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Distribution Characteristics of the Overburden Three-Zone Structure in the Goaf of a Y-Type Ventilation Working Face

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Abstract

To elucidate the development law of the overburden three-zone structure in the goaf of a Y-type ventilation working face, the 32010 working face of a coal mine was selected as the engineering background, and the evolutionary characteristics of the overburden three zones were investigated by combining theoretical analysis with numerical simulation. First, the formation mechanism of the overburden three-zone structure was analyzed. Second, empirical formulae were employed to estimate the heights of the caving zone and fractured zone. Finally, a UDEC numerical model was established to simulate the evolution of overburden fractures during face advance. The results indicate that the theoretical calculation gives a caving-zone height of 10.24-14.45 m and a fractured-zone height of 37.86-51.04 m. The numerical simulation shows that when the working face advances to 80 m, the caving-zone height is approximately 14 m and the fractured-zone height is approximately 55 m. The theoretical and numerical results are in good agreement, indicating that the proposed model can effectively capture the development law of the overburden three-zone structure in the goaf of a Y-type ventilation working face.

Keywords

Y-Type Ventilation; Goaf; Overburden Three-Zone Structure; Fracture Evolution; Numerical Simulation; Gas Control

1. Introduction

With the continuous increase in coal-mining depth, growing attention has been paid to the evolution of overburden structures and the distribution of fracture fields in goafs induced by mining. The development height of the overburden three-zone structure is an important basis for evaluating goaf stability. For Y-type ventilation working faces, the air-leakage behavior in the goaf is strongly coupled with the degree of fracture development in the overburden. Consequently, the failure law of the overburden directly affects the distribution of gas-enriched zones and the effectiveness of gas drainage, making research on the development law of the three

zones of considerable engineering significance.

Based on key-strata theory, Qian et al.[1] first clarified the “O-shaped” fracture-ring distribution formed under mining disturbance. Fan et al. addressed the problem of excessive gas concentration in the upper corner of a working face caused by large gas emissions from adjacent coal seams, and, through theoretical calculation and UDEC simulation, determined the subsidence of different overburden strata together with the vertical development range of the three zones[2]. Meng et al. carried out an experimental study on the distribution characteristics of the overburden three zones in a large mining-height face to investigate the cross-strata collapse evolution of overburden during extraction of an extra-thick coal seam, and derived a formula suitable for estimating the heights of the three zones under such conditions[3]. Guo[4] used UDEC to analyze the evolution of overburden fractures in the goaf under repeated mining and characterized fracture development using fractal dimension. Cui[5] adopted a comprehensive analytical method to determine the heights of the three zones in a large mining-height working face. Tian[6] investigated the upper and lower boundaries of overburden movement using borehole television and theoretical analysis. Taking the 52306 working face of Daliuta Mine as the study object, He et al. determined the development heights of the three zones through geological analysis, exploration drilling, theoretical calculation, and field measurements[7]. Li et al. combined in-situ tube-bundle monitoring, manual observation, and numerical simulation to determine the distribution of the three zones in a goaf and further obtained the safe advance rate of the working face[8].

In the present study, the 32010 working face of a coal mine is taken as the research object. Empirical formulae and UDEC numerical simulation are used to characterize overburden failure during mining, and the distribution characteristics of the three zones together with the law of fracture development are analyzed.

2. Engineering Background

The 32010 working face is a typical deep-mining Y-type ventilation face characterized by a large burial depth, pronounced movement of the overlying strata, and stringent gas-control requirements. Its strike length is 2028-2236 m, the dip length is 180 m, the surface elevation is 180-280 m, and the working-face elevation is -470 to -650 m. The transportation roadway adopts a retained-roadway technique and is subsequently reused as the return airway for the next working face. The coal-seam dip direction ranges from 1° to 15°, the seam dip angle ranges from 2° to 13°, and the average dip angle is approximately 7°. The coal thickness varies from 0.4 to 3.1 m, with an average of 2.2 m. In terms of roof lithology, the immediate roof consists of 10.0-15.15 m of sandy mudstone, while the main roof is 3.0-5.75 m of fine sandstone. For the floor, the immediate floor consists of 5.0-7.8 m of sandy mudstone, and the main floor is 0-2.4 m of fine sandstone. The overall geological

structure of the working face is relatively simple, with no collapse columns, igneous intrusions, or fluvial scour zones and other adverse geological structures; therefore, the influence on mining is limited.

