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PREDICTION OF MULTI-SEAM MINING-INDUCED SURFACE SUBSIDENCE IN UNDERGROUND COAL MINE IN INDONESIA

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Graphical abstract

Abstract

This paper attempts to predict the surface subsidence induced by multi-seam longwall mining in the PT Gerbang Daya Mandiri (GDM) underground coal mine in Indonesia. Several numerical models of multi-seam longwall mining under various depths were built in the finite difference code software "FLAC3D" which was used as a tool for numerical simulations. Effect of mining sequence and influence of lower seam mining were firstly investigated. The angle of draw (AoD) and maximum surface subsidence (S_{max}) were used to describe characteristics of the surface subsidence. Based on simulated results, it is indicated that the undermining provides a better mining sequence in multi-seam longwall mining compared to the overmining. Mining the coal seam in an undermining order will not cause any difficult mining conditions in a lower seam, whereas some ground control problems in an upper seam are expected when the coal seam is mined in an overmining order. Under all mining depths in the undermining, extracting the lower seam panels significantly influences the magnitude of surface subsidence. The AoD and S_{max} increase significantly after all panels in the lower seam is mined. This indicates that very large surface subsidence is expected when multi-seam mining is applied at GDM underground coal mine. An application of some countermeasures such as adopting a large pillar width and a small panel width is suggested in this underground coal mine in order to minimize the surface subsidence caused by multi-seam longwall mining. Minimizing the surface subsidence by adopting a large pillar width and a small panel width is therefore numerically investigated in this paper. Based on simulated results, it is found that the AoD and S_{max} decrease significantly when larger pillar width and narrower panel width are adopted. The use of larger pillar width and narrower panel width result in smaller AoD and S_{max}.

Keywords: FLAC3D, multi-seam longwall mining, numerical simulation, surface subsidence, weak geological condition

1.0 INTRODUCTION

Coal is globally used as a fuel in various industrial sectors such as electricity, steel, and cement productions. The coal production in Indonesia has increased significantly in the past years (Figure 1). Indonesia exports the coal abroad, mostly to China and India, accounted roughly for 70 to 80% of the total coal production, while the remaining is sold on domestic markets [1].

The coal in Indonesia is mainly produced using the surface mining method. Recently, numerous surface mines have been left abandoned due to an increase in the stripping ratio as the mining depth increased. The development of new surface mines has been challenged by their environmental impacts and protections. As a result, some underground coal mines have been developed in order to meet the demand for coal production in the country [2, 3]. A longwall mining is the most popular coal extracting technique by underground mining in Indonesia.

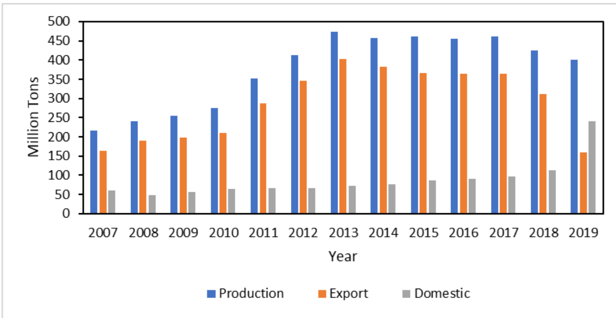


Figure 1 Production, export, and domestic consumption of Indonesian coal [1]

Longwall mining is a highly productive and safe underground mining technique. It is normally applied to extract coal seams of a large horizontal extent with uniform thickness [4, 5]. Figure 2 demonstrates mechanisms of strata movement above a longwall mining [6]. The rock strata behind the longwall mining face are collapsed when a longwall panel of sufficient width and length is mined, hence causing the immediate roof strata to subside toward the surface. Figure 3 illustrates the basic subsidence profile resulting from a single panel longwall mining [5]. In general, maximum surface subsidence (S_{max}) and angle of draw (AoD) are used to define the magnitude, shape, and limitation of the subsidence at the surface. In multi-seam longwall mining, during the mining of the lower seam (or upper seam), the strata movement in the interburden and overburden will arise which can result in difficult mining conditions when the subsequent seam is mined, as illustrated in Figure 4 [7]. Consequently, coal recovery from the seam that overlies (or underlies) the mined-out seam may be significantly reduced. The percent of coal loss is a function of rock type, extraction sequence, mine geometries, and interburden thickness [8].

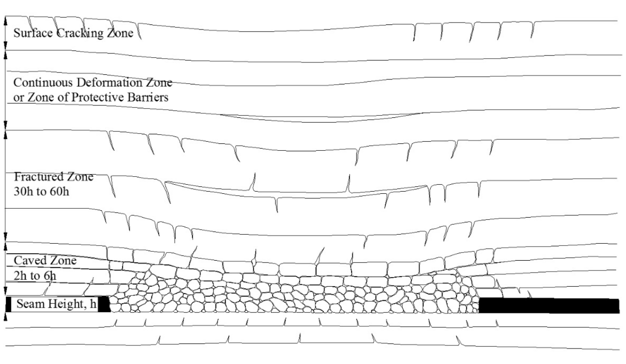


Figure 2 Movement of roof strata resulting from longwall mining [6]

In Indonesia, the coal measure strata consist of sedimentary rocks such as sandstone, claystone, siltstone, shale, and mudstone. Their mechanical properties are generally weak and deteriorated due to water. According to the results of uniaxial compressive strength (UCS) tests, it is indicated that the strengths of rocks in Indonesian coal mines are much lower than that of coal mines in other countries (Figure 5). The UCS values of coal measure rocks range from 1-20 MPa [3, 9-12]. Therefore, the rocks of Indonesian coal mines can be classified into weak and low strength rocks [13, 14]. Because a large extent of coal is removed from the seam, and due to the coal measure rocks are weak, large subsidence at the surface can be expected when a longwall mining is applied in an Indonesian underground coal mine. A study of surface subsidence is needed in order to avoid the adverse impacts of subsidence at the surface. The knowledge of surface subsidence will improve the design of longwall mining.

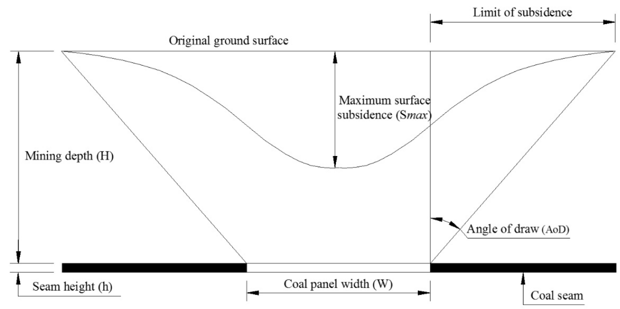


Figure 3 Subsidence profile above single longwall mining [5]

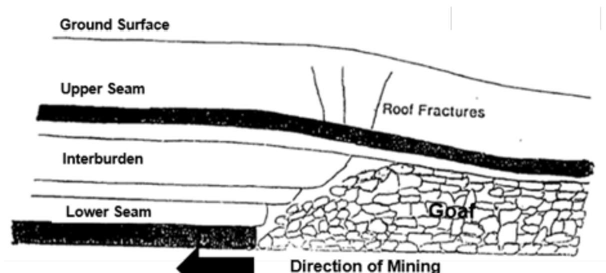


Figure 4 Effect of caving and settlement of strata around upper seam after mining lower seam [7]

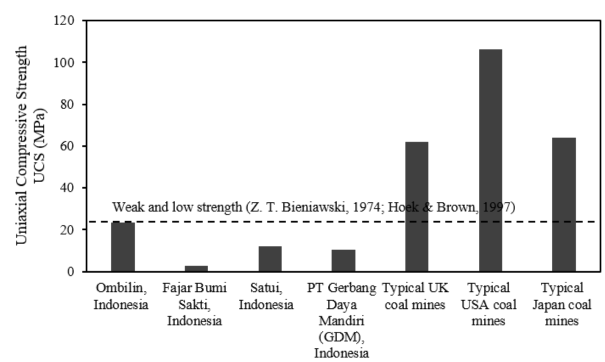


Figure 5 Uniaxial compressive strength of coal measure rocks in Indonesia, UK, USA, and Japan [3, 9-12]

Due to characteristics of the surface subsidence induced by multi-seam longwall mining, especially under weak geological conditions, have not been researched sufficiently, therefore, the deep understanding of the strata movement caused by multi-seam mining is still restricted. Most of the available researches are found on the understanding of the strata movement due to single-seam mining, and they are unable to account for specific multi-seam subsidence characteristics. The multi-seam longwall mining has brought new challenges to

Indonesian coal mines for the prediction of multi-seam mining-induced surface subsidence since the characteristics of surface subsidence induced by single-seam and multi-seam mining are different. Therefore, the engineers of Indonesian coal mines must understand the subsidence characteristics induced by multi-seam longwall mining. This is to minimize the coal loss and ensure the safe working conditions of a subsequent seam and also prevent adverse impacts on the surface.

The objective of this research was to study the characteristics of surface subsidence induced by multi-seam longwall mining under poor ground conditions in Indonesia. The PT Gerbang Daya Mandiri (GDM) underground coal mine in Indonesia was selected for this study. Several numerical models of multi-seam longwall mining under various depths were built in the finite difference code software "FLAC3D" which was used as a tool for numerical simulations. Effect of mining sequence, the influence of lower seam mining, and influence of pillar and panel widths on the surface subsidence were investigated, while the angle of draw (AoD) and maximum surface subsidence (S_{max}) were used to describe characteristics of the surface subsidence at the surface.

2.0 PT GERBANG DAYA MANDIRI COAL MINE AND ITS GEOLOGICAL CONDITIONS

The PT Gerbang Daya Mandiri (GDM) coal mine is one of the underground coal mines which is being operated in Indonesia. This coal mine is situated in the Kutai Kertaegara Regency, approximately 16.5 kilometers going northwest from the center of Samarinda City, East Kalimanta, Indonesia. The location map of this underground coal mine is shown in Figure 6. GDM coal mine has reserved approximately 29.2 million tons of the recoverable sub-bituminous coal. Annually, the GDM coal mine plans to extract the coal of 1 million tons from the underground by using the longwall mining technique. Figure 7 illustrates the layout of coal panels of the GDM coal mine.

