Deformation mechanism of mining roadway and establishment of its mechanical model

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Abstract: Accurately understanding of the strata behaviors law and stability characteristics of the mining roadway is the basics of effective surrounding rock control, and the structural characteristics of the surrounding rock is the decisive factor for large deformation of that in mining roadways. In this paper, the surrounding rock structure characteristics of mining roadway in different conditions were discussed and mechanical model was established accordingly. And the deformation characteristics of the material were simulated by the combined model of deformation elements, and the theory of the surrounding rock deformation in the mining roadway with time was obtained.

1. Introduction

The surrounding rock of the mining roadway is composed of a variety of rock masses, and its mechanical properties will undergo complex changes under the influence of mining. Moreover, most of the surrounding rock is in a position that cannot be accurately observed. Therefore, it is almost impossible to accurately reveal the mechanical effects and the amount of deformation in different layer under different mechanical states during the roadway service[1]. However, if the surrounding rock is abstracted into the corresponding mechanical model according to the variation law of the rock deformation and the surrounding rock stress characteristics of the mining roadway, a mechanical model that can reflect the overall structural characteristics of the surrounding rock is established, and the surrounding rock of the mining roadway will be obtained[2-6]. The basic law of strata behaviors and its deformation plays a positive role[7].

2. Establishment of mechanical model

2.1. Mechanical model of rock structure without gob-side entry

The broken position of the main roof rock is located inside the coal wall, as shown in figure 1(a). The mechanical model (figure 2(a)) is mainly composed by main roof rock block, immediate roof rock block, solid coal and falling gangue.

The broken position of the main roof rock is located outside the coal wall, as shown in figure 1(b). The mechanical model (figure 2(b)) mainly consists of the main roof rock block, the immediate roof rock block, the solid coal and the falling gangue.

The fracture of the main roof rock located inside the coal wall indicates that the uniform support structure composed of the immediate roof and the coal seam is relatively rigid.
2.2. Gob-side entry driving with small coal pillar
According to the structural characteristics of the rock body shown in figure 3, the mechanical model established is shown in figure 4[8].

Figure 4(a) shows the mechanical model of the main roof rock when the breaking position is located inside the coal wall, mainly including the main roof rock block, the immediate roof rock block, the coal pillar, the solid coal, the immediate roof rock layer and the falling gangue.

Figure 4(b) shows the mechanical model of the main roof rock when the breaking position is outside the coal wall, mainly including the main roof rock block, the immediate roof rock block, the coal pillar, the solid coal, the immediate roof rock layer and the falling gangue.
2.3. Gob-side entry driving with big coal pillar
The mechanical model established according to the rock mass structure characteristics shown in figure 5 is shown in figure 6.

Figure 6(a) shows the mechanical model of the main roof rock with the breaking position inside the coal wall, mainly including the main roof rock block, the immediate roof rock block, the immediate roof unbroken rock stratum, the inner and outer parts of the coal pillar (the side of the roadway and the goaf), solid coal and falling gangue.

Figure 6(b) shows the mechanical model of the main roof rock when the breaking position is outside the coal wall. It consists of two parts of the main roof rock block, the inner and outer parts of the coal pillar (the side of the roadway and the goaf), the immediate roof rock formations of the corresponding position, solid coals, and falling gangue.

\[ \sigma_1 = E_1 \varepsilon_1 (1 - \beta_1 \varepsilon_1) \quad \varepsilon_1 \leq \frac{1}{\beta_1} \tag{1} \]

\[ \sigma_2 = E_2 \varepsilon_2 (1 - \beta_2 \varepsilon_2) \quad \varepsilon_2 \leq \frac{1}{\beta_1} \tag{2} \]

Where \( \beta_1, \beta_2 \) are constants that characterize nonlinearities, in which \((1 - \beta_1 \varepsilon_1) \geq 0\), and \( \varepsilon_1 \leq \frac{1}{\beta_1} \).

