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Numerical Study on Effect of Longwall Mining on Stability of Main Roadway under Weak Ground Conditions in Indonesia

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Abstract: The purpose of this research is to study the effect of longwall mining on the stability of main roadway in the underground coal mine. The PT GDM (Gerbang Daya Mandiri) underground coal mine in Indonesia, where the rocks are weak, was selected as a representative study site. To accomplish the objective of the research, the finite difference code software FLAC3D was used as a tool for the numerical simulations. The longwall mining of several panel and barrier pillar widths at various depths was simulated and discussed. Based on the simulation results, it indicates that the effect of coal panel extraction on the main roadway stability depends on the width of panel and barrier pillar. The greatest effect occurs when the large panel width and the small barrier pillar width are applied, whereas the smallest effect happens when the narrow panel width and the large barrier pillar width are adopted. In this paper, therefore, to maintain the stability of the main roadway with the aim of maximizing the coal recovery, the appropriate size of panel and barrier pillar width is proposed for each mining depth for this underground coal mine.

Key words: FLAC3D, longwall mining, numerical simulation, weak ground conditions, roadway stability.

1. Introduction

PT GDM (Gerbang Daya Mandiri) underground coal mine was selected as a representative mine site in this research, in order to study the effect of the longwall mining on the stability of the main roadway under weak ground conditions in Indonesia. GDM coal mine is a new underground coal mine which is still in the process of developing the mine portal and main roadway. It is located in Kutai Kertanegara, about 15 km north of the Samarinda City of East Kalimantan, Indonesia. Fig. 1 shows the location map of GDM coal mine.

GDM Company has conducted an exploration for underground mining from June 2010 to May 2011. The total geological and recoverable sub-bituminous coal

reserves are approximately 58.3 million tons and 29.2 million tons, respectively. The annual coal production of this company has been planned for 1 million tons during its mine lifetime by a longwall mining method. Fig. 2 illustrates the layout of mine portals, main roadways, and longwall panels of GDM coal mine. Two mine portals namely North and South Portal, are being excavated by using the road header machine to access the coal seams (Fig. 3). The portal excavation commenced in April 2014 from the final highwall of the old surface mine. The total height of the final highwall is about 15 m from the ground surface. The portals are designed using semi-circular shape with 5 m width, 3 m height, and 60 dip. The portals are stable in the current situation at the shallow depth with the occurrence of some cracks and rock mass deformations along the roof and sidewalls. These rock failures are well supported by the pattern of 1 m spaced steel arches.

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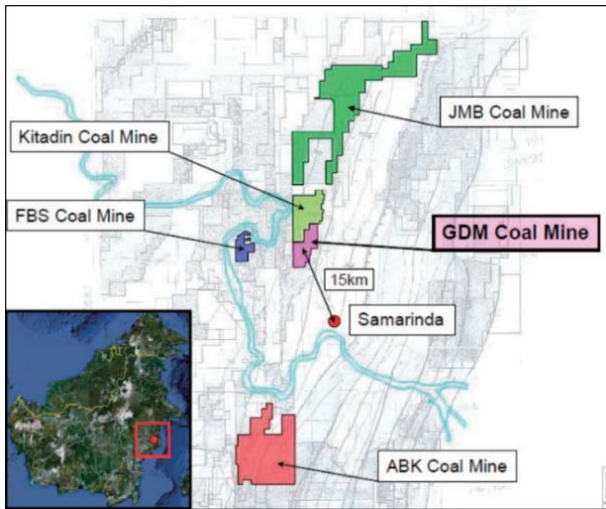


Fig. 1 Location of GDM coal mine.

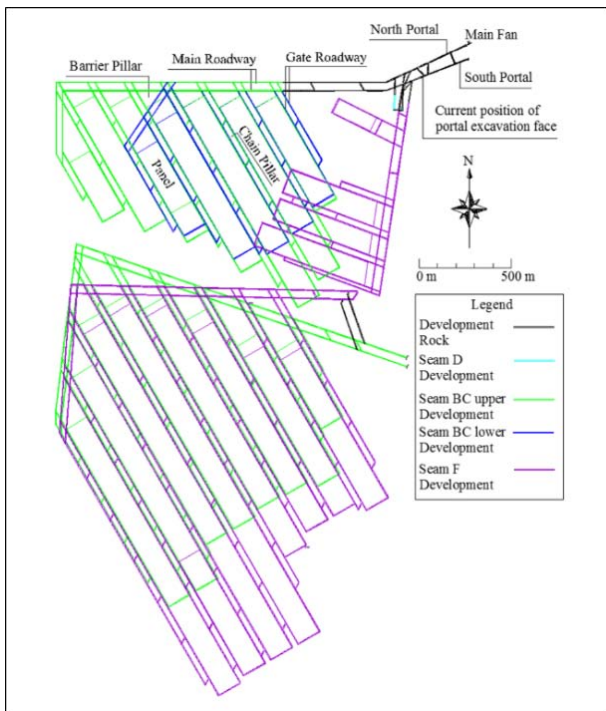


Fig. 2 Mine layout of GDM underground coal mine.

The GDM coal mine is situated in the Kutai Tertiary Basin. Balikpapan Formation and Pulau Balang Formation are the major coal-bearing formations in this basin (Fig. 4). Balikpapan Formation consists of dark to light gray mudstone, dark to brownish-gray sandstone, dark to light gray siltstone and claystone, coal, and coaly shale. Pulau Balang Formation mainly composes of mudstone, sandstone, siltstone, coal, and coaly shale. In Pulau Balang Formation, mudstone is

dark to light gray in color. Sandstone is dark to whitish-gray and brownish-gray, the grain size is very fine to coarse. Siltstone is dark gray to light gray. The fault was not found in GDM coal mine. Geological structure is simple monocline structure. GDM coal consists of several seams which are part of the Kutai Basin with the dip ranging from 3° to 13°, and the coal



Fig. 3 South Portal of GDM coal mine.

