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Reducing subsidence technology by overlying bed separation grouting in thick coal seams top coal caving mining

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Abstract

The overlying bed separation grouting in the course of coal mining can control surface subsidence and protect the surface structures from damage. Accurate identification of the bed separation position in overburden grouting and the reasonable determination of the protective layer thickness are very important for this technology. In order to realize the accurate grouting and reduce subsidence in multi-bed separation grouting, the method for determining separation positions was improved based on the composite beam theory and the grouting positions for multi-bed separation grouting were determined. Using the theory of elastic thin plates, a structural mechanical model of the protective layer for overburden grouting was established. An equivalent model for the grouting filling space of overburden isolated separation was set up, and the minimum and maximum total volumes of the grouting filling space were determined. The effect of multi-bed separation grouting in "three soft" thick coal seams was evaluated by combining with actual surface monitoring results. Additionally, the 22151 working face of Peigou Coal Mine in Zhengzhou mining area was analysed as case study. The results show that field borehole observation validated the accuracy of the bed separation positions. The surface subsidence control effect of mining with multi-bed separation grouting was remarkable, and the subsidence reduction rate was about 80.77%. This research enriches the theoretical system of overburden grouting, providing technical support for the design of overburden grouting and subsidence reduction in top coal caving mining of "three soft" thick coal seams.

Keywords

Thick coal seams; Overlying rock strata; Bed separation grouting; Subsidence control

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1 Introduction

China is rich in coal resources, and coal plays an important role in supporting the national economic development, and remains one of the most important energy resources in China for quite a long time (Guo et al. 2020; Bai et al. 2024; Guo et al. 2024). The large-scale mining and stripping of coal resources from underground rock strata inevitably leads to the destabilization of rock strata and triggers geological and environmental disasters, which has been one of the important problems restricting the healthy development of the coal industry (Zhang et al. 2020; Bian et al. 2021). At the same time, the coal mining and utilization process inevitably produces coal gangue, fly ash, slag and other solid wastes, which increases the risk of environmental pollution such as water, soil and gas and threatens the safety and health of the public, and there is an urgent need to carry out the work of solid waste reduction and disposal and utilization (Xuan et al. 2022; Yang et al. 2022).

Under the national strategic situation of ecological civilization construction and green development, “green and waste-free mining” has become a general trend. As a new technology of grouting and filling to reduce subsidence and reduce deformation of the ground surface, the overburden off-layer grouting technology reveals the development of off-layer and the movement law of rock layer under the influence of mining, which can effectively control the subsidence of the ground surface and guarantee the safety, economy and reasonableness of coal mining under structures (Bai et al. 2023; Guo et al. 2023). The proposal and application of overburden off-seam grouting technology marks an important progress in the field of rock stratum control of underground coal mining, and is of great theoretical and practical significance in promoting environmental protection and prevention of geologic disasters in mining areas (Guo et al. 2022; Peng et al. 1981).

The "three soft" coal seam refers to an unstable roof that is prone to collapse, a low coefficient of softness and solidity of the coal seam, and a low compressive strength of the soft floor (Lai et al. 2021; Bai et al. 2022; Guo et al. 2022). Under the geological conditions of high interaction rate between soft and hard rocks and small rock thickness in the overlying strata, there are characteristics such as large overall deformation and fast movement speed of the overlying strata, rapid development closure transmission of overlying strata separation during the fully mechanized top coal caving mining process of the "three soft" thick coal seam (Bai et al. 2024). However, there are currently few reports on grouting research for the separation of overlying strata in fully mechanized top coal mining with "three soft" thick coal seams under geological conditions such as medium burial depth, large mining thickness, high interaction rate between soft and hard overlying strata, and small rock layer thickness (Hou et al. 2021; Kohli et al. 1980). In view of this, based on previous research, the author has explored and implemented the multi layer separation grouting mining technology for overlying strata from multiple aspects such as distinguishing the separation position, determining the grouting layer, and whether the thickness of the protective layer is reasonable. This technology can provide technical support for the design of grouting subsidence reduction in the separation layer of overlying strata in the "three soft" thick coal seam fully mechanized mining, and plays an important role in promoting the application and development of grouting subsidence reduction technology in the separation layer of overlying strata.

