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Mechanics criterion and factors affecting overburden stability in solid dense filling mining

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ABSTRACT

The effect of controlling strata movement in solid filling mining depends on the filling rate of the goaf. However, the mechanical property of the overburden in the backfill stope and the designed size of the backfill mining workface should also be considered. In this study, we established a main roof strata model with loads in accordance with the theory of key strata to investigate the stability of the overburden in solid dense filling mining. We analyzed the stress distribution law of the main roof strata based on elastic thin plate theory. The results show that the position of the long side midpoint of the main roof strata failed more easily because of tensile yield, indicating that this position is the area where failure is likely to occur more easily. We also deduced the stability mechanics criterion of the main roof strata based on tensile yield criterion. The factors affecting the stability of the overburden in solid dense filling mining were also analyzed, including the thickness and elasticity modulus of the main roof strata, overlying strata loads, advanced distance and length of workface, and elastic foundation coefficient of backfill body. The research achievements can provide an important theoretical basis for determining the designed size of the solid dense filling mining workface.

1. Introduction

Although large-scale and extensive coal mining can meet China's ever-growing energy needs, it also causes considerable waste of coal resources and environmental damage. One reason is that the all caving method is applied in dealing with the goaf, causing strata movement and large areas of ground subsidence. Thus, old management of goaf roof at the mining workface must be disrupted to balance the demand for coal mining and the need for ecological protection to achieve sustainable development of coal mines, green mining, and reasonable mining [1,2]. Solid filling coal mining method uses gangue, fly ash, and other solid wastes to backfill goaf. In this way, recycling "three-under" coal seam can reduce waste emission, improve the production capacity of coal mines, mitigate subsidence disasters, and raise resource recovery rate. This method has become a key technical solution to realize green coal mining [3,4].

Solid filling coal mining uses separate filling system, equipment, and technology to fill solid wastes, such as underground gangue waste into goaf to create a compacted backfill that can replace the role of the original coal rock in supporting the workface roof strata and ensuring that surface constructions can endure the consequent ground subsidence. Previous experiences have shown that the control effect of strata movement in solid filling mining depends on the filling rate (the ratio of mining height and final compacted height of the backfill body when its roof strata reaches a stable condition after full movement and subsidence) of the goaf. A solid filling coal mining research group at China University of Mining and Technology conducted a systematic study on relevant questions. Zhou et al. suggested using filling rate as a technical criterion to evaluate the results of solid backfilling and analyzed key factors to filling rate [5]. Zhang et al. proposed theoretical evidence and control measures of the design of solid filling rate based on the principle that strata stability varies with filling rate and "equivalent mining height" casts ground subsidence [6]. Based on the concept of equivalent mining height and field geological conditions, Huang et al. analyzed how the filling rate of different gangue and fly ash backfill may affect equivalent mining height and how it curbs strata movement during solid filling mechanized coal mining, and applied this discovery into practice [7]. In addition, Zhang et al. established a mechanical model on the key rock of the main roof at solid filling mechanized coal mining by analyzing the move-

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ment features of roof strata, and deduced a mechanic equation on the supporting strength of the workface at solid filling mechanized coal mining after analyzing the deformation pattern of gangue backfill and broken immediate roof compaction; and they also established a mechanical model on the key strata in the roof strata at solid filling mechanized coal mining based on the analysis of the deformation patterns of the roof strata in traditional mechanized coal mining and solid filling mechanized coal mining [8]. They discovered relationships between maximum deflection and strength of the key strata as well as between elastic foundation coefficient of the lower strata and lithologic parameter based on the analysis of the deformation features of the key strata and in view of elastic foundation beam theory [9].

These studies show that the higher the filling rate in the goaf, the better the stability of the roof strata [5–9]. However, available filling coal mining technology cannot yet achieve one hundred percent filling rate. Raising filling rate means raising mining costs, equipment expenditure, and on-field management level. Factors including the mechanical property of overburden in backfill stope, designed size of the backfill mining workface, and elastic foundation coefficient should also be considered to curb the movement and deformation of the roof strata more economically and efficiently. So, further research on relevant theories is also necessary.

Based on key strata theory on strata control, we analyzed the movement and deformation features of the roof strata at filling stope, and established a mechanical model of main roof in the solid compacted filling stope. We introduced Griffith yield criterion and deduced the mechanical criterion of the stability of the main roof strata in the stope while considering tensile yield failure mechanism. We also analyzed factors concerning the stability of the roof strata in the solid compacted filling stope in a systematic manner in an attempt to provide reliable theoretical basis for the size design in a filling mining workface.

2. Mechanics model of the main roof in solid dense filling stope

As the mining workface advances, solid backfills, such as gangue, would immediately be filled into goaf and fully connect with the roof strata of goaf with the support of the rear ramming structure. Curbing or Mitigating the deformation of the immediate roof, main roof, and overlying strata is possible to avoid immediate roof fracture or fracture but not collapse, while the main roof strata only has bend subsidence. In this way, the movement and deformation of the roof strata can be controlled, as shown in Fig. 1 [10–13].

