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Research on Coal Pillar Width in Roadway Driving Along Goaf Based on The Stability of Key Block

Zhengzheng Cao[1], **Yuejin Zhou**[1,2]

Abstract: Reasonable width design of narrow coal pillar is the key for ensuring stability of surrounding rock in the roadway driving along next goaf. Based on movement characteristics of overlying strata in gob-side entry, the paper establishes the mechanical model of surrounding rock structure for roadway driving along next goaf, and analyzes the interaction mechanism between key blocks and coal pillar. Besides, in allusion to the mechanical equilibrium of key block B in basic roof, the stability coefficients K_1 and K_2 of key block B and sensitive coefficient of influencing factor are introduced. When the stability coefficient K_1 is larger than 1, rotation instability occurs; while the stability coefficient K_2 is larger than 1, slip instability occurs. According to the stability analysis of key block B, the width design of coal pillar in roadway driving along goaf is obtained. By taking No.3307 working face in Xinan coal mine in Shandong Province as project background, the paper determines reasonable width of coal pillar, calculates stability coefficients of key blocks, and obtains sensitive coefficients of influencing factors on the stability of key blocks. The practical results indicate that the stability of key block in roadway driving along next goaf can be guaranteed when the width of coal narrow is 5.0 m. The results can provide theoretical basis and technical guidance for engineering application with similar mining conditions.

Keywords: Roadway driving along goaf, width design of coal pillar, the stability of key block, stability coefficient.

1 Introduction

For the sake of improving coal resource recovery and relieving the tension of successive productions, an increasing number of mines radically prepare for the next working face by excavating the roadway along the adjacent goaf with narrow coal

[1] State Key Laboratory for Geomechanics & Deep Underground Engineering, School of Mechanics & Civil Engineering, China University of Mining & Technology, Xuzhou 221116, China
[2] Corresponding author: Zhou Yuejin. Tel: +86-13914884696. Email: yuejinzh@163.com

pillar, which is called gob-side entry driving technology [Jia and Kang (2002); Tu, Bai and Tu (2011); Wang, Zhang, Lin and Wang (2014); Zhang, Zhang, Guo, Gao and Li (2015)]. The gob-side entry driving technology is a type of green and advanced mining technology, which should be encouraged to be implemented widely. However, the rapid development of gob-side entry driving technology is based on the surrounding rock control technology of gob-side entry, in which the key approach for maintaining surrounding rock stability at roadway driving along goaf is to keep the coordination between the key block and narrow coal pillar [Xie, Yang and Liu (2006); Liu and Wang (2013)]. To be more precise, the balance of overlying strata structure is heavily affected by the stability of narrow pillar, and the reasonable pillar width is the key to the success of gob-side entry driving technique and improvement of the coal recovery rate [Ma and Wang (2009); Ma and Mao (2011); Yang (2013); Deng and Wang (2014)].

The stability principle of big and small structures of rock surrounding gob-side entry demonstrates that the biggest influence exerted on roadway driving along goaf comes from the spherical triangle key block B of basic roof in the big structure of overlying strata, while the stability of small structure surrounding rock depends on the width of narrow coal pillar and the enhancement to the surrounding rock intensity by bolt supporting [Hou and Ma (1989); Bai, Hou and Huang (2004); Xi, Mao and Yang (2008); Ning, Wang, Liu, Qian and Sun (2014)]. It is believed that the narrow coal pillar supported by high-strength bolts is an important component in the rock bearing structure of roadway driving along next goaf, and according to various conditions of coal seams, the rational width of the corresponding narrow coal pillar is determined. The stress distribution of coal pillar with different width in the stage of excavation and mining is studied, and the characteristics of stress evolution of narrow coal pillar and entity coal sidewall caused by different width of coal pillar is analyzed. The opinion was put forward that the infection of roadway driving and coal mining need considered simultaneously when determination the reasonable width for coal pillar [Hou and Li (2001); Li, Yao and Ding (2008); Cao, Zhou, Xu and Li (2014)]. The structural mechanical model of roadway driving along next goaf is put forward, and the width expression of internal stress fields is derived. Based on this, the rational position of roadway driving along next goaf is determined and the deformation of the surrounding rock is also calculated [Zheng, Yao and Zhang (2012)].