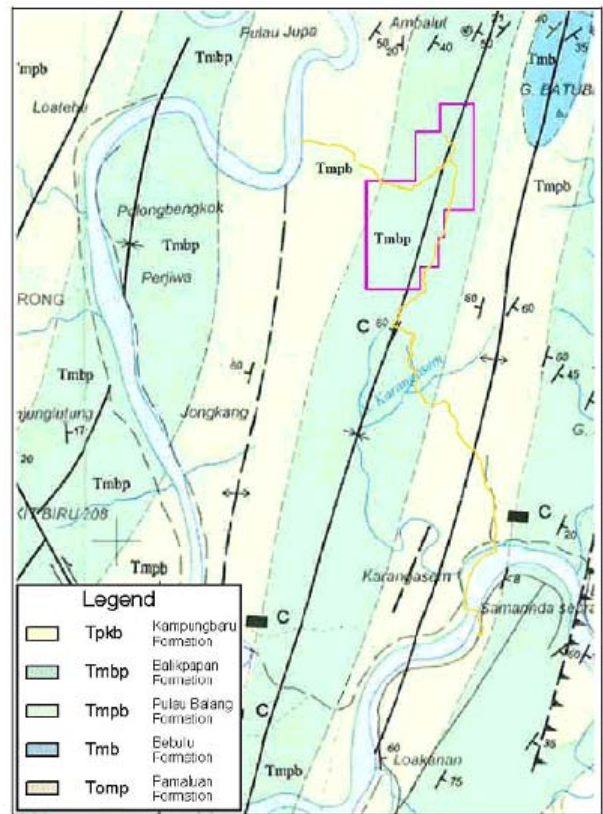


Fig. 4 Geological map of GDM coal mine.

seam thickness varies from 0.15 m to 9.8 m. Typical stratigraphy of GDM underground mine is shown in Fig. 5. It shows that the major mineable seams for underground mining are found in Seam BC and Seam F. The thickness of Seam BC varies from 3.39 m to 9.80 m, whereas the thickness of Seam F varies from 0.70 m to 3.20 m. The coal seams are separated by the layers of claystone and sandstone. Claystone is a dominant rock unit in GDM coal mine.

Fig. 6 illustrates the relationship between uniaxial compressive strength and Young's modulus of rock and coal. These results were obtained from laboratory tests of the rock and coal samples which were collected from boreholes at different depths. Based on the laboratory test results, the rock and coal in this underground mine are classified into weak and low strength rocks as the UCS values are mostly below 25 MPa [1, 2].

Although the mine portals are currently stable at a shallow depth, to reach the targeted coal seams, the main roadway has to be constructed at a greater depth connecting with the mine portal, and when the longwall mining is started, a series of ground control problems of the main roadway, such as roof fall, sidewalls collapse, and floor heave can be expected in this

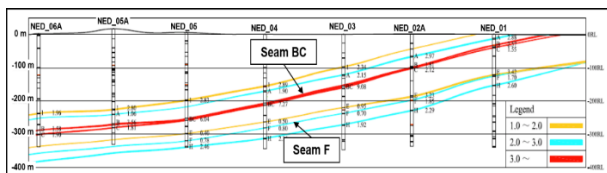


Fig. 5 Stratigraphic column of GDM coal mine.

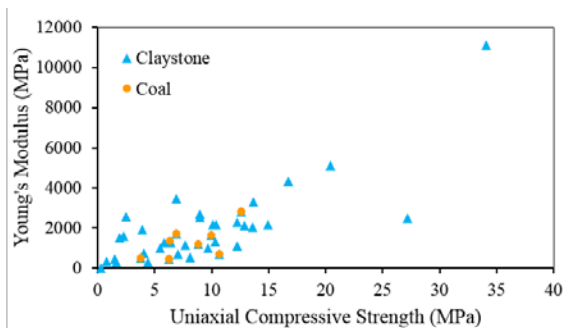


Fig. 6 Relationship between uniaxial compressive strength and Young's modulus of claystone and coal of GDM coal mine.

underground coal mine unless a proper size of barrier pillar width is provided. The problems can arise due to weak mechanical properties of surrounding rocks.

Longwall mining is a highly productive, efficient, and safe underground mining method, which applies to extract the coal seams of relatively large horizontal extent and uniform thickness with an orebody dip of less than 20°. Up to 80% of the coal can be recovered by this mining method [3-6]. In longwall mining, after the main roadways reach the targeted coal seam, the coal seam is blocked into panels by developing the gate roadways along the panel sides. The gate roadways are then connected and form the chain pillar. Another pillar is also formed in order to separate the main roadway from the excavation face. This pillar is known as a barrier pillar (Fig. 7) [7]. The effect of longwall mining on the stability of the gate roadway and the chain pillar width design is out of this research objective. During the mining of a longwall panel, the rock strata above the mined-out area are allowed to collapse and cave in to the goaf (Fig. 8) [8]. Cave-in of the roof strata above the mined-out area induces the stress redistributions of the surrounding rocks. The stresses which previously existed in the rocks are redistributed to the face of the panel as illustrated in Fig. 9 [6, 9, 10]. These stress redistributions have a pronounced impact on the stability of the main roadway. An adequate width of barrier pillar and longwall panel is needed in order to prevent the failure of the main roadway due to the panel extraction. Undersized barrier pillar and oversized longwall panel may lead to a severe instability of the main roadway. In contrast, oversized barrier pillar and undersized longwall panel can result in the reduction of coal productivity.