3. Formation Mechanism and Theoretical Estimation of the Overburden Three-Zone Structure

3.1. Formation Mechanism of the Overburden Three-Zone Structure

According to the degree of failure and the movement characteristics of the overburden, the strata above the goaf can be divided into the caving zone, fractured zone, and bending-subsidence zone. The caving zone is located in the lower part immediately above the goaf and is a strongly damaged zone formed by instability and collapse of the immediate roof. It is characterized by highly fragmented rock blocks and high porosity, and is usually also a region with relatively high gas accumulation. The fractured zone lies above the caving zone and serves as an important channel for air leakage and gas migration within the goaf. The bending-subsidence zone is located in the upper part, where the strata mainly undergo integral bending deformation with relatively few fractures and comparatively intact structural integrity. In addition, the theory of the "O-shaped" mining-induced fracture ring indicates that fractures around the goaf are often distributed in an approximately O-shaped spatial pattern along the working-face boundary and the overlying strata. The closure, opening, and connectivity of these fractures have a significant influence on goaf ventilation and gas migration. For a Y-type ventilation working face, the height and extent of the fractured zone are directly related to the effectiveness of gas control in the goaf.

3.2. Theoretical Estimation of the Three-Zone Heights

According to the original geological data, the roof strata above the coal seam are mainly composed of sandstone and mudstone, and the uniaxial compressive strength of the roof rock ranges from 31.22 to 38.5 MPa, indicating a medium-hard roof. Based on empirical formulae applicable to medium-hard roof conditions, the heights of the three zones were estimated. The results show that the caving-zone height is 10.24-14.45 m, while the fractured-zone height is 37.86-51.04 m.

The theoretical results indicate that the caving-zone height of this working face is relatively limited, whereas the fractured zone develops upward more markedly, implying that mining-induced disturbance can be transmitted to higher strata through fracture propagation. This conclusion is generally consistent with the failure characteristics of overburden strata in deep working faces with medium-hard roofs, and it also provides a reasonable value range for subsequent UDEC numerical simulation.

4. Establishment of the Numerical Model

4.1. Principles for Model Construction

Considering the pronounced complexity of the actual development process of overburden fractures, the stratigraphic structure and boundary conditions were appropriately simplified. The following principles were mainly followed during model construction: (1) the effects of coal thickness, overburden stratification, and mining disturbance on the movement of the overlying strata were fully considered; (2) the model was required to represent the mechanical properties of the coal and rock strata as realistically as possible; and (3) the boundary conditions were reasonably defined so as to mitigate boundary effects.

4.2. Numerical Model Parameters

The physical and mechanical parameters adopted for the coal and rock strata in the model, including density, elastic modulus, cohesion, and internal friction angle, were obtained from the original geological data of the working face. The mechanical parameters of the rock strata are listed in Table 1.

Table 1. Mechanical parameters of coal and rock strata.

Stratum	Elastic modulus (G Pa)	Poisson's ratio	Density (kg/m^3)	Cohesion (MPa)	Internal friction angle (°)
Coal	2.2	0.36	1294	3.52	24.68
Sandy mudstone	10.5	0.38	2590	2.96	30.34
Mediums and stone	9.55	0.35	2560	5.12	33.96
Fine s and stone	5.2	0.34	2625	4.34	34.01
Siltstone	4.2	0.32	2540	6.45	33.86

Based on the lithologic assemblage of the overburden above the 32010 working face and the geological conditions of the panel, a UDEC numerical model with dimensions of 150 m × 200 m was established. Considering the influence of model boundary effects on the simulation results, the upper boundary was defined as a free boundary; horizontal displacement constraints were imposed on the left and right boundaries; a certain thickness of rock mass was retained below the coal seam; and the model floor was set as a fully constrained boundary, as shown in Figure 1.

