DEFORMATION AND HEAT TRANSFER MODEL FOR SURROUNDING ROCK IN THICK LOOSE LAYER-EXTRA THICK COAL SEAM WORKING FACE

by

Fei LIU[a*], Guang-Heng GE[b,c], Peng GONG[b,c], and Xin-Lei FU[d]

[a] School of Resources and Civil Engineering, Suzhou University, Suzhou, China
[b] State Key Laboratory for Geo-Mechanics and Deep Underground Engineering, China University of Mining and Technology, Xuzhou, China
[c] School of Mechanics and Civil Engineering, China University of Mining and Technology, Xuzhou, China
[d] National Science and Technology Venture Capital Development Center, Beijing, China

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By using theoretical analysis and numerical calculation, the mechanical properties of the surrounding rock of the thick loose layer and extra thick coal seam comprehensive discharge face were deeply studied. The multi-parameter critical control equation for the sudden change of the roof plate along the working face was derived, and the influence of variables such as fracture block degree, rotation angle, breaking angle, friction factor and corner end extrusion coefficient on the stability of the roof "rotation-slide" was obtained. A heat transfer model for the broken layers under the underground ventilation is proposed. This study has great significance for the safe mining and high yield and efficiency of the mine.

Key words: *instability criterion, heat transfer model, thick loose seam, extra thick coal seam*

Introduction

In the western mining area in China, the self-bearing capacity of the roof structure is poor, the vertical transmission effect of the overburden loose layer load is significant, and the risk of cutting off before the roof frame is large, which threatens the safe production of the working face and greatly limits the efficient promotion and ventilation operation of the working face [1]. The research on key scientific issues such as the evolution characteristics of the surrounding rock structure, the law of load transfer, and the critical conditions of roof bending and breaking of the bending and breaking of the roof have become urgent work at this stage [2].

Academician Qian Minggao's team summarized Rabas's *pre-fracture hypothesis* and Kuznetsov's *articulated rock block hypothesis* on the technique of a large number of on-site measurements of overburden migration laws, and believed that the upper overburden of the stope was hinged to become a stable *large structure* after breaking, and proposed a *masonry beam structure* [3]. The fracture of a single key layer is the main factor causing the subsidence of the roof of shallow buried coal seam, and based on this, he pioneered the theory of *short masonry beam* and *step rock beam* theory of working face periodic pressure, which opened up new ideas and directions for the study of shallow buried coal seam roof structure.

* Corresponding author, e-mail: szxylf@126.com

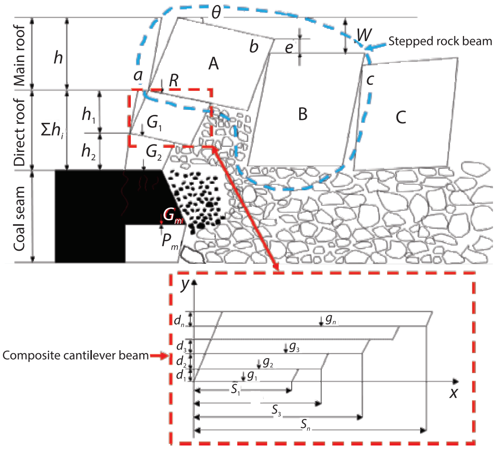

Figure 1. Structural mechanics model of *bench rock beam combined cantilever beam* in fully mechanized top coal caving with large mining height

Structural mechanics model of *Step Rock Beam-Composite Cantilever Beam*

Similar simulation tests and field practice show that with the mining of large-scale mining and high comprehensive surface, the overlying direct top forms a combined cantilever beam on the hydraulic support, and the basic top form *short masonry beam* structure. It is difficult to maintain the stability of the basic top *short masonry beam* structure, the combination of the basic top and the direct top form a relatively stable structural mechanical model of the *step rock beam-combined cantilever beam*, as shown in fig. 1.

In order to further reveal the surrounding rock structure and deformation law of the stope, the stability of the key block A and B of the basic top *step rock beam* hinged was analyzed.

