Conversion mechanism of a continuous pressure arch structure in strip filling mining

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Abstract

Strip mining is the key technology to solve the problem of coal mining under water, so mastering the law of overburden load transfer in strip mining is the key to safe production in working face. We studied it in the context of the shallow seam No. 3 in the Shanghe Coal Mine (northern Shaanxi Province, China) through similarity simulation and field measurement analysis. A theoretical analysis, based on the concept of pressure arch, allowed the establishment of a continuous arch theoretical model for the strip coal pillars (or filling bodies) of the mine. A similar simulation study on strip filling and staged mining has previously shown that, in a first stage, the overlying strata load is mainly transferred to the remaining strip coal pillars; in a second stage, this load is mainly sustained by the odd-numbered strip coal pillars; finally, in a third stage, this load is mainly sustained by the first-stage strip filling body, while the third-stage filling body is not loaded. Our theoretical analysis showed that, during the first stage, the overlying rock load outside the arch was mainly sustained by the arch structure, while that inside of the arch was sustained by the filling body; in the second stage, the arch structure lost stability during the recovery of the even-numbered coal pillars and the arch axis developed upward, leading to the formation of a new arch with an odd number of coal pillars as the arch foot; in the third stage, after the recovery of the odd-numbered coal pillars, a new arch was formed. The arch foot of the new supporting structure was represented by the first-stage filling body; moreover, the load was mainly borne by the second-stage filling body, ensuring the stability of the overburden rock after mining. The theoretical analysis revealed that the pillar or filling body only bears part of the overburden load in strip filling mining. The pillar (filling body) load in correspondence of working face 3216 during each stage of filling was measured and analyzed, proving a continuous arch structure transformation between the pillar and the filling body. Finally, we verified the reliability of the proposed theoretical model.

Keywords Shallow coal seam · Strip filling mining · Pressure arch · Load transfer law

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Introduction

The Yushen mining area (northern Shaanxi Province, China) is located at the border between the Maowusu Desert and the Loess Plateau, within a shallow seam mining area. The ecological environment of the mining area is fragile, since it is interested by serious soil erosion and desertification phenomena (Fan et al. 2015; Xia et al. 2016; Liu et al. 2019) (Fig. 1). In view of these problems, Limin Fan put forward the idea of “coal mining with water conservation.” Since then, a large number of scholars have conducted further theoretical researches on “water-conserving mining” and proposed some engineering applications of this concept (Fan 2005; Sun et al. 2019; Sun et al. 2017; Ma et al. 2019; Wang et al. 2018; Liu et al. 2017; Wang et al. 2019a), including strip filling mining (Cao et al. 2018; Du et al. 2019a; Sun et al. 2018; Yu et al. 2018a; Mu et al. 2019; Tan et al. 2018).

The integrity of the overburden structure after mining and filling is an important index to evaluate the effect of water conserving. Therefore, it is of great significance to study the stability of this type of structure and further analyze the transmission of the overburden load during mining and filling. Zhang et al. (Zhang et al. 2017) defined the concept of “critical backfill ratio” and analyzed the failure degree of the overburden rock under different backfill ratios. Zhu et al. (Zhu et al. 2018) analyzed the subsidence mechanism linked to local mining in mining cities, improved the application of the backfill technology in caving zones to mine strip pillars, and guaranteed the safety of buildings located at the surface. Yin et al. (Yin et al. 2019) put forward a design method for retaining width, which considered the stability of the coal pillar, and deduced the relationship between recovery rate and surface deformation. Gao (Gao 2018) provided a mechanical analysis method based on the composite rock mass, analyzed the influence of different roof and floor rock masses on the stability of coal pillars, and demonstrated the mechanical relationship between coal pillars, roof, and floor. Du et al. (Du et al. 2019b) proposed the principle of direct roof control in strip structure filling (e.g., “water-retaining and water-storing” coal

