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Innovative Cut-and-Fill Mining Method for Controlled Surface Subsidence and Resourceful Utilization of Coal Gangue

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Abstract: Existing coal filling mining technologies face significant challenges of controlled surface subsidence, efficient utilization of waste rock in coal mines, and a shortage of adequate filling materials. This study introduces an innovative cut-and-fill mining method designed to strategically partition the goaf into cutting and filling zones. In the cutting zone, in situ filling materials are employed to construct waste rock column supports adjacent to the filling zone, thereby achieving controlled surface subsidence. This approach is integrated with long-wall mining operations and implemented using advanced, comprehensive equipment. FLAC3D simulations were conducted to investigate the patterns of stress distribution, surface deformation, and plastic zone formation within the mining field. With the implementation of the cut-and-fill mining balance, key observations include a reduction in maximum principal stress near the center of the goaf, an increasing trend in minimum principal stress, regular displacement distributions, and intact plastic zones positioned vertically away from the stope and horizontally close to the center of the stope. Compared to traditional caving methods, the cut-and-fill technique significantly reduces maximum vertical displacement, by nearly 95%, and maximum horizontal displacement, by approximately 90%. Additionally, it minimizes energy accumulation, lowers overall energy release, and prolongs the release period. Importantly, this method facilitates the resourceful utilization of approximately 800 million tons of waste rock, potentially leading to an estimated reduction of 500 million tons in CO_2 emissions. By achieving a balance of three effects—harmonizing coal extraction and filling capacity, aligning the supply and demand of filling materials, and optimizing the balance between filling costs and mining benefits—this method provides a sustainable and eco-friendly solution for the coal mining industry. The findings of this study are crucial for guiding the industry towards more environmentally responsible practices.

Keywords: cut-and-fill mining; material self-sufficiency; mining characteristic; dual reduction; triple effect

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1. Introduction

Traditional approaches to control surface subsidence in mining include partial extraction [1,2], paste filling [3–5], strata separation grouting [6,7], and highly mechanized gangue filling technology behind efficient fully mechanized mining faces [8–10]. These methods are widely applied in coal mining sites, sometimes combining two or more techniques based on specific site conditions. With the development of green mining, several new coal mining methods with a high integration capability, maturity, or originality have emerged, such as the mixed mining technology of the gangue filling and caving method [11], the novel strip-style Wongawilli coal mining method [12], short-wall block-segment green mining technology [13], and the N00 mining method [14].

The novel strip-style Wongawilli coal mining method originates from the Wongawilli colliery in Australia and involves the sequential extraction of coal seams in narrow strips. By using this technique, miners can achieve higher recovery rates while minimizing surface subsidence. Short-wall block-segment green mining technology refers to the extraction of coal using a continuous miner on shorter faces compared to long-wall mining. The block-segment approach divides the mine into manageable sections, allowing for more controlled operations and reduced impact on the surrounding rock mass. The N00 mining method represents an advanced pillarless mining technique designed to improve safety and efficiency. It eliminates the need for permanent pillars, thereby maximizing coal recovery. This method also reduces ground control issues and enhances worker safety through continuous support systems.

In China, approximately 0.15 to 0.2 tons of coal gangue is generated for every ton of raw coal produced, making coal gangue the largest accumulated and annually produced industrial waste, occupying the most land in storage yards [15–17]. Comprehensive mechanized coal gangue filling mining technology has become an effective solution for special mining methods [15,18,19]. For example, to address the major dual technical challenges of recovering the lower coal mining pillars and handling underground gangue, mines can prioritize the method of using gangue to replace coal pillar extraction. Aiming to reduce carbon emissions and use carbon dioxide, the mineralization filling method has gradually become a research hotspot, and some mining areas have been subjected to industrial tests [20–22].

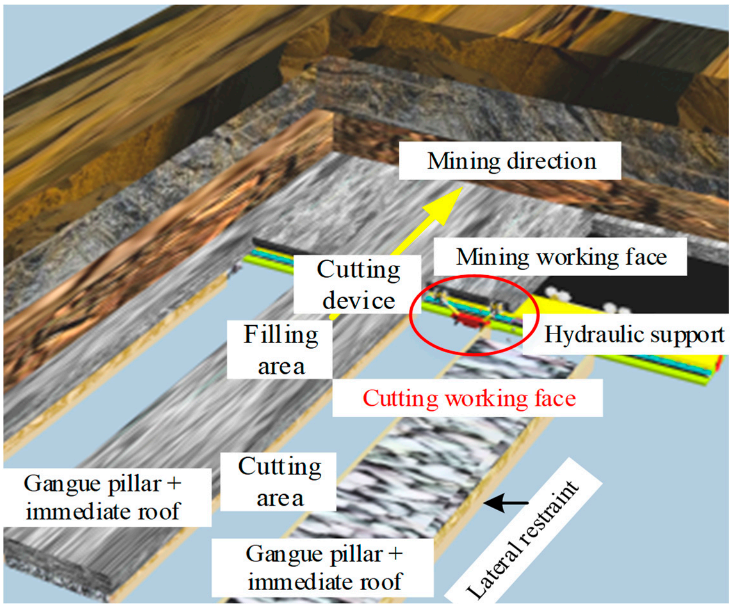
From the perspective of meeting filling material requirements and conserving coal resources, the traditional methods for controlling surface subsidence have inherent flaws. Partial extraction yields extraction rates of only 40% to 60%, and as coal resources decline, the extraction of residual strip coal pillars has become an inevitable choice for extending the service life of mines in the old mining areas of east-central China [23,24]. Filling materials with paste filling requires a certain solidification time, resulting in high economic and time costs. The low filling efficiency severely constrains coal mining efficiency, making widespread adoption challenging [25–27]. Strata separation grouting can avoid interference between mining and filling, almost without affecting coal mining efficiency. However, the prediction of grouting zones is difficult, accurate grouting implementation is challenging, and the subsidence reduction effect remains a matter of debate, leading to its limited current use [28]. Gangue filling suffers from limitations in pre-determined filling and restricted production scales [29–31].

Filling mining is a key technology for green mining because it reduces environmental damage by stabilizing the surface, minimizing subsidence, and reducing waste disposal. It also limits harmful gas emissions and prevents ecological damage, promoting sustainable mining practices. However, balancing the need for filling materials, reducing filling costs, and ensuring high-efficiency production are critical bottlenecks for coal mine filling mining technology. In light of these challenges and based on the advantages and disadvantages of existing mining methods, a new method called “cut-and-fill mining” in coal mining is proposed. Cut-and-fill mining designates the goaf scientifically into the cutting area and the filling area, utilizing the in situ roof of the cutting zone as filling material for the filling zone. This creates a supporting structure of gangue pillars in the goaf, achieving partial filling to control surface subsidence. Cut-and-fill mining combines the high efficiency of long-wall caving with the effective roof control of filling methods, providing a new approach to address the challenges faced by filling mining.

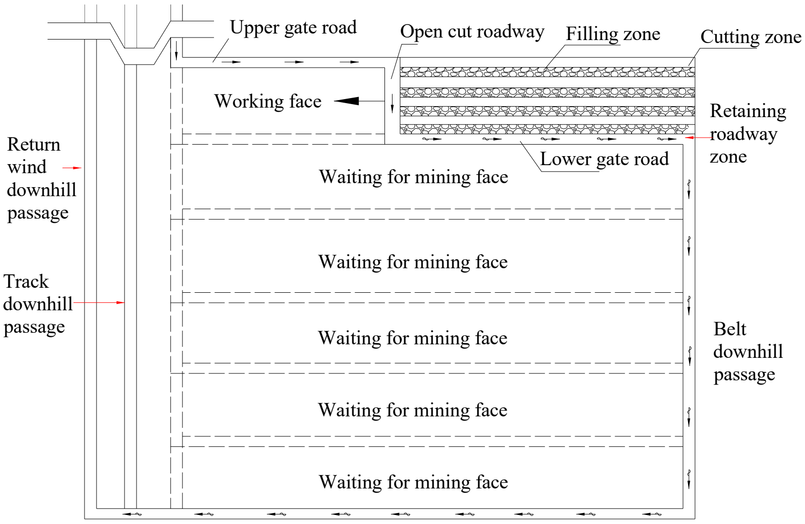
2. Implementation Method of Cut-and-Fill Mining

2.1. Roadway Layout

Figure 1a shows the three-dimensional schematic diagram of the cut-and-fill mining working face. The cut-and-fill mining working face includes the coal mining face before the support and the roof cutting and filling face after the support. The back roof cutting and filling surface is divided into the roof cutting area and filling area, and the roof cutting area and filling area are arranged in sequence. The cutting device in the roof cutting area fractures the immediate roof into crushed gangue, which serves as material for the adjacent filling area. As the hydraulic supports along the boundary of the filling area advance, metal mesh preinstalled on the hydraulic support on both sides automatically unfolds, providing lateral confinement to contain the crushed gangue. The fractured gangue is then automatically conveyed to the adjacent filling area in real time via a transfer mechanism on the cutting device. Once deposited within the metal mesh, the crushed gangue is compacted by a compaction device, completely filling the filling area. With this lateral confinement, a load-bearing structure comprising the broken gangue pillar and the immediate roof is established within the filling area, serving the function of partial backfilling and effectively reducing subsidence.



