + \frac{1}{2}q_sX_2\left(X_1 + \frac{2}{3}X_2\right)Y + q_sX_3\left(X_1 + X_2 + \frac{1}{2}X_3\right)Y + \frac{1}{2}q_sX_4\left(X_1 + X_2 + X_3 + \frac{1}{3}X_4\right)Y + N_2(X_1 + X_2 + X_3 + X_4 + X_5) - \frac{1}{2}(\gamma XYh - qXY)(X_1 + X_2 + X_3 + X_4 + X_5) = 0. \tag{3}$$

At the same time, according to the principle of static equilibrium, when the roof sinking and backfill body interaction reaches equilibrium and the roof is under static conditions, the support force of the coal wall (including support resistance) on both sides of the gob satisfies the following conditions:

$$N_1 = q(X_1 + X_2) + \gamma(X_1 + X_2)Yh - \frac{q_s}{2}X_2, \tag{4}$$

$$N_2 = q(X_4 + X_5) + \gamma(X_4 + X_5)Yh - \frac{q_s}{2}X_4. \tag{5}$$

In the above equation, X_1, X_2, X_3, X_4, X_5 indicate the length of different positions of the roof in the gob, X indicates the advancing length along the gob ($X = X_1 + X_2 + X_3 + X_4 + X_5$), Y indicates the length of goaf along the inclined direction, q indicates the direct roof overburden load, q_s indicates the backfill body support load, γ indicates the roof capacity, F_1 and F_2 are the horizontal force of the coal wall on both sides to the roof, N_1 and N_2 are the support force of the coal wall on both sides to the roof, M_1 and M_2 are the moment of the coal wall on both sides to the roof.

4. Simulation of Overburden Rock Migration Law in Solid Backfill Stope

The solid backfill mining is used as the engineering background, and a working face backfill mining model of 100 m × 80 m × 60 m is constructed by using the built-in fish language of FLAC^{3D} simulation and calculation software, and 5.2 Mpa normal load is applied to the top surface to ensure that the simulation conditions are consistent with the engineering reality. During the simulation process, the working face was advanced 10 m each time, and the gob is filled with solid materials in turn. The stress transfer and displacement variation of overburden during the solid filling working face advancing 80 m along the strike direction are observed. The physical and mechanical parameters of the coal and rock bodies involved in the simulation process are shown in Table 1.

4.1. Stress Characteristics of Surrounding Rock in Backfill Mining Stope. Figure 8 reflects the vertical stress distribution characteristics during the process of mining reaches and backfill. When mining 10 m and the gob is not filled, stress concentration mainly occurs 10 m above the overrunning work face, and the maximum concentrated stress is 10.381 Mpa. The minimum stress above the roof is 0.237 Mpa. When mining advances 30 m and the gob is filled with 20 m, stress concentration mainly occurs 15 m above the overrunning work face, and the maximum concentrated stress is 10 Mpa. In the 20 m backfilled goaf, the stress in the 10 m goaf near the working face remains significantly reduced, while in the 10 m goaf further away from the working face, the stress in the goaf roof, floor, and backfill returns to the original rock stress state due to the compaction of the backfill. This indicates that the 20 m backfill plays a supporting role in the subsidence of the overlying strata, but the lag distance of its effect can reach 10 m. When mining advances 60 m and the gob is filled with 50 m, stress concentration mainly occurs 18 m above the overrunning work face, and the maximum concentrated stress is 10.95 Mpa. Stress concentration occurs above the roof of the backfill gob at 35 m

