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In situ identification of water-permeable fractured zone in overlying composite strata

W.P. Huang[a,*], C. Li[a], L.W. Zhang[b], Q. Yuan[a], Y.S. Zheng[c], Y. Liu[d]

[a] State Key Laboratory of Mining Disaster Prevention and Control, Shandong University of Science and Technology, Qingdao 266590, China
[b] Shandong Energy Group Co. Ltd., Jinan 250100, China
[c] Zhaizhen Coal Mine, Shandong Energy Group Co. Ltd., Tai'an, 271204, China
[d] College of Mechanical and Electronic Engineering, Shandong University of Science and Technology, Qingdao 266590, China

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ABSTRACT

The height and boundary shape of a water-permeable fractured zone (WFZ) play an important role in mining safety under challenging conditions; for example, when the coal seam is subject to a confined aquifer or the roadway is designed in close range to the coal seam. For the accurate estimation of the WFZ height, the theoretical prediction method was introduced based on the overlying composite strata structure and an empirical equation. In situ detection of the WFZ height and shape was performed in the Zhaizhen coal mine, China. The field detection was executed by injecting water into boreholes. Based on the analysis results of the variation in water seepage along these boreholes, the fracture intensity and the permeability of the overlying strata were studied, and the height and boundary shape of the WFZ were also confirmed. The measured height was consistent with the theoretical estimation, verifying that the WFZ developed upwards through the strata group acting as a unit. The final boundary of the WFZ presented an irregular saddle shape, and the boundary angle was approximately 75°–78°. According to the height and shape of the WFZ induced by mining of the lower coal seam, the fracture intensity and scope of the surrounding rock and the mining feasibility of the upper coal seam was evaluated in the Zhaizhen mine. A suitable roadway layout of the upper coal seam was also designed.

1. Introduction

In subsurface coal mining, due to the creation of free space to allow movement, the overlying strata will gradually bend, first at the bottom and then through the strata to the surface. When the bending tensile stress exerted on a stratum exceeds the corresponding ultimate tensile strength, the stratum will fail and collapse. Additionally, a "three-zone" morphological distribution forms in the overlying strata and includes a caved zone (I), fractured zone (II) and bending zone (III),[1–3] as presented in Fig. 1. As the number of penetrating fissures in the caved and fractured zones increase, the water seepage capacity of the strata also increases; consequently, these two zones are defined as the water-permeable fractured zone (WFZ). Determining the height of the WFZ is important for mining safety evaluation under a confined aquifer and mine water hazard prevention. These WFZ height has been the focus of studies regarding WFZs. In contrast, in close-range coal seam mining, not only the height but also the final shape of the WFZ boundary can affect the mining safety and the design of reasonable roadway layouts. Research on the WFZ boundary shape has not yet received adequate attention.

The final height and shape of a WFZ are affected by numerous factors, such as the mining thickness, mine depth, span of the working face, mechanical properties and composite structures of the overlying strata. Many scholars have studied WFZ formation, including the movement law of the strata overlying a mined area and the classification index of the fracture permeability, by using comprehensive research methods.[4–15] These methods include mechanical theory analysis, physical modelling and numerical simulation. Several important results were obtained in the previous studies and help to predict the development of a WFZ in terms of its height and morphological shape. From a long-term research project, we discovered that the composite strata contained various soft and hard rocks; certain strata, which are thicker and have higher strength, will often play a key role in controlling the WFZ development. Therefore, the WFZ was found to develop upwards through strata groups acting as a unit. On the basis of this finding, a theoretical prediction method for the WFZ height was established.

Currently, the main method used to determine the height and shape of a developing WFZ is field detection, which is also the most direct and reliable method. Detection methods include the ground borehole flushing fluid method, downhole segmented water injection method

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[*] Corresponding author.
E-mail address: hwp20033@sdust.edu.cn (W.P. Huang).

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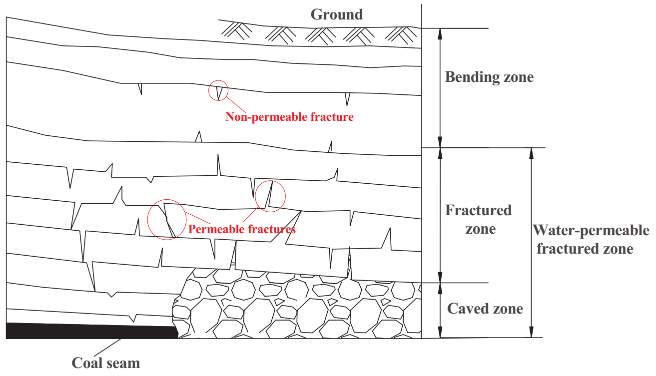

Fig. 1. "Three-zone" morphological distribution in the strata overlying a mined coal seam.

and geophysical exploration methods.[16–22] In practical engineering applications, the ground borehole flushing fluid method requires a complicated construction and installation process and offers low detection accuracy because it is executed through borehole drilling from the ground surface. The geophysical exploration methods are costly and easily could be affected by the harsh mine conditions, such as high temperatures and high humidity. The downhole segmented water injection method is executed by drilling into the upper strata around the goaf; therefore, this method requires less engineering construction and is less costly. Additionally, the downhole segmented water injection method directly detects fracture permeability by using an aqueous medium, and the observation results are accurate and reliable.

