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Damage statistical mechanics model of top coal in steep top caving coal

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Abstract: Damage statistical mechanics model of horizontal section height in the top caving was constructed in the paper. The influence factors including supporting pressure, dip angle and characteristic of coal on horizontal section height were analyzed as well. By terms of the practice project analysis, the horizontal section height increases with the increase of dip angle β and thickness of coal seam M. Dip angle of coal seam β has tremendous impact on horizontal section height, while thickness of coal seam M has slight impact. When thickness of coal seam is below 10 m, horizontal section height increases sharply. While thickness exceeds 15 m, it is not major factor influencing on horizontal section height any long.

Key words: steep-grade coal; horizontal section height; damage; statistic mechanic model

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The value of horizontal section height in steep-grade top caving in China is usually 10 m, with the maximum value up to 16 m. It is a key question that the value is suitably chosen and optimized in the steep-grade coal caving. It is important for mining enterprise to improve the horizontal section height possibly, so that excavating ratio and moving frequency of working face can be decreased and significant economic profits can be produced [1,2].

It is proven that the process of forming unstable arch construction in overlying rock strata is identical to the process of loading. When caused by the loading displacement exceeded the critical value, the coal mass will be damaged. In the process, the top coal is pseudo-continuous medium between continuous medium and loose medium, which is complied with the macro damage mechanical characteristics. Accordingly, supporting pressure, dip angle and coal mass features are taken into consideration while optimizing horizontal section height. Based on the damage mechanic theory, factors influencing on horizontal section height in steep-grade top caving are analyzed and reliable and efficient theoretical evidences are presented.

1 The construction of damage statistical mechanic evolution model

1.1 Construction of the damage constitutive equation

Under the external force, the constitutive relationship can be described by the non-damage pattern in which Cauchy stress was simply replaced by the valid stress, namely, equivalent hypothesis of strain [3]. So the damage constitutive relationship can be described as:

$$[\sigma]=[\sigma^*][\boldsymbol{I}-\boldsymbol{D}]=[\boldsymbol{E}][\varepsilon][\boldsymbol{I}\text{-}\boldsymbol{D}] \tag{1}$$

where $[\boldsymbol{E}]$ is elastic matrix; $[\varepsilon]$ is strain matrix; $[\boldsymbol{D}]$ is damage matrix; $[\boldsymbol{I}]$ is unit matrix; $[\sigma]$ is stress matrix; $[\sigma^*]$ is valid stress matrix.

1.2 Construction of the damage evolution equation

A micro-unit is taken from the coal mass which is supposed to be linear. But it has non-linear character in macro mechanic of state. Considering the homogeneity of internal construction, strength of each unit is not equal, and the damage is discontinuous in the process of loading. Based on the quoting statistical theory, it is postulated that every unit is accorded with the Weibull's distribution, the probability density function is [4]:

$$P_{(F)}=\frac{m}{F_0}\left(\frac{F}{F_0}\right)^{m-1}\exp\left[-\left(\frac{F}{F_0}\right)^m\right] \tag{2}$$

where F is random distributional variant of micro-unit, m and F_0 are Weibull's distributional parameters which donate the mechanical characteristics of coal mass. It is the continuous damage of the micro-units, resulting in the damage of the coal and rock materials.

Based on the damage mechanic theory, in the condi-

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tion of isotropy damage, damage variant D can be symbolized with damage area and non-damage area of material:

$$D=\frac{A'}{A}=\int_0^F \frac{m}{F_0}\left(\frac{x}{F_0}\right)^{m-1}\exp\left[-\left(\frac{x}{F_0}\right)^m\right]dx=$$
$$1-\exp\left(-\frac{F}{F_0}\right)^m \tag{3}$$

It is called the damage evolution formula in which A' is the damage area and A is non-damage area.

1.3 Determination of random distributional variant *F*

Because coal-rock is subject to not only uniaxial strain, but also to stress and strain relationship. So random distributional variant is expressed by parameter F determined by Mohr-Coulomb criterion [5], that is:

$$f_{(\sigma)}=\sigma_1=\sigma_3\tan^2\alpha+\frac{2c\cos\phi}{1-\sin\phi},\ \alpha=45°+\frac{\phi}{2} \tag{4}$$

where ϕ is internal frictional angle, c is cohesion.

