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EFFECTS OF LONGWALL MINING ON GATE ROADWAY STABILITY EXCAVATED IN WEAK ROCKS

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Abstract— **The objective of this study is to investigate the effect of longwall mining on the stability of the gate roadway in an underground coal mine. The PT Gerbang Daya Mandiri (GDM) underground coal mine in Indonesia, with weak rocks, was chosen as a representative study site. To achieve the research objective, the finite diffrence code software FLAC3D was used for numerical simulations. The longwall mining of several panel and chain pillar widths at different depths was simulated and discussed. According to the simulation results, the influence of coal panel extraction on gate roadway stability is determined by the panel and chain pillar widths. The largest effect occurs when the large panel width and small barrier pillar width are used, whereas the smallest effect occurs when the narrow panel width and large chain pillar width are used. To ensure the stability of the gate roadway while increasing coal recovery, the suitable panel and chain pillar widths are proposed for each mining depth in this underground coal mine.**

Keywords—**Gate Roadway Stability, Numerical Simulation, FLAC3D, Weak Rock**

I. INTRODUCTION

The PT Gerbang Daya Mandiri (GDM) underground coal mine was chosen as a sample mine site for this study to investigate the effect of longwall mining on the stability of the gate roadway excavated in weak rocks in Indonesia. GDM coal mine is located in Kutai Kertanegara, about 15 km north of Samarinda City in East Kalimantan, Indonesia. Fig. 1 depicts the location map of the GDM coal mine.

The geological and recoverable sub-bituminous coal reserves of GDM mine are approximately 58.3 million tons and 29.2 million tons, respectively. The annual coal production has been planned for 1 million tons during its mine lifetime by a longwall mining method. Fig. 2 illustrates the layout of mine portals, gate roadways, and longwall panels of GDM coal mine. Two mine portals namely North and South Portal, have been excavated by using the road header machine to access the coal seams (Fig. 3). The portal excavation is commenced 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 6^o dip. The portals are stable in the current situation 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.

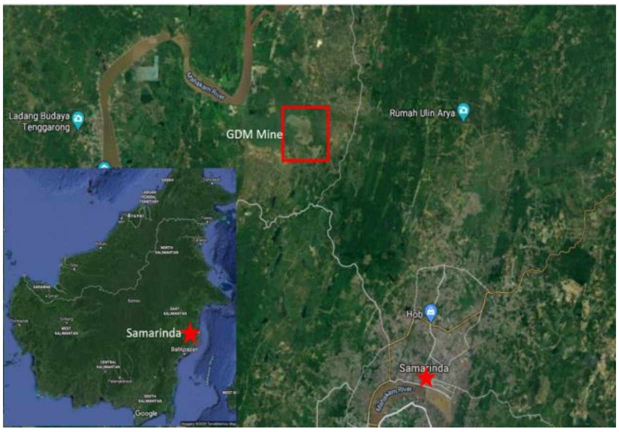

Fig. 1. Location map of GDM underground coal mine

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.

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GDM coal consists of several seams which are part of the Kutai Basin with the dip ranging from 3^{o} to 13^{o}, and the coal 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 3.31 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.

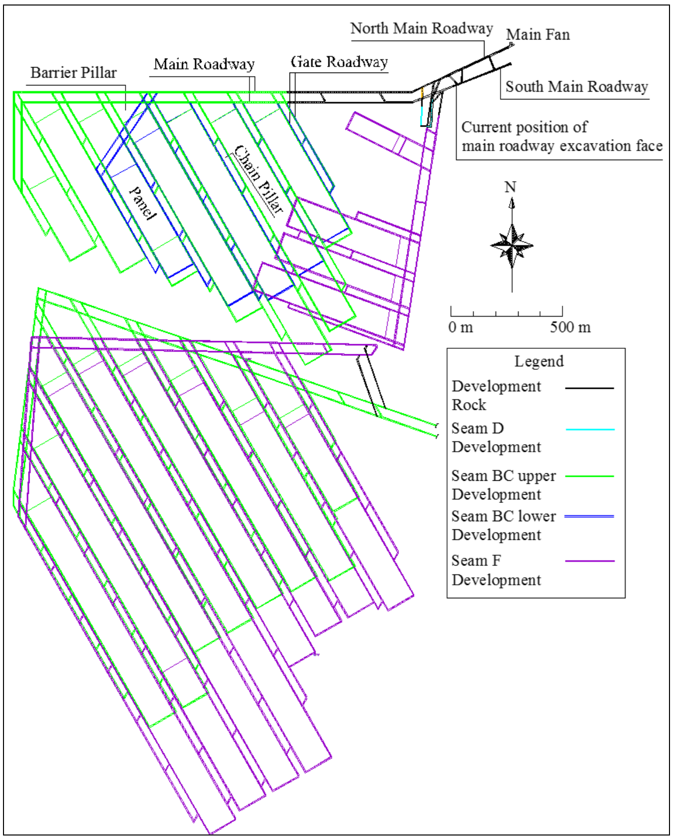

Fig. 2. Mine layout of GDM underground coal mine

Fig. 3. South Portal of GDM underground 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].