Therefore, to make the development of longwall mining in this underground coal mine possible, by ensuring the safety of mine workers and stability control, and avoiding an interruption of coal extracting that may occur due to the roadway instability, this paper attempted to study the effect of longwall mining on the stability of the main roadway. A three-dimensional

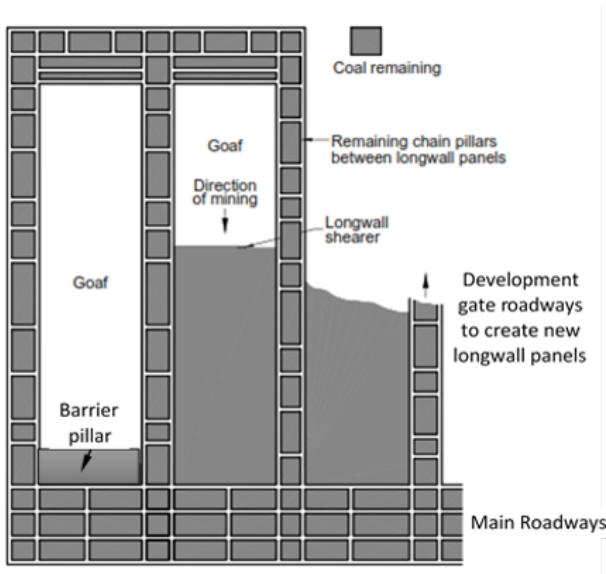


Fig. 7 Typical panel layout of a longwall coal mine.

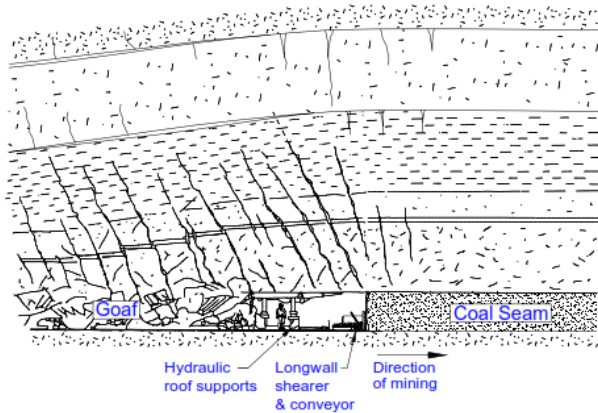


Fig. 8 Cave-in of the roof strata above mined-out area.

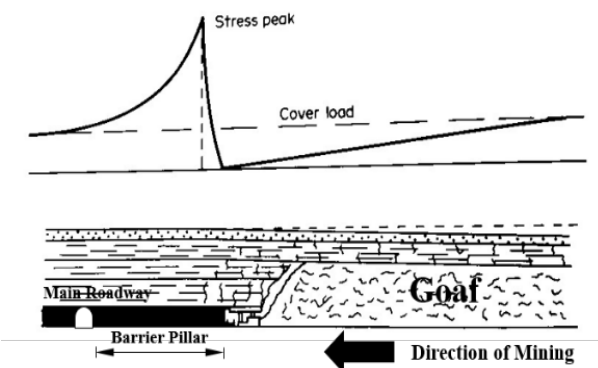


Fig. 9 Vertical stress redistribution ahead longwall panel face.

finite difference code software, FLAC3D was used as a tool for the numerical simulations. The influence of coal panel extraction was analyzed and discussed, and

the appropriate barrier pillar width and panel size were investigated and proposed in this study. Future longwall mining projects in Indonesia would certainly benefit by adopting the techniques developed at GDM underground coal mine.

2. Description of Numerical Model

To study the effect of longwall mining on the main roadway stability, and to investigate the appropriate size of barrier pillar and longwall panel, several numerical models at various depths of 50 m, 100 m, 150 m, and 200 m were created using the finite difference code FLAC3D software. The width and length of the model are 230 m and 235 m, respectively, while the height is varied depending on the depth of longwall mining. Fig. 10 demonstrates an example of numerical model of longwall mining at 200 m depth. The bottom of the model was fixed in the vertical direction, the sides were fixed in the horizontal direction, and the surface was free in all directions. In simulations, the stress ratio of 1 ($k = 1$) was considered. The elasto-plastic Mohr-Coulomb criterion was used as a failure criterion in the analyses. Three-dimensional analysis under symmetric condition was considered, and only half side from the center of the model was analyzed. The main roadway was excavated in the coal seam, and it was modeled as a semi-circular shape of 5 m width, 3 m height, and 230 m length. The main roadway was supported by the steel arch with different spaces of 1 m and 0.5 m (Fig. 11). The mechanical properties of rock mass and coal seam, and the properties of steel arch used in the simulations are presented in Tables 1 and 2, respectively.

Firstly, the paper investigated the influence of barrier pillar on the stability of main roadway at various depths, and the appropriate width of barrier pillar was designed and proposed based on the results. Several widths of barrier pillar ranging from 5 m to 150 m were investigated. The panel width was fixed at 130 m in this case. Secondly, the paper assessed the influence of panel width on main roadway stability.

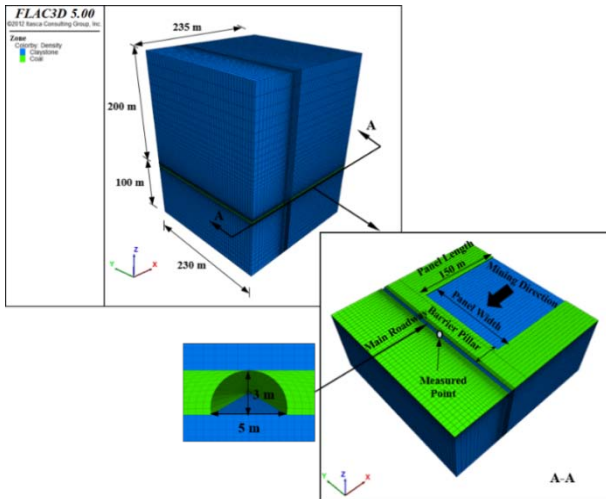


Fig. 10 Numerical model of longwall mining for main roadway stability analysis at 200 m depth.



Fig. 11 Steel arch support.

Table 1 Mechanical properties of rock and coal used in simulations.

