

# Stability analysis of coal face based on coal face-support-roof system in steeply inclined coal seam

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**Abstract.** Rib spalling is a major issue affecting the safety of steeply inclined coal seam. And the failure coal face and support system can be affected with each other to generate a vicious cycle along with inducing large-scale collapse of surrounding rock in steeply inclined coal seam. In order to analyze failure mechanism and propose the corresponding prominent control measures of steeply inclined coal working face, mechanical model based on coal face-support-roof system and mechanical model of coal face failure was established to reveal the disaster mechanism of rib spalling and the sensitive analysis of related factors was performed. Furthermore, taking 3402 working face of Chen-man-zhuang coal mine as engineering background, numerical model by using FLAC3D was built to illustrate the propagation of displacement and stress fields in steeply inclined coal seam and verify the theory analysis as mentioned in this study. The results show that the coal face slide body in steeply inclined working face can be observed as the failure height of upper layer smaller than that of lower layer exhibiting with an irregular quadrilateral pyramid shape. Moreover, the cracks were originated from the upper layer of sliding body and gradually developed to the lower layer causing the final rib spalling. The influence factors on the stability of coal face can be ranked as overlying strata pressure ( $P$ ) > mechanical parameters of coal body (e.g., cohesion ( $c$ ), internal friction angle ( $\varphi$ )) > support strength ( $F$ ) > the support force of protecting piece ( $F^*$ ) > the false angle of working face ( $\Theta$ ). Moreover, the corresponding control measures to maintain the stability of the coal face in the steeply inclined working face were proposed.

**Keywords:** steeply inclined coal seam; coal face-roof-support system; rib spalling; sensitively analysis; numerical simulation

## 1. Introduction

At present, numerous coal mines gradually extend to exploit steeply inclined coal seams due to the special occurrence in many western areas of China, such as Huainan, Xinjiang, Chongqing, Guizhou, Ningxia, Gansu, where have become the major mining producing areas. Meanwhile, 17% of the key state-owned coal mines in China have been performing the mining of steeply inclined coal seams. Of course, foreign coal mines will also face steeply inclined coal seam mining in the future, such as India, Poland and so on (Jawed *et al.* 2018, Zorychta *et al.* 2008, Cheng *et al.* 2018, Liu *et al.* 2018, Liu *et al.* 2019, Zhang *et al.* 2019, Zhao *et al.* 2020, Zhao *et al.* 2021). Therefore, researching on mining steeply inclined coal seam can be listed on a high priority to maintain the sustainable development of coal industry. Obviously, compared with mining horizontal coal seams, the great significant difference of mining steeply inclined coal seams can be demonstrated in the fields of mining method, overlying strata structures, mine pressure and displacement rules, stability control of supports (Ma *et al.* 2011, Hu *et al.* 2018,

Lou *et al.* 2021). Especially, the surrounding rock control in steeply inclined coal seam was emphasized through the structure of the overlying strata along the inclination, which was also the main base of stope support design (Liu *et al.* 2015, Chris *et al.* 2019, Cheng *et al.* 2019a, b, Lv *et al.* 2019, Liu *et al.* 2020).

The coal seam dip angle influenced the stability of coal mining face as well as caused the ability of support cannot be mobilized (Yao *et al.* 2017, Alejano *et al.* 1999, Asadi *et al.* 2004, Mandal *et al.* 2016, Cheng *et al.* 2020). Many scholars have paid more attention on investigating the problems of surrounding rock control, the failure mechanism of rib spalling, the failure shape and type of coal body in steeply inclined coal seam through comprehensive research methods (spatial stress analysis, shearing slip model, physical simulation, field measurement). Meng (2013) proposed the concepts of stress-control and structure-control instability mechanism of steeply inclined larger mining height working face through investigation and statistics, theoretical analysis and numerical simulation methods. Tu *et al.* (2015) comprehensively introduced the main difficulties of fully mechanized mining technology in coal seam with steeply inclined, such as surrounding rock and equipment stability control. Wu *et al.* (2016) proposed the main failure mode of steeply inclined coal working face was shear-slip interface

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mainly occurring in the middle and upper part of working face with irregular quadrilateral pyramid of failure coal shape. Meanwhile, the rib spalling caused overlying strata caving followed by support tilting and floor sliding. Wang (2016) performed a study on the support stability of thick coal seam with steeply inclined, analyzed the unstable mode of the support and the equilibrium state of the street, and clarified the influence of the supporting force on the stability of the support, as well as the influence of the roof's failure movement on critical supporting force of the support. Li *et al.* (2017) studied the roof structure and support stability of longwall top coal caving face in steeply inclined coal seams by means of physical simulation and theoretical analysis, indicating that the roof is easily formed into a three-hinged arch structure above the coal seam with steeply inclined. With the growth in the dip angle, the sinking of the arched foot formed above is significantly reduced, which reduces the possibility that the roof structure becomes unstable due to large deformation. Liu (2017) described the rules of overlying strata collapse and stress distribution in steeply inclined larger mining height working face. Through theory analysis and numerical simulation, Yun *et al.* (2018) revealed the failure mechanism of rib spalling with special geological condition (e.g., false inclined arrangement working face). Wang *et al.* (2018) analyzed the influence of mining thickness on the stability of steeply inclined working face and determined the relative critical instability conditions based on the mechanical model of coal face. Zhang (2019) concluded that the characteristics of alternating evolution, slippage and rotary can be observed in steeply inclined coal working face. The serious rib spalling was occurred under the various factors (e.g., mining height, false angle and repeat dynamic load). Das *et al.* (2017) evaluated and analyzed the stability of coal mining surrounding rock based on the inclination angle of coal seams, and studied various parameters through numerical simulation.

It can be seen that there were various studies to reveal the influence of mining height, false angle, overlying strata self-weight, mechanical parameters of coal body and repeat dynamic load on the failure mechanism of rib spalling. And based on these main factors, the corresponding control measurements were also proposed. However, there are limit references to consider the asymmetry rib spalling shape in steeply inclined coal working face and take coal face-support-roof as a whole system, which includes the support force of protecting piece to coal face.

Therefore, in this study, the mechanical model based on the system of coal face-support-roof is established to analyze the failure mechanism of rib spalling in steeply inclined coal seam. Moreover, sensitive analysis is also performed to obtain the prominent influence factors on rib spalling. Meanwhile, taking 3402 working face of Chenman-zhuang coal mine as engineering background, the proposed failure mechanism is further verified through numerical simulation.

## 2. Failure mechanism of rib spalling

In general, with the advance of working face, the stress

redistribute of surrounding rock can be observed along with the occurrence of initial and periodic weightings, and the suspend of main roof was applied on the coal body in the front of the working face and the gangue in the goaf, respectively (Jaszczuk *et al.* 2017). Meanwhile, the overlying load of immediate roof can be directly borne by the coal body and support (Kong *et al.* 2019, Xia *et al.* 2019, Tien *et al.* 2020, Wang *et al.* 2020a). However, in terms of steeply inclined coal seam, the overlying strata can be observed asymmetric characteristic in dip direction seeming like shell structure due to the gangue falling from the upper part of working face sliding to the lower part (Wang *et al.* 2020b, Tu *et al.* 2017). Therefore, it causes a large hanging area of the upper roof along with the occurrence of rib spalling in middle and upper part of working face. For this zone, a mechanical model with coal face-support-roof system is established to obtain the criteria of rib spalling in steeply inclined coal working face. Meanwhile, the prominent factors influencing on the instability of coal face in steeply inclined coal seam are obtained through sensitive analysis.

