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Breaking process and mining stress evolution characteristics of a high-position hard and thick stratum

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ABSTRACT

Based on the boundary support conditions of overlying high-position, hard and thick strata, a Winkler foundation beam mechanical model was built. Computational expressions for the characteristics and position of the bending moment for high-position, hard and thick strata were constructed by theoretical analysis, and the initial breaking position of high-position, hard and thick strata was also analyzed. The breaking process and evolution law of mining stress in high-position, hard and thick strata were studied by similar material simulation tests. Studies show that: due to the foundation deformation effect of the lower strata, the initial break position in high-position, hard thick layers is in the middle of goaf; vertical tension fractures first occur under the middle surface, then tilt tension fractures form at both sides and a non-uniform thickness of the fracture structure forms and produces subsidence deformation; behind the coal wall tilt fractures extend and eventually complete the migration. Mining stress produces obvious changes before and after the breakage of the high, hard and thick stratum; high stress concentration forms in front of the coal wall before breakage and fracture stress concentration significantly reduces after migration. Coal seam mining under high-position, hard thick strata can easily induce dynamic phenomena.

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1. Introduction

The overburden of a coal seam is often comprised of high-position, thick, hard strata such as magmatic rock, ultra-thick conglomerate and quartz sandstone [1–3], which has the characteristics of high strength, heavy bulk and large thickness and extent, and tends to form large suspended beams which raise the stress concentration in the surrounding rock. When the mining-induced stress exceeds the ultimate strength limit of the rock and induces fractures within the rock mass, a number of mining pressure phenomena may result including: maximum interval breakage, massive migration and energy release of accumulated stress in the surrounding rock. These may induce dynamic disasters including rock burst, outbursts of gas and water inrush in bed separation and can seriously affect the safe and efficient production of a coal mine [4–6].

Where the main roof of the working face is comprised of hard and thick strata, Jiang et al. studied the facture and instability law of a high-position, hard and thick stratum by adopting an elastic thin plate mechanics model and produced a formula for hard, thick rock breakage span calculations [7]. Shi and Jiang studied the migration law of fully-mechanized mining overlying thick and hard strata, based on elastic mechanics and proposed three mechanical criteria for extensive damage to hard and thick strata [8]. Liao et al. analyzed the breakage of an overlying thick or super-thick main roof of a working face by using thick-plate theory and numerical simulation, and showed the relationships between the change in thickness and location in the main roof of stress at the fracturing point [9]. Hou et al. studied the roof breakage principle of a fully mechanized mining face in a shallow coal seam under soft rock conditions using numerical simulation and similar material simulation tests to analyze the effect of key strata on overlying rock movement and mining stress [10]. Tan et al. studied the breakage and migration characteristics of overlying strata under super-thick magmatic rock by using UDEC^{2D} discrete element analysis [11]. Previous research has analyzed either the migration of a hard and thick stratum or the breakage characteristics of a thin, weak main roof or the structure of hard and thick strata cover rock after being transported and broken. In view of the mechanical state and load characteristics of a hard and thick stratum, this paper describes the studies of the breakage process

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and mining stress evolution characteristics of a working face under high-position, hard and thick strata according to theoretical analysis and similar material simulation testing.

The physical and mechanical properties and structural characteristics of high-position, hard and thick strata are different from other types of overlying strata, and can cause large midair suspension. Such strata are supported by lower strata and coal in the goaf and these bearing bodies are relatively weak in strength and stiffness and have significant deformability. Under the effect of overburden pressure, the hard thick layers undergo significant elastic deformation and thus form a Winkler foundation which is subject to bending, sinking and breakage. A hard and thick stratum can be represented as a simple beam, the behavior of which is still in conformity with the real situation, and can better reflect the stress environment of hard and thick strata. Therefore, according to the state and structural characteristics of underlying coal rocks, the Winkler foundation beam mechanical model can be employed, combined with the theory of an elastic foundation. The paper also describes the calculated characteristics of the bending moment of a high-position, hard, thick stratum and the characteristics of the bending distribution prior to fracturing, and finally identifies the initial position and form of breakage. As the overburden strata motion caused by exploitation and the mechanical complexity after initial breakage of a high-position hard, thick stratum cannot readily be observed, the breakage situation and mining stress evolution characteristics of a high-position hard, thick stratum was studied intuitively by using a similar material simulation test, which provided scientific theoretical guidance for safe and efficient mining production of a working face beneath the hard, thick stratum.

2. Mechanical model of an elastic foundation beam

With advance of a working face, the suspension span of a high-position, hard and thick stratum is increasingly large and, given the stress condition and deformation characteristics, behaves as a rock beam. The strength and flexural rigidity of the lower part on both sides of the beam which supports the coal and rock beam, are lower and the coal is regarded as a cushion to support the hard, thick layers above, and undergoes elastic deformation, thus forming a Winkler foundation under the high-position, hard and thick stratum above.

