Numerical Study on Roadway Stability under Weak Geological Condition of PT Gerbang Daya Mandiri Underground Coal Mine in Indonesia

P. Phanthoudeth, T. Sasaoka, H. Shimada, B. Ulaankhuu, J. Oya, S. Dwiki, and T. Karian

Abstract—**This paper aims to assess the roadway stability of the PT Gerbang Daya Mandiri (GDM) underground coal mine. A numerical analysis method using 3D finite difference code (FLAC 3D) was used to investigate the failure zone behavior of the roadway at various overburden depths (50 m, 100 m, 200 m, and 300 m). The outcome of this research was the most appropriate support system of the roadway. The results of numerical analyses indicated that the excavation depth affected the thickness of failure zone, and the capacity of the support system was significantly associated with an increase of the overburden depth. Steel set, cablebolt, and rockbolt supports were assessed in this paper. The steel set is selected as the main support system in GDM coal mine, and it is effective to stabilize the roof and sidewalls of the roadway until 200 m depth. As the failure zone becomes larger at the deeper sites, the cablebolt support is introduced to control the floor stability, and the use of rockbolt in combination with steel set is suggested to support the roof and sidewalls.**

Keywords-roadway stability; weak geological condition; support system; numerical analysis; FLAC3D

I. INTRODUCTION

Indonesia is one of the world's largest producers and exporters of coal. The major source of the coal is from the Kalimantan coal deposit. The coal production of Indonesia has increased significantly in the past years (Fig. 1). Indonesia exports the coal mostly to China and India, accounted on average 70 to 80% of Indonesia's total coal production while the remaining is consumed in domestic markets [1]. The coal production in Indonesia is mainly relied on the open pit mining method. Recently, the financial situation of open pit mines in Indonesia becomes worse. As a result, many mines are abandoned due to an increase of the stripping ratio, especially because mining depth increases. Also, there are many problems concerning the environmental impacts and protection challenges to expand the current open pit mines and exploit the new ones. Therefore, to meet the demands of increased coal production in Indonesia, some underground coal mines need to be developed [2, 3].

The instability of the roadway in weak strata is one of the major ground control problems in Indonesian underground coal mines [4, 5, 6]. It causes the reduction of safety, productivity, or even the interruption of an operation. Coal measure strata in Indonesia consist of sedimentary rocks that are typically found in deltaic and shallow marine depositional environments, such as sandstone, claystone, siltstone, and mudstone. These rocks are considered young in geological time and very weak that are susceptible to the weathering phenomena. Results of uniaxial compressive strength (UCS) test indicated that the strengths of rocks in Indonesian coal mines are much lower than that of coal mines in other countries [4, 5, 7, 8]. In recent years, several attempts have been made to develop the underground operations from open pit mines in South Kalimantan. However, these mines were abandoned due to fatal accidents of a falling roof in the main roadways. The accidents occurred due to inadequate roof support system in weak ground conditions [4, 6].

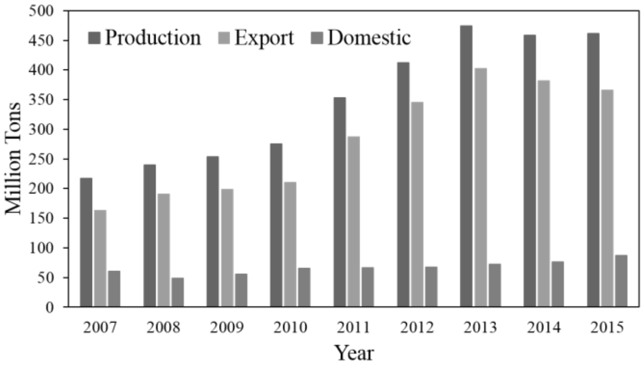


Figure 1. Production, export, and domestic consumption Indonesian coal.

The GDM coal mine is a new underground coal mine in Indonesia, which is being developed from the final highwall of an open pit mine. Based on the laboratory test results (uniaxial compressive strength, UCS) of the rock samples which were collected from boreholes at different depths, the rocks in this coal mine are classified into very weak and low strength rocks [9], whose UCS values range from 0.31-20.43 MPa with 10.37 MPa on average (Fig. 2). Although the roadways are currently in a stable condition at a shallow depth, when an excavation moves to a greater depth, a series of ground control problems such as roof fall, sidewalls collapse, and floor heave can be expected due to the weak geological conditions of the surrounding rocks. Therefore, to make this underground coal mine possible, by ensuring the safety of mine workers and avoiding an interruption of the coal extracting that may occur

DOI: 10.5176/2335-6774 3.1.26

due to the roadway instability, it is necessary to study the stability of the roadway, and obtain the most appropriate support system. To meet the objectives of the research, several numerical simulations of the roadway excavation by using the 3D finite difference code (FLAC3D) were carried out in this paper.

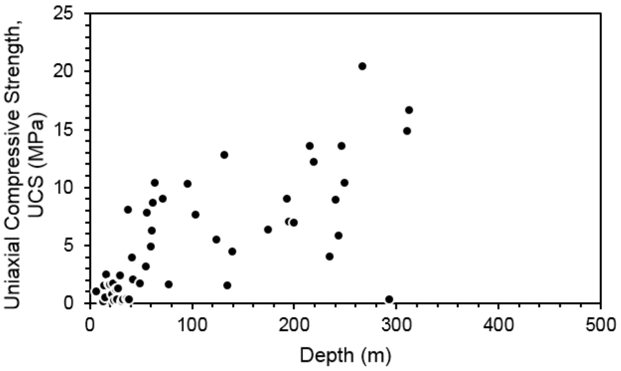


Figure 2. Uniaxial compressive strength of rocks in GDM coal mine.