The curves of \( \sigma-\varepsilon \) is a parabola, as shown in figure 7, taking component 1 as an example. If the stress meets \( \sigma_1 = 0 \), and there will be \( \varepsilon_1 = 0 \) or \( \varepsilon_1 = \frac{1}{\beta_1} \) when parameters meet \( E_1 \varepsilon_1 (1 - \beta_1 \varepsilon_1) = 0 \).
Similarly, there will be $\varepsilon_i = \frac{1}{2\beta_i}$ when parameters meet $\frac{d\sigma_i}{d\varepsilon_i} = E_i - 2E_i\beta_i\varepsilon_i = 0$. The load $\sigma_{\text{max}}$ is obtained by the following formula:

$$\sigma_{\text{max}} = E_i \frac{1}{2\beta_i} (1 - \beta_i \frac{1}{2\beta_i}) = \frac{E_i}{4\beta_i} \quad (3)$$

![Figure 7. The curve of $\sigma$-\varepsilon](image)

![Figure 8. The curve of $\varepsilon$-\varepsilon](image)

It can be concluded that when the stress $\sigma$ reaches and exceeds $\sigma_{\text{max}}$, even that decreases, the strain still increases, which does not against the laws of thermodynamics, because the system needs positive work when the strain meets $\frac{1}{2\beta_i} \leq \varepsilon_i \leq \frac{1}{\beta_i}$.

For viscous components, a linear relationship is used, that is $\sigma_\eta = \eta \varepsilon_\eta$.

The three-element model consists of a nonlinear K-body and a nonlinear spring, and the strains of the K-body and the spring when the stress meets $\sigma_i = \sigma_\varepsilon$ are obtained and then superimposed, respectively.

3.1. Kelvin body

$$\sigma_K = \sigma_{H2} + \sigma_\eta \quad (4)$$

And because $\varepsilon_k = \varepsilon_\varepsilon = \varepsilon_\eta$, $\sigma_\eta = \eta \varepsilon_\eta$, $\sigma_{H2} = E_2\varepsilon_\varepsilon (1 - \beta_2\varepsilon_\varepsilon)$, $\sigma_K = E_2\varepsilon_\varepsilon (1 - \beta_2\varepsilon_\varepsilon)$.

The constitutive equation is:

$$\sigma_K = \eta \varepsilon_k + E_2\varepsilon_k (1 - \beta_2\varepsilon_k) \quad (5)$$

Which means $\varepsilon_k = \frac{\beta_2 E_2}{\eta_k} \varepsilon_k^2 + \frac{E_2}{\eta_k} \varepsilon_k = \frac{\sigma_k}{\eta_k}$, this is a nonlinear first-order differential Riccati equation, and the solution form differs from the $\gamma = \frac{4\beta_2 \sigma_k}{E_2} = \frac{\sigma_k}{\sigma_{H2}}$ size. Here we named $\frac{\sigma_k}{\sigma_{H2}}$ as the “Stress ratio”.

3.2. The spring

The instantaneous strain generated by the nonlinear elastic element $E_1$ is obtained by $\sigma_i = E_1\varepsilon_\varepsilon (1 - \beta_i\varepsilon_\varepsilon)$:

$$\varepsilon_\varepsilon = \frac{1}{2\beta_i} \left[1 - \sqrt{1 - \frac{\sigma_{\text{max}}}{\sigma_{\varepsilon}}} \right] \quad (6)$$
Where \( \sigma_{\text{max}} = \frac{E_i}{4\beta_i} \).