Fig. 1 Surface conditions of the Shanghe Coal Mine

mining) by applying the finite-length beam model to an elastic foundation. Xie et al. (Xie et al. 2019) put forward the concept of “spherical stress shell,” and employed it to analyze the stability of an overburden structure. Liu et al. (Liu and Zhao 2019) established a mechanical model to explain the interaction between roof, support, and filling body; moreover, they provided a theoretical basis for the determination of the key parameters related to filling support. Zhou et al. (Zhou et al. 2017a) used an elastic foundation beam model to analyze the bending and subsidence deformation of the overburden rock in the stope of fill mines; additionally, they deduced the law of subsidence and deformation interesting the stope roof in fill mines containing gangue. Yu, et al. (Yu et al. 2018b) proposed a method for calculating the stress sustained by a coal pillar, analyzed the influence of the mine scale, and reduced the waste of coal resources related to an overestimation of this stress. Few theoretical studies, however, have researched the transfer of the overlying strata load in the context of strip-paste filling mining.

Here, based on the pressure arch and key stratum theories (Li et al. 2017; Yang et al. 2016; Yu and Ma 2019; Huang et al. 2017), we studied the application of solid coal paste filling mining to the Shanghe Coal Mine, which is located in a shallow coal seam area of the northern Shaanxi Province. In particular, we analyzed the load transfer of the overlying strata during the strip filling mining process through similarity simulation and theoretical analysis. The results of this study provide a theoretical basis for the safety production of strip working faces.

Experimental materials and methods

General situation of engineering

The Shanghe Coal mine is located in the northeast of Yuyang District, Yulin City and belongs to “coal mining with water conservation” area. Since it was built and put into operation in 1994, the room-pillar mining method has been used for a long time. Since 2005, the “mining six retaining six” strip mining method has been popularized in the mine. In view of the limited remaining recoverable reserves of the mine and in order to release the coal resources under the water-retaining area and prolong the service life of the mine, strip paste filling mining has been applied since 2016. Coal seam No. 3 has a thickness of 6.15–6.57 m (average = 6.34 m), a depth of 100–130 m (average = 115 m), and is part of a stable thick coal seam (Shao et al. 2020b).

Physical simulation design

For our similar simulation experiment (Huang and Cao 2019; Huang et al. 2019; Yang et al. 2018), we constructed a plane stress model (a frame experimental platform) with a length of 2 m. The simulated strike had a length of 200 m and a height

Fig. 2 Similar simulation experimental platform

of 115 m (Fig. 2). The density similarity constant of the model was 1.53, the geometric similarity constant 100, and the stress similarity constant 153 (Shao et al. 2020b). The similar simulation material is made up of sand as aggregate, calcium carbonate and gypsum as cementation material, and adding water according to the similar proportion in Table 1. The configured similar materials are layered in the model frame according to the geometric similarity ratio, and the mica simulation structure surface is sprinkled between each layer. After filling and drying, the simulated mining is divided into three stages (Shao et al. 2020b) and carried out gradually. Sixty-five pressure sensors were present on the floor of the coal seam.

Measuring method

In order to monitor the change in backfill abutment pressure during replacement mining on strip coal pillars, ZYG-10 load sensors were pre-embedded in the filling body during the strip coal pillar filling process. Any influence of the boundary effect was avoided by placing the load sensors at 2 m from the return airway and at 0.5 m from the coal seam floor. A total of 22 load sensors were set up at the site, one for each strip during filling (Fig. 3).

Similar simulated filling materials

The preparation of the filling material was key for the replacement mining on coal pillars. In this paper, sand (particle size < 1 mm), gypsum, and calcium carbonate were used as similar simulation filling materials. The ratio of the filling body for the similar simulation experiment on the Shanghe Coal Mine was determined to be sand:gypsum:calcium carbonate = 3.12:0.21:0.35. The filling body was prefabricated as shown in Fig. 4. According to the mining parameters, a proportion of the filling material was put into the mold for compaction and curing, and the filling body was put into the strip goaf during the filling process.