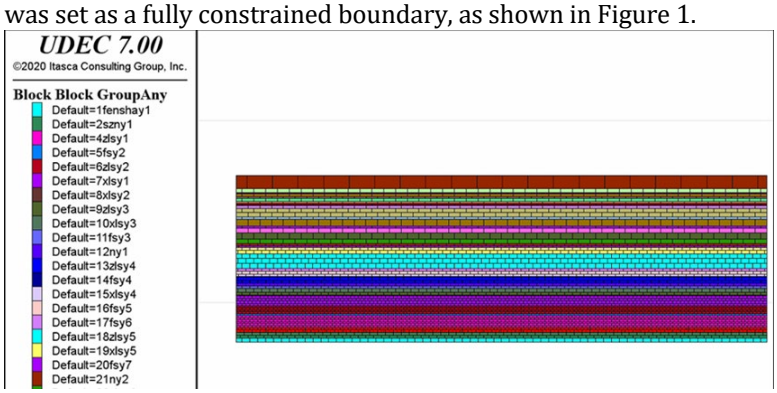


Figure 1. UDEC numerical model and boundary conditions.

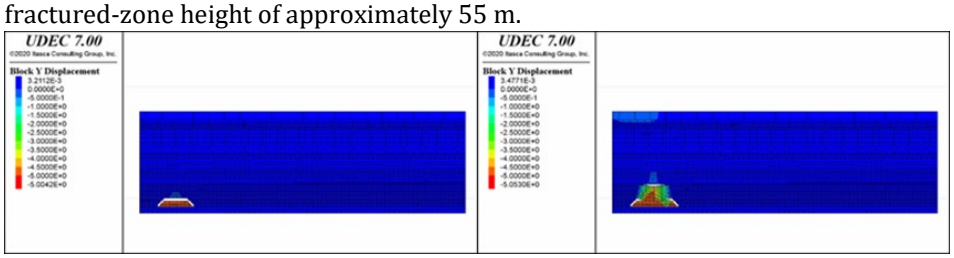
4.3. Simulation Scheme

To investigate the characteristics of roof collapse and fracture development at different advance distances, dynamic simulations were conducted for six stages corresponding to face advances of 30, 40, 50, 60, 70, and 80 m. Particular attention was paid to the evolution of fracture height, fracture morphology, and the failure range of the roof.

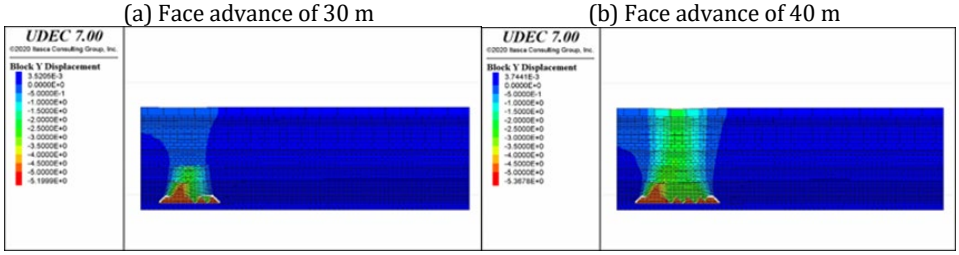
5. Results and Discussion

5.1. Evolution Law of Overburden Fractures

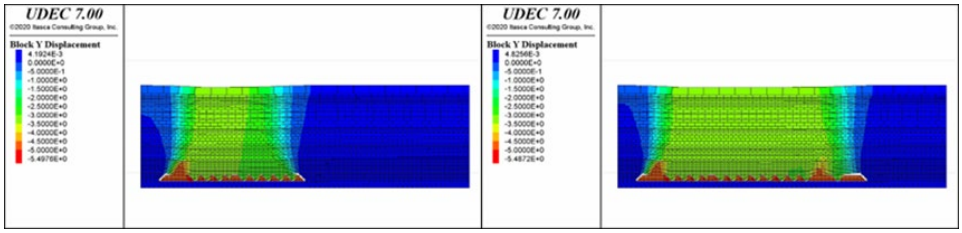
The simulation results in Figure 2 show that, with continued face advance, the overburden fractures exhibit an overall evolutionary pattern characterized by upward development, expansion from local damage to integral failure, and a transition from rapid growth to gradual stabilization. Specifically, when the face advances to 30 m, local collapse begins to occur in the immediate roof, the caving zone starts to form, and both the height and extent of fracture development remain limited. When the advance distance increases to 40-50 m, the instability of the overlying strata becomes significantly more pronounced, fractures propagate rapidly upward, the height of the fractured zone increases markedly, and overburden failure enters a stage of rapid development. At advance distances of 60-70 m, fractures continue to extend upward, but the propagation rate becomes slower than that in the earlier stage; accordingly, the overburden failure process starts to shift from intense expansion to relative stability. After the face advances to 80 m, the fracture morphology tends to become stable, the height of the caving zone no longer changes significantly, and the upper strata are dominated by bending deformation and overall subsidence. At this stage, the three-zone structure is basically stabilized, with a caving-zone height of approximately 14 m and a fractured-zone height of approximately 55 m.