Figure 6 Location of GDM underground coal mine

Figure 8 illustrates the geological map of the GDM underground coal mine. The GDM coal mine is laid within the Kutai Basin formed during the Tertiary geological period. Balikpapan formation and Pulau Balang formation are major coal-bearing formations in the Kutai Basin. Many coal seams in the Balikpapan formation have been found in the GDM coal mine from the drill hole at the open cut area and the mining activity. Balikpapan formation consists of mudstone, sandstone, siltstone, coal, and coaly shale. Mudstone is dark gray to light gray, mudstone often becomes coaly mudstone. This locally contains plant remains, iron oxide, which has filled up the cracks of layers, locally contains calcareous sandstone lenses. Sandstone is dark gray to whitish-gray and brownish-gray; grain size is very fine to coarse. Relatively coarser grain contains quartz grain (especially coarse sandstone), those rarely contain gravels (granule to pebble). Sandstone shows graded bedding and cross bedding, contains small foraminifera. Siltstone is dark gray to light gray; partial siltstone is sandy siltstone.

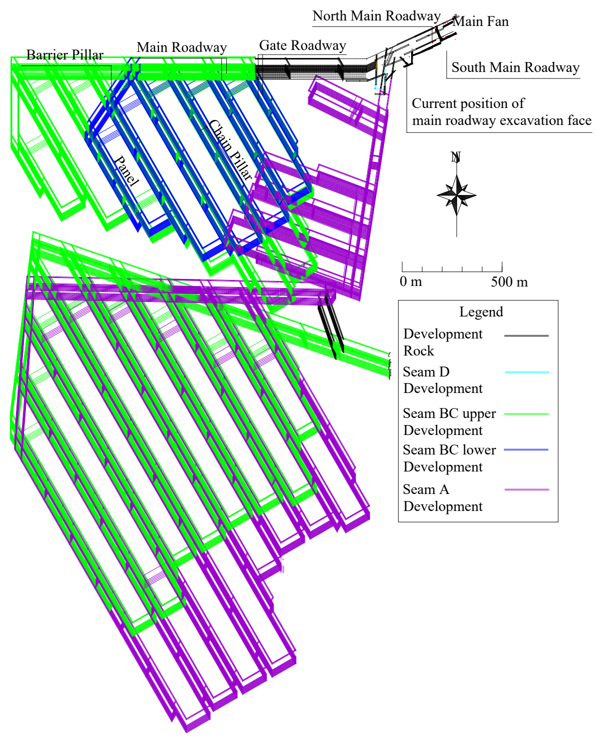


Figure 7 Mine layout of GDM underground coal mine

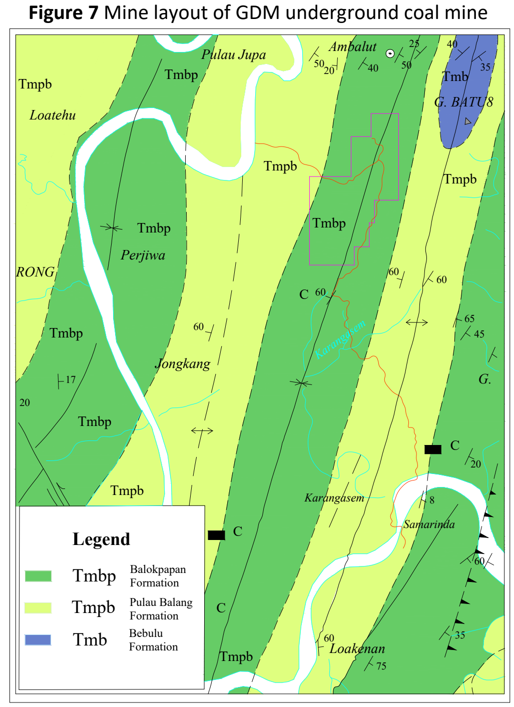


Figure 8 Geological map of GDM underground coal mine

Pulau Balang formation consists of mainly mudstone, sandstone, siltstone, coal, and coaly shale. Mudstone is dark gray to light gray, mudstone often becomes coaly mudstone. Sandstone is dark gray to whitish-gray and brownish-gray, grain size is very fine to coarse, coarse sandstone and medium sandstone contain many quartz grains, those rarely contain gravels (granule to pebble size). Siltstone is dark gray to light gray; partial siltstone is sandy siltstone. Sometimes mudstone, sandstone, and siltstone contain coal and plant fragments, this is a remarkable feature near coal seam. There are siltstone laminas to a thin layer and mudstone lamina to a thin layer in sandstone, there are sandstone laminas in siltstone. In the GDM coal mine, the geological structure is a simple monocline structure and the fault was not found. Figure 9 illustrates the typical stratigraphy of the GDM underground coal mine. Seam A and Seam BC are major mineable seams for underground mining. Seam A varies from 1.06 m to 6.14 m in thickness, while the thickness of Seam BC differs from 3.31 m to 9.80 m. Claystone and sandstone are rock layers that separate the coal seams. However, claystone is a dominant rock unit.

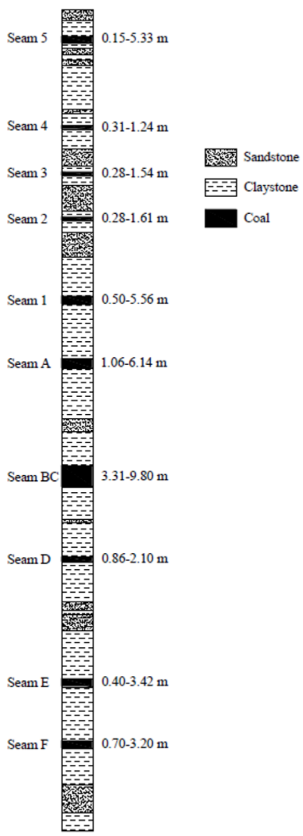


Figure 9 Stratigraphic column of GDM underground coal mine

Table 1 shows the mechanical properties of coal and rock of the GDM coal mine. These parameters were obtained from the Laboratory of Geomechanics and Mine Equipment, Institute of Technology of Bandung, Indonesia. Coal and rock samples were collected from boreholes at different depths ranging from 37 m to 350 m. Figure 10 illustrates the quality of cores collected from the NED-02A Borehole at the GDM underground coal mine.

The technique of the Uniaxial Compressive Test was adopted for testing Young's modulus, Poisson's ratio, and uniaxial compressive strength (UCS) of rock and coal in the GDM underground coal mine. The rock and coal samples were prepared in a cylinder shape with a diameter and length of 54 mm and 108 mm, respectively. To obtain Young's modulus, Poisson's ratio, and uniaxial compressive strength values, the specimens were placed on the lower part of a testing apparatus. The axial load was then applied continuously on samples under constant stress. The maximum load and strains at the failure point were measured for calculating Young's modulus, Poisson's ratio, and the uniaxial compressive strength of coal and rock.

Table 1 Properties of materials used in simulations

No.	Parameters	Rock Mass	Coal Seam
1	Uniaxial compressive strength (MPa)	10.49	8.16
2	Density (kg/m^3)	2140	1380
3	Young's modulus (MPa)	2324.68	1295
4	Poisson's ratio	0.27	0.32
5	Internal friction angle (◦)	37.48	45
6	Cohesion (MPa)	0.56	2.63

Cohesion and Friction angle of rock and coal in the GDM underground coal mine were determined by the technique of Triaxial Compression Strength Test. The sample shape is cylindrical and the diameter is 54 mm. The height to diameter ratio of 2 of the samples was prepared for the test. The ends and lateral sides of the samples were smoothed and this is to ensure that the applied loads are uniformly transmitted to the sample. After the samples of rock and coal were completely prepared, a cylindrical rock/coal sample was placed in a testing cell. The testing cell was then placed in the loading apparatus which is used to apply a vertical load and lateral pressure to the sample at a constant rate. The maximum load and pressure for a rock/coal sample to fail were recorded for calculating the cohesion and friction angle.

Figure 10 Photos of cores collected from NED-02A Borehole (a) cores at 63-68 m depth (b) cores at 148-153 m depth (c) cores at 204-209 m depth (d) cores at 280-285 m depth

Figure 11 shows the relationship between Young's modulus and uniaxial compressive strength (UCS) of coal and rock. The UCS values of coal and rock were not used in the simulations, however, this property was used for indicating the strength of rock and coal in the GDM underground coal mine. Based on the UCS results, coal and rock in this underground mine are said to be weak and low strength rocks [15, 16].

3.0 NUMERICAL MODEL

Several numerical models of multi-seam longwall mining under various depths (50 m, 100 m, 150 m, and 200 m) were built in FLAC3D. An example of the numerical model at 200 m depth is described in Figure 12. The width, length, and height of the model is 1500 m, 2000 m, and 350 m, respectively. The bottom and sides of the model were fixed in the vertical direction and horizontal direction, respectively. The surface of the model was set free in all directions. The vertical stress was simulated as a function of the overburden thickness (P_v = γH, γ is the unit weight of overburden, and H is overburden thickness) [10-12]. The horizontal stress was presumed to be equal to the vertical stress. The Mohr-Coulomb failure criterion was used throughout the analyses.