Parameter	Rock	Coal
Uniaxial compressive strength (MPa)	10.49	8.16
Density (kg/m ³)	2,140.00	1,380.00
Young's modulus (MPa)	2,324.68	1,295.81
Poisson's ratio	0.27	0.32
Friction angle (°)	37.48	45.66
Cohesion (MPa)	0.56	2.63

Table 2 Mechanical properties of steel arch used in simulations.

Parameter	Value and description
Steel arch type, JIS 3010	SS540
Dimension (mm)	95 × 115
Area (cm ²)	36.51
Young's modulus (MPa)	200,000.00
Poisson's ratio	0.30
Maximum yield strength (MPa)	551.00

The simulations were carried out at 50 m, 100 m, 150 m, and 200 m depth. Three panel widths of 70 m, 100 m, and 130 m were simulated numerically. Based on the simulated results, appropriate designs of barrier pillar for each panel width and mining depth were suggested in order to maintain the stability of the main roadway with the aim of maximizing the coal recovery. To observe the effect of longwall mining, and to efficiently obtain the width of barrier pillar and panel size, the failure zone and steel arch axial stress were monitored in the main roadway as illustrated in Fig. 10. The results of these parameters were measured after every step of longwall panel extraction.

3. Modeling of Goaf

After extraction of the coal seam, the immediate roof strata above the mined-out area bend and cave into the stope void behind the excavation face, known as a caved area or goaf. The goaf is mainly made of broken rock pieces, hence it was modeled as aggregate of fractured rocks [11]. To simulate the goaf in longwall mining, both the coal seam and immediate caved roof were excavated, and then the caved area was filled with a very soft material [12]. Since the measurement of deformations in the goaf is difficult due to the inaccessibility, there is still no standard method for modeling the goaf. In this research, the following equation was used for estimating the height of caved roof [13].

$$H_c = 100h/(c_1h+c_2) \quad (1)$$

where H_c (m) is the height of caved roof, h (m) is the seam height, and c_1 and c_2 are coefficients depending on the strata lithology. The values of c_1 and c_2 for different lithologies are presented in Table 3. By considering the condition of GDM coal measure rocks, the height of caved roof was calculated as 5.93 m.

In simulation, a longwall panel was extracted step by step. After the excavation face moved forward, the caved area behind the coal face was filled with the very soft goaf material. The excavation steps were repeated until the longwall panel was entirely extracted. An

example of goaf installation in the longwall mining simulation is illustrated in Fig. 12. The properties of the goaf used in the analyses are given in Table 4.

4. Influence of Barrier Pillar on Main Roadway Stability and Its Design for Fixed Panel Width as 130 m

The effect of longwall mining on the stability of the main roadway was firstly investigated by leaving different

Table 3 Coefficients for different strata lithologies.

Lithology	Uniaxial compressive strength (MPa)	c_1	c_2
Strong and hard	> 40	2.1	16
Medium strong	20-40	4.7	19
Soft and weak	< 20	6.2	32

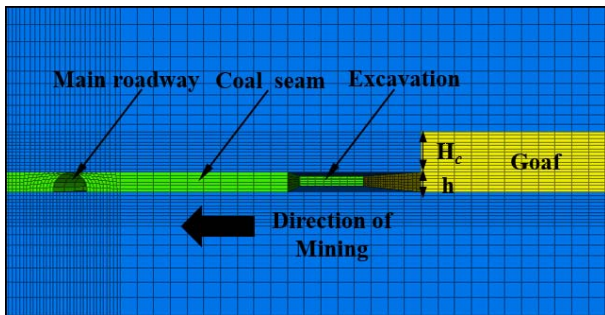
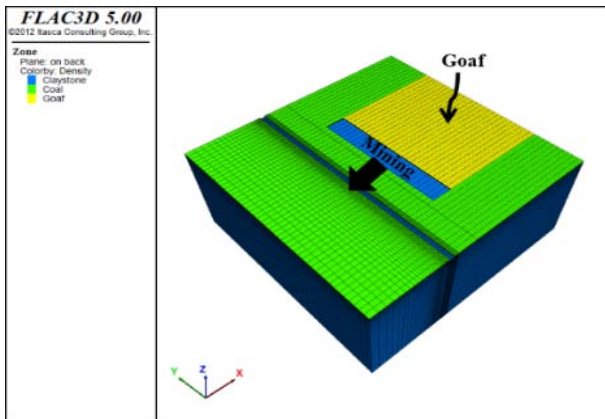