In order to study the influence law of the fracture structure in basic roof on the stability of narrow coal pillar, the mechanical model of surrounding rock structure in gob-side entry is built, and three fracture forms of the overlying main roof in gob-side entry are put forward, and the correlation between the fracture structure of main roof and the stability of narrow coal pillar is analyzed [Wang, Hou and Li

(2001); Yu and Tu (2006); Cao, Zhou, Zhang and Wang (2015)]. In consideration to the researches on movement and deformation laws of surrounding rock and the control technology of gob-side entry, the surveyed results show that most technologies and researches are concentrated on the fully-mechanized working face with numerical simulations, and the width design of narrow coal pillar is finally obtained in engineering practices [Chang, Xie and Yang (2006); Li, Bai and Wang (2012)]. Obviously, there is hardly research on mechanical analysis of the interaction between key blocks and narrow coal pillar in roadway driving along goaf, then to decide the width design of narrow coal pillar.

In this paper, the structural mechanical model of roadway driving along next goaf is established. By analyzing the interaction between key blocks and coal pillar, the paper derived a method of the width design of coal pillar in roadway driving along goaf.

2 Mechanical model of surrounding rock structure for roadway driving along goaf

2.1 The structural mechanical model of roadway driving along goaf

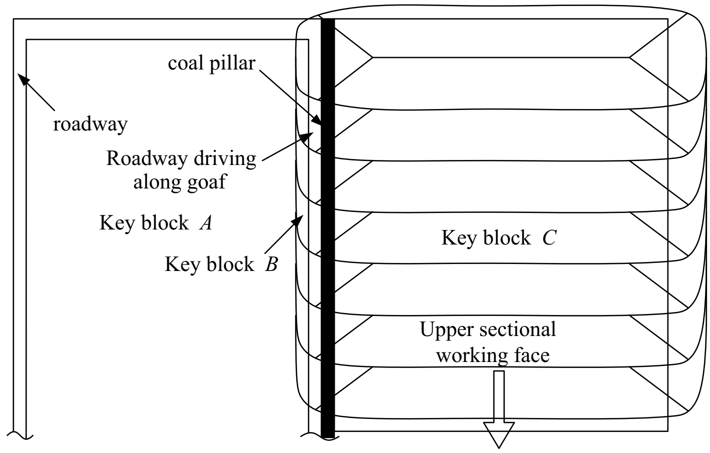
After the upper sectional working face has been mined, the immediate roof will cave and fall in the gob, and the basic roof will break inside the coal wall and sag down while rotating, making great effects on the coal pillar in the roadway driving along nest goaf. The structural mechanical model of roadway driving along goaf is shown in figure 1.

Based on key block theory of overlying strata structure in gob-side entry driving, the stability of key block B is considered as the key factor to the surrounding rock deformation, and the stability of block B is heavily affected by the stability of narrow pillar, thus the reasonable width design of narrow coal pillar is the key to the success of gob-side entry driving technique.

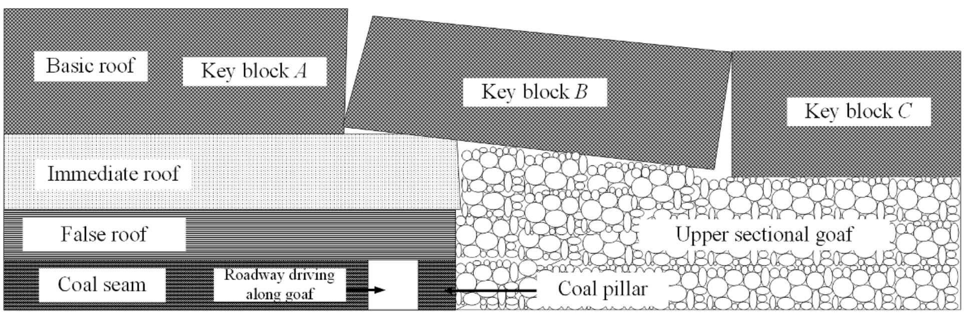
2.2 The mechanical model of key block B

Based on the analysis of the surrounding rock in roadway driving along goaf, the key block B is simplified into the mechanical model of triangular block as is shown in Figure 2.