### 2.1 Mechanical model of coal face-support-roof system

Fig. 1 illustrates the mechanical model of coal face-support-roof system. As mentioned before, in the middle and upper part of working face, the stresses of immediate roof, the main roof and overlying strata directly applying on the support and coal body in the front of working face can be expressed as follows

$$\begin{cases} G_1 \cos \alpha + qLB = 2f + P_1 \\ \frac{l}{2} P_1 + lf + HT = \frac{L}{2} (qLB + G_1 \cos \alpha) \\ f = \mu T \\ G_1 = \gamma_1 HLB \end{cases} \quad (1)$$

where  $G_1$  is the self-weight of the main roof,  $P_1$  is the overlying strata acting on immediate roof,  $\gamma_1$  is the unit weight of the main roof,  $H$  is the thickness of the main roof,  $L$  is the periodic weighting interval of the main roof,  $B$  is the center distance of the support,  $q$  is the load intensity of the overlying strata,  $f$  is the friction of broken rock blocks,  $\mu$  is the friction coefficient,  $T$  is the horizontal stress of broken rock blocks,  $\alpha$  is the dip angle of coal seam,  $l$  is the hanging length of the immediate roof.

According to Eq. (1), the overlying strata pressure acting on the immediate roof can be obtained as Eq. (2).

$$P_1 = \frac{HLB(\gamma_1 H \cos \alpha + q) + \mu qLB(L-1)}{H + \mu(L-l)} \quad (2)$$

Therefore, the total bearing resistance of support ( $F$ ) and coal body ( $P$ ) consists of two parts with the gravity of immediate roof and overlying strata acting on immediate roof can be illustrated as shown in Eq. (3).

$$\begin{cases} P_1 + G_2 \cos \alpha = P + F \\ G_2 = \gamma_2 hLB \end{cases} \quad (3)$$

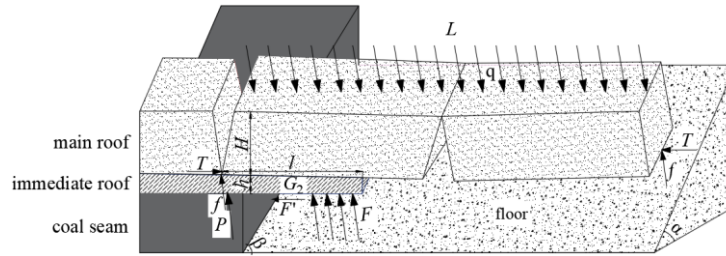


Fig. 1 Mechanical model of coal face-support-roof system

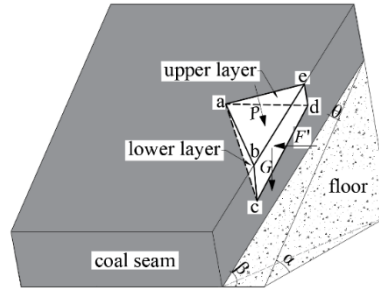


Fig. 2 Mechanical model of coal face failure

where  $G_2$  is the self-weight of the immediate roof;  $\gamma_2$  is the unit weight of immediate roof;  $h$  is the thickness of immediate roof. Combined with Eqs. (2) and (3), the total overlying strata acting on coal body in the working face can be derived as Eq. (4).

$$P = P_1 + G_2 \cos \alpha - F \quad (4)$$

Obviously, with the increase of support resistance, the overlying strata pressure acting on coal face decreases, which contributes on the stability of working face.

## 2.2 Mechanical model of coal face failure

Based on the previous study of coal face failure and the theory and research of rock shear strength (Ren *et al.* 2008; Barton *et al.* 1978, Sheorey 1997, Ran *et al.* 1994), the mechanical model of coal face can be established as shown in Fig. 2 to obtain the shear slip failure criterion of rib spalling.

In terms of the false arrangement working face in steeply inclined coal seam, two mainly factors of the overlying strata pressure on coal face ( $P$ ) and the self-weight of coal body ( $G$ ) contribute on the failure and sliding of coal face with the formation of two weak planes ( $abc$  and  $ade$ ) as shown in Fig. 2). Therefore, an irregular quadrilateral pyramid sliding body ( $abcde$ ) can be created due to the damage of two weak planes along a certain direction and height when the external force is greater than the failure strength of coal face. Under this condition, the sliding body failure planes of  $abc$  and  $ade$  are defined as upper layer and lower layer, respectively.

As shown in Fig. 2, the relationship of false dip angle of working face ( $\beta$ ) with the dip angle of coal seam ( $\alpha$ ) and the oblique angle of working face ( $\theta$ ) can be expressed as follows

$$\beta = \arcsin(\sin \alpha \cos \theta) \quad (5)$$

Based on the mechanical model of coal face-support-roof system, the protecting piece of support still has a certain horizontal force  $F'$  on the coal face, which is decomposed into  $F' \cos \theta$  along the vertical direction of the coal face. Therefore, the maximum normal stress on the shear plane of  $abc$  and  $ade$  can be expressed as  $\sigma_1$  and  $\sigma_2$ , respectively.

$$\sigma_1 = P \sin \delta + F' \cos \theta \cos \delta + G \cos \left( \frac{\pi}{2} - \delta \right) \quad (6)$$

$$\sigma_2 = P \sin \delta + F' \cos \theta \cos \delta + G \cos \beta \sin \delta \quad (7)$$

$$\delta = \pi/4 - \varphi/2 \quad (8)$$

where  $\delta$  is the angle between shear slip plane and coal face,  $\varphi$  is the internal friction angle of coal body.

According to Mohr-coulomb theory, the corresponding shear resistance of two shear slip planes can be expressed as  $\tau_1$  and  $\tau_2$ , respectively.

$$\tau_1 = \sigma_1 \tan \varphi + ch_1 \sec \delta \quad (9)$$

$$\tau_2 = \sigma_2 \tan \varphi + ch_2 \sec \delta \quad (10)$$

where  $c$  is the cohesion of coal body,  $h_1$  and  $h_2$  are the failure height of coal face on the weak plane  $abc$  and  $ade$ , respectively.

Combined with Eqs. (6) and (7), the shear resistance of shear slip plane can be expressed as follows

$$\tau_1 = \left[ P \sin \delta + F' \cos \theta \cos \delta + G \cos \left( \frac{\pi}{2} - \delta \right) \right] \tan \varphi + ch_1 \sec \delta \quad (11)$$

$$\tau_2 = (P \sin \delta + F' \cos \theta \cos \delta + G \cos \beta \sin \delta) \tan \varphi + ch_2 \sec \delta \quad (12)$$

Therefore, the slide force of each shear slip plane is calculated as  $S_1$  and  $S_2$ , respectively.