II. BRIEF INFORMATION OF GDM COAL MINE

A. General Background

PT Gerbang Daya Mandiri (GDM) coal mine is located in Kutai Kertanegara, about 15 km north of the Samarinda city of East Kalimantan, Indonesia. Fig. 3 shows the location map of GDM coal mine. GDM Company has conducted exploration for underground mining from June 2010 to May 2011. The total geological and recoverable 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 about 1 million tons during its mine lifetime by a longwall mining method. In GDM coal mine, two main roadways namely North and South Roadway, are being excavated by using the road header machine to access the coal seams. Fig. 4 illustrates the layout of mine roadways and longwall panels. The roadway excavation commenced in April 2014 from the final highwall of an open pit mine. The total height of the final highwall is about 20 m from the ground surface. The roadways are designed using semi-circular shape with 5 m width, 3 m height, and 6° dip. The total heading length of each roadway is 280 m, where the overburden thickness above an ending point of the excavation is about 50 m. The roadways 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 spacing steel sets. However, based on the mining plan, the roadways are designed to reach the coal seams at the deeper site, until 300 m depth below the ground surface.

When the excavation depth of the roadway increases, and due to the weak mechanical properties of the rocks, the instability of the roadway can be a major geotechnical issue in GDM underground coal mine. This problem affects the safety of miners, coal productivity, and economic benefits of the mine. Thus, to prevent such that problem, the stability of the roadway at the deeper site and the most proper support system are being investigated at present.

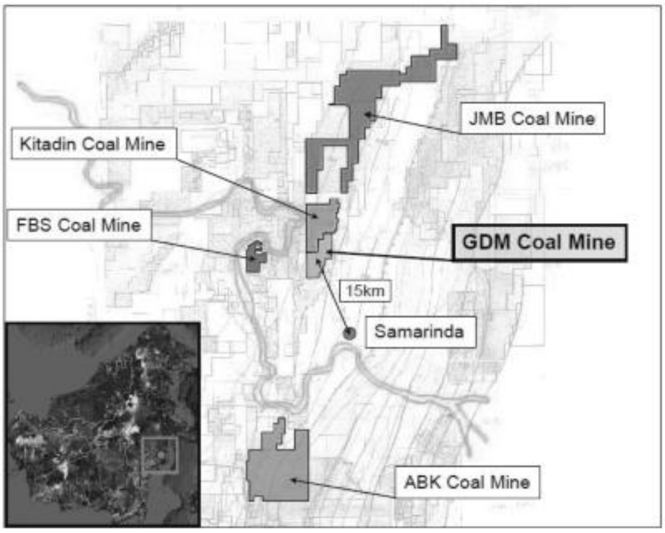


Figure 3. Location of GDM coal mine.

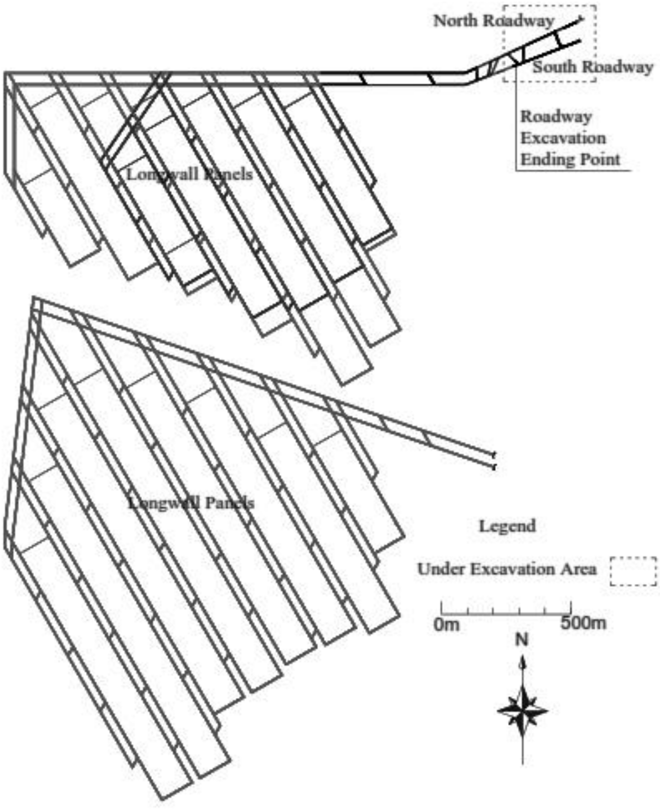


Figure 4. Roadway and longwall panel layouts of GDM coal mine.

B. Geological Settings of GDM 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. 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. GDM coal consists of several seams which are part of the Kutai Basin with the dip ranging from 3º to 13º, 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 1, Seam A, and Seam BC. The thickness of Seam 1 varies from 0.50 m to 5.56 m. Seam A thickness varies from 1.06 m to 6.14 m. Whereas the thickness of Seam BC varies from 3.39 m to 9.80 m. The coal seams are separated by the interburden of claystone and sandstone.

