Journal of Engineering Science and Technology
Vol. XX, No. Y (Year) PPP - QQQ

UNDERCUTTING MINING METHOD, WHY NOT? A GEOTECHNICAL CONSIDERATION FOR COAL OPTIMIZATION

Abstract

To reduce the stripping ratio, mining with undercutting method can be an alternative even though it has high geotechnical risk. The method is carried out by cutting the low-wall slope so that the dip of rock bedding at low-wall is smaller than the slope angle. This study describes geotechnical consideration for undercutting design of coal mine in order that mining activity can be carried out with minimum risk. The analysis used finite element method by taking into account the aspect of mining sequence. The variables included the conditions of geological structure, rock structure, bedding, and geohydrology. Material properties used for the analysis were based on laboratory tests. The result shows that the slope resulted from undercutting method was stable even though with critical safety factor. The values of safety factor for undercutting design with and without buttress were 1.03 and 1.08, respectively. By considering the short mining sequence, undercutting method can still be implemented by preventing the potential for degradation of physical and mechanical properties of material from occurring. This method was successfully carried out, so mining activity was able to be done properly without any instability issues.

Keywords: Undercutting, Lowwall, Coal Mine, Slope Stability, Daylight

1. Introduction

Coal deposits, especially in back-arc basin and fore-arc basin, usually form successive layers with specific bedding position. The dip of coal bedding varies from gently sloping to perpendicular forming a vertical bedding. In several locations of the study area, folding structures were found in either micro or macro scales. Based on the geological condition, mining activity will form high-wall and low-wall sections. High-wall is a part of mine slope that is perpendicular to the dip of rock bedding, while low-wall is the dip of mine slope that is in the same direction as the dip of rock bedding (Fig. 1). Undercutting mining is defined as mining activity that cuts low-wall slope so that the angle of mine slope is greater than the angle of rock bedding or discontinuous plane (daylight).

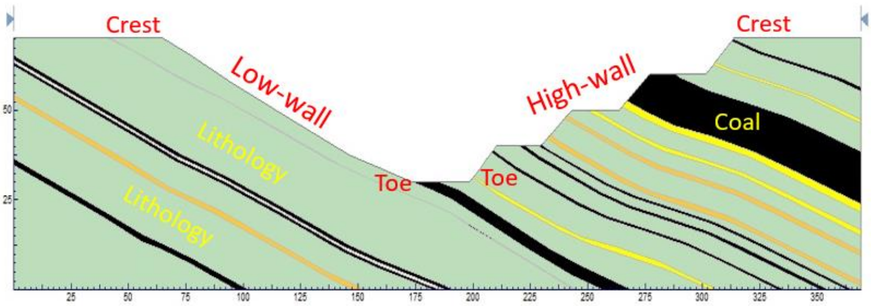

Fig. 1. Low-wall and high-wall of coal open-pit mine [1].

Contact between beds is a weak zone, and at the contact of rock bedding, it is usually found a thin layer that can trigger instability of slope. Slope stability of low-wall is affected by bedding contact between two rocks [2]. Bedding contact is usually in the form of clay which has high plasticity, thus it will separate two different beds. Because it separates two different parts, the cohesion value becomes zero and the internal friction angle becomes 13°, which were obtained based on back analysis result [2]. When a weak plane is formed at contact of two rocks, it is assumed that the upper bed only relies on the bed below it, so, with the concept of stress, the smaller the lower part, the greater the stress received, leading to potential for overstress at the toe. Overstress occurs due to difference in bedding ratio between the top and the bottom. The smaller the bedding ratio, the smaller the safety factor produced (Fig. 2) [1]. Since the rock bedding has a weak zone, it may cause failure at the toe. The toe failure is one of the contributing factors that leads to landslide at low-wall (Fig. 3) [3].

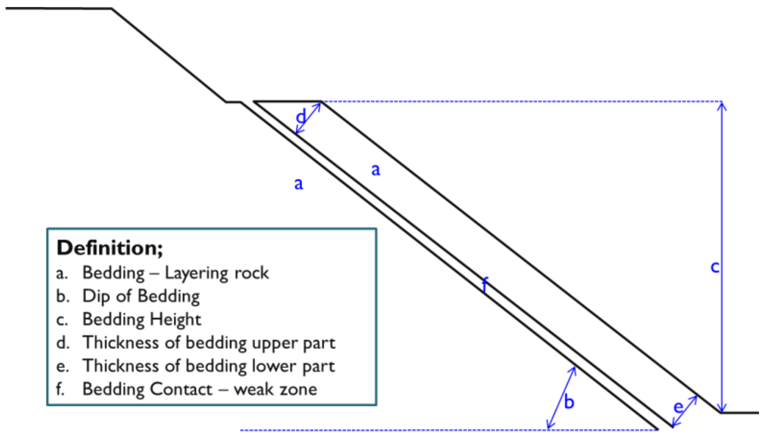

Fig. 2. Bedding ratio at low-wall [1].

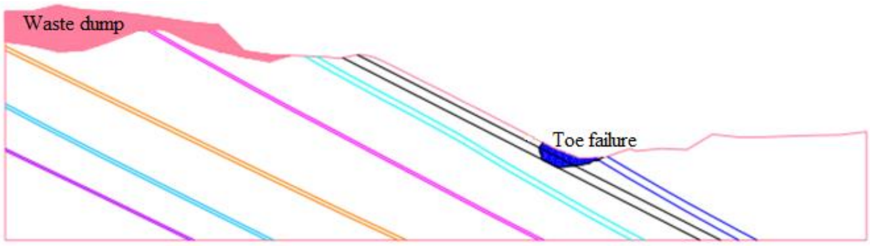

Fig. 3. Landslide at low-wall due to toe failure [3].