The physical and mechanical parameters of key block B contains the roof breakage pace of basic roof L_1, the lateral fractured span L_2, the block thickness of basic roof h, the fracture position of the basic roof in lateral coal wall x_0, the supported force by coal gangue F_G, the supported force by immediate roof F_M, the horizontal force T_{CB}, T_{AB} and vertical force F_{CB}, F_{AB} by key blocks.



(a) Top view



(b) Frontal plane

Figure 1: The structural mechanical model of roadway driving along goaf

(1) The roof breakage pace of basic roof L_1

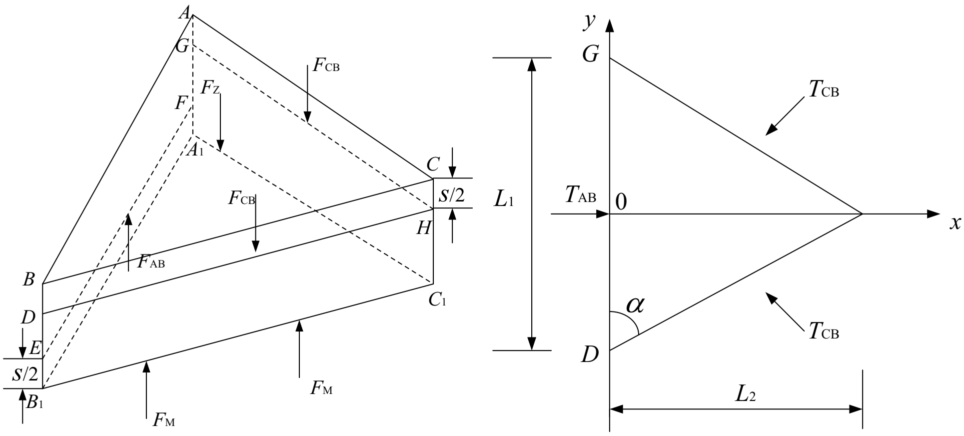
L_1 is the roof breakage pace of basic roof, which can be actually measured or calculated by equation (1).

$$L_1 = h\sqrt{\frac{R_t}{3q}} \tag{1}$$

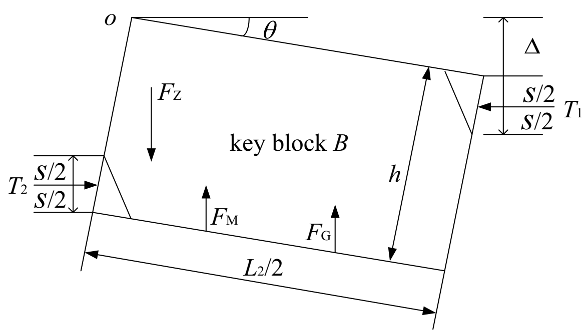
h is the basic roof thickness, m; R_t is the tension strength of basic roof, MPa; and q is the loading on unit area of basic roof, MN/m^2.

(2) The lateral fractured span L_2

According to yield line analytical method, L_2 is related to face length S and basic roof breakage pace L_1, which can be calculated by equation (2).