2 Geological and mining conditions

Peigou coal mine is located southwest of the Zhengzhou coalfield in Henan Province, China, as shown in Figure. 1.The main coal seam of the mine is Seam No.2_1 , which has an average thickness of 7.5m. It is a typical “three soft” unstable coal seam. The panel 22151 of Peigou coal mine is used as a research site for multi-bed separation grouting in "three soft" thick coal seams. The strike and dip length of the panel are 350 m and 106 m, respectively. The average coal seam depth and thickness of the panel are 302 m and 7.1 m, respectively. The dip angle of the coal seam in the panel is 12 °.The working face adopts a comprehensive mechanized top coal caving mining method, and the natural collapse method is used to manage the roof.

The village houses and structures are on the ground surface over the panel. The Wangguan Highway runs north-south through the area, and the buildings (structures) on both sides of the highway are relatively dense. According to on-site investigations, most of the buildings on both sides of the highway are 1-2 story brick and concrete structures, with a small number of buildings being 3-5 stories. There are also some important buildings such as gas station and hospital buildings.

To sum up, the geological and mining conditions of the panel of 22151 are complex. The mining is subject to multiple constraints of surface buildings and road. Therefore, Multi-bed separation grouting in coal seams mining is selected to recover the coal resources of the panel.

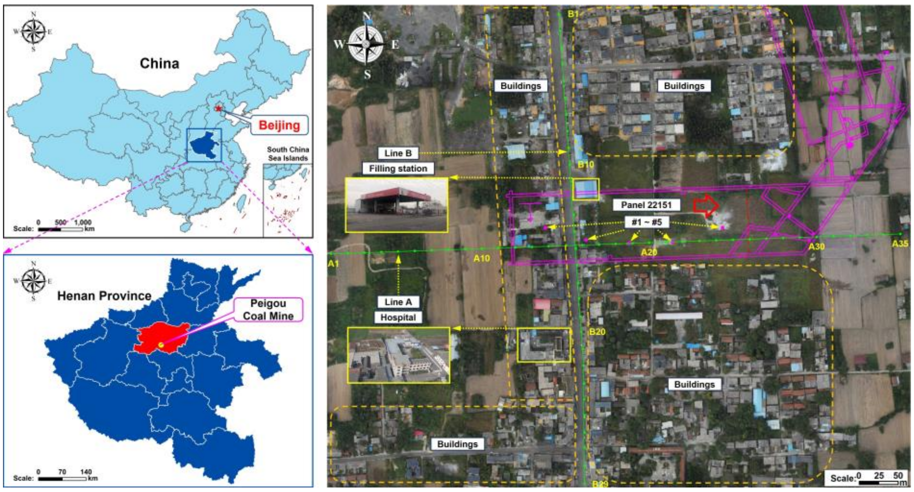


Fig. 1 Location of Peigou coal mine and layout of panel 22151

3 Multi-bed separation grouting in coal seams mining

3.1 Design of multi-bed separation grouting

3.1.1 identification of the bed separation position

In the development process of roof interlayer separation and fracturing, the soft and hard interacting overlying formations can be analyzed as a number of strata superimposed into a combined rock beam, and it is assumed that the load on each formation is uniformly distributed. According to the theory of combined beam and the theory of mine pressure and formation control, the following formula can be expressed by Eq. (1).

$$E_{n+1}(h_{n+1})^2 \sum_{i=1}^{n} \gamma_i \, h_i > \gamma_{n+1} \sum_{i=1}^{n} E \, h_i^3 \qquad (1)$$

Where E_i Elastic modulus of the ith layer, Gpa
h_i Thickness of the ith layer, m
γ_i Specific weight of the ith layer, kN/m^3

3.1.2 Equivalent Model of multi-bed separation grouting mining

An equivalent model of multi-bed separation grouting mining was stablished. When the thickness of the grouting and filling body ($H_{u\max}$ and $H_{m\max}$) in the upper and middle layers is 0, it is equivalent to grouting in a single layer of overlying strata; When $H_{u\max}+H_{m\max} > 0$, the upper and middle layers of the grouting separation filling material can be projected onto the lower grouting separation zone, making the separation zone space equivalent to an inverted trapezoid, and the filling material boundaries are located directly above the edge of the working face direction, as shown in Figure 2.