The key block B completely collapses on the crushed coal rock in the goaf, and the rotation of key block A is constrained by key block B at point *b*, assuming that the crushed rock below key block B is in a basic compaction state, it can be approximated that the supporting force of the broken rock in the goaf on key block B is equal to the load of the overlying rock layer on key block B, namely: $R_B = P_2$. At this point, the constraint of key block C on key block B is released, as $Q_c = 0$. The rotation angle of key block A is θ, and for key block B, according to literature and the author's previous research, it is found that key block B is almost horizontal after basic settlement, and it has a breaking angle, α. Force analysis of critical block A:

Force arm for load P_l [2]:

$$2l = l\cos\theta - 2d\cot(\alpha-\theta) \tag{1}$$

Force arm of the shear force Q_a at the hinge point *a*:

$$l_2 = l\cos\theta + \frac{h}{\sin\alpha}\cos(\alpha-\theta) - d\cot(\alpha-\theta) \tag{2}$$

According to other scholars' research and reference materials [4], the height of the extrusion surface is: $2h_a = h/\sin\alpha - (l\sin\theta)/2$. The horizontal thrust at point an act on the center of the extrusion surface, from which the force arm of the horizontal thrust, T, is obtained:

$$l_3 = \frac{h\sin(\alpha-\theta)}{\sin\alpha - W - 0.5h_a} \tag{3}$$

Assuming that the shear arm of the hinge point *c* is l_4 , we get [2]:

$$Pl_1 - Q_a l_2 + Tl_3 + Q_c l_4 = 0 \tag{4}$$

$$T_3 = \frac{\dfrac{h\cos(\alpha-\theta)}{\sin\alpha + 0.5\cos\theta}}{\dfrac{h\sin(\alpha-\theta)}{\sin\alpha - W - 0.5h_a}} P_1 \tag{5}$$

In fig. 1, e is the settlement difference between key block A and key block B, according to the geometric relationship of the structural mechanics model: $e = W - l\cos(\theta)$, and $i = h/l$, is the block-ness of the critical block.

According to the [4] and the field measurement data, the value range of the block-ness i of the key block is: $0.5 \leq i \leq 1.3$, the value range of the rotation angle θ is: $0° \leq \theta \leq 15°$, for the study of the breaking angle, α, there is almost no involvement at present, according to similar experiments and field observations, the value range of the breaking angle, α, is: $45° \leq \alpha \leq 90$ °. Further analysis of eq. (5) shows that the median value of e/l is approximately 0, and substituting the formula yields:

$$\frac{T}{P_1} = \frac{\dfrac{\cos(\alpha-\theta)}{\sin\alpha + 0.5\cos\theta}}{\dfrac{i\left[\sin(\alpha-\theta) - 0.25\right]}{\sin\alpha - \cos\theta + 0.125\sin\theta}} \tag{6}$$

Based on MATLAB software, the numerical analysis of eq. (6) yields the α of different breaking angles, and the relationship between T/P_1 and θ is shown in fig. 2.

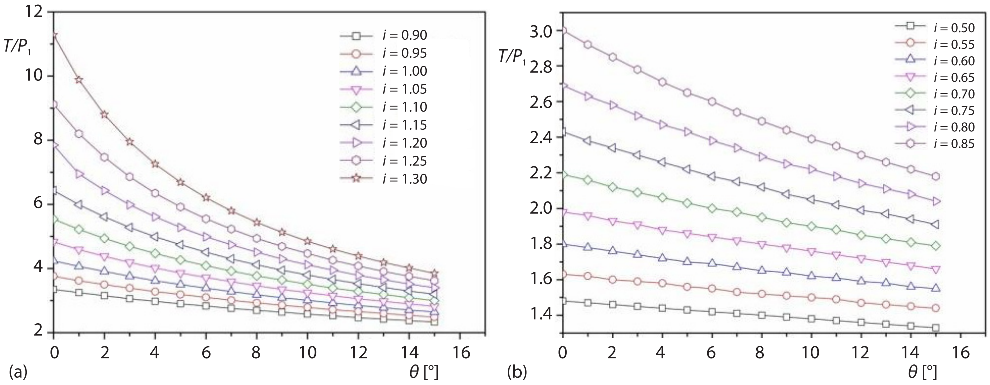

Figure 2. The T/P_1 and θ relationship (α = 45°); (a) 0.50 ≤ i ≤ 0.85 and (b) 0.90 ≤ i ≤ 1.30

It can be seen from fig. 2 that when the breaking angle, α, is 45°, the horizontal thrust, T, decreases with the increase of θ, and the smaller the breaking angle, α, the greater the decrease in value of T with the increase of θ.

Based on MATLAB software, the numerical analysis of eq. (6) shows that the relationship between T/P_1 and i under different breaking angles, α, is shown in fig. 3.