Slope stability analysis is closely related to the existing structure pattern, especially discontinuous plane. In this analysis, rock was assumed to be a rigid plane separated by weak plane that is cut by joints making the bed look like being cut into pieces; thus, the movement is purely due to frictional force at the bottom of the slope. When driving force gets bigger, buckling will potentially occur (Fig. 4).

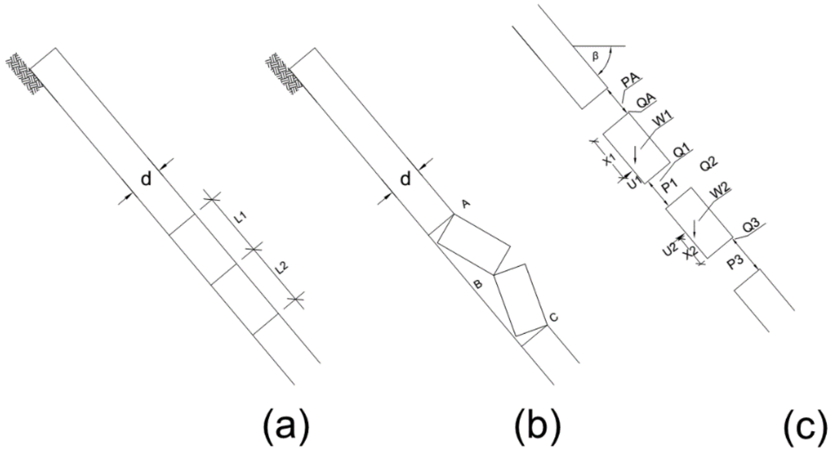

Fig. 4. Inaccurate application of rigid-and-jointed bed for low-wall stability [4].

Analysis of landslide due to buckling is carried out with assumption that at the toe of slope there are joints receiving pressure along the slope, and additional assumption of Young's modulus (Fig. 5). As a result of the pressure, buckling occurs. The shorter buckling (L), the greater the force required for the buckling process to occur. Water flowing in sandstone pore and impermeable mudstone cause a decrease in values of cohesion and internal friction angle.

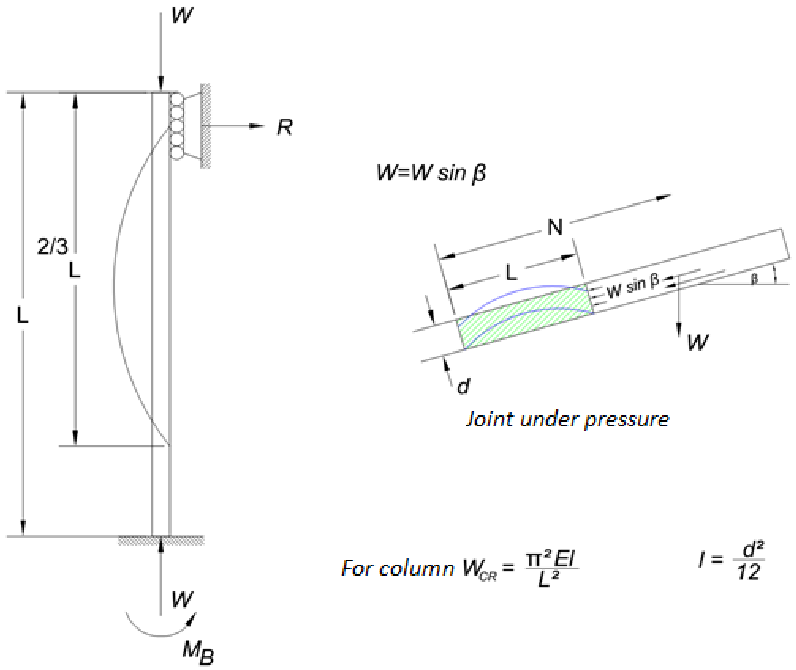

Fig. 5. Buckling concept at low-wall [4].

Analysis of low-wall stability uses concept of toe failure that occurs very quickly without showing any indication of instability. This type of landslide is triggered by low angle joint at the base of excavation. The low angle joint often cannot be detected from drilling, so field observation is very important in determining the possibility of low angle joint.

Landslide at low-wall is affected by pile load at the top of slope, which is considered to provide a significant burden to the low-wall slope. Loose pile material will put the load fully at the base which is passed on to the slope. Placement of overburden must be spaced from the slope to reduce load on the slope surface [3]. Landslide at low-wall can also be triggered by weathered rock on the slope surface. This type of landslide usually occurs in tropics which have very high weathering rate, and the surface is influenced by rill erosion.

Joint pattern plays a very important role for instability because there are some joints that are key to all joint systems. This type of instability is triggered by joint or fracture that cuts each other forming a shape of "X". Under normal condition, instability of natural slope is generally in stable condition. However, if a part of the "X" formation is taken due to slope forming, then instability may occur due to reduced horizontal force and increased groundwater level in joint area that results in increased hydrostatic pressure either vertically or horizontally (Fig. 6). Instability will occur when resisting force is smaller than driving force. If this mechanism can be known from the beginning, then instability can be anticipated early.