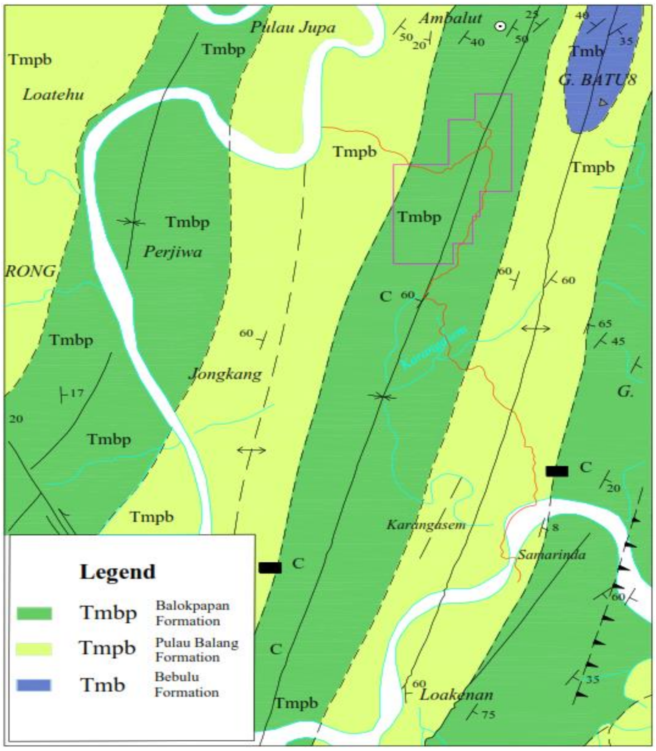

Fig. 4. Geological map of GDM underground coal mine

Although the mine portals are currently stable at a shallow depth, to reach the targeted coal seams, the main and gate roadways have 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 and gate roadways, such as roof fall, sidewalls collapse, and floor heave can be expected in this underground coal mine unless a proper size of 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 main roadway and the barrier pillar width design are 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 gate roadway. An adequate width of chain pillar and longwall panel is needed in order to prevent the failure of the gate roadway due to the panel extraction. Undersized chain pillar and oversized longwall panel may lead to a severe instability of the gate roadway. In contrast, oversized chain pillar and undersized longwall panel can result in the reduction of coal productivity.

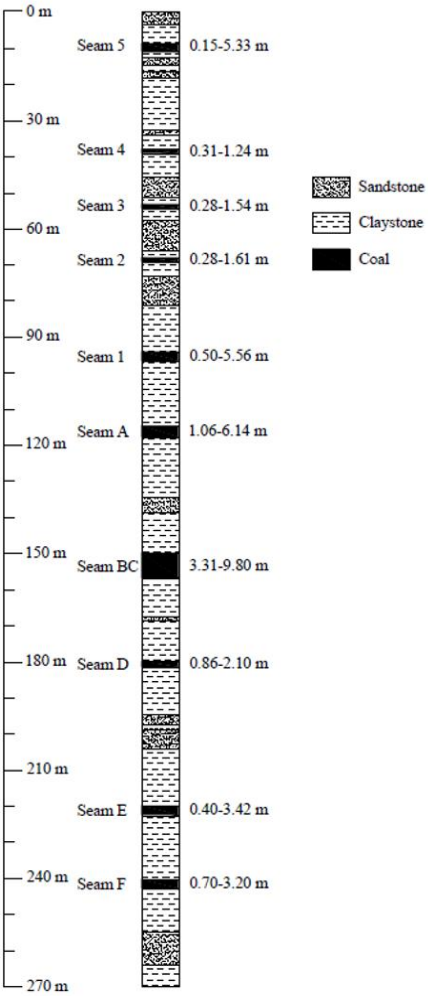

Fig. 5. Stratigraphic column of GDM underground coal mine

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 gate roadway. A three-dimensional 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 chain 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.