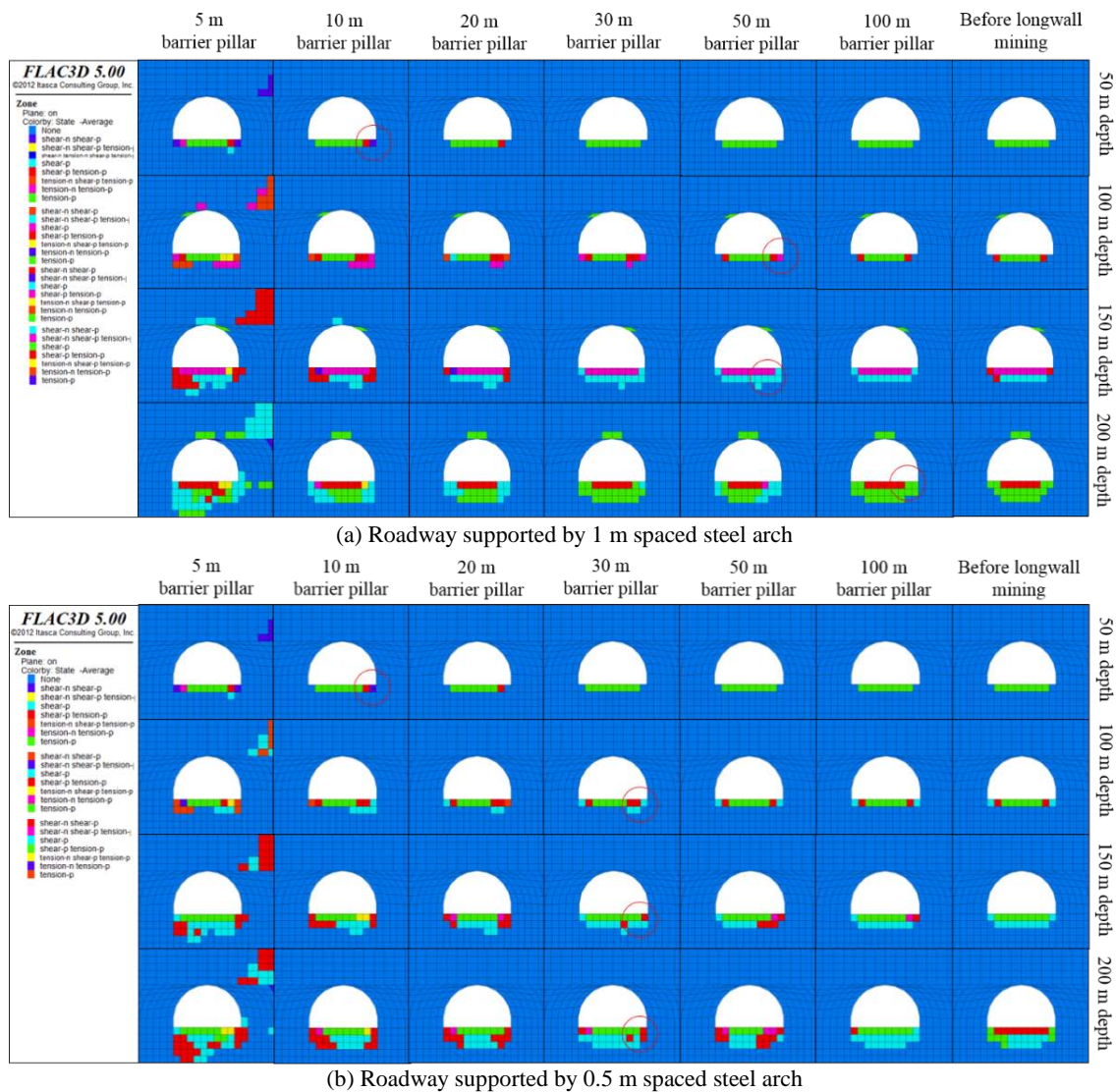
Fig. 12 Installation of goaf in longwall mining simulation.

Table 4 Mechanical properties of goaf used in simulations.

Parameter	Value
Density (kg/m ³)	1,700.000
Young's modulus (MPa)	15.000
Poisson's ratio	0.250
Friction angle (°)	25.000
Cohesion (MPa)	0.001

barrier pillar widths during the panel extraction. The panel width was fixed at 130 m, and four mining depths of 50 m, 100 m, 150 m, and 200 m were considered in the simulations. The simulated results were used as a guideline for designing the appropriate barrier pillar. Fig. 13 illustrates the failure zone of the main roadway supported by 1 m and 0.5 m spaced steel arches. The column in Fig. 13 indicates the width of barrier pillar, while the row indicates the depth of longwall mining. It was noticed from the results that the additional failure zone progressively increased as the barrier pillar width decreased. This happened because when the excavation face moved closer to the main roadway, the main roadway experienced higher impacts of longwall mining, and more additional failure zones developed. A significant increment of failure zone was observed when a small barrier pillar of 5 m was left at all mining depths. Based on the failure zone results, it can be said that the width of barrier pillar influences the stability of the main roadway. Ground control problems of the main roadway can be expected unless an adequate width of barrier pillar is provided.

As a steel arch is the support applied to stabilize the main roadway. Apparently, the stress occurring on the steel arch is caused by the panel extraction. Hence, analysis of the steel arch axial stress can be a proper method for studying the stability of the main roadway. The definition of the steel arch axial stress is given as the stress which is accumulated in the steel arch axially due to acted forces from the ground. If it exceeds the maximum yield strength of the steel arch, the steel arch may start to deform. Fig. 14 illustrates the results of steel arch axial stress. The results confirmed that the width of barrier pillar has a significant impact on the stability of main roadway. An increase in steel arch axial stress was associated with a decrease in barrier pillar width. The steel arch axial stress increased gradually after the longwall mining started, and a significant change of steel arch axial stress occurred when a small barrier pillar was left. It revealed that a thinner barrier pillar produced a greater steel arch axial



(a) Roadway supported by 1 m spaced steel arch

(b) Roadway supported by 0.5 m spaced steel arch

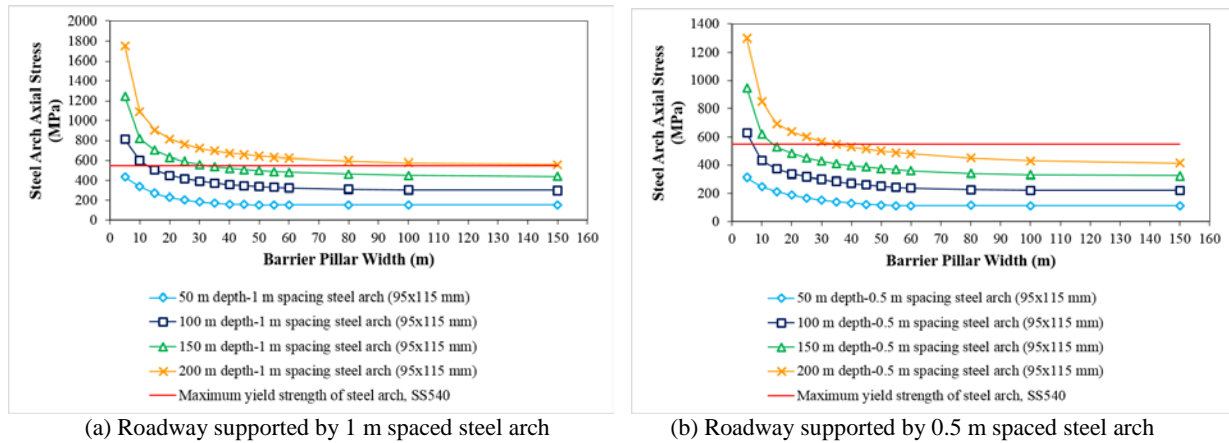
Fig. 13 Failure zone of main roadway under different barrier pillar widths at various depths for fixed panel width as 130 m.