(a) Overall view (b) Top view



(c) Frontal plane

Figure 2: The mechanical model of key block *B*

$$L_2 = \frac{2L_1}{17}\left[\sqrt{\left(10\frac{L_1}{S}\right)^2 + 102} - 10\frac{L_1}{S}\right] \tag{2}$$

(3) The fracture position of the basic roof in lateral coal wall x_0

The fracture position of the basic roof in lateral coal wall x_0 is always located in the junction of elastic and plastic area, and the fractured basic roof may rotate around the position as its rotation axis, sinking towards the gob. The value of x_0 can be calculated by equation (3).

$$x_0 = \frac{mA}{2\tan\phi_0}\ln\left(\frac{k\gamma H + \frac{C_0}{\tan\phi_0}}{\frac{C_0}{\tan\phi_0} + \frac{p_x}{A}}\right) \tag{3}$$

m is the coal seam thickness, m; A is the horizontal pressure coefficient, $A = \mu/(1-\mu)$, μ is Poisson's ratio; ϕ_0 is the internal friction angle; C_0 shows the cohesion in coal seam interface; k the stress concentration factor; γ shows the average bulk density of the strata; H is the buried depth of roadway; p_x shows the supporting resistance to entity coal side.

(4) The supported force by coal gangue F_{G}

The subsidence of key block B is $s_x = x\sin\theta$, θ is the rotation angle of key block B. then the compression s_y of coal gangue in goaf is

$$s_y = s_x - \{h_m - [h_m(1-\eta)K_m H_1 (K_1 - 1)]\} \tag{4}$$

Then the supported force by coal gangue F_{G} is

$$F_{\mathrm{G}} = \int_{x_0}^{L_2\cos\theta} K_{\mathrm{G}} s_y \left[-\frac{2}{\tan\alpha}(x-L_2)\right] dx \tag{5}$$

η is the coal recovery rate; h_m is the mining thickness; K_m and K_1 is the hulking coefficient of coal seam and immediate roof, respectively; H_1 is the thickness of immediate roof; K_{G} is the supported coefficient of coal gangue.

(5) The supported force by immediate roof F_{M}

The mechanical model of immediate roof in the gob-side entry is shown in figure 3. With reference to limit equilibrium theory, the supported force f_s is

$$f_s = \left(\frac{c_0}{\tan\phi_0} + \frac{p_x}{A}\right) e^{\frac{2\tan\phi_0}{mA}x} - \frac{c_0}{\tan\phi_0} \tag{6}$$

f_d is the uniaxial pressure of coal mass, which could be obtained with the Rock mechanics experiment. The moments generated by the force F_{H}, f_s, f_d, F_{M}, F_{G} as rotation axis EF of key block B are:

$$\begin{cases} R_{\mathrm{H}} = F_{\mathrm{H}} x_0/2 \\ R_s = \int_0^{x_0-a-b} f_s \left[\frac{-2}{\tan\alpha}(x-L_2)\right] x dx \\ R_d = \int_{x_0-b}^{x_0} f_d \left[\frac{-2}{\tan\alpha}(x-L_2)\right] x dx \\ R_{\mathrm{G}} = \int_{x_0}^{L_2\cos\theta} K_{\mathrm{G}} s_y \left[\frac{-2}{\tan\alpha}(x-L_2)\right] x dx \\ R_{\mathrm{M}} = F_{\mathrm{M}} x_0/2 \end{cases} \tag{7}$$

Since the equation $\sum M = 0$ should be satisfied, the supported force by immediate roof F_{M} is obtained.

$$F_{\mathrm{M}} = \frac{2(R_s + R_d + M_{\mathrm{B}} - R_{\mathrm{H}})}{x_0} \tag{8}$$

M_B is the bending moment of immediate roof in point B; a is the width of the roadway; b is the width of the coal pillar.

