ENGINEERING DESIGN OF SELECTING PARTICLE SIZE OF GANGUE UNDER SOLID BACKFILL MINING FOR PROTECTING WATER RESOURCES

by

Yun ZHANG*, Peng-Fei SHAN, Rui BAI, and Jing-Jing DAI
School of Energy Science and Engineering, Xi'an University of Science and Technology, Xi'an, China

Original scientific paper
https://doi.org/10.2298/TSCI2006019Z

In view of the ecological environment damages caused by the loss of water resources and the gangue accumulation during coal mining, this paper proposed a solid backfill mining method to recover the coal seam under the water body, which could fundamentally reduce the sinking space of the overlying strata, and better prevent water-flowing fractures expanding. Consequently, according to the deformation characteristics of the overlying strata of the solid backfill mining, a mechanical model was established for superimposed beams on elastic foundation with simulating the expansion water-flowing fractures under solid backfill mining. A method of calculating the height of the water-flowing fractured zone was provided, and the mechanical mechanism of the development of water-flowing fractures in the overlying strata under solid backfill mining was expressed. Meanwhile, the backfill rate of the experimental working face was designed as 80% to avoid the ecological environment damages caused by gangue accumulation. The stress-strain characteristics of gangue samples under different grading size schemes were further studied.

Key words: *solid backfill mining, water-flowing fractures, backfill rate, particle size of gangue*

Introduction

The center of coal mining in China had shifted rapidly to the eastern areas. The western area had large reserves of coal resources, which had simple geological structure and excellent quality. However, the coal seams in the western mining area were shallow buried and near-horizontal, with thin bedrock above the coal seam [1]. Therefore, the surface was severely affected, and the water-flowing fractures (WFF) was a relatively high, which caused damage to superficial water and the ecological environment, such as stream betrunking, sparse surface vegetation and serious soil erosion. It severely interferes with the local industrial and agricultural development and ecological environment balance [2-4]. According to statistics, from the 1980's to the early 1990's, the mortality rate of sand sagebrush in the subsidence area of Shendong Coal Mine was 16% higher than that in the areas with no subsidence [5]. At the same time, due to large-scale, high-intensity coal mining, the large amounts of gangue were discharged and accumulated to the surface [6, 7], which had caused great harm to the ecological environment of the mining area. Consequently, given that protect water resources and solve the environmental damages caused by gangue accumulation, this paper proposed to use solid

* Corresponding author, e-mail: zhangyun@cumt.edu.cn

backfill mining (SBM) method to recover the coal seam under the water body, which was an effective, feasible, environment-friendly solution for the above problems.

At present, the main researches on the development of WFF included: Xu *et al.* [8] believed that key stratum had an important influence on the height of the water-flowing fractured zone (HWFFZ), and proposed a method for predicting the HWFFZ based on the position of key stratum. Hu *et al.* [9] obtained the functional relationship between each element and the HWFFZ according to the analysis of various elements affecting the HWFFZ in the stope. Meanwhile, researches on SBM with gangue mainly include: Zhang *et al.* [10] proposed the equivalent mining height model from the analysis of the kinematic mechanical properties of the basic roof during SBM. From the perspective of stratum control, Huang *et al.* [11] put forward a design method for the backfill rate of the working face based on the compacting characteristics of the backfill material. Nonetheless, the current research work toward the theoretical understand the development of WFF under SBM remain lacking, and to further study it.

The aim of the paper is to suggest that the SBM method with gangue is proposed for recovering coal seam under water body. Based on the control characteristics of the overlying strata under SBM, a mechanical model is established for a superimposed beam on elastic foundation with simulating the expansion WFF under SBM. The minimum critical backfill rate is theoretically calculated to protect water resources. The engineering design for gangue particle selection is conducted for a Shaanxi experimental coal mine.

