Analysis and Application of Backfill Mining in Thin Coal Seams for Preventing Building Damage

(Analisis dan Aplikasi Perlombongan Kambus Balik dalam Jalur Arang Batu Nipis untuk Mencegah Kerosakan Bangunan)

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ABSTRACT

As coal resources trapped under surface buildings impede the efficient mining of coal seams and constrain the sustainable development of coal mines, a super-high-water backfill mining technique for preventing building damage was adopted. According to the established model of equivalent mining height (EMH), the influence factors were obtained. Afterwards, a measurement to improve the backfill rate was analyzed based on the slurry fluidity. Meanwhile, the relationships between the backfill body compression and its influence factors were studied by numerical simulation. In this way, a more accurate EMH was obtained. To prove this trial practicable, the obtained EMH and the probability integral method were used to predict the surface movement and deformation of the C7401 panel. At the same time, a surface movement observation was set up to observe the mining influence on the surface ground and buildings. The comparison between the predicted and measured data indicated that they corresponded well with each other, the surface movement and deformation values were all controlled within grade I, which protected the surface buildings. Moreover, by applying the super-high-water backfill mining technique, not only building damage has been controlled within Grade I, but the impact on the ecological environment has been reduced also, such as surface subsidence, groundwater leakage and groundwater lowering, which is in harmony with the construction of green mines. The practical trial can provide a reference for mining under similar conditions and is vital for the sustainable development of the mining industry and economic growth.

Keywords: Backfill mining; environment protection; overburden movement; surface subsidence; thin coal seam

ABSTRAK

Disebabkan sumber arang batu terperangkap di bawah bangunan permukaan, hal ini menghalang perlombongan arang batu yang cekap dan mengekang pembangunan lestari lombong arang batu, perlombongan secara kambus balik air super-tinggi diterima pakai. Menurut model ketinggian perlombongan setara (EMH), faktor pengaruh diperoleh. Selepas itu, langkah untuk meningkatkan kadar pengisian semula dianalisis berdasarkan kecairan buburan. Sementara itu, hubungan antara mampatan badan pengisian semula dan faktor pengaruhnya dikaji secara terperinci dengan menggunakan simulasi berangka. Dengan cara ini, EMH yang lebih tepat diperoleh. Untuk membuktikan bahawa kaedah ini dapat dijalankan, EMH yang diperoleh dan kaedah integral kebarangkalian digunakan untuk meramalkan pergerakan permukaan dan canggaan panel C7401. Pada masa yang sama, pergerakan permukaan diperhatikan untuk melihat pengaruh perlombongan terhadap permukaan tanah dan bangunan. Berdasarkan perbandingan antara data yang diramalkan dengan yang diukur, ia menunjukkan bahawa mereka bersesuaian antara satu sama lain, iaitu, nilai pergerakan dan canggaan permukaan semuanya dikawal dalam gred I, yang melindungi bangunan permukaan. Lebih-lebih lagi, dengan menggunakan perlombongan sumber air super-tinggi, satu siri masalah alam sekitar ekologi yang disebabkan oleh aktiviti perlombongan dapat dikurangkan. Percubaan praktikal boleh digunakan sebagai rujukan untuk perlombongan dalam keadaan yang sama dan sangat penting untuk pembangunan lestari industri perlombongan dan pertumbuhan ekonomi.

Kata kunci: Jalur arang nipis; penenggelaman permukaan; pergerakan tanah beban; perlindungan persekitaran; perlombongan pengisian semula

INTRODUCTION

China is the world's largest coal producer. With technological and economic development, coal production has grown rapidly from 1.67 Billion tons (Bt) in 2003 to 3.68 Bt in 2018. China is also a large energy consumer. This is mainly because coal is the primary energy source in China and provides the basis of the energy infrastructure necessary for long-term rapid economic growth (Lin & Liu 2010). As is well-known, the exploitation of coal resources can lead to a series of environmental problems, such as surface subsidence, farmland reduction, slope instability, and building damage, which is becoming a global problem (Bai et al. 2019; Chen et al. 2019; Hsieh et al. 2011; Rendana et al.

2017; Xu et al. 2008). Thus, China's '13th Five-Year' plan once again emphasizes that all coal mines should be built in accordance with modernization, green, safety, and ecological requirements. In China, there is an estimated 13.7 Bt of coal reserves trapped under buildings, water bodies, and railways ('under-three'), among which coal resources under buildings account for 9.5 Bt (Guo & Xu 2016). It not only delays efficient mining of coal seams but constrains sustainable development of coal mines, especially for old mining areas, such as, Lvgou coalmine. At present, the coal buried under buildings or other structures in the Lvgou coalmine has reached 2.4 Mt, which greatly shortens its service life and increases the difficulty of subsequent mining activities. Therefore, it is important to adopt a proper mining method to protect the surface buildings and remain in harmony with green mining practices.