While, micro-units are damaged which illuminates that σ_1 donates the criticality of micro-units. It is indicated that top coal damage mining in steep-grade coal seam was stemmed from compressing and shearing damage. It is feasible to determine random distributional variant with Mohr-Coulomb criterion, as shown in equation (5).

$$F=F_{(\sigma)}=\sigma_1=\sigma_3\tan^2\alpha+\frac{2c\cos\phi}{1-\sin\phi} \tag{5}$$

2 Breaking mechanics of top coal

Deformation and damage of top coal are a complicated process, which is related to the burying conditions and mechanical characters of the coal-rock. However, It depends on mining pressure in great extent. To reduce the pressure, manual exploding and hydraulic weakening occasionally are required. In terms of theory and practice, it has been proven that coal seam mining resulted in redistribution of stress in the coal mass, especially in supporting pressure area where micro-crack occurred and evolved, then, top coal tended to be damaged. Transition from in-situ stress to supporting pressure is a process of increment of strain step by step. Many experiments of synthesized caving illuminate that vertical displacement evolved in exponential function. Given horizontal section height h, trend angle β of coal seam, strain along the trend direction is:

$$\varepsilon_3=\frac{y}{h}\sin^2\beta=\frac{ax^b}{h}\sin^2\beta \tag{6}$$

where x is distance between maximum pressure position and working face, a and b are two constants.

With the advancing of mining, stress in coal mass transites from three dimensions to two dimensions and tendes to zero near working face, and supporting pressure is distributed along the trend direction shown in **figure 1.**

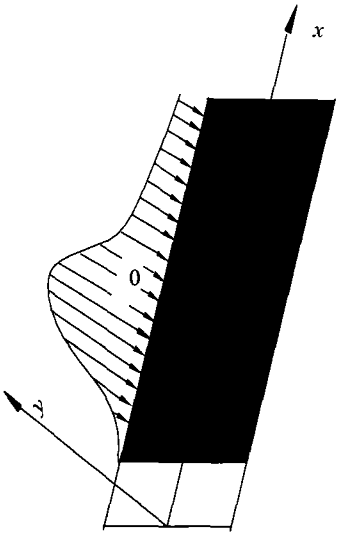


Figure 1 Distribution of supporting pressure along the trend direction.

Assuming $\sigma_y=\sigma_1$ and $\sigma_x=\sigma_3$, according to references [7,8], through deducing, it can be expressed as below:

$$\begin{cases}\sigma_1=\sigma_y=Q=c\cdot\cot\phi\cdot\tan^2\alpha e^{\frac{2fx}{M\tan^2\alpha}}\cos\beta \\ \sigma_3=\sigma_x=AQ=Ac\cdot\cot\phi\cdot\tan^2\alpha e^{\frac{2fx}{M\tan^2\alpha}}\cos\beta\end{cases} \tag{8}$$

where A is side pressure coefficient, M is thickness of coal seam, f is frictional coefficient between layers. Using Hoke rule, it can be gotten.

$$\begin{cases}\varepsilon_3=\frac{1}{E}(\dot\sigma_3-\mu\dot\sigma_1-\mu\dot\sigma_2)=\frac{1}{E}(\dot\sigma_3-\mu\dot\sigma_1) \\ \dot\sigma_3=E\varepsilon_3+\mu\dot\sigma_1\end{cases} \tag{9}$$

Based on the equations (1),(3),(4),(5),(9), it can be gotten:

$$\sigma_3=E\varepsilon_3(1-D)+\mu\sigma_1=E\varepsilon_3\exp\left(-\frac{\sigma_3\tan2\alpha+\frac{2c\cos\phi}{1-\sin\phi}}{F_0}\right)+$$
$$\mu\sigma_1 \tag{10}$$

Based on the equations (6),(8),(10), it can be gotten:

$$h=$$
$$\frac{Eax^b\sin^2\beta\exp\left(-\left(Ac\cdot\cot\phi e^{\frac{2fx}{M\tan^2\alpha}}\tan^4\alpha\cos\beta+\frac{2c\cos\phi}{1-\sin\phi}\right)/F_0\right)}{Ac\cdot\cot\phi e^{\frac{2fx}{M\tan^2\alpha}}\tan^2\alpha\cos\beta} \tag{11}$$

Project analysis: Wulumuqi coal mine is the biggest coal base in Xinjiang Weiwur Autonomous Region where there are 32 layers of coal seam with trend angle bigger than 45. Horizontal section caving is the method in special thick coal seam mining developed in recent 10 years. Taking Liudaowan coal mine as example, the parameters of coal seam are shown as follows: $a=0.01$; $b=2$; $E=10.7\times10^3$ MPa; $x=2$ m; $f=0.25$; $\mu=0.2$; $\phi=30°$; $A=0.54$; $F_0=11.4$ MPa; $\beta=70°$; $c=3.7$ MPa; $M=35$ m.