Discussion and results

Analysis of the similar simulation experiment

The staged mining and filling methods were adopted for the similar simulation experiment on the mining and filling process, in order to reconstruct a slow transit of the overlying rock load onto the filling body. The strip-mining method “mining 7

Table 1 Simulation experiment ratios for similar materials present in the upper river coal mine (Huang and Cao 2019)

No.	Lithology	Stratum depth/m	Model layer thickness/cm	Ratio (fly ash, sand, gypsum, calcium carbonate)				
1	No. 3 seam	6.3	6.3	20:20:1:5	2.13	2.13	0.1	0.51
2	Grey mudstone	4.5	4.5	70:2:8	0	5.6	0.16	0.64
3	Coarse-grained feldspar sandstone	15.3	15.3	80:4:6	0	5.69	0.26	0.52
4	Medium-grained feldspar sandstone	9.3	9.3	80:4:6	0	5.69	0.28	0.43
5	Grey mudstone	19.0	19.0	70:2:8	0	5.6	0.16	0.64
6	Fine-grained feldspar sandstone	7.3	7.3	80:4:6	0	5.69	0.28	0.43
7	Mudstone	10.9	10.9	70:2:8	0	5.6	0.16	0.64
8	Medium-fine feldspar sandstone	10.5	10.5	80:4:6	0	5.69	0.33	0.40
9	Sandy soil and sandy loess	39.59	39.6	90:2:8	0	11.52	0.26	1.02

Fig. 3 (a) On-site embedding of the pressure gauge; (b) ZYG-10 load sensors

and retaining 8" was adopted for coal seam No. 3 during the first stage of the similar simulation (Fig. 5). The roof of No. 3 coal seam did not break during the strip filling mining. After this process, 10 strip goafs and 9 strip coal pillars were created in the mining area; then, forward filling was carried out in each strip goaf. The strength of the designed filling body was of ~ 6.0 MPa. The results derived from the monitoring of the coal seam floor pressure are shown in Fig. 6. These results indicate that, during the first stage, the filling body did not bear the overburden load, while the load on the strip coal pillar (i.e., the main body bearing the overburden load) increased significantly. The support pressure value of this coal pillar increased from 2.51 to 4.1 MPa. The maximum abutment pressure (4.48 MPa) was registered by pressure sensor No. 28. All the remaining strip coal pillars remained in a stable state.

A similar recovery process was simulated for the even-numbered strip coal pillars during the second stage. When coal pillars Nos. M2, M4, and M6 were recovered, a local caving phenomenon was noted in correspondence of the top coal and direct roof (Fig. 7). After the recovery of the even-numbered coal pillars was completed, the goaf was progressively filled. Fig. 8 shows that, after the completion of the second stage of mining and filling, the overlying rock load was mainly carried by the remaining odd-numbered coal pillars. The average abutment pressure on the coal pillars was of 5.5 MPa; additionally, the maximum load (5.96 MPa) was distributed on sensor No. 31. During the first stage, the abutment pressure on the filling body increased. The pressures on sensors Nos. 25, 27, and 38, in correspondence of the upper Z5 and Z7 strip filling bodies, were > 0.5 MPa. In the second

stage, the filling body was not bearing any load; moreover, the overburden and odd-numbered strip coal pillars remained in a stable condition.

The third stage of the similar simulation saw the recovery of the odd-numbered coal pillars. The caving of the top coal and direct roof occurred during the recovery of these pillars, indicating an increase in the strength required to support the roof during the mining and filling processes (Fig. 9). After recovery, filling was carried out on the odd-numbered coal pillar goafs, without consequences on the bearing structure of the overburden-filling body. Fig. 10 shows that after the completion of mining and filling in the third stage, the abutment pressure value of the backfill in the first stage increases significantly, from 1.0–1.5 MPa after the second-stage filling to 2.0–4.0 MPa, and the average abutment pressure is 2.76 MPa. In the second stage, the abutment pressure on the backfill began to increase. The average abutment pressure on filling bodies Nos. M2, M4, M6, and M8 was of 0.25 MPa, 0.75 MPa, 0.5 MPa, and 0.25 MPa, respectively. The overburden load was transferred to the filling body in a relatively even way, and the filling body played the main bearing role during the first stage.

