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Research on Strip Coal Pillar Technology under the Construction Group of Gangue Filling and Recycling

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Abstract

In order to reduce the various impacts of surface movement caused by coal mining on the human living environment, avoid the accumulation of coal gangue on the surface, and recover the strip coal pillar resources left under urban areas, based on the stability of the binary bearing structure composed of backfilled gangue and narrow coal pillars after strip mining and the characteristics of the equivalent mining height model, theoretical analysis and numerical simulation methods were comprehensively used to analyze the factors affecting the stability of coal pillars, the ultimate strength of coal pillars, and the safety factor of coal pillar stress under the condition of binary bearing structure. Through comparative analysis of deformation of surrounding rock after strip mining and coal pillar recovery, it was found that the mining pressure manifestation of strip coal pillar gangue filling is weak, without obvious initial and periodic pressure phenomena, and the top control is relatively easy without the risk of dynamic pressure. The research results provide useful reference and guidance for the first application of fully mechanized mining technology in urban strip coal pillar recovery in coal mines.

Keywords

Backfill Mining; Coal Pillar Recycling; Overburden Movement; Factor Analysis; Numerical Simulation.

1. Introduction

The "three underground" coal mining volume of state-owned coal mines in China is as high as tens of billions of tons [1]. Therefore, safe and efficient mining of this coal resource is one of the key technologies to extend the service life of mines and ensure their sustainable development. Many strip coal pillar design theories have been developed abroad, such as effective zone theory, pressure arch theory, limit equilibrium theory, etc. Various formulas for calculating coal pillar strength have been proposed, such as the most commonly used Obert Duvall/Wang formula, Holland formula, Salamon Mnuro formula, Bieniawski formula, etc. [2-7]. The domestic strip mining method began in 1967. A coal mine in Fushun adopted the filling strip mining method to recover coal under buildings and achieved good results. Jiang Zhenquan and Ji Liangjun analyzed the crushing and compaction characteristics of coal gangue, and found that the insufficient particle size distribution of coal gangue can be compensated by crushing the gangue [8]. Miao Xiexing conducted laboratory experiments to study the fragmentation and compaction characteristics of coal gangue, and obtained the lateral pressure curve, fragmentation coefficient, and compaction curve of coal gangue [9]. Ma Zhanguo pointed out that the stress-strain of saturated coal gangue is an exponential function, the stress and fragmentation coefficient are logarithmic functions, the stress and porosity are cubic functions, and the stress and deformation modulus are linear functions. At the same time, the particle size

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of gangue has a significant impact on the changes of the above functions [10]. Tang Zhixin analyzed the mining and compaction characteristics of coal gangue foundation through numerical simulation, and theoretically provided the engineering mechanics laws of coal gangue, as well as the range of variation of bearing capacity and compaction coefficient [11].

In response to the dense and important buildings on the ground in coal mining areas, the use of collapse mining method is difficult to ensure the safe use of buildings and may bring unforeseeable social conflicts. If partial mining is adopted, it will result in huge losses of coal resources. From the analysis of relocation costs, site selection, and feasibility, it is almost impossible to relocate a complex of buildings. Therefore, based on the new progress of the "three underground" coal pressing technology in recent years, theoretical analysis, numerical simulation and other methods are used to study the stability of coal pillars, the rationality of roadway support, and the control of overburden deformation and damage under strip coal pillar mining conditions. This can maximize the recovery of coal resources under buildings and improve the economic benefits of mines.

2. Engineering Technical Conditions

The first mining area of Huayuan Coal Mine is the first mining area, with a flat terrain and an elevation of+36.1 to+38.0m. The relative height difference is small, and the overall trend is high in the west and low in the east. Most of the ground is composed of buildings and farmland, and the western part of the mining area is crossed by National Highway 105, with a relatively dense density of surface buildings. The 130 I strip coal pillar test face is located underground to the east of the protective coal pillar at the foot of the East Belt, with the 1309 working face in the north, the 1307 working face in the south, and the boundary protection coal pillar in the east. The upper part of the strip coal pillar and surrounding villages have urban buildings north of Wenfeng Road passing through the middle of the test face.