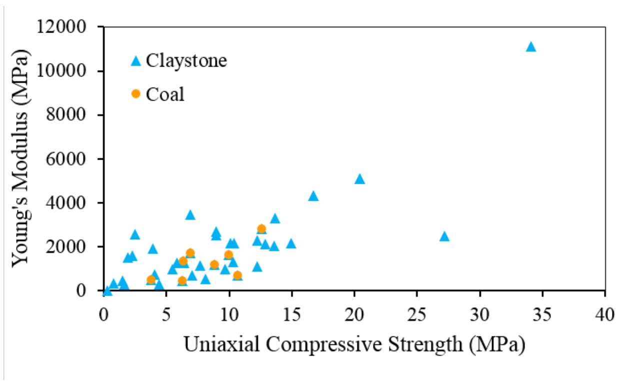


Figure 11 Relationship between Young's modulus and uniaxial compressive strength of coal and claystone of GDM underground coal mine

The model contains two coal seams including upper and lower seams (Figure 12a). The upper seam and lower seam were separated by the interburden layer. According to the conditions of the GDM coal mine, the minimum interburden thickness between Seam A and Seam BC is approximately 50 m. Hence, a 50 m thick interburden was initially selected. In the simulation, three coal panels of 3 m thickness were extracted in each seam, and they were separated by coal pillars (Figure 12b). The panel width of 100 m was initially selected for multi-seam longwall mining. Moreover, the coal panel of 1000 m length was considered throughout the simulations. The properties of rock mass and coal seam used in the simulations are summarized in Table 1. Since the measurement of deformations in the goaf is difficult due to inaccessibility, there is still no standard method for modeling the goaf. In this paper, the properties of goaf are summarized from the previous researches [17-19] and given in Table 2.

Table 2 Properties of goaf used in simulations

No.	Parameters	Goaf
1	Density (kg/m^3)	2140
2	Young's modulus (MPa)	2324.68
3	Poisson's ratio	0.27
4	Internal friction angle (◦)	37.48
5	Cohesion (MPa)	0.56

4.0 RESULTS AND DISCUSSIONS

4.1 Effect of Mining Sequence on Subsequent Seam Conditions

The effect of mining sequence on subsequent seam conditions was firstly investigated in order to confirm the most appropriate sequence for multi-seam longwall mining. Two mining sequences were studied and compared, such as undermining and overmining.

Undermining is a top-down multi-seam mining where the upper seam is mined first and followed by the lower seam. Overmining is a bottom-up multi-seam mining where the lower seam is mined first and followed by the upper seam. In the simulation, the coal panel of 100 m width and 1000 m length, and the coal pillar of 30 m width, were considered. The upper coal seam and lower coal seam were separated by a 50 m thick interburden layer.

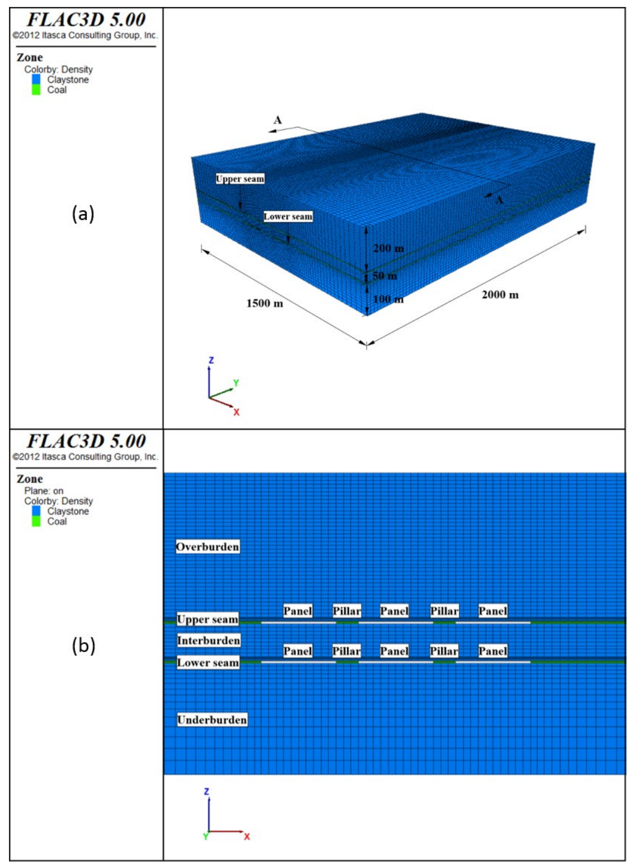


Figure 12 Description of numerical model of multi-seam longwall mining at 200 m depth (a) model geometries (b) cross-section of numerical model

Figures 13 and 14 show the strata failure and surface subsidence induced by undermining and overmining operation, respectively. From these figures, it was found that the undermining provided a better mining sequence compared with the overmining. In the undermining sequence, the strata deformation in the lower seam was not observed after the upper seam mining. This indicates that mining the upper seam will not cause any difficult mining conditions in the lower seam. From this, it is expected that the lower seam can be subsequently mined without any ground control problem. Differ from the overmining sequence, the large failure zone and subsidence occurred and extended to the upper seam after the lower seam was mined. This indicates that the difficult mining conditions of the upper seam are expected, and the ground control problems can occur in the upper seam that is subsequently mined. Generally, for any mining activities to be conducted with overmining sequence, the upper seam must be above the failure zone. If the upper seam is within the failure zone of the lower seam, it must be concluded that the upper seam will be lost entirely [20].

Based on the simulated results, in short, it can be said that the overmining sequence is inappropriate to be applied for multi-seam mining in the case of the GDM coal mine. Ideally, to prevent difficult mining conditions, expected ground control problems, and to maximize the coal recovery of the subsequent seam, the sequence of mining should proceed in an undermining order. As undermining is a preferred method of multi-seam mining in comparison with the overmining, therefore, only the undermining case is considered in the following sections for predicting the surface subsidence induced by multi-seam longwall mining.

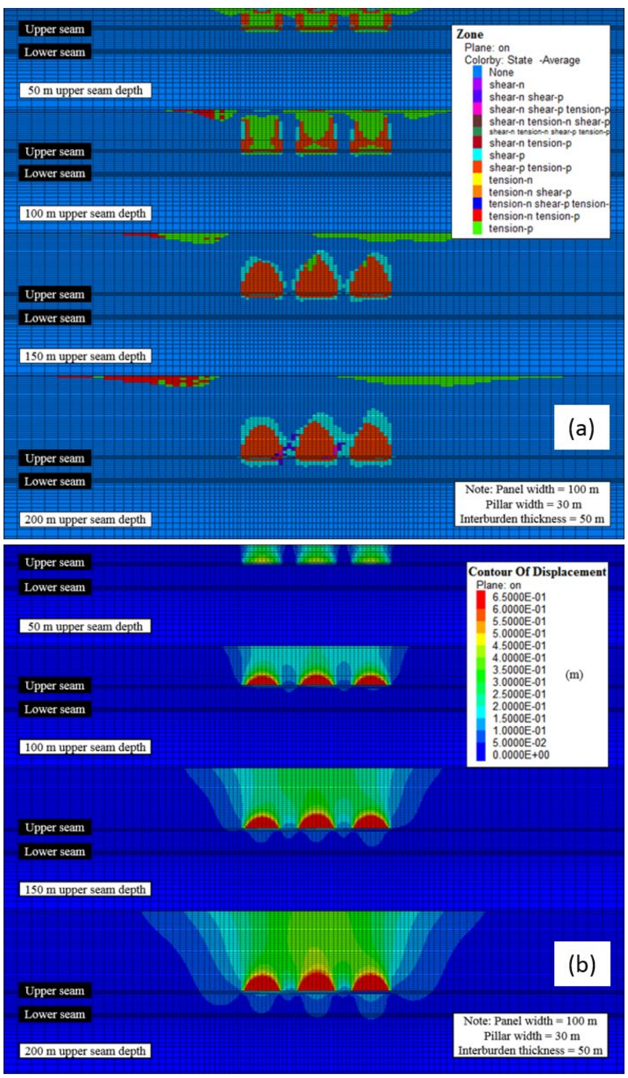


Figure 13 Failure zone and subsidence induced by undermining (a) failure zone (b) subsidence contours

4.2 Effect of Lower Seam Mining on Surface Subsidence

This section investigated the characteristics of surface subsidence induced by the lower seam mining. The mining schematic considered in the simulations is presented in Figure 15. The model consists of two coal seams with three panels in each seam. The panel was 100 m in width and 1000 m in length. The coal pillar of 30 m width was used to separate the coal panels. The upper and lower coal seams were separated by a 50 m thick interburden. Four mining depths to the upper seam were simulated numerically, such as 50 m, 100 m, 150 m, and 200 m. To understand the effect of the lower seam mining in simulation, three coal panels in the upper seam were extracted first. The angle of draw (AoD) and maximum surface subsidence (S_{max}) were recorded after the upper seam was mined. The panel in the lower seam was then extracted panel by panel in the order from left to right. After each panel in the lower seam was mined, the AoD and S_{max} were monitored.