(**a**) 3 D schematic diagram



(**b**) Schematic plan

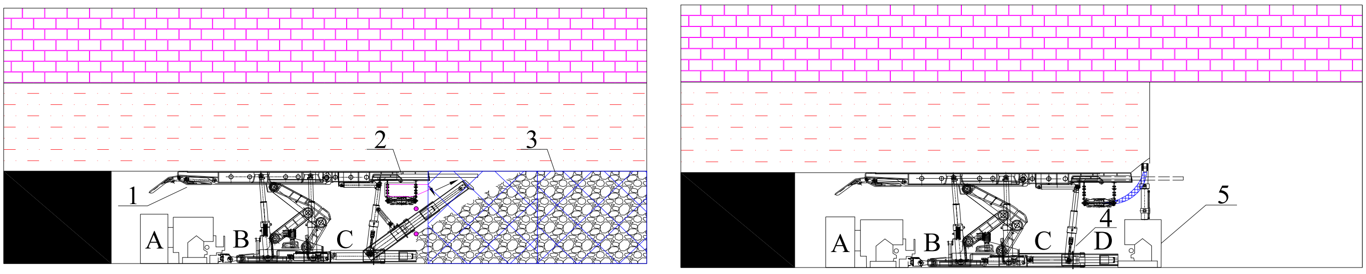
Figure 1. Layout of cut-and-fill mining [32,33].

As shown in Figure 1b, multiple working faces are established in a new panel area to achieve mining without roadway excavation and coal pillar extraction. On one side of the entire panel area, there are downhill return air passages and downhill track passages, while on the other side, a downhill belt passage surrounds the entire panel area and connects with the downhill return air passage after encircling the area, ultimately linking to the shaft. An open-cut roadway is arranged on the first working face, with a section of the downhill belt passage serving as the upper entry groove for this working face. During the extraction process, a goaf is left near the position adjacent to the next working face, forming an upper entry groove for the initial extraction working face. The goaf area near the next coal mining face serves as the upper entry groove for the subsequent coal mining face. The upper entry groove, open-cut roadway, lower entry groove, downhill belt passage, and downhill return air passage are sequentially connected to form the ventilation system for the working face. In the mining process of the panel area, the downhill return air passage and downhill track passage remain unchanged throughout the entire mining process, constituting fixed passages. However, the downhill belt passage and open-cut roadway gradually change with the mining goafs, representing variable passages.

To facilitate roadway-free excavation and coal pillar-free mining, the cut-and-fill mining method modifies the ventilation pathways and conditions at the working face, necessitating careful design to prevent air leakage. Strategies such as installing hanging curtains to obstruct airflow and applying grouting treatments to the goaf section using gangue pillars positioned behind the support can be implemented to improve the efficiency of the ventilation system.

2.2. Integrated Equipment

Figure 2 illustrates the working schematic diagram of the integrated equipment for cut-and-fill mining. In Figure 2, Area A represents the coal mining machine working zone, Area B is the pedestrian passage in the coal mining zone, Area C is the pedestrian passage in the cut-and-fill zone, and Area D is the cut-and-fill zone. The main components of the cut-and-fill integrated mining equipment include the protective support, cutting device, and compaction device.



(**a**) In the filling zone (**b**) In the cutting zone

Figure 2. Schematic diagram of integrated equipment for cut-and-fill mining. 1—front support; 2—rear support; 3—lateral support metal mesh; 4—compaction device; 5—cutting device.

The protective support system features a six-column configuration, adapted from the solid backfill coal hydraulic support used in the "Mining + Separation + Filling + X" coal mining method. It consists of the bottom walking device, front support on the front side, rear support on the rear side, and compaction device. The rear support is appropriately extended to provide the space required for the cutting device. A retractable rear probing beam is set on the rear support, ensuring that the cutting and filling zone's roof is within the protective range of the support. The conveyor belt is suspended and fixed beneath the rear support, with several adjustable plow-type unloaders on the filling zone conveyor belt, controlling the discharge position of the backfilled gangue.

The front and rear supports are interconnected via an intermediate connection, while the compaction device and walking device are connected through a telescopic mechanism. This combination of the intermediate connection and telescopic device allows for independent operation of mining and filling processes. The suspension of the conveyor belt is fixed under the rear support. The conveying belt of the filling zone is equipped with multiple position-adjustable plow unloaders to control the unloading position of the filling gangue and facilitate the adjustment of the filling zone.

The cutting device of the cutting zone is derived from the scaling transformation of the continuous highwall mining system. The main body of the cutting device in the cutting zone is located within the rear support range and can travel along the inclination of the working face. When the cutting device cuts the roof of the cutting zone, the rear probing beam retracts, and the cutting part extends to cut the roof. The rear probing beam in the filling zone remains extended. The cutting device is connected to the conveyor belt through a movable belt, feeding crushed gangue onto the conveyor belt.

The lateral support metal mesh is pre-placed on the protective support on both sides of the filling zone. As the support advances forward, it automatically unfolds continuously, serving as the boundary on both sides of the filling zone. Mechanical automated anchor bolts, evenly spaced and fixed to the roof and floor, provide lateral constraint to the gangue pillars in the filling zone. Simultaneously, the compaction device applies prestress compaction to ensure the stability of the gangue pillars in the filling zone.

3. Simulation of Cut-and-Fill Mining

In this study, the mining effect of the cut-and-fill mining and caving method is calculated with the help of the classical numerical simulation of FLAC3D 5.0, which can obtain reliable result data and provide some data support for the validation and application of this method. Although the use of FLAC3D 5.0 for stress analysis is not new and FLAC3D 5.0 primarily models plastic failure mechanisms rather than realistic fracture formation, using indirect methods like equivalent plastic strain distributions to represent complex geological phenomena, these simulations are crucial to demonstrate the effectiveness and feasibility of our method, particularly in the context of coal mining, where ground control is a significant challenge.

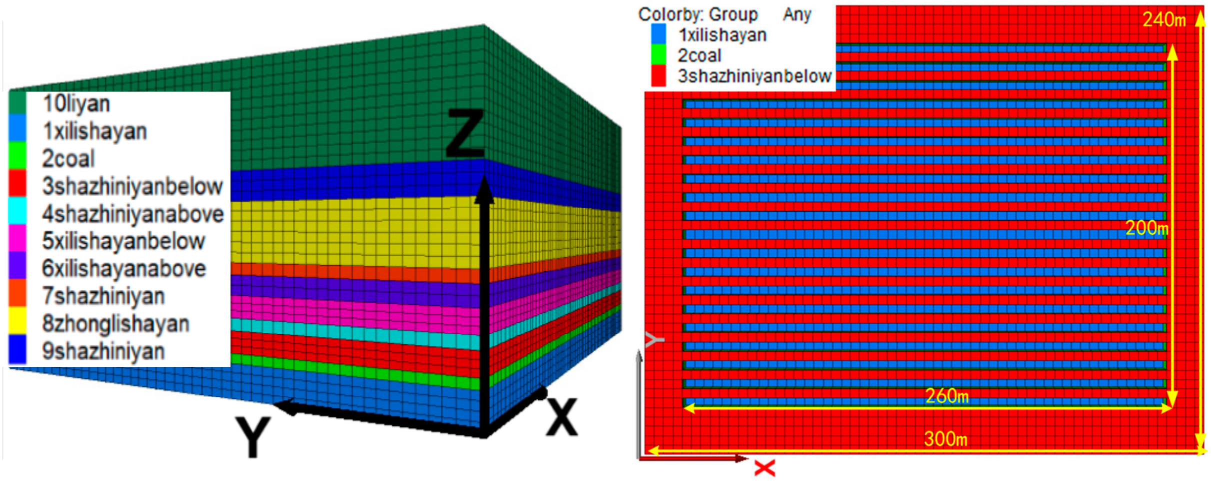
3.1. Model Construction

The coal mine used in this section is in Inner Mongolia, China. The closer the rock parameters used in numerical simulation are to the actual field conditions, the better the simulated results. However, some simplifications are necessary in the actual process of model construction. Regarding the results of previous rock mechanics tests and crushed-gangue compression tests, the rock layers in the simulation model are simplified and reasonably assigned, as shown in Table 1.