The average coal thickness in the first mining area is 2.9m, and the coal seam structure is relatively simple. The maximum thickness of the interbedded gangue is 0.35m, located in the middle and lower parts of the coal seam. The interbedded gangue lithology is generally mudstone and carbonaceous mudstone. The overall characteristic of coal seam thickness variation is that it is thicker in the northeast and thinner in the southwest. The roof development is stable, while the direct floor development is unstable. The adjacent 1309 working face in the first mining area is a monocline structure. During the excavation process of the 1309 working face, a total of 28 faults were exposed, all of which are normal faults, with 9 faults greater than 1m having a significant impact. The mine is a low gas mine, with 3 coal seams having explosive properties and Class II spontaneous combustion, and the coal rock has a weak impact tendency. The hydrogeological type is Class II Type I, which refers to mineral deposits with mainly fractured aquifers and simple hydrogeological conditions.

3. Analysis of coal Pillar Stability, Overburden Movement and its Influencing Factors

3.1. Equivalent Mining Height Model for Coal Pillar Filling Mining

According to the mechanical property testing of gangue, its deformation is a constant value when the compressive stress is constant. Therefore, under specific mining conditions, due to a certain burial depth, the compression of gangue in the goaf during strip coal pillar filling mining can be calculated. One of the main factors affecting surface subsidence is mining height, and strip coal pillar gangue filling mining, due to the gangue occupying the goaf space, is equivalent to reducing the coal seam mining height.

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In order to use traditional mining pressure theory for predicting surface deformation, the concept of "equivalent mining height" [12] was introduced (the difference between the actual mining height of the working face and the compacted height of the strip coal pillar gangue filling body). The equivalent mining height Hz of strip coal pillar gangue filling is shown in formula 1.

$$Hz=hz+k(H-hz) \tag{1}$$

Where, Hz is equivalent mining height of strip coal pillar filling mining, m. hz is insufficient roof connection in strip coal pillar filling mining, m. K is the difference between the fragmentation coefficient of gangue and the residual fragmentation coefficient, generally ranging from 0.15 to 0.3. H is mining height, m.

The input data is: Hz=hz+k(H-hz)=0.05+0.17×(3-0.05)=552 mm.

3.2. Analysis of Factors Affecting Coal Pillar Stability

After the strip mining is completed, the goaf gangue and the coal pillars on both sides form a binary bearing structure to support the overlying bearing rock layer and control surface subsidence during the comprehensive mining recovery process of coal pillar gangue filling. Therefore, analyzing various influencing factors on the stability of binary load-bearing structures, studying the stability and failure mechanism of binary load-bearing structures, is crucial for designing reasonable coal pillar recovery parameters.

(1) Calculation of yield zone width of coal pillar

The middle of the yielding elastic zone of the coal pillar is the "core zone", where the coal pillar has high strength and elastic or strain hardening characteristics. As the deformation of the coal pillar increases, its ability to resist deformation gradually increases. The strength of the coal pillar in the yielding plastic zone is relatively low, and its ability to resist deformation gradually decreases with the increase of coal pillar deformation. Through the theory of limit equilibrium, the relationship between the support pressure in the failure zone and the distance between the two sides of the strip coal pillar can be derived, and the width of the plastic zone of the coal pillar can be calculated.

The general calculation formula for the yield zone width of coal pillars [13] is as follows:

$$X_0=\frac{H_z d}{2tg\phi}\left\{\ln\left[\frac{C+\sigma_{Z1}tg\phi}{C+P_x\dfrac{tg\phi}{\beta}}\right]+tg^2\phi\right\}^{\beta} \tag{2}$$

By substituting the mining parameters of Huayuan Coal Mine into formula (3.6), X0 can be obtained:

$$X_0=\frac{H_z d}{2tg\phi}\left\{\ln\left[\frac{C+\sigma_{Z1}tg\phi}{C+P_x\dfrac{tg\phi}{\beta}}\right]+tg^2\phi\right\}^{\beta}=\frac{0.552\times0.25\times1.8}{2tg30^{o}}\left\{\ln\left[\frac{4.1+9.8tg30^{0}}{4.1+0.5\dfrac{tg30}{0.25}}\right]+tg^2 30^{0}\right\}^{0.34}=1.12m$$