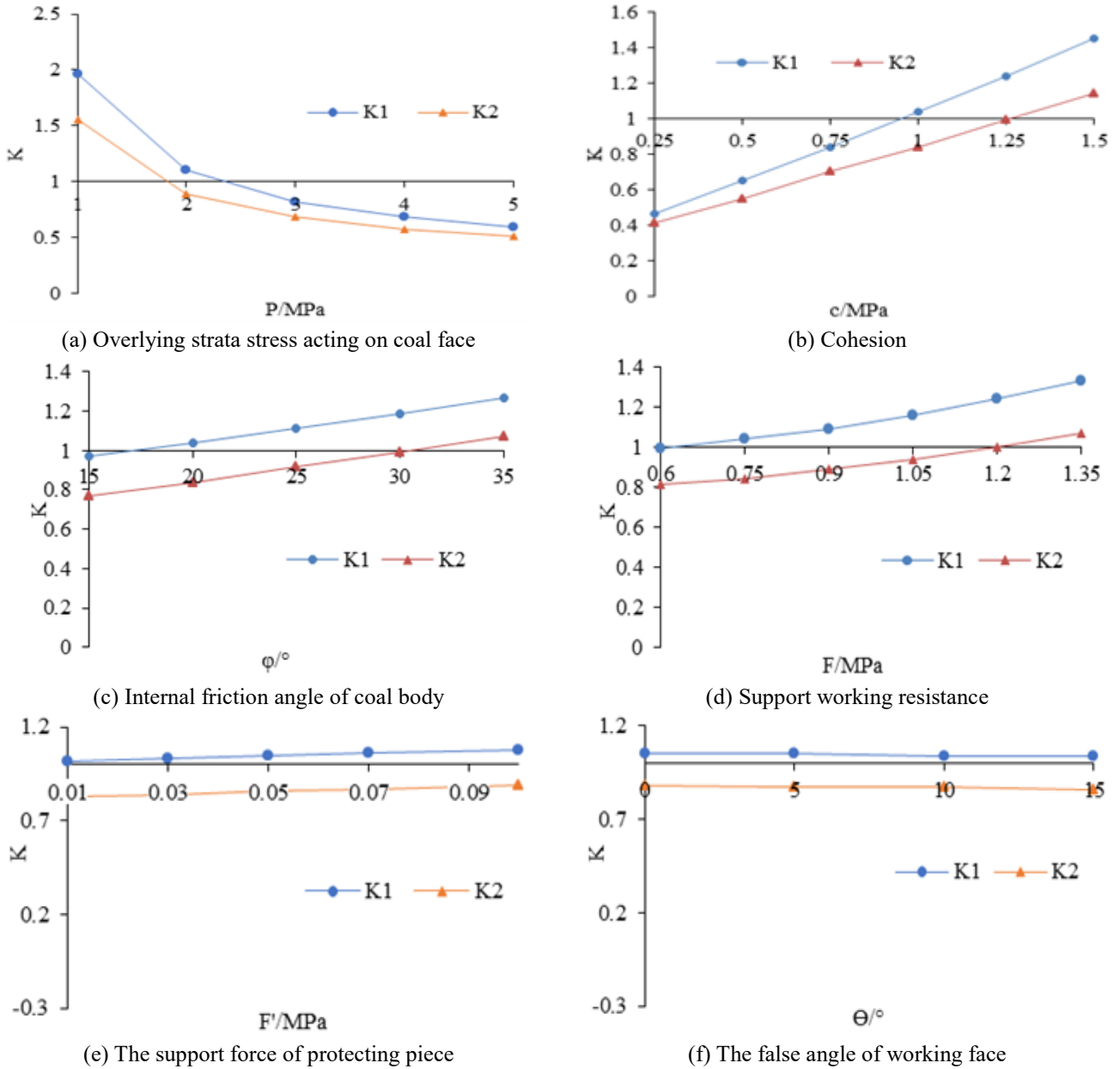


Fig. 3 Sensitive analysis of influencing factors

$$S_1 = P \cos \delta - F' \cos \theta \sin \delta + G \sin \left( \frac{\pi}{2} - \delta \right) \quad (13)$$

$$S_2 = P \cos \delta - F' \cos \theta \sin \delta + G \cos \beta \cos \delta \quad (14)$$

### 2.3 Sensitive analysis of the stability of coal face

The occurrence of rib spalling depends on whether the slide force of shear slip plane ( $S$ ) is larger than that of shear resistance ( $\tau$ ). Therefore, the stability coefficient  $K$  can be defined as the ratio of  $\tau$  to  $S$ . In terms of two shear slip planes, both stability coefficients are less than 1 causing rib spalling formed with an irregular quadrilateral pyramid sliding body. If either the stability coefficient  $K_1$  or  $K_2$  is less than 1, the corresponding shear slip plane can be

observed the occurrence of fractures with a slight rib spalling. Combined with Eqs. (11)-(14), the stability coefficient expressions of coal face ( $K_1$  and  $K_2$ ) are as follows

$$\begin{cases} K_1 = \frac{[(P+G)\tan \delta + F' \cos \theta] \tan \varphi + ch_1 \sec^2 \delta}{P+G-F' \cos \theta \tan \delta} \\ K_2 = \frac{[(P+G \cos \beta)\tan \delta + F' \cos \theta] \tan \varphi + ch_2 \sec^2 \delta}{P+G \cos \beta - F' \cos \theta \tan \delta} \end{cases} \quad (15)$$

It can be seen that the influence factors on the stability of coal face are overlying strata stress acting on coal face, cohesion and internal friction angle of coal body, support working resistance, the support force of protecting piece, and the false angle of working face. Actual data of coal face at working face  $P = 2.1$  MPa,  $c = 1$  MPa,  $\varphi = 20^\circ$ ,  $F = 0.75$  MPa,  $\theta = 10^\circ$ . Under the premise of keeping other

parameters unchanged, different values of the above parameters are taken to study the influence of each parameter on the stability coefficient. Sensitive analysis about these factors is performed as shown in Fig. 3.

(1) As shown in Fig. 3(a), with the increase of overlying strata stress acting on the coal face ( $P$ ), the stability coefficient ( $K$ ) of coal face decreases causing the easier occurrence of rib spalling. When the overlying strata stress at the coal face increases to about 1.8 MPa, there are  $K_1 > 1$ ,  $K_2 = 1$ , then the coal face is in a critical state to cause the occurrence of fracture; When the overlying strata stress at the coal face is between 1.8 MPa and 2.3 MPa, there are  $K_1 > 1$ ,  $K_2 < 1$ , the coal face fractures can be observed from *ade* surface; When the overlying strata stress at the coal face reaches 2.3 MPa or more, there are  $K_1 < 1$ ,  $K_2 < 1$ , the coal face will undergo shear slip failure along the weak surfaces of the *abc* and *ade* joints, and then form a rib spalling.

(2) As shown in Fig. 3 (b), with the increase of cohesion ( $c$ ) in coal, the stability of coal face is better. In the above figures, under the same conditions, With the increase of cohesion in coal seam, the stability coefficient ( $K$ ) of coal face increases. When the coal seam cohesion is less than 0.95 MPa, there are  $K_1 < 1$ ,  $K_2 < 1$ , then the coal face is prone to spalling; When the coal seam cohesion is between 0.95 MPa and 1.26 MPa, there are  $K_1 > 1$ ,  $K_2 < 1$ , then the coal face fractures can be observed from the *ade* surface; When the coal seam cohesion is 1.26 MPa, there are  $K_1 > 1$ ,  $K_2 = 1$ , the coal face is in a stable critical state.

(3) As shown in Fig. 3 (c), with the increase of internal friction angle ( $\varphi$ ) of coal body, the stability coefficient ( $K$ ) of the coal face increases to improve the stability performance of coal face and avoid the potential occurrence of rib spalling. When the friction angle in the coal seam is less than  $17^\circ$ , there are  $K_1 < 1$ ,  $K_2 < 1$ , then the coal face is prone to spalling; When the friction angle in the coal seam is between  $17^\circ$  and  $31^\circ$ , there are  $K_1 > 1$ ,  $K_2 < 1$ , then the coal face fractures can be observed from the *ade* surface; When the friction angle in the coal seam is  $31^\circ$ , there are  $K_1 > 1$ ,  $K_2 = 1$ , then the coal face is in a stable critical state.

(4) As shown in Fig. 3(d), with the increase of support strength ( $F$ ), the stability coefficient ( $K$ ) of coal face increases along with the low possible occurrence of rib spalling. When the supporting strength is less than 0.62 MPa, there are  $K_1 < 1$ ,  $K_2 < 1$ , then the coal face is prone to spalling; When the support strength is between 0.62 MPa and 1.2 MPa, there are  $K_1 > 1$ ,  $K_2 < 1$ , then the coal face fractures can be observed from the *ade* surface; When the supporting strength is 1.2 MPa, there are  $K_1 > 1$ ,  $K_2 = 1$ , the coal face is in a stable critical state.

(5) As shown in Fig. 3(e), the support force of protecting piece has limit effect on the stability of coal face with the increase of  $F'$ . In the picture, there are  $K_1 > 1$ ,  $K_2 < 1$ , the coal face fractures can be observed from the *ade* surface, and there will be no large-scale rib spalling.