In recent years, various mining methods have been applied to control surface subsidence, including strip mining, harmonic mining, room mining and backfill mining (Bai et al. 2018a; Guo et al. 2016; Zhang et al. 2015; Zhao et al. 2004). However, strip mining and room mining have a low mining rate, directly leading to massive coal resources left in the gob, which is a huge waste of coal resources (Sun et al. 2017). Although harmonic mining would achieve the same production as traditional longwall mining method, it cannot control the destruction of the overburden strata. As is well-known, rupture failure of overburden strata is the internal cause of dynamic instability in mining area (Wang et al. 2017). Therefore, to prevent surface building damage and other geological disasters controlling overburden strata is key. By contrast, backfill mining, an important technique in green mining, is a significant revolution in ground control (Bai et al. 2018b). It has been developed to solve the global problems mentioned above, especially in 'under-three' mining, such as hydraulic backfilling, solid backfilling, and high-water material consolidation tailing backfilling (Bell & Genske 2001; Huang et al. 2011; Kostecki & Spearing 2015). Moreover, the solid backfill mining method can be used for preventing rock burst and solid waste disposal (Zhang et al. 2014). However, according to the study conducted by Szcepanska and Twardowska (1999), heavy metal pollution caused by mining waste in the backfill mining area can result in groundwater pollution lasting decades, and the pollution intensity increases with time. Moreover, it has already been noted that potential secondary pollution of the underground water quality and underground environment can be caused by solid backfill technology with gangue or waste rock (Bian et al. 2012). To avoid secondary pollution and save the backfill material, super-high-water backfill material has been tested to be 'green' for groundwater by Feng (2009). Therefore, combined with green mining theory, the super-high-water backfill mining method is adopted for mining thin coal seams, which will protect the buildings and is consistent with stable and sustainable production and ecological environmental protection.

In this study, a surface subsidence model for backfill coal mining was established based on the equivalent mining height (EMH) theory. This was followed by the analysis of EMH influence factors. Afterwards, a measure to improve the backfill rate was analyzed based on the slurry fluidity. To obtain a more accurate EMH, the relationships between backfill body compression and its influence factors were studied in detail by numerical simulation. Finally, by taking the C7401 panel of the Lvgou coal mine as an example, the obtained EMH and the parameters of probability integral method were used to predict the surface movement and deformation. The practical engineering case indicated that the measured data corresponded well with the predicted values. In addition, the surface movement and deformation parameters are both controlled within Grade I deformation, protecting the surface buildings and supporting coalmine sustainable development.

GEOLOGICAL CONDITIONS

Lvgou coal mine is located to the northwest of Xuchang City, Henan province, China, in a field area of 10.33 km^2. The current mining coal seam (occurring in the Upper Shihezi Formation of the Permian) has a simple structure. The first trial area is panel C7401, which has a 190 m width and 760 m length, located in the eastern mining area. The coal seam ranges from 0.6 to 1.2 m in thickness, with an average of 0.9 m. Dip angle ranges from 13 to 15°, with an average of 14°. Panel average mining depth is 271 m. The ground surface mainly consists of buildings made of brick and concrete. They all require grade III protection (according to the regulations mentioned in 'Fortification criteria for mining under buildings, water bodies and railways'). The immediate roof and floor are a carbonaceous mudstone with thicknesses of 1.22 m and 2.6 m, respectively. The location and the buildings in the mining area are shown in Figure 1.

