Fracture Mechanism of Hard Main Roof and Determining the Width of Coal Pillars when Extracting Flat-lying Coal Seams

Quang Phuc LE[1], Van Chi DAO[2], Phi Hung NGUYEN[3], Thai-Tien Dung VU[4]

[1] Faculty of Mining, Hanoi University of Mining and Geology, 18 Vien Street, Hanoi 100000, Vietnam; email: lequangphuc@humg.edu.vn
[2] Faculty of Mining, Hanoi University of Mining and Geology, 18 Vien Street, Hanoi 100000, Vietnam; email: daovanchi@humg.edu.vn
[3] Faculty of Mining, Hanoi University of Mining and Geology, 18 Vien Street, Hanoi 100000, Vietnam; email: nguyenphihung@humg.edu.vn
[4] Faculty of Mining, Hanoi University of Mining and Geology, 18 Vien Street, Hanoi 100000, Vietnam; email: vuthaitiendung@humg.edu.vn

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Abstract

In underground coal mining, the stability of roadways and gob-side entry depends on the coal pillar width. An unreasonable width of the coal pillar will cause the roadway to be in a dangerous zone of influence of the abutment pressure, leading to severe roadway deformation. This paper studies the fracture mechanism of the hard main roof and reasonable coal pillar width to protect the stability of gob-side entry driving. The research results show that when mining a coal seam under a hard main roof, the console of the main roof on the edge of the coal seam has the form of hinge structure. The great load of the roof layers and the rotation of the console are the main causes leading to the variation of the stress field in the coal seam. According to the development law of the stress field, after the main roof completes the collapse process, the peak of the maximum stress will move deep into the solid coal seam, and on the edge of the coal seam it will form a low-stress zone. Research results from the case of Seam #11 of Khe Cham coal mine, Vietnam show that the gob-side entry will be well stabilized when the narrow coal pillar between it and the boundary of the gob is 4–5 m.

Keywords: *failure mechanism, coal pillar, stress distribution, roadway deformation, retained roadway, hard main roof, gob-side entry*

Introduction

In Vietnam, coal is mainly mined in the Quang Ninh coal basin (Figure 1). According to statistics, the Quang Ninh coal basin ensures nearly 90% of Vietnam's state-owned coal production. The main technology of underground coal mining in Vietnam is the longwall mining system. The panels are prepared with two roadways and a 20–30 m wide coal pillar between them. In particular, the coal pillar has the role to protect and maintain of the retained of one of the two roadways for the next panels. As a result, coal losses in the coal pillars are large, accounting for about 20–30% of the coal reserves of the mined panel (Vietnam, 2016). In particular, the loss of coal in the pillars will increase when exploiting coal seams with hard main roof and at great depths. Currently, underground coal mining activities in Vietnam are carried out at depths of greater than 350–400 m. Statistical results show that underground coal mines in Vietnam contain about 30–85% of coal seams with hard roof (Zubov & Le, 2022). Therefore, this is a challenge for coal pillar design and loss of coal reduction in underground coal mines in Vietnam.

The cases that occur when mining coal seams with hard main roofs, it affects roadway stability issues, such as heaving floors, collapsing of ribs, etc., which occur frequently. It increases the risk of occupational accidents and is the cause of increased production costs and reduced labor productivity. This finally affects the competitiveness of mining companies. Most of these problems occur because the coal pillar is not wide enough, and the roadway is located in the high-stress region of the abutment pressure. At that time, they will be directly affected by the static and dynamic loads of the formation and collapse of the main roof console in the gob. When the main roof breaks, it will rotate and collapse on the gob. And on the edge of the coal pillar, the immediate roof was crushed, and the effect of high abutment pressure caused the pillar to compact and collapse. This is the cause of the severe deformation of the roadway, which is protected by the coal pillar. The long console formation of the hard main roof above the pillar, and the overloaded strata exert great abutment pressure, causing the coal seam to be compressed into the roadway. The deformation of the roadway sometimes leads to inaccessibility of the working face, making it difficult to repair, transport and ventilate. Especially the work of maintaining stability at the intersection between the roadway and the working face. In addition, shear forces along the fracture line of the main roof can extend to the site of the roadway, causing serious rock bust problems.