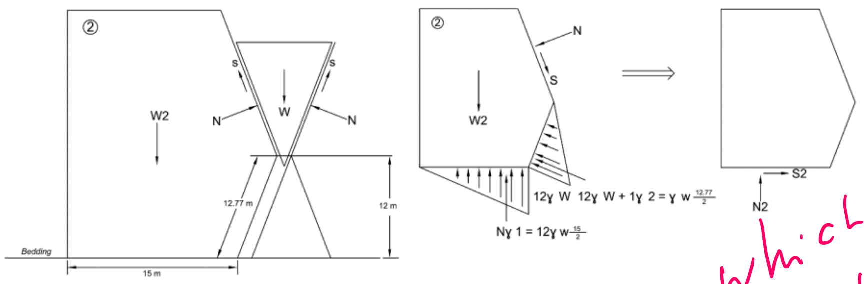

Fig. 6. Unfavorable joint mechanism [4].

The increased factor of safety for 'closed' joint ends cases over their 'open' counterparts for small scale slopes confirms the effectiveness of support measures such as bolting and wire meshes that essentially force exposed joint ends to move together. The modelling in the paper also confirms the loss in efficiency of such support with increasing slope height and suggests that other stabilization methods be considered for large slope [5]. The consideration of this variability was essential to reproduce buckling failure. Back analyses of failure mechanism were done, leading to representative values of the in-situ stress state and the normal and shear stiffness modulus of the foliation discontinuities [6].

Clastic sedimentary rocks in the Warukin Formation have low hardness [7] and the rocks will degrade when exposed to the surface [8]. With this condition, clastic sedimentary rocks, especially claystone, have limited engineering properties, and type of clay mineral must be considered before choosing construction material [9-10]. Large scale low-wall failures cause considerable disruptions to mining associated with a loss of production, damaged infrastructure, and the potential loss of life [11]. Depressurization is indispensable in pit optimization and pit design [12]. Numerical modeling in slope stability analysis for optimizing mine slope is more convincing in the result of slope stability analysis [13]. Theoretical aspects of resonant and chaotic dynamics to practical applications, and lays an essential logical foundation for future developments [14].

2.Methods

The method used in this study is back analysis on landslide at low-wall. Back analysis was carried out by exploring all geological and geohydrological conditions as well as physical and mechanical properties of slope rock, then evaluating slope stability analysis that had been carried out before the landslide occurred. Geological condition was explored by detailing slope material, identifying contact zone, calculating bedding ratio, and mapping structure seen after the landslide; while geohydrological component was explored by identifying slope bedding to obtain the type of aquifer.

Structure was mapped to determine the orientation of joint pattern found on the slope and identify the existence of low angle joint. Field observation includes identification of failure zone found in the landslide area as an indication of release point of force from rock bedding. Physical and mechanical properties were evaluated by comparing sampling position to the results of laboratory tests that have been carried out. Additional number of samples required for further analysis was added for detailing back analysis later. Laboratory tests such as hardness test, triaxial test, and uniaxial test were carried out by following the ASTM standards. Material properties used for analysis are in Table 1.

Table 1. Material properties.

Material	Properties					
	Unit weight (kN/m^3)	Cohesion (kPa)	Friction angle (°)	Tensile strength (kPa)	Young mod. (kPa)	Poisson ratio
Disposal and buttress	17	75	20	75	125000	0.4
Mudstone	18	160	35	160	125000	0.4
Weak zone	14	10	30	5	50000	0.4
Coal seam	14	189	35	189	50000	0.4

3. Results and Discussion

The research area was located at one of the coal mines in the Warukin Formation with low-wall dip of about 9°. The area consists of sandstone, claystone, and coal with hardness below 1 MPa. The groundwater level was relatively high, about 10 m from the surface. Undercutting was planned to be carried out to the toe of landslide that had occurred before. The landslide caused mining activity to stop, leaving the pit neglected, so 1/3 toe of the landslide was submerged in water. Mining was carried out again after 5 years the pit had been abandoned and the mining process began with dewatering of the water in the pit.

The stratigraphic unit of research area in the form of landslide material was on slope surface with a dip of about 14° and a material thickness of about 30 m. In-situ materials were beddings of claystone, mudstone, and coal with dips of about 7-9°. Counterweight was put on the toe of landslide material by back filling up the overburden material layer by layer, so that optimal buttress was obtained. Undercutting was carried out about 15 m from the buttress toe with an undercut depth of about 35 m, calculated from the elevation of buttress toe. The dip of undercutting slope was about 38°, therefore there was daylight due to the bedding dip of 9° (Fig. 7).

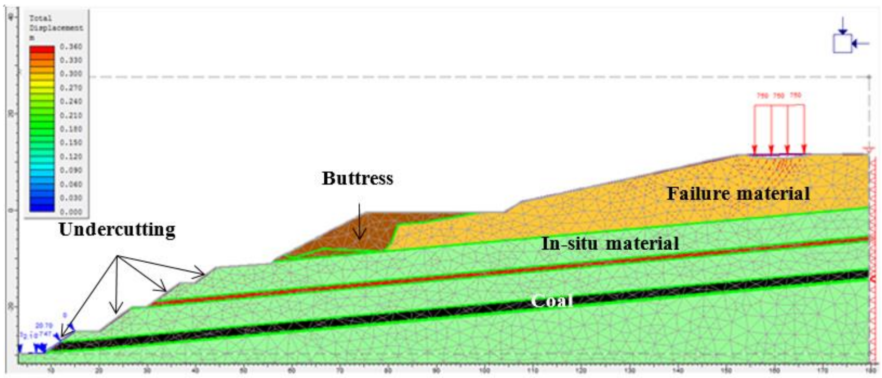

Fig. 7. Distribution of in-situ and failure materials.