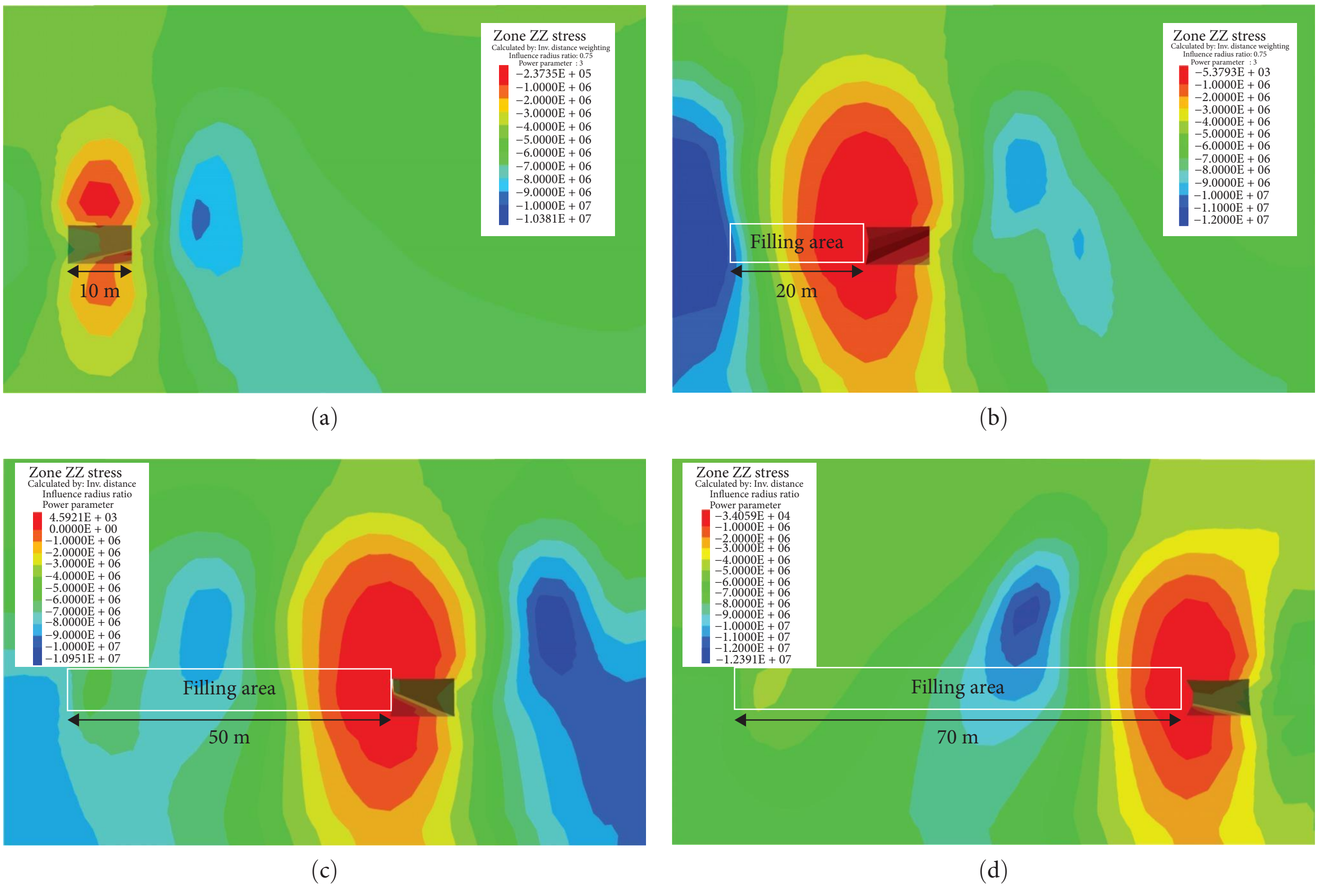

Figure 8: Cloud map of vertical stress distribution in the rock strata of backfill mining: (a) working face advancing 10 m, unfilled; (b) working face advancing 30 m, backfill 20 m; (c) working face advancing 60 m, backfill 50 m; (d) working face advancing 80 m, backfill 70 m.

Table 2: Advanced stress concentration characteristics of working face.