(6) As shown in Fig. 3 (f), with the false angle ( $\theta$ ) of working face increases, the stability coefficient of the coal seam is almost unchanged, but slightly decreased, and the stability of the coal face becomes worse. In the picture, there are  $K_1 > 1$ ,  $K_2 < 1$ , the coal face fractures can be observed from the *ade* surface, the coal face is subjected to

gravity, and the gravity component points to the direction of the goaf. Therefore, the greater the false angle, the greater the possibility of spalling occurrence on the coal face.

Based on the above analysis, the overlying strata pressure has the prominent role on the stability of coal face. With the increase of overlying strata pressure, the condition of coal face becomes worse. Subsequently, with the increase of the mechanical parameters of coal body (e.g., cohesion, internal friction angle), the stability of coal face can also be of great significant improvement. Similarly, the borne pressure of coal face decrease with providing enough support strength to undertake the overlying strata pressure. Thus, the potential occurrence of rib spalling can also decrease. However, the stability of coal face can be hardly maintained only with the increase of the support force of protecting piece. The pseudo-inclined layout of the working face, although the false angle has little effect on the stability of the coal face, but the larger the false angle, the greater the possibility of rib spalling due to the gravity component of the coal face. In total, the influence factors on the stability of coal face can be ranked as overlying strata pressure ( $P$ ) > mechanical parameters of coal body (e.g., cohesion ( $c$ ), internal friction angle ( $\varphi$ )) > support strength ( $F$ ) > the support force of protecting piece ( $F'$ ) > the false angle of working face ( $\theta$ ). It should be noted that  $K_1$  is always larger than  $K_2$  with the same geotechnical condition, which indicates the weak surface *ade* more likely to be failure than weak surface *abc*. Therefore, the initial cracks are generated from the upper part of sliding body to the lower part of sliding body and finally causing the occurrence of rib spalling.

#### 2.4 Stability control measurements of coal face in steeply dipping coal seam

According to the failure mechanism of coal face in the coal face-support-roof system and the influencing factors affecting the stability of coal face, the following control measures in steeply inclined coal seam are proposed.

(1) Increasing the initial working resistance of support properly. Based on the mechanical model of coal face-support-roof system, the overlying strata pressure acting on coal face can decrease if support can undertake large partial overlying strata pressure. Therefore, ensuring the support has sufficient strength and fully attaches to the roof contributing to the stability of coal face.

(2) Increasing the support force of protecting piece on coal face. Normally, the steeply inclined working face adopts false layout with a certain false angle causing support protecting piece cannot sufficient contact with coal face. Therefore, it is necessary to design anisotropic (parallelogram) support or adjust the angle of support protect piece to ensure fully contacting with coal face. Meanwhile, the appropriate increase of the area of support protecting piece can also contribute to the better performance of coal face in steeply inclined coal seam.

(3) Reasonable determination of false inclined angle. The coal face stability coefficient  $K$  is inversely proportional to false Angle. Therefore, it is necessary to reduce the false angle of working face for avoiding the occurrence of rib spalling.

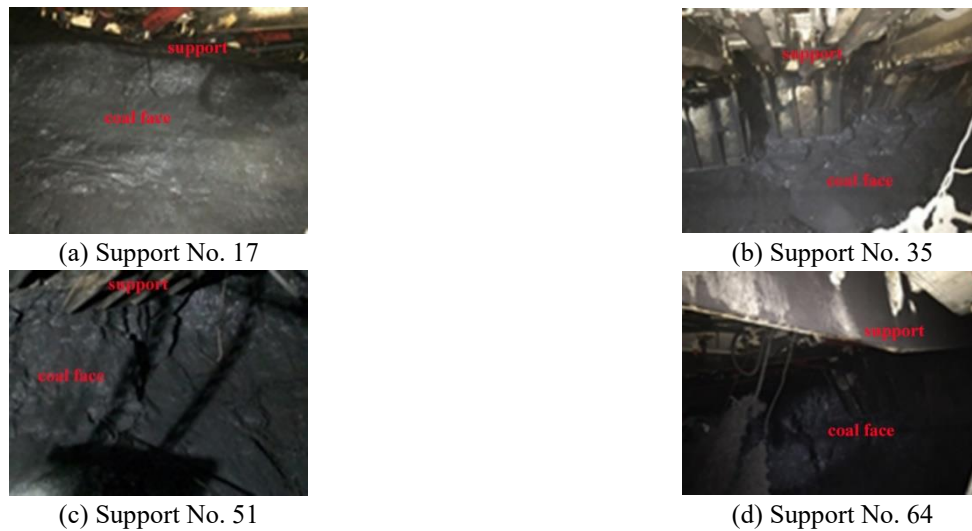


Fig. 4 Rib spalling in 3402 working face

Table 1 Physical and mechanical parameters of coal and rock formations

Rock strata	Unit weight /(Kg/m <sup>3</sup> )	Elastic modulus /GPa	Bulk modulus /GPa	Shear modulus /GPa	Cohesion /MPa	Friction angle /°	Tensile strength (MPa)	Thickness (m)
Medium sandstone	2680	39	20.31	10.83	3	37	3.17	20
Mudstone	2800	28	15.56	11.67	1	30	1.79	4
Medium Sandstone	2680	40	20.83	16.95	3.3	37	4.0	6
Siltstone	2690	22	13.1	9.02	1.26	33	1.47	5
Mudstone	2800	28	15.56	11.67	1	30	1.79	2
Coal	1800	10	8.33	3.85	0.5	20	1.00	3
Mudstone	2800	28	16.09	11.57	1.1	29	1.80	2
Fine sandstone	2700	26	14.44	10.83	2.5	37	1.9	8

(4) Increasing the mechanical parameters of coal body (e.g., cohesion and internal friction angle). In the failure zones of working face, the cementing agent can be properly filled in coal fractures through high pressure to increase the mechanical parameters of coal body. Furthermore, the shear resistance and stability of coal body can be enhanced.

### 3. Numerical simulation

#### 3.1 Engineering background

Taking Chen-man-zhuang coal mine as engineering background, the thickness and average mining height of 3<sup>#</sup> coal seam are 0.7~4.6 m and 3 m respectively, with soft coal body and plenty of cracks. Moreover, the lithology of immediate roof is mudstone with low strength and developed joints, while the main roof is siltstone with an average thickness of 5.2 m and high compressive strength (80-110 MPa). In terms of 3402 working face arranged in 3<sup>#</sup> coal seam, the length, false slanting angle and total advancing distance are 80 m, 10° and 884.8m, respectively. In the mining process, 3402 working face was difficult to be controlled with the occurrence of rib spalling in the middle and upper parts, especially in the zones of supports 8<sup>#</sup>~24<sup>#</sup>,

32<sup>#</sup>~35<sup>#</sup>, 50<sup>#</sup>~53<sup>#</sup> and 60<sup>#</sup>~65<sup>#</sup> as shown in Fig. 4. It can be observed the failure characteristics of coal face presenting large height, wide range and irregular tetrahedron in most of sliding blocks caused as a result of large overlying strata pressure, low mechanical properties of coal body and insufficient support strength, which seriously affects the normal progress of working face and threatens the safety of equipment and even staff. Table 1 summarizes the related input physical and mechanical parameters of 3402 working face in simulation model.