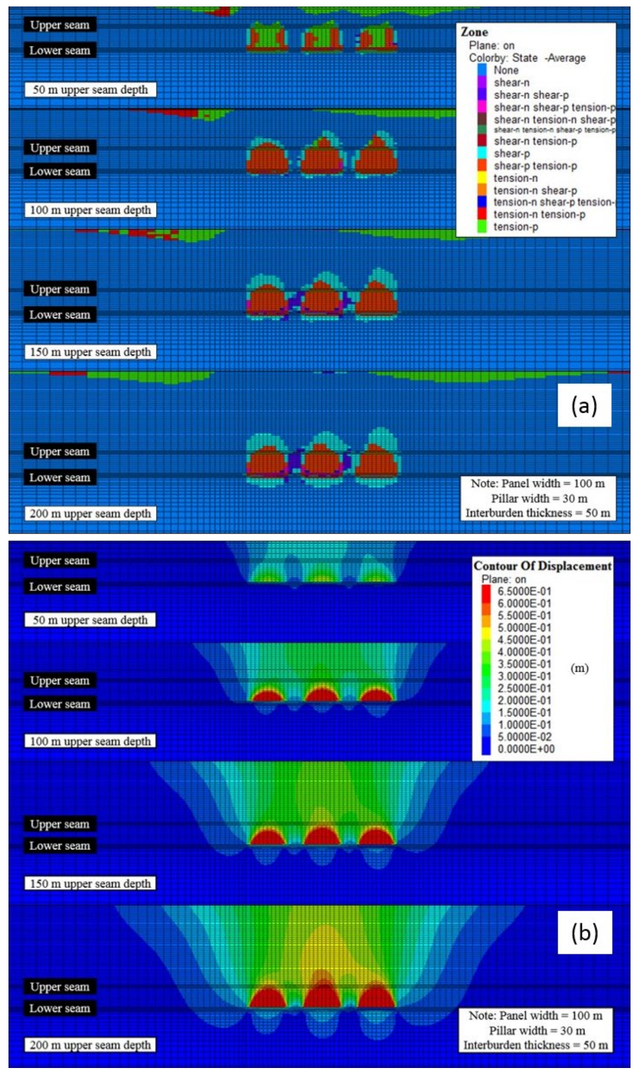


Figure 14 Failure zone and subsidence induced by overmining (a) failure zone (b) subsidence contours

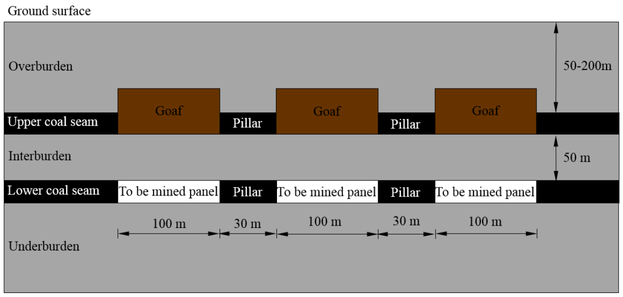


Figure 15 Mining schematic considered in simulation for lower seam mining effect on surface subsidence

Figures 16-19 show the results of surface subsidence affected by the lower seam mining for each mining depth. Under all mining depths, it can be found that extracting the lower seam panels significantly influenced the magnitude of AoD and S_{max}. After mining the first panel in the lower seam, the AoD and S_{max} increased considerably. The AoD increased from 10° to 13° and S_{max} increased from 0.22 m to 0.49 m at 50 m depth, whereas the AoD increased from 27° to 33° and S_{max} increased from 0.24 m to 0.50 m at 100 m depth, while AoD increased from 43° to 50° and S_{max} increased from 0.29 m to 0.52 m at 150 m depth, and AoD increased from 50° to 54° and S_{max} increased from 0.38 m to 0.66 m at 200 m depth. This could be due to the extraction of the first panel in the lower seam re-activated the strata movement in the previously caved zone and pillar in the upper seam. The caved zone and pillar in the upper seam were deformed for the second time (see failure zone results). This new deformation of the previously caved zone and pillar reduced the strength and bridging ability of the overburden strata, causing extra deformation in the overburden area and eventually led to the enhanced magnitude of the AoD and S_{max}.

In addition, a larger magnitude of AoD and S_{max} was observed apparently when the extraction area increased as the second and third panels were mined in the lower seam. The AoD and S_{max} increased largely because the previously caved zone and coal pillar in the upper seam experienced a greater re-activation of the strata movement due to a larger area was extracted in the lower seam. For this reason, more deformation in the overburden layer occurred, causing less bridging ability, and leading to a greater magnitude of AoD and S_{max} consequently.

Table 3 summarizes the progressive and total AoD and S_{max} values observed at the surface caused by the lower seam mining. From the table, for example under 200 m depth, the AoD considerably increased from 50° to 54°, 57°, and 58° while the S_{max} significantly increased from 0.37 m to 0.66 m, 1.25 m, and 1.70 m after the first, second, and third panel of the lower seam was extracted, respectively.

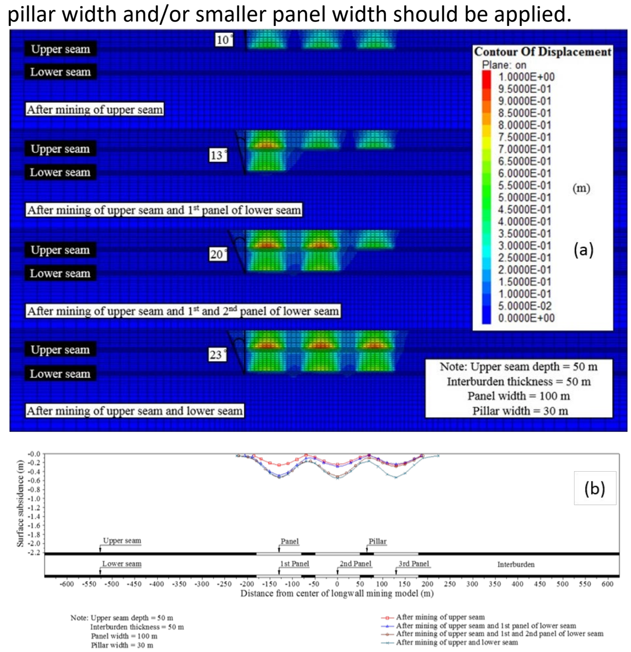
Table 3 Comparison of progressive AoD and S_{max} values caused by lower seam extraction

No.	Mining Depth (m)	After Upper Seam Mining		After 1st Panel of Lower Seam		After 2nd Panel of Lower Seam		After 3rd Panel of Lower Seam	
		AoD (°)	S_{max} (m)	AoD (°)	S_{max} (m)	AoD (°)	S_{max} (m)	AoD (°)	S_{max} (m)
1	50	10	0.22	13	0.49	20	0.53	23	0.55
2	100	27	0.24	33	0.50	45	0.61	47	0.79
3	150	43	0.29	50	0.52	54	0.95	56	1.28
4	200	50	0.38	54	0.66	57	1.25	58	1.70

Based on the simulated results, it can be said that the extraction of the lower seam has a significant impact on the surface subsidence. The magnitude of surface subsidence greatly increases in comparison with the single-seam extraction (upper seam only). Therefore, to prevent the adverse impacts on the surface due to the large subsidence, and to minimize the subsidence magnitude, some countermeasures for subsidence control must be prepared when the multi-seam longwall mining is conducted at the GDM coal mine.

As observed from the subsidence profile and S_{max} value, the S_{max} at 50 m depth remained almost stable although the extraction of the second and third panels in the lower seam was already completed. Only a small increment of S_{max} was observed. The S_{max} increased from 0.49 m to 0.53 m and 0.55 m after the second and third panels were mined, respectively. This happened because the pillars in both the upper seam and lower seam were still maintained in a stable condition, only a small failure zone of the pillar was observed (Figure 16c). Under this situation, the pillar provided adequate support to constrain the development of additional S_{max}. Therefore, it is indicated that the use of a 30 m pillar width will be sufficient in multi-seam longwall mining at 50 m depth. To minimize the surface subsidence at this depth, the consideration of using a smaller panel width should be made.

On the contrary, the S_{max} at 100 m, 150 m, and 200 m depth dramatically increased after the second and third panels of the lower seam were extracted. The S_{max} increased from 0.50 m to 0.61 m and 0.79 at 100 m depth, while the S_{max} increased from 0.52 m to 0.95 m and 1.28 m at 150 m depth, and it increased from 0.66 m to 1.25 m and 1.70 m at 200 m depth after the second and third panels in the lower seam were mined, respectively. This was due to the failure of the pillars (Figures 17-19c). The pillar under this condition could not provide a support to the roof strata sufficiently. As a consequence, an increment of Smax was observed. From the results, thus, to minimize the magnitude of surface subsidence caused by multi-seam mining at 100 m, 150 m, and 200 m depth, the larger pillar width and/or smaller panel width should be applied.



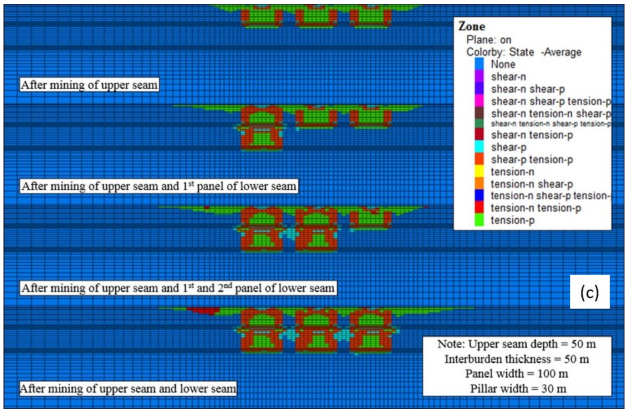
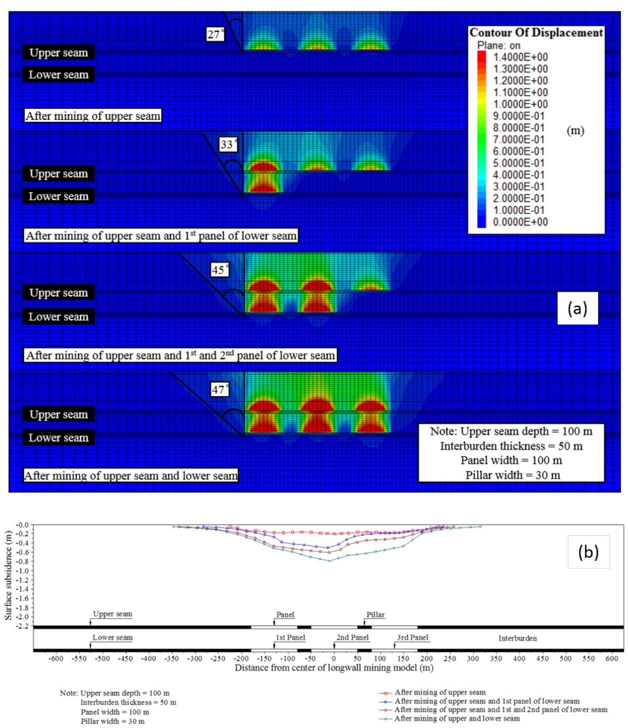


Figure 16 Results of subsidence affected by lower seam mining at 50 m depth (a) contour of subsidence and angle of draw (b) profile of surface subsidence (c) failure zone of overburden and interburden

4.3 Countermeasures for Controlling Surface Subsidence

According to the simulation results of surface subsidence induced by multi-seam longwall mining which are discussed in previous sections, it is found that the occurrence of large subsidence at the surface is expected when the multi-seam mining is applied at GDM underground coal mine. To prevent the adverse impacts that may occur at the surface due to the large subsidence, some countermeasures for subsidence control must be prepared such as adopting a large size of coal pillar or small size of longwall panel. Certainly, these methods will reduce the effect of lower seam mining, and increase the supporting and bridging ability of the interburden and overburden strata.