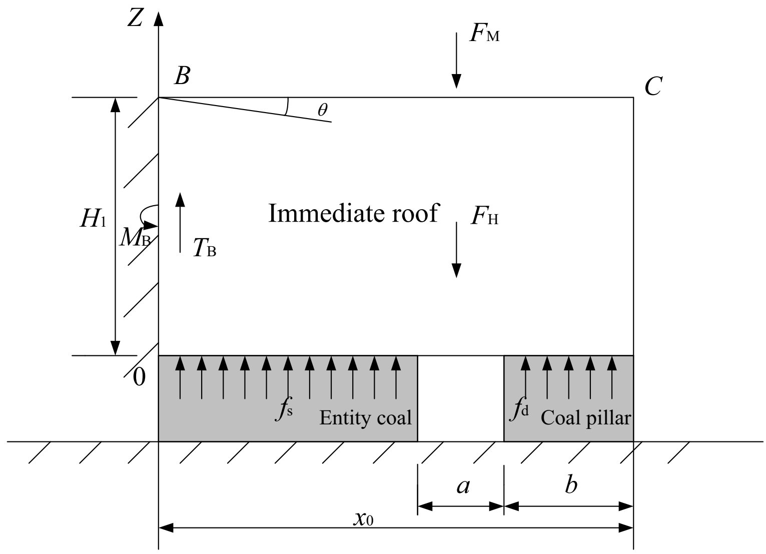


Figure 3: Mechanical model of immediate roof in gob-side entry

(6) The horizontal force T_{CB}, T_{AB} and vertical force F_{CB}, F_{AB} by key blocks

According to the figure 2, $\Delta = \frac{L_2}{2}\sin\theta$, $T_1 = T_2$, $T_1 = 2T_{CB}\cos\alpha$, $T_2 = T_{AB}$, and the expression of s is

$$s = \frac{1}{2}\left(h - \frac{L_2}{2}\sin\theta\right) \tag{9}$$

The moment balance equation $\sum M_o = 0$ is satisfied, then

$$-T_1(\Delta + \frac{s}{2}) + T_2(h - \frac{s}{2}) + R_M + R_G - F_Z\frac{L_2}{3} = 0 \tag{10}$$

Therefore, the horizontal force T_{CB}, T_{AB} by key blocks are obtained,

$$T_{AB} = \frac{4F_ZL_2 - 12(R_M + R_G)}{3(2h - L_2\sin\theta)} \tag{11}$$

$$T_{CB} = \frac{2F_ZL_2 - 6(R_M + R_G)}{3(2h - L_2\sin\theta)\cos\alpha} \tag{12}$$

According to figure 2, the moment sum of rotation axis EF is

$$2F_{CB}\frac{L_2\cos\theta}{2} + F_Z\frac{L_2\cos\theta}{3} - R_M - R_G - 2T_{CB}(h - s - \frac{L_2\sin\theta}{2})\cos\alpha = 0 \tag{13}$$

Then,

$$F_{\rm CB} = \frac{T_{\rm CB}\cos\alpha}{L_2\cos\theta}(h - s - \frac{L_2\sin\theta}{2}) + \frac{R_{\rm M}+R_{\rm G}}{L_2\cos\theta} - \frac{F_{\rm Z}}{3} \tag{14}$$

The force equilibrium in y direction $\sum F_y = 0$ is satisfied, then

$$F_{\rm AB} = 2F_{\rm CB} + F_{\rm Z} - F_{\rm M} - F_{\rm G} \tag{15}$$

3 The stability of key block B and the width design of coal pillar

With reference to the "*S-R*" stability principle, there are two kinds of instability for key block *B* in basic roof, namely slip instability and rotation instability.

3.1 The instability coefficient K1 and K2

When the shear force between the blocks is large than the friction between the contact surface, the slip instability occurs. In order to prevent the slip instability of key block *B*, the condition $T_{\rm AB}\tan(\varphi-\beta) > F_{\rm AB}$ should be satisfied, and the slip instability coefficient K_1 is introduced,

$$K_1 = \frac{F_{\rm AB}}{T_{\rm AB}\tan(\varphi-\beta)} \tag{16}$$

ϕ is the friction angle in the block surface, and β is the breaking angle of the strata. When the horizontal force exceeds the ultimate strength of rock, the rock will be destroyed by extrusion, further leads to the rotation instability. In order to prevent the rotation instability of key block *B*, the condition $T_{\rm AB} < L_1 s\psi\sigma_c$ should be satisfied, and the slip instability coefficient K_2 is introduced,

$$K_2 = \frac{T_{\rm AB}}{L_1 s\psi\sigma_c} \tag{17}$$

σ_c is the compressive strength, and ψ is the contact coefficient between key blocks. When the conditions $K_1 < 1$ and $K_2 < 1$ are met, the instability of key block *B* would not occur. The lesser the value of instability coefficients are, the safer the key block *B* is.