#### 3.2 Numerical model

The stability of coal face-support-roof system mainly depends on the organic interaction of each part. However, the overlying strata pressure is difficult to be controlled under a specific working face. Therefore, as mentioned above, numerical model, which is length 160 m, width 210 m and 240 m with totally units and nodes of 192900 and 230303, respectively, was established to explore the influence of the properties of coal body and support strength on the stability of coal face-support-roof system based on Mohr-Coulomb constitutive model as shown in Fig. 5. And the physical and mechanical parameters of each layer are listed in Table 1. Meanwhile, the inclined length of

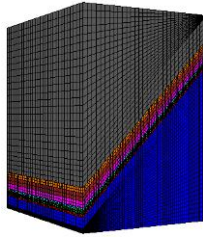


Fig. 5 Numerical model

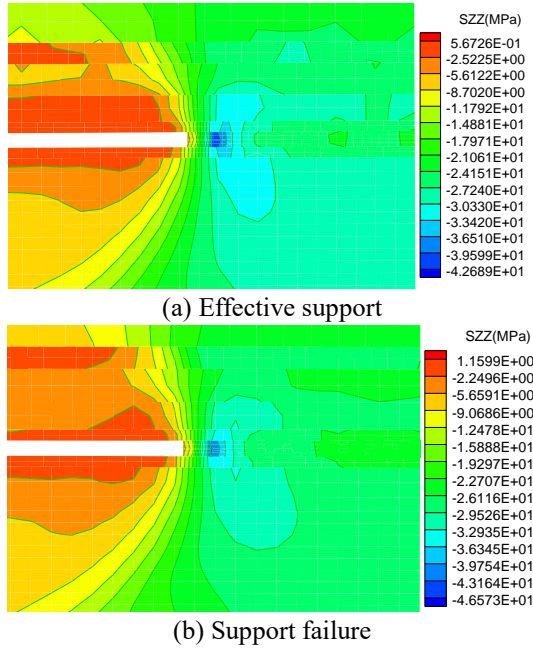


Fig. 6 Stress nephogram of surrounding rock

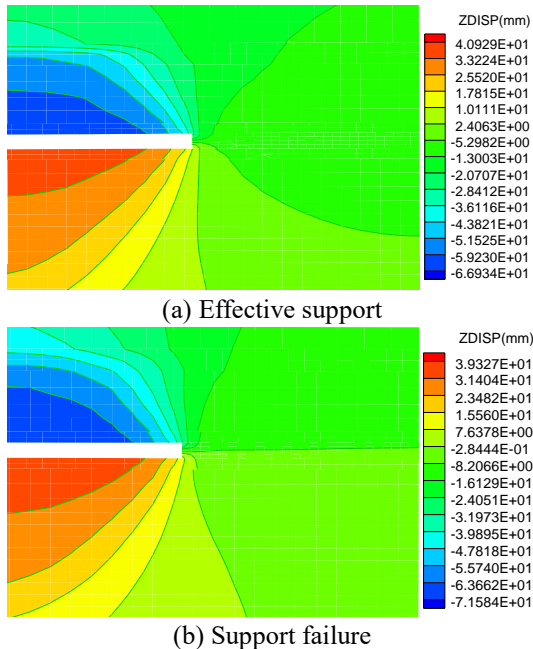


Fig. 7 Displacement nephogram of surrounding rock

working face is 80 m with the protective coal pillars of 50 m. In terms of boundary conditions, top surface is applied the equivalent stress of stratum load about 20 MPa, while

fixed displacement is applied on other surfaces. Without considering tectonic stress, the horizontal stress is 1.5 times of vertical stress.

### 3.3 Results and analysis

#### 3.3.1 Support conditions

The influence of support conditions (effective support and failure support) on the stability of coal face is explored under a specific overlying strata load. And slicing the model along the strike (upper part of working face) is performed to obtain the stress and displacement nephograms under different support conditions with the advancing distance of 100 m as shown in Figs. 6 and 7, respectively. It can be observed that the vertical roof pressure of 0.75 MPa (average support strength) is applied on in the range of 600 mm ~ 4590 mm (within support protecting range) behind coal face.

Fig. 6 illustrates the maximum stress at coal face reaching 42.69 MPa when the working face support is effective, and the maximum pressure at the lower roof above the support is about 8.70 MPa; When the working face support failure, the maximum stress at the coal face up to 46.57 MPa, the maximum pressure at the lower roof above the support is about 9.07 MPa. According to the vertical displacement distribution shown in Fig. 7, when the working face support is effective, the maximum displacement of the lower roof can reach 67 mm, and the maximum displacement at the coal face is about 28 mm; when the working face support failure, the maximum displacement of the lower roof can reach 72 mm, the maximum displacement at the coal face is about 32 mm.

It can be seen that after the support of the working face failure, the stress at the lower roof above the support and coal face will increase, and the stress at the coal face will increase more, the corresponding vertical displacement of the lower roof and coal face will also increase. This means that when the support of the working face failure, the stability of the roof and coal face will be reduced, and roof structure instability and rib spalling are prone to occur, which threatens the stability of the "coal face-support-roof" system.

#### 3.3.2 Different influence factors of coal face

Keeping effective support, the influence of coal mining height (2 m, 3 m, 4 m and 5 m), coal body cohesion (0.5 MPa, 1 MPa, 1.5 MPa and 2 MPa) and coal seam inclination (10°, 20°, 35° and 45°) on the stability of coal face is illustrated with working face advancing 100 m as shown in Figs. 8-12.

##### (1) Mining height

Figs. 8 and 9 reveals the stress and displacement of surrounding rock in steeply inclined coal seam with different mining heights. It can be observed that the maximum stress at coal face is 44.50 MPa, 42.69 MPa, 39.67 MPa and 37.95 MPa with mining height 2 m, 3 m, 4 m and 5 m, respectively, while the related maximum pressure at lower roof above support is correspondingly 12.29 MPa, 8.70 MPa, 5.16 MPa and 4.95 MPa, respectively. And the stress at upper roof decreases greatly with the increase of mining height, while the peak stress