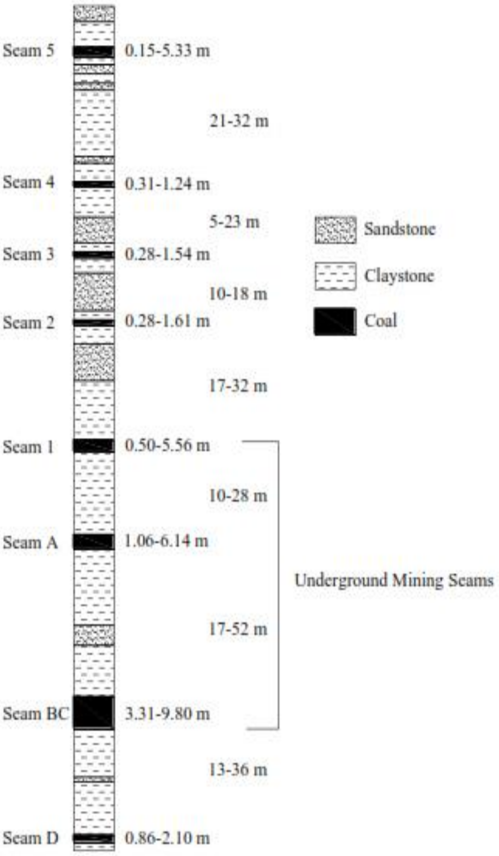


Figure 5. Stratigraphic column of GDM coal mine.

III. NUMERICAL MODELING

In this paper, the stability of the roadway in GDM coal mine was investigated using several models of the roadway excavations and rock support systems. Different overburden depths (50 m, 100 m, 200 m, and 300 m) were created by using the 3D finite different code (FLAC3D). FLAC3D is a numerical software which is widely used for analyzing stress and deformation around the surface and underground openings conducted in both soil and rock. The software utilizes an explicit finite-difference formulation that can model complex behaviors of three-dimensional geomechanical problems [10].

A. Description of Numerical Models

Four numerical models were created using FLAC3D with various overburden depths of 50 m, 100 m, 200 m, and 300 m. Fig. 6 (a)-6 (d) describe the geometries of the models. All the numerical models are 105 m in width and 250 m in length. The heights are varied based on the depth of overburden. The height of the model for 50 m, 100 m, 200 m, and 300 m overburden depth is 203 m, 253 m, 353 m, and 453 m, respectively. The size of roadway excavation was designed as 5 m in width, 3 m in height, and 250 m in length. As the claystone is a dominant rock type in the GDM underground coal mine, to simplify, the overburden and underburden were modeled as homogenous claystone layers. To obtain the more precise result of the rock failure distribution, the smaller mesh size was set up around the excavation area. The bottom of each model was fixed in the vertical direction, while the sides were fixed in the horizontal direction. Due to the field measurement data of in-situ stresses in the mine site have been unknown, the vertical initial stress component was modeled as a function of the overburden thickness ($P_v=\gamma h$, γ=unit weight of overburden and h=overburden depth) [11, 12, 13], while the horizontal stress was assumed to be half the vertical stress. The elasto-plastic Mohr-Coulomb criterion was used in the analyses. The mechanical properties of claystone are given in Table I.

TABLE I. MECHANICAL PROPERTIES OF CLAYSTONE USED IN ANALYSES

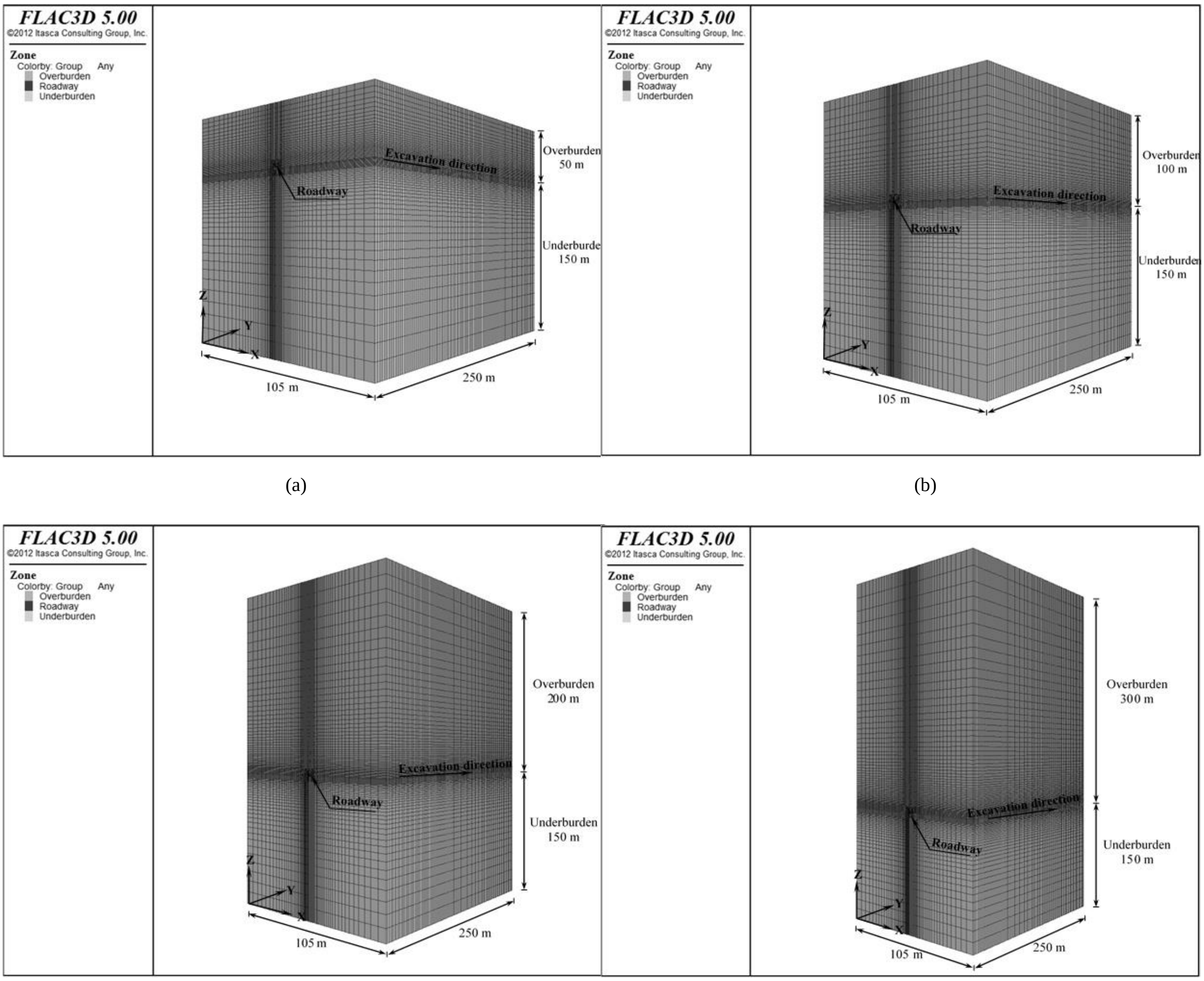
Parameters	**Claystone**
Uniaxial compressive strength (MPa)	10.37
Density (kg/m^3)	2140
Young’s modulus (MPa)	2324.68
Poisson’s ratio	0.27
Friction angle (°)	38.56
Cohesion(MPa)	0.54
Tensile strength (MPa)	0.10