Working face advancing length (m)	Backfill length of goaf (m)	Vertical stress of working face (MPa)	Vertical stress at 5 m position in front of working face (MPa)	Vertical stress at 10 m position in front of working face (MPa)	Vertical stress at 15 m position in front of working face (MPa)
10	0	3–4	6–7	9–10	9–10
30	20	3–4	6–7	7–8	7–8
60	50	2–3	5–6	8–9	9–10
80	70	4–5	6–7	9–10	—

behind the mining area, and the stress can reach 9 Mpa. When mining advances 80 m and the gob is filled with 70 m, stress concentration occurs above the roof of the backfill gob 35 m behind the mining area, and the stress can reach 12.39 Mpa. During the whole backfill process, within the gob range of 0–15 m near the mining area, the stress decreases significantly. After 15 m, the backfill body in the gob has been compacted, and the stress is basically restored to the original rock stress value (6–7 Mpa).

Table 2 reflects the characteristics of vertical stress concentration in advance of mining area during mining advance and backfill compaction stage of gob. From the Table 2, the stress value in the 15 m coal wall in front of the working face is between 3 and 10 MPa in the process of advancing the fully mechanized solid backfill working face from the open offcut along the advancing direction to 80 m. Within 15 m ahead of the coal wall, the vertical stress shows an obvious growth trend. The stress value at the position of 5 m ahead of coal wall is mainly between 6 and 7 Mpa, which is basically close to the original rock stress value. The vertical stress inside the coal wall is mainly between 3 and 4 Mpa, the minimum value is 2 Mpa, and there is a significant stress reduction phenomenon. In the working face ahead of 10–15 m, the stress value is mainly stable in the range of 9–10 Mpa, which is much higher than the original rock stress. With the continuous change of the advancing length of the working face, the vertical stress at the same position in the coal wall fluctuates in a small range. In general, within 15 m ahead, the stress