Soft material at the toe of landslide material had been cleaned before the buttress construction. Removal of the landslide toe caused creeping on 1/3 part of the slope (after being submerged) but did not cause major failure (Fig. 8). Counterweight was formed at the toe of slope with a height of 15 m and a width of 25 m, and buttress dip of 17°. Undercutting formed a slope by cutting the bedding plane of in-situ rock on the low-wall side, causing daylight. Slope formation in the undercutting position was adjusted to the overall slope for undercutting.

Fig. 8. Excavation using box cut method at low-wall.

Analysis was performed to determine the stability of landslide material before the undercutting began. Stabilization of landslide material is required to know the impact on stability of undercutting that will be carried out. In general, the analysis was performed on:

1. Stability of landslide material with and without buttress.
2. Slope stability of landslide material and undercutting with and without buttress.

The analysis shows that the landslide material had safety factor of 1.01 which indicated repose condition, and this was in accordance with the real condition where the slope dip of landslide material was formed naturally when landslide occurred (Fig. 9). Stress accumulation was found at the toe of slope with slip surface in the contact area between the in-situ material and the landslide material above it. This was in line with the characteristics of the location. Buttress construction increased the stability of landslide material to 1.08, but when undercutting was carried out, the slope stability changed to 1.03 (Figs. 10 and 11).

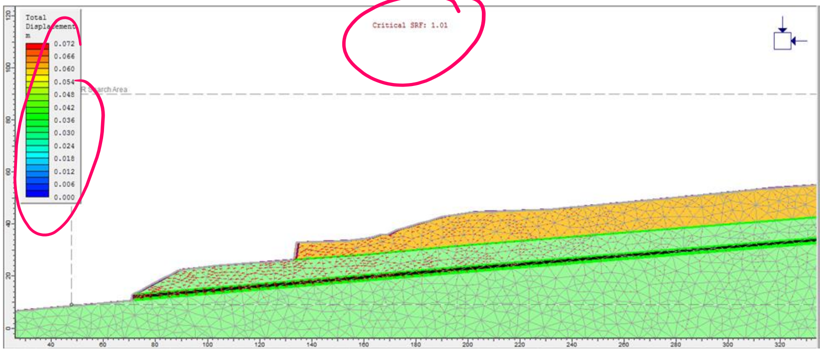

Fig. 9. Single step of in-situ and failure materials without buttress.

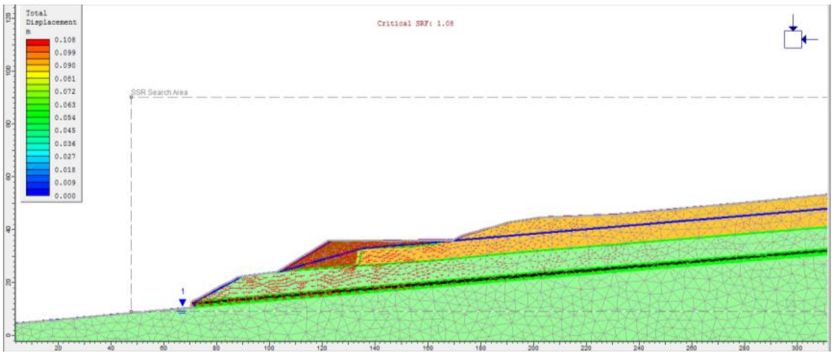

Fig. 10. Single step of in-situ and failure materials with buttress showing groundwater level to buttress.

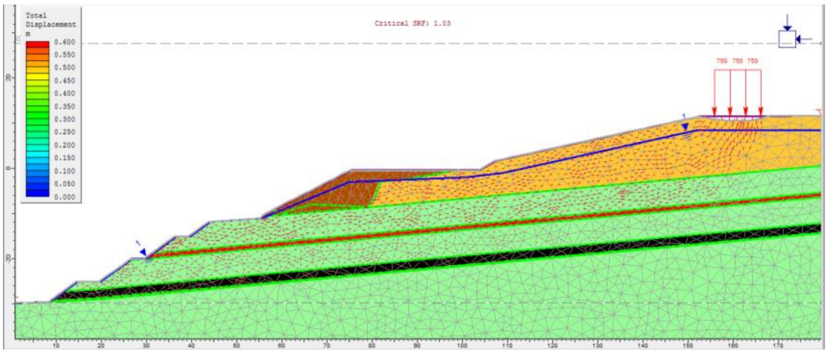

Fig. 11. Undercutting final design and showing distribution displacement.

Potential for landslide was found in the landslide material and in the discontinuous plane along the rock bedding which was a weak zone that controlled instability (Fig. 12). Material deformation occurred more in the landslide material and in the upper in-situ bed. Undercutting mining can be carried out with strict control to maintain the material properties at the top and in the in-situ material. The safety factor of 1.03 is a critical number, therefore, this should be utilized in undercutting mining. Surface water must also be managed to avoid either surface water flow into the landslide zone or infiltration to the contact zone between the in-situ and the landslide materials. If water gets into the contact zone, it will trigger slip surface along the contact zone. Heavy equipment in the landslide zone must also be restricted to keep the load stable. Heavy equipment activity in the landslide area can increase the material load, so the driving force becomes greater.