Table 1. Mechanical parameters of rock formation.

Rock Type	Bulk Modulus (GPa)	Shear Modulus (GPa)	Density (kg/m^3)	Internal Friction Angle (°)	Cohesion (MPa)	Tensile Strength (MPa)
Fine Sandstone	2.270	2.050	1760	28	1.10	1.100
Mudstone	1.800	1.560	2080	32	1.50	1.200
Sandy Mudstone	2.060	1.860	2000	31	1.50	1.300
Coal	1.400	0.540	1400	32	0.50	0.500
Crushed Gangue	0.006	0.004	1280	15	0.03	0.002

As illustrated in Figure 3a, the three-dimensional computational model created for this simulation measures 300 m in length, 240 m in width, and 134 m in height. The side boundaries of the model are constrained in horizontal displacement, the bottom boundary is constrained in the vertical direction, and the upper boundary is free.



(**a**) 3 D schematic diagram (**b**) Schematic plan

Figure 3. The numerical simulation mode.

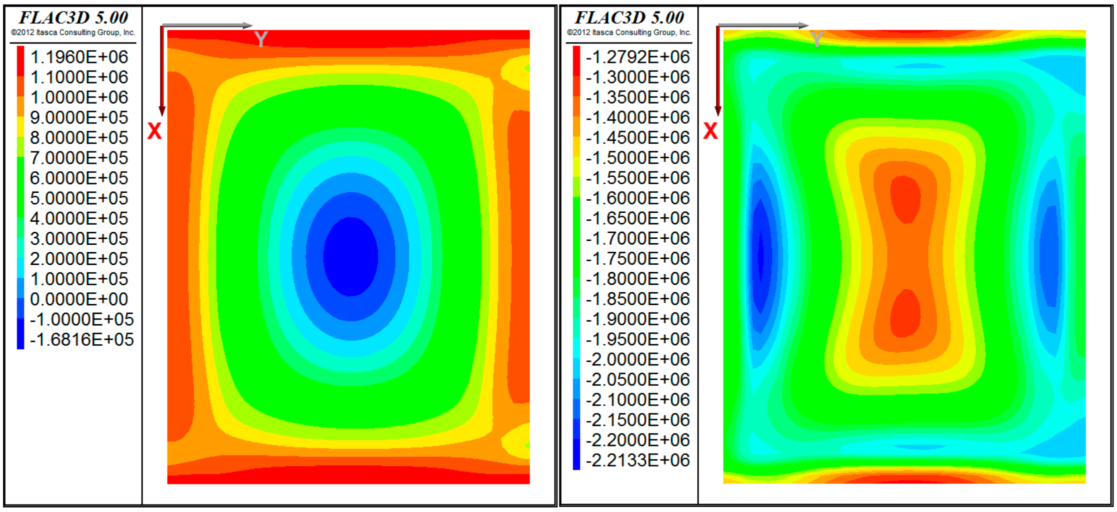
During the mining process, two monitoring lines are established: one for vertical and horizontal displacement on the surface and another for the maximum and minimum principal stresses within the rock layers. Monitoring Line 1 is positioned at the top of Layer 1 ($Z = 130$ m), with coordinates $Y = 120$. Monitoring points are placed every 10 m along the X direction to observe both the horizontal and vertical displacement of the ground. Monitoring Line 2 is located at the top of Layer 8 ($Z = 78$ m), and also has coordinates $Y = 120$. Monitoring points are set every 10 m along the X direction to measure the maximum and minimum principal stresses at that location.

As shown in Figure 3b, the mining area is divided into 20 cutting and filling strips along the strike, with each strip having a mining width of 10 m, consisting of a 5 m cutting width and a 5 m filling width. The cutting height is 3 m, and the filling height is 4 m (with a mining height of 4 m), resulting in an expansion coefficient of 1.33. A 20 m boundary is left around the perimeter of the mining area. The working face is arranged along the coal seam's dip, with a working face length of 200 m and an accumulated filling width of 100 m. The working face is mined along the coal seam's strike, with a total mining length of 260 m. The data in this paper are derived from the simulation software and edited by Origin software.

3.2. Result Analysis

3.2.1. Analysis of Stress Distribution Patterns

Based on the numerical calculation results, stress contour maps at equilibrium were obtained for Layer 8 at Z = 78 m and Y = 120 m, as shown in Figure 4. Additionally, the stress monitoring data curves at Z = 78 m are presented in Figure 5.



(**a**) Minimum principal stress (**b**) Maximum principal stress

Figure 4. Maximum and minimum principal stress contour at Z = 78 m when at mining equilibrium.

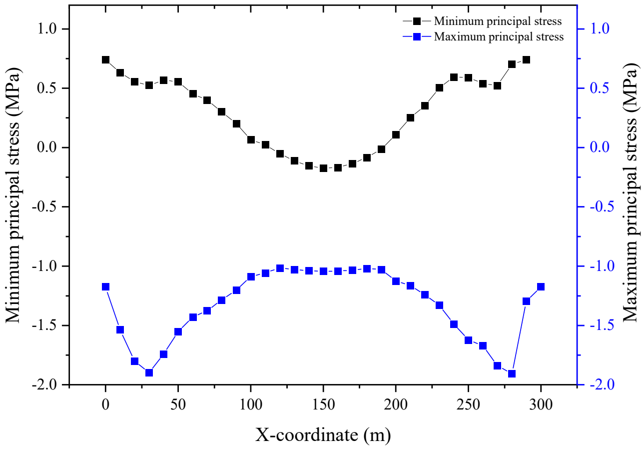


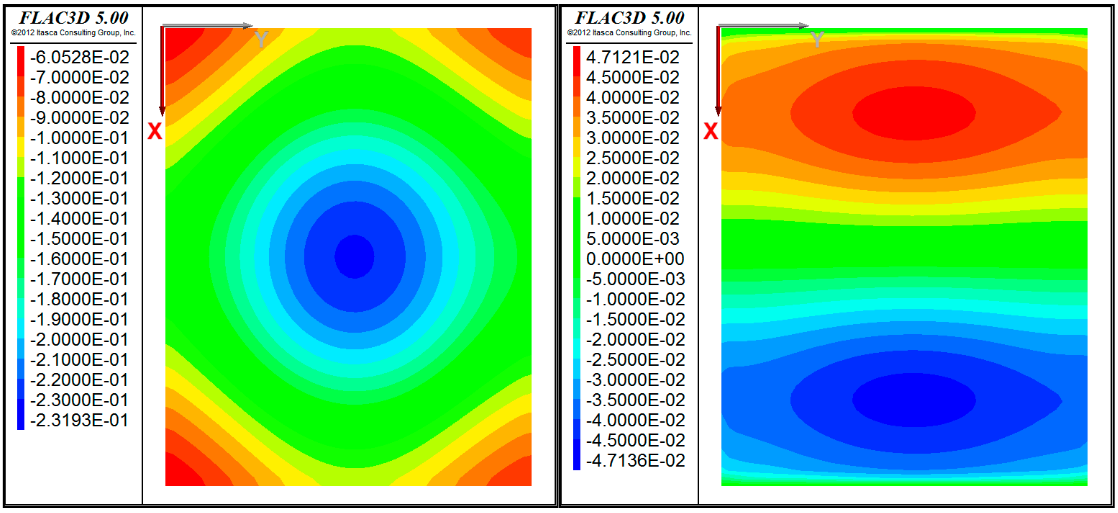
Figure 5. Principal stress curve of Y = 120 m × Z = 78 m when at mining equilibrium.