B. Result and Discussion

An appropriate rock support system can provide the roadway in a stable condition, and ensure its safety during mining activities. There are several types of supports that have been used in the tunnel for decades, such as rockbolt, cablebolt, shotcrete, and steel set. To use the rockbolt or cablebolt as the main support system, the rock has to be hard enough to provide a good grip for the anchor [12]. In the case of GDM coal mine, due to the rocks are very poor, the use of rockbolt or cablebolt is unsuitable due to the difficulty in achieving adequate anchorage. Thus, the support system has to be either in the form of shotcrete or steel set. Nonetheless, since the roadway is excavated in the weak rock mass, the support should be installed immediately behind the roadway advance, this makes the placement of a full shotcrete lining during the excavation is impractical due to time-consuming of the shotcrete curing. Hence, the remaining option for the main support of the roadway in GDM underground coal mine is using the steel set.

In the GDM coal mine, steel set is selected as the main support system to stabilize the roadway in the roof and sidewalls (Fig. 7). The steel set properties are given in Table II. This support type works effectively to control the development of the failure zone at the shallow depth. However, the larger failure zone can be expected with the increasing of the overburden depth. Therefore, application of the steel set at the deeper site was investigated and discussed in this research. Rockbolt or cablebolt may be proposed as auxiliary support if the steel set alone is ineffective to control the stability of the roadway.

Fig. 8 exhibits the failure zones which developed around the roadway at 50 m depth with no support system. The result was taken in the center of the model and expressed in a cross-section. The explanations of failure terms given in the legend in Flac3D are as follows: "none" indicates no-failure zone, "shear-n" indicates the region failed under shear loading, and failure process is still in progress, "shear-p" indicates the region failed under shear loading, and failure process is stopped due to lowered amount of shear forces, "tension-n" means the region failed under tensile loading, and failure process is still in progress, and the last is "tension-p" explains the region failed under tensile loading, and failure process is stopped due to lowered amount of tensile forces [14]. According to the result presented in Fig. 8, the small rock failures of about 0.5 m thick occurred in the roof, sidewalls, and floor. In this case, no major failure occurred due to the roadway was excavated at the shallow depth. Therefore, no major support was required. However, for safety reason, the wide spacing steel sets were applied to support the roadway. Typically, a 1 m spacing steel set pattern will be sufficient to protect workers and equipment from the small roof falls. Fig. 9 illustrates the failure condition after the steel sets were employed. The stability of the roadway was improved significantly as no failure in the roof and sidewalls could be observed. Thus, it can be said that the installation of steel sets with 1 m spacing is adequate to support the roadway at 50 m depth.



(a) (b)

(c) (d)

Figure 6. Geometries of Numerical models, (a) 50 m overburden depth, (b) 100 m overburden depth, (c) 200 m overburden depth, (d) 300 m overburden depth.

Figure 7. Steel set support installed in GDM underground coal mine roadway.

TABLE II. PROPERTIES OF STEEL SET

Dimension (mm)	Area (cm^2)	Young's modulus (MPa)	Poisson's ratio	Unit weight (kg/m)	Yield strength (MPa)
115 x 95	36.51	200000	0.30	28.70	300.9

For the 100 m deep roadway, the failure zones around the roadway without support are illustrated in Fig. 10. Compared to the roadway excavation with no support at 50 m depth (Fig. 8), the failure zones in the roof, floor, and sidewalls expanded conspicuously. It was found that the stability of the roadway decreased with increasing the overburden depth. The failure zones of 0.5 m in thickness were observed in the roof and sidewalls, while the failure zones of 0.5 m and 1 m were found in the floor center and floor corners, respectively. In this case, the roof fall and sidewalls collapse can be expected unless adequate supports are provided. Therefore, the application of steel sets with 1 m spacing was investigated in this 100 m deep roadway.

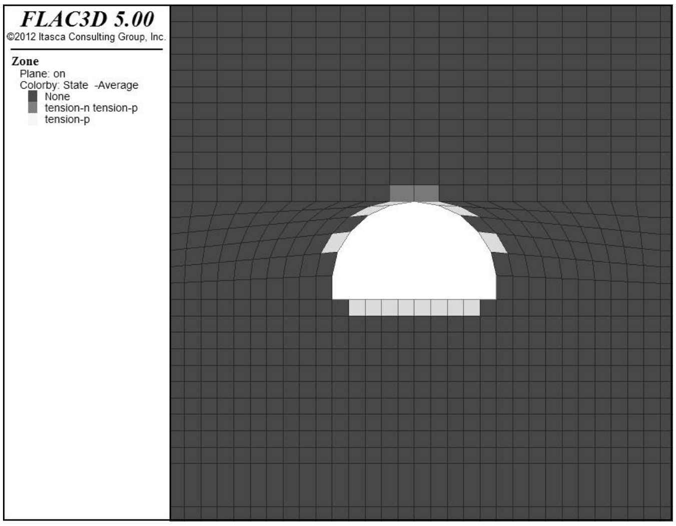


Figure 8. Failure zone around roadway without support at 50 m overburden depth.