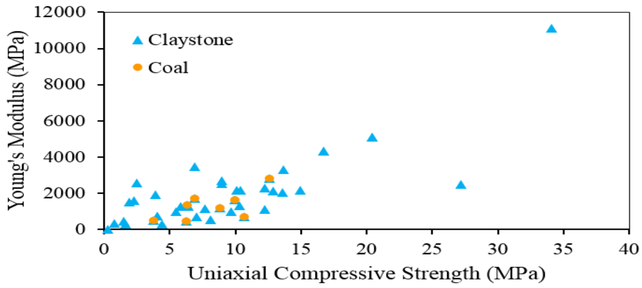

Fig. 6. Relationship between uniaxial compressive strength and young's modulus of claystone and coal of GDM coal mine

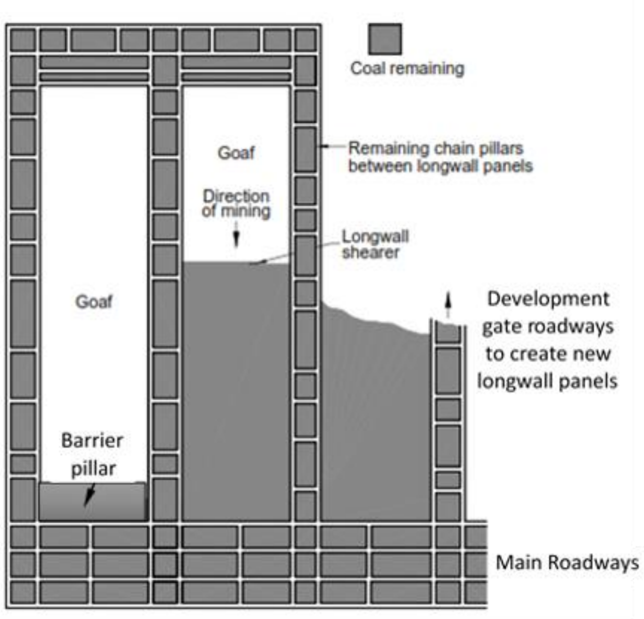

Fig. 7. Typical panel layout of a longwall coal mine

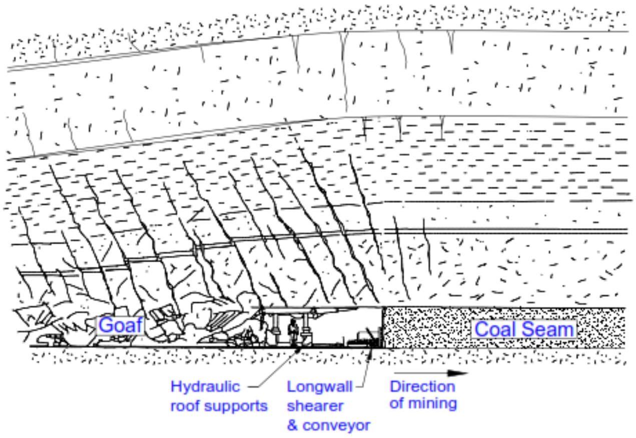

Fig. 8. Cave-in of the roof strata above mined-out area

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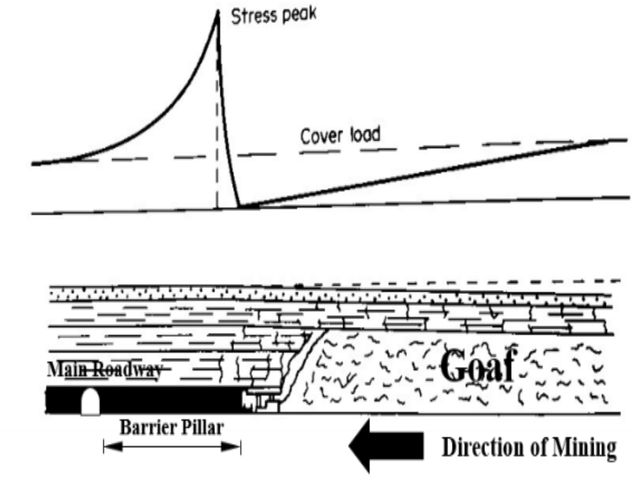

Fig. 9. Vertical stress redistribution ahead longwall panel face

II. DESCRIPTION OF NUMERICAL MODEL

The effect of the longwall mining on the stability of the gate roadway was studied in this paper. The simulation includes the influence of chain pillar and panel width. Several numerical models were created at various depths of 50 m, 100 m, 150 m, and 200 m. The model is 200 m in width, 400 m in length, while the height is varied depending on the mining depth. An example of the numerical model created at 200 m depth is illustrated in Fig. 10. The model was fixed at two sides and bottom, and it was free at the surface. The stress ratio of 1 (k = 1) was considered, and the failure criterion of Mohr-Coulomb was employed. Generally, a single-entry gate roadway is a typical gate roadway system for longwall mining in Indonesia. However, due to the coal measure rocks are very weak, for safety reasons, the two-entry gate roadway system is adopted in GDM coal mine. In simulation, therefore, the two-entry gate roadway system was considered. The gate roadway was excavated inside a 3 m thick coal seam, semi-circular in shape, 5 m in width, and 3 m in height. The steel arch support was applied to maintain the stability of the gate roadway (Fig. 11). The properties of rock mass, coal seam, and steel arch used in the simulations are given in Tables 1 and 2, respectively.