(a) Face advance of 30 m (b) Face advance of 40 m



(c) Face advance of 50 m (d) Face advance of 60 m



(e) Face advance of 70 m (f) Face advance of 80 m

Figure 2. Relationship between overburden fractures and face advance distance.

5.2. Comparison between Theoretical Calculation and Numerical Simulation

The theoretical calculation yields a caving-zone height of 10.24-14.45 m and a fractured-zone height of 37.86-51.04 m, whereas the numerical simulation gives a final caving-zone height of approximately 14 m and a fractured-zone height of approximately 55 m. Overall, the two methods show good consistency, indicating that the empirical formulae can provide a reasonable estimate of the overburden failure range of this working face, while the UDEC simulation further reveals the dynamic evolutionary process of the three-zone structure.

It should be noted that the fractured-zone height obtained by numerical simulation is slightly higher than the upper limit predicted by the theoretical calculation. This is mainly attributable to the following factors. First, the theoretical formulae are empirical in nature and have a broad range of applicability, but they cannot precisely reflect local stratigraphic differences in a specific working face. Second, under deep-mining conditions, mining disturbance is stronger, making the tendency of fractures to develop toward higher strata more pronounced. Therefore, in engineering applications, a combined approach of preliminary assessment by theoretical calculation followed by verification through numerical simulation should be adopted to improve the reliability of model design.

5.3. Engineering Implications

Air leakage and gas migration in the goaf of a Y-type ventilation working face are highly dependent on the development degree of the overburden fracture network. The present study shows that the fractured zone of the working face can develop to approximately 55 m, indicating that the layout of high-level gas-drainage engineering should fully cover the principal development range of the fractured zone while also taking into account the dynamic characteristics of the most active stage of fracture evolution. From the perspective of the advance law, the range of 40-70 m represents the critical stage for the rapid development and interconnection of fractures, and is also the key period for goaf gas control and ventilation regulation. Therefore, in similar engineering conditions, monitoring of gas concentration in the goaf, regulation of negative pressure for high-level gas drainage, and air-leakage control should all be strengthened during this stage to ensure safe extraction.

6. Conclusions

(1) The 32010 working face is a deep Y-type ventilation face with an overall stable coal-seam thickness and a roof dominated by medium-hard strata, making it a representative case for investigating the development law of the overburden three-zone structure.

(2) Based on empirical formulae applicable to medium-hard roof conditions, the caving-zone height of the working face is calculated to be 10.24-14.45 m and the fractured-zone height to be 37.86-51.04 m, indicating that the mining-induced effect of this face is mainly manifested as upward propagation of overburden fractures.

(3) The UDEC numerical simulation shows that with face advance, the evolution of overburden fractures follows a development law of upward propagation, transition from local to integral failure, and gradual stabilization after rapid growth. When the three-zone structure finally becomes stable, the caving-zone height is approximately 14 m and the fractured-zone height is approximately 55 m.

(4) The theoretical calculation and numerical simulation are generally consistent, indicating that the combination of empirical formulae and numerical simulation can effectively reveal the distribution law of the overburden three-zone structure in the goaf of a Y-type ventilation working face. The results may provide a reference for the layout of high-level roadways, gas drainage in the goaf, and roof control.

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