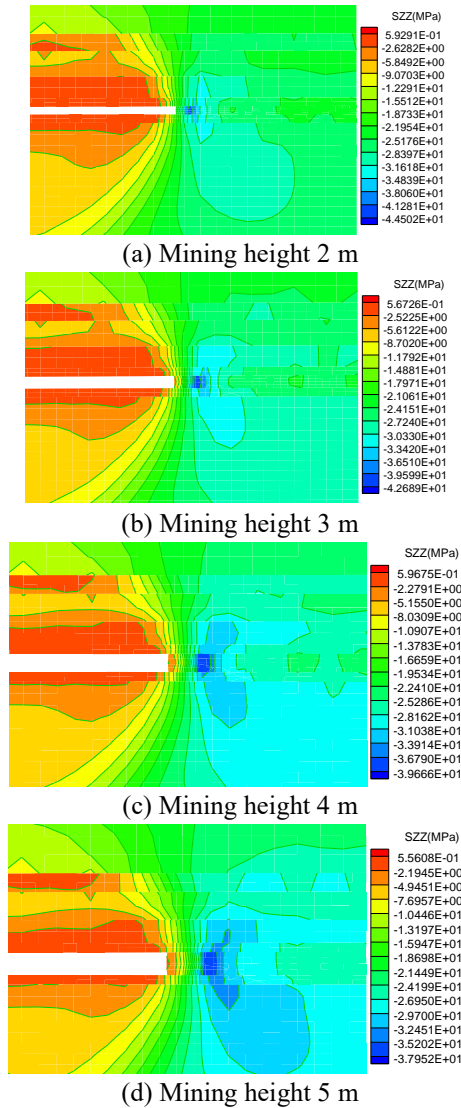


Fig. 8 Stress nephogram of surrounding rock

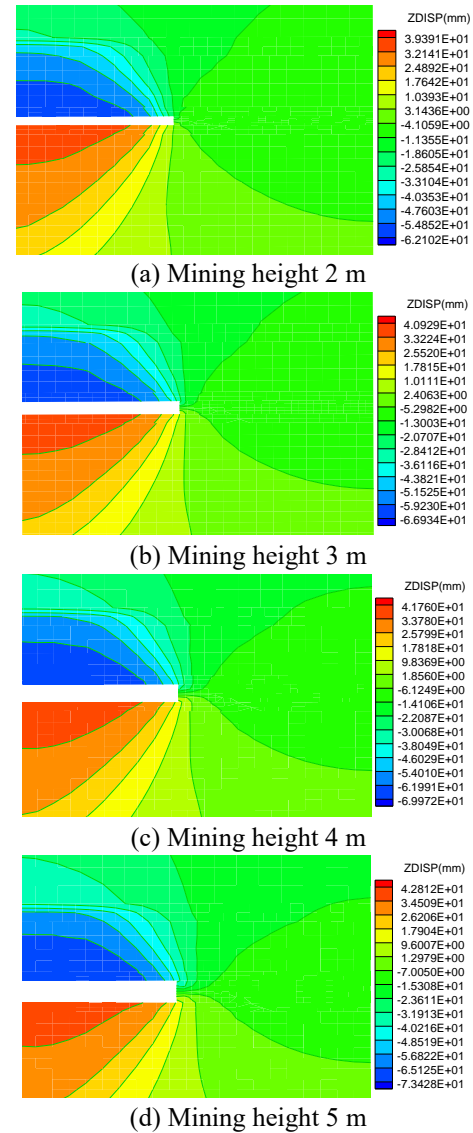


Fig. 9 Displacement nephogram of surrounding rock

point is constantly away from working face. Fig. 9 illustrates the maximum vertical displacement of surrounding rock increases with the increase of mining height. To be specific, the maximum displacement at coal face is 19 mm, 28 mm, 38 mm and 40 mm, while the corresponding maximum displacement at lower roof is 62 mm, 67 mm, 70 mm and 73 mm with mining height 2 m, 3 m, 4 m and 5 m, respectively. As a result, the first weight distance increases with the increase of mining height to form a large space in goaf zone.

The overlying strata load is jointly borne by support and coal face. With the increase of mining height, the vertical stress at lower roof applied on support sharply decrease causing coal face bearing large pressure. It is accompanied with the increase of vertical displacement at lower roof and coal face. Therefore, in the mining process, the roof structure and coal face are prone to failure and rib spalling, respectively, which seriously affects the stability of the coal face-support-roof system.

### (2) Cohesion of coal body

With the increase of cohesion of coal body, Fig. 10 illustrates the maximum displacement of surrounding rock

in steeply inclined coal seam has a slight decrement. To be specific, the maximum displacement at lower roof is 67 mm, 64 mm, 59 mm and 52 mm, while the corresponding value at coal face is 28 mm, 20 mm, 17 mm and 15 mm with cohesion 0.5 MPa, 1 MPa, 1.5 MPa and 2 MPa, respectively. And the occurrence of rib spalling can be easily observed with the large vertical displacement of coal face and lower roof. Therefore, it can be regards as the mechanical parameters of coal body directly affecting the vertical displacement of surrounding rock and low strength of coal body can accelerate the destruction of roof structure causing the occurrence of rib spalling at coal face.

### (3) Inclination angle of coal seam

Four conditions ( $10^\circ$ ,  $20^\circ$ ,  $35^\circ$ , and  $45^\circ$ ) are selected to explore the influence of inclination angle of coal seam on the stress and displacement distribution of surrounding rock. Fig. 11 illustrates the maximum stress of surrounding rock decreases with the increase of inclination angle of coal seam. Specifically, the maximum stress at coal face is 48.02 MPa, 46.97 MPa, 44.46 MPa and 42.69 MPa, while the maximum stress at lower roof is 10.16 MPa, 9.90 MPa, 9.21

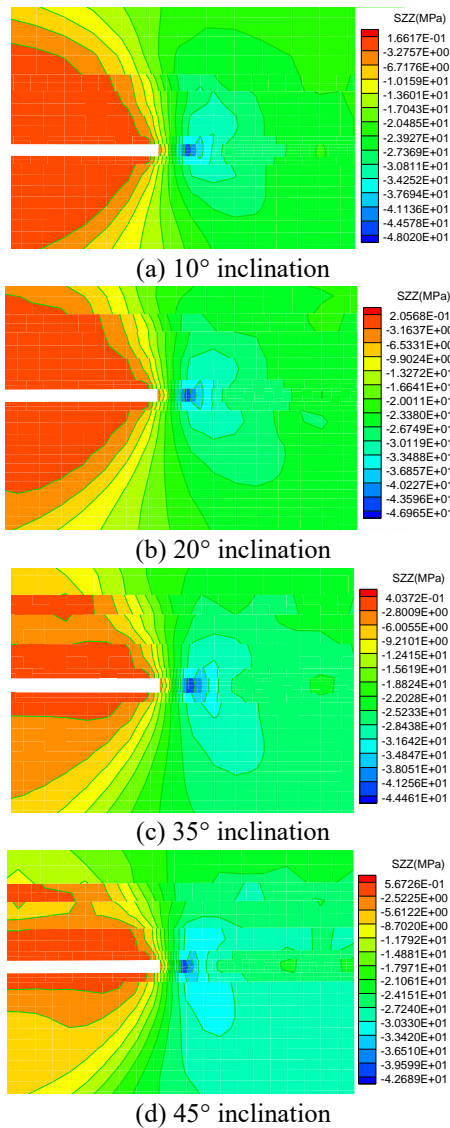


Fig. 11 Stress nephogram of surrounding rock

MPa and 8.70 MPa with inclination angle of coal seam 10°, 20°, 35°, and 45°, respectively. In term of vertical displacement, the maximum value dramatically decreases with the increase of inclination angle of coal seam as well. At coal face, this value is 36 mm, 33 mm, 30 mm and 28 mm when inclination angle is 10°, 20°, 35° and 45°, respectively. Correspondingly, the maximum vertical displacement is 114 mm, 100 mm, 80 mm and 67 mm, respectively.

Normally, a space shell stable structure of rock layer is easier to be formed under a large inclination angle of coal seam. And coal face and support bear small overlying strata pressure with a stable roof shell structure. Therefore, rib spalling is easily to be occurred with small inclination angle of coal seam leading to high stress at coal face in the mining process. On the other hand, with the continuously increase of inclination angle of coal seam, it is damaged to the related equipment (e.g., support) in working face. Therefore, under the premise of ensuring the stability of the support, the appropriate geotechnical condition of large inclination angle of coal seam is favorable to keep the

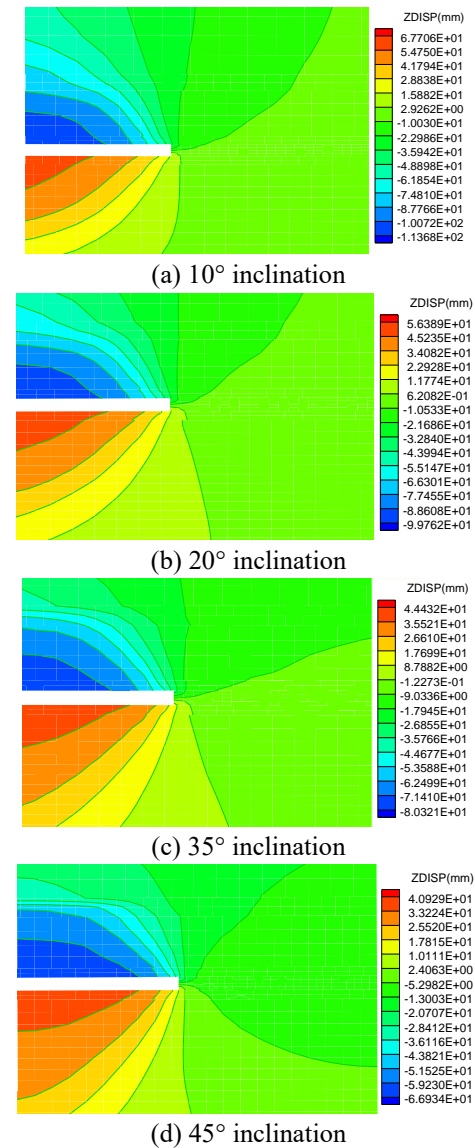


Fig. 12 Displacement nephogram of surrounding rock

safety of coal face-support-roof system.