stress, and this can deliver a worse stability condition to the main roadway. Therefore, careful design of barrier pillar width is particularly necessary in order to keep the main roadway stable during the longwall panel extraction. An appropriate width of barrier pillar was designed based on the results of steel arch axial stress in comparison with the maximum yield strength of steel arch SS540. According to the results, when the roadway was supported by the 1 m spaced steel arch, a barrier pillar width of 5 m, 13 m, 30 m, and 130 m was sufficient to control the stability of main roadway at 50 m, 100 m, 150 m, and 200 m depth, respectively. On the contrary, a barrier pillar width of 5 m, 7 m, 14 m,

and 35 m was adequate to maintain the main roadway at 50 m, 100 m, 150 m, and 200 m depth, respectively when the roadway was supported by the 0.5 m spaced steel arch.

Based on the size of the barrier pillar obtained from the numerical simulation results, even though a 5 m barrier pillar width can be designed at 50 m depth, the GDM coal mine must consider the spontaneous combustion issue that potentially arises. To adopt this design, the prevention measures should be anticipated for this condition. From Fig. 14, the equations for estimating the barrier pillar width are proposed. These equations can be used only for longwall mining

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(a) Roadway supported by 1 m spaced steel arch
Fig. 14 Axial stress of steel arch support for main roadway under different barrier pillar widths at various depths for fixed panel width as 130 m.

of a 130 m panel width. The equation forms are written as below.

$$BP = (SS/(10.61D + 99.44))^{-1/0.31}; R^2 = 0.89 \quad (2)$$

$$BP = (SS/(8.39D + 63.43))^{-1/0.32}; R^2 = 0.93 \quad (3)$$

where BP (m) is the barrier pillar width, SS (MPa) is the maximum yield strength of steel arch, and D (m) is the mining depth.

5. Influence of Panel Width on Main Roadway Stability and Barrier Pillar Design

The effect of longwall mining on the main roadway stability under various panel widths was investigated in this section. Three panel widths of 70 m, 100 m, and 130 m were simulated numerically. Similar to the previous section, four mining depths of 50 m, 100 m, 150 m, and 200 m, and the barrier pillar width ranging from 5 m to 150 m, were considered in the simulations. Fig. 15 illustrates the failure zone of the main roadway affected by coal panel extraction under various panel widths and depths. Fig. 15 only shows the results of the main roadway supported by 0.5 m spaced steel arches. The row of Fig. 15 indicates the panel width, while the column indicates the width of barrier pillar. Based on the results, it was obviously seen that the effect of longwall mining on the main roadway stability was minimized effectively by reducing the panel width. The additional failure zone of the main roadway developed earlier at a bigger barrier pillar width when a larger

panel was mined. On the other hand, it developed later at a thinner barrier pillar width when a smaller panel was extracted. For example, at 200 m depth, the additional failure was noticed at 30 m, 20 m, and 10 m barrier pillar width when a 130 m, 100 m, and 70 m panel width was mined, respectively. This confirms that a thinner barrier pillar can be designed if a smaller panel is adopted.

The results of steel arch axial stress obtained from longwall mining of three different panel widths are presented in Fig. 16. The steel arch axial stress results support the results of failure zone. It revealed that the stability of the main roadway improved with decreasing the panel width. A decrease in panel width considerably influenced the decrement of the steel arch axial stress. A lesser amount of steel arch axial stress was observed when a smaller panel width was mined. Compared the results of steel arch axial stress with the maximum yield strength of the SS540 steel arch, the width of the barrier pillar for different panel widths at various depths are suggested and summarized in Table 5. It can be seen from the table that a thinner barrier pillar width can be designed if a smaller coal panel is adopted. For example, at 200 m depth, a barrier pillar width of 16 m, 21 m, and 32 m will be sufficient to maintain the main roadway during the longwall mining of a 70 m, 100 m, and 130 m panel width, respectively when the roadway is supported by 0.5 m spaced steel arches.