Fig. 11 illustrates the development of failure zones after the steel sets were installed. From the result, it was found that the failure zones decreased significantly, only spotted rock failures of about 0.5 m occurred in the roof and sidewalls. Hence, it can be concluded that the installation of steel sets with 1 m spacing can restrain the development of failure zones around the 100 m deep roadway in GDM underground coal mine effectively.

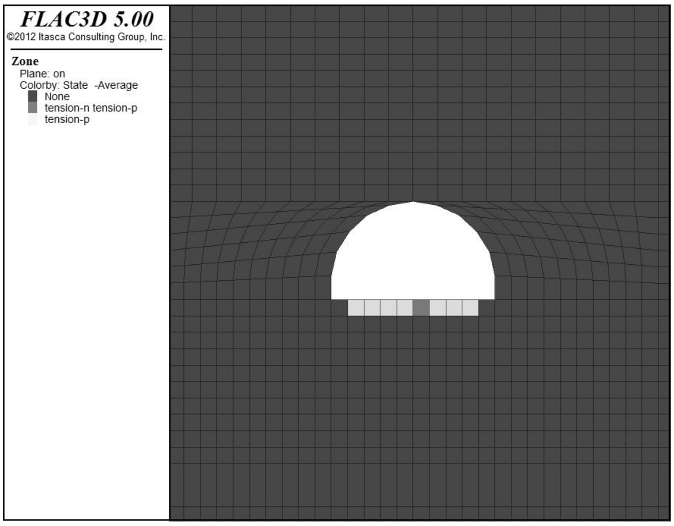


Figure 9. Failure zone around roadway with 1 m spacing steel set support at 50 m overburden depth.

At 200 m depth, the large failure zones were observed in the roof, sidewalls, and floor (Fig. 12). The failure zones were found to be larger than that of the roadway at 50 m, and 100 m overburden depth. This happened due to an increase of the in-situ vertical stress which resulted from increasing the thickness of the overburden. The maximum failure zones in the roof and sidewalls were about 1 m, while in the floor center and floor corners were 1.5 m. According to the result presented in Fig. 12, the failure zones in the floor tended to be larger than that of the roof and sidewalls. This happened because the sharp corners at the junction between the floor and the sidewalls created high stress concentrations. Thus, the failures of the floor occurred. In this case, the large floor failure may lead to severe floor heave and even to failure of the entire roadway perimeter [13]. Therefore, an appropriate support system should be installed in this situation.

To control the development of failure zones in the roof and sidewalls at 200 m depth, the same support system of 1 m spacing steel sets which applied in the roadway at 100 m depth was firstly investigated. Moreover, to maintain the floor stability, the installation of an auxiliary support in the floor was also considered. In this case, the installation of six fully grouted cablebolts of 1 m row spacing was introduced. To select an appropriate cablebolt length, the thickness of the failure zone must be identified. The cablebolt length should be 1.5 to 2 m longer than the thickness of the failure zone so that they can be anchored in an undamaged rock mass [14]. From

Fig. 12, when the thickness of the failure zone in the floor is 1.5 m, the length of cablebolt should be 3.5 m long. The pattern of rock supports for the roadway at 200 m depth is illustrated in Fig. 13. The cablebolt properties used in the analyses are given in Table III.

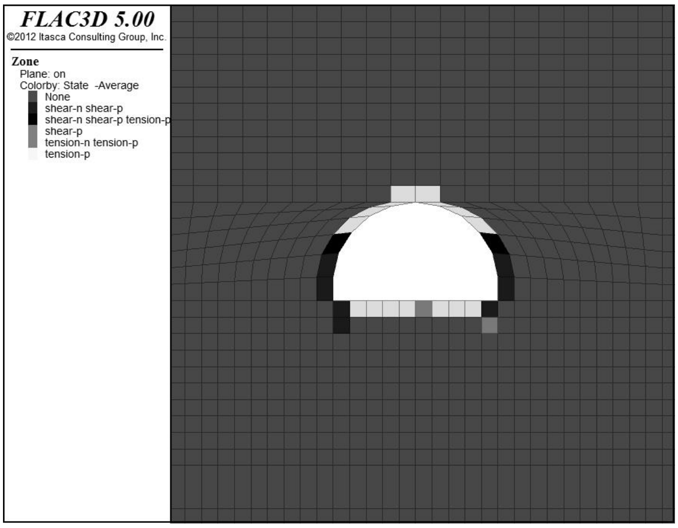


Figure 10. Failure zone around roadway without support at 100 m overburden depth.