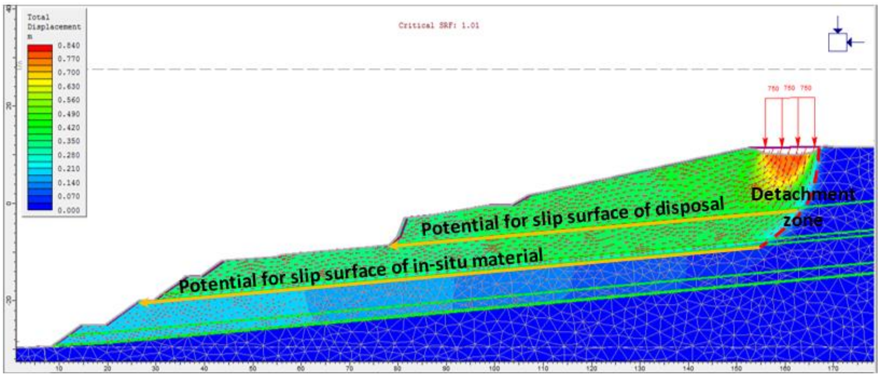

Fig. 12. Distribution of total displacement showing semi-circular pattern.

Slope monitoring system is also mandatory to obtain real condition of slope stability. The monitoring can use simple tool, considering the material has a high plasticity, so that the potential for sudden failure is quite small. Visual observation on drainage condition and buttress stability should also be regularly carried out during undercutting. With strict control, undercutting can be carried out safely and coal can be mined out properly. Coal reserves increased significantly based on the result of this analysis. When the mining was completed, the stability of undercutting and buttress were maintained (Fig. 13).

Fig. 13. Mining was completed using undercutting method without any instability issue.

Based on the analysis result, undercutting can be carried out by considering detailed geological aspects of the area, and the analysis should pay attention to the aspects. Although the safety factor is quite critical, with efforts to maintain the physical and mechanical properties, stability can be maintained.

4. Conclusions

Undercutting mining can be carried out by paying attention to the detailed aspects of geological condition. The analysis result using finite element method shows a critical safety factor, but with strict control of slope stability variables, undercutting activity can still be carried out. The analysis identified details of geological condition such as lithology, stratigraphy, aquifer, and weak zone between beds. Identification of discontinuous plane pattern must be done to ensure the kinematics of a bedding. In high stress zone, the condition of discontinuous plane has a significant role in stability of low-wall slope. Calculation of bedding ratio after modelling weak plane is highly recommended so that at the time of analysis, it will be close to the real field condition. Finite element method is recommended for low-wall stability analysis even though limit equilibrium method is still possible if circular pattern only occurs in one bedding. Depressurization is required to reduce aquifer stress due to the presence of distressed aquifer.

References

1. Supandi; and Hidayat, H. (2013). The impact of geometry bedding toward slope stability in coal mining. *Proceedings of the Fourth International Symposium of Geotechnical Safety and Risk*. Hong Kong, China, 559-562.
2. Supandi. (2014). Determination material properties on bedding contact at the low-wall part of coal mine. *Proceedings of International Society for Rock Mechanics and Rock Engineering EUROCK*. Vigo, Spain, 229-233.

3. Sulistijo, B.; and Kusumo, A.D. (2013). Stabilitas low wall. *Proceedings of TPT XXII PERHAPI*. Yogyakarta, Indonesia.
4. Giani, G.P. (1992). *Rock slope stability analysis*. Rotterdam: A.A. Balkema.
5. Hammah, R.E.; Yacoub, T.; and Curran, J.H. (2009). Variation of failure mechanisms of slopes in jointed rock masses with changing scale. *Proceedings of the Thrid CANUS Rock Mechanics Symposium*. Toronto, Canada.
6. Silva, C.H.C; and Lana, M.S. (2014). Numerical modeling of buckling failure in a mine slope. *Revista Escola de Minas*, 67(1), 81-86.
7. Supandi; and Hartono, H.G. (2020). Geomechanic properties and provenance analysis of quartz sandstone from the Warukin formation. *International Journal of GEOMATE*, 18(66), 140-149.
8. Supandi; Zakaria, Z.; Sukiyah, E.; and Sudradjat, A. (2018). The correlation of exposure time and claystone properties at the Warukin formation Indonesia. *International Journal of GEOMATE*, 15(52), 160-167.
9. Supandi; Zakaria, Z.; Sukiyah, E.; and Sudradjat, A. (2019). The influence of kaolinite-illite toward mechanical properties of claystone. *Open Geosciences*, 11(1), 440-446.
10. Ballantyne, S.; Nolan, D.; and Merry, M. (2003). Lowwall instabilities in coal mines in Indonesia from a geotechnical perspective. *Proceedings of Seminar Sehari Kemantapan Lereng di Pertambangan Indonesia III*. Bandung, Indonesia, 1-8.
11. Vangsness, T.A. (2020). *Shear strength characterisation of in-pit mud to ensure lowwall stability*. PhD Thesis, School of Civil Engineering, The University of Queensland.
12. Waterhouse, J.; Crisostomo, J.; Nolan, D.; and Dutton, A. (2008). An integration of hydrogeology and geotechnical engineering for the design of the Tutupan Coal Mine T100 low wall, South Kalimantan, Indonesia. *Proceedings of International Mine Water Association*. Ostrava, Czech Republic, 1-4.
13. Suratha, I.G. (2007). Numerical modelling and slope stability analysis for optimizing open pit coal mine at Binuang South Kalimantan. *Indonesian Mining Journal*, 10(1), 1-7.
14. Rosengren, A.J; Daquin, J.; Tsiganis, K.; Alessi, E.M.; Deleflie, F.; Rossi, A.; and Valsecchi, G.B. (2017). Galileo disposal strategy: stability, chaos, and predictability. *Monthly Notice of the Royal Astronomical Society*, 464(4), 4063-4076.