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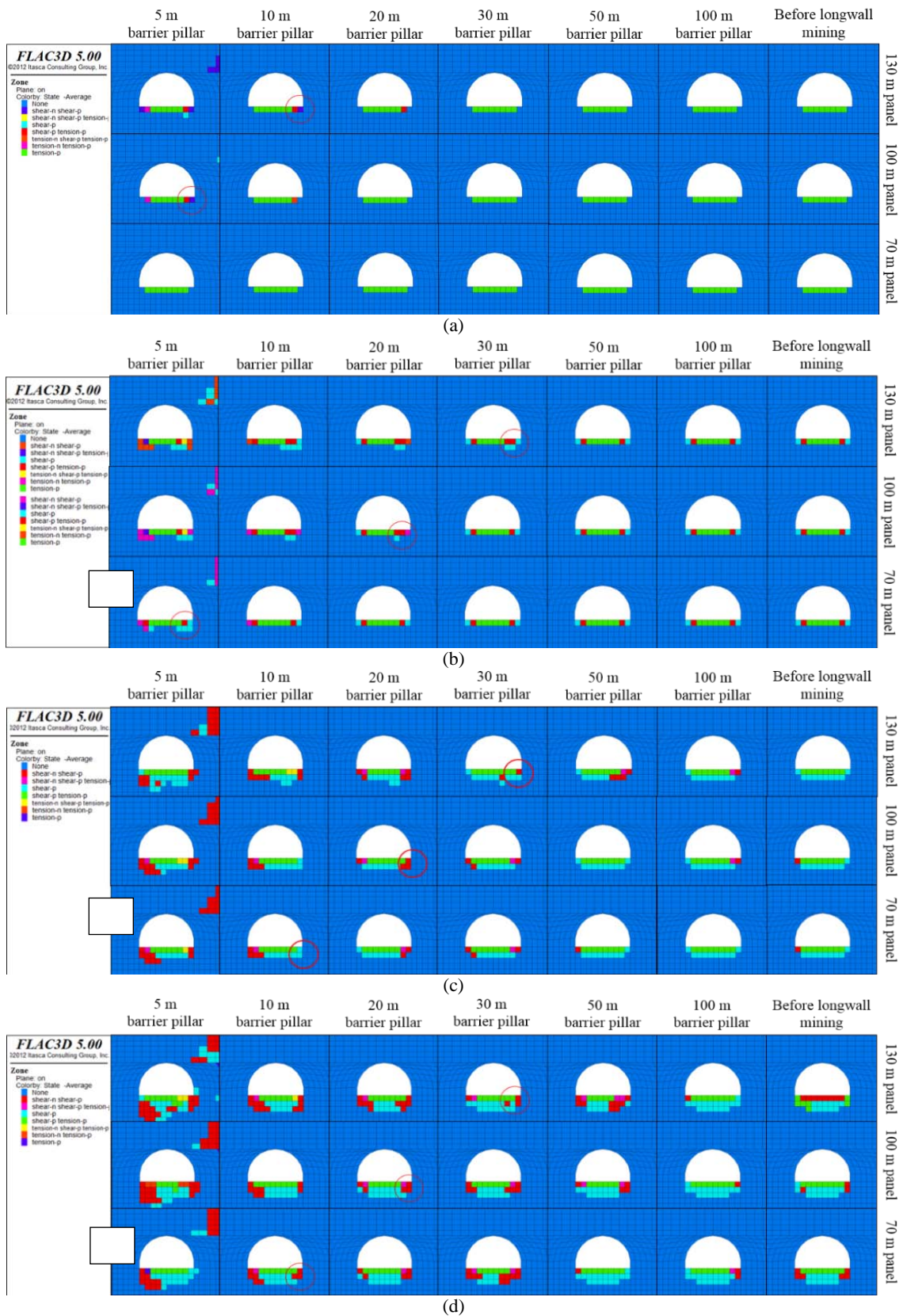
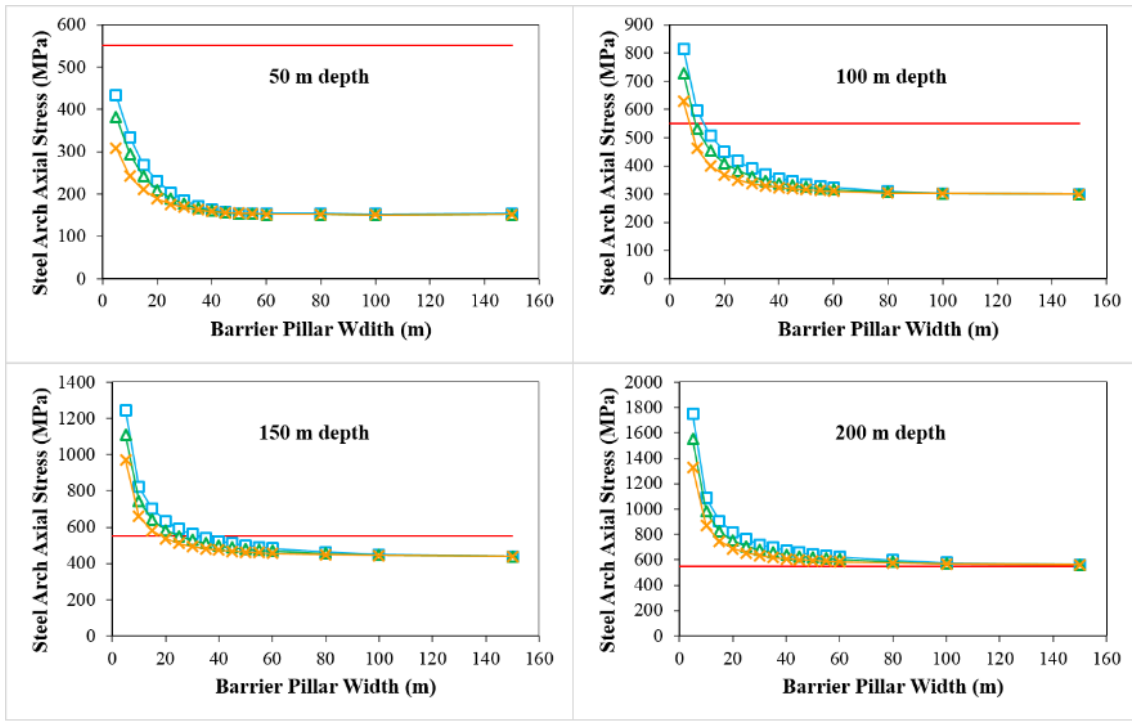


