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Instability characteristics of the cracked roof rock beam under shallow mining conditions

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ABSTRACT

To establish the movement relationship for the roof breaking under shallow mining conditions, the mechanical model of the roof rock beam was built, then the structure instability process of the roof rock beam was analyzed. The changing criterion of the vertical displacement was established and the relationship between the deflection and the rotary motion of roof block was determined. Regarding a mining face in Shangwan Mine, the responsing laws of the deflection and horizontal thrust of the roof rock beam were obtained through FLAC3D numerical analysis. The results show that the structure instability of the cracked roof rock beam depends on the interaction between the vertical load and the horizontal thrust. For the roof rock beam, when the vertical load keeps constant, the horizontal thrust fluctuating rises with increasing deflection. The horizontal thrust increases constantly with the deeper buried depth and the smaller span.

1. Introduction

The breaking instability of the roof in shallow mining shows particularity, the mining pressure behaves abnormally especially when the working face is too long, which often results in step sinking, bracket damage, and so on. In the high yield and efficient mining for the large coal field, it is a key problem to research on the deformation and breaking law, and controlling countermeasure for the roof stability under shallow mining. Considering the stratified depositing feature of coal-bearing strata, the stratified roof is often regarded as the elastic rock beam or block beam by scholars.

Hou et al. regarded the stratified cracked roof as beam-type elastic component, and studied the static bifurcation behavior and the mechanism of bending catastrophe phenomena separately using stability theory of elastic systems [1,2]. Yang concluded that the mechanism of main roof breaking in shallow depth was caused by the bifurcation instability of the roof structure [3]. Taking unit-wide rock stratum structure of the middle part of the mining face as a study object, Pan et al. derived the related expressions of roof deflection, bending moment and bending strain energy density distribution of the rock stratum ahead of coal face before and after initial fracturing [4]. Li et al. analyzed a new mechanical model of the roof rock beam with both ends fixed in cemented filling mining, and deduced the calculating formulas of limit span based on tensile and shear strength [5]. Wang et al. obtained the limit position of rotary instability of the roof rock beam according to the principle of minimum potential energy, and put forward a dynamic method for determining the supporting resistance according to the specific instability form of shallow buried high-intensity mining face [6].

Under the shallow mining conditions, Zhao and Song thought that the small angle of rotation and the horizontal thrust of the block with different fragmentations increases slightly with the length of mining face and the angle of rotation [7]. Diederichs and Kaiser summarized the critical span-thickness-modulus relationship of the unsupported stability of the jointed roof rock beam [8]. Nomikos et al. found that the multi-jointed roof rock beam had relatively small deflection, which indicated an increase in the deflection and a decrease in the extreme strain especially at the abutment [9]. Alejano et al. thought it was very difficult to predict the occurrence of buckling instability of the roof rock beam, because small changes produced significant stability variations from the practical engineering perspective [10]. Marcak believed that the distribution of stresses, the average energy of seismic events and their frequencies, whose significant changing trend was caused by the bending of the roof layers over the exploited area in many Polish underground mines [11]. Assuming the

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undermined sedimentary rock layers as multi-cracked hinged beams, Tsesarsky concluded that the thickness of the compressing arch at the abutments was inversely proportional to beam stiffness, and at the mid span was positive proportional [12]. Please et al. found the roof layer formed a beam, clamped by pillars of two ends, whose adjacent cracks would occur when the stresses exceed the tensile strength of the beam [13].

In the mining process analysis, the cracked roof is usually simplified as a simple-supported beam, which often leads to defects if ignoring the effect of the deflection and the horizontal thrust. In addition, current research rarely involved the bending instability process of the roof rock beam under the combined effect of the vertical and horizontal loads. It is difficult to judge the deflection effects on the structure stability of the beam pre-and-post breaking. In this paper, considering a mining face at Shangwan Mine of Inner Mongolia in China as the background, a modified model of Euler beam was used to analyze the bending instability process of the cracked roof rock beam under shallow mining conditions. Applying the stability theory of elastic systems, the relationship between the deflection of roof rock beam and the state of block rotary motion in voussoir beam was established, which would provide the theoretical reference for the roof management in mining practice.

2. Mechanical model for the cracked roof rock beam under shallow mining conditions

2.1. Formation of the cracked roof rock beam

Taking the main roof of a mining face at Shangwan Mine as the investigated object, the comprehensive mechanized longwall mining method is used with double drums coal cutter which type is JOY 7LS7/lws630 and shield type hydraulic support which type is ZY18000/32/70. The mining face is advanced in inclined back type as shown in Fig. 1a, the length of the mining face is 290 m and advanced distance is 2970 m. The dip angle of coal seam is 1°–3°, nearly horizontal coal seam at an average depth of 117 m. The designed mining height is 5 m, and full thickness of coal seam is mined in one time. The goaf area is handled by caving method as shown in Fig. 1b. Assuming the dimensions of the working face satisfied that the ratio of the advancing distance a to the working face length b is less than one ($a/b \leq 1$) before initial weighting of the main roof.