As shown in Figure 4, after cut-and-fill mining equilibrium, the distribution of the maximum principal stress generally exhibits a trend of decreasing stress near the center of the goaf. Similarly, the minimum principal stress generally shows a trend of increasing stress near the center of the goaf. That is, the σ_1-σ_3 values become smaller, indicating that in the Z = 78 m, areas closer to the center of the goaf are less prone to instability and failure. The rock layer's load-bearing capacity is stronger, reflecting the load-bearing role of the critical layer.

Figure 5 reveals that after the cut-and-fill mining equilibrium, the stress distribution along the Y = 120 m × Z = 78 m monitoring line shows a symmetrical pattern. The maximum principal stress for cut-and-fill mining is 1.93 MPa, located at X = 30 m and 280 m, while the maximum value of the minimum principal stress is 0.17 MPa, located at the center of the goaf. This pattern again suggests that the maximum principal stress generally decreases near the center of the goaf, while the minimum principal stress generally increases near the center of the goaf. This is beneficial for the rock layer to resist failure and stabilize the mining-induced stress after instability.

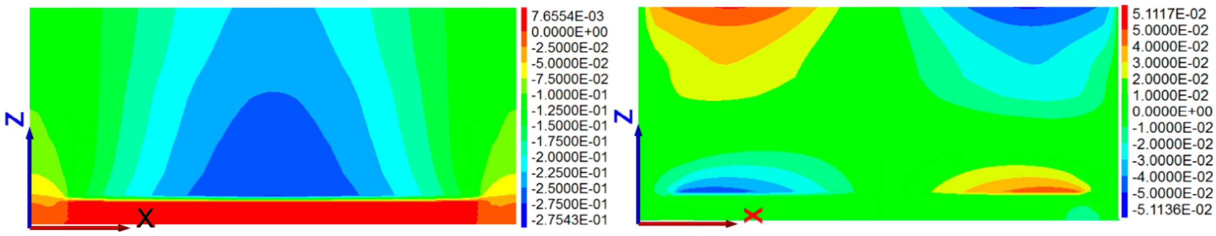
3.2.2. Analysis of Displacement Distribution Patterns

Based on the numerical calculation results, displacement contour maps at equilibrium were obtained for Z = 130 m and Y = 120 m, as shown in Figures 6 and 7. Additionally, displacement monitoring data at Z = 130 m × Y = 120 m are presented in Figure 8.



(**a**) Vertical displacement (**b**) Horizontal displacement

Figure 6. Displacement contour maps at equilibrium for Z = 130 m.



(**a**) Vertical displacement (**b**) Horizontal displacement

Figure 7. Displacement contour maps at equilibrium for Y = 120 m.

As illustrated in Figures 6 and 7, after the cut-and-fill mining equilibrium, the vertical displacement exhibits a standard symmetric distribution, while the horizontal displacement shows a standard anti-symmetric distribution. The vertical displacement value increases with being near the mined coal seam, while the horizontal displacement value increases with being near the surface or mined coal seam.

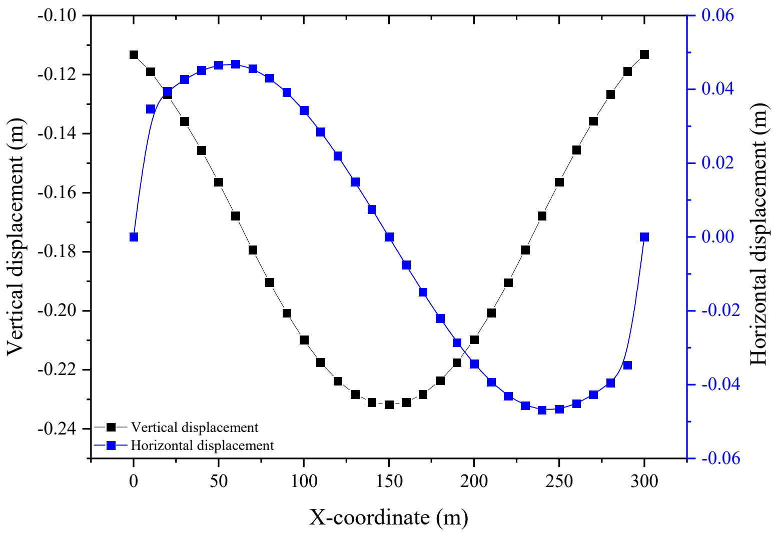


Figure 8. Displacements of Z = 130 m × Y = 120 m when at mining equilibrium.

Figure 8 demonstrates that after the cut-and-fill mining equilibrium, the maximum vertical displacement is 0.23 m, coinciding with the center of mining. The corresponding subsidence coefficient is 0.06. The horizontal displacement has two extreme centers at X = 50 m and X = 250 m, with an absolute maximum value of 0.05 m.

3.2.3. Analysis of Plastic Zone Distribution

Based on the numerical simulation results, plastic zone distribution maps at the equilibrium are shown in Figure 9. Plastic zone failure is mainly characterized by shear failure, and the distribution of plastic zones exhibits development along the edge of the mined-out area and the coal mining boundary. The overlying strata are well-preserved vertically away from the mining area and horizontally close to the central part of the mining area. In the central part of the mining area, the overlying strata exhibit mainly horizontal subsidence with small fractures. Therefore, the cut-and-fill mining method is beneficial for reducing crack formation in the overlying strata above the mining area and preserving their integrity.

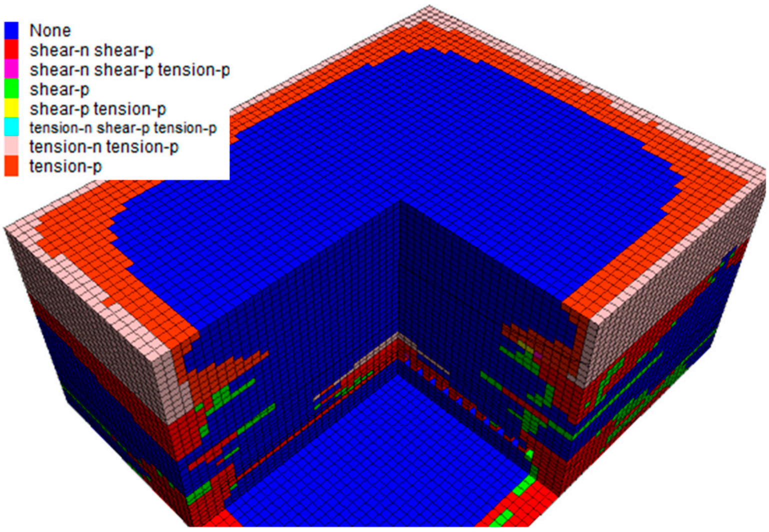


Figure 9. Distribution of plastic zones when at mining equilibrium.

4. Dual Reduction and Triple-Effect Balance

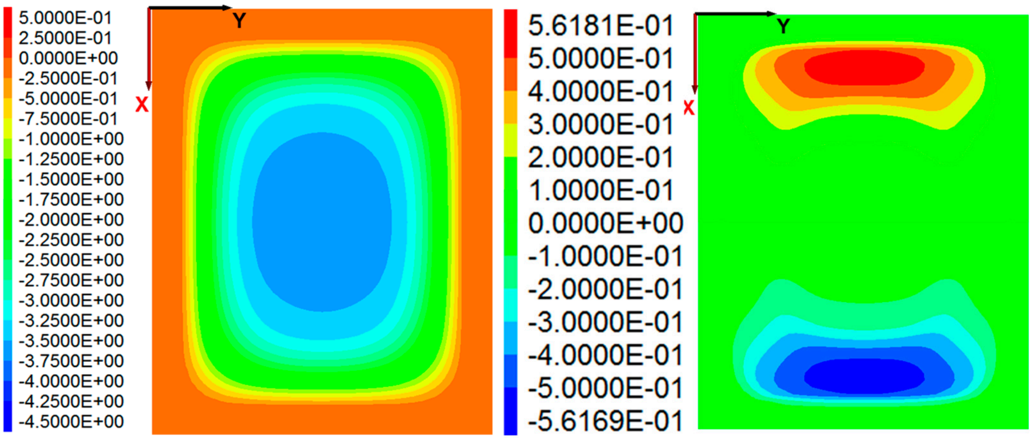
4.1. Dual Reduction Effect

4.1.1. Subsidence Reduction Effect

Continuing to use FLAC3D, we simulated the overlying strata failure characteristics during the caving method, focusing on displacement and plastic zone characteristics. The model construction is almost identical to that of the cut-and-fill mining, with the only difference being that after mining, the model parameters are halved under cut-and-fill mining conditions to simulate the damage caused to the overlying strata by coal seam mining. To prevent excessive subsidence of the roof strata, the calculation is stopped before the roof contacts the floor.