The similar simulation process of strip filling mining showed that the overlying strata and coal pillars formed a stable bearing structure after the first strip mining; however, in the second stage, the overlying rock load acting on the even-numbered strip coal pillars gradually shifted to the odd-numbered strip coal pillars and to the first-stage filling body, becoming mainly carried by the odd-numbered strip coal pillars. In this stage, the even-numbered filling strip goafs, the first-stage filling body, and the odd-numbered strip

Fig. 4 Similar simulation filling body

Fig. 5 Simulated strip filling and mining. (a) Mining strips, (b) Filling strip goaf

pillars still constituted the main bearing bodies and ensured the stability of the overlying strata. In the third stage, after the recovery of the odd-numbered strip pillars, the overlying rock load was transferred to the filling body more evenly; meanwhile, the first-stage filling body became the main bearing body, and the overall stability of the overlying rock was maintained (Zhou et al. 2017b).

Overburden bearing mechanical model

Establishment of the mechanical model for strip filling mining

The overburden bearing structure during the filling stage could be analyzed applying the pressure arch theory (Han et al. 2019; Wang et al. 2019b; Ding et al. 2018; Zha and Xu 2019). When coal seam mining follows a nearly horizontal direction, the correspondent pressure arch will be symmetrical and horizontal. Moreover, the axis of this pressure arch would be located in correspondence of the bending zone, resulting in an unstable overburden on the strip pillar. After such pillar is recovered, a new pressure arch would form and act on the adjacent filling body to maintain the overburden stability. To facilitate our analysis, we considered the pressure arch between adjacent coal pillars. The height of the pressure arch was indicated as h , the span as B , the strip width as l , the width of the coal pillar as a , and the thickness of the coal pillar as m . The structure model of the pressure arch is shown in Fig. 11.

In our model, the pressure arch was simplified into a three-hinged arch structure, and the left half of the structure was taken for analysis. The arch was subjected to a uniform load (q);

additionally, the arch foot was subjected to horizontal (P) and vertical (N) reaction forces. The arch roof has the horizontal tangential support force of the OC section of the right half arch to the AO section of the left half arch (T), as shown in Figure 12.

The pressure arch was in equilibrium under the force. In order to ensure the balance of the pressure arch, the following conditions should be met:

$$\begin{cases} \sum F_x = 0 \\ \sum F_y = 0 \\ \sum M_c = 0 \end{cases} \quad (1)$$

Therefore,

$$P = T = \frac{1}{8h} qB^2 \quad (2)$$

$$N = \frac{1}{2} qB \quad (3)$$

The horizontal reaction force (P) was obtained by multiplying the vertical reaction force (N) by a correction coefficient (f), where f is the friction coefficient and taking $f = 0.5$ – 1 (Li et al. 2017; Yang et al. 2016). Therefore:

$$P = f \times N. \quad (4)$$

Considering any point (x, y) on the arch axis, and a bending moment on the optimal arch axis = 0, we obtain the following:

$$M = M^0 - Py = 0$$

where M^0 is the bending moment of the simply supported beam corresponding to the pressure arch.

$$M^0 = \frac{1}{2} qBx - \frac{1}{2} qx^2$$

Pressure arch-axis equation is the following:

$$y = \frac{M^0}{P} = \frac{4h}{B^2} x(B-x). \quad (5)$$

The angle (θ) between the crack slip surface of the coal pillar and the lower coal-wall side of the strip goaf on the working face was obtained considering the active rock mass pressure:

Fig. 6 First-stage support pressure registered by the bottom plate sensors

Fig. 7 Simulated even-numbered filled coal pillars: Recovery of the even-numbered coal pillars; filling of the even-numbered goafs

$$\theta = 45^\circ - \frac{\varphi}{2} \quad (6)$$

where φ is the angle of internal friction of the rock.