The field engineering example used in this paper was the close-range coal seam mining in the Zhaizhen mine. A theoretical method for predicting the WFZ height was proposed based on the overlying composite strata structure and an empirical formula. Then, in situ detection of the WFZ height and shape was conducted with the downhole segmented water injection method.

2. Engineering background

2.1. Mining condition

The Zhaizhen mine is in the Xinwen mining area in eastern China. In this area, the No. 6 mining district has an elevation of − 400 m. The primary mined coal seams are the No. 2 and the No. 4. The No. 2 coal seam is on approximately 27.8 m above the No. 4 coal seam. The coal seam dip angle is approximately 3°–7°. The average thicknesses of the No. 2 and No. 4 coal seams are 1.82 m and 2.65 m, respectively. The No. 4 coal seam was mined first to optimize the economic exploitation of these high-quality coal resources. The strike longwall coal mining method and comprehensive mechanized mining technology were utilized. The goaf management was controlled with the roof collapse method. The design of the No. 2 coal seam mining started one year after the No. 4 coal seam mining was complete. The first working face in the No. 2 coal seam was located just above the goaf of the 6403 working face in the No. 4 seam. The two working faces almost overlapped, which is common in ascending mining. Fig. 2 presents planar and vertical views of the 6403 working face in the No. 4 coal seam and the mining area of the first working face in the No. 2 coal seam. The 6403 working face length was 161 m, and its strike length was 430 m. The average mining thickness was 2.5 m. The fractured zone, which was induced by the mining of the 6403 working face, will reduce the integrity of the surrounding rock in the No. 2 coal seam. Consequently, to evaluate the mining feasibility of the No. 2 coal seam, the WFZ height must be detected to determine if the No. 2 seam is located in the WFZ and to evaluate the influence of the WFZ on the mining. Additionally, because the first face in the No. 2 coal seam was located just above the goaf of the 6403 working face, to design a reasonable roadway layout in the No. 2 seam and evaluate the integrity of the surrounding rock, the shape of the WFZ induced by the No. 4 coal seam mining must also be detected.

2.2. Analysis of the surrounding rock structure

Fig. 3 presents the strata structure above the No. 4 coal seam. The strata structure surrounding the No. 2 and No.4 coal seam is complicated, whereas the roof strata above the No. 4 coal seam exhibited a composite structure. The lithology mainly included muddy siltstone, fine sandstone, siltstone and medium-fine sandstone. Several thin coal seams (< 1 m) that do not have any mining value are mixed within the formation. To elucidate the mechanical properties of the surrounding rock, samples were collected from the main rock types and tested in a laboratory. Table 1 presents the compressive strengths and other mechanical parameters of the rock samples.

The lithology of the surrounding rock varies, and the overlying strata include both hard and soft rocks of various thicknesses. The uniaxial compressive strength of the muddy siltstone was 21.4 MPa, similar to other soft rock types, whereas the uniaxial compressive strength of the fine sandstone was 62.5 MPa, classifying the fine sandstone as a hard rock. Additionally, a section with multiple thick layers of siltstone and medium-fine sandstone was observed. The corresponding hardness coefficient was approximately 3–4. According to the relevant theoretical research, the overlying strata are mainly affected by the strength and thickness of each stratum.[23,24] As shown in the strata structure in Fig. 3, only one hard stratum, a fine sandstone layer 7.7 m thick, is observed. In addition, three soft muddy siltstone strata with a total thickness of 2.1 m are present in the overlying strata. The other strata are categorized as medium-hard and include medium-fine sandstone and siltstone; the total thickness of these medium-hard strata is up to 45 m. Therefore, according to the comprehensive analysis of the strata structure and the mechanical properties, the entire strata overlying the No. 4 coal seam can be categorized as having a medium strength.

On the basis of the considerable difference in thickness and lithology, as the No. 4 coal seam is mined, layers within the overlying strata would move independently. This movement should demonstrate, to some extent, a group movement phenomenon.

3. Prediction of the WFZ height before in situ detection

An accurate prediction of the WFZ height constitutes the basis for the design of the field detection programme, influencing the key detection borehole parameters such as the length and dip angle. The reasonable prediction of the WFZ height is expected to effectively reduce the amount of field construction work and improve the accuracy of the borehole observations.

3.1. Existing empirical formulas for WFZ calculation

Currently, empirical formulas (1) to (4) are widely utilized by field technicians in China to predict WFZ height.[2,25] These formulas were obtained through the statistical analysis of many measurements and were included in the "Coal mining regulations under the buildings, water and rails". This method divided the overlying strata into hard, medium-hard, soft and significantly soft categories according to the comprehensive compressive strength. Additionally, the WFZ height could be calculated from the mining thickness by the corresponding empirical formulas.

$$\text{For the hard strata category:}\quad H=\frac{100\sum M}{1.2\sum M+2.0}\pm 8.9 \tag{1}$$

$$\text{For the medium–hard strata category:}\quad H=\frac{100\sum M}{1.6\sum M+3.6}\pm 5.6 \tag{2}$$