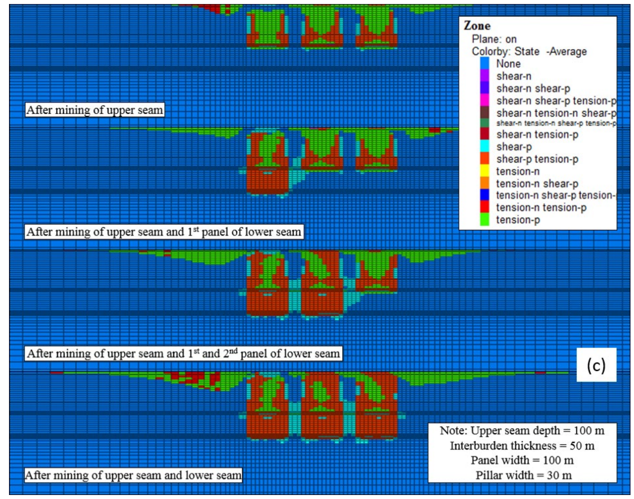
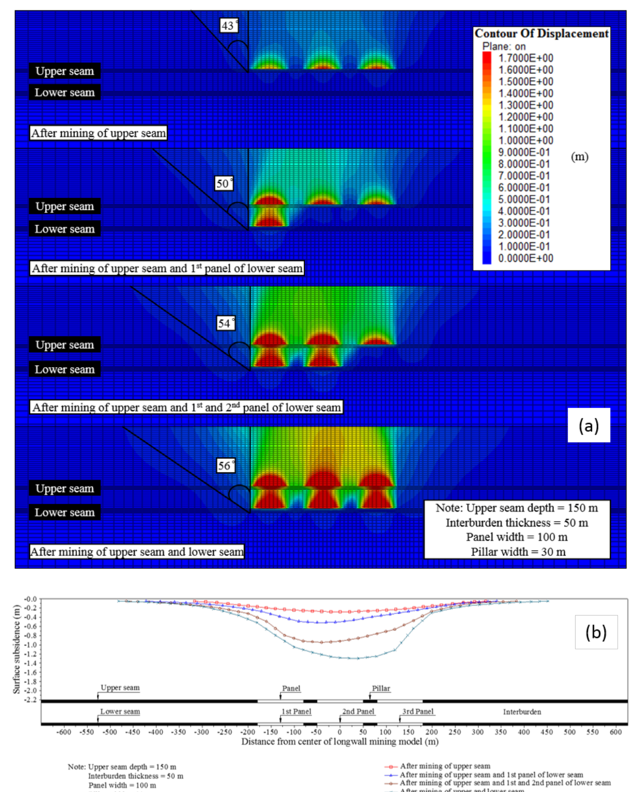


Figure 17 Results of subsidence affected by lower seam mining at 100 m depth (a) contour of subsidence and angle of draw (b) profile of surface subsidence (c) failure zone of overburden and interburden

In this research, therefore, two countermeasure techniques such as adopting a large size of coal pillar and a small size of longwall panel were investigated for subsidence control in multi-seam longwall mining. The characteristics of surface subsidence under different pillar and panel widths were given in the following sections.



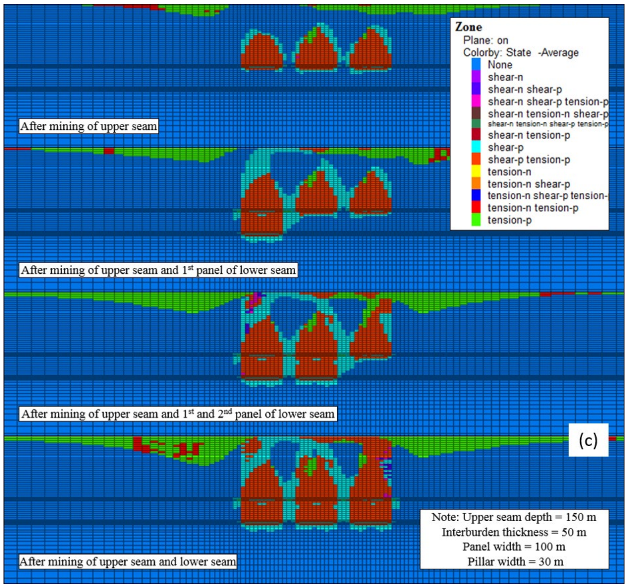
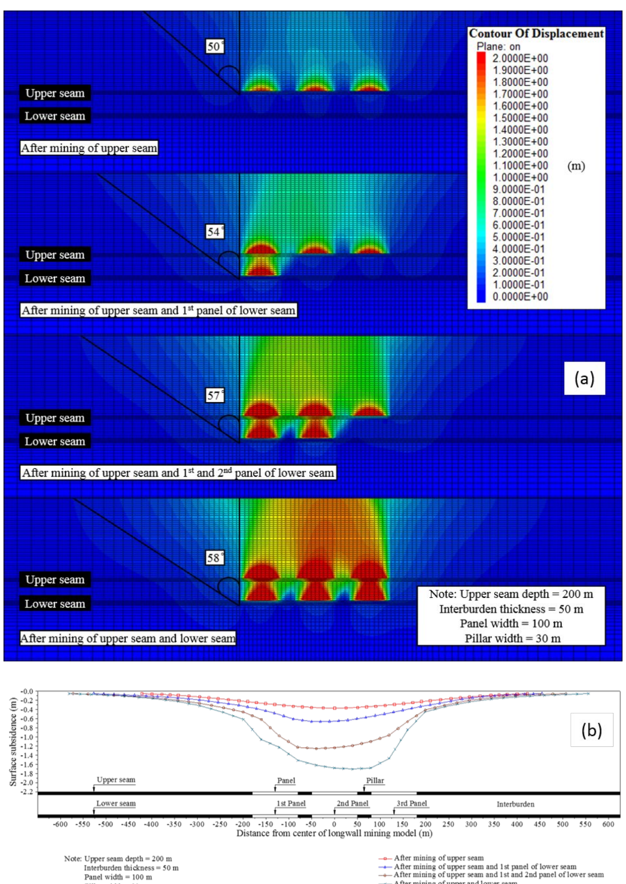


Figure 18 Results of subsidence affected by lower seam mining at 150 m depth (a) contour of subsidence and angle of draw (b) profile of surface subsidence (c) failure zone of overburden and interburden

4.3.1 Influence of Pillar Width on Surface Subsidence

In this section, the influence of pillar width on multi-seam mining-induced surface subsidence was analyzed and discussed. In the numerical simulation, four sizes of coal pillar width were considered, such as 30 m, 40 m, 50 m, and 60 m.



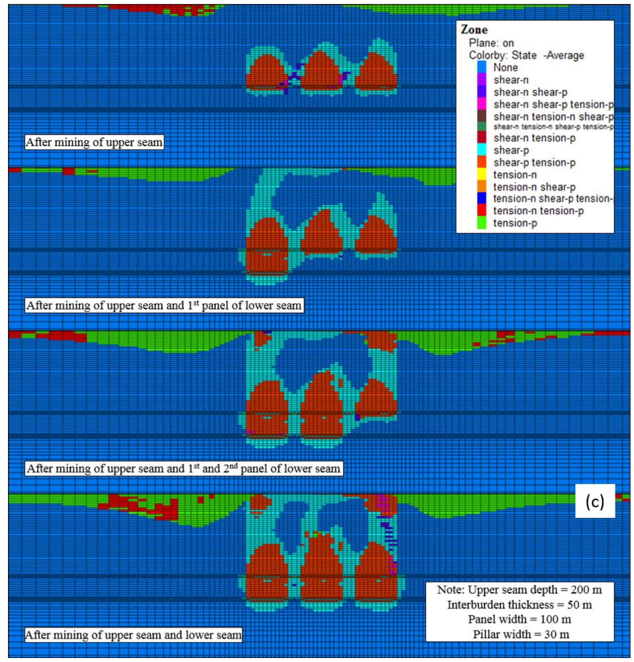


Figure 19 Results of subsidence affected by lower seam mining at 200 m depth (a) contour of subsidence and angle of draw (b) profile of surface subsidence (c) failure zone of overburden and interburden

Figure 20 demonstrates the mining schematic of the model considered in the simulations. The model contains two coal seams that are separated by a 50 m thick interburden layer. In each seam, three panels of 100 m width and 1000 m length were extracted. Similar to previous section simulations, four depths of multi-seam longwall mining (depth to upper seam) were simulated numerically, such as 50 m, 100 m, 150 m, and 200 m. The AoD and S_{max} were recorded after all panels in both the upper and lower seams were mined.