The relationship between the pressure arch span (B) and the height (h) can be expressed as

$$B = l + 2a = l + 2m \tan \theta \quad (7)$$

$$h = \frac{a(l + 2m \tan \theta)}{4f} \quad (8)$$

Moreover, the load on the arch can be expressed as

$$q = \gamma(H-h) \quad (9)$$

where, γ is the average overburden capacity, H the coal seam depth, and h the arch structure height.

Therefore,

$$N = \frac{1}{2}qB = \frac{1}{2}\gamma(H-h)B. \quad (10)$$

During strip mining, each strip coal pillar acted as the arch foot of two arch structures (Fig. 11); hence, the pressure of the coal pillar was 2 times the vertical reaction force (i.e., coal pillar load = 2 N).

Analysis of pressure transfer at the arch foot

After the first stage of strip mining, a pressure arch structure was formed between the two odd- and even-numbered pillars to maintain the overburden stability (Fig. 13). The pressure

Fig. 8 Second-stage support pressure registered by the bottom plate sensors

arch structure bore the overburden load outside the arch, while the overburden load inside the arch was mainly loaded by the filling body. Because of the small span of the arch structure in the first stage, the top coal and the direct roof under the arch structure did not reach the last collapse step (i.e., the roof did not collapse); hence, the filling body did not bear the load after the first stage of mining and filling. In the second stage, after the recovery of the even-numbered coal pillars, the pressure arch foot acting on the even-numbered coal pillars became unstable, resulting in the fracture of the pressure arch structure near the even-numbered coal pillars (Fig. 14). After this fracture, the original pressure acting on the side was transferred to the first-stage filling body, and a new continuous arch structure was gradually formed. The arch foot of this structure initially corresponded to the first-stage filling body and derived from the upward development of the arch axis of the odd-numbered coal pillars' sides. This further developed in a pressure arch structure in which the arch foot corresponded to the adjacent odd-numbered coal pillars. After the recovery of these pillars (in the third stage), the second-stage arch structure became unstable. The continuous arch structure having the filling body as the arch foot was stable in the first stage and played a major supporting role in the stability of the overlying strata. During the second and third stages, most of the arch load was borne by the filling body (Fig. 15).

Field measurement and analysis of strip filling mining

According to the laboratory test, the filling material is composed of aeolian sand:fly ash:cement = 228:53:70 (Shao et al. 2020a). The uniaxial compressive strength can reach 6.05 MPa after 28 days of maintenance. According to the analysis of coal pillar abutment pressure, the ratio can meet the actual needs of the site. Eleven strip goafs were formed as in 3216 working face of Shanghe Coal Mine after mining 7 coal pillars retaining 8. After filling in the first stage, the support pressure of the retained pillar increased to 4.25 MPa, and the load value of filling body was generally between 0.4 and 0.6 MPa. After filling even-numbered strip pillars in the second stage, the abutment pressure of filling body in the first stage rises significantly, the support load rises from 0.5 to 1.4 MPa, the stress value rises about three times, and the support

Fig. 9 Simulated picking odd-numbered strips: Recovery of the odd-numbered coal pillars; filling odd goafs

Fig. 10 Third-stage support pressure registered by the bottom plate sensors

pressure of odd-numbered pillars increases to 5.45 MPa. After the filling of odd-numbered strip pillars in the third stage, the abutment pressure of filling body in the first stage continued to rise significantly, and the mean abutment pressure increased from 1.4 to 2.50 MPa, and the stress value increased about 2 times.