Journal of Engineering Science and Technology
Vol. 17, No. 3 (2022) 1921 - 1933

UNDERCUTTING MINING METHOD, WHY NOT? A GEOTECHNICAL CONSIDERATION FOR COAL OPTIMIZATION

SUPANDI

Department of Mining Engineering, Institut Teknologi Nasional Yogyakarta, Jalan Babarsari, Depok, Sleman, Yogyakarta, Indonesia, 55281.
E-mail: supandi@itny.ac.id

Abstract

To reduce the stripping ratio, mining with undercutting method can be an alternative even though it has high geotechnical risk. The method is carried out by cutting the low-wall slope so that the dip of rock bedding at low-wall is smaller than the slope angle (daylight). This study describes geotechnical consideration for undercutting design of coal mine in order that mining activity can be carried out with minimum risk. The analysis used finite element method by taking into account the aspect of mining sequence. The variables included the conditions of geological structure, rock structure, bedding, and geohydrology. Material properties used for the analysis were based on laboratory tests. The result shows that the slope resulted from undercutting method was stable even though with critical safety factor. The values of safety factor for undercutting design with and without buttress were 1.03 and 1.08, respectively. By considering the short mining sequence, undercutting method can still be implemented by preventing the potential for degradation of physical and mechanical properties of material from occurring. This method was successfully carried out, so mining activity was able to be done properly without any instability issues.

Keywords: Coal mine, Daylight, Low-wall, Slope stability, Undercutting.

1. Introduction

In risk management of mining activity, geotechnical factor becomes an important aspect that must be considered in terms of both severity and probability. Undercutting design can increase probability of geotechnical risk [1]. The risk of undercutting can be reduced by conducting detailed technical study that considers detailed geological aspects. Characteristic of geological condition is one of the things that must be explored in detail so that in geotechnical analysis, all of the geological conditions can be included in the analysis model.

Coal deposits, especially in back-arc basin and fore-arc basin, usually form successive layers with specific bedding position. The dip of coal bedding varies from gently sloping to perpendicular forming a vertical bedding. In several locations of the study area, folding structures were found in either micro or macro scales. Based on the geological condition, mining activity will form high-wall and low-wall sections. High-wall is a part of mine slope that is perpendicular to the dip of rock bedding, while low-wall is the dip of mine slope that is in the same direction as the dip of rock bedding (Fig. 1). Undercutting mining is defined as mining activity that cuts low-wall slope so that the angle of mine slope is greater than the angle of rock bedding or discontinuous plane (daylight).

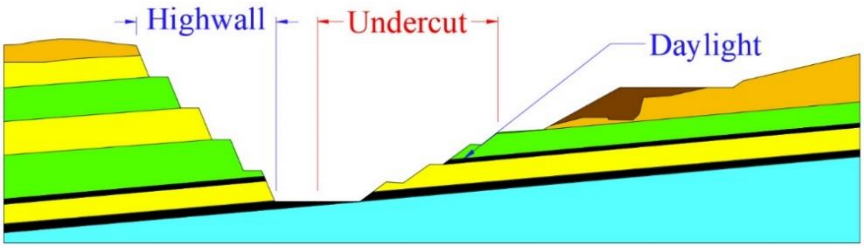

Fig. 1. Investigated shapes of projectiles (Geometry and dimensions).

Contact between beds is a weak zone, and at the contact of rock bedding, it is usually found a thin layer that can trigger instability of slope. Slope stability of low-wall is affected by bedding contact between two rocks [2]. When a weak plane is formed at contact of two rocks, it is assumed that the upper bed only relies on the bed below it, so, with the concept of stress, the smaller the lower part, the greater the stress received, leading to potential for overstress at the toe. Overstress occurs due to difference in bedding ratio between the top and the bottom. The smaller the bedding ratio, the smaller the safety factor produced (Fig. 2) [2]. Bedding contact is usually in the form of clay which has high plasticity; thus it will separate two different beds. Because it separates two different parts, the cohesion value becomes zero and the internal friction angle becomes 13°, which were obtained based on back analysis result [3].

Since the rock bedding has a weak zone, it may cause failure at the toe. The toe failure is one of the contributing factors that leads to landslide at low-wall (Fig. 3) [4]. Geotechnical analysis at the low-wall part shall be consider with some geological characteristics [5] such as: 1) weak layer on bedding contact, 2) bedding ratio, 3) aquifer type below bedding material, 4) geotechnical analysis method using finite element, 5) type of slip surface, and 6) discontinuity orientation of rock mass. Determination of critical buckling height (CBH) must consider the slope dip angle, friction angle, material cohesion on bedding contact, and elastic modulus of slope rock [6]. Calculation of rock dilation is one of the important factors in calculating block above slip surface where dilation is influenced by shear displacement and base distance [7]. Fracture in rock mass begins by displacement of bedding contact and distribution of stress [8]. Footwall slope stability analysis also gives serious attention to condition of bedding profile, from the dip of bedding, orientation of bedding, to joint set or discontinuous plane on bedding [9].

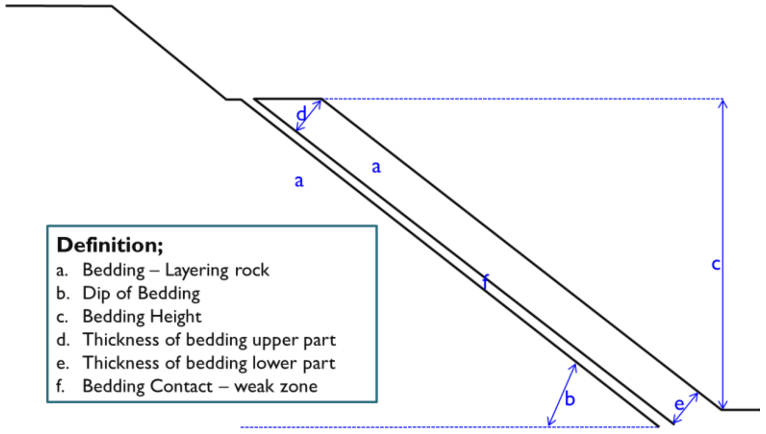

Fig. 2. Bedding ratio at low-wall [2].