If the coal pillar recovery adopts the caving method, there will be triangular space left on the coal wall in the goaf. At this time, no reinforcement measures such as side protection have been

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taken on the coal wall. It can be considered that the lateral constraint force Px of the coal wall is 0. By inputting the mining parameters of Huayuan Coal Mine into:

$$X_0 = \frac{T\beta d}{2tg\phi}\ln\left[1+\frac{\sigma_{z1}}{C}tg\phi\right]+\frac{d}{2}Ttg\phi = \frac{3\times 0.25\times 1.5}{2tg30^0}\ln\left[1+\frac{9.8}{4.1}tg30^0\right]+\frac{1.5}{2}\times 4.5tg30^0 = 5.1m$$

(2) Ultimate strength of coal pillar

The ultimate strength of coal pillars is not only related to the uniaxial compressive strength of coal samples, but also to the rheological coefficient η of coal rock, which determines that the ultimate strength of coal pillars depends on the rheological properties of coal rock. The yielding coal can generate lateral stress on its inner coal body, ultimately leading to plastic constraint. Therefore, the actual peak stress zone should be between unidirectional and triaxial stress states.

After determining the plastic constraint coefficient of the coal pillar, the ultimate strength of the coal pillar can be calculated based on literature [14]:

$$\sigma=\delta\times\eta\times\sigma c=1.67\times0.59\times10.4=10.24MPa$$

3.3. Analysis of Factors Affecting Overburden Failure

(1) Mechanical structure and properties of overlying rock

After the hard rock layer ruptures, the coefficient of fragmentation and expansion is high, filling some of the goaf and reducing the subsidence of the rock layer and surface. However, due to the difficulty of re compaction caused by the fracture of the hard rock layer, large overhangs and voids are formed at the boundary of the goaf, forming a good water conducting channel, resulting in a high height of the water conducting fracture zone. The height of the water conducting fracture zone gradually decreases with the softening of the overlying rock properties. Rigid and brittle rock layers are prone to cracking, while plastic and ductile rock layers are less prone to cracking. Rock layers with rigid plastic and thin thick combinations have good waterproof and seismic resistance.

(2) Structure of overlying rock mass

The rock structure plays a controlling role in the movement and failure of rock layers, and rock masses with different rock structures have significant differences in the process of rock movement and failure. If the overlying rock of the mining site is a loose structure rock mass, it is highly likely to collapse after mining. If the working face is close to a strongly weathered or fault zone rock mass, it is highly likely to be pumped out, and water and sand will flood into the coal mining face, affecting production safety. In the case of repeated mining or coal mining in the downhill direction of inclined coal seams, the collapsed rock mass in the goaf generally slides down along the floor or even rolls and fills into the goaf, and may continue to develop to the surface. Such rock mass is extremely unfavorable for coal mining under water bodies.

(3) The controlling effect of hard rock layers

Practice has shown that one to several hard rock layers play a major controlling role in the activity of overlying rock layers in the mining area. This type of rock formation has the following characteristics: ①Geometric features, relatively thicker than other similar rock layers in a single layer. ②Lithological characteristics, relatively hard compared to other rock layers, with high elastic modulus and strength. ③ Denaturation characteristics refer to the synchronous subsidence of all or part of the rock layers above it during its sinking and deformation. ④Breaking characteristics, the breaking of this rock layer will result in synchronous breaking of all or part of the overlying rock layers, causing movement of the rock layers over a large area.

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⑤The bearing characteristic is that before the rock layer breaks, it takes the form of a "slab" structure as the main bearing body.

After the hard rock layer breaks, it drives the soft rock on top to also break, causing the internal movement of the rock mass to have sudden subsidence and combination. When the separation fissures develop to the bottom of the hard rock layer, they no longer develop upwards due to the support of the hard rock, and the height no longer increases. The hard rock layer can reduce the height of separation fissure development.