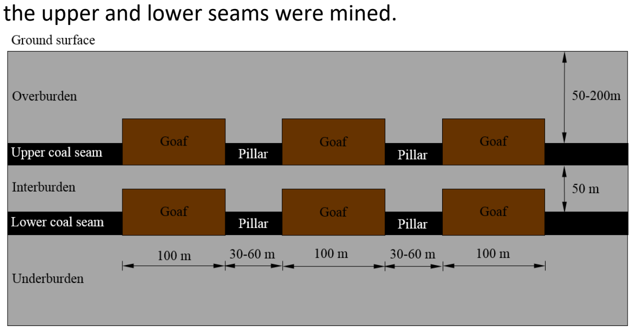


Figure 20 Mining schematic considered in simulation for pillar width effect on surface subsidence

Results of the surface subsidence generated from multi-seam mining under different pillar widths are presented in Figures 21-24. It was observed from the figures that increasing the pillar width significantly decreased the magnitude of AoD and Smax, especially at 100 m, 150 m, and 200 m depth. The AoD decreased from 23° to 21° and the S_{max} decreased from 0.55 m to 0.52 m at 50 m depth, while the AoD decreased from 47° to 46° and the S_{max} decreased from 0.79 m to 0.53 m at 100 m depth, whereas the AoD decreased from 56° to 55° and the S_{max} decreased from 1.28 m to 0.84 m at 150 m depth, and the AoD decreased from 58° to 56° and the S_{max} decreased from 1.70 m to 1.17 m at 50 m depth, when the pillar width was increased from 30 m to 40 m, respectively (Table 4). For this reason, after the upper seam was mined, the large coal pillar applied in the upper seam increased the support to the overburden strata when compared with the small pillar, and increased the ability of the overburden to bridge over the caved zone, as a result, the magnitude of AoD and S_{max} was minimized. At the same time, when the lower seam panels were mined, the large coal pillar used in the lower seam also increased the supporting effect to the interburden, and decreased the movement within the interburden layer. As the movement within the interburden decreased, the effect of the lower seam mining on the previously caved zone and coal pillar in the upper seam also decreased, resulted in a decrease in the magnitude of AoD and S_{max} consequently. Additionally, it was found that a smaller AoD and S_{max} was observed when a larger pillar width was applied, especially at 100 m, 150 m, and 200 m depth. This was due to a larger coal pillar provided stronger support to the overburden and interburden strata. Under this situation, less effect of lower seam extraction on the previously caved zone and coal pillar in the upper seam was produced due to a smaller movement within the interburden occurred. Hence, smaller AoD and S_{max} were generated. Based on the simulated results, it can be said that the surface subsidence caused by multi-seam mining can be effectively minimized by increasing the width of the coal pillar. However, the appropriate width of the coal pillar should be carefully selected, since the oversized coal pillar will cause a big loss of coal production.

Based on the S_{max} results presented in the subsidence profile and given in Table 4, it was found that increasing the pillar width was very effective to minimize the surface subsidence at 100 m, 150 m, and 200 m. However, its effectiveness was less at 50 m. At 50 m depth, the S_{max} remained almost stable. As the pillar width increased from 30 m to 40 m, 50 m, and 60 m, the S_{max} slightly decreased from 0.55 m to 0.52 m, 0.51 m, and 0.50 m, respectively. The difference of the S_{max} after increasing the pillar width was very small. This happened because the thin pillar width of 30 m in both the upper seam and lower seam could maintain in a very stable condition after the panel extractions, only a small failure of the pillar in the upper seam was observed (Figure 21c). Under this condition, the pillar could provide enough support to the interburden and overburden strata, as a result, an additional magnitude of S_{max} was restricted. From this, it can be said that the pillar width of 30 m will be adequate to be used in multi-seam mining at 50 m depth. To minimize the surface subsidence at this depth, it is not necessary to increase the pillar width. Since the large subsidence occurred at 50 m depth was due to the use of large panel width, therefore the use of a smaller panel width will be more effective.

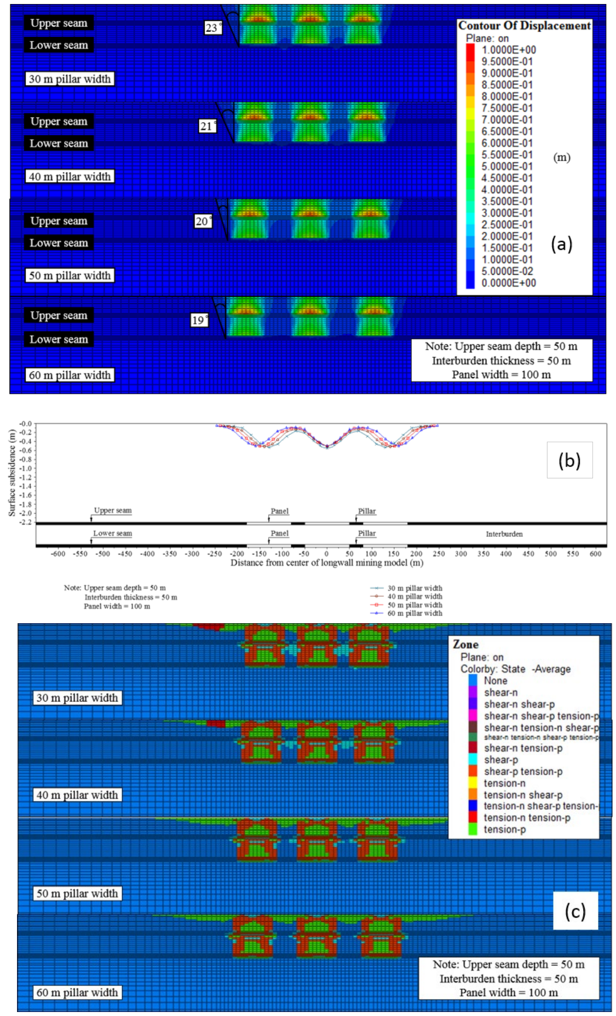


Figure 21 Results of surface subsidence induced by multi-seam mining under various pillar widths at 50 m depth (a) contour of subsidence and angle of draw (b) profile of surface subsidence (c) failure zone of interburden and overburden

On the contrary, magnitudes of the S_{max} decreased significantly at 100 m, 150 m, and 200 m depth as the pillar width increased. The S_{max} decreased from 0.79 m to 0.53 m, 0.39 m, and 0.33 m at 100 m depth, while the S_{max} decreased from 1.28 m to 0.84 m, 0.59 m, and 0.45 m at 150 m depth, and the S_{max} decreased from 1.70 m to 1.17 m, 0.87 m, and 0.67 m at 200 m depth, when the pillar width increased from 30 m to 40 m, 50 m, and 60 m, respectively. This happened because the failure zone of the pillar in the lower seam significantly reduced as the pillar width increased (Figures 22-24c). Under this condition, the lower seam pillar increased the support to the interburden strata, resulted in minimizing the movement within the interburden. As the movement of interburden strata reduced, the additional failure zone of the overburden strata induced by the lower seam mining became smaller. Therefore, it increased the ability of the overburden to bridge across the mined-out area. As a consequence, the magnitude of S_{max} decreased. From the results, it is revealed that a large coal pillar should be applied at 100 m, 150 m, and 200 m depth in order to minimize the magnitude of surface subsidence. Furthermore, having a smaller magnitude of surface subsidence is expected at these depths if a large width of coal pillar is used together with a small width of longwall panel.

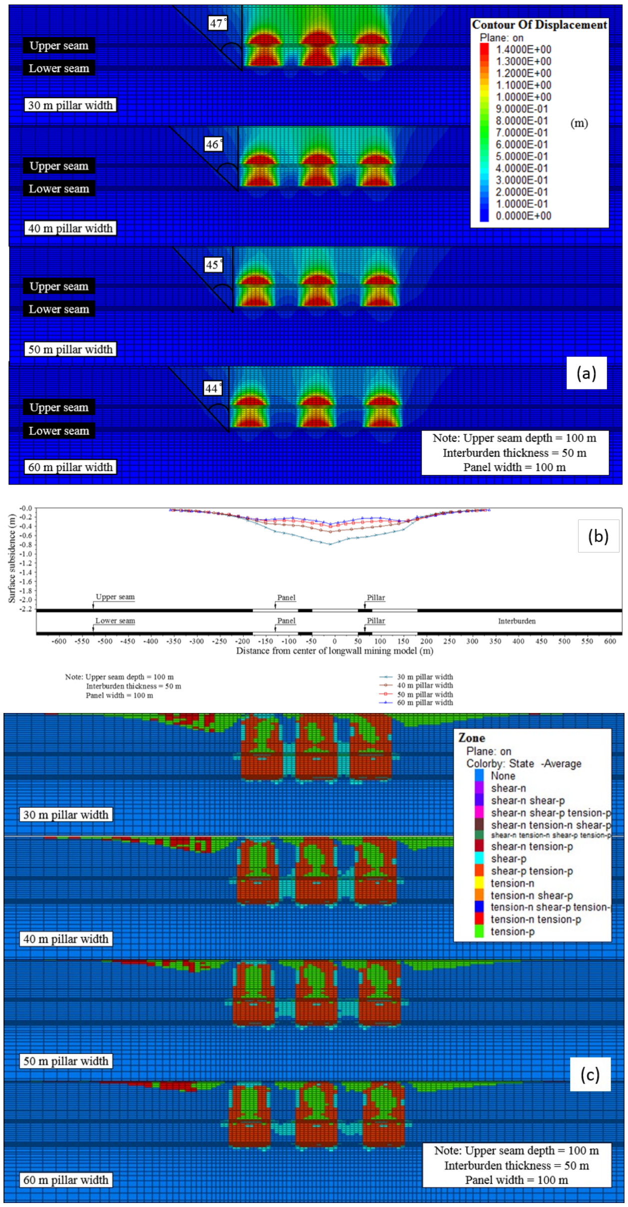


Figure 22 Results of surface subsidence induced by multi-seam mining under various pillar widths at 100 m depth (a) contour of subsidence and angle of draw (b) profile of surface subsidence (c) failure zone of interburden and overburden

Table 4 Comparison of AoD and S_{max} values caused by multi-seam longwall mining under various pillar widths

No.	Mining Depth (m)	30 m Pillar Width		40 m Pillar Width		50 m Pillar Width		60 m Pillar Width	
		AoD (◦)	S_{max} (m)	AoD (◦)	S_{max} (m)	AoD (◦)	S_{max} (m)	AoD (◦)	S_{max} (m)
1	50	23	0.55	21	0.52	20	0.51	19	0.50
2	100	47	0.79	46	0.53	45	0.39	44	0.33
3	150	56	1.28	55	0.84	54	0.59	53	0.45
4	200	58	1.70	56	1.17	56	0.87	55	0.67