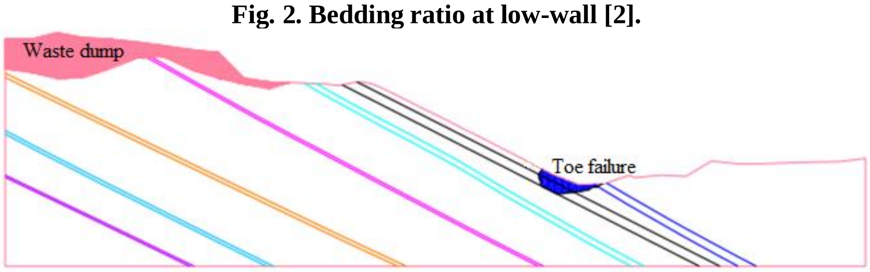

Fig. 3. Landslide at low-wall due to toe failure [4].

Slope stability analysis is closely related to the existing structure pattern, especially discontinuous plane. In this analysis, rock was assumed to be a rigid plane separated by weak plane that is cut by joints making the bed look like being cut into pieces; thus, the movement is purely due to frictional force at the bottom of the slope. When driving force gets bigger, buckling will potentially occur (Fig. 4). Surface of toe breakout is a key control in kinematics of landslide mechanism on bi-planar failure at footwall slope [10, 11].

Analysis of landslide due to buckling is carried out with assumption that at the toe of slope there are joints receiving pressure along the slope, and additional assumption of Young's modulus (Fig. 5). As a result of the pressure, buckling occurs. The shorter buckling (*L*), the greater the force required for the buckling process to occur. Water flowing in sandstone pore and impermeable mudstone cause a decrease in values of cohesion and internal friction angle.

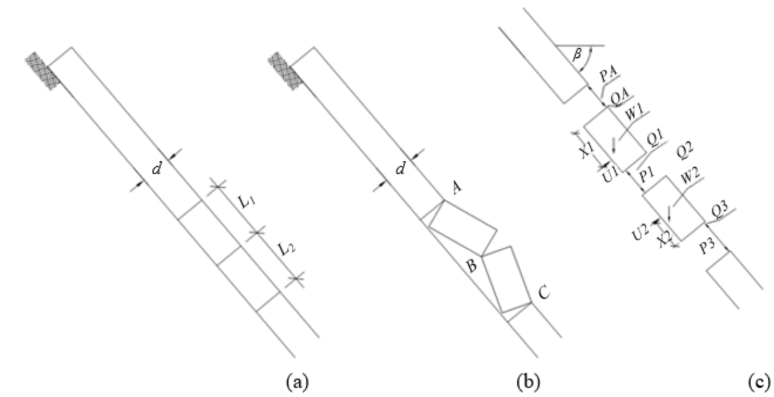

Fig. 4. Inaccurate application of rigid-and-jointed bed for low-wall stability [12].

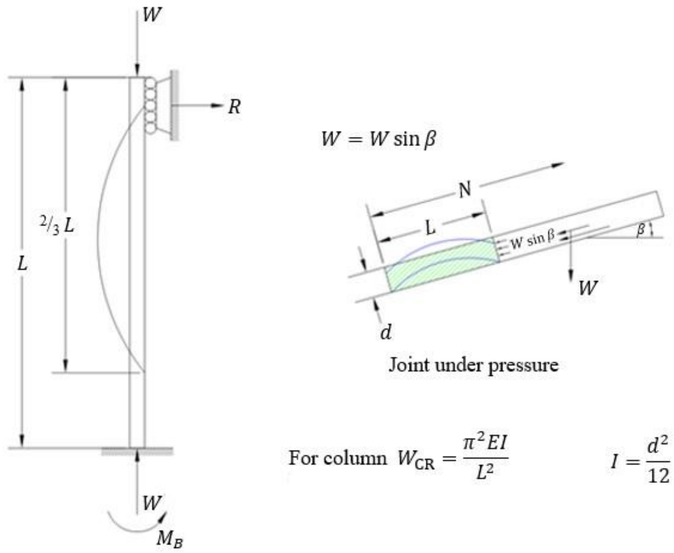

Fig. 5. Buckling concept at low-wall [12].

Analysis of low-wall stability uses concept of toe failure that occurs very quickly without showing any indication of instability. This type of landslide is triggered by low angle joint at the base of excavation. The low angle joint often cannot be detected from drilling, so field observation is very important in determining the possibility of low angle joint.

Landslide at low-wall is affected by pile load at the top of slope, which is considered to provide a significant burden to the low-wall slope. Loose pile material will put the load fully at the base which is passed on to the slope. Placement of overburden must be spaced from the slope to reduce load on the slope surface [4]. Landslide at low-wall can also be triggered by weathered rock on the slope surface. This type of landslide usually occurs in tropics which have very high weathering rate, and the surface is influenced by rill erosion.

Joint pattern plays a very important role for instability because there are some joints that are key to all joint systems. This type of instability is triggered by joint or fracture that cuts each other forming a shape of "X". Under normal condition, instability of natural slope is generally in stable condition. However, if a part of the "X" formation is taken due to slope forming, then instability may occur due to reduced horizontal force and increased groundwater level in joint area that results in increased hydrostatic pressure either vertically or horizontally (Fig. 6). Instability will occur when resisting force is smaller than driving force. If this mechanism can be known from the beginning, then instability can be anticipated early.