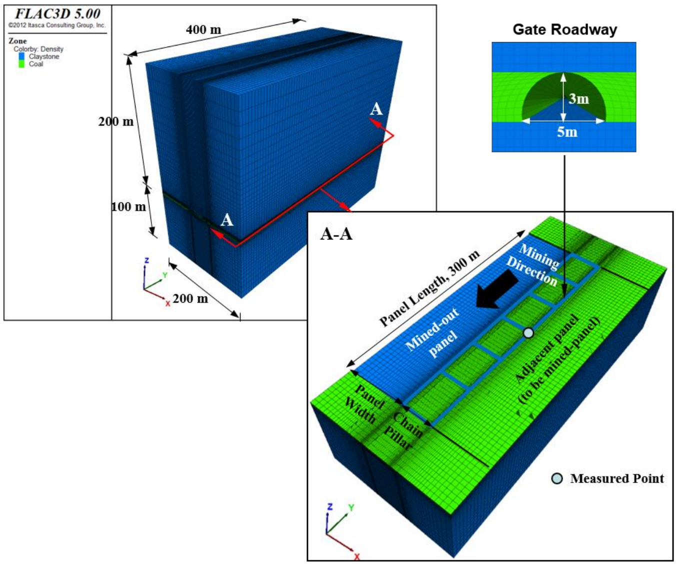

Fig.1. Numerical model of longwall mining for gate roadway stability analysis at 200 m depth

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)	**2140.00**	**1380.00**
Young's modulus (MPa)	**2324.68**	**1295.81**
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 x 115**
Area (cm^2)	**36.51**
Young's modulus (MPa)	**200,000.00**
Poisson's ratio	**0.30**
Maximum yield strength (MPa)	**551.00**

As illustrated in Fig.10, two gate roadways were developed along the panel sides, forming the chain pillar. However, only the stability of gate roadway along the adjacent panel (to be mined-panel) was studied. The stability of the gate roadway along the mined-out panel was not considered in this study since this gate roadway has already finished its task and will not be used any longer. In simulation, the longwall mining is started from the far end of the panel. The coal panel with the length of 300 m was extracted step by step, and the mined

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void behind the excavation face was filled with the goaf material. The extraction steps were repeated until the coal panel was entirely extracted. The panel extraction was simulated under the symmetric condition, so that only half side from the center of the model was analyzed. In order to observe the effect of longwall mining on the stability of the gate roadway, the results of failure zone and steel arch axial stress were monitored at the middle of the gate roadway after the coal panel was completely mined out.

Fig. 11. Steel arch support

III. 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].

$Hc = 100h/(c_1h+c_2)$

Where Hc (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.

Table-3 Coefficients for different strata lithologies

Lithology	**Uniaxial compressive strength (MPa)**	**c1**	**c2**
Strong and hard	**> 40**	**2.1**	**16**
Medium strong	**20-40**	**4.7**	**19**
Soft and weak	**< 20**	**6.2**	**32**

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.

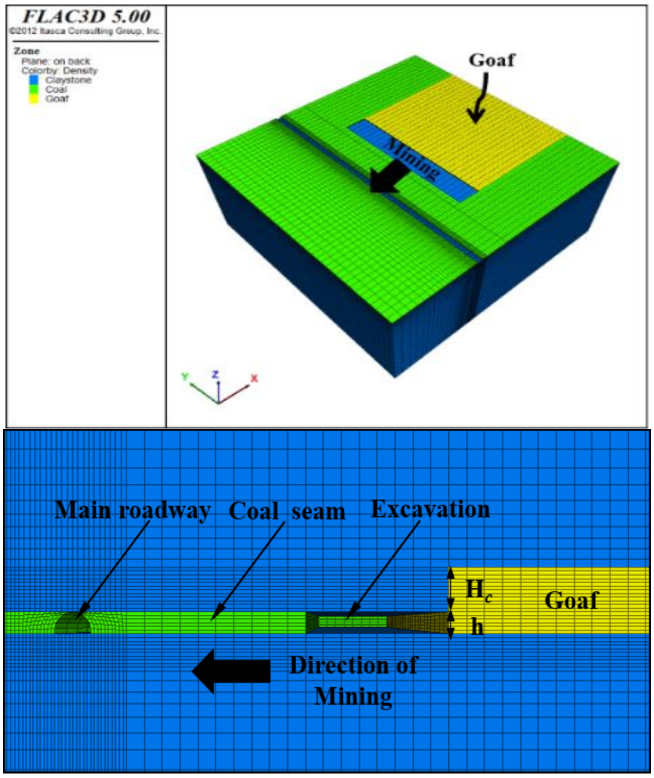

Fig. 12. Installation of goaf in longwall mining simulation

Table-4 Mechanical properties of goaf used in simulations

Parameter	**Value**
Density (kg/m^3)	**1700.000**
Young's modulus (MPa)	**15.000**
Poisson's ratio	**0.250**
Friction angle (°)	**25.000**
Cohesion (MPa)	**0.001**

