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Dynamic structural evolution of overlying strata during shallow coal seam longwall mining

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1. Introduction

The mining depth at the Shendong coal mine in the Northwestern region of China is typically 50–250 m. The typical characteristics of the coal seams include shallow burial depths, thin bedrocks, and thick unconsolidated quaternary layers. It has also been observed from practice that roof step-form subsidence and chock closure failure disasters often occur during the weighting periods. In most cases, the broken main roof is hardly capable of sustaining itself, with its movement often affecting the ground surface, resulting in discontinuous subsidence and the formation of obvious graben on the ground surface. If the mining activities induces severe roof step-form subsidence, coalescence of open cracks along the palisades may occur, with the consequent formation of penetrating passageways through which water and sand may rush in, resulting in a water and sand inrush disaster on the working face.[1–3] The rush in of underground water unto the working face causes soil and water loss, vegetation damage, and desertification in the vicinity, as shown in Fig. 1. Coal mine roof disasters constitute serious safety threats in mining practice. Incomplete statistics show that 12 support failure incidents have occurred since 2007 in the Shendong shallow coalfield longwall mining area, with the direct asset loss amounting to more than $15 million.[4] Because of the obvious roof behavior, a longwall mining coal seam is generally referred to as a typical shallow coal seam to distinguish it from other types of coal seams.[1,2] Conventional strata control mechanisms and theories do not adequately explain the special roof movement characteristics of a shallow coal seam, because a conventional roof gradually caves layer-by-layer from the bottom to the top. It is, therefore, of great theoretical and practical significance to investigate the form and stability of the roof-bearing structure of a shallow coal seam under longwall mining, in order to determine the fundamental mechanism of roof step-form subsidence and implement necessary safety measures to avert such disasters.

The core problem of ground pressure and strata control is the clarification of the movement principles of the overlying strata during coal extraction under different geological conditions. Numerous relevant studies have been conducted from different perspectives, and valuable results have been obtained with regard to shallow coal seams. Ju et al.[5] investigated the mechanism of longwall chock support failure in the Shendong shallow coalfield when the working face of the lower coal seam underpasses the coal pillars left in the upper coal seam. The study involved a stability analysis of key blocks above the coal pillars, and the findings were used to propose some preventative measures. Hou[6] suggested a combinatorial key stratum theory of the synchronous movement of the full thickness overlying strata in a shallow coalfield. Huang[7] noted that roof step-form subsidence under shallow coalfield longwall mining was caused by the instability of the single key stratum structure in the overlying strata. The researcher used "short block voussoir beam" and "step voussoir beam" models to explain the behavior during main roof periodic weighting, and proposed support resistance for the control of roof sliding. However, Hou[8] believed that a voussoir beam could not be formed in a shallow coal seam, because the size of the ruptured rock blocks could not satisfy the requirement for a voussoir beam, namely, a block length that is more than twice the block

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Fig. 1. Surface fracture distribution after longwall mining.

thickness. Yang[9] used the initial post-buckling theory to discuss the breaking mechanism of the roof structure of a shallow coalfield under longwall mining, and used the catastrophe theory to examine the unstable movement of the structure. These previous studies have contributed to understanding strata movements in shallow coal seams. The roof-bearing structure undergoes a dynamic evolution process with the advancement of the longwall face, representing a special engineering phenomenon. The structural form, structural components, and structural mechanical characteristics vary with time, the mining method, the geological conditions, and the powered support performances. However, the roof-bearing structure of a shallow coal seam is still not fully understood, and there is the need for further investigation of the interaction and relationship between the roof behavior and the support resistance.

Numerical analysis, physical modelling, field observation, and numerical simulation have all been used to investigate the dynamic structural evolution of the overlying strata under longwall mining. However, due to the complexity of the lithology and its combination relationships, there have been only a few analytical studies, with available classical research results mainly obtained by field tests and physical similar simulation tests. In addition, most of the available analytical solutions are based on multiple preconditions, with the employed simplifications exaggerating the effects of some major factors on the outcomes. Overall, physical modelling and field observations are the most important approaches to investigating the dynamic structural evolution of overlying strata. Physical similar simulation tests have particularly afforded substantial insight into the complicated breaking mechanism of the roof structure of a coal seam. A physical similar simulation model is constructed based on the in-situ characteristics of the overlying strata. To facilitate stress and strain measurements, the materials used to construct the model differ from those of the actual overburden. Dimensional analysis and the similarity principle are used to design the model and correlate the test results to the prototype. Although physical similar simulation tests enable reproduction of the dynamic structural evolution of the overlying strata, the accuracy of the results is limited by many factors, the major ones being (1) difficulty of accurately matching the material properties; (2) difficulty of accurately reproducing the mining-induced stress field, due to the effects of friction between the model and the clapboards of the similar simulation test bed; and (3) artificial uncertainties introduced during the model construction process.

Numerical simulation is increasingly being used to investigate the dynamic structural evolution of the overlying strata of a coal seam. It enables reproduction of the typical roof behaviors and establishment of some underlying principles. However, considering that numerical models are interpretations and simplifications of reality, their indications require validation by physical modelling or field observation. The movement of the overlying strata of a shallow coal seam under longwall mining constitutes a major discontinuous deformation problem. Numerical simulation analysis based on a continuous medium is not suitable for solving this problem and cannot be used to accurately track the dynamic propagation of the mining-induced fractures. Compared with numerical simulation analysis based on a continuous medium, the greatest advantage of the use of Particle Flow Codes (PFC2D and PFC3D)[10–12] is that it enables reproduction of the entire roof movement process, from the unaffected continuum state up to breaking, caving, accumulating, and compaction. The use of Particle Flow Codes (PFCs) is thus more suitable for investigating the dynamic structural evolution of