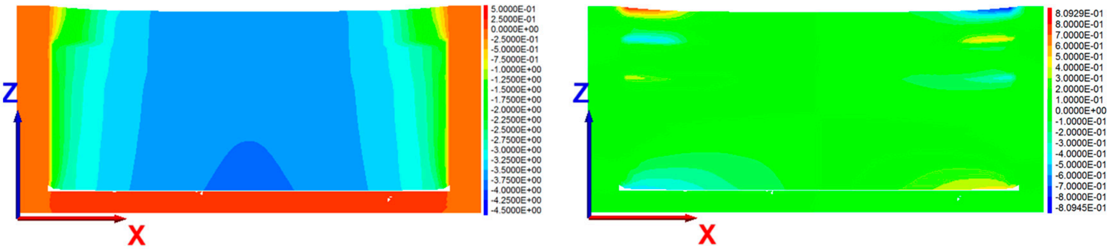
(1) Analysis of displacement distribution

According to the numerical calculation results, displacement contour maps at equilibrium for Z = 130 m and Y = 120 m are shown in Figures 10 and 11, and displacement monitoring data at Z = 130 m × Y = 120 m are presented in Figure 12. As illustrated in Figures 10–12, in the caving method, vertical displacement exhibits a standard symmetrical distribution, and horizontal displacement shows a standard anti-symmetrical distribution. As we move away from the surface, the vertical displacement values increase, but the magnitude of increase is not substantial. The maximum vertical displacement at the surface is 3.67 m, while in the goaf, it reaches 3.79 m. Compared to cut-and-fill mining, the maximum vertical displacement has increased nearly 20 times, and the subsidence coefficient is almost equal to 1. As one moves closer to the surface or the mining area, the horizontal displacement values increase. The maximum absolute value of horizontal displacement at the surface is 0.6 m, representing an almost 10-fold increase compared to cut-and-fill mining.



(**a**) Vertical displacement (**b**) Horizontal displacement

Figure 10. Displacement contour maps at equilibrium for Z = 130 m.



(**a**) Vertical displacement (**b**) Horizontal displacement

Figure 11. Displacement contour maps at equilibrium for Y = 120 m.

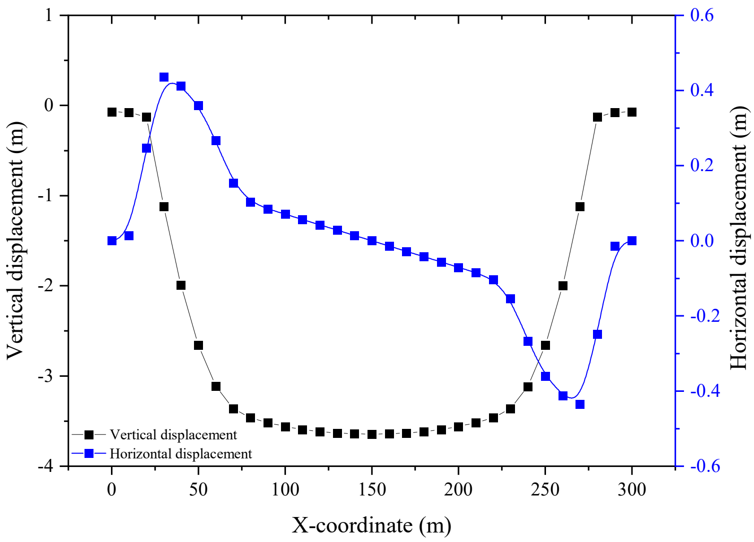


Figure 12. Displacements of Z = 130 m × Y = 120 m when at mining equilibrium.

(2) Analysis of distribution law of plastic areas

According to the numerical calculation results, Figure 13 shows the distribution of plastic zones at the balanced state. It can be observed that the overlying strata in the mined area are almost completely damaged. Through comprehensive comparative analysis, the conclusion can be drawn that, compared to the caving method, the cut-and-fill mining significantly reduces surface deformation and the distribution of plastic zones. The stress distribution in the mined area also exhibits clear regularity, which is beneficial for better prediction and the prevention of surface subsidence.

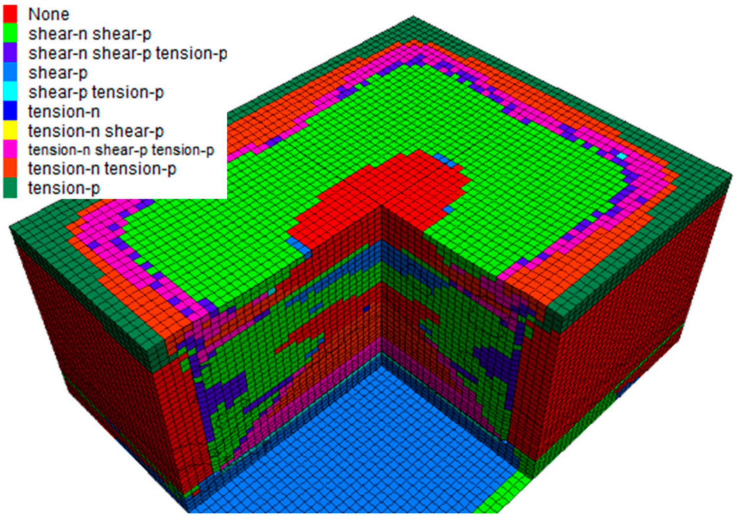


Figure 13. Distribution of plastic zones when at mining equilibrium.

(3) Analysis of energy change during roof failure

In the process of cut-and-fill mining, the roof has been in the process of the accumulation, dissipation, and mutual conversion of various energy from the open-off cut to the roof collapse. The energy involved includes strain energy, gravitational potential energy, kinetic energy, surface energy, and radiation energy. In the coal seam mining process, the gravitational potential energy is the source of other energy [34,35]. As shown in Figure 14, the change of roof energy in the stope can be divided into two parts: energy accumulation and energy release. Meanwhile, energy accumulation and energy release run through the whole process of roof failure.

When the roof is broken, the energy is mainly released by surface energy, radiation energy, and kinetic energy. At this time, the energy conversion rate is almost completed in an instant, and there is a risk of dynamic disasters such as energy accumulation, strain energy release, and gravitational potential energy release. When the roof is broken, part of the gravitational potential energy and strain energy are converted into radiation energy, which is transmitted to the front roof and coal body in the form of a vibration wave. If the strain energy accumulation in the front coal rock mass is in a critical state, the disturbance of this radiation energy will cause instability and cause dynamic disasters of strain energy release.