The balance between the requirement of roadway stability when mining the coal seam under the hard main roof and reducing the loss of coal in the pillar is a difficult problem. The articles (Wang et.al., 2019, He et.al., 2018, Qi et.al., 2019, Ma et.al., 2018) have presented the no-pillar exploitation method with the technique of directional roof cutting. They proved that the no-pillar mining technique with automatically formed gob-side entry retaining is feasible for longwall mining and achieves the goal of safe and efficient mining. However, the high cost to implement and a large amount of work necessary to be done at the intersection between the roadway and the working face. The presence of a hard-to-collapse main roof poses a high risk of rock bust incidents. Dynamic and static loads of the curving process, rotatory, and sagging of the main roof console along the line behind the first working face are known to cause accident risks in this solution. In addition, the gas pressure caused by the massive collapse of the main roof in the gob has a serious effect on the labor safety and stability

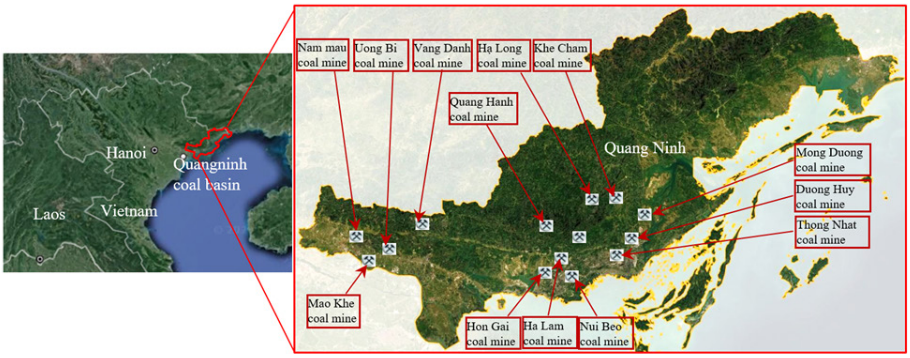


Fig. 1. Location of Quang Ninh coal basin in North Vietnam

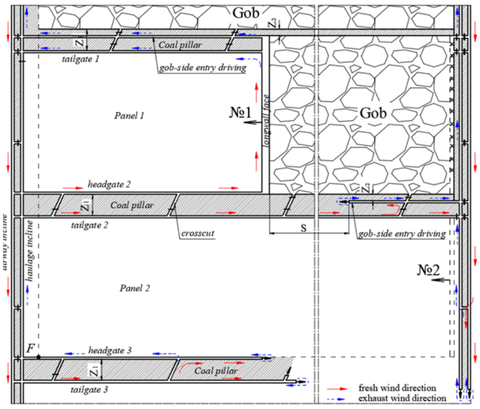


Fig. 2. Longwall mining system, in which coal pillar will be extracted together with the adjacent longwall face

of the roadway. In the second option, methods of constructing artificial pillars to replace coal pillars have also been studied (Zhao et.al., 2019, Wu et.al., 2019). In particular, artificial pillars are built of wood, stone, concrete, or other materials. This method has proven to be advantageous in reducing coal loss in the pillars. However, the excessive consumption of insert material and high technical requirements put limits on the popularity of this method. Therefore, it is necessary to search for a more efficient and economical method to improve the sustainability and safety of mining (Zhen et.al., 2019).

In study (Zubov & Le, 2022) has shown that the road is guaranteed to be stable when in a solid coal seam, or the low-stress zone at the edge of the coal seam. That is, a wide coal pillar must be designed to ensure the stability of the retained roadway. Then a new gob-side entry done along the gob (after the fracture of the main roofs) would be optimal. It will ensure that the coal pillar will be extracted together with the adjacent longwall face (Figure 2). The tailgate is also guaranteed to be stable because of the wide coal pillar that protects it. After the complete fracture of the main roof, the gob-side entry is safer when done in the low-stress zone under the console.

When applying the solution in Figure 2, the problem of reducing coal loss in the coal pillar has been improved. However, the task posed in the coal seam mining process has a hard main roof to predict the stress-deformation state of the surrounding rock and determine the width of the coal pillar. In Figure 2, the width of the coal pillars (Z1, Z2) will determine the stress-deformation state of the surrounding rock as well as the stability of the roadway (Zhang et.al., 2018, Liang et.al, 2018) . The decrease in strength of the coal pillar is considered as the reduction ratio between the width and the height of the pillar (Mark et.al, 2010), and the small coal pillar will put the roadway in a stress-releasing state, while the wide pillar will put it at high-stress state (Li et.al., 2015). Shabanimashcool and Li (Shabanimashcool & Li, 2013) found that the stress in the wide coal pillar would fluctuate up and down in process mining at the adjacent longwall face. And it also depends on the periodic collapse of the roof rock in the gob. The conclusions in the study of Wang et al. (Wang et.al, 2013) suggest that the risk of rock burst for the retained roadbed will increase significantly when there is no elastic zone in the coal pillar. Bai et al. (Bai et.al., 2015) used the law of stress development to analyze the roof-sagging mechanism of the retained roadway. They have determined that the width of a coal pillar less than 5 m or more than 22 m will ensure better roadway stability than a coal pillar of medium width. Mohammadi et al. (Mohammadi et.al., 2016) demonstrated that the expansion of the plastic failure zone in the rock surrounding the retained roadway occurred when the width of the coal pillar was reduced from 30 m to 10 m based on computational geometry. Shen et al. (Shen et.al., 2018) concluded that the ratio of the width to the height of the coal pillar also plays a significant role in the stability of the pillar. When there is a delamination plane in the roof rock layer, the roof of the retained roadway will easily slip when the ratio between the width and height of the coal pillar is less than 8. Many other important studies have been done to study the stress distribution in the surrounding rock and the solution to stabilize the roadway next to the narrow coal pillar (Shen et.al., 2018, Jiang et.al., 2017, Zhang et.al., 2018, Yu et.al., 2020, Zubov et.al., 2023, Le et.al., 2022, Le et.al., 2020).