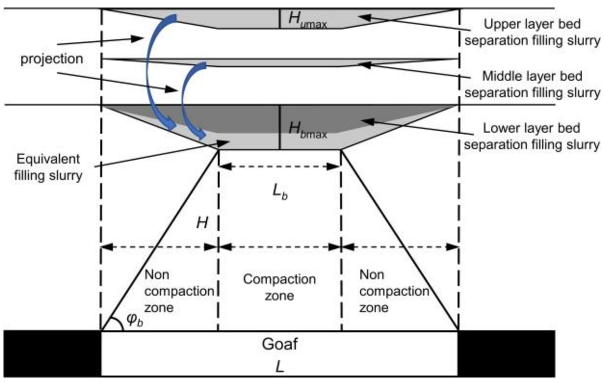


Fig. 2 Equivalent Model of multi-bed separation grouting mining

The thickness of the filling slurry can be expressed by Eq. (2):

$$H_{b\max} = \frac{ML\alpha}{L - H/\tan\varphi_b} \tag{2}$$

Where L_b The Length of flat bottomed collapse zone in the delamination zone
W The strike length of the panel, m
$H_{b\max}$ The Thickness of filling slurry, m
L The dip length of the panel, m
α The comprehensive injection-production ratio, (0.35 ~ 0.45)
φ_b The angle of full subsidence, (50 °~ 60 °)

Engineering solution for surface subsidence caused by multi-bed separation grouting mining can be expressed by Eq. (3):

$$\begin{cases} H_{h\max} = M - H_{b\max} - H_{c\min} \\ H_{c\min} = H_k(K_p - 1) \end{cases} \tag{3}$$

Where $H_{h\max}$ The subsidence of main control rock, m
$H_{c\min}$ The minimum residual thickness of caving rock mass in goaf, m
H_k The height of caving zone, m
K_p The residual bulking factor of caving rock mass

3.1.3 Strata mechanical model of protective layer

The protective layer was simplified into a single layer. And the protective layer will sink, deform, and contact with the underlying rock layers after coal mining. Based on the theory of elastic thin plates, the deformation mechanics analysis and calculation of the protective layer are carried out. Firstly, the following assumptions are made: ① The protective layer is in contact with the lower rock layer as a whole, and the load on the upper part of the protective layer is a uniformly distributed load, with the load size being the grouting layer pressure (σ_f), and the supporting force on the lower part of the protective layer is uniformly distributed load; ② The overall coordinated deformation of the rock layers that make up the protective layer ignores the interlayer shear effect; ③ Neglecting the influence of complex geological structures such as weakened fault zones on the mechanical properties of protective layers.

As can be seen from Fig. 3, when the separation layer first develops, the upper and lower rock layers are firmly supported by the surrounding rock layers, and each side is rigidly fixed. Select an elastic composite rock slab with four fixed supports as the mechanical calculation model for rock fracture.

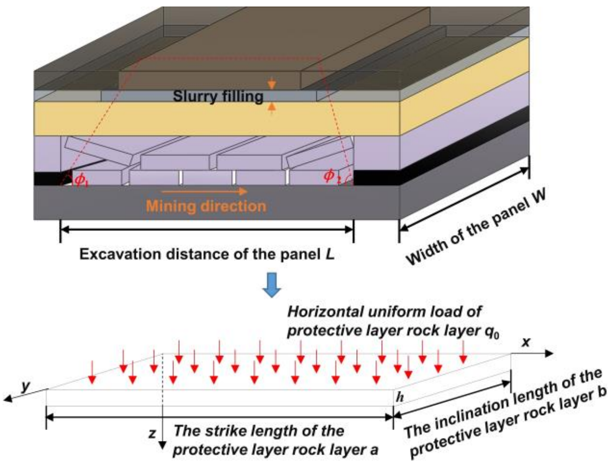


Fig. 3 Strata mechanical model of protective layer

3.1.4 Calculation of the Volume of multi-bed separation grouting mining

As seen from Fig. 4, the separation space generally exists at the interface between soft and hard rock layers. As the distance of coal seam advancement increases, the vertical deflection of soft rock and hard rock is not consistent. The formation of separation is caused by the difference in deflection, and it is believed that the four sides of separation are enclosed intervals.