Engineering background and control overlying strata of SBM

Engineering background

The experimental coal mine was located in the south of Yan'an City, Shaanxi Province. The mining area extended northward to Yan'an urban area, Yulin and other places, and southward to Tongchuan and Xi'an. The mine field was about 13 km wide from east to west and 23 km long from north to south. The area of the mine field was about 197.5 km^2. The designed production capacity was 4.2 million tons per year. According to the hydrogeological conditions, the aquifer of the experimental coal mine belonged to surface waters, which are mainly the potential-protection water resources in mining area. Therefore, in order to protect the surface water resources and improve the recovery rate, the SBM method was proposed for recovering the coal seam under the surface water resources, which was an effective and environmental-friendly mining method to improve the recovery coefficient and avoid the destruction to water resources. According to the S81 borehole near the experimental working face, the geological location and columnar pattern of the experimental mining area is shown in fig. 1.

Deformation characteristics of overlying strata of SBM

In the process of SBM, when the coal had been mined, the gangue material was backfilled to the gob timely. The bulldozer was used to let the gangue material fully connected to the roof, then the gangue material as a permanent carrier to bear the load of the overlying strata. It could effectively reduce the sinking space of the roof, and limit the movement and breakage of the strata. The SBM changed the deformation characteristics of the overlying strata above the stope, and limited the development of the WFF in the overlying strata. The backfill rate referred the ratio of the final height of the SBM (after being compressed by overlying strata) and the mining height in the gob, and its expression was:

$$\varphi = \frac{h_c - H_z}{h_c} \tag{1}$$

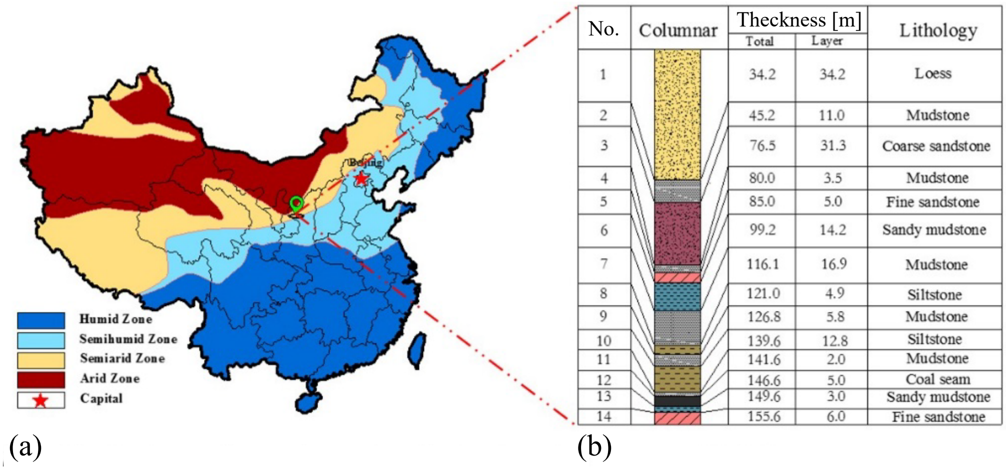

Figure 1. Distribution of Chinese water resources and columnar pattern of the experimental coal mine; (a) water distribution and experimental coal mine location and (b) columnar pattern

where φ is the backfill rate, h_c – the mining height, and H_z – the roof settlement.

Through a lot of filed measurements, it was shown that, compared with the long-wall caving mining, if the backfill rate of the working face reached a certain value, there were only *two zones* above the backfill working face, namely, the fractured zone and the bending zone, without caving zone. Therefore, it could be seen that SBM method could effectively prevent the loss of water resources by coal mining.

Mechanical analysis of the development of WFF under SBM

Establishment of the mechanical model for the expansion of WFF under SBM

According to the assumption of Winkle elastic foundation, the pressure of a point of the foundation, denoted as p, is expressed:

$$p = kw(x) \tag{2}$$

where $w(x)$ is the foundation settlement, and k – the elastic foundation coefficient.

Based on the theory of the elastic foundation beam, the loading, denoted as q, can be written:

$$EI\frac{\mathrm{d}^4 w(x)}{\mathrm{d}x^4} + p = q \tag{3}$$

where EI is the flexural rigidity of rock beam.