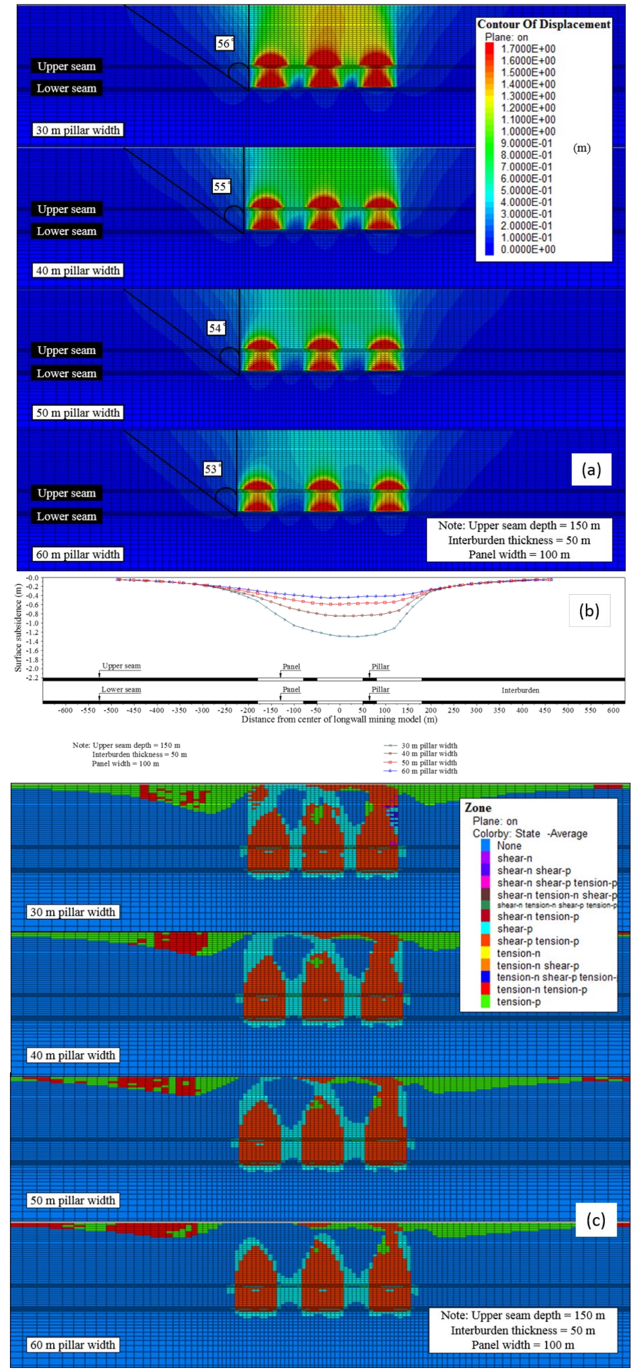


Figure 23 Results of surface subsidence induced by multi-seam mining under various pillar widths at 150 m depth (a) contour of subsidence and angle of draw (b) profile of surface subsidence (c) failure zone of interburden and overburden

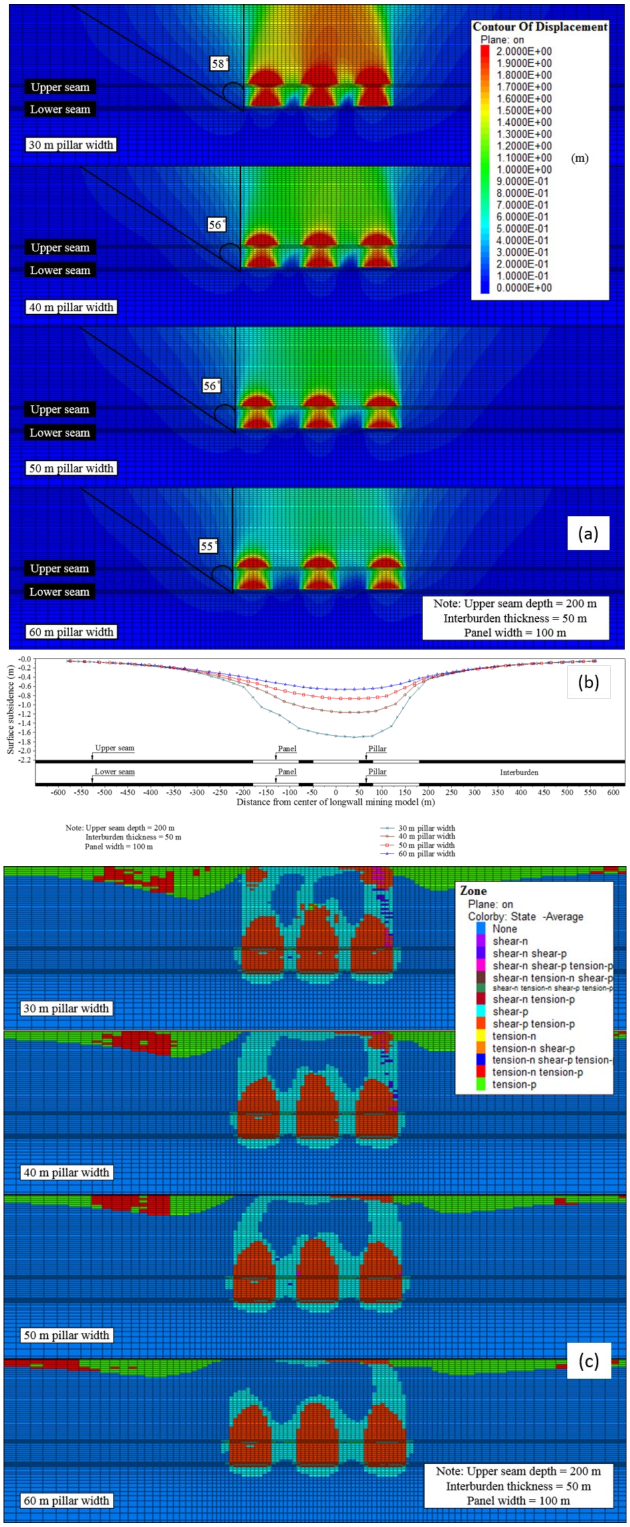


Figure 24 Results of surface subsidence induced by multi-seam mining under various pillar widths at 200 m depth (a) contour of subsidence and angle of draw (b) profile of surface subsidence (c) failure zone of interburden and overburden

4.3.2 Influence of Panel Width on Surface Subsidence

Minimizing the magnitude of surface subsidence induced by multi-seam mining by panel width was numerically analyzed and investigated in this section. Two panel widths such as 70 m and 100 m were simulated. Figure 25 illustrates the mining schematic of the numerical model considered for panel width effect simulation. Two coal seams such as the upper seam and lower seam were comprised in the model. The upper seam and lower seam were separated by a separation distance of 50 m thick interburden. In each seam, three coal panels were extracted with a length of 1000 m. The panels were separated by a 30 m wide coal pillar. In the simulation, four mining depths of 50 m, 100 m, 150 m, and 200 m to the upper seam were considered. The AoD and S_{max} were recorded after all panels in both the coal seams were mined.

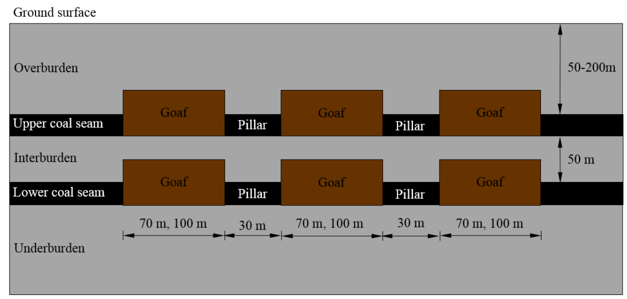


Figure 25 Mining schematic considered in simulation for panel width effect on surface subsidence

Figures 26-29 show the results of surface subsidence obtained from multi-seam mining of two panel widths. At all mining depths, it was illustrated from the results that the AoD and S_{max} decreased considerably as the panel width decreased. A smaller panel width showed less value of AoD and S_{max}. The AoD decreased from 23° to 12° and the S_{max} decreased from 0.55 m to 0.13 m at 50 m depth, whereas the AoD decreased from 47° to 32° and the S_{max} decreased from 0.79 m to 0.18 m at 100 m depth, while the AoD decreased from 56° to 43° and the S_{max} decreased from 1.28 m to 0.24 m at 150 m depth, and the AoD decreased from 58° to 49° and the S_{max} decreased from 1.70 m to 0.30 m at 200 m depth, when the panel width was decreased from 100 m to 70 m, respectively (Table 5). This was due to a decrease in the failure zone of the pillar, interburden, and overburden resulted from decreasing the extraction area in the underground (Figures 26-29c).

Table 5 Comparison of AoD and S_{max} values caused by multi-seam longwall mining under various panel widths

No.	Mining Depth (m)	100 m Panel Width		70 m Panel Width	
		AoD (◦)	S_{max} (m)	AoD (◦)	S_{max} (m)
1	50	23	0.55	12	0.13
2	100	47	0.79	32	0.18
3	150	56	1.28	43	0.24
4	200	58	1.70	49	0.30

When a 70 m panel width was applied in the upper seam, a smaller failure zone of the overburden occurred above the mined-out panels, while the upper seam pillars were maintained in a good condition. Under this situation, the upper seam pillar provided sufficient support to the overburden, and the overburden strata were more able to bridge across the mined-out areas. As the overburden could bridge appropriately, the movement of overburden strata decreased, and therefore the magnitude of the surface subsidence was minimized consequently. At the same time, a small panel width of 70 m applied in the lower seam also reduced the failure zone of the lower seam pillars and the interburden. Under this situation, the lower seam pillar provided stronger support to the interburden strata and enhanced the bridging ability of the interburden over the mined-out area, consequently, the movement of the interburden strata was decreased. As the movement in the interburden decreased, the effect of the lower seam mining on the previously caved zone and coal pillar in the upper seam also reduced. As a result, a smaller magnitude of AoD and S_{max} was generated. Therefore, it can be said from the results that the magnitude of surface subsidence induced by multi-seam longwall mining can be minimized effectively by decreasing the width of the longwall panel.