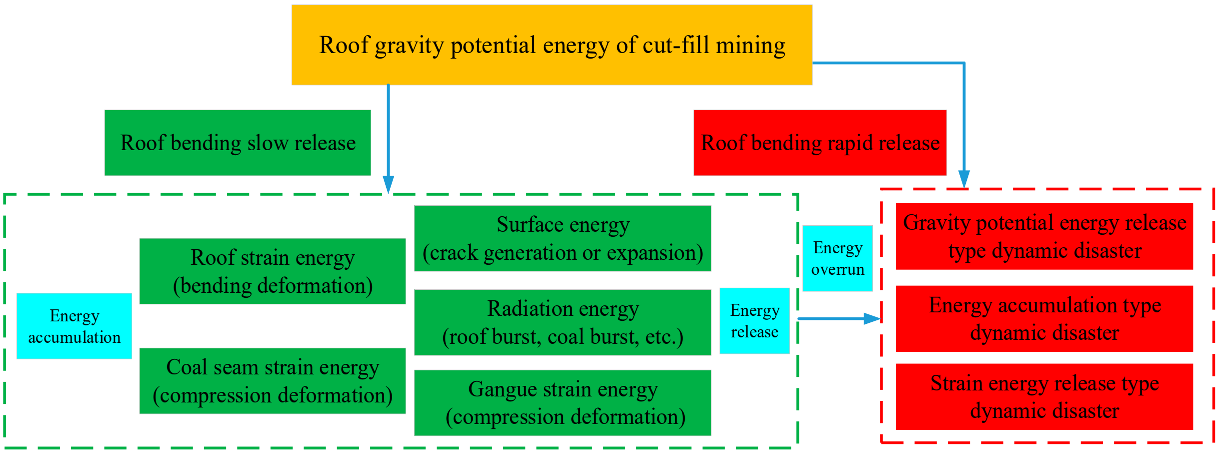


Figure 14. Energy variation in process of deformation until breaking of roof.

From the simulation analysis above, it can be observed that the maximum vertical displacement in cut-and-fill mining is only 5% of that observed in caving mining, while the maximum horizontal displacement is reduced to 10% of that in caving mining. This significant reduction in vertical displacement of the roof greatly enhances safety by controlling the source of energy generation that leads to dynamic disasters. Additionally, the substantial decrease in horizontal displacement of the surrounding rock indicates that the transfer of gravitational potential energy from the roof substantially reduces the risk of local energy accumulation.

Moreover, cut-and-fill mining slows down the roof movement rate, thereby reducing the rate of energy conversion and the release rates of surface and radiation energy. This approach aligns with the strain energy change rate, promotes energy dissipation before roof fracture, and minimizes energy release during roof failure, thus mitigating the occurrence of dynamic disasters associated with strain energy release.

In conclusion, the surrounding rock deformation in cut-and-fill mining is significantly reduced, leading to a notable decrease in both the amount and rate of energy release during roof failure. This, in turn, lowers the risks associated with dynamic disasters caused by elastic energy accumulation and gravitational potential energy release. This paper analyzes the energy source responsible for dynamic disaster events, particularly the roof deformation induced by mining and the energy conversion process. The next phase of research will focus on quantifying the amount and proportion of energy conversion during specific processes in cut-and-fill mining.

4.1.2. Emission Reduction Effect

Coal gangue accounts about for 15% to 20% of China's total coal production [16,36]. Due to its low calorific value and difficulties in utilization, it is often openly piled around the mining area. As shown in Figure 15, the coal gangue production was approximately 8.13×10^8 tons in 2023. The carbon emissions caused by the traditional caving mining method mainly come from the following aspects: coal bed methane release, the spontaneous combustion of coal and coal mine waste, and machinery and equipment transportation, among others. According to some studies [37–40], the unit carbon emission of collapse coal mining is about 0.2–0.4 tons of carbon equivalent/ton of coal. Cut-and-fill mining enables the underground selection of coal gangue, facilitating on-site filling and saving energy consumption and surface disposal management costs. At the same time, it can greatly reduce the carbon equivalent/ton of coal.

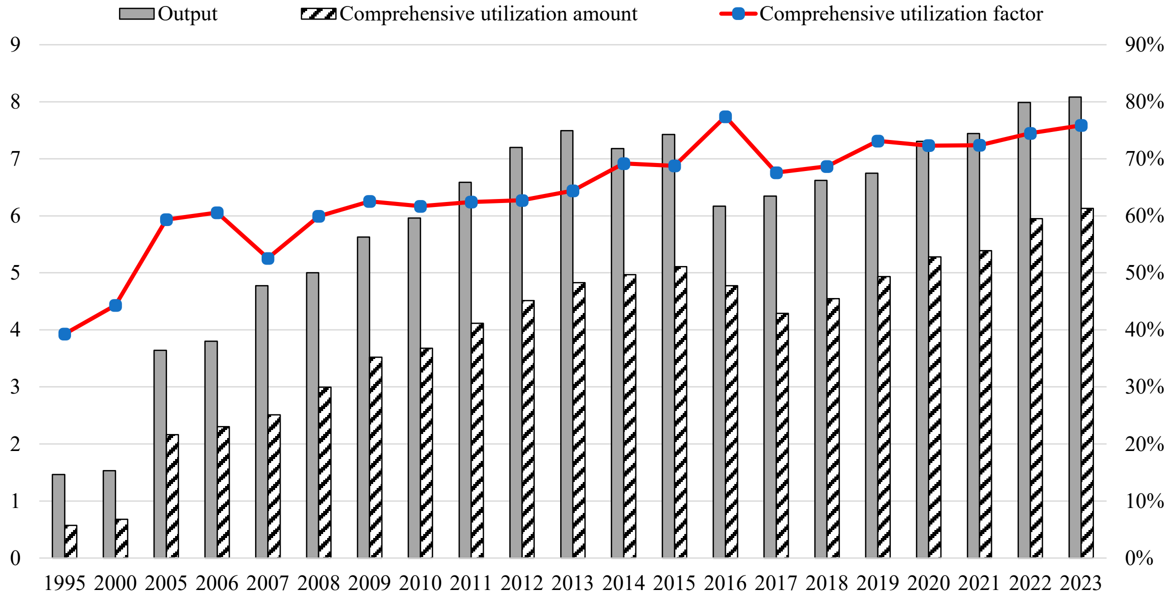


Figure 15. History of the output and utilization of coal gangue in China.

With certain combustible substances in coal gangue, spontaneous combustion can occur under certain conditions, and the toxic and harmful gasses such as nitrogen oxides, carbon oxides, sulfur dioxide, and smoke are discharged. The carbon content of coal gangue is about 25%~30% [16,17,41,42]. The ground accumulation of coal gangue easily causes slow oxidation, which generates greenhouse gasses such as CO_2, and so this is estimated to reduce the production of about 500 million tons of CO_2.

4.2. Triple-Effect Balance

4.2.1. Balancing Coal Mining Capacity with Filling Capacity

Based on practical experience from filling mining at the Daizhuang Coal Mine in China, as shown in Figure 16, the additional cost per ton of coal due to filling mining is 105 yuan. After excluding expenses such as tunneling costs, coal gangue treatment, land restoration, and policy support, the actual increase in the cost per ton of coal is approximately 24.3 yuan. The primary constraint limiting the widespread adoption of filling mining methods in China is not the increase in cost per ton of coal, but the significant mismatch between filling capacity and coal mining capacity.

Traditional filling mining methods severely constrain coal mining efficiency, leading to a substantial reduction in production capacity and, consequently, a significant decrease in coal mine profits. In contrast, cut-and-fill mining allows for the separation of the mining and filling processes, enabling the simultaneous operation of both. This effectively eliminates mutual interference and the time losses associated with staggered operations. Since cut-and-fill mining is a form of partial filling, it results in a shortened filling time. Additionally, the integration of long-wall mining in cut-and-fill operations ensures high coal mining efficiency.

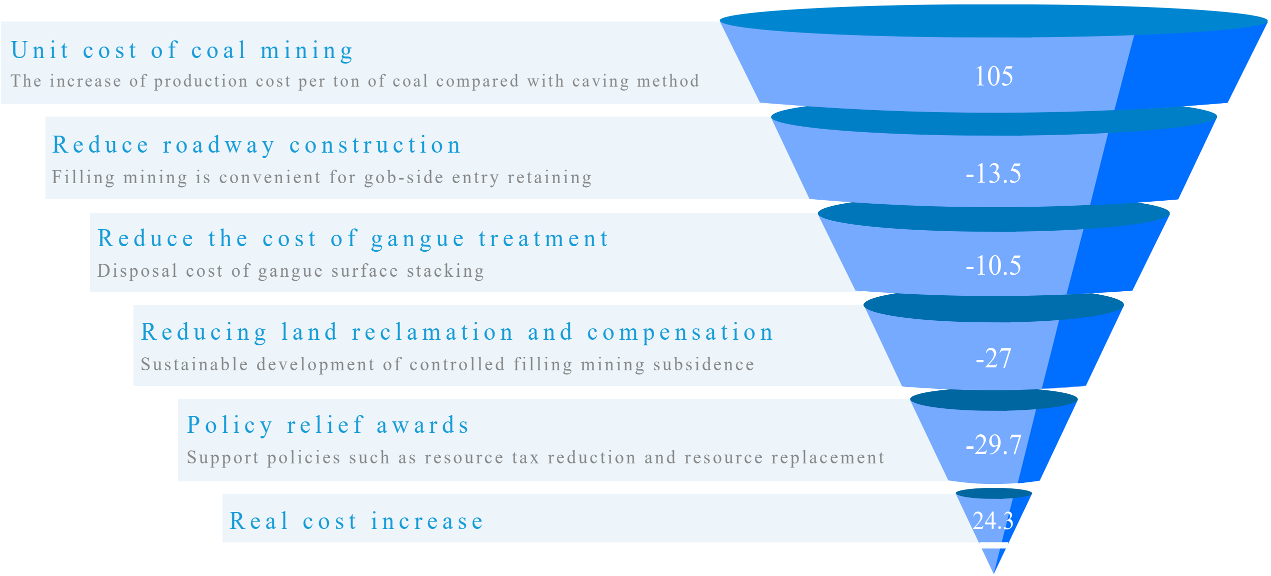


Figure 16. Increase in filling mining cost in Daizhuang Coal Mine in China.