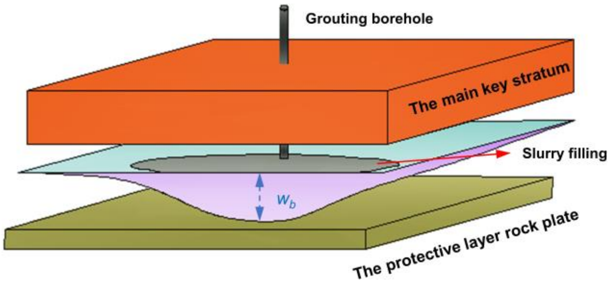


Fig. 4 Grouting space of bed separation

The height of the space w_b between the two plates can be expressed by Eq. (4):

$$w_b = \frac{\left(\frac{q_x}{G_x} - \frac{q_s}{G_s}\right)}{\pi^4\left(\frac{3}{a^4} + \frac{3}{b^4} + \frac{2}{a^2b^2}\right)} \sin^2(\frac{\pi x}{a}) \sin^2(\frac{\pi y}{b}) \tag{4}$$

Where q_s The transverse uniform load on the upper rock layer in the filling slurry, kPa
q_x The transverse uniform load on the lower rock layer in the filling slurry, kPa
G_s The bending rigidity on the upper rock layer in the filling slurry, N*mm^2
G_x The bending rigidity on the lower rock layer in the filling slurry, N*mm^2

According to the research consensus on the maximum deflection at the center of the rock layer (*a*/2, *b*/2) in thin plate theory, it can be concluded that the maximum height of the grouting space can be expressed by Eq. (5):

$$w_{b\max} = \frac{1}{\pi^4\left(\frac{3}{a^4} + \frac{3}{b^4} + \frac{2}{a^2b^2}\right)}\left(\frac{q_x}{G_x} - \frac{q_s}{G_s}\right) \tag{5}$$

The volume of a separated layer grouting layer can be expressed by Eq. (5) :

$$\begin{aligned} V_i &= \iint_{a_i \times b_i} (w_x(x,y)) - (w_s(x,y))\, dx\, dy = \iint_{a_i \times b_i} w_b\, dx\, dy \\ &= \frac{\left(\frac{q_x}{G_x} - \frac{q_s}{G_s}\right)}{\pi^4\left(\frac{3}{a^4} + \frac{3}{b^4} + \frac{2}{a^2b^2}\right)} \int_0^a \int_0^b \sin^2(\frac{\pi x}{a}) \sin^2(\frac{\pi y}{b})\, dx\, dy \\ &= \frac{\left(\frac{q_x}{G_x} - \frac{q_s}{G_s}\right)}{4\pi^4\left(\frac{3}{a^4} + \frac{3}{b^4} + \frac{2}{a^2b^2}\right)} ab = \frac{w_{b\max} ab}{4} \end{aligned} \tag{5}$$

Where w_s The deflection of each point of the upper rock plate, m
w_x The deflection of each point of the lower rock plate, m

The total volume of grouting space is the sum of the volumes of each grouting space can be expressed by Eq. (6):

$$V = \sum V_i \tag{6}$$

3.2 On-site application

As seen from Fig. 5, fly ash produced by coal-fired power plant was selected as the grouting material. Fly ash was stored in a fly ash tank, and then conveyed to a mixing tank through a screw feeder. At the same time, water was conveyed to the primary mixing station. The slurry formed by mixing water and fly ash in the ratio and then conveyed to a second mixing station. After mixing again, the slurry was pumped by grouting pumps into bedding plane separations through the surface boreholes.