Taking parameters into equation (11), the horizontal section height equals 7.7 m (h=7.7 m). The real maximum height of top coal is 10 m [9]. It is practical to determine the horizontal section height with equation (11).

3 Analysis of factors influencing on horizontal section

According to equation (11), the relationship curves between h and β, ϕ, M, c, x as shown in **figures 2** (a), (b), (c), (d), and (e).

When maximum supporting pressure is far away from working face, horizontal section height tends to increase. When dip angle is lower than 60°, horizontal section height does not exceed 10 m, while exceeding 70°, it could be elevated more than 20 m. When cohesion c and frictional angle increases, horizontal section height decreases significantly. When ϕ>30°or c>4.0 MPa, the damage accumulation tends to be smooth. If nothing is done to break coal, horizontal section height should be below 10 m. In thin coal seam, top coal is subjected to clamping of top rock and bottom rock. So when thickness of coal seam is below 10 m, horizontal section height increases sharply. While thickness exceeds 15 m, it is not major factor influencing on horizontal section height any long. By far, those do not take support pressure and dip angle and character of coal seam into account, the conclusion is partial and impractical.

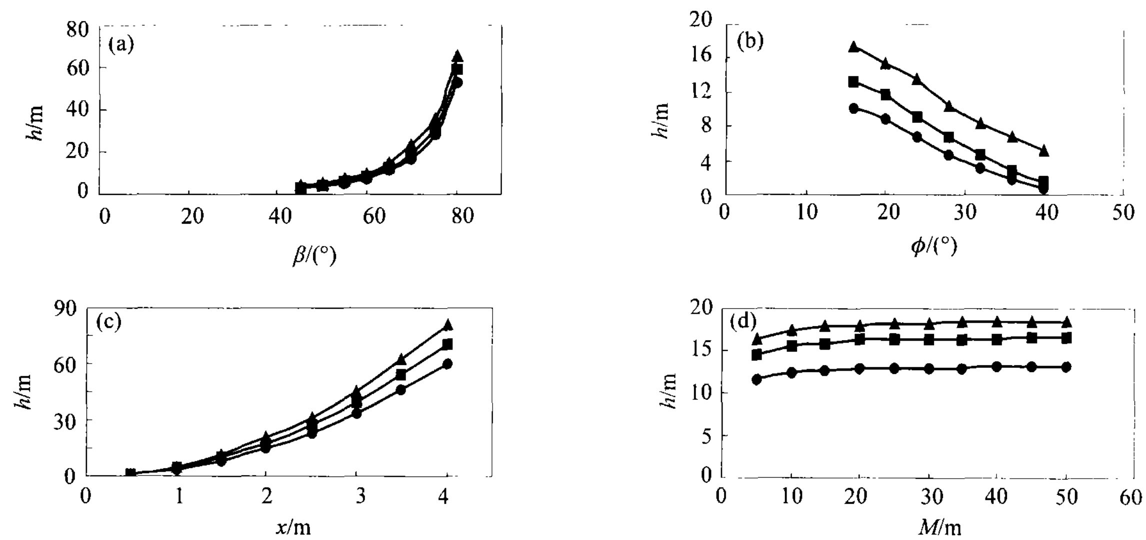
4 Conclusion

(1) The forming and unstable process of arch structure in overlying coal rock is consistent with the process of loading. Moreover top coal complies with the macro damage mechanical characteristics.

(2) Because of mining influence, stress distribution in coal mass transits from three dimensional states to two dimensional states and tends to be zero near the working face.

(3) Micro-unit strength of coal mass complies with Weibull's distribution, top coal damage in forms of compressing and shearing, and it's random distribution variant is accorded with the Coulomb law.

(4) Horizontal section height increases with the increment of dip angle β and thickness of coal seam M. Dip angle of coal seam β has tremendous impact on horizontal section height, while thickness of coal seam M has slight impact. When cohesive strength c and internal frictional angle ϕ increases, horizontal section height decreases notably. The far support pressure extends, the bigger horizontal section height is chosen.



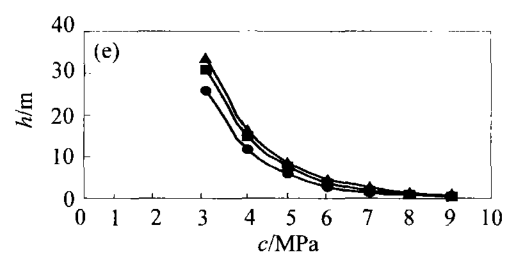


Figure 2 The relationship between h and β (a), φ (b), x (c), M (d), c (e). •—F_0=10.4; ■—F_0=11.4; ▲—F_0=12.4.

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