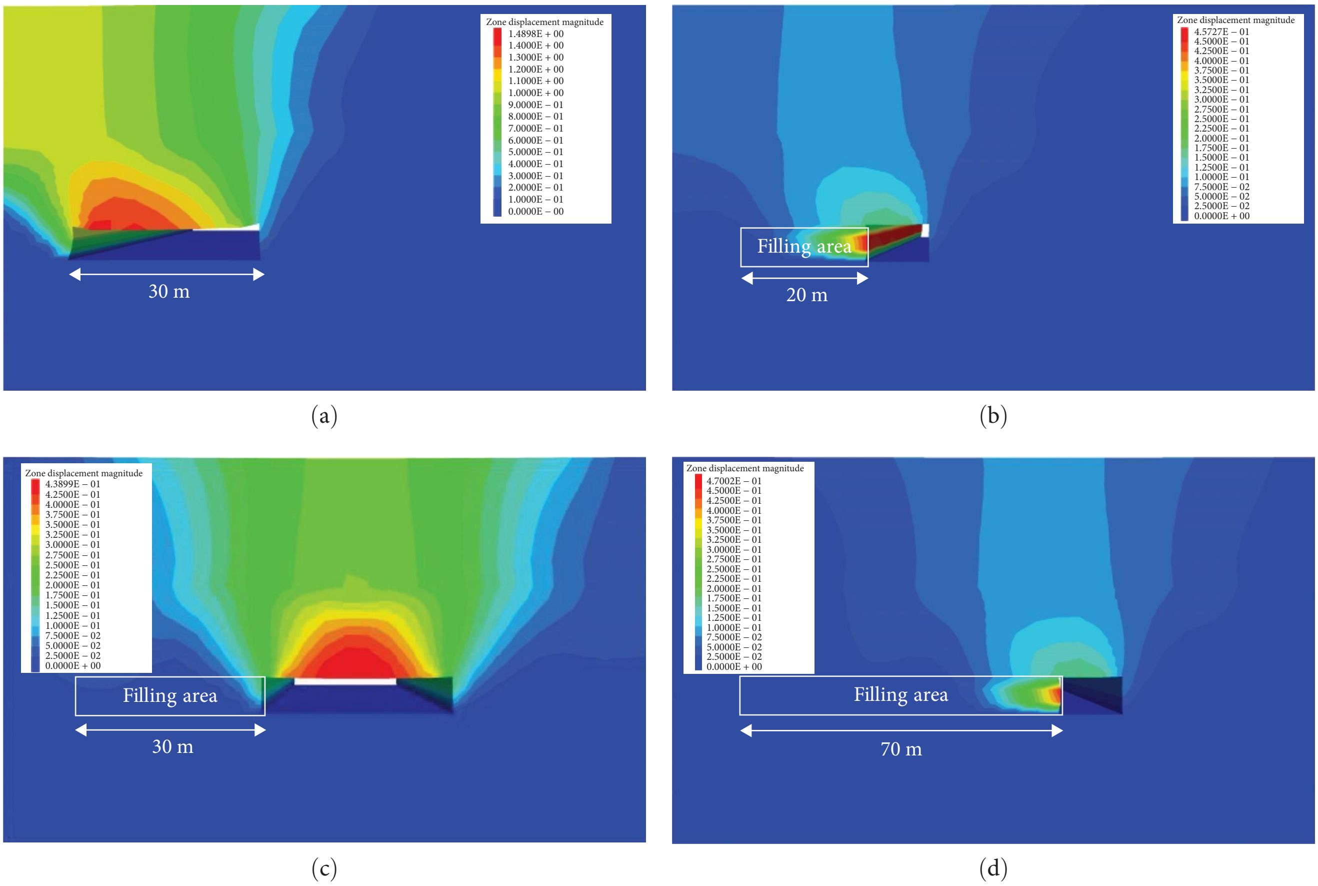

FIGURE 9: Total deformation nephogram of surrounding rock under different advancing lengths of working face. (a) working face advancing 30 m, unfilled: (b) working face advancing 30 m, backfill 20 m; (c) working face advancing 60 m, backfill 30 m; (d) working face advancing 80 m, backfill 70 m.

decreases in the range before 5 m, and the stress increases in the range after 5 m. The characteristics of advanced stress concentration are independent of the mining length.

4.2. Displacement Characteristics of Surrounding Rock in Backfill Mining Stope. Figure 9 reflects the total deformation characteristics of surrounding rock during mining and backfill. According to the diagram, when the mining reaches 30 m and the gob is not filled, the roof deformation of the whole gob is the largest, the maximum deformation is 1.4 m. After the gob is filled by 20 m, the deformation of the whole stope is decidedly reduced. The maximum displacement occurs in the backfill body near the side of the coal wall, and the maximum deformation is 0.457 m. When the mining reaches 60 m and the gob is filled with 30 m, the maximum deformation of the whole stope occurs above the roof of the unfilled gob, and the maximum deformation is 0.44 m. After the gob continues to be filled to 50 m, the deformation and deformation range of the whole stope are significantly reduced. The maximum displacement still occurs in the backfill body near the side of the coal wall, and the maximum deformation is 0.47 m.

Figure 10 reflects the total deformation characteristics of the surrounding rock of the stope, when the working face is