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IV. RESULT AND DISCUSSION

A. Influence of chain pillar width on gate roadway stability

Fig. 13 shows an example of the strata deformation above the mined-out panel and the visualization of how the plan extraction affects the stability of the gate roadway at 50 m depth. It can be expected from the figure that the stability of the gate roadway will significantly depend on the width of the chain pillar and longwall panel. Hence, having an appropriate width of the chain pillar and longwall panel is very important to minimize the effect of the longwall mining on the gate roadway stability. In this section, the influence of the chain pillar width on the gate roadway stability during the longwall mining was studied and discussed. In simulation, four chain pillar widths of 30 m, 40 m, 50 m, and 60 m, and four mining depths of 50 m, 100 m, 150 m, and 200 m were considered. The panel width was fixed at 130 m.

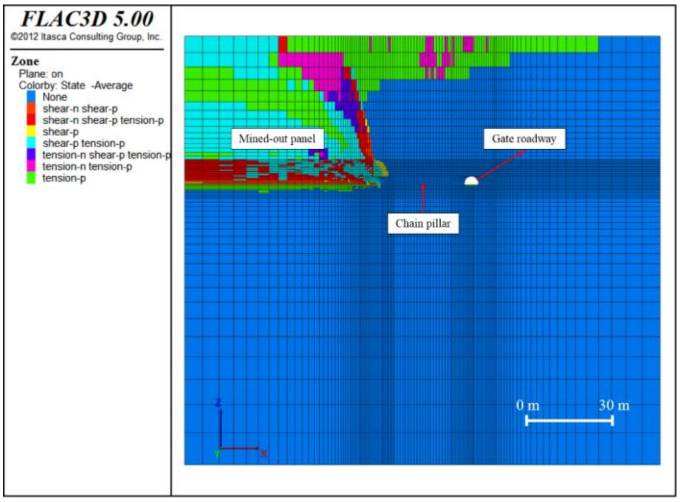
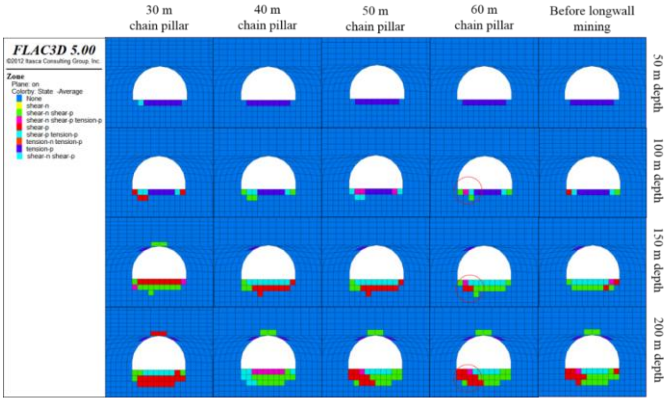
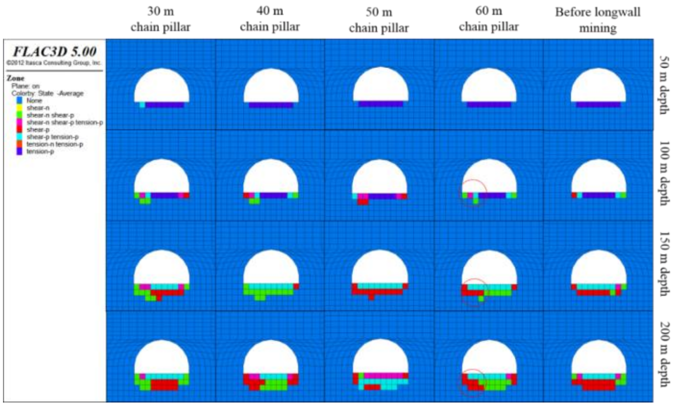


Fig. 13. Illustration of strata deformation above mined-out panel and visualization of how panel extraction influences stability of gate roadway

The failure zone of gate roadway after longwall mining under different chain pillar widths and mining depths is presented in Fig. 14. The chain pillar width is arranged in the column, while the mining depth is arranged in the row of the figure. The results show that the additional failure zone increased with decreasing the chain pillar width. This could be due to that when a smaller chain pillar was used during the longwall mining, the gate roadway experienced larger induced stresses caused by the coal panel extraction, resulting in a larger additional failure zone developed. Thus, it can be said that the chain pillar width has a significant influence on the stability of the gate roadway. A longwall mining with a wider chain pillar gives a better stability condition to the gate roadway.