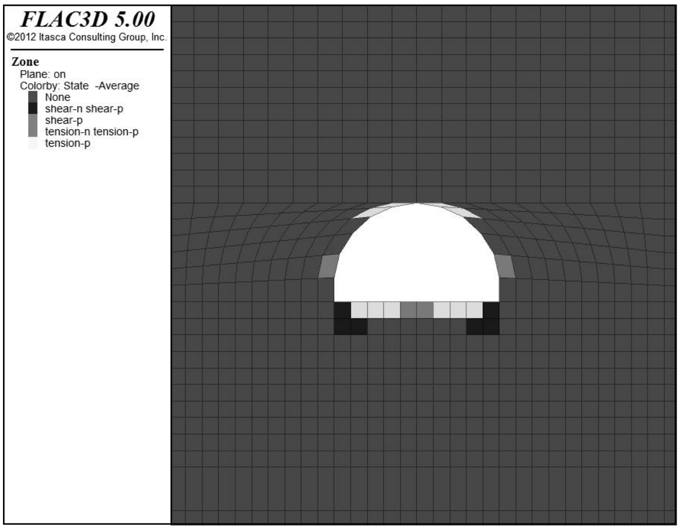


Figure 11. Failure zone around roadway with 1 m spacing steel set support at 100 m overburden depth.

After the roadway at 200 m depth was supported by 1 m spacing steel sets in the roof and sidewalls, the large failure zones have remained around its perimeter (Fig. 14). The rock failures of 0.5 m thick were found in both the roof and sidewalls. In this instance, the rock collapses from these parts could still be expected. Based on the simulated result, it can be said that the application of 1 m spacing steel sets is insufficient to stabilize the roadway in the roof and sidewalls. The modification of the support system for these parts has to be considered. Furthermore, by installing the cablebolts in the floor, the failure zones have reduced significantly, particularly in the floor center. The thickness of the failure zone at this point decreased from 1.5 m to 0.5 m. In contrast, the failure zones at floor corners, compared to the ones before installing the rock support, were larger. This happened, maybe due to the redistribution of the stress from the roof and sidewalls to be concentrated more at floor corners after the steel sets were installed. However, the extension of rock failures at floor corners would have no effect on the roadway stability since they occurred within the length of cablebolt. Therefore, it can be concluded that the installation of cablebolts in the floor is adequate to maintain the floor stability of the roadway.

As mentioned above, although the 1 m spacing steel sets were applied to support the roadway at 200 m depth, the stabilization of the roof and sidewalls remained difficult. For this reason, the support system for these parts of the roadway has been modified by decreasing the spacing of steel sets from 1 m to 0.5 m. Fig. 15 illustrates the failure zones in the roof and sidewalls after the 0.5 m spacing steel sets were installed. It could be obviously seen that the stability conditions were improved significantly. Only spotted rock failures of 0.5 m thick were observed in the roof and sidewalls. Hence, the application of steel sets with 0.5 m spacing is sufficient to restrict the development of rock failures in the roof and sidewalls of the roadway at 200 m depth in GDM underground coal mine.

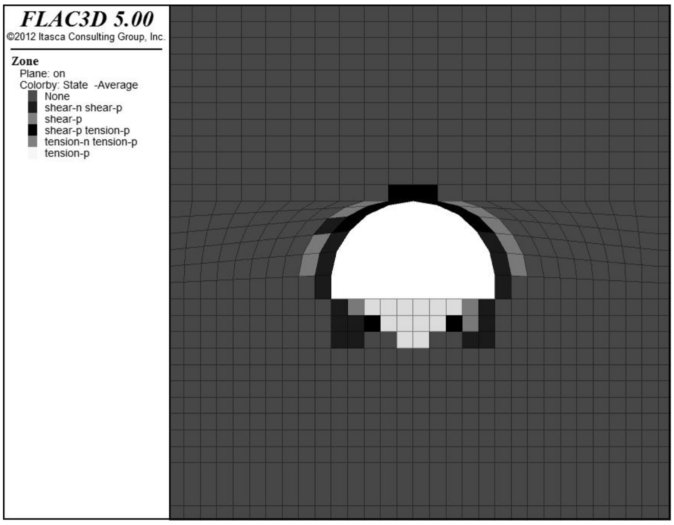


Figure 12. Failure zone around roadway without support at 200 m overburden depth.

Fig. 16 shows that for a roadway at 300 m depth, the failure zones developed largely around its perimeter. The thickness of the failure zone was about 1.5 m in the roof, while in the sidewalls were 1 m, and in the floor center and corners were 1.5 m and 2 m, respectively. According to the thickness of failure zones, the roadway exhibited in a large squeezing condition. Severe roof falls, or even the entire collapse of the roadway can be expected if no such a significant amount of the support is properly installed. In this case, to prevent the severe ground control problems that may occur, the same rock support systems that used in 200 m deep roadway were firstly employed and investigated. The support systems include the 0.5 m spacing steel sets in the roof and sidewalls, and six fully grouted cablebolts of 3.5 m long and 1 m row spacing in the floor.

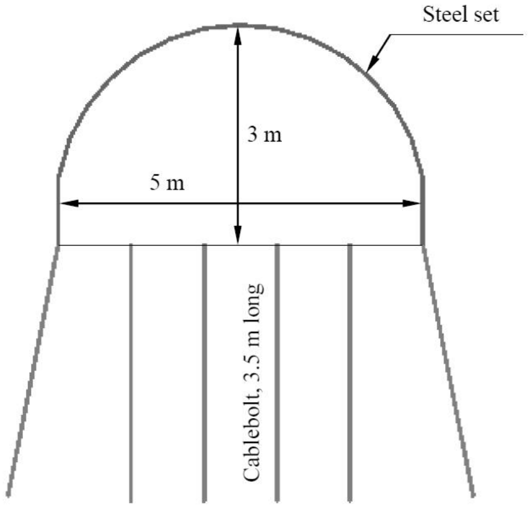


Figure 13. Pattern of support systems for roadway at 200 m overburden depth.