In order to study the development characteristics of WFF during SBM, the HWFFZ was determined by calculating the plastic failure height of the rock layers above the stope [12]. An arbitrary stratum (denoted as the i^{th} stratum) above the coal seam was taken as the research object, and the loading of the upper stratum on the i^{th} stratum was simplified into linear loading $q_1(i)$ and $q_2(i)$. At the same time, the strata, backfill body and coal mass below the i^{th} stratum were simplified as a Winkler elastic foundation. Based on the structure state of overlying stratum and foundation under SBM, see fig. 2, with the position O of the starting cut as the origin, the advancing direction of the working surface as the x-axis, and the displacement $w^i(x)$ direction as the y-axis, a mechanical model was established and analyzed for a superimposed

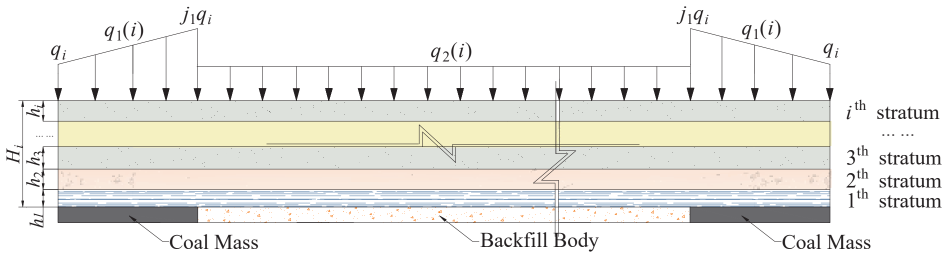

Figure 2. Structure state of overlying stratum and foundation under SBM

beam on elastic foundation with simulating the expansion WFF under SBM. The mechanical model is shown in fig. 3.

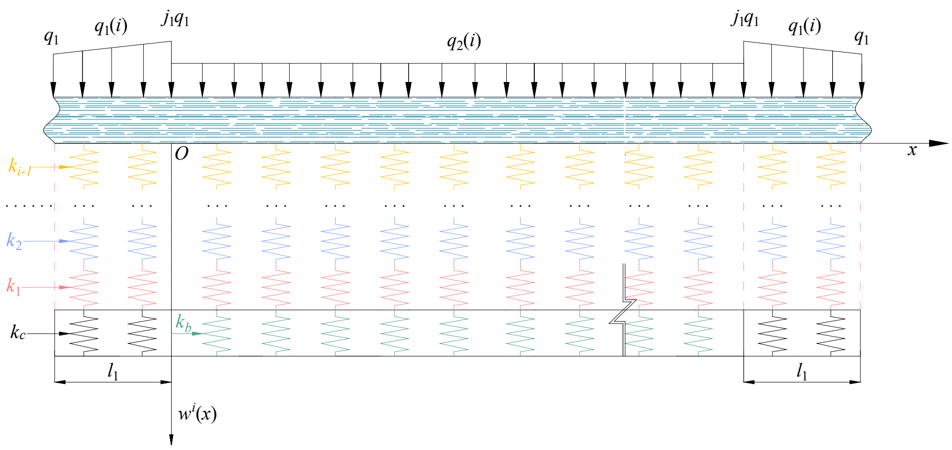

Figure 3. A mechanical model with simulating the expansion WFF under SBM

Due to the influence of coal mining, the bearing stress of the i^{th} stratum can be expressed as follows:

$$q_1(i)=\begin{cases}\dfrac{(j_1-1)q_i}{l_1}x+j_1q_i & \text{, coal mass on the left}\\[2ex] \dfrac{(1-j_1)q_i}{l_1}x+\dfrac{2j_1l_1q_i-lq_i}{l_1} & \text{, coal mass on the right}\end{cases} \tag{4}$$

where l is the advancing length, j_1 – the bearing stress coefficient, l_1 – the influence range of bearing stress, and q_i – the initial rock stress.

After the coal seam was mined, the backfill body was backfilled into the gob in time, and the roof above the backfill body still moved slightly downward. The loading of the i^{th} stratum above the backfill body reads:

$$q_2(i)=\gamma(d'-H_{i\text{-}1}) \tag{5}$$

where γ was bulk density of the stratum, d' – the potential caving height, and H_{i-1} – the total thickness of all strata from the 1^{st} stratum to the $(i-1)^{th}$ stratum.