(A)



(B)

Fig. 14. Failure zone of gate roadway under different chain pillar widths at various depths for fixed panel width as 130 m (a) roadway supported by 1 m spaced steel arch (b) roadway supported by 0.5 m spaced steel arch

Fig. 15 illustrates steel arch axial stress results of the steel arch support installed in the gate roadway. The same thing happened here as that happened with the failure zone. The steel arch axial stress increased significantly as the chain pillar width decreased. This confirms that a decrease in chain pillar width promoted an increase in longwall mining effect on the gate roadway stability. A proper chain pillar width must be selected in order to ensure the stability control of the gate roadway during the mining of coal panel. The appropriate chain pillar width was recommended based on the comparison of steel arch axial stress results and the maximum yield strength of the steel arch. According to the comparisons, when the roadway was supported by the 1 m spaced steel arch, a chain pillar width of 30 m was sufficient to ensure the stability of gate roadway at 50 m and 100 m depth, whereas a 50 m chain pillar width was needed at 150 m depth, and a chain pillar width of over 60 m was required at 200 m depth. In contrast, a chain pillar width of 30 m was adequate to maintain the gate roadway at 50 m, 100 m, and 150 m depth, while a chain pillar width of 50 m was adequate at 200 m depth, when the roadway was supported by the 0.5 m spaced steel arch.

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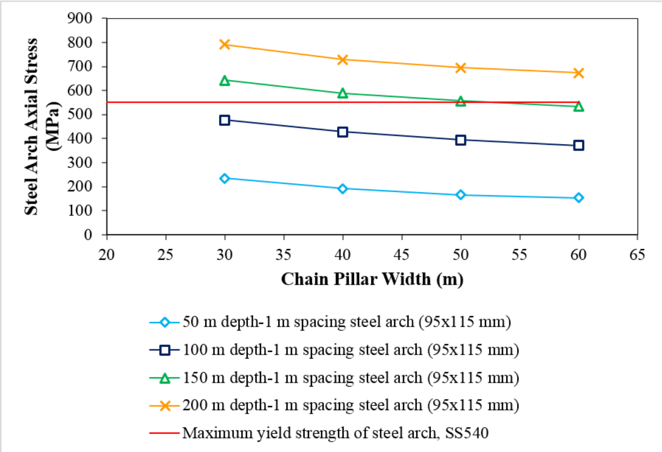
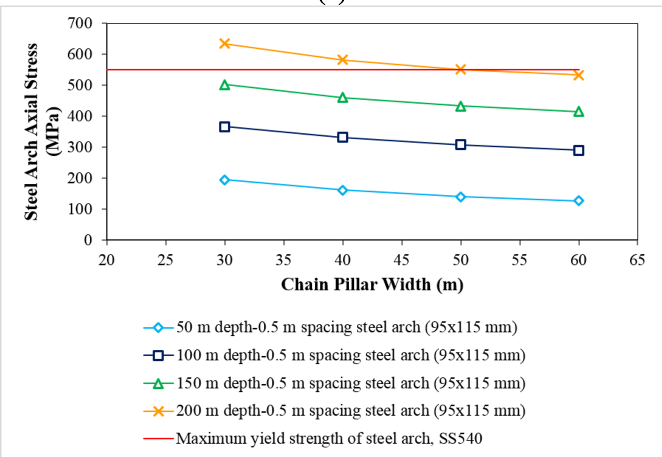


(a)



(b)

Fig. 15. Axial stress of steel arch support for gate roadway under different chain pillar widths at various depths for fixed panel width as 130 m (a) roadway supported by 1 m spaced steel arch (b) roadway supported by 0.5 m spaced steel arch

From Fig. 15, the relationship between the chain pillar width, mining depth, and steel arch axial stress (use for representing the maximum yield strength of the steel arch) in form of equations were made. The equation form that fits the most to the graph and has the highest value of correlation coefficient (R^2) was selected. The use of these equations is limited to the longwall mining of a 130 m panel width only. The equations are written as below.

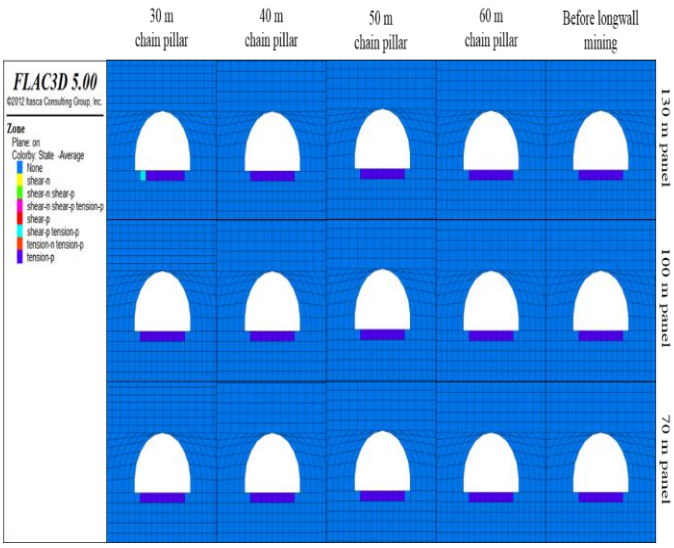
$$CP = (3.87H+147.27-SS)/3.42 \quad ; R^2 = 0.96$$
$$CP = (3.11H+112.37-SS)/3.33 \quad ; R^2 = 0.96$$

Where CP (m) is the chain pillar width, SS (MPa) is the steel arch axial stress, and H (m) is the mining depth.