When mining coal pillars on the same line as the adjacent longwall face, the ventilation task has posed a requirement to excavate a gob-side entry after completing the collapse of the main roof in the gob. Hao et al. (Hao et.al., 2020) used an equiv-

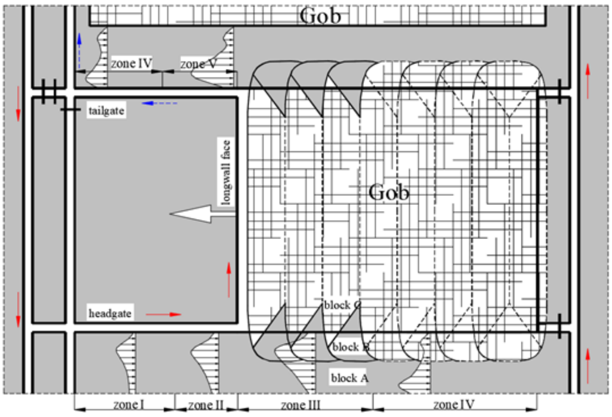


Fig. 3. Law of main roof collapse and characteristics of stress-deformation changes of the surrounding rock

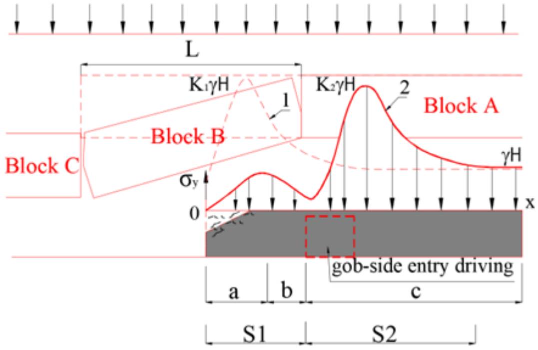


Fig. 4. Mechanical model of the "hanging-collapse" structure of the main roof and the stress distribution on the edge of coal seam

alent material model to determine the location of the gob-side entry. They assume that the gob-side entry will be stable when it is excavated in the low stress zone on the gob side. That is, the distance between gob-side entry and gob is not more than 5 m, and this result is successfully applied at Shengyuan coal mine 4#, China. Yang Yu et al. (Yu et.al., 2020) also evaluated that the fracture, rotation, and sagging processes of the main roof negatively affected the stability of the gob-side entry. With numerical simulation, they determined the reasonable distance between the gob-side entry and the gob to be 6 m. Li et al. (Li et.al., 2022) performed field investigation, theoretical calculations, and numerical simulation for a specific case in the Xinji coal mine, China. They have determined that a reasonable distance between the gob-side entry and the gob is 5 m. When the width of the pillar is reduced to 3–4 m, the coal pillar is destroyed, and when it is increased to 8 m, the gob-side entry is in the region of concentrated stress, leading to it being unstable. These studies are useful in common applications of retained roadway protection and gob-side entry. However, there is a lack of studies on the fracture mechanism of the hard main roof and the rationality of the coal pillar width. Therefore, there is a need for additional analysis and experimental studies on this issue.

In this paper, the theoretical analysis method for the formation of the stress-strain state of the rock mass has been performed. After that, an experimental study on the equivalent material model and numerical model was applied to evaluate the fracture mechanism of the hard main roof and determine the coal pillar width.

Research Methods

In this paper, the method of theoretical analysis of the fracture mechanism of the hard main roof is used. This is the basis for evaluating the collapse rule of the main roof in the gob, thereby leading to the principle of determining the position of gob-side entry driving. Then, a physical model and a computer program are used to simulate the mining of the panels, the stress distribution in the surrounding rock, and the deformation of the gob-side entry. In the case study, we use typical geological conditions of coal seam #11 of Khe Cham coal mine in Quang Ninh coal basin, where the thickness of the hard main roof is 10–20m.