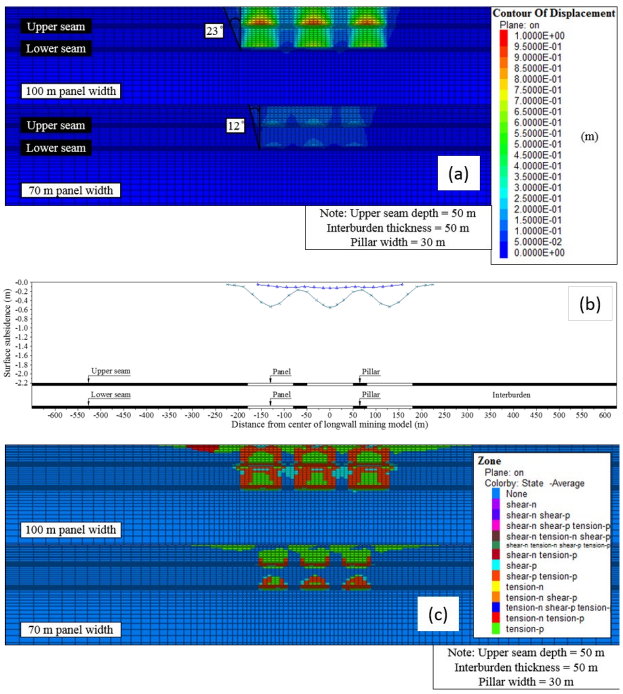


Figure 26 Results of surface subsidence induced by multi-seam mining under two panel widths at 50 m depth (a) contour of subsidence and angle of draw (b) profile of surface subsidence (c) failure zone of interburden and overburden

Based on the simulation results, it is interestingly found that by applying a small panel width of 70 m at 100 m, 150 m, and 200 m depth, a small pillar width of 30 m can be adopted in multi-seam mining without any occurrence of severe subsidence at the surface. However, if the panel width of 100 m should be applied at 100 m, 150 m, and 200 m depth, the use of a large pillar width must be considered. Moreover, the surface subsidence at 100 m, 150 m, and 200 m depth is expected to be more minimized if a small panel width is used together with a large pillar width.

Although the use of a small panel width is very effective to control the surface subsidence in multi-seam mining, a decrease in panel width can cause some additional costs as well as a reduction of the coal production of the mine. To use a small panel width, more gate roadways have to be developed, and more coal pillars have to be left in the underground. Thus, a careful selection of the panel width must be done before starting the multi-seam mining in order to prevent the adverse subsidence impacts due to oversized panels and to avoid the reduction of coal production as well as the additional costs due to the undersized panel.

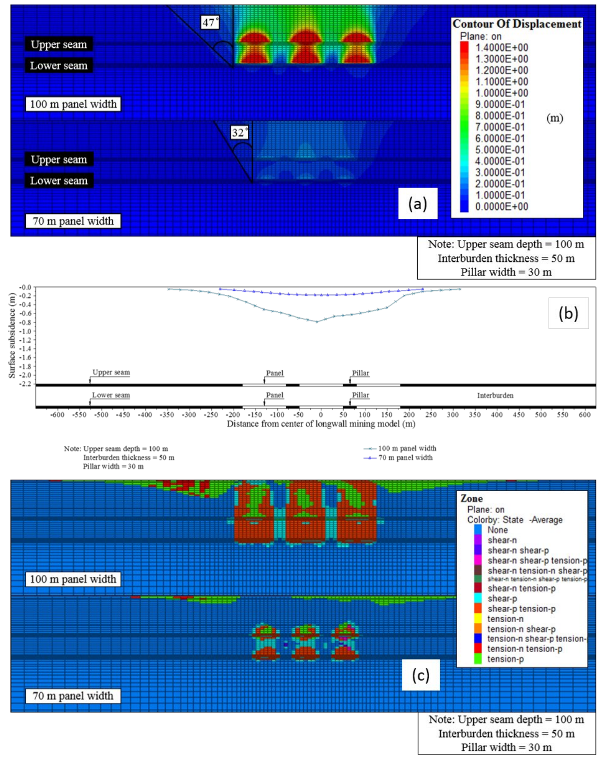


Figure 27 Results of surface subsidence induced by multi-seam mining under two panel widths at 100 m depth (a) contour of subsidence and angle of draw (b) profile of surface subsidence (c) failure zone of interburden and overburden

4.0 CONCLUSION

In This paper predicts the surface subsidence induced by multi-seam longwall mining in the PT Gerbang Daya Mandiri (GDM) underground coal mine in Indonesia. The finite difference code "FLAC3D" is used as a tool for numerical simulations. According to the simulated results, important findings can be concluded as follow:

- The undermining shows a better mining sequence in multi-seam mining compared with the overmining. Mining in an undermining order will not cause any difficult mining conditions in the lower seam. In contrast, when mining the coal seams in an overmining, the difficult mining conditions and ground control problems in the upper seam are expected.
- Under all mining depths, extracting the lower seam panels significantly influences the magnitude of surface subsidence. The AoD and S_{max} increase greatly after the first, second, and third panels in the lower seam are mined. It is indicated that very large surface subsidence is expected when multi-seam mining is applied at GDM underground coal mine.
- Minimizing the surface subsidence using some countermeasures such as adopting a large pillar width and a small panel width is investigated in this paper. Based on simulated results, it is found that the AoD and S_{max} decrease significantly when larger pillar width and narrower panel width are adopted. The use of larger pillar width and narrower panel width results in smaller AoD and Smax.

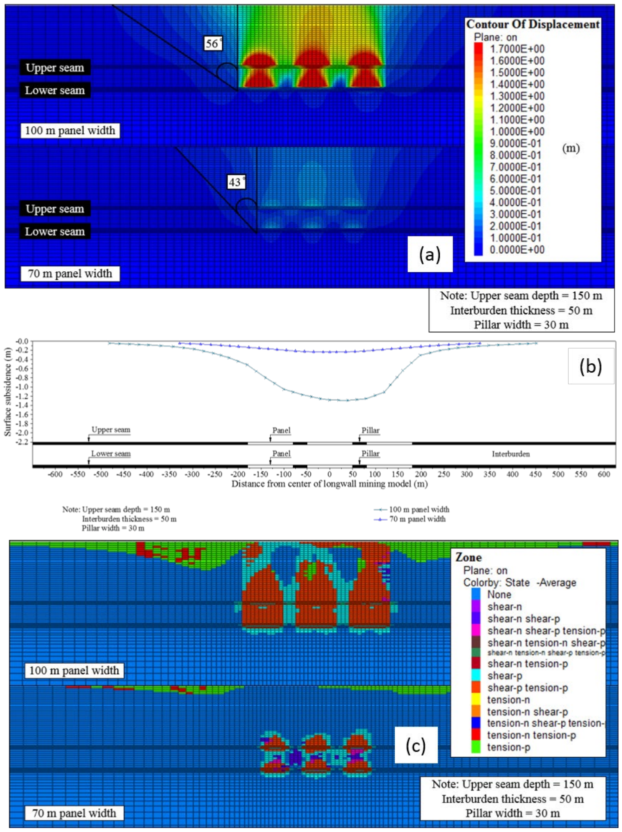


Figure 28 Results of surface subsidence induced by multi-seam mining under two panel widths at 150 m depth (a) contour of subsidence and angle of draw (b) profile of surface subsidence (c) failure zone of interburden and overburden

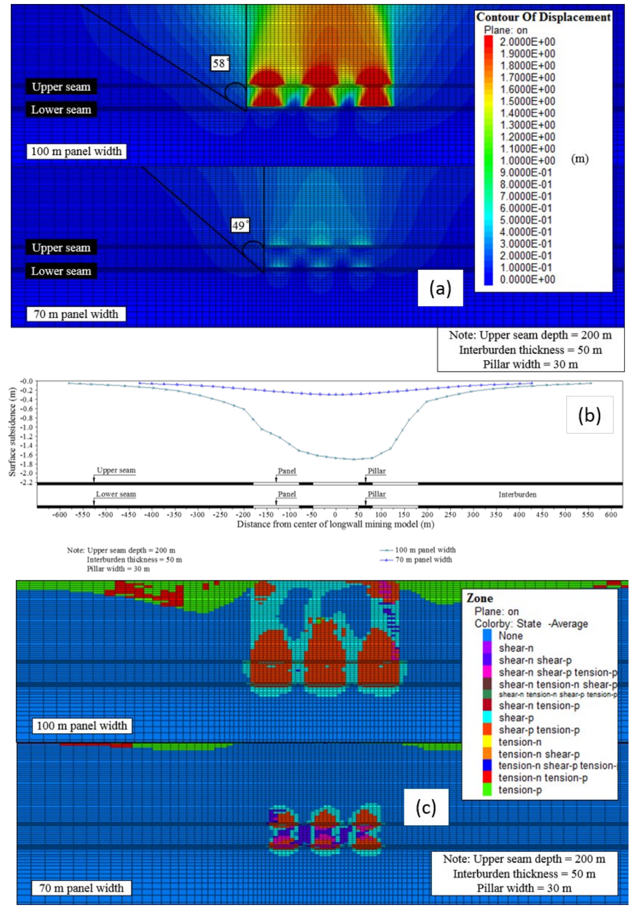


Figure 29 Results of surface subsidence induced by multi-seam mining under two panel widths at 200 m depth (a) contour of subsidence and angle of draw (b) profile of surface subsidence (c) failure zone of interburden and overburden

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