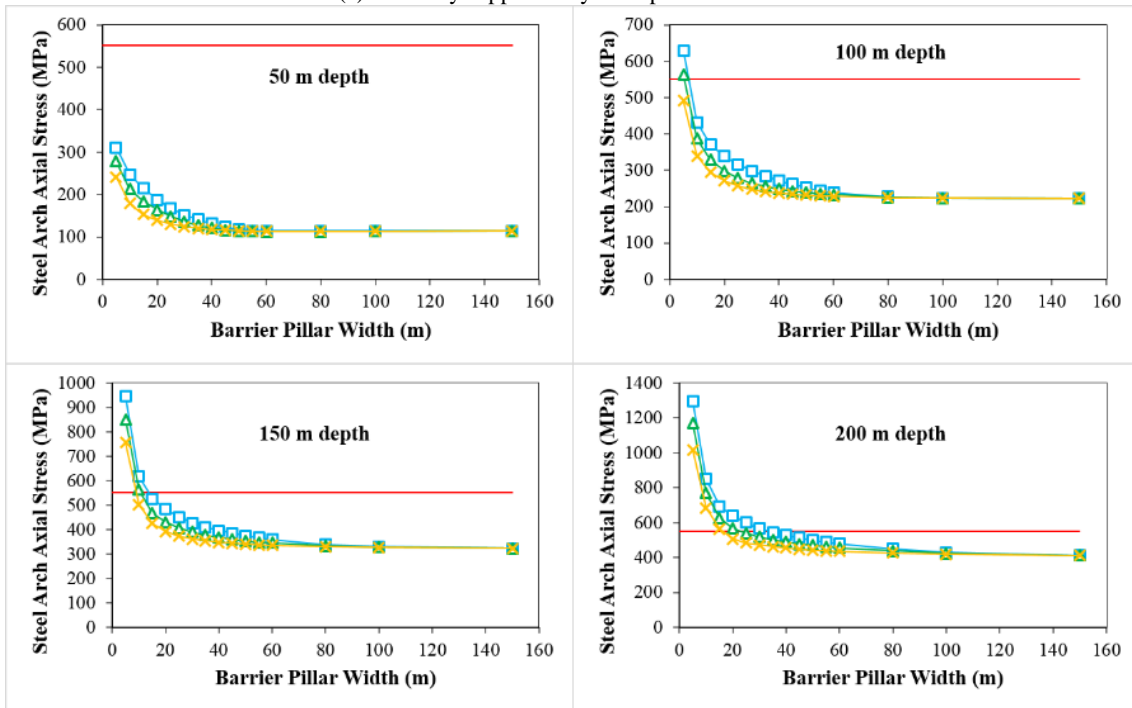
Fig. 15 Failure zone of main roadway affected by longwall mining under various panel widths (a) at 50 m depth (b) at 100 m depth (c) at 150 m depth (d) at 200 m depth.

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— Maximum yield strength of steel arch, SS540
 — 130 m panel width-1 m spacing steel arch (95x115 mm)
 — 100 m panel width-1 m spacing steel arch (95x115 mm)
 — 70 m panel width-1 m spacing steel arch (95x115 mm)

(a) Roadway supported by 1 m spaced steel arch



— Maximum yield strength of steel arch, SS540
 — 130 m panel width-0.5 m spacing steel arch (95x115 mm)
 — 100 m panel width-0.5 m spacing steel arch (95x115 mm)
 — 70 m panel width-0.5 m spacing steel arch (95x115 mm)

(b) Roadway supported by 0.5 m spaced steel arch

Fig. 16 Axial stress of steel arch support for main roadway under different panel widths at various depths.

Table 5 Barrier pillar width (m) for different panel widths at various depths.

Support of main roadway (SS540, 95 × 115 mm)		1.0 m space			0.5 m space		
Panel width (m)		70	100	130	70	100	130
Depth (m)	50	5	5	5	5	5	5
	100	7	9	12	5	5	7
	150	18	25	32	8	10	14
	200	> 150	> 150	> 150	16	21	32

Table 6 Equations for estimating barrier pillar width under various panel widths for different mining depths.

Mining depth (m)	Support of main roadway (Steel Arch SS540, 95 × 115 mm)	
	0.5 m space	1.0 m space
50	$BP = (SS/(3.76PN + 19.21))^{-1/0.29}; R^2 = 0.87$	$BP = (SS/(4.51PN + 67.77))^{-1/0.28}; R^2 = 0.86$
100	$BP = (SS/(5.54PN + 162.08))^{-1/0.26}; R^2 = 0.88$	$BP = (SS/(7.26PN + 218.46))^{-1/0.3}; R^2 = 0.89$
150	$BP = (SS/(7.11PN + 336.11))^{-1/0.3}; R^2 = 0.86$	$BP = (SS/(8.98PN + 457.03))^{-1/0.294}; R^2 = 0.87$
200	$BP = (SS/(10.25PN + 449.23))^{-1/0.32}; R^2 = 0.88$	$BP = (SS/(13.07PN + 560.87))^{-1/0.27}; R^2 = 0.85$

Although the GDM coal mine can adopt a small size of barrier pillar, especially when a narrow panel width is applied at a shallow depth, it is strongly recommended that the potential occurrence of spontaneous combustion must be carefully taken into an account. Some preventing methods for this mentioned problem have to be prepared, such as constructing a good ventilation system, injecting the nitrogen, etc. However, by doing these it will cause some additional costs. To avoid adding these additional costs to the project, a larger barrier pillar width has to be adopted, but this will minimize the coal production of the mine. Table 6 summarizes the equations for estimating the barrier pillar width under various panel widths for different mining depths. The equations are derived from the relationship between the panel width and maximum yield strength of the steel arch support. In Table 6, BP (m) is the barrier pillar width, SS (MPa) is the maximum yield strength of steel arch, and PN (m) is the panel width.

6. Conclusion

In this paper, the effects of longwall mining on the stability of the main roadway under various barrier pillar and panel widths at different mining depths are studied numerically using a three-dimensional finite difference code software, FLAC3D. The simulated results indicate that the effect of longwall mining on

the main roadway stability depends mainly on the barrier pillar and panel width and the mining depth. The greatest effect occurs when the large panel width and the small barrier pillar width are applied, whereas the smallest effect happens when the narrow panel width and the large barrier pillar width are adopted. The stability of the main roadway can be improved by increasing the barrier pillar width or decreasing the width of the panel. Mining a wide coal panel, a large barrier pillar width is needed. A small barrier pillar width can be designed if a narrow longwall panel is adopted. Based on the results of steel arch axial stress, several barrier pillar widths are suggested for different panel widths at various depths. The barrier pillar width is also able to estimate by the equations proposed in this study.

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