Note: The first equation is used when the gate roadway is supported by the steel arches of 1 m space, whereas the last equation is used when the gate roadway is supported by 0.5 m spaced steel arches. The dimension of steel arch is 95x115 mm.

B. **Influence of panel width on gate roadway stability and chain pillar design**

The effect of longwall mining on the gate roadway stability under various panel widths of 70 m, 100 m, and 130 m was studied numerically in this section. Four mining depths of 50 m, 100 m, 150 m, and 200 m, and four chain pillar widths of 30 m, 40 m, 50 m, and 60 m, were considered in the simulations. Fig. 16 demonstrates the comparison of failure zones occurred in the gate roadway after three panel widths were extracted. The figure only shows failure zone results of the gate roadway supported by 0.5 m spaced steel arches. The row of the figure indicates the panel width, while the column indicates the width of chain pillar. The results show that a decrease in effect of longwall mining on the stability of the gate roadway was considerably associated with a decrease in panel width. The additional failure zone was developed earlier at a wider chain pillar when a larger longwall panel was mined. In contrast, it was developed later at a narrower chain pillar when a smaller longwall panel was extracted. For example, at 200 m depth, the additional failure was noticed at 60 m, 40 m, and 30 m chain pillar width when a 130 m, 100 m, and 70 m panel width was mined, respectively. This confirms that a narrower chain pillar can be designed if a smaller panel is adopted.



(a)

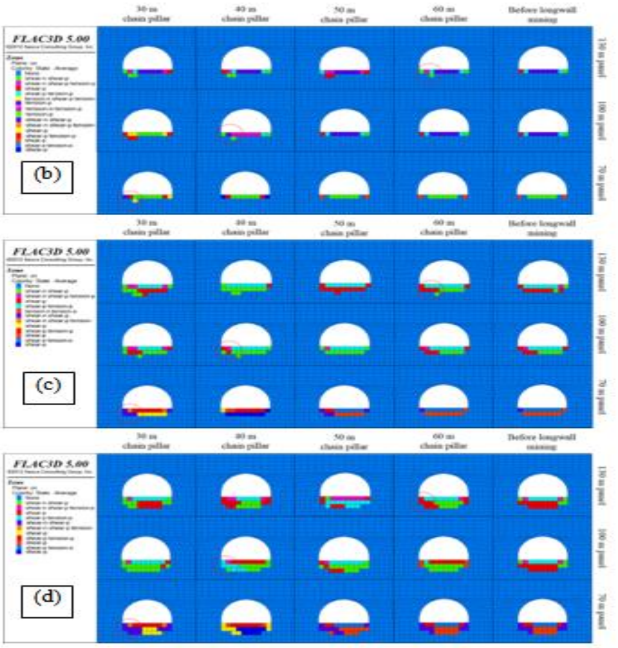
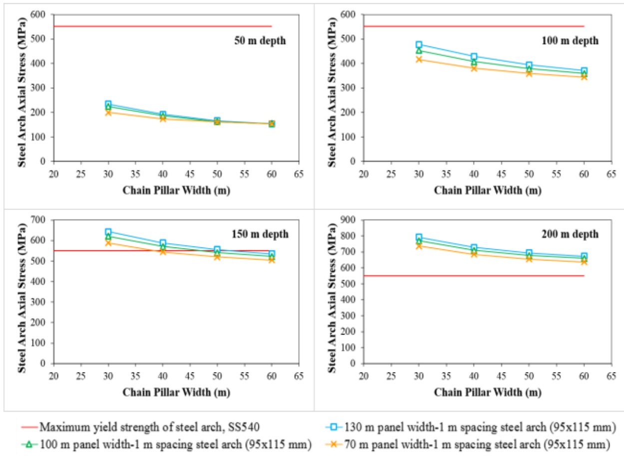


Fig. 16. Failure zone of gate roadway affected by longwall mining under various panel widths (a) at 50 m depth (b) at 100 m depth (c) at 150 m depth (d) at 200 m depth