BACKFILL MINING METHOD WITH SUPER-HIGH-WATER MATERIAL BASIC MECHANISM

Super-high-water backfill mining means two different materials, A and B, are mixed together and transported to the gob area via pipelines. At the same time, the mixed liquid will cure to form the supporting body, resisting the overlying strata and realizing subsidence control. Material A is mainly composed of aluminate or additives while material B consists of gypsum, lime, and clay. Both materials A and B are added into a certain amount of water to make grout. After they are mixed at a ratio of 1:1, the setting time of the material could be regulated from 8 to 90 min with different additive contents. Its compressive strength could also be changed under different water contents. For instance, when the water volume content varies between 95 ~ 97%, its final strength varies between 0.66 ~ 1.5 MPa (Zhang et al. 2016). The slurry formed with A or B alone could keep 30 to 40 h without solidification, whereas the mixture of A and B hardens quickly.
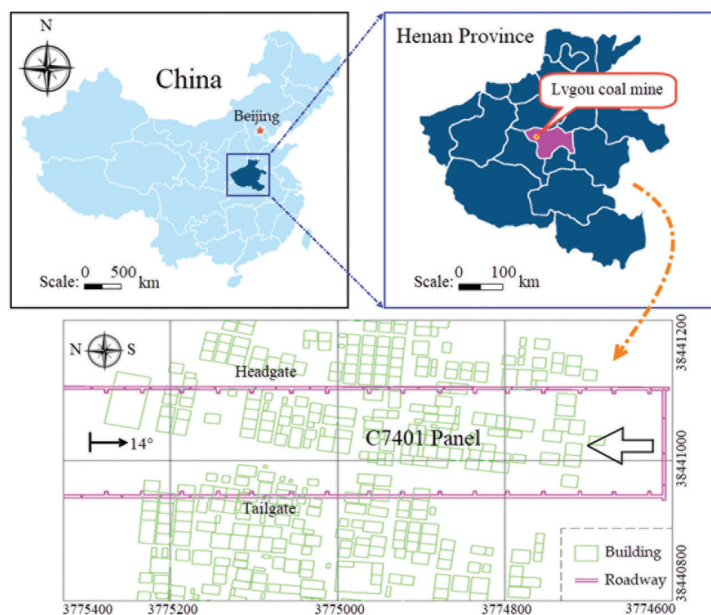
FIGURE 1. The location and buildings in the mining area

MODEL OF BACKFILL MINING TO PREVENT BUILDING DAMAGE

To reduce surface subsidence, decrease building damage, and improve the coal recovery ratio, the backfill mining method with super high-water material was adopted. The essence of backfill mining reduces the overburden movement by replacing coal resources with backfill material. This method is based on the balance model theory of the strata beam. In this case, a stress balance arch is formed on the top of the gob. The strata self-weight causes the arch to bend and subside. However, as the gob is filled with dense backfill materials, the backfill body achieves a triaxial stress state after compression and becomes part of a supporting body. Then, the overburden strata above the gob gradually become the overburden strata beam due to the backfill body's support. Ultimately, the overburden strata movement is limited to slow bending. Therefore, the surface subsidence can be effectively controlled. This is the principle of backfill mining used to reduce the overburden movement and realize coalmine sustainable production, as well as surface building and ecological environmental protection (Chang et al. 2014).

Backfill mining can be regarded as a method for replacing coal with backfill material. In the gob area, the backfill height after full compression must be lower than the actual mining height, the backfill rate is less than 100%. Therefore, the backfill mining is equivalent to limited thickness extraction, and the unfilled height is the limited thickness. According to the EMH theory for backfill mining (Guo et al. 2014; Miao & Zhang 2007), the EMH is the height calculated by subtracting the height of the dense backfill body in the gob from the actual mining height. The EMH model was established as shown in Figure 2.

Figure 2 shows the effects of overburden movement and surface subsidence when the actual mining height,
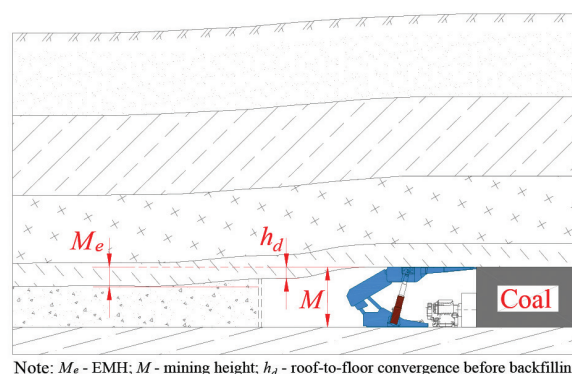

Note: M_e - EMH; M - mining height; h_d - roof-to-floor convergence before backfilling

FIGURE 2. Sketch of the EMH model for backfill mining

M, is equivalent to those in the roof caving method, M_e. Therefore, the EMH is M_e. Sometimes, the roof will experience subsidence before backfilling. Consequently, M_e consists of two parts, the roof-to-floor convergence of the panel before backfilling and the compression of the backfill body. Therefore, M_e can be calculated as shown in (1):

$$M_e = M - \varphi(1 - k)(M - h_d) \tag{1}$$

where M is the actual mining height, m; φ is the backfill rate; k is the compression rate of the backfill body; and h_d is the roof-to-floor convergence of the panel before backfilling, m. The values of k and φ are obtained from laboratory tests on the backfill material and field measurements specified by the standard for high water backfilling materials, respectively.

From (1), M_e is mainly related to the backfill rate, compression rate, and the roof-to-floor convergence before backfilling. Meanwhile, it has a direct impact on the degree

of surface subsidence control. For backfill mining under buildings, the maximum M_e should be controlled according to surface building criteria to ensure that any surface subsidence that occurs is within an allowable range.