Before the overlying hard and thick stratum breaks, the overlying strata are under the influence of a uniform, dead load, as shown in Fig. 1.

Based on symmetry, the left part of the rock beam can be studied separately. The mechanical model of a hard and thick stratum is a long semi-infinite elastic foundation beam which is supported by a foundation in front of the working face coal wall, and the cantilever which is influenced by both the upper uniformly distributed load and the middle moment behind the coal wall, as shown in Fig. 2.

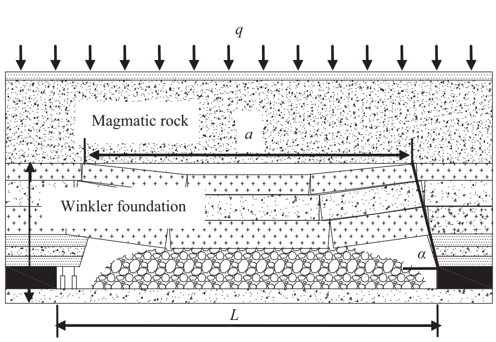

Fig. 1. Roof condition before initial breaking of hard thick strata.

From Fig. 2a, the flexural differential equation of the rock beam, based on mechanics of materials and elastic foundation beam theory [12], is:

$$EIy_1^{(4)}(x) = q - ky_1(x) \quad (x \geqslant 0) \tag{1}$$

where k is the supporting body foundation stiffness, $k = k_0B$, relating to the rock beam width B, Pa; k_0 is the foundation coefficient which reflects the required pressure generating unit subsidence of the foundation and is determined by the elasticity modulus and thickness of the coal and rock beam under the hard and thick stratum and superficial floor strata, Pa/m; E is the elasticity modulus and can be taken as $E/(1-\mu^2)$ under the condition of plane strain, Pa; I is the moment of inertia of the hard and thick stratum, $I = Bh^3/12$, m^4.

Setting $\beta = \sqrt[4]{k/(4EI)}$, combined with the initial parameter method, the flexural deflection is similar to that of a long, semi-infinite elastic foundation beam affected by a uniformly distributed load. The total displacement, assuming no bending subsidence of the rock beam at infinity, is:

$$y_1(x) = \frac{2\beta}{k}[Q_0\theta(x) + \beta M_0\psi(x)] \quad (x \geqslant 0) \tag{2}$$

where β is the characteristic parameter of the foundation beam [13], m^{-1}; $\psi(x) = e^{-\beta x}(\cos\beta x - \sin\beta x)$, $\theta(x) = e^{-\beta x}\cos\beta x$ [14].

The elastic foundation beam bending moment expression, based on $EIy_1'' = M_1(x)$ is:

$$M_1(x) = \frac{1}{\beta}e^{-\beta x}[Q_0\sin\beta x + \beta M_0(\cos\beta x + \sin\beta x)] \quad (x \geqslant 0) \tag{3}$$

On the cantilever beam, it can be determined from Fig. 2b that the bending moment expression under the combined action of the overlying uniformly distributed load q and the middle bending moment M_z is:

$$M_2(x) = M_z + \frac{q}{2}\left(\frac{a}{2} + x\right)^2 \quad (-a/2 \leqslant x \leqslant 0) \tag{4}$$

In the formula, $M_z = M_0 - \frac{1}{8}qa^2$.

In consideration of the continuity and deformation coordinate conditions, simultaneously with the above solution, we get:

$$Q_0 = \frac{qa}{2}, \quad M_0 = \frac{qa^2}{12}\phi_0, \quad M_z = -\frac{qa^2}{24}\phi_z \tag{5}$$

where ϕ_0 and ϕ_z are, respectively, the bending correction coefficients of the terminal and middle sections of the rock beam. $\phi_0 = \frac{m^2-6}{m^2+2m}$, $\phi_z = \frac{m^2+6m+12}{m^2+2m}$, $m = \beta a$, all three are dimensionless.

Under the action of the overburden, the terminal end of the rock beam inevitably forms a corner due to the effects of deformation of the lower part of the foundation, thereby conforming to the elastic boundary conditions of a simple, clamped support. Hence the terminal bending moment shifts to a position in front of the coal wall, and significantly affects the bending moment distribution of the rock beam.

Therefore, taking the derivative of $M_1(x)$, it can be determined from $dM_1(x)/dx = 0$ that the maximum bending moment M_q and its position on a beam on an elastic foundation in front of a coal wall is:

$$x = \frac{1}{\beta}\arctan\frac{3}{m\phi_0 + 3}, \quad M_q = \frac{qa^2}{12}\phi_q \tag{6}$$

where ϕ_q is the bending correction coefficient of a beam on an elastic foundation in front of a coal wall, and $\phi_q = \phi_0\varphi(x) + \frac{6\xi(x)}{m}$, $\varphi(x) = e^{-\beta x}(\sin\beta x + \cos\beta x)$, $\xi(x) = e^{-\beta x}\sin\beta x$.

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