TABLE III. PROPERTIES OF CABLEBOLT

Parameters	Values
Diameter (mm)	25.4
Typical tensile capacity (kN)	548
Cablebolt modulus (MPa)	200000
Grout compressive strength (MPa)	20
Grout cohesion (MPa)	10
Grout friction angle (°)	30

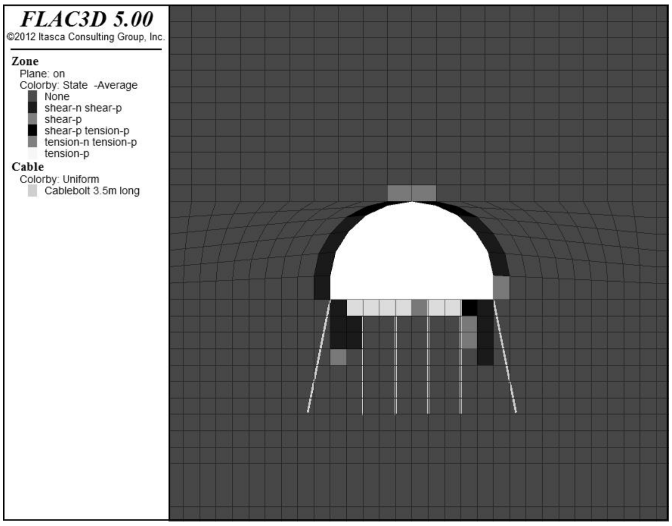


Figure 14. Failure zone around roadway with 1 m spacing steel set and 1 m row spacing cablebolt supports at 200 m overburden depth.

As shown in Fig. 17, after the roadway at 300 m depth was supported by the rock support systems as presented in Fig. 13, the reduction of floor failures could be observed, especially in the floor center. The failure zone at this position reduced significantly from 1.5 m to 0.5 m. This means that the 1 m row spacing cablebolts helped to maintain the stability of the floor effectively. In contrast, even though the steel sets with a closely spacing of 0.5 m were employed in the roof and sidewalls, the large failure zones still remained. The failure zones of about 1 m and 0.5 m could be observed in the roof and sidewalls, respectively, and the potential of the roof fall and sidewalls collapse could still be expected in this case. It was found that when the depth of an excavation increased, a higher capacity of the support system was needed. Therefore, to improve the stability condition, particularly in these parts of the roadway, the application of the rockbolt as an auxiliary support was then introduced. The length of the rockbolt was selected as 2.5 m. Eight fully grouted rockbolts were installed in the roof and sidewalls with 0.5 m row spacing. The mechanical properties of this support type are given in Table IV. The modified pattern of rock supports for the roadway at 300 m depth is illustrated in Fig. 18.

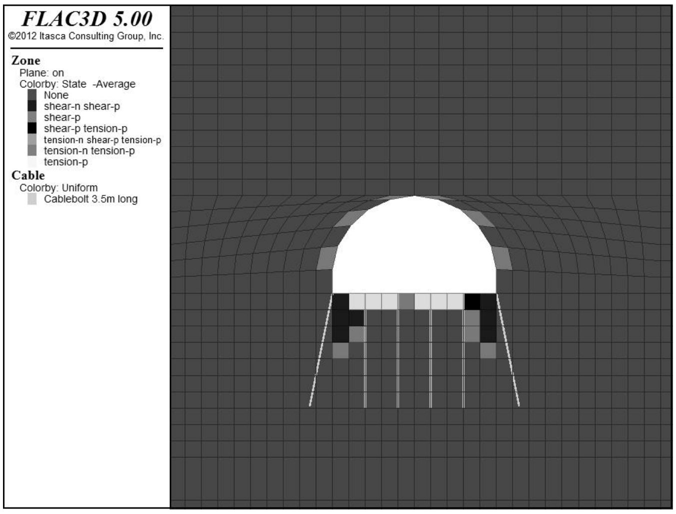


Figure 15. Failure zone around roadway with 0.5 m spacing steel set and 1 m row spacing cablebolt supports at 200 m overburden depth.

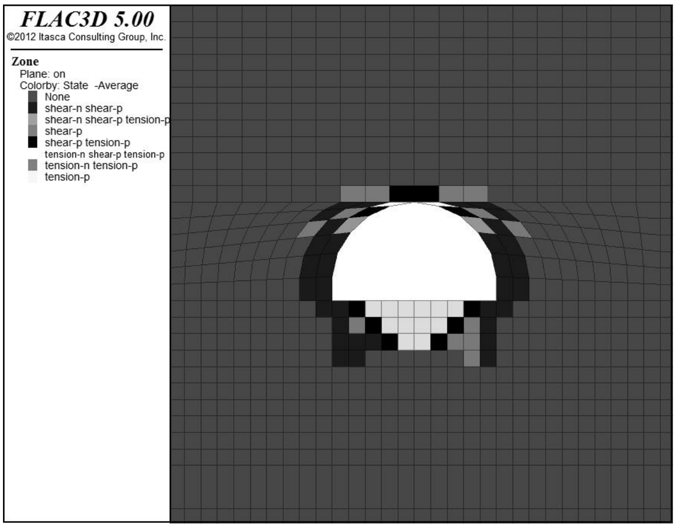


Figure 16. Failure zone around roadway without support at 300 m overburden depth.

Fig. 19 shows the performance of the rockbolt in reducing the failure zones in the roof and sidewalls of the roadway at 300 m depth. The roof and sidewalls have been maintained in a very stable condition as there were only small spotted failure zones could be found. Furthermore, the rockbolt support helped to decrease the rock failure not only in the roof and sidewalls but also in the floor, particularly at floor corners. Based on the simulated results, it can be summarized that the stability of the roadway at 300 m depth in GDM underground coal mine can be maintained by installing the 0.5 m spacing steel sets together with eight fully grouted rockbolts of 0.5 m row spacing in the roof and sidewalls, and six fully grouted cablebolts of 1 m row spacing in the floor.