ANALYSIS OF INFLUENCE FACTORS

As indicated in (1), the backfill rate and the compression rate are closely related to the EMH. Because underground mining is a complicated process, it is necessary to analyze the influence factors of EMH. The analysis of influence factors is as follows:

BACKFILL RATE

Backfill rate is a key index influencing overburden movement, controlling surface subsidence, and protecting the ecological environment. It represents the actual effect of the gob, as well as reflects the ultimate contact between the backfill body and the roof, and its supporting effect on the overburden strata. Meanwhile, it also directly relates to the control degree of surface subsidence. For the stope with the same backfill conditions, at a higher backfill rate, a smaller void forms in the gob and the smaller activity space of the rock mass. That is, a smaller degree of bending deformation occurs at the top of the base, and there is a better control effect on the rock strata. However, when the backfill rate is low, the mining pressure and strata movement characteristics are similar to the caving method (Zhang et al. 2015). Therefore, the backfill rate is a key index for protecting surface buildings. The inclined coal seam should be adopted longwall topple mining, i.e., the panel advances along the dip direction, as shown in Figure 3.
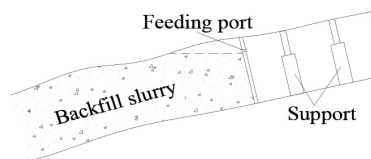

FIGURE 3. Panel advances along the dip direction

As indicated in Figure 3, the gob side behind the panel is low-lying while the backfill port side is high terrain. The enclosure space is easy to form in the gob area, and the sealing requirement on the top of the support side is lower. Moreover, the backfill slurry can automatically flow to the rear gob, and easily achieve a higher backfill rate. This natural advantage can greatly reduce the performance of backfill materials, such as the fluidity, bleeding rate and sealing requirement in gob. Additionally, the backfill process is equivalent to the moving setup room, and the mining process has less influence on the overburden strata. Therefore, the longwall topple mining method is adopted to improve the backfill rate and reduce the EMH value, which realizes surface building and environment protection.

BACKFILL BODY'S COMPRESSION

To be specific, the backfill body compression mainly includes mining depth, mining height, and overburden strata lithology.

Mining depth   As is well known, with different mining depths, the overburden pressure of backfill body is different. The larger the mining depth is, the greater the pressure on the backfill body, and the larger compression strain of backfill body. In other words, the larger mining depth leads to an EMH increase in backfill mining and causes serious surface movement and deformation. According to the close packing theory, the influence on EMH decreases gradually with the increase of mining depth.

Mining height   The influence of mining height on M_e is mainly due to the increase of mining height and the increase of backfill space. In general, the backfill material will increase with a larger mining height, i.e. there is a positive correlation between the amount of backfill material and mining height. Generally known, the upper backfill body easily slides down and flows during the backfilling process, which results in a lower compaction degree. Therefore, combined with other influencing factors, the mining height is closely related to the backfill rate, and it can be intuitively reflected in the backfill rate.

Overburden strata lithology   The overburden strata lithology affects its movement. The harder the rock mass is, the smaller the overburden movement will be. The reason is that the fracture distance of the overburden strata is small when the lithology is soft. Meanwhile, due to the roof fracture, the pressure on the backfill body is large, resulting in significant compression. However, as the overburden strata is hard, its fracture distance is large and the backfill body has enough time to solidify and enhance its strength for supporting overburden strata. Therefore, the compression of the backfill body under hard strata will be smaller than that under soft strata.

NUMERICAL MODELLING

Numerical simulation can be very good for analyzing the stress and deformation of overburden strata. To further study the influence factors of the backfill body, combined with the actual situation of Lvgou mine, FLAC[3D] software was used to establish the numerical model. The rock strata used in the model have been simplified and the simplified lithologies are, from bottom to top, carbonaceous mudstone, coal seam, carbonaceous mudstone, fine sandstone, mudstone, medium grain sandstone, siltstone, and an unconsolidated layer. The mechanical properties of these lithologies are listed in Table 1. The constitutive model used is the Mohr-Coulomb model.

The model uses a rectangular coordinate system with the x–y directions in the horizontal plane and the z-axis in the vertical. The strike of the coal seam is parallel to

TABLE 1. Mechanical property parameters of model strata

Rock type	Elastic modulus (MPa)	Poisson ratio	Cohesion (MPa)	Tensile strength (MPa)	Internal friction angle (°)	Density (kg·m^{-3})
Unconsolidated layer	150	0.30	0.10	0.00	17	1900
Siltstone	21900	0.25	4.93	2.47	29	2600
Medium grain sandstone	14500	0.23	4.12	1.96	33	2630
Mudstone	6500	0.32	2.05	1.10	30	2200
Fine sandstone	16400	0.23	4.40	2.06	33	2540
Carbonaceous mudstone	9380	0.32	2.52	1.30	30	2320
Coal seam	3300	0.33	1.20	0.64	25	1440
Carbonaceous mudstone	9380	0.32	2.52	1.30	30	2320

the x-axis. The model's design simulates a mining panel measuring 190 m along the strike and 760 m along the dip of the coal seam. A step-by-step method is used for the simulated excavation. There are 38 excavation steps with each step excavating 20 m. To eliminate boundary effects and replicate actual surface subsidence, 300 m coal pillars are left on all four sides of the excavated portion. The model size is 1360 × 790 × 280 m. Boundary conditions of the model are lateral horizontal displacement constraints, a vertical displacement constraint on the bottom, and a free boundary on the top.