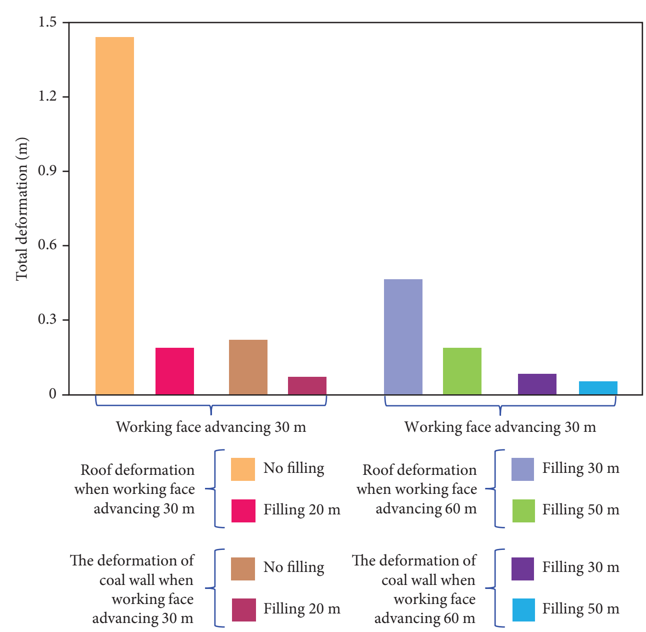

FIGURE 10: Deformation of surrounding rock in solid backfill mining stope.

gradually advancing and the gob is continuously filled. According to the diagram, when the mining reaches 30 m, the total deformation of the stope roof and the advance position of the working face under the condition of no backfill and backfill 30 m in the gob is observed. It can be seen that when the gob is not filled, the maximum deformation of the whole stope roof can reach 1.4 m, and the maximum total deformation of the coal wall is 0.24 m. After backfill 20 m in the 30 m gob, the deformation of the whole stope is greatly reduced. The maximum deformation of the roof of the stope is 0.17 m, which is 1.16 m lower than that without backfill in the gob. The total deformation of the coal wall is reduced to 0.05 m, which is 0.19 m lower than that without backfill in the gob. When the mining reaches 60 m, the total deformation of the stope roof and the coal wall under the conditions of backfill 30 m and backfill 50 m in the gob is observed. It can be seen that when the gob is filled with 30 m, the maximum deformation of the whole stope roof can reach 0.43 m, and the maximum total deformation of the coal wall is 0.08 m. After backfill 50 m in the 60 m gob, the deformation of the whole stope is greatly reduced. The maximum deformation of the roof of the stope can be 0.18 m, which is 0.25 m less than that without backfill in the goaf. The total deformation of the coal wall is reduced to 0.05 m, which is 0.03 m less than that with only 30 m backfill in the gob. With continuous backfilling of the goaf, the maximum displacement occurs in the backfill body near the working face. The total deformation of the surrounding rock in the goaf is reduced by 58%. The total deformation of coal wall is reduced by ~37.5%. It can be seen that the method of solid backfill in gob can effectively reduce the deformation of surrounding rock in stope, so as to control the movement and deformation of roof strata and coal wall in working face.

5. Evaluation of Surface Subsidence Reduction Effect of Solid Backfill Mining

In order to test the protection effect of solid backfill mining measures on the ground surface, a measurement plan for surface subsidence in the mine area under traditional caving method mining and solid backfill mining conditions was developed separately, and the starting base for surface subsidence observation was determined. The location of the observation line was setup from the cut-hole of the back mining face, and 37 measurement points were laid on the surface along the strike line of the working face, and abundant actual measured data of surface subsidence were obtained. Regular and repeated daily observations and stability monitoring were carried out during the mining period, and the monitoring mainly included the changes of the spatial position of each measurement point on the ground surface in different periods before, during and after the mining.

This monitoring is mainly done with the help of static Shteh Lous GPS receiver, Huawei T5 dual-frequency RTK and Trimle Dini 12 level, and other measuring instruments. In accordance with the requirements of reasonable operation specifications, regular inspection and calibration of the testing equipment are carried out to ensure the reliability of the

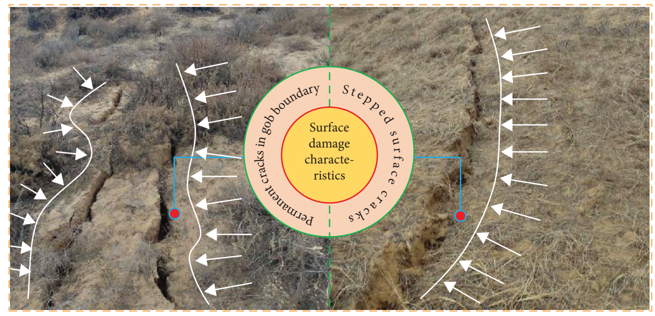

Figure 11: Surface damage characteristics of the mining void area by traditional caving method.