3.2 The sensitivity coefficient

For the sake of sensitive assessment of influencing factors on the stability of key block *B*, the sensitivity coefficient S_i is introduced,

$$S_i = \left|\frac{dK(e)}{de}\frac{e_i}{K(e_i)}\right| \tag{18}$$

S_i is the sensitivity coefficient of the factor e in point e_i; $K(\cdot)$ is the sensitivity evaluation function of key block B, taken K_1 and K_2. The larger the sensitivity coefficient is, the higher the influence degree of stability factor on key block B.

3.3 The width design of coal pillar b1

Since the stability of key block B is heavily affected by the coal pillar width b_1, the width of narrow coal pillar is the key to the success of gob-side entry driving technique.

When the critical state of slip instability for key block B is met, $K_1 = 1$, combined with the equation (16), then

$$F_{\mathrm{AB}} = T_{\mathrm{AB}} \tan(\varphi - \beta) \tag{19}$$

Combined with the related equations (15), the expression b_1 could be obtained.

When the critical state of rotation instability for key block B is met, $K_2 = 1$, combined with the equation (17), then

$$T_{\mathrm{AB}} = L_1 s \psi \sigma_c \tag{20}$$

Combined with the related equations (15), the expression b_2 could be obtained.

In order to guarantee the stability of key block B, the width of coal pillar b should satisfy the condition,

$$b \geq \max(b_1, b_2) \tag{21}$$

4 A case study in the field

4.1 Project background

The engineering practice is carried out in No.3307 working face in Xinan Coal Mine, Zaozhuang Mining Group. The average burial depth of the working face is 530 m, which is a flat seam with an average thickness of 3.85 m, and a hardness coefficient $f = 0.8$. The immediate roof of the working face is sandy mudstone of 10.5 m thickness, and a hardness coefficient $f = 5.7$; the basic roof is fine-grained sandstone of 22 m thickness, and a hardness coefficient $f = 11.9$; The immediate floor of the working face is siltstone of 6.5 m thickness, and a hardness coefficient $f = 4.77$; the basic floor is fine-grained sandstone of 20 m thickness, and a hardness coefficient $f = 10.8$.

The roadway, which is driven along the roof, is rectangular, with a width of 4.6 m and a height of 3.85 m. A narrow coal pillar entry protection with a width of 5 m is right along the goaf of No. 3305 working face. The entry along goaf begins to drive while the upper sectional working face mining is about to close.

4.2 Engineering application

According to the geographical condition in No.3307 working face, the lateral length of working face $S = 185$m, the roof breakage pace of basic roof $L_1 = 33$m, the lateral fractured span $L_2 = 27$m, the fracture position of the basic roof in lateral coal wall $x_0 = 15$ m, the horizontal pressure coefficient $A = 0.45$, the cohesion in coal seam interface $C_0 = 2.2$MPa, the internal friction angle $\phi_0 = 40°$, the average bulk density of the strata $\gamma = 25$ kN/m^3, the stress concentration factor $k = 2.4$, the supporting resistance to entity coal side $p_x = 0.2$ MPa, the compressive strength $\sigma_c = 52$ MPa, the contact coefficient between key blocks $\psi = 0.3$, $\tan(\varphi - \beta) = 0.4$.

Putting the related parameters into equation (19), equation (20) and equation (21), the width of coal pillar for No.3307 working face is 5.0m.

Three measurement points are set in the roadway. The overburden roof subsidence of the roadway driving along goaf and the displacement variation between coal pillar and entity coal are shown in figure 4 and figure 5. The roadway deformation values are within the scope in engineering allowance.

The control effect of surrounding rock in roadway driving along goaf is shown in figure 6. The practical results indicate that the stability of key block in roadway driving along next goaf can be guaranteed when the width of coal narrow is 5.0 m.