In this case, considering the factors that affect the mining height or EMH, only the mining depth, mining width and lithology are considered. According to the analysis of the influence factors, the single factor analysis method is adopted in the experiment and the panel is mined by using the following mining schemes:

Scheme 1: When the mining height is 1 m and the backfill rate is 100%, the mining depths are 150 m, 200 m, 250 m, 300 m, and 350 m, respectively. Scheme 2: When the mining depth is 300 m, the mining height is 1 m, and the backfill rate is 100%, the mining widths are 40 m, 80 m, 120 m, 160 m, 200 m, respectively. Scheme 3: When the mining depth is 300 m, the mining height is 1 m and the backfill rate is 100%, the lithology of the overburden strata is reduced based on the initial model lithology, and the reduction coefficients are 0.33, 0.50, 1.00, 1.50, and 2.00, respectively.

PREDICTION PARAMETERS AND SURFACE MOVEMENT OBSERVATION

The probability integral method model is based on random medium theory. At present, it has become the most widely used prediction method for mining under buildings and industries (Dai et al. 2010; Guo et al. 2017; Ma et al. 2017). Many years of practice have shown that the method's precise predictions of surface subsidence can fully meet engineering requirements (Guo 2013). In addition, the EMH probability integral method can be used to predict surface subsidence after backfilling mining. The prediction parameters for surface movement and deformation mainly include the subsidence factor, q; tangent of major influence angle, $\tan\beta$; offset distance of inflection point, s; influence

transference angle, θ_0; and horizontal movement factor, b. Moreover, they are the primary data for the recovery schemes. During backfill mining under surface buildings, the surface subsidence is closely related to the EMH. Based on the geological and mining conditions, the related surface subsidence prediction parameters are calculated and listed in Table 2.

In addition, to thoroughly study rock strata movement characteristics in the Lvgou coal mine, surface movement observation stations were built in corresponding positions above the panel, and a monthly survey was carried out during the backfilling period. Each observation station consists of a series of interconnected observation points. According to the topographic conditions above the panel, the strike observation line was set up along the village road, denoted Z1 to Z18. Similarly, the dip direction observation line was arranged along the farmland or road, named N1 to N29. The crossing point of the two lines was Nz. The control points were buried next to the roadside out of the mining impact.

In order to analyze the influence of super-high-water backfill mining on the buildings, two mining schemes have been designed to recover the coal resource trapped under the buildings. The schemes are: backfill and caving mining. The surface movement and deformation of two mining methods are analyzed in the results and analysis section.

RESULTS AND ANALYSIS

MEASURES TO IMPROVE THE BACKFILL RATE AND ROOF SEPARATION MONITORING

During backfill mining, the initial mining process parameters are as follows: the mining cycle and the caving distance is 1 m, and the backfill cycle is 2 m, i.e. 'two mining one backfilling' (two cutting for each backfilling). Currently, the maximum control distance of the panel is 4.2 m, and the minimum is 3.2 m. In addition, the maximum control distance of the machine head and tail is 5.2 m, and the minimum is 4.2 m. Because the immediate roof is a 1.22 m thick carbonaceous mudstone with fissure development, it collapses immediately after the pillar is withdrawn. Meanwhile, the coal seam is thin, and the collapsed roof

TABLE 2. Parameters of probability integral method for surface subsidence

Subsidence factor	Tangent of major influence angle	Offset distance of inflection point	Influence transference angle	Horizontal movement factor
0.72	2.2	0	81.6°	0.3

seriously affects the flow path of the super-high-water slurry in the gob, with a backfill rate of only 66%. However, the key to backfill mining is to ensure an adequate backfill rate. Hence, the backfill process is changed from 'two mining one backfilling' to 'one mining one backfilling' (one cutting for each backfilling) to improve the backfill rate, i.e. the backfill cycle is changed to 1 m. After implementation, although the backfill rate increases, there is roof collapse in many areas, and the backfill space is difficult to maintain effectively before backfilling. To reduce roof collapse and improve the backfill rate, the end row pillar technology used to overhang the cantilever beam and protect the roof is adopted based on 'one mining and one backfilling', as shown in Figure 4. Therefore, the roof at the side of the gob is basically no longer falling, the backfill space is effectively maintained, and the backfill rate increases to 85%. Then, it can be calculated that φ is 85%.