For solid dense filling coal mining, the inclination length of the workface is usually in the range of 100–180 m, the advanced distance of workface is 600–1000 m, and each layer of the main roof thickness is 3–20 m. The main roof usually consists of thick and hard strata that forms the first key strata in the overlying strata [14]. Under solid dense filling mining, backfill in goaf and bracing reaction from hydraulic support used in filling mining workface can cause immediate roof fracture but not collapse, while the main roof strata only has bend subsidence. Therefore, the main roof can be viewed as a rectangular thin plate with four edges clamped at the elastic foundation (the ratio of the thickness and width of the main roof is 1/80–1/5), and a main roof strata model with loads in solid dense backfill mining can be established, as shown in Fig. 2.

In Fig. 2, x is the workface advanced direction with width a, y is the workface inclination direction with length b, and z is the downward direction perpendicular to the main roof. The thickness of the main roof strata is h_1, and its average bulk density, elastic modulus, Poisson's ratio are γ_1, E_1, μ_1, respectively. Effective roof-control distance of hydraulic support at the front of the workface is L.

The load acting on the main roof of stope in the solid dense filling mining workface includes the overlying strata load q (regarded as equivalent uniform load), body force of the main roof G, bracing reaction P from hydraulic support at the front of the workface. The bracing reaction kw from the backfill body at the goaf rear (the backfill is considered as elastic foundation, k is the elastic foundation coefficient which reflects the bearing capacity of the roof strata, and w is the deflection of the main roof strata). The bracing reaction P and kw can transfer the load to the main roof strata through the immediate roof.

The deflection function of the main roof strata under the overlying strata load with four edges clamped at the elastic foundation is as follows:

$$w_{mn} = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} A_{mn} \sin^2\left(\frac{m\pi x}{a}\right)\sin^2\left(\frac{n\pi y}{b}\right) \tag{1}$$

where A_{mn} is the coefficient of w_{mn}; and m and n the any positive integers. Clearly, w_{mn} meets the boundary conditions of the support for the four edges.

Coefficient A_{mn} can be determined according to the principle of minimum potential energy [15]. In practical engineering, as long as $m = n = 1$, the accuracy requirement of mining engineering can be ensured to a certain degree, and the deflection function of the main roof strata with four edges clamped at the elastic foundation can be shown as follows:

$$\begin{aligned} w_{11} &= A_{11}\sin^2\left(\frac{\pi x}{a}\right)\sin^2\left(\frac{\pi y}{b}\right) \\ &= \frac{\left[(q+\gamma_1 h_1) - P\left(\frac{L}{2a} - \frac{1}{4\pi}\sin\left(\frac{2\pi L}{a}\right)\right)\right]\sin^2\left(\frac{\pi x}{a}\right)\sin^2\left(\frac{\pi y}{b}\right)}{\pi^4 D\left(\frac{3}{a^4}+\frac{2}{a^2b^2}+\frac{3}{b^4}\right) + \frac{3k}{2}\left[\frac{3}{8}\left(1-\frac{L}{a}\right) - \frac{1}{32\pi}\sin\left(\frac{4\pi L}{a}\right) + \frac{1}{4\pi}\sin\left(\frac{2\pi L}{a}\right)\right]} \end{aligned} \tag{2}$$

where

$$A_{11} = \frac{(q+\gamma_1 h_1) - P\left(\frac{L}{2a} - \frac{1}{4\pi}\sin\left(\frac{2\pi L}{a}\right)\right)}{\pi^4 D\left(\frac{3}{a^4}+\frac{2}{a^2b^2}+\frac{3}{b^4}\right) + \frac{3k}{2}\left[\frac{3}{8}\left(1-\frac{L}{a}\right) - \frac{1}{32\pi}\sin\left(\frac{4\pi L}{a}\right) + \frac{1}{4\pi}\sin\left(\frac{2\pi L}{a}\right)\right]}.$$

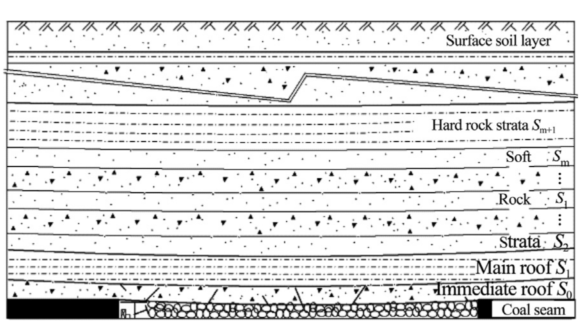

Fig. 1. Movement and deformation of roof strata in solid dense filling stope.

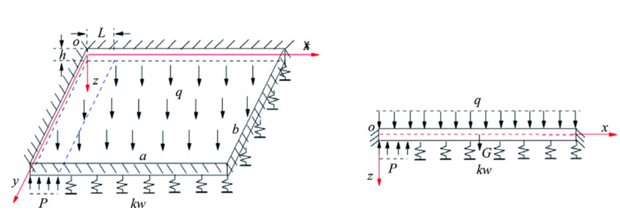

Fig. 2. Main roof strata model with loads in solid dense backfill mining.