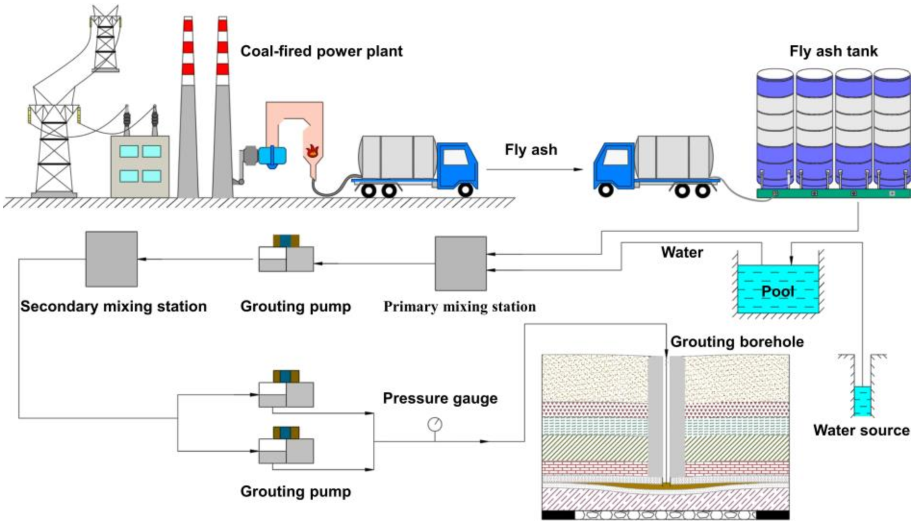


Fig. 5 The technological flow diagram of overburden grout injection

To verify the accuracy of the separation position in the multi-bed separation grouting, grouting holes were added at higher levels and the grouting position was identified through drilling observation. According to the drilling observation results, it was found that there was fly ash slurry in the theoretical grouting layer, which verified the feasibility of the multi layer separation grouting design. The drilling observation results are shown in Figure 6.

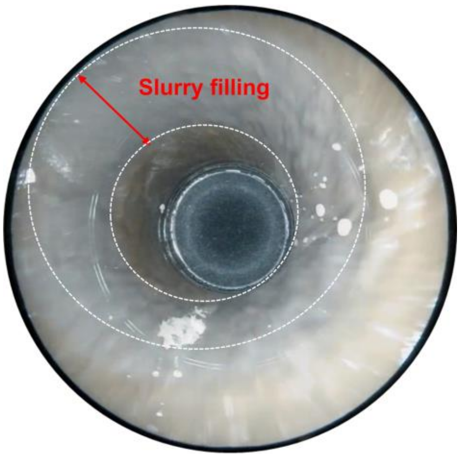
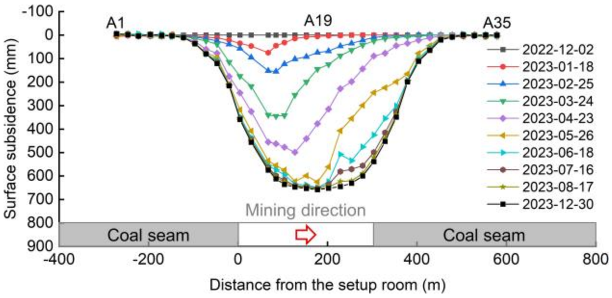


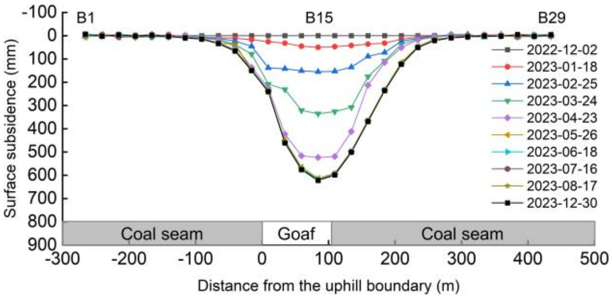
Fig. 7 Drilling hole peeping

4 Subsidence monitoring and effect evaluation

To evaluate the surface subsidence reduction effect of multi-bed separation grouting in "three soft" thick coal seams, a method combining probability integration prediction and on-site monitoring was adopted. And the surface dynamic subsidence curves along the strike and dip main cross section on the subsidence are shown in Figs. 7(a, b) respectively. Based on the monitoring data, the parameters of the surface movement angle of thick coal mining are obtained as shown in Table 1.