Results and discussion

Theoretical analysis of the fracture mechanism of the main roof and the formation of the stress-strain state of the rock mass on the edge of the coal seam:

The studies (Shen et.al., 2018, Wang et.al., 2020) all show that the rule of roof collapse is cyclical, as shown in Figure 3. On the coal seam around the gob, the formation of the console beam of the roof rock depends on many factors, such as the collapse step of the main roof, the slope angle of the coal seam, the thickness of the coal seam, and the immediate roof rock layer. Figure 3 shows 5 main stages of the stress-strain state, including: Zone I – initial stress zone; Zones II and V – zones of influence of static pressure, forming in front of the working face; Zone III – zone of influence of both static and dynamic pressure, forming behind the working face; and Zone IV – stable lateral stress zone, formed after the collapse of the main roof in the gob.

Among these, zones II and V are dangerous mine pressure zones with a high probability of rock bursts. Zone 3 – right behind the working face, is the place where the high stress concentration is due to the formation of the console of the main roof and the intense displacement of the surrounding

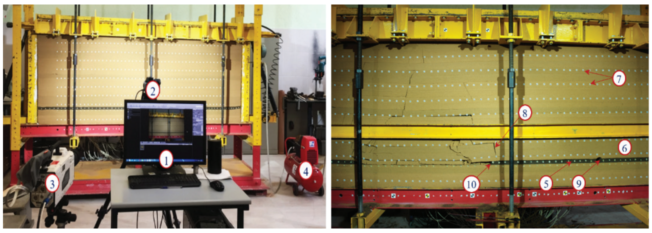
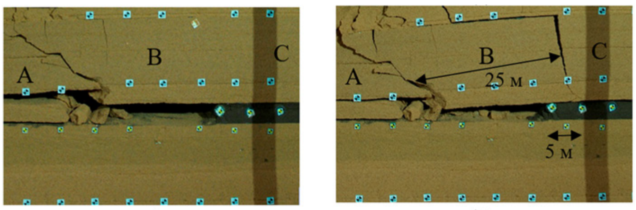


Fig. 5. Law of main roof collapse and characteristics of stress-deformation changes of the surrounding rock

Tab. 1. Physical and mechanical characteristics of rocks in the field and on models (Le & Dao, 2023, Le, 2021)

Type rock	Tensile strength (MPa)	Cohesion (MPa)	Friction angle (degree)	Uniaxial compressive strength (MPa)		Density (kg/m³)	
				Prototype	On the model	Prototype	On the model
Sandstone	1,6	3.22	34.2	83,2	0,64	2785	1853
Mudstone	0,9	2.14	30.1	50,6	0,39	2552	1700
Siltstone	1,2	1.83	26.4	16,5	0,21	2253	1500
Coal	0,4	1.54	19.3	14,5	0,21	1454	967



a) b)

Fig. 6. Fracture mechanism of hard main roof: a – the formation and sagging displacement of the main roof; b – collapse of the main roof

rock. The loading of the rock layers to the console of the roof during this period is enhanced over time, and at the same time, the collapse of the edge of the coal pillar occurs on the boundary of the gob. The result of this process is the sagging, rotation, and eventually fracture of the console of the main roof at the boundary of the gob. Before the fracture of the console occurs, the peak of the maximum stress is 2–5 m from the gob. This is an area of increased stress and possible rock bursts. After the console breaks, the load of the roof rock layers is transferred to the collapsed rock in the gob, and the stress on the edge of the coal seam is reduced. The peak of the maximum stress moves deep into the coal seam. At the end of the collapse of the roof rock, the displacement of the surrounding rock stops, and the stress distribution on the edge of the coal seam reaches a new steady state (as in zone IV in Figure 3).

Thus, to ensure the stability of the retained roadway, it should be outside the danger zone of abutment pressure. Surveying the displacement of the main roof shows that, when the roadway is outside the affected area of increased abutment pressure, its stability does not depend on the reception of protection solutions. Therefore, this can be the main factor in choosing the location of the roadway and the solutions to protect it in the mine design.

In the case of coal seam mining with a hard main roof, the sagging, rotation, and fracture of the roof rock layers will have a great influence on the retained roadway. Therefore, the location of the retained roadway should be chosen outside the abutment pressure zone. If the coal pillar is not width enough, the static and dynamic loads of the fracture of the roof rock will break the supporting structure and lead to deformation of the roadway.

As analyzed, in the process of coal pillar mining, gob-side entry is necessary and excavated according to ventilation requirements. However, if the movement of the roof rock has not ended, then excavating the gob-side entry will be detrimental, and there is a potential risk of a rock burst. Because the edge of the coal pillar has not been completely unloaded from the main roof, it will be difficult for the gob-side entry to be stable. Therefore, it is necessary to ensure that the gob-side entry is performed at a safe time behind the previous longwall face during coal seam mining. According to statistics, in the current underground coal mines in Vietnam, the working surface has an average moving speed of 25–30 m/month. Corresponding to this, the distance from the previous working face to the gob-side entry (parameter S in Figure 2) is about 200 m to 240 m.