Verification of the theoretical model

The buried depth (H) of working face 3216 was 115 m, the strip width in the first stage of strip mining 7 m, the retained coal pillar (a) 8 m, and the mining height (m) 5.5 m. According to the physical parameters of the overlying strata upon the working face, the friction coefficient (f) was 1 (Li

et al. 2017; Yang et al. 2016), the internal friction angle (φ) 30, and the average volume weight of the overlying strata (γ) 0.025 MN/m³. Substituting these values in Eqs. (7) and (8), we obtain the following:

$$B = 7 + 2 \times 5.5 \times \tan 30^\circ = 13.35 \text{ m}$$

$$h = \frac{8 \times (7 + 2 \times 5.5 \times \tan 30^\circ)}{4 \times 1} = 26.7 \text{ m}$$

Moreover, by substituting them in Eq. (10) we obtain

$$N = \frac{1}{2a} \gamma (H-h) B = \frac{1}{2 \times 8} \times 0.025 \times (115-26.7) \times 13.35 = 1.84 \text{ MPa}$$

Please note that $2N=3.68 \text{ MPa}$.

Fig. 11 Pressure arch structure model between coal columns

Fig. 12 Simplified diagram of the stress arch force analysis

The arch load was

$$\gamma h = 0.025 \times 26.7 = 0.66 \text{ MPa.}$$

In the first stage, the load on a single coal pillar after filling was of 3.68 MPa, and the load on the filling body in the arch was of 0.66 MPa.

After recovering the even-numbered coal pillars in the second stage, the load on the odd-numbered coal pillars increased to 5.16 MPa, while that in the arch increased to 1.3 MPa. After the recovery of the odd-numbered coal pillars in the third stage, the load on the filling body rose to 2.65 MPa, gradually approaching the original rock stress.

The monitoring data regarding the supporting pressure on the coal pillars and filling body of working face 3216 at each stage show that, after the first and second stages of mining and filling, the overlying rock load was mainly carried by the retained coal pillar, while the filling body played an auxiliary supporting role. In the third stage, all the coal pillars were recovered, and the overlying rock load was transferred to the filling body, which was mainly carried by the filling body in the first stage. Overall, the field measured results were in good agreement with the results of the similar simulation and theoretical analysis.

Conclusions

- (i) Our similar simulation experiments, based on three stages of strip filling mining, demonstrated the following: in the

Fig. 13 Pressure arch structure during the first stage

Fig. 14 Pressure arch structure during the second stage

first stage, after strip mining, the overlying strata load was mainly transferred to the remaining strip pillars, and the mean abutment pressure on the pillars increased from 2.51 to 4.10 MPa; after the second stage of filling, the mean abutment pressure on the odd strip pillars (which played the main bearing role) was of 5.50 MPa; after the third stage of filling, the overburden load was mainly supported by the first-stage strip filling body, the mean abutment pressure was 2.76 MPa, and the third-stage filling body was not loaded.

- (ii) We established a mechanical structure model of the overlying strata in strip filling mining, in which the strip coal pillar (or filling body) represented the arch foot of the supporting pressure arch structure. Moreover, we obtained a formula to calculate the load value at the arch foot, as well as an equation for the continuous arch axis. Based on this, we could formulate the law of pressure transfer in a continuous arch in the context of strip filling mining. The pressure bearing mechanisms of the coal pillars and filling body were analyzed during different stages.
- (iii) The field measurements showed that, after the first stage of filling, the supporting pressure on the retained coal pillar rose to 4.25 MPa, while the loading on the filling body was generally 0.4–0.6 MPa. In the second stage, after the filling of the even-numbered strip pillars, the abutment pressure on the first-stage filling body rose to 1.4 MPa, while the support pressure on the odd-numbered pillars increased to 5.45 MPa. In the third stage, after the filling of the odd-numbered strip pillars, the filling support pressure in the first stage rose to 2.50 MPa.

Fig. 15 Pressure arch structure during the third stage

- (iv) The theoretical analysis indicated the overburden load after mining and filling was mainly carried by the first-stage filling body.
- (v) The field measured data were in good agreement with the theoretical calculations, proving the reliability of our theoretical model.

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Declarations

Conflict of interest The author(s) declare that they have no competing interests.

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