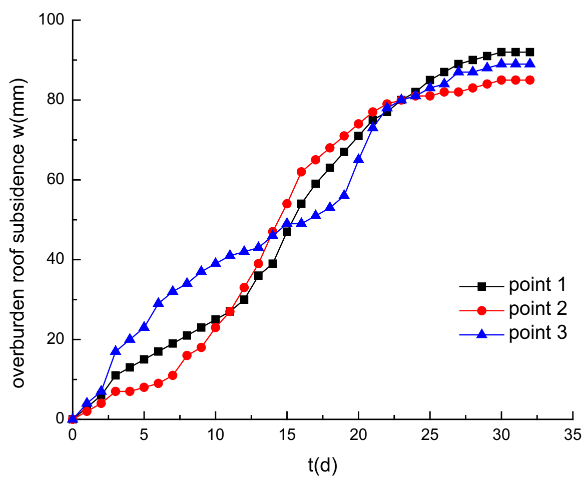


Figure 4: Overburden roof subsidence of the roadway

4.3 Sensitivity analysis of key block stability

Based on the calculation results, combined with the equation (16), the equation (17) and the equation (18), the sensitivity coefficients of influencing factors on the

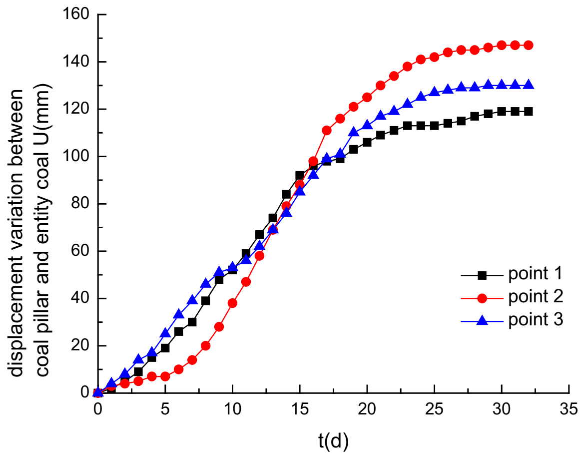


Figure 5: Displacement variations between coal pillar and entity coal

Figure 6: Control effect of surrounding rock in gob-side entry

Table 1: Sensitivity coefficients of influencing factors on of key block stability

The influencing factors on the key block stability	The sensitivity evaluation function K_1	The sensitivity evaluation function K_2
Coal pillar width b	4.48	5.74
Mining thickness h_m	2.76	4.89
Basic roof thickness h	1.85	3.14
Immediate roof thickness H_1	1.04	2.42
Buried depth H	0.37	0.81

stability of key block B is shown in table 1. It is obvious that the width of narrow pillar is the most important and priority factor in gob-side entry driving technique, followed by the mining thickness.

5 Conclusions

(1) The deformation and movement regularity of overlying strata in roadway driving along goaf technology is concluded, and based on this the structural mechanical model of surrounding rock for gob-side entry is established. Through the analysis of the interaction mechanism between key blocks and coal pillar, the viewpoint that the reasonable pillar width is the key to the success of gob-side entry driving technique is put forward.

(2) Based on the stability analysis of key block B in basic roof, the rotation stability coefficient K_1 and the slip stability coefficient K_2 of key block B and sensitive coefficient of influencing factor are introduced. Besides, the critical width of narrow coal pillar is derived when both the stability coefficient K_1 and K_2 are larger than 1. When the stability coefficient K_1 is larger than 1, rotation instability occurs; while the stability coefficient K_2 is larger than 1, slip instability occurs.

(3) By taking No.3307 working face in Xinan coal mine as project background, the paper suggests that reasonable width of coal pillar s 5.0 m. The practical results indicate that the stability of key block in roadway driving along next goaf can be guaranteed when the width of coal narrow is 5.0m. Through the calculation of sensitivity coefficients of influencing factors on the stability of key blocks, the width of narrow pillar is the priority factor in gob-side entry driving technique.

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