When \( \gamma \) meets \( \gamma = 1 \), we can regard the stress of the surrounding rock of the roadway as the elastic limit. At this point, the surrounding rock strain increases with time until it ends with plastic failure.

\[
\varepsilon(t) = \frac{1}{2\beta_i} \left[ 1 - \sqrt{1 - \frac{4\beta_i \sigma_0}{E_i}} \right] + \frac{1}{2\beta_i} \frac{t}{\frac{2\eta}{E_z} + t}
\]

When \( \gamma \) meets \( \gamma < 1 \), the stress of the surrounding rock can be regarded as an elastic state. At this point, the strain growth rate of the surrounding rock decreases with time, and then stabilizes until plastic failure occurs.

\[
\varepsilon(t) = \frac{1}{2\beta_i} \left[ 1 - \sqrt{1 - \frac{4\beta_i \sigma_0}{E_i}} \right] + \frac{1}{2\beta_i} \frac{t}{\frac{2\eta}{E_z} + t}
\]

When \( \gamma \) meets \( \gamma > 1 \), the stress of the surrounding rock reaches the yield limit. At this point, the strain growth rate of the surrounding rock increases with time, and finally the surrounding rock tends to destroy and end.

\[
\varepsilon(t) = \frac{1}{2\beta_i} \left[ 1 - \sqrt{1 - \frac{4\beta_i \sigma_0}{E_i}} \right] + \frac{1}{2\beta_i} \frac{t}{\frac{2\eta}{E_z} + t}
\]

4. Conclusion

Based on the structural characteristics of the surrounding rock of the mining roadway, the fractures of the main roof rock stratum were summarized as two types of in the coal wall and out of the coal wall, and the corresponding mechanical model was established;

Established the concept of “Stress ratio” and used it to discuss the deformation of surrounding rock in three cases of \( \gamma \) greater than 1, less than 1, and equal to 1, explaining the mechanical mechanism that after the tunneling, the initial surrounding rock does not collapse, but after a period of time a large number of tunnel collapse phenomenon;

Established the theoretical basis for the optimization of surrounding rock structure, selected the appropriate sectional form and the position of the roadway, and optimized the surrounding rock structure of the roadway, which means increase \( \sigma_{\text{max}} \) and reduce the degree of influence of the stress ratio.

Reference

[1] Song ZQ. (1988) Pressure and Control in Practical Mines[M]. China University of Mining and Technology Press, Xuzhou.
[2] Zhang YJ. (2002) 3D Viscoelastic-viscoplastic FEM Analysis for Stability of Underground Opening in Orthotropic Rock Mass[J]. Rock Soil Mech., 23(3): 278-283.
[3] Jiang JQ. (1998) Structural Stability and Control Design of Roadway Surrounding Rock[M]. Coal Industry Press, Beijing
[4] Fan QZ, Gao YF, Cui XH, et al. (2007) Study on Nonlinear Creep Model of Soft Rock[J]. Chin. J. Geotech. Eng., 25(5): 452-455.
[5] Han CQ. (2007) Study of Surrounding Rock Structure and Deformation Mechanism of Roadway under Different Widths of Section Coal Pillar. Mater dissertation, Shandong University of Science and Technology.

[6] Wen ZJ, Jiang YJ, Song ZQ, et al. (2011) Study on Mechanical Model and Surrounding Rock Catastrophe System of Gob-Side Retaining Entry[J]. J. Hunan Univ. Sci. Technol., 26(3):12-16.

[7] Ling T. (2015) The Impact Studies of Fracture Structure on the Coal Pillar Stability and Supporting of Roadway Driving along next Goaf. Mater dissertation, Hunan University of Science and Technology.

[8] Zhao GZ, Ma ZG, Sun K, et al. (2010) Research on Deformation Controlling Mechanism of the Narrow Pillar of Roadway Driving Along Next Goaf[J]. J. Min. Saf. Eng., 27(4):517-521.

[9] Jiang HF. (2014) Study of Unload Creep Properties of Rock under High Confining reassure and High Water Pore Pressure and Its Application Engineering. Doctoral dissertation, Chongqing University.

[10] Yuan Y, Zhu HH, Sun J. (1993) Recognizing Viscoelastic Constitutive Equation of Surrounding Rock Through Back Analysis[J]. J. Tongji Univ., (4):439-445.