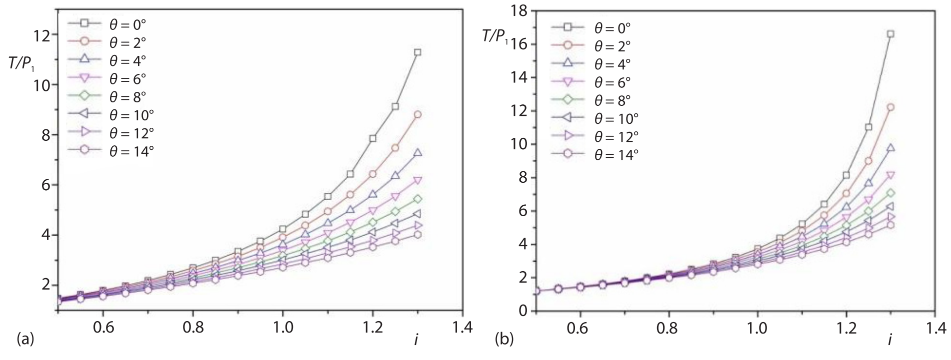

Figure 3. The T/P_1 and i relationship; (a) α = 60° and (b) α = 60°

It can be seen from fig. 3 that the horizontal thrust T increases with the increase of i, and the greater the breaking angle α, the greater the amplitude of the horizontal thrust T with the increase.

Based on MATLAB software, the numerical analysis of eq. (6) shows that the relationship between T/P_1 and α under different block degrees i is shown in fig. 4.

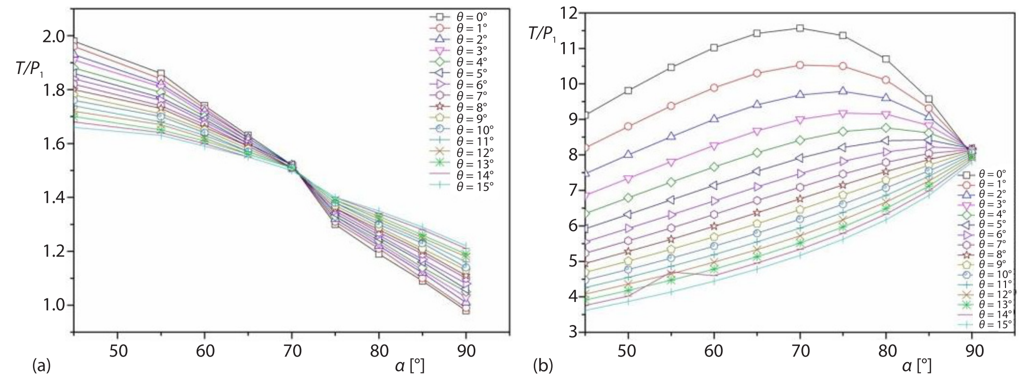

Figure 4. The T/P_1 and α relationship; (a) i = 0.65 and (b) i = 1.25

As can be seen from fig. 4, when the key block degree, i, is 0.65, the horizontal thrust, T, decreases with the increase of the α angle. When the key block degree i is 1.25, $0° \leq \theta \leq 6°$, the horizontal thrust, T, first increases with the increase of α, then decreases, and when $8° \leq \theta \leq 15°$, the horizontal thrust, T, increases with the increase of α.

The *R-S* instability criterion

Slip instability criterion

According to a large number of previous scholars' studies, the conditions to ensure that the roof structure does not slip and become unstable are [3, 4]:

$$T \tan\varphi \geq Q_a \tag{7}$$

Substituting eq. (6) into the previous equation yields:

$$\frac{T}{Q_a} = \frac{\dfrac{\cos(\alpha-\theta)}{\sin\alpha + 0.5\cos\theta}}{\dfrac{i\left(\sin(\alpha-\theta)-0.25\right)}{\sin\alpha - \cos\theta + 0.125\sin\theta}} \tag{8}$$

where $\tan\varphi$ is the friction factor between the key blocks, and the general value is 0.3. According to the previous research of the author's research group [4], when the test mine No. 6 coal seam is pressed during the period of high mining and high comprehensive release, the blockiness of the key block is in the range $0.90 \leq i \leq 1.05$. According to the literature, the breaking angle α is 80°. By substituting into the eq. (8), it can be obtained:

$$0° \leq \theta \leq 15°,\ 2.01 \leq T/Q_a \leq 3.18 \leq 1/\tan\varphi = 3.33,$$

does not meet the eq. (7), the roof structure of the test mine is slipped and unstable.