4.2.2. Balancing Supply and Demand of Filling Materials

As shown in Figure 17, in the "Mining + Cutting + Filling" mode of cut-and-fill mining, all filling materials are sourced from the partially cut roof in the goaf. One of the fundamental principles of cut-and-fill mining is to maintain an equal volume of cutting and filling, meaning the volume of crushed gangue generated from cutting the roof should be equal to the volume of the filling material. By determining the parameters of the cutting area, the corresponding parameters of the filling area can thus be established.

In cases where subsidence control is a critical requirement, an alternative "Mining + Cutting + Separation + Filling" mode may be adopted. In this mode, gangue selected from underground serves as auxiliary filling material for the cut-and-fill mining process. This approach enhances the filling effect without increasing the support and cutting strength of the cut-and-fill mining operation, thus minimizing the environmental impact while improving the overall effectiveness of the filling process.

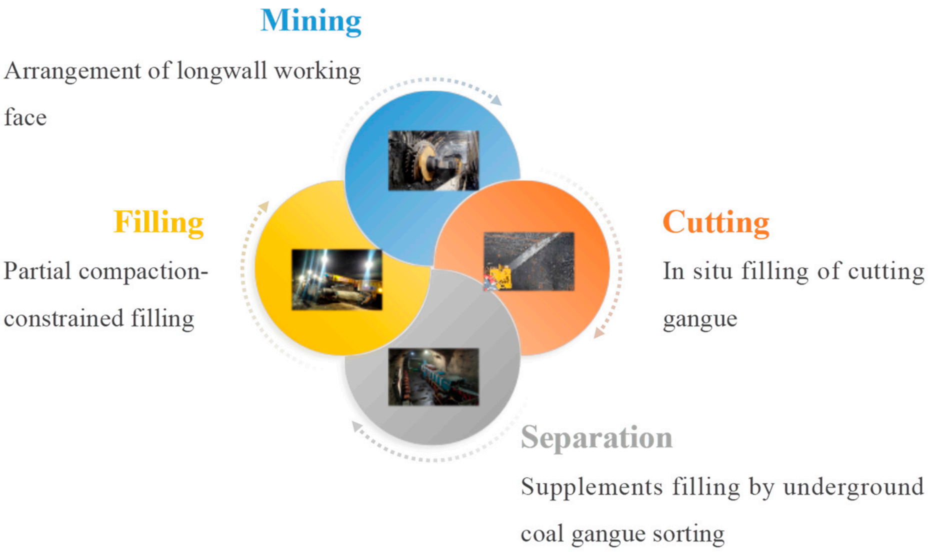


Figure 17. Mining technology and gangue source of cut-and-fill mining.

4.2.3. Balancing Filling Costs and Mining Benefits

For coal mines, the primary motivation for filling is to avoid resettlement conflicts and land compensation. However, once the cost of filling exceeds that of land compensation, coal mines often choose not to backfill production under profit-driven motives, leading to irreparable environmental losses.

As shown in Figure 18, cut-and-fill mining significantly improves filling efficiency, reduces costs related to filling materials, and decreases the emissions of mining damage and coal gangue. This is beneficial for achieving a balance between filling costs and mining benefits, promoting the application of filling mining methods.

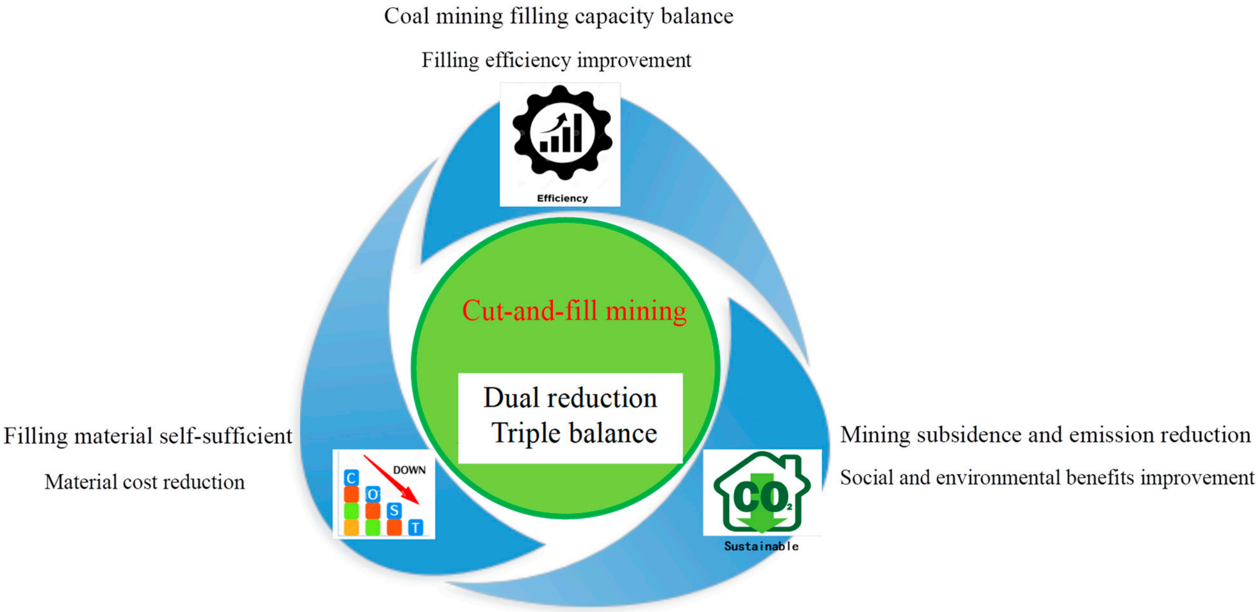


Figure 18. Double reduction and triple effect of cut-and-fill mining.

5. Discussion

5.1. Existing Technical Foundation

The key to cut-and-fill mining lies in the stability of the cutting space and the safety of the cutting operation. Achieving these objectives requires innovation based on the existing coal gangue filling technology system. After nearly 20 years of development, coal gangue filling technology has evolved through four generations, forming a new paradigm for modern green coal mining known as ‘mining and filling + X’. The primary research and development goal at this stage is to minimize ecological damage at the source of mining methods. The specific process is outlined in Figure 19 [8–10].