The combined elastic foundation coefficient, denoted as k_i^1 and k_i^2, respectively, are:

$$\begin{cases} \dfrac{1}{k_i^1} = \dfrac{1}{k_c} + \dfrac{1}{k_1} + \dfrac{1}{k_2} \cdots + \dfrac{1}{k_{i-2}} + \dfrac{1}{k_{i-1}}, & \text{combination of coal mass and strata} \\ \dfrac{1}{k_i^2} = \dfrac{1}{k_b} + \dfrac{1}{k_1} + \dfrac{1}{k_2} \cdots + \dfrac{1}{k_{i-2}} + \dfrac{1}{k_{i-1}}, & \text{combination of backfill body and strata} \end{cases} \tag{6}$$

where k_c was the elastic foundation coefficient of coal mass, k_b – the elastic foundation coefficient of the backfill body, and k_1, k_2, ..., k_{i-1} were the elastic foundation coefficient of each stratum.

Analysis on mechanical model of bending deformation

Based on the theory of elastic foundation beam, the coal mass and backfill body left in the stope could be assumed to be independent springs, the deflection equations of each section at the i^{th} stratum, denoted as $w_1^i(x)$, $w_2^i(x)$, and $w_3^i(x)$, could be written:

$$\begin{cases} w_1^i(x) = \mathrm{e}^{\alpha x}(A_1 \cos\alpha x + A_2 \sin\alpha x) + \mathrm{e}^{-\alpha x}(A_3 \cos\alpha x + A_4 \sin\alpha x) + \dfrac{q_1(i)}{k_i^1}, & (l_1 \le x \le 0) \\ w_2^i(x) = \mathrm{e}^{\beta x}(B_1 \cos\beta x + B_2 \sin\beta x) + \mathrm{e}^{-\beta x}(B_3 \cos\beta x + B_4 \sin\beta x) + \dfrac{q_2(i)}{k_i^2}, & (0 \le x \le l) \\ w_3^i(x) = \mathrm{e}^{\alpha x}(C_1 \cos\alpha x + C_2 \sin\alpha x) + \mathrm{e}^{-\alpha x}(C_3 \cos\alpha x + C_4 \sin\alpha x) + \dfrac{q_1(i)}{k_i^1}, & (l \le x \le l + l_1) \end{cases} \tag{7}$$

where $\alpha = [k_i^1/(4EI)]^{1/4}$ and $\beta = [k_i^2/(4EI)]^{1/4}$.

Combining with eq. (1), the relationship between the elastic foundation coefficient of the backfill body and the backfill rate could be expressed [13, 14]:

$$k_b = \frac{\sigma_c}{h_c(1-\varphi)} \tag{8}$$

where σ_c is the initial rock stress of coal seam.

The boundary condition can be given:

$$\begin{cases} \theta_1^i(-l_1) = 0, \quad w_1^i(-l_1) = 0 \\ \theta_3^i(l + l_1) = 0, \quad w_3^i(l + l_1) = 0 \end{cases} \tag{9}$$

where θ is the angle of rotation.

The continuity conditions reads as follows:

$$\begin{cases} \theta_1^i(0) = \theta_2^i(0), \quad w_1^i(0) = w_2^i(0), \quad M_1^i(0) = M_2^i(0), \quad Q_1^i(0) = Q_2^i(0) \\ \theta_2^i(l) = \theta_3^i(l), \quad w_2^i(l) = w_3^i(l), \quad M_2^i(l) = M_3^i(l), \quad Q_2^i(l) = Q_3^i(l) \end{cases} \tag{10}$$

where M is the angle of rotation, and Q is the shear force.

Calculation of HWFFZ

According to the mechanics theory of material, the maximum tensile stress of the i^{th} stratum, denoted as $\sigma_{\max}^i$, is expressed:

$$\sigma_{\max}^{i} = \left| \frac{6M_{\max}^{i}}{h_i^2} \right| \tag{11}$$

where h_i is the thickness of the i^{th} stratum and $M_{\max}^{i}$ is the maximum bending moment.

Based on the first strength theory, we have that:

$$\sigma_{\max}^{i} \geq [\sigma_i] \tag{12}$$

where $[\sigma^i]$ was the tensile strength.