observation data. After the observation work is completed, detailed calculations and analyses are carried out based on the observation data, and the geological conditions and topography of the observation area. The observation data is the main basis for calculating and analyzing the surface movement deformation, and at the same time, after data processing, the time and process of surface observation, the location of the mining face in the observation area and the bedrock lithology of the overlying coal seam, and other influencing factors are comprehensively compared and analyzed, so as to accurately describe the surface movement deformation law and provide basis and reference for the roof control of the backfill mining.

The surface cracks caused by coal seam mining are the visual manifestation of surface damage. Figure 11 shows the characteristics of surface damage under the mining conditions of traditional caving method. The use of complete caving method for roof control in the gob is bound to form permanent cracks at the boundary of the gob, step-like cracks at the surface, step-like cracks near the open cut, cracks parallel to the boundary of the gob, and dynamic cracks at the surface generated during the advancement process, etc. The drying up of rivers and disappearance of vegetation caused by these surface cracks bring great disasters to the ecological environment; so, it is urgent to adopt solid backfill technology for ecological protection [25–28].

From the surface subsidence curve along the advancing line (Figure 12), it can be seen that when the natural caving method is used for roof control, when mining to 100 m, the sinking value of some points (points Z10–Z18) on the advancing line has reached or exceeded 10 mm, indicating that the movement of the overburden on the working face has reached the surface monitoring points; when mining to 360 m, the maximum sinking value on the advancing line has exceeded 3,500 mm (point Z18 sinking value reached 3,513 mm). When mining to 920 m, the surface movement and deformation amplitude has tended to weaken from strong, and when mining to 3,300 m, the surface sinking curve along the advancing direction is basically the same as when mining to 920 m.

From the surface subsidence curve along the advancing line for solid backfill mining (Figure 13), it can be seen that when solid backfill mining is used, when mining to 150 m, the monitoring point sinking value is almost close to 0 mm;

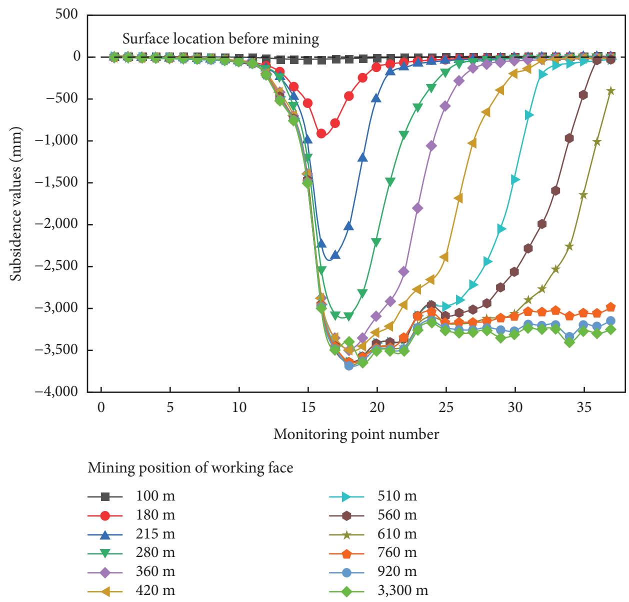

FIGURE 12: Surface subsidence curve along the advancing line for conventional caving mining.