Three influence factors of coal face (mining height, cohesion and inclination angle) are considered to analyze the stability of coal face-support-roof system. If the condition of coal face is poor or even rib spalling is occurred, it can accompany with the failure of support and the instability of roof structure.

#### 4. Conclusions

1) The mechanical model considering coal face-roof-support system in steeply inclined coal seam is established to obtain the overlying strata pressure. With the increase of support working resistance, overlying roof pressure applied on coal face can be reduced to improve the stability of coal face. The influence factors on the stability of coal face can be ranked as overlying strata pressure ( $P$ ) > mechanical parameters of coal body (e.g., cohesion ( $c$ ), internal friction angle ( $\phi$ )) > support strength ( $F$ ) > the support force of

protecting piece ( $F'$ ) > the false angle of working face ( $\theta$ ).

2) The stability coefficient of surface  $ade$  ( $K_1$ ) is always larger than the stability coefficient of surface  $abc$  ( $K_2$ ) with the same geotechnical condition, which indicates the weak surface  $ade$  more likely to be failure than weak surface  $abc$ . Therefore, the initial cracks are generated from the upper part of sliding body to the lower part of sliding body to form irregular pyramid coal block and finally causing the occurrence of rib spalling.

3) With the increase of mining height, the maximum stress and vertical displacement significantly increase, and the first weight distance increases as well to form a large space in goaf zone, while the peak stress point is constantly away from working face. On the other hand, the vertical stress at lower roof applied on support sharply decrease causing coal face bearing large pressure, which is prone to occur rib spalling.

4) The maximum displacement of surrounding rock in steeply inclined coal seam has a slight decrement with the increase of cohesion of coal body, which is beneficial to keep the stability of coal face-support-roof system. Moreover, the maximum stress and vertical displacement greatly decrease with the increase of inclination of coal seam, a space shell stable structure of rock layer is easier to be formed under a large inclination angle of coal seam contributing to the stability of coal face-support-roof system. However, with the continuously increase of inclination angle of coal seam, it is damaged to support stability

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## References

- Alejano, L.R., Ramirez-Oyanguren, P. and Taboada, J. (1999), "FDM predictive methodology for subsidence due to flat and inclined coal seam mining", *Int. J. Rock Mech. Min. Sci.*, **36**(4), 475-491. [https://doi.org/10.1016/S0148-9062\(99\)00022-4](https://doi.org/10.1016/S0148-9062(99)00022-4).
- Asadi, A., Shakhriar, K. and Goshtasbi, K. (2004), "Profiling function for surface subsidence prediction in mining inclined coal seams", *J. Min. Sci.*, **40**(2), 142-146. <https://doi.org/10.1023/B:JOMI.0000047856.91826.76>.
- Barton, N. and Choubey, V. (1978), "The shear strength of rock joints in theory and practice", *Rock Mech. Rock Eng.*, **10**(1-2), 1-54. <https://doi.org/10.1007/BF01261801>.
- Chris, R., David, C. and Jake B. (2019), "Highwall mining of thick, steeply dipping coal—A case study in geotechnical design and recovery optimization", *Int. J. Min. Sci. Technol.*, **29**(5), 777-780. <https://doi.org/10.1016/j.ijmst.2017.12.022>.
- Cheng, Z.B., Zhang, Y.N., Li, L.H. and Lv, H.Y. (2018), "Theoretical solution and analysis of the elastic modulus and foundation coefficient of coal-rock combination material", *Int. J. Mater. Sci. Res.*, **1**(1), 23-31. <https://doi.org/10.18689/ijmsr-1000104>.
- Cheng, Z., Yang, S., Li, L. and Zhang, L. (2019a), "Support working resistance determined on top-coal caving face based on coal-rock combined body", *Geomech. Eng.*, **19**(3), 255-268. <https://doi.org/10.12989/gae.2019.19.3.255>.
- Cheng, Z., Pan, W., Li, X. and Sun, W. (2019b), "Numerical simulation on strata behaviours of TCCWF influenced by coal-rock combined body", *Geomech. Eng.*, **19**(3), 269-282. <https://doi.org/10.12989/gae.2019.19.3.269>.
- Cheng, Z.B., Li, L.H. and Zhang, Y.N. (2020), "Laboratory investigation of the mechanical properties of coal-rock combined body", *B. Eng. Geol. Environ.*, **79**(4), 1947-1958. <https://doi.org/10.1007/s10064-019-01613-z>.
- Das, A.J., Mandal, P.K. and Bhattacharjee, R. (2017), "Evaluation of stability of underground workings for exploitation of an inclined coal seam by the ubiquitous joint model", *Int. J. Rock Mech. Min. Sci.*, **93**, 101-114. <https://doi.org/10.1016/j.ijrmms.2017.01.012>.
- Hu, S.X., Ma, L.Q., Guo, J.S. and Yang, P.J. (2018), "Support-surrounding rock relationship and top-coal movement laws in large dip angle fully-mechanized caving face", *Int. J. Min. Sci. Technol.*, **28**(3), 533-539. <https://doi.org/10.1016/j.ijmst.2017.10.001>.
- Jawed, M. and Sinha, R.K. (2018), "Design of rhombus coal pillars and support for Roadway Stability and mechanizing loading of face coal using SDLs in a steeply inclined thin coal seam—a technical feasibility study", *Arab. J. Geosci.*, **11**(15), 1-14. <https://doi.org/10.1007/s12517-018-3747-4>.
- Jaszczuk, M. and Pawlikowski, A. (2017), "A model of equilibrium conditions of roof rock mass giving consideration to the yielding capacity of powered supports", *Arch. Min. Sci.*, **62**(4), 689-704. <https://doi.org/10.1515/amsc-2017-0049>.
- Kong, D.Z., Cheng, Z.B. and Zheng, S.S. (2019), "Study on the failure mechanism and stability control measures in a large-cutting-height coal mining face with a deep-buried seam", *B. Eng. Geol. Environ.*, **78**(8), 6143-6157. <https://doi.org/10.1007/s10064-019-01523-0>.
- Li, X.M., Wang, Z.H. and Zhang, J.W. (2017), "Stability of roof structure and its control in steeply inclined coal seams", *Int. J. Min. Sci. Technol.*, **27**(2), 359-364. <https://doi.org/10.1016/j.ijmst.2017.01.018>.
- Liu, F., Guo, Z., Lv, H. and Cheng, Z. (2018), "Test and analysis of blast wave in mortar test block", *Int. J. Rock Mech. Min. Sci.*, **108**, 80-85. <https://doi.org/10.1016/j.ijrmms.2018.06.003>.
- Liu, J., Chen, Shan, L., Wang, H.J., Li, Y.C. and Geng, X.W. (2015), "The migration law of overlay rock and coal in deeply inclined coal seam with fully mechanized top coal caving", *J. Environ. Biol.*, **36**(4), 821-827.
- Liu, K.Z. (2017), "Research on the Stability of Coal Wall on Large Mining Height Longwall Face in Steeply Inclined Coal Seams and Its Application", Ph.D. Dissertation, Xi'an University of Science and Technology, Xi'an, China.
- Liu, X. and Cheng, Z. (2019), "Changes in subsidence-field surface movement in shallow-seam coal mining", *J. S. Afr. Inst. Min. Metall.*, **119**(2), 201-206. <http://doi.org/10.17159/2411-9717/2019/v119n2a12>.
- Liu, X., Cheng, Z. and Dai, J. (2020), "Performance analysis of soft roadway surrounding rock in Yushujing Coal Mine", *Geotech. Geol. Eng.*, **38**, 497-505. <https://doi.org/10.1007/s10706-019-01040-7>.
- Lou, J.F., Gao, F.Q., Yang, J.H., Ren, Y.F., Li, J.Z., Wang, X.Q. and Yang, L. (2021), "Characteristics of evolution of mining-induced stress field in the longwall panel: Insights from