If the stratum satisfied eq. (12), the stratum broke down and the WFF occurred. On the contrary, if eq. (12) was not satisfied, the WFF would not occur in the stratum. The analysis started from first stratum of overlying strata above the coal seam. If the maximum tensile stress of this stratum was greater than its tensile strength, the stratum would break down and the WFF would occur. Then the adjacent upper strate was checked until the maximum tensile stress of a stratum was less than its tensile strength. The value of the thickness of each broken stratum (HWFFZ), denoted as H, can be expressed:

$$H = h_1 + h_2 + h_3 + \cdots\cdots \tag{13}$$

where h_1, h_2, and h_3 is the thickness of each stratum above the coal seam.

Therefore, in order to prevent the loss of water resources, it must be ensured that $H <$ 141.4 m. The relate parameters of the roof were substituted into the mechanical model, the minimum critical backfill rate of the experimental working face for protecting water resources was 18.5%.

Engineering design: selection of particle size of gangue

According to statistics, the gangue production of the coal mine was about 230000 tones. In order to avoid water resources loss and gangue accumulation, the coal mine decided to design the backfill rate in the experimental working face as 80%. The selection of gangue particle size of the working face was decisive to the final backfilling effect. Therefore, in combination with the original gangue screened in experimental coal mine, nine graded gangue samples with three groups of uniform grading, three groups of large grading and three groups of small grading were prepared through a grading sieve. Furthermore, the gangue samples were placed in a steel chamber, and the stress-strain characteristics of the gangue samples were tested. The gangue grading size scheme is shown in tab. 1. The gangue samples of each particle size range are shown in fig. 4.

Three groups of samples with different schemes were prepared according to tab. 1. The average value of three tests was taken as the final test result. The loading control system in compression tests of gangue adopted MTS815.02 rock mechanics electro-hydraulic servo testing machine. The stress-strain curves of different gangue grading size schemes are shown in fig. 5. It could be found that the stress reached 3.5 MPa, the strains corresponding to the gangue

Table 1. Scheme of gangue grading size for testing

Scheme	Percentage of gangue quality in each particle size range [%]				
	5-10 mm	10-20 mm	20-30 mm	30-40 mm	40-50 mm
1	20.0	20.0	20.0	20.0	20.0
2	–	–	–	30.0	70.0
3	70.0	30.0	–	–	–

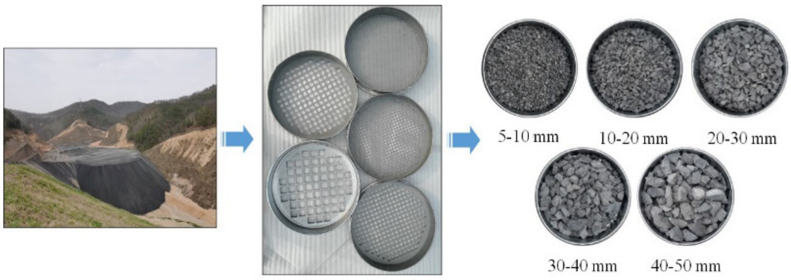

Figure 4. Gangue samples of each particle size range

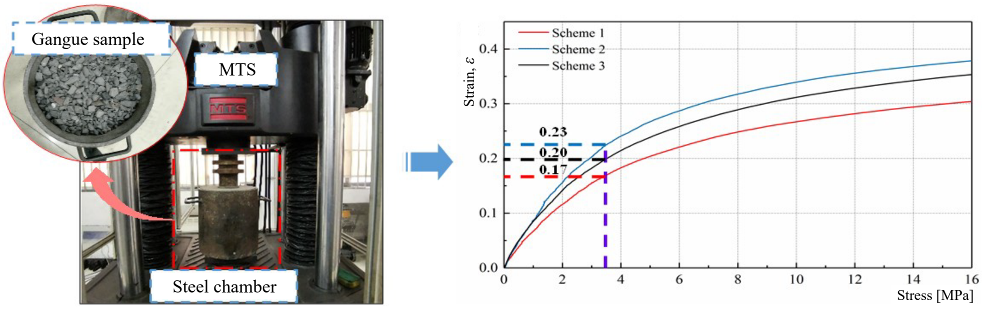

Figure 5. The loading control system and stress-strain curves of gangue

grading size Schemes 1-3 were about 0.17, 0.23, and 0.2, respectively. Therefore, when the grading Scheme 3 was adopted, the backfill rate of the experimental working face would reach 80%. That was, particle size of gangue with 70% 40-50 mm and 30% 30-40 mm mixed were chosen to be the backfill materials. The backfill rate could meet the designed requirements.