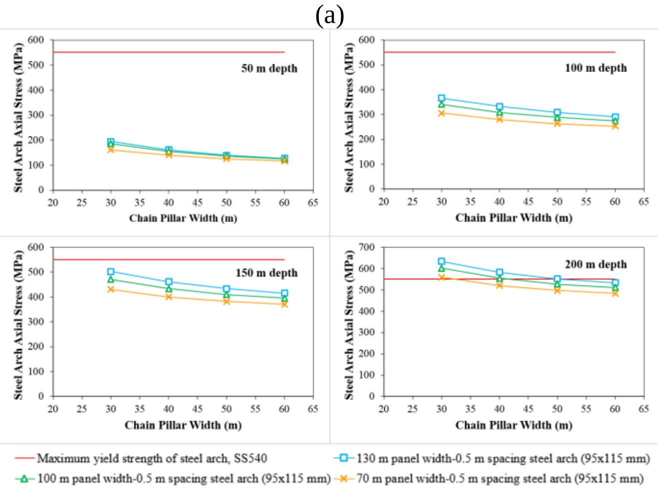
Fig. 17 presents the results of steel arch axial stress obtained from longwall mining under different panel widths. The results represent that the effect of longwall mining on the gate roadway stability can be minimized by decreasing the panel width. A smaller panel width gave less effect of longwall mining, while a wider panel width gave more. A decrement of steel arch axial stress was observed when the panel width decreased. Several widths of the chain pillar for different panel widths at various depths were recommended based on the results of steel arch axial stress compared with the maximum yield strength of the SS540 steel arch. These chain pillar widths are summarized in Table 5. It can be seen from the table that a narrower chain pillar width can be designed if a smaller longwall panel is adopted. When the gate roadway was supported by 1 m spaced steel arches, a chain pillar width of 30 m was enough at 50 m and 100 m depth for longwall mining of all panel widths of 70 m, 100 m, and 130 m. At 150 m, a chain pillar width of 37 m, 45 m, and 50 m was sufficient for longwall mining of a 70 m, 100 m, and 130 m panel width, respectively. Besides, the use of chain pillar width larger than 60 m was suggested at 200 m depth for longwall mining of all panel widths. In contrast, when the gate roadway was supported by 0.5 m spaced steel arches, a chain pillar width of 30 m was adequate until 150 m for longwall mining of all panel widths. However, the use of a larger chain pillar width of 32 m, 40 m, and 50 m was recommended at 200 m depth for longwall mining of a 70 m, 100 m, and 130 m panel width, respectively.

Table-5 Chain pillar width (m) for different panel widths at various depths

Support of gate roadway (SS540, 95x115 mm)		1.0 m space			0.5 m space		
Panel width (m)		**70**	**100**	**130**	**70**	**100**	**130**
Depth (m)	**50**	**30**	**30**	**30**	**30**	**30**	**30**
	100	**30**	**30**	**30**	**30**	**30**	**30**
	150	**37**	**45**	**50**	**30**	**30**	**30**
	200	**>60**	**>60**	**>60**	**32**	**40**	**50**



(a)



(b)

Fig. 16. Axial stress of steel arch support for gate roadway under different panel widths at various depths (a) roadway supported by 1 m spaced steel arch (b) roadway supported by 0.5 m spaced steel arch

From Fig. 16, the relationship between the chain pillar width, panel width, and steel arch axial stress in form of equations were also made and summarized in Table 6.

Table-6 Equations of relationship between chain pillar width, panel width, and steel arch axial stress.

Mining depth (m)	Support of gate roadway (steel arch SS540, 95x115 mm)	
	0.5 m space	1.0 m space
50	CP = (0.88PN+145.51-SS)/2.23 R^2 = 0.96	CP = (1.11PN+167.39-SS)/2.5 R^2 = 0.93
100	CP = (1.4PN+258.42-SS)/2.52 R^2 = 0.97	CP = (1.59PN+374-SS)/3.55 R^2 = 0.97
150	CP = (1.63PN+373.61-SS)/2.47 R^2 = 0.96	CP = (1.29PN+575.5-SS)/3.19 R^2 = 0.95
200	CP = (1.64PN+514.34-SS)/2.98 R^2 = 0.95	CP = (1.17PN+747.37-SS)/3.61 R^2 = 0.94

Where CP (m) is the chain pillar width, SS (MPa) is the steel arch axial stress, and PN (m) is the panel width.

V.CONCLUSION

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

To maintain the gate roadway during the longwall mining, an appropriate width of chain pillar is recommended. When the gate roadway is supported by 1 m spaced steel arches, a chain pillar width of 30 m can be used at 50 m and 100 m depth for longwall mining of all panel widths of 70 m, 100 m, and 130 m. At 150 m, a chain pillar width of 37 m, 45 m, and 50 m is sufficient for longwall mining of a 70 m, 100 m, and 130 m panel width, respectively. In addition, the use of chain pillar width larger than 60 m is suggested at 200 m depth for longwall mining of all panel widths. In contrast, when the gate roadway is supported by 0.5 m spaced steel arches, a chain pillar width of 30 m can be used until 150 m for longwall mining of all panel widths. However, the use of a larger chain pillar width of 32 m, 40 m, and 50 m is recommended at 200 m depth for longwall mining of a 70 m, 100 m, and 130 m panel width, respectively.

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