Although it is known that the collapse process of the main roof is characterized by the geotechnical condition and the length of the console. However, with the cyclical collapse of the main roof (Figure 3), the suitable location for excavating the gob-side entry is in the reduced stress zone under the hard main roof at the gob side (under block A, Figure 4). Because, in this location, the hard main roof acts as a stable beam to pick up the load of the rock layers above and transfer the pressure deep into the coal seam. At the same time, it prevents the transfer of loads from the roof rocks to the edge of the coal seam. And the load acting on the support frame of the roadway will be determined only by the immediate roof. Therefore, the gob-side entry excavated at this location is advantageous in that it remains stable despite the small amount of displacement of the surrounding rock. The distance from the gob-side entry to the gob is not less than the distance from the crack of the main roof to the gob. According to experience, the fracture of the main roof is located on the coal seam at a distance of 4.0–5.0 m from the gob.

It should be noted that, under the collapse rule of the main roof (Figure 3), the console can hang in the gob for a relatively long time. The mechanical model of its formation and collapse is shown in Figure 4.

In Figure 4, before and after the main roof is broken, the stress distribution is shown by curves 1 and 2. The internal

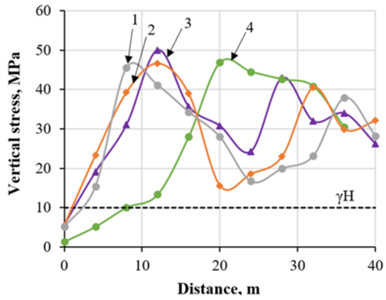


Fig. 7. Stress distribution on the edge of coal seam: 1 – before the collapse of the main roof with a console of 10 m; 2 – before collapsing main roof with a console of 15 m; 3 – before collapsing main roof with a console of 20 m; 4 – after the main roof collapse

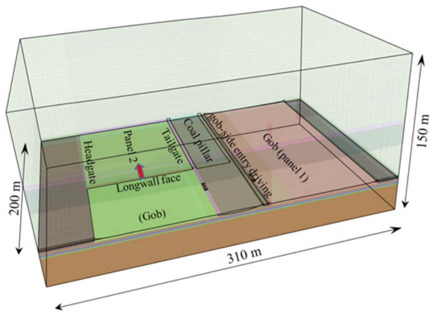


Fig. 8. Configuration of longwall model using FLAC3D

force of the coal seam on the edge is formed by three corresponding zones to support the load of the roof rock layers: a plastic deformation zone (a), an elastic region (b), and an initial stress region (c). Over time, and with the increased load from the roof rock layers, in the "a" area of the coal seam, a landslide triangle is formed. This triangular block has the greatest effect on the stability of the surrounding rock of the gob-side entry. Under the influence of stress, the coal seam and immediate roof connect with adjacent blocks to form a hinged structure. This structure is relatively stable because it is horizontal and subject to the pushing action of the adjacent rock mass. The junction between the elastic zone "b" and the initial stress zone "c" exhibits sufficient strength for the coal seam not to deform, and thus the main roof will rotate and crack at this section.

When the main roof is cracked, the pressure is transmitted to the edge of the coal seam and is divided into two zones: Zone S1 has a console head resting on the edge of the coal seam, an external stress field (reduced stress zone); Zone S2 is located under the hard main roof, an internal stress field (stress increase zone). The abutment pressure in the "external stress field" arises from the movement of the console at fracture.

The basic rule for determining the width of coal pillars located between the gob-side entry and the gob is to ensure the gob-side entry is in the reduced stress zone of the coal seam. That is, it should be excavated in the "external stress field" and the reduced stress zone of the "internal stress field", which provide a favorable stress environment for the stability of the surrounding rock. This is the basic element for gob-side entry stability, reducing repair costs. Then, the width of the coal pillar will correspond to the width of the "external stress field", where the maximum reaction of the coal seam will appear to support the roof rock. At the same time, the outer console head resting on the collapsed rock in the gob will unload most of the load of the roof rock layers.

Case studies

Research using equivalent materials model

With the task of studying the fracture mechanism of the main roof and the stress distribution on the coal seam, an equivalent material model was built. The model has dimensions of 2800 mm in length, 200 mm in width, and 1000 mm in height. The input data to make the model corresponds to the coal seam #11 mining conditions of the Khe Cham coal mine. The coal seam has a thickness of 3 m, a slope angle of 9 degrees, and is mined at a depth of 400 m. The coal seam has a small slope angle, so in this research model, the rock layers and the coal seam are built in the horizontal direction (Figure 5) (Zubov & Le, 2022). The characteristics of the similarity ratio between the model and the field are determined according to Equation 1.

$$\begin{cases} C_L = L_m / L_p = 1/100 \\ C_\mu = \mu_m / \mu_p = 1 \\ C_\rho = \rho_m / \rho_p = 1/1.5 \\ C_\sigma = \sigma_m / \sigma_p = 1/130 \end{cases} \quad (1)$$

here L_p, μ_p, ρ_p, and σ_p, respectively, geometric dimensions, Poisson's ratio, density, and uniaxial compressive strength of rock layers in the field; L_m, μ_m, ρ_m, и σ_m, respectively, geometric dimensions, Poisson's ratio, density, and uniaxial compressive strength of rock layers in the model.