Rotational instability criterion

In the process of face mining, the conditions to ensure that the roof structure does not undergo rotation instability [5]:

$$\frac{T}{h_a} \geq \eta \sigma_c^* \tag{9}$$

where η is the extrusion coefficient of the key block at point a at the corner end, $\eta\sigma_c^*$ – the extrusion strength of the key block at point a at the corner end, and according to [6], η generally takes a value of 0.3. According to the experiment, the value of the compressive strength limit $\eta\sigma_c^*$ of the key block in the test mine is 33.07 MPa, according to the field observation, the length of the key block l is 15 m, and the value of P_1 is 2.5 MPa, and the eq. (6) is substituted into the aforementioned equation obtain [5]:

$$\frac{4\sin\alpha\left[\dfrac{i\cos(\alpha-\theta)}{\sin\alpha+0.5\cos\theta}\right]P_1 l}{\dfrac{(2i-\sin\alpha\sin\theta)\left(i\left[\sin(\alpha-\theta)-0.25\right]\right)}{\sin\alpha-\cos\theta+0.125\sin\theta}} \geq \eta\sigma_c^* \tag{10}$$

Substituting $0.90 \leq i \leq 1.05$, $0° \leq \theta \leq 15°$, and the previous values into eq. (10) yields:

$$\eta\sigma_c^* = 9.92 \text{ MPa} \leq 233.8 \text{ MPa} \tag{11}$$

Equation (11) is satisfied, and the roof structure does not undergo rotational instability. The theoretical calculation results show that the value range of the blockage of the key block is $0.90 \leq i \leq 1.05$, and the value range of the swing angle θ is $0° \leq \theta \leq 15°$, and the possibility of slippage instability of the *step rock beam* is greater.

Heat transfer model

The energy conservation for the broken layers can be described as [7]:

$$C_c \frac{\partial \Theta}{\partial t} + C_g v_f \nabla \Theta - K_{eq} \nabla^2 \Theta = 0 \tag{12}$$

where Θ is the temperature, K_{eq} – the effective thermal conductivity of broken layer, C_c and C_g are the specific heat capacity of coal and gas, and v_f – the flux velocity of underground ventilation in broken rock.

For each rock layer, the flux velocity has linear relationship with the angle α as:

$$v_f = v_{f0}\alpha \tag{13}$$

where v_{f0} is the reference value for flux velocity.

Conclusion

When the breaking angle, α, is small, the horizontal thrust, T, decreases with the increase of θ, and the smaller the breaking angle, α, the greater the decrease of T value with the increase of θ. When the breaking angle, α, is large, when the block degree, i, is small, the T value increases with the increase of θ, and the larger the breaking angle, α, the greater the increase amplitude. When the breaking angle, α, and block degree, i, are large, the T value decreases with the increase of θ. The horizontal thrust, T, increases with the increase of the block i, and the larger the breaking angle, α, the greater the amplitude of the horizontal thrust, T, with the increase of block i. When the key block degree, i, is small, the horizontal thrust, T, decreases with the increase of the α angle. When the key block degree, i, is large, and θ is small, the horizontal thrust, T, decreases with the increase of α angle. When θ is large, the horizontal thrust, T, increases with the increase of the α angle.

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Nomenclature

C_g, C_c – specific heat capacity of gas and coal, [$Jk^{-1}K^{-1}$]
i – blockiness of the key block, [–]
Q_a – shear force, [MPa]
l – force arm for load, [m]
T – horizontal thrust, [MPa]
v_f – flux velocity, [ms^{-1}]

Greek symbols

η – extrusion coefficient, [–]
Θ – temperature, [K]
σ – stress, [MPa]

References

[1] Zhang, J. C., Investigations of Water Inrushes from Aquifers under Coal Seams, *International Journal of Rock Mechanics and Mining Sciences*, *42* (2005), 3, pp. 350-360
[2] Chen, Z. H., *et al*., Numerical Simulation on 3-D Deformation and Failure of Top Coal Caving, *Chinese Journal of Rock Mechanics and Engineering*, *21* (2002), 3, pp. 309-313
[3] Miao, X. X., Qian, M. G., Overall Structure of Surrounding Rock and Mechanical Model of Masonry Beams in Stope, *Mine Pressure and Roof Management*, *3* (1995), pp. 3-12
[4] Teng, T., *et al*., Overburden Failure and Fracture Propagation Behavior under Repeated Mining, *Mining Metallurgy & Exploration*, *42* (2025), Jan., pp. 219-234.
[5] Zhang, J., *et al.*, Analysis of Sand Outburst During the Rotation of Old Top Rock Blocks in Shallow Buried Coal Seam, *Journal of Xi'an University of Science and Technology*, *26* (2006), 2, pp. 158-166
[6] Qian, M. G., *et al*., Key Block Analysis of Masonry Beam Structure in Stope, *Journal of China Coal Society*, *19* (1994), pp. 557-563
[7] Teng, T., *et al*., A fully Coupled Thermo-Hydro-Mechanical Model for Heat and Gas Transfer in Thermal Stimulation Enhanced Coal Seam Gas Recovery, *International. Journal of Heat and Mass Transfer*, *125* (2018), Oct., pp. 866-875

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