(a) Subsidence of inclination line (line A)



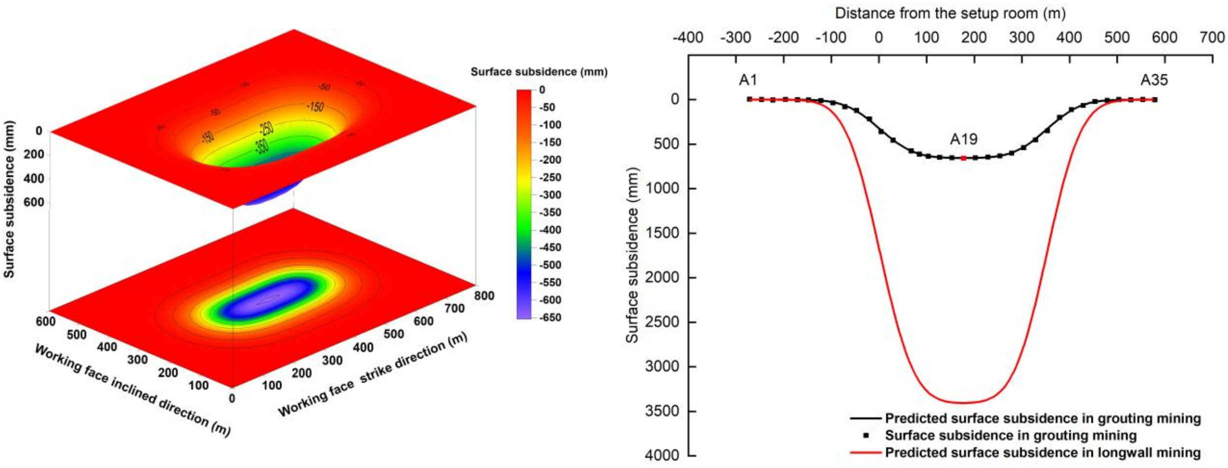
(b) Subsidence of strike line (line B)

Fig. 7 Surface subsidence of observation station under the panel 22151 mining

Table 1 The parameters of the surface movement angle

	Angle of critical deformation			Angle of draw			Subsidence factor
	Strike	**Rise**	**Downhill**	**Strike**	**Rise**	**Downhill**	
Longwall mining	71.5 °	71.8 °	68.5 °	55.9 °	56.4 °	54.4 °	0.78
Ming with grouting	77.4 °	74.9 °	74.4 °	68.9 °	66.6 °	59.6 °	0.15
Difference	5.9	3.1	5.9	13.0	10.2	5.2	0.63

Figure 8(a) is the three-dimensional surface subsidence basin and contour based on the surveying data after panel 22151 mining with bed separation grouting in overburden strata. Figure 8(b) are the two surface subsidence curves: one is the field surveying results and the other is the predicted results with probability integration method but no bed separation grouting. From the figure 8, the maximum subsidence value of the surface using multi-bed separation grouting mining is 649.8mm, and the subsidence reduction rate is about 80.77%, which has obvious effect on the surface subsidence caused by mining and the protection of surface structures.



(a) Three-dimensional model of surface subsidence in panel 22151

(b) Comparison of predicted surface subsidence values between two mining methods

Fig. 8 The model of surface subsidence in panel 22151

5 Conclusions

Multi-bed separation grouting in "three soft" thick coal seams mining has improved the extraction rate of coal resources, effectively controlled surface subsidence. This technology can avoid or reduce the impact of coal mining on surface buildings. And the concept of green mining and the strategy of surface ecological protection can get the economic and social benefits. At the same time, new technological approaches have been explored and some experiences has been accumulated for the coal mining under structures in coalmines. Some conclusions through this case study are drawn:

(1) A multi-bed separation grouting technology in the overlying strata was proposed, and a calculation method for grouting volume in separation space was obtained.

(2) According to the improved separation discrimination method, the grouting positions of multi-bed separation were determined, and the accuracy of the grouting positions of multi-bed separation was verified.

(3) The surface movement and deformation laws of thick coal seam longwall mining with multi-bed separation grouting mining were obtained. The grouting subsidence reduction effect of the multi-bed separation grouting in the overlying strata are also obtained.

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