To monitor the roadway roof separation under the supporting bolt, 17 monitoring points were arranged along the transportation roadway and return air roadway, respectively. The roof separation indicator was installed in the middle of the roadway, the deep base point was anchored to 300 mm in the stable rock layer above the anchor, and the shallow base point was fixed at the end of the anchorage.

According to the monitoring data, the separation values of the transportation roadway inside and outside the anchorage range are 1~11 mm and 0~7 mm, respectively. For the return air roadway, they are 0~12 mm and 0~9 mm, respectively. The roof anchorage is in good condition,

and the roof deformation is controlled effectively, which maintains the integrity of the roof strata. Meanwhile, the maximum parameter h_d in (1) is 20 mm.

NUMERICAL SIMULATION RESULTS AND ANALYSIS

To illustrate the relationship among the influence factors, Figure 5 is constructed from schemes 1 to 3. Figure 5(a) is constructed from scheme 1 to illustrate the relationship between mining depth H and backfill body compression rate k; Figure 5(b) illustrates the influence of the mining panel width on the backfill body compression from scheme 2; Similarly, Figure 5(c) shows the lithology influence of overburden strata on the backfill body compression from scheme 3. The results are as follows.

As shown in Figure 5(a), during backfill mining with super-high-water material, the mining depth has a positive linear correlation with the backfill body compression. That is, the backfill body compression increases with the increase of the mining depth. The relationship between mining depth H and backfill body compression rate k is shown in Figure 5. When the mining depth is 150 m, the backfill body compression rate is 0.010. Currently, the stress of overburden strata is small, and the pressure on the backfill body is also small. With the increase of mining depth, the pressure of the overburden strata on the backfill body increases, which increases the backfill body compression. Therefore, when the mining depth increases from 150 to 350 m, the backfill body compression rate increases to 0.025.
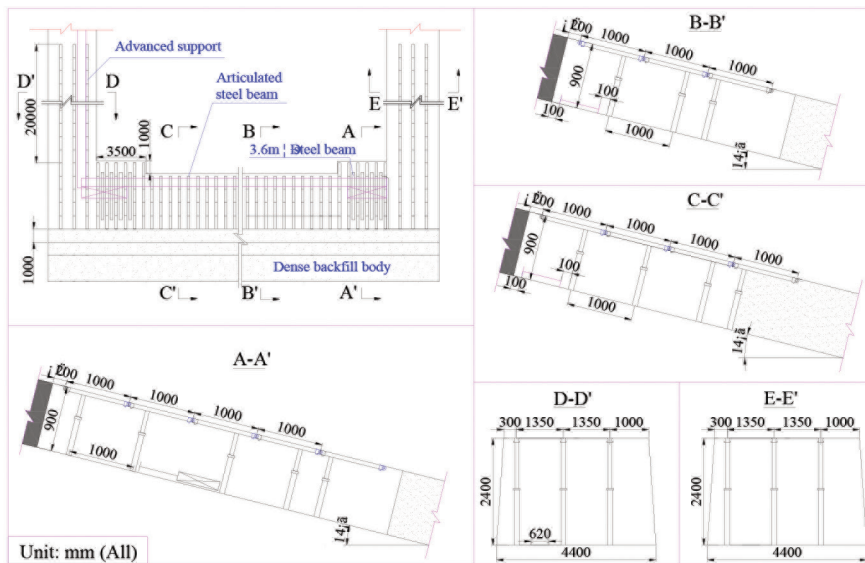

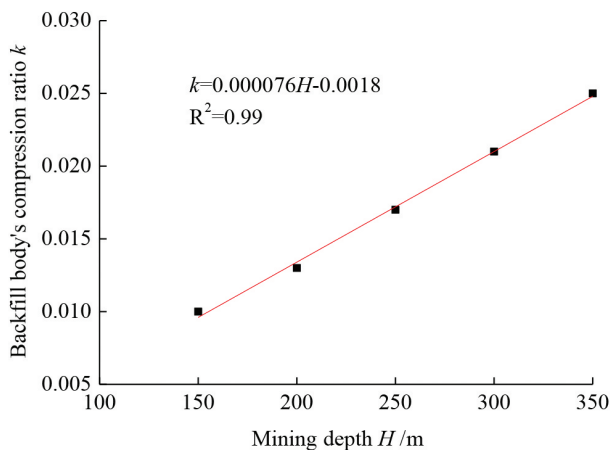FIGURE 4. Support pattern of super-high-water backfill mining

FIGURE 5a. Relationship between the mining depth and backfill body compression rate