The main roof before being fractured can be regarded as a fixed beam at two ends. The span L, thickness h, and the action of uniform load p are shown in Fig. 2a. According to the bending stress theory of materials mechanics, the maximum moment M_{max} acting at two ends of the roof rock beam in a constant section equals to $-\frac{1}{12}pL^2$, while the maximum normal stress $\sigma_{\max}$ acting at the same section keeps the furthest distance from neutral axis. $\sigma_{\max} = M_{\max}y_{\max}/I_z$, where $y_{\max}$ and I_z can be regarded as constants. When $\sigma_{\max}$ reaches the tensile strength σ_t, the tensile cracks will occur at two ends of the roof rock beam as shown in Fig. 2b.

Based on the maximum shear stress value, $\tau_{\max} = 3F_s/2A$, where A is a constant sectional area, F_s is the shear force operating at the cross section, when the maximum value of shear stress acting at the beam ends equals to $\frac{pL}{2}$, the cracks will begin to form at both ends of the roof rock beam. So the fixed beam converts to the simple-supported structure as shown in Fig. 2, and the cracked roof rock beam can be described as this kind restraint at both ends.

During loading, a vertical tension fracture develops at the midspan of the cracked roof rock beam, and the roof beam is broken into two blocks. The voussoir beam is formed with the rotation of two blocks, the cracked roof rock beam of simple-supported structure is the previous configuration of the voussoir beam, and vertical deflection and lateral thrust of the cracked roof affects the stability of the voussoir beam. Thus it is essential to analyze the mechanical behavior of the cracked roof rock beam converting to the voussoir beam.

2.2. Mechanical model for the cracked roof rock beam

With the working face advancing, the cracks formed at both ends of the main roof beam when the beam reached the limit span, as shown in Fig. 2a. Before the initial weighting of the main roof, the deflection of the roof is not enough to form vertical fracture at the midspan of the roof beam, and the roof layer can be seen as continuous, the failure of the roof is related to the strain energy, focusing on the initial deflection and strain energy of the roof, the roof beam is treated as elastic when ignoring local plastic deformation in small scale [3,4,6].

Since almost no tensile resistance exists in the cracks, the cracked roof in unit width can be regarded as a no-tension beam. As shown in Fig. 2c, an Euler beam model is established considering its boundary condition to simulate cracked roof rock beam, and the overlying strata weight and dead weight are simplified as uniform load p. For the roof rock beam, the horizontal thrust is T, the span is L, and its deflection ω can be expressed as follow:

$$\omega = u\sin\frac{\pi x}{L} \tag{1}$$

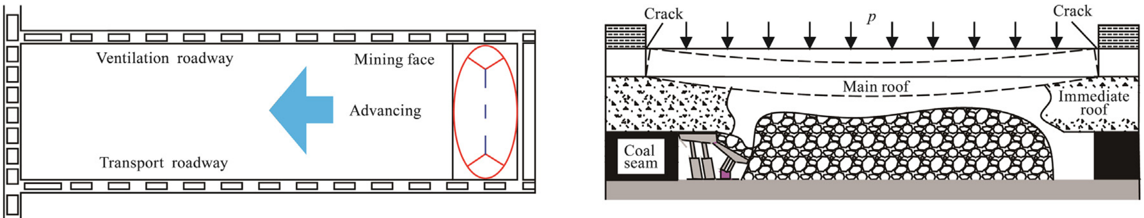
where x is the arch length between origin O and arbitrary point A, m; ω the x point deflection, m; and u the midpoint deflection, m.

In general, rock failure is an instability phenomenon driven by the energy [14]. So the instability state of the roof rock beam can be analyzed through examining the total potential energy changes in the roof system.

The total potential energy U is composed by the structural strain energy U_1 and the external load potential energy (the work done by the vertical load p and horizontal thrust T). Due to the beam bending, then the strain energy U_1 is accumulated as follows.

$$U_1 = \frac{EI}{2}\int_0^L k^2 dx \tag{2}$$

where I is the inertia moment of the beam cross section, m^4; and E the elastic modulus, GPa; and k the curvature at arbitrary point A of the beam.



(a) Arrangement of the mining face (b) Cracked rock roof

Fig. 1. Sketch of the mining face and the cracked rock roof.

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