(4) Influence of loose layers

The presence or absence of loose layers covering the surface has a significant impact on the characteristics of surface movement, especially on the distribution patterns of horizontal movement and deformation. When the loose layer is thick, the horizontal movement generated by the movement of bedrock attenuates and cannot reach the surface when transmitted within the loose layer. At this time, the surface only experiences horizontal movement caused by the vertical bending of the loose layer. Due to the fact that all three working faces in Huayuan Coal Mine are of medium burial depth or below, and the thickness of the bedrock is relatively large, the loose layer has little impact on the development of overlying rock failure.

(5) Effects of mining thickness and bedrock thickness

When mining single thin, medium thick, and thick coal seams, the height of the caving zone, water conducting fracture zone, and mining thickness are approximately linearly related. The mining thickness is the most important factor affecting the height of overlying rock failure, and the goaf area only plays a role under conditions of insufficient mining. Actual measurements have shown that as the mining thickness increases and the bedrock thickness decreases, the proportion of weak rock layers in the water conducting fracture zone increases. This weak rock layer has a more significant inhibitory effect on the development height of the water conducting fracture zone, resulting in a greater reduction in fracture height.

4. Numerical Simulation of Roadway Support and Strip Coal Pillar Recovery

4.1. Numeric Simulation Scheme

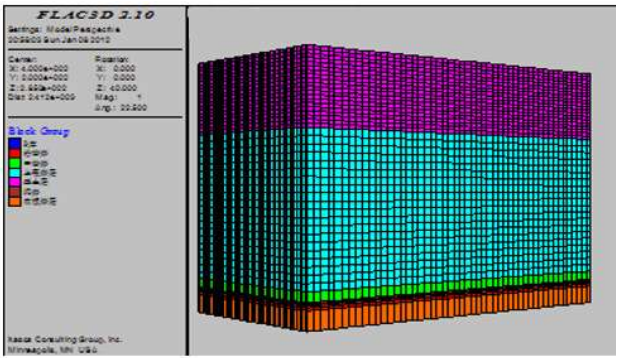

Figure 1. Three-dimensional numerical simulation model

This article mainly uses FLAC3D simulation to study the vertical stress, displacement, and maximum principal stress of strip mining and coal pillar recovery. UDEC simulation is used to study the characteristics of surface subsidence and plastic zone after strip mining and coal pillar recovery. Simplify and establish a simulation model based on the specific ground buildings, geological structures, and hydrogeological conditions of the first mining area of Huayuan Coal Mine under Jining Mining Group. The physical model is an elastic-plastic model, and the plastic yield criterion uses the Mohr Coulomb criterion. Horizontal displacement constraint on the left and right boundaries of the model, fixed constraint on the lower boundary, loading on the upper

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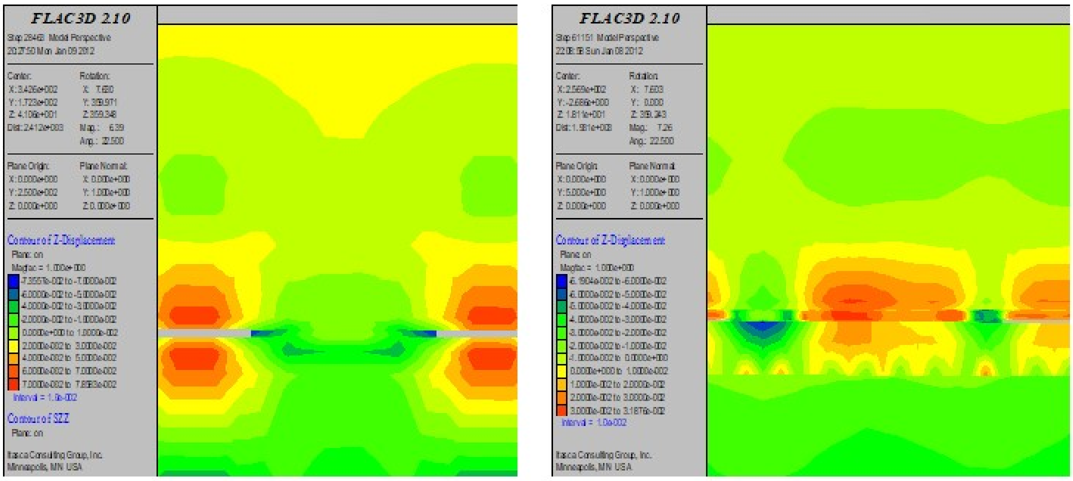
boundary, model burial depth of 670m, model size of 400m (x) × 200m (y) × 250m (z). The established three-dimensional numerical model is shown in Figure 1.