Figure 5 depicts the research model and related tools. The physical and mechanical parameters of rock in the field and in the model are shown in Table 1. The results of the model study are shown in Figure 6.

Figure 6 shows the visual observation of the main roof's fracture mechanism on the model. The results show that when exploiting a coal seam with a hard main roof, a cantilever beam with a large length (about 25 m) is created on the edge of the coal seam. The crack location of the main roof is above the coal seam at a distance of 5 m to the gob.

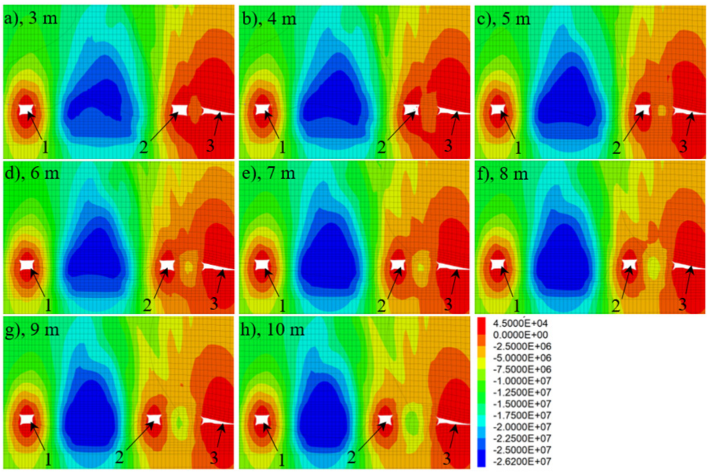


Fig. 9. Vertical stress distribution in the surrounding rock of gob-side entry driving with different narrow pillar widths: 1 – Tailgate; 2 – gob-side entry driving; 3 - gob.

The stress data distributed on the edge of the coal seam is obtained from stress sensors installed on the model. The stress sensors are connected to the computer and stored and processed in real-time. The results of stress distribution on the edge of the coal seam are shown in Figure 7.

Figure 7 shows that, when the console of the main roof has not collapsed, even in cases of different console lengths, the peak of the maximum stress is distributed over a distance of 8–11 m from the boundary of the gob. For example, when the console is 10 m long, the maximum stress is 45.5 MPA at a location 8 m from the boundary of the gob. When the console of the main roof is 15 m or 20 m, the peak of the maximum stress increases to 48.8 MPA, and the distance to the gob is 11 m. It can be observed that, in most cases when the console has not collapsed, the high-stress area is distributed on the edge of the coal pillar at a distance of 8–11 m. However, after the collapse of the console, the peak of the maximum stress moved deep into the coal seam and stopped at a distance of 20 m from the boundary of the gob. At this time, within 10 m on the edge of the coal seam, the stress decreases and is lower than the initial stress.

Thus, from the simulation results, it can be concluded that the sagging and rotation of the console of the main roof have created a strong compressive pressure at the edge of the coal seam and gradually formed many cracks. When the console beam's rotation is maximized, and then it collapses, one head of it rests on the collapsed rock in the gob and unloads almost the entire load of the roof rock layers. As a result, there will be very little stress on the edge of the coal seam, where the main console breaks, and this location is good for the excavation of a gob-side entry. As shown in Figure 7, a reasonable location to excavate a gob-side entry is within a distance of 4–8 m from the boundary of the gob.

Research with numerical model

A numerical simulation is constructed based on the computer program FLAC3D to study the stability of retained roadway and stress distribution when coal pillar width varies (Itasca, 2019). FLAC3D is a computer program for numerical modelling of continuum media to investigate the stress-strain state of rock mass. FLAC3D uses an explicit finite volume method to represent complex behaviors of rock mass, experiencing large displacements and deformations and considering non-linear material behavior. The program is capable of modelling material failure over large areas.