Conclusion

At the present work, the SBM method was proposed to recover the coal seam under the water body, which is used gangue material as backfill body into the gob to reduce the sinking space of the roof, limit the movement and the breakage of the strata and the development of the WFF. The water resources loss by coal mining was effectively prevented, and the economic and environmental benefits were balanced. The mechanical model was established for a superimposed beam on elastic foundation with simulating the expansion WFF under the SBM, and a method of calculating the HWFFZ was provided.

Acknowledgment

This work was supported by the National Natural Science Foundation of China (51874284, 51904227).

References

[1] Huang, Q. X., Ground Pressure Behavior and Definition of Shallow Coal Seams (in Chinese), *Chinese Journal of Rock Mechanics and Engineering*, *21* (2002), 8, Part 1, pp. 217-227
[2] Chi, M. B., *et al.*, Prediction of Water Resource Carrying Capacity by the Analytic Hierarchy Process-Fuzzy Discrimination Method in a Mining Area, *Ecological Indicators*, *96* (2019), Part 1, pp. 647-655
[3] Xue, Y., *et al.*, Productivity Analysis of Fractured Wells in Reservoir of Hydrogen and Carbon Based on Dual-Porosity Medium Model, *International Journal of Hydrogen Energy*, *45* (2020), 39, pp. 20240-20249

[4] Fan, L. M., Scientific Connotation of Water-Preserved Mining, *Journal of China Coal Society*, *42* (2017), 1, pp. 27-35
[5] Miao, X. X., *et al.*, Research on Basic Theory of Mining with Water Resources Protection and Its Application to Arid and Semi-Arid Mining Areas, *Chinese Journal of Rock Mechanics and Engineering*, *28* (2009), 2, pp. 217-227
[6] Zhang, J. X., *et al.*, Surface Subsidence Control Theory and Application to Backfill Coal Mining Technology, *Environmental Earth Sciences*, *74* (2015), 2, pp. 1439-1448
[7] Zhang, Y., *et al.*, The Application of Short-Wall Block Backfill Mining to Preserve Surface Water Resources in Northwest China, *Journal of Cleaner Production*, *261* (2020), July, pp. 121232
[8] Xu, J. L., *et al.*, New Method to Predict the Height of Fractured Water-Conducting Zone by Location of Key Strata, *Journal of China Coal Society*, *37* (2012), 5, pp. 762-769
[9] Hu X. J., *et al.*, Index of Multiple Factors and Expected Height of Fully Mechanized Water Flowing Fractured Zone, *Journal of China Coal Society*, *37* (2012), 4, pp. 613-620
[10] Zhang, J. X., *et al.*, Application of Solid Backfilling to Reduce Hard-Roof Caving and Longwall Coal Face Burst Potential, *International Journal of Rock Mechanics Mining Science*, *88* (2016), Oct., pp. 197-205
[11] Huang, Y. L., *et al.*, Strata Movement Control Due to Bulk Factor of Backfilling Body in Fully Mechanized Backfilling Mining Face, *Journal of Mining. & Safety Engineering*, *29* (2012), 2, pp. 162-167
[12] Zhang, Y., *et al.*, Mechanisms of the Development of Water-Conducting Fracture Zone in Overlying Strata During Shortwall Block Backfill Mining: A Case Study in Northwestern China, *Environmental Earth Sciences*, *77* (2018), 14, 543
[13] Huang, Y. L., *et al.*, Analysis on Filling Ratio and Shield Supporting Pressure for Overburden Movement Control in Coal Mining with Compacted Backfilling, *Energies*, *10* (2017), 1, 31
[14] Liu, J., *et al.*, Numerical Evaluation on Multiphase Flow and Heat Transfer during Thermal Stimulation Enhanced Shale Gas Recovery, *Applied Thermal Engineering*, *178* (2020), Sept., 115554

Paper submitted: April 3, 2020
Paper revised: May 30, 2020
Paper accepted: August 7, 2020

© 2020 Society of Thermal Engineers of Serbia
Published by the Vinča Institute of Nuclear Sciences, Belgrade, Serbia.
This is an open access article distributed under the CC BY-NC-ND 4.0 terms and conditions