As indicated in Figure 5(b), the mining width has a logarithmic relationship with the backfill body compression. When the mining width increases, the backfill body compression also increases. The backfill body compression rate is 0.023 as the mining width is 40 m. This is because the coal pillar is great support to the overburden strata, while the backfill body only bears a small part of the load. Besides, due to the limited load of the coal pillar, the load of the backfill body becomes larger and larger as the mining width increases. Then, the compression rate increases to 0.097 as the mining width is 200 m.
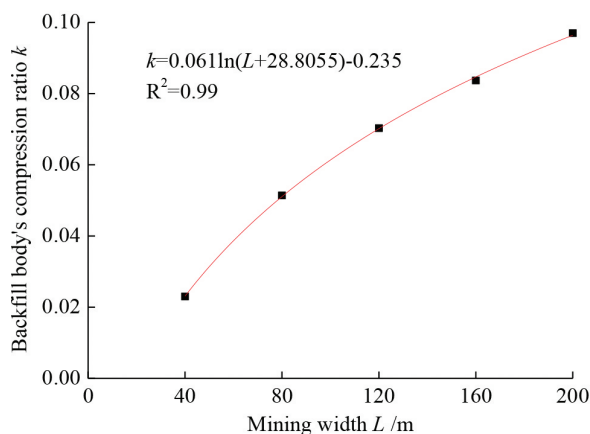

FIGURE 5b. Relationship between the mining width and backfill body compression rate

From the Figure 5(c), the backfill body compression gradually decreases when the reduction factors of the rock properties increase from 0.33 to 2.00, which is in accordance with the logarithmic relationship. When the reduction factor is 0.33, the backfill body compression rate is 0.111. At this moment, the overburden strata lithology is weak, leading to it becoming broken continuously. Meanwhile, the supporting effect of the coal pillar on the

overburden strata is weakened, resulting in great pressure on the backfill body, resulting in a large compression of the backfill body. The overburden strata lithology is hard when the reduction factor is 2.00, and the backfill body compression is 0.037, which decreases by 66.7%.
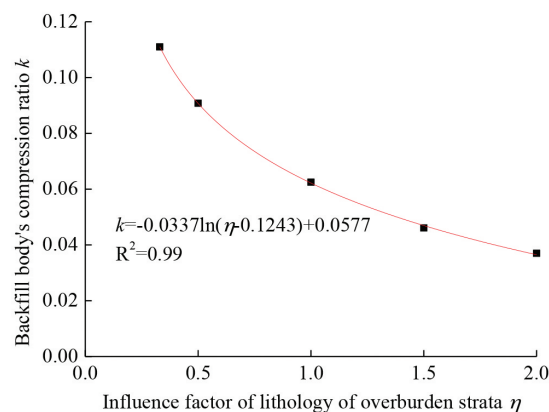

FIGURE 5c. Relationship between lithology influence factor and backfill body compression rate

Therefore, according to the above analysis and parameters, the maximum value of the backfill body compression rate, k is 0.1.

PREDICTION PARAMETERS AND SURFACE SUBSIDENCE

The probability integral method is also used to calculate the surface movement and deformation for using the backfill mining and caving methods. From the analysis, it can be determined that M_e is 0.2268 m from formula (1). Meanwhile, M_e provides a basis for a more accurate prediction of the surface subsidence. Table 3 lists the maximum values of surface movement and deformation for the two mining methods based on the criteria of 'under-three'.

Based on the prediction data, the maximum surface subsidence above the panel is 580.4 mm when caving mining is adopted. However, it is only 115.7 mm when using backfill mining, which is reduced by 80.1%. For caving mining, the maximum surface slope is 4.2 mm·m^{-1} and the maximum horizontal deformation is 4.0 mm·m^{-1}, which exceeds the criterion of Grade II for buildings. For backfill mining, they are both reduced to 0.7 mm·m^{-1}, which are decreases of 83.3% and 82.5%. Certainly, the surface ground and buildings are controlled within Grade I. From the comparison, it can be found that super-high-water backfill mining can greatly reduce the surface movement and deformation, effectively reducing the damage grade of buildings and preserving them for safe use.