The model has a length of 310 m, a width of 200 m, and a height of 150 m, as shown in Figure 8. This model size was determined through a trial-and-error process considering the size and density of finite volume. Panels 1 and Panel 2 and associated roadways are included in the model. The roadway's and gob-side entry driving width and height are 4.0 and 3.0 m, respectively. With the research results of [2], under similar conditions at Khe Cham coal mine, the tailgate is guaranteed to be stable when the distance between it and the gob is over 40 m. In this study, numerical modeling is used to determine the location of the gob-side entry. Thus, the distance between the retained roadway and the gob is fixed at 40 m. The distance between the gob-side entry and the gob built in the cases is 3, 4, 5, 6, 7, 8, 9, and 10 m (narrow pillar), respectively. The overburden stress is 7.0 MPa applied to the top boundary. The specific gravity of rocks is 2500 kg/m^3 with a gravity of 10 m/s^2 (Le et.al., 2020). The horizontal boundaries of model are fixed in X direction while the bottom boundary is fixed in Y direction. The Mohr-Coulomb constitutive law is used for materials. The physical-mechanical properties of coal and rocks used in the model are based in Table 1. The results are shown in Figure 9, and 10.

Stress distribution characteristic analysis:

The vertical stress distribution in narrow coal pillars between the gob and gob-side entries (Figures 9, 10) shows that, when the narrow pillar width is from 3 to 9 m, the vertical stress in the narrow coal pillar is less than the initial stress (γH). Especially when the pillar width is 3 m, the maximum stress value is only about 3.1 MPA. Figure 9a shows that the coal pillar seems to have a plastic failure because the stress concentration value in the coal pillar is larger than the value of the critical compressive strength of the coal. As a result, the coal pillar loses its bearing capacity and does not guarantee the separation between the gob-side entry and gob. When the narrow pillar width is 10 m, the maximum stress value is about 10.6 MPA (the stress concentration factor is 1.06). Thus, the maximum stress value in the narrow pillar increases in proportion to the increase in the width of the pillar. This is

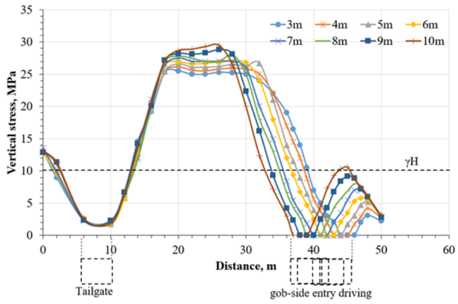


Fig. 10. Distribution of vertical stress with different narrow pillar widths

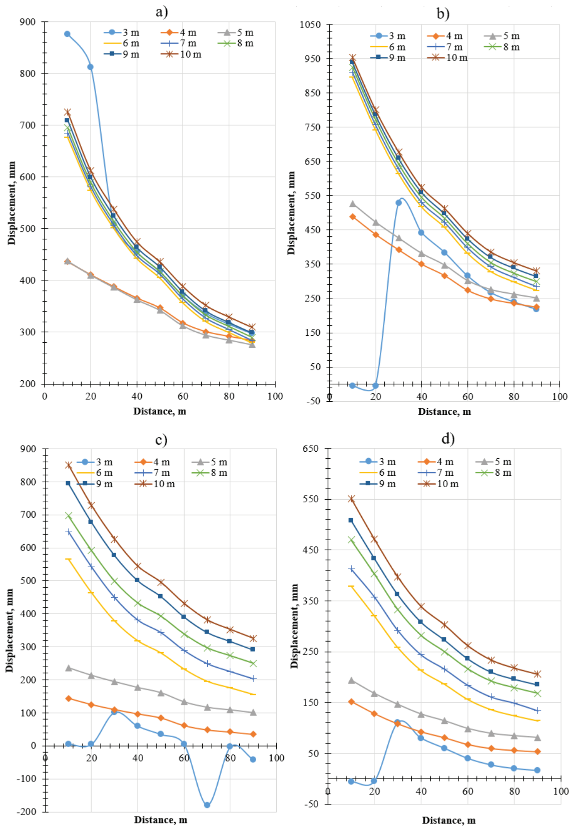


Fig. 11. Convergence of the roadway different narrow pillar width: a – roof sagging; b – displacement of solid coal side; c – floor heave; d – displacement of narrow coal pillar side.

similar to the theoretical analysis in Figure 4, where the edge of the coal seam adjacent to the gob is broken by the main roof's fracture and collapse mechanism.