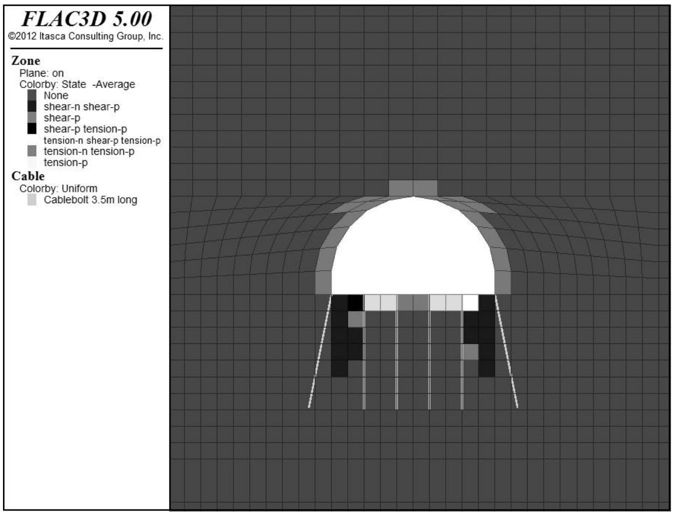


Figure 17. Failure zone around roadway with 0.5 m spacing steel set and 1 m row spacing cablebolt supports at 300 m overburden depth.

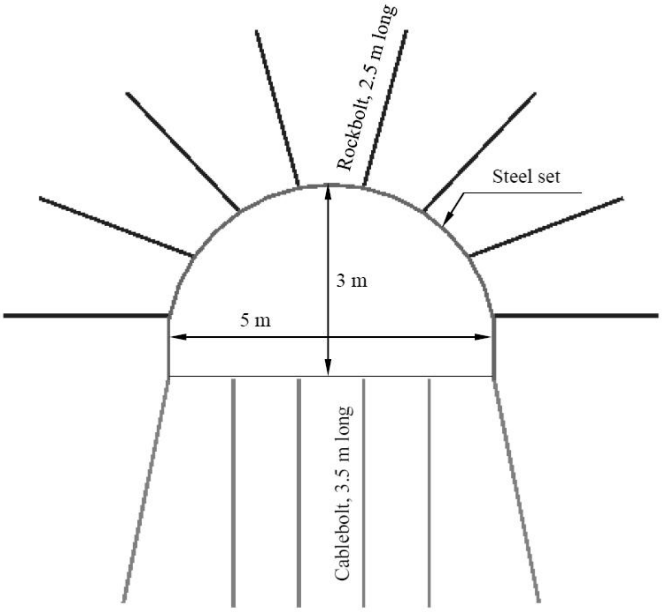


Figure 18. Pattern of modified support systems for roadway at 300 m overburden depth.

TABLE IV. PROPERTIES OF ROCKBOLT

Parameters	Values
Length (m)	2.50
Typical tensile capacity (kN)	178
Bolt modulus (MPa)	200000
Poisson’s ratio	0.25
Bond shear stiffness (MN/m/m)	12000
Yield strength (MPa)	588

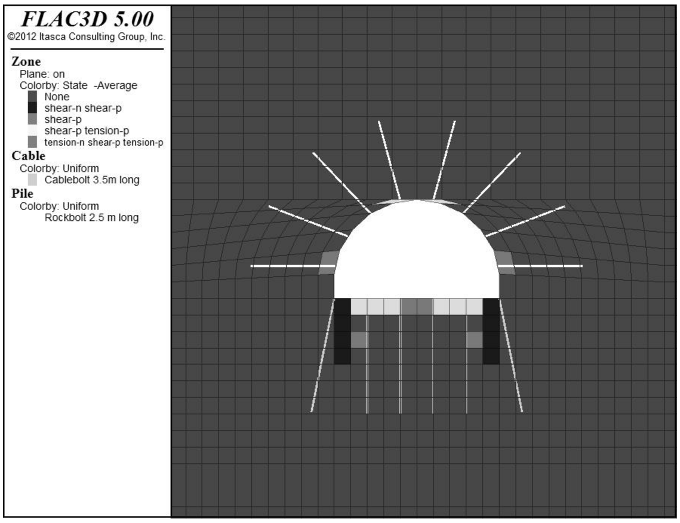


Figure 19. Failure zone around roadway with 0.5 m spacing steel set, 0.5 m row spacing rockbolt and 1 m row spacing cablebolt supports at 300 m overburden depth.

IV. CONCLUSION

The GDM coal mine is a new underground coal mine in Indonesia, which is being developed from the final highwall of an open pit mine. This coal mine possesses poor quality rock masses. Although the roadways are currently in a stable condition at the shallow depth, some ground control problems can be encountered at the deeper area if no effective support is provided. In this paper, the stability of the roadway at the deeper site and the most capable support system are analyzed and discussed. According to the results of a series of numerical analyses of the roadway excavation with rock supports, it is found that the installation of a 1 m spacing pattern of steel sets is sufficient to support the roadway at 50 m and 100 m depth. At 200 m depth, the installation of the 0.5 m spacing steel sets is adequate to stabilize the roof and sidewalls, while six cablebolts work effectively to control the development of failure zones in the floor. Furthermore, at 300 m depth, it is found that the installations of the 0.5 m spacing steel sets together with eight fully grouted rockbolts of 0.5 m row spacing in the roof and sidewalls, and six fully grouted cablebolts of 1 m row spacing in the floor are sufficient to provide the roadway in a stable condition.

ACKNOWLEDGMENT

The authors are grateful to the managers, engineers, and miners of GDM underground coal mine for providing useful information for this study. Without their supports, this study would not be achieved.

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