In addition, real-time monitoring of surface subsidence was conducted by using an observation station. Surface movement observing occurred over 1 year. Because the subsidence of each observation points on the strike line is less than 10 mm, the observation point is considered to

TABLE 3. Maximum values of surface movement and deformation

Mining method	Surface subsidence (mm)	Surface slope (mm·m⁻¹)	Horizontal deformation (mm·m⁻¹)	
Backfill mining	115.7	0.7	-0.7	0.3
Caving mining	580.4	4.2	-4.0	2.0

be within the safety range. Because the longwall topple mining method is adopted in the panel, the subsidence in the dip direction is larger than the strike. The curve of accumulated surface subsidence can be seen in Figure 6.
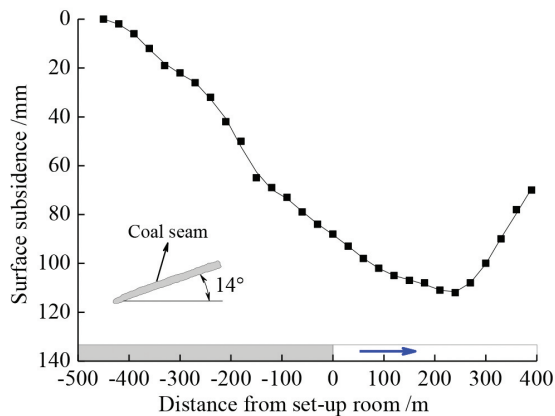

FIGURE 6. The accumulated surface subsidence in the incline direction

According to the analysis of the surface monitoring data, with the advance of the C7401 panel, the subsidence of each observation points increases gradually. However, the accumulated maximum subsidence at the surface monitoring point is 112 mm and the maximum horizontal deformation is 0.5 mm·m⁻¹. These are both controlled within Grade I deformation. Meanwhile, according to the field investigation, the surface ground and buildings exhibit no obvious deformation after the implementation of the super-high-water backfill method, indicating that the goals of protecting the surface buildings and sustainable development are achieved.

In summary, when the super-high-water backfill method is adopted in the Lvgou coal mine, the overburden strata of the gob are well-supported, preventing strata movement and surface subsidence, thereby protecting the ecological environment at the local mining area. Successful application of the super-high-water backfill method may provide some references to mining thin coal seams under buildings or other structures and supporting coal mine sustainable development while protecting the buildings and environment.

SOCIAL AND ECONOMIC BENEFITS
ECONOMIC BENEFITS

Before using the backfill method for a thin coal seam, coal resources are all trapped under the surface buildings. If the caving mining method is adopted, the damage grade of most surface buildings (a total of 650 households in 2 villages) will be Grade II. According to the local compensation price, the coal profits are not enough to compensate for the damaged buildings. However, if it is not exploited, the mine will be closed with no other available resources. By taking the C7401 panel as an example, the mined coal resource using the super-high-water backfill mining method will not only maintain the current production, 1.9×10^5 tons, but also protect the surface buildings from the mining damage. The details are listed in Table 4. Additionally, after the super-high-water backfill mining method is applied under all of the surface buildings and other structures, the mined coal resource can increase by 2.4×10^6 tons for a better economic benefit.

SOCIAL AND ENVIRONMENTAL BENEFITS

The super-high-water backfill mining of the thin coal seam has extended the mine's service life, which not only promotes local economic development, but also provides certain jobs and increases local income. It can also provide some references for mining thin coal seams under buildings or other structures, which can promote the development of social science and technology. For the environmental damage, the backfill mining method has a smaller environmental impact than the caving mining method, and it also causes less damage to groundwater resources and buildings. The implementation of this method can maintain the ecological balance, therefore, the production and living environment of the local enterprises and surrounding residents will not deteriorate, i.e. the environmental benefits are better.

TABLE 4. Economic benefit comparison of different mining methods in the C7401 panel

Mining method	Recovery ratio	Production (10^5 t)	Damage grade of buildings	Benefits (Million Yuan)
Backfill mining	100%	1.94	I	11.32
Caving mining	100%	1.94	II	-0.86

CONCLUSION

For surface buildings protection and sustainable production of Lvgou coal mine, the super-high-water backfill mining method for extracting the thin coal seam under surface buildings was analyzed and applied on the C7401 panel. The main conclusions of this study were:

According to the analysis of the backfill mining model, the caving zone is not generated in the overburden strata after super-high-water backfill mining. Most are in the bending zones and only few areas are fracture zone, i.e., the strata structures are continuous. Therefore, the Mohr-Coulomb model is chosen as the constitutive model in the numerical simulation.

Based on the EMH theory, the influence factors are analyzed. The backfill rate increases from 71% to 85% after the implement of 'one mining one backfilling', meanwhile, the relationships between the backfill body compression and mining depth, mining width, and overburden strata lithology are obtained by numerical simulation. During the actual mining process, the basis and guarantee are provided for the accurate determination of EMH and surface subsidence.

The maximum surface subsidence is 112 mm and the maximum horizontal deformation was 0.5 mm/m after adopting the backfill coal mining method, which is basically the same as that obtained by using the probability integral method. Meanwhile, the surface buildings are both controlled within Grade I as specified by the Coal Industry Criterion, which indicates that the integrity of the overburden is competent. Therefore, this practice has proven effective in terms of controlling the geo-environmental hazards and extending the mine's service life, which is vital for the sustainable development of the mining industry and economic growth.

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