- physical modeling”, *Int. J. Coal Sci. Technol.*, 1-18.  
<https://doi.org/10.1007/s40789-020-00390-5>.
- Lv, H., Tang, Y., Zhang, L., Cheng, Z. and Zhang, Y. (2019), “Analysis for mechanical characteristics and failure models of coal specimens with non-penetrating single crack”, *Geomech. Eng.*, **17**(4), 355-365.  
<https://doi.org/10.12989/gae.2019.17.4.355>.
- Ma, F.H., Sun, L. and Li, D. (2011), “Numerical simulation analysis of covering rock strata as mining steep-inclined coal seam under fault movement”, *T. Nonferr. Metal. Soc.*, **21**, s556-s561. [https://doi.org/10.1016/S1003-6326\(12\)61640-9](https://doi.org/10.1016/S1003-6326(12)61640-9).
- Meng, C. (2013), “Instability mechanism of the coal wall in coalface with large dip angle and Great Ming Height and its control”, Ph.D. Dissertation, China University of Mining and Technology, Xuzhou, China.
- Mandal, P.K., Das, A.J., Misra, P.K. and Roy, L.B. (2016), “Design of extraction methodology for semi-mechanised depillaring of an inclined coal seam”, *Proceedings of the 6th Asian Mining Congress*, Kolkata, India, February.
- Ran, J.Q., Passaris, E.K.S. and Mottahed, P. (1994), “Shear sliding failure of the jointed roof in laminated rock mass”, *Rock Mech. Rock Eng.*, **27**(4), 235-251.  
<https://doi.org/10.1007/BF01020201>.
- Ren, F.H., Lai, X.P. and Cai, M.F. (2008), “Dynamic destabilization analysis based on AE experiment of deep-seated, steep-inclined and extra-thick coal seam”, *Int. J. Min. Met. Mater.*, **15**(3), 215-219.  
[https://doi.org/10.1016/S1005-8850\(08\)60041-9](https://doi.org/10.1016/S1005-8850(08)60041-9).
- Sheorey, P.R. (1997), *Empirical Rock Failure Criteria*, Balkema, Rotterdam, The Netherlands.
- Tien, D.L. and Xuan, N.B. (2020), “Effect of key parameters on top coal first caving and roof first weighting in longwall top coal caving: A case study”, *Int. J. Geomech.*, **20**(5), 04020037.  
[https://doi.org/10.1061/\(ASCE\)GM.1943-5622.0001667](https://doi.org/10.1061/(ASCE)GM.1943-5622.0001667).
- Tu, H.S., Tu, S.H., Yuan, Y., Wang, F.T. and Bai, Q.S. (2015), “Present situation of fully mechanized mining technology for steeply inclined coal seams in China”, *Arab. J. Geosci.*, **8**(7), 4485-4494. <https://doi.org/10.1007/s12517-014-1546-0>.
- Tu, H.S., Tu, S.H., Zhang, C., Zhang, L. and Zhang, X.G. (2017), “Characteristics of the roof behaviors and mine pressure manifestations during the mining of steep coal seam”, *Arch. Min. Sci.*, **62**(4), 871-891.  
<https://doi.org/10.1515/amsc-2017-0060>.
- Wang, H.W., Wu, Y.P., Xie, P.S., Luo, S.H. and Liu, K.Z. (2018), “Coal rib stability effect of mining-thickness with large mining height of working face in steeply inclined seams”, *J. Min. Safety Eng.*, **35**(1), 64-70. <https://doi.org/10.13545/j.jmse.2018.01.009>.
- Wang, J.A. and Jiao, J.L. (2016), “Criteria of support stability in mining of steeply inclined thick coal seam”, *Int. J. Rock Mech. Min. Sci.*, **82**, 22-35.  
<https://doi.org/10.1016/j.ijrmms.2015.11.008>.
- Wang, J.C., Wang, Z.H. and Li, Y. (2020a), “Longwall top coal caving mechanisms in the fractured thick coal seam”, *Int. J. Geomech.*, **20**(8), 06020017.  
[https://doi.org/10.1061/\(ASCE\)GM.1943-5622.0001722](https://doi.org/10.1061/(ASCE)GM.1943-5622.0001722).
- Wang, H.W., Wu, Y.P., Liu, M.F., Jiao, J.Q. and Luo, S.H. (2020b), “Roof-breaking mechanism and stress-evolution characteristics in partial backfill mining of steeply inclined seams”, *Geomat. Nat. Hazard Risk*, **11**(1), 2006-2035.  
<https://doi.org/10.1080/19475705.2020.1823491>.
- Wu, Y.P., Lang, D. and Xie, P.S. (2016), “Mechanism of disaster due to rib spalling at fully-mechanized top coal caving face in soft steeply dipping seam”, *J. China Coal Soc.*, **41**(8), 1878-1884. <https://doi.org/10.13225/j.jccs.2015.1547>.
- Xia, K., Chen, C., Zhou, Y., Liu, X., Zheng, Y. and Pan, Y. (2019), “Catastrophe instability mechanism of the pillar-roof system in gypsum mines due to the influence of relative humidity”, *Int. J. Geomech.*, **19**(4).  
[https://doi.org/10.1061/\(ASCE\)GM.1943-5622.0001378](https://doi.org/10.1061/(ASCE)GM.1943-5622.0001378).
- Yao, Q.L., Li, X.H., Sun, B.Y., Ju, M.H., Chen, T., Zhou, J., Liang, S. and Qu, Q.D. (2017), “Numerical investigation of the effects of coal seam dip angle on coal face stability”, *Int. J. Rock Mech. Min. Sci.*, **100**, 298-309.  
<https://doi.org/10.1016/j.ijrmms.2017.10.002>.
- Yun, D.F., Ren, F.T., Wu, Y.P., Lei, Q. and Gu, B. (2018), “Pseudo-inclined layout of fully-mechanized mining face with large mining height in large dip soft seam”, *Safety Coal Mines*, **49**(11), 145-149. <https://doi.org/10.13347/j.mkaq.2018.11.035>.
- Zorychta, A. and Burtan, Z. (2008), “Conditions and future directions for technological developments in the coal mining sector in Poland”, *Gospod. Surowcami Min.*, **24**(1), 53-70.
- Zhang, H. and Wu, Y.P. (2019), “Coal wall caving mechanism of longwall large mining height stope in steeply dipping coal seams”, *J. Min. Safety Eng.*, **36**(2), 331-337.  
<https://doi.org/10.13545/j.jmse.2019.02.015>.
- Zhang, Y.N., Cheng, Z.B. and Lv, H.Y. (2019), “Study on failure and subsidence law of frozen soil layer in coal mine influenced by physical conditions”, *Geomech. Eng.*, **18**(1), 97-109.  
<https://doi.org/10.12989/gae.2019.18.1.097>.
- Zhao, S., Zhang, D.M. and Huang, H.W. (2020), “Deep learning-based image instance segmentation for moisture marks of shield tunnel lining”, *Tunn. Undergr. Sp. Tech.*, **95**, 1-11.  
<https://doi.org/10.1016/j.tust.2019.103156>.
- Zhao, S., Shadabfar, M., Zhang, D., Chen, J. and Huang, H. (2021), “Deep learning-based classification and instance segmentation of leakage-area and scaling images of shield tunnel linings. Struct”, *Control. Health Monit.*, e2732.  
<https://doi.org/10.1002/stc.2732>.

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