4.2. Analysis of Simulated Result

Numerical calculations were conducted using FLAC3D and UDEC software to simulate the vertical stress, maximum principal stress, and maximum subsidence values of the 1309, 1307, and 1305 working faces after mining. The results were compared with the deformation of the surrounding rock after the recovery of the 130I and 130II coal pillar working faces, as shown in Figure 2.



(a)The maximum mine stress after the mining of the bands (b)The maximum mine stress after the recovery of the pillar

Figure 2. The maximum mine stress after the mining of the bands and the recovery of the pillar

From Figure 2, it can be seen that after the strip coal pillar is mined, the stress state of the coal pillar and the overlying rock layer is changed. The increase in vertical stress causes the coal pillar to undergo compressive deformation. Due to the superposition effect, the subsidence increases continuously from the coal seam roof upwards, leading to surface subsidence. The gangue of the strip coal pillar filling working face bears the force of the overlying rock layer on the roof. The lateral expansion of the gangue filling body will apply lateral stress to the narrow coal pillar, thereby improving the stability and strength of the narrow coal pillar. The vertical compression will ease the pressure of the overlying rock layer on the gangue filling body, which transfers the stress to the rock mass above the coal pillar. The roof rock mass of the working face plays a role as a medium in the stress transfer process between the gangue filling body and the narrow coal pillar, and the pressure of the overlying rock layer acts on the gangue filling body and the narrow coal pillar through this medium.

The peak of the displacement cloud map is the location of strip mining. Due to the suspended top plate, the displacement of the top and bottom plates is greater at this location than at other locations, as shown in Figure 3. From Figure 3, it can be seen that the subsidence value increases within the range of 0-40m from the coal seam roof after strip mining, and gradually increases from top to bottom within the range of 40-80m. After reaching a certain height, the subsidence value remains basically constant or slightly increases. Through the displacement cloud map, it can be found that there is a certain solid rock layer in the overlying rock layer after strip mining, which plays a key controlling role in the movement of the roof of the entire goaf. In this model, the key rock layer is located approximately 75-90 meters away from the top rock layer.

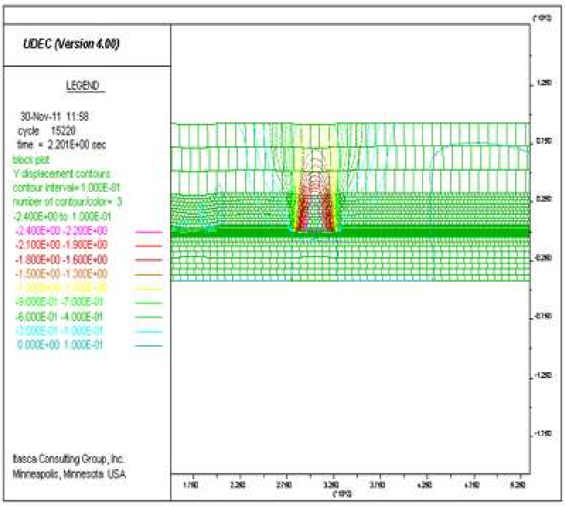


Figure 3. The subsidence after the mining of the 1309 face

The filling of gangue in goaf limits the deformation and failure of narrow coal pillars, ensuring their long-term stability, while also limiting large roof delamination and bending deformation within the mining area. The maximum vertical stress of equivalent mining height is 44.2 MPa. There is a stress reduction zone above the gangue filling material, with a vertical stress of 6.5 MPa. However, there is a stress increase zone above the narrow coal pillar, with a vertical stress of 42.7 MPa. From Figure 4, it can be seen that stress concentration occurs at the interface between the narrow coal pillar and the gangue filling material. The surrounding stress of the filled gangue is relatively low, while the stress at the interface between the gangue and the narrow coal pillar is relatively high, showing a decreasing trend of diffusion towards the surrounding area.