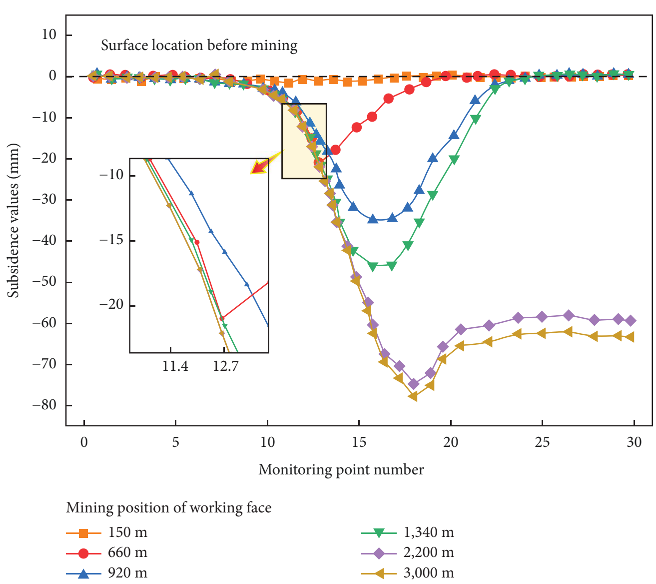

FIGURE 13: Surface subsidence curve along the advancing line for solid backfill mining solid backfill.

when mining to 660 m, the maximum sinking value is about 20 mm; when mining to 1,340 m, the maximum sinking value of the strike line is about 45 mm; when mining to 3,000 m, the maximum sinking value along the advancing line is 78 mm, and the maximum sinking value basically does not change as the working face continues back to mining.

According to the early subsidence of the monitoring points can be explained, with the continuous mining promotion, the affected range of the ground surface is always in the overrun position. When the working face is completed, the subsidence of each monitoring point along the advancing line decays rapidly and gradually stabilizes.

Based on the monitoring results, a comprehensive comparison of the surface damage under natural caving mining and solid backfill mining conditions shows that the maximum surface subsidence value reaches 3,697 mm with a subsidence coefficient of 0.59 for the traditional caving mining technology, and the surface subsidence value will continue to expand with the further mining of the working face; the maximum surface subsidence value is 78 mm with a subsidence coefficient of 0.013 for the solid backfill mining technology. It can be seen that the use of solid backfill mining technology has effectively restrained the surface subsidence and damage, and has played a great role in protecting the ecological environment.

6. Conclusions

(1) By comparing the movement characteristics of the surrounding rock between the natural caving method and the solid backfill method of mining, the control mechanism of the solid backfill mining on the roof formation is theoretically derived. It also analyzes the factors influencing the control of the roof strata by the backfill body as long as they include geology, material and technology. The relationship between the sinking of the roof of the face area and the support force of the backfill body is clarified, and the mechanical model of the roof of the backfill mining is established to give the mechanical conditions when the direct roof of the backfill mining is in equilibrium.

(2) The solid backfill mining condition obtained by using $FLAC^{3D}$ numerical simulation shows that the peak stress ahead of the working face is concentrated 15 m in front of the working face, and the concentrated stress is located 35 m behind the working face. At the same time, due to the lag of the backfill effect, a significant stress reduction phenomenon occurs in the 10 m range of the goaf behind the working face. With the continuous backfilling of the goaf, the deformation amount and range of the surrounding rock in the entire stope are significantly reduced, and the maximum displacement occurs within the backfill body near the working face. After adopting the backfill measures, the total deformation of the surrounding rock in the goaf is reduced by 58.14%, and the total deformation of the coal wall in front of the working face is ~37.5%.

(3) By the method of in situ measurement on site, we analyzed and compared the degree of surface damage under the natural caving method and solid backfill mining conditions, and concluded that after adopting solid backfill mining technology, the maximum surface subsidence value was reduced from 3,697 to 78 mm, and the subsidence coefficient decreased from 0.59 to 0.013, which visually verified the protection effect of solid backfill mining technology on the surface.

Data Availability

Data are available on request.

Disclosure

The paper funds are mainly used for field investigation, data collection, numerical simulation, and paper polishing.

Conflicts of Interest

The authors declare that they have no conflicts of interest. There is no conflicts of interest between the authors, participants or funders.

Authors' Contributions

Xingping Lai, Longquan Wu, and Jiantao Cao contributed to numerical simulation and writing–original draft preparation; Longquan Wu and Yuhang Tu contributed to writing–review and editing.

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