When the width of the coal pillar is 4 m or 5 m, the maximum vertical stress in the coal pillar is 4.2 MPA and 5.2 MPA, respectively. The stress concentration zone in the coal pillar is gradually being formed. However, both of these cases give a stress value less than the initial stress, i.e., 10.0 MPA. As the width of the coal pillar increases to 6 m, 7 m, 8 m, and 9 m, the vertical stress in the coal pillar is essentially increasing to equal the initial stress. Its maximum vertical stress values are 5.6 MPA, 7.0 and 8.1 MPA, and 9.2 MPA, respectively. Observations in Figures 9d, 9e, 9f, and 9g show that the area of stress concentration is gradually increasing in the core of the coal pillar. This can be explained by the stress superposition when excavating the gob-side entry and the residual stress caused by the mining operation on the previous longwall face. With increasing the pillar width, the stress superposition effects will be more obvious, causing the stress concentration value to increase gradually. An increased stress concentration would be a bad sign for the stability of the gob-side entry. Because then the coal pillar will receive more load from the roof rock layers, the possibility of a rock burst increases. When the width of the coal pillar is 10 m, the vertical stress in the coal pillar is 10.6 MPA and exceeds the initial stress. The area of concentration of stress in the coal pillar has been clearly seen (Figure 9h). The coal pillar seems to be intact. But it should be noted that a high-stress concentration in a coal pillar is not good. It can cause rock explosion risks and harder support for gob-side entry.

Deformation characteristic analysis of gob-side entry:

Different stress environments in a narrow coal pillar can lead to different displacements. In this case study, the section performing deformation control of the gob-side entry was performed in front of working face #2 (at a distance of 20 m). Analyzing the convergence of the gob-side entry, the displacement values gradually increased, corresponding to the increase in the width of the narrow coal pillar (Figure 11). However, the displacement analysis results show that, with a width of 3 m of the narrow pillar, the gob-side entry is completely deformed at a distance of 20 m in front of working face #2. Therefore, a coal pillar with a width of 3 m is not guaranteed to stabilize the roadway and separate the gob-side entry and gob. When the width of the coal pillar is 4 to 5 m, the convergence of the gob-side entry is much smaller than in the other cases. Specifically, with the widths of the pillars of 4 m and 5 m, the roof convergence is 430 m, respectively. But, with a pillar width of 6 m to 10 m, the corresponding roof convergence increases from 676 mm to 725 mm, respectively. The convergence of the left rib of the gob-side entry is 489 mm and 528 mm, respectively, for the widths of the coal pillars of 4 m and 5 m. Conversely, if the width of the coal pillar is 6 m, this value is 895 mm, and 953 mm corresponds to the coal pillar with a 10 m width.

The convergence of the right rib is 144 mm and 236 mm, respectively, of the coal pillar with a width of 4 m and 5 m. Meanwhile, this value is 566 mm and 851 mm when the width of the coal pillars is 6 m and 10 m, respectively. The floor convergence is 152 mm and 193 mm, with the cases of coal pillars having widths of 4 m and 5 m, respectively. As the coal pillar width increased from 6 m to 10 m, the floor convergence increased from 379 mm to 551 mm, respectively. Thus, it can be seen that a coal pillar with a width of 4–5 m is suitable for the case of excavating gob-side entry. In this case, the converging values of the gob-side entry are always two times smaller than in the other cases.

As such, when excavating a gob-side entry, the coal pillar between it and the gob with a width of 3 m will be destroyed. However, then the deformation of the gob-side entry will increase proportionally with the distance between it and the gob. This is quite similar to the results of the analysis of the main roof's fracture mechanism mentioned in Figure 4. That is, after the main roof's fracture process, the larger-width coal pier will place the gob-side entry in the area of maximum abutment pressure. Therefore, with the requirement for the reduction of coal loss and improving the level of work safety, on the basis of the theoretical analysis of the main roof's fracture mechanism and the case study results, the optimal distance between the gob-side entry and the boundary of the gob should be chosen at a distance of 4–5 m.

Conclusion

The fracture mechanism of the main roof on the edge of the coal seam has been theoretically analyzed. The results show that, after the main roof collapses, two stress fields will be formed on the edge of the coal seam, including an external stress field (S1) and an internal stress field (S2). The boundary of these two stress fields is determined at the crack location of the main roof. A favorable location to excavate a gob-side entry should be located in the S1 zone.

A study by an equivalent material model shows that the fracture location of the main roof is 4-5 m from the boundary of the gob. After the collapse of the main roof, the peak of the maximum stress moved deep into the coal seam. Then, on the edge of the coal seam, there is a reduced stress zone due to the console of the main roof breaking and unloading into the gob. With this method, a favorable location to excavate a gob-side entry should be located between 4 m and 8 m from the boundary of the gob.

Numerical simulation has demonstrated that a coal pillar which is too narrow (3 m) will be easily destroyed, and it does not guarantee stability and separation between the gob-side entry and the gob. As the pillar width increases, the stress concentration in the pillar also increases. However, the great stress concentration will not be favorable for maintaining the stability of the gob-side entry and coal pillar because the coal pillar has to play the main role in supporting the load of the roof rock layers. The deformation monitoring results show that the gob-side entry is stable when the width of the coal pillar is 4-5 m. As the pillar width increases, the stress concentration increases that leads to greater deformation of the gob-side entry.

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