From Figure 5, after strip mining, the stress is redistributed, and the edges of the coal pillars on both sides of the 130 I and 130 II strip coal pillar working faces are first destroyed and expand towards the center. Eventually, the coal pillars in this area reach the stress limit equilibrium state. Due to the high strength of filling gangue support and the small width of the yield zone of narrow coal pillars, it can be seen that increasing the support resistance of gangue has a significant effect on limiting the size of the yield zone of coal pillars and the stability of overlying rock layers.

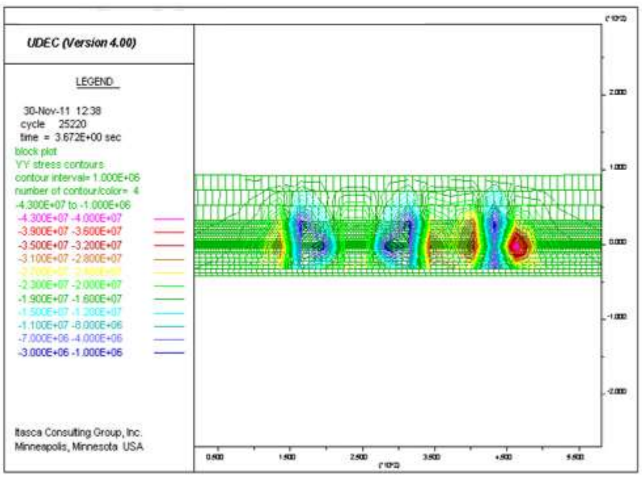


Figure 4. The isogram of stress at the recovered face of 1031 bands pillar

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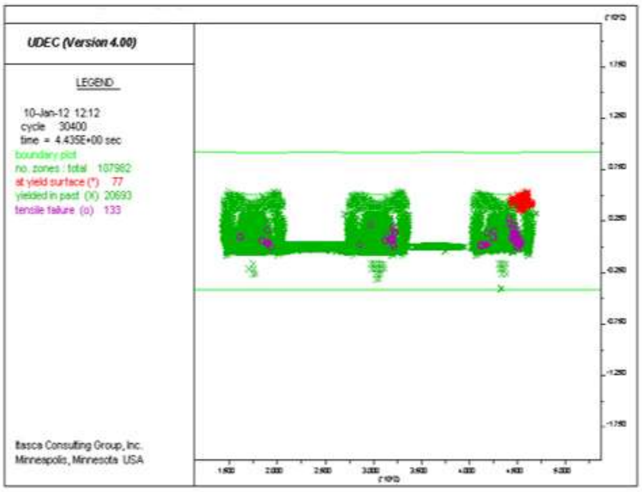

Figure 5. The plastic zone after recycling strip pillar of 130 I and 130 II

5. Conclusion

(1) Theoretical calculations were conducted on the factors affecting the stability of coal pillars, such as yield zone width, ultimate strength, and stress safety factor. The factors affecting overburden failure were analyzed from the aspects of overburden mechanics structure, rock mass structure, rock layer control, mining thickness, and bedrock thickness.

(2) Numerical simulations were conducted on the processes of strip mining and coal pillar gangue filling mining, and the displacement of overlying rock layers, distribution of plastic zones, and stress transmission laws were obtained, demonstrating the feasibility of strip coal pillar recovery.

(3) The simulation results show that the displacement curve of the rock layer above the working face is distributed in a wave shape, and the wave amplitude decreases as the distance from the roof increases, and it will disappear in a certain rock layer. The presence of a thick and hard rock layer in the overlying rock layer plays a crucial role in the distribution and displacement of overlying rock stress, located approximately 75-90 meters away from the top rock layer.

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