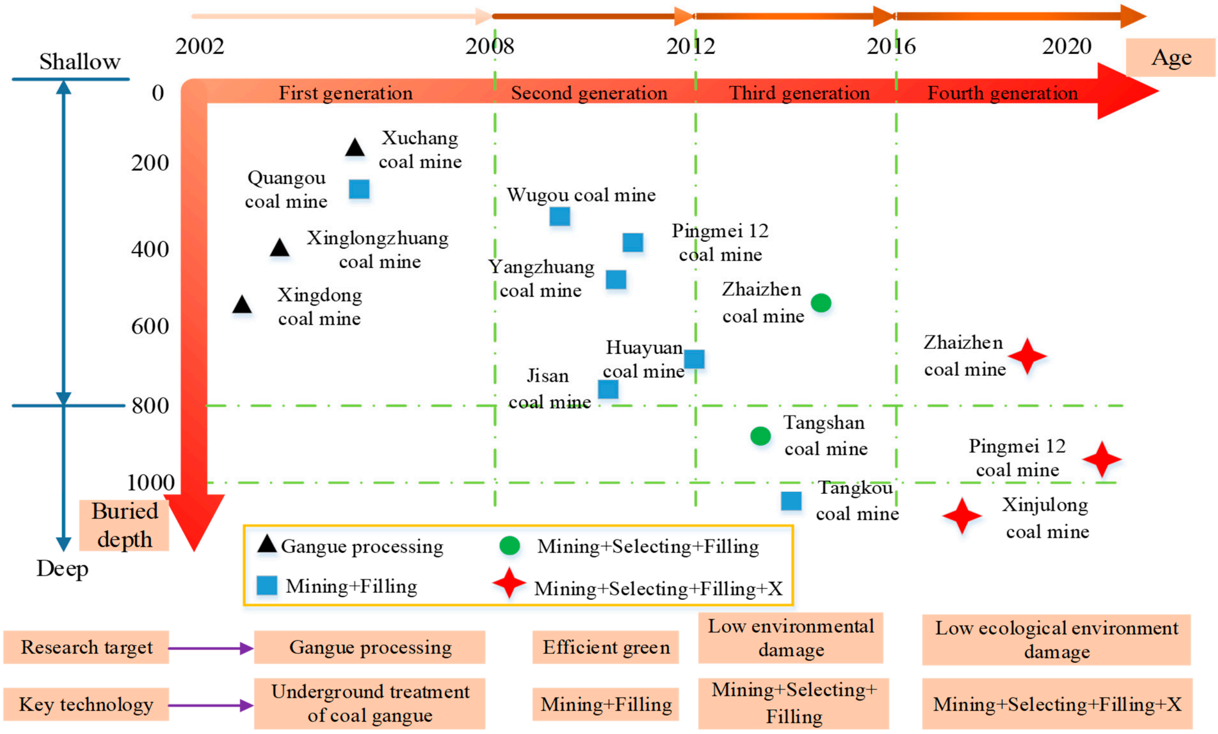


Figure 19. Development history of mining–dressing–backfilling + X.

Throughout the development of coal gangue filling technology, numerous new technologies and processes have emerged, particularly with the continuous upgrading of coal gangue filling hydraulic supports. This evolution has undergone four generations of innovation. Currently, ◎mining and filling + X′ coal mining has achieved the parallel operation of mining and filling, as well as the integration of mining and filling equipment. The main challenges remain the shortage of gangue materials and the complexities of filling and transportation.

The starting point of cut-and-fill mining is to ensure the self-reliance of filling materials and in situ underground filling, aiming to reduce and control subsidence. This approach provides a feasible solution to the current issues faced by ◎mining and filling + X′. However, cut-and-fill mining requires the addition of a roof cutting device behind the support, necessitating the transformation and upgrading of existing coal gangue filling hydraulic supports. With its development history and the current strong manufacturing industry as a support, it is feasible to further modify existing filling supports to meet the needs of cut-and-fill mining.

The coal mining filling technology, and potential underground coal gangue separation in cut-and-fill mining, are largely consistent with the current fully mechanized solid filling method and can serve as the foundation for cut-and-fill mining. The main distinction between cut-and-fill mining and current ◎mining and filling + X′ coal mining is the roof cutting process, and the roof cutting process can be realized by advanced manufacturing.

5.2. Distinct Advantages

Compared to traditional caving and filling mining methods, cut-and-fill mining presents several distinct advantages:

(1) Efficiency: it allows for simultaneous mining and filling processes, minimizing interference and time losses, which maintains a high coal mining efficiency.

(2) Economic balance: It achieves a better balance between coal mining capacity and filling capacity, optimizing the supply and demand of filling materials, and providing a favorable cost–benefit ratio.
(3) Technological innovation: it incorporates advanced technology into the mining process, such as hydraulic supports equipped with cutting devices, which not only facilitates the roof cutting process but also represents an evolution from traditional coal gangue filling technology.

In summary, the cut-and-fill mining method investigated in this study provides a sustainable approach that enhances mine safety, efficiency, and ecological conservation. Its adoption could lead to significant advancements in addressing technical challenges faced by the coal industry, making it a promising practice for future mining operations.

5.3. Prospects for Further Research

According to industry statistics, the total number of coal mines in China is about 4000, and about 200 coal mines adopt the filling mining process. The proportion of filling mining in China is about 5%, and the proportion of the gangue filling process is even less. The main reason why it is difficult to popularize is the shortage of adequate filling materials; the cut-and-fill mining proposed in this paper can realize the partial filling and the partial filling materials for cut-and-fill mining come from part of the cutting roof of the goaf, which can realize self-sufficiency and in situ filling. However, there are several areas where improvements can be made.

(1) Refining the cut-and-fill mining system: developing advanced methods and equipment specifically designed for the unique requirements of cut-and-fill mining.
(2) Comparative analysis of parameters: To better understand the parameters influencing the cut-and-fill mining method, a comparative analysis was conducted between different coal mines and similar operations in other regions worldwide. This comparison revealed variations in geological conditions, equipment capabilities, and operational practices, highlighting the need for site-specific optimizations. For instance, differences in strata thickness, rock hardness, and water content can significantly impact the effectiveness of the cut-and-fill method.
(3) Influence of key parameters on simulation results: One significant advantage of numerical simulation is its ability to conveniently study the influence of key parameters on calculation results. Variables such as the depth of cut, spacing of cuts, material properties, and support systems were systematically varied to assess their impacts on mining stability and productivity. The simulations allowed us to identify optimal parameter settings that maximize efficiency while minimizing risks. For example, increasing the depth of cut may enhance productivity but could also lead to greater stress concentrations and potential instability. Therefore, finding a balance through iterative simulations is crucial.
(4) Detailed analysis of energy changes during deformation: A more detailed analysis of the change in energy during the deformation process before roof failure is essential for predicting and preventing catastrophic failures. Numerical models provided insights into how energy accumulates within the rock mass as it deforms, eventually leading to sudden release at the point of failure. By monitoring energy levels throughout the deformation process, we can anticipate critical thresholds and implement preemptive measures to stabilize the roof structure. Understanding these energy dynamics allows for the development of early warning systems and the improved design of support structures, enhancing mine safety.

6. Conclusions

This study has focused on investigating the cut-and-fill mining method, specifically its effects on stress distribution, displacement patterns, plastic zone formation, and energy changes during the mining process. To achieve this, numerical simulations using FLAC3D were conducted to analyze the behavior of overlying strata and the extent of surface deformation under different mining conditions compared to traditional caving methods.

(1) Stress distribution and displacement patterns: The simulation results demonstrate that near the mined-out area center, the maximum principal stress decreases, while the minimum principal stress increases, after mining with cut-and-fill methods. The analysis of displacement shows a symmetric vertical displacement pattern and an anti-symmetric horizontal displacement pattern. Notably, the maximum vertical displacement at the mining center is 0.23 m, with a subsidence coefficient of 0.06, and horizontal displacement peaks at 0.05 m. These findings indicate significantly reduced surface deformation compared to caving mining.

(2) Plastic zone analysis: Plastic zone development primarily occurs along the edges of the mined-out area, while the overlying strata remain largely intact in the central region, exhibiting mainly horizontal subsidence with minimal fractures. This suggests that cut-and-fill mining can preserve the integrity of the overlying strata and minimize plastic zones, thereby reducing the risk of surface fractures.

(3) Energy release mitigation: Cut-and-fill mining notably reduces the amount and rate of energy release during roof failure, lowering the risks associated with dynamic disasters caused by elastic energy accumulation and gravitational potential energy release. By controlling the source of energy generation and slowing down the roof movement rate, this method minimizes energy release during roof failure.

(4) Environmental and economic benefits: One of the most significant advantages of cut-and-fill mining is its positive impact on the environment and economy. It decreases coal gangue emissions through on-site filling, reducing the need for surface disposal and lowering carbon emissions, potentially cutting CO_2 production by approximately 500 million tons. Moreover, it offers economic benefits by improving filling efficiency, reducing costs related to filling materials, and achieving a favorable balance between filling costs and mining benefits.

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