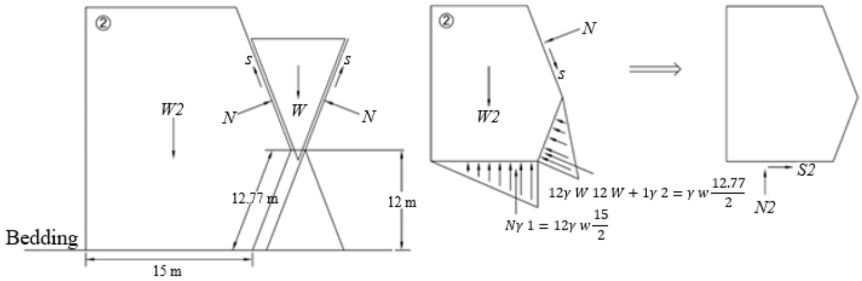

Fig. 6. Unfavourable joint mechanism [4].

The increased factor of safety for 'closed' joint ends cases over their 'open' counterparts for small scale slopes confirms the effectiveness of support measures such as bolting, and wire meshes that essentially force exposed joint ends to move together. The modelling in the paper also confirms the loss in efficiency of such support with increasing slope height and suggests that other stabilization methods be considered for large slope [13, 14]. The consideration of this variability was essential to reproduce buckling failure. Back analyses of failure mechanism were done, leading to representative values of the in-situ stress state and the normal and shear stiffness modulus of the foliation discontinuities [15].

Clastic sedimentary rocks in the Warukin Formation have low hardness [16] and the rocks will degrade when exposed to the surface [17]. With this condition, clastic sedimentary rocks, especially claystone, have limited engineering properties, and type of clay mineral must be considered before choosing construction material [18]. Large scale low-wall failures cause considerable disruptions to mining associated with a loss of production, damaged infrastructure, and the potential loss of life [19]. Depressurization is indispensable in pit optimization and pit design [20]. Numerical modelling in slope stability analysis for optimizing mine slope is more convincing in the result of slope stability analysis [21]. Theoretical aspects of resonant and chaotic dynamics to practical applications and lays an essential logical foundation for future developments [22].

Physical and mechanical properties of sedimentary rock and mud rock change when they are in either dry or wet conditions or when the water content changes. When in dry condition, cohesion and shear strength increases. Geohydrological condition under low-wall is an important factor in low-wall stability. Aquifer stress can trigger buckling at low-wall, therefore, identifying geohydrological condition is very important [23, 24].

2. Methods

The method used in this study is back analysis on landslide at low-wall. Back analysis was carried out by exploring all geological and geohydrological conditions as well as physical and mechanical properties of slope rock, then evaluating slope stability analysis that had been carried out before the landslide occurred. Stratigraphy of rock is obtained based on detailed geological drilling and geotechnical drilling. Sampling of rock from the drilling was carried out to obtain the rock properties. To obtain the data of rock properties, laboratory testing was carried out on core samples from drilling activity. The test method used unconsolidated undrained triaxial test based on ASTM D2850-87 standard. The drilling activity to sampling referred to ASTM D2113-99 regarding rock core drilling and sampling of rock site investigation, ASTM D5434-97 regarding field logging of subsurface exploration of soil and rock, and ASTM D4220-95 regarding preserving and transporting sample. Rock description used ASTM D2488-00 standard for description and identification of soil (visual manual procedure). This method was chosen because the sedimentary rocks in research location have characteristics like soil.

Geological condition was explored by detailing slope material, identifying contact zone, calculating bedding ratio, and mapping structure seen after the landslide; while geohydrological component was explored by identifying slope bedding to obtain the type of aquifer. Structure was mapped to determine the orientation of joint pattern found on the slope and identify the existence of low angle joint. Field observation includes identification of failure zone found in the landslide area as an indication of release point of force from rock bedding. Physical and mechanical properties were evaluated by comparing sampling position to the results of laboratory tests that have been carried out. Additional number of samples required for further analysis was added for detailing back analysis later. Laboratory tests such as hardness test, triaxial test, and uniaxial test were carried out by following the ASTM standards. Geotechnical analysis was carried out using finite element method with help of Phase 2 program. Material properties used for analysis are in Table 1. The research area was located at one of the coal mines in the Warukin Formation with low-wall dip of about 9°. The area consists of sandstone, claystone, and coal with hardness below 1 MPa. The groundwater level was relatively high, about 10 m from the surface. Undercutting was planned to be carried out to the toe of landslide that had occurred before. The landslide caused mining activity to stop, leaving the pit neglected, so 1/3 toe of the landslide was submerged in water. Mining was carried out again after 5 years the pit had been abandoned and the mining process began with dewatering of the water in the pit.

Table 1. Material properties.

Material	Properties					
	Unit weight (kN/m^3)	Cohesion (kPa)	Friction angle (°)	Tensile strength (kPa)	Young mod. (kPa)	Poisson ratio
Disposal and buttress	17	25	34	75	85,000	0.23
Mudstone	18	160	45	160	125,000	0.38
Weak zone	15	10	20	10	35,000	0.12
Coal seam	14	189	35	189	200,000	0.16

3. Results and Discussion

The stratigraphic unit of research area in the form of landslide material was on slope surface with a dip of about 14° and a material thickness of about 30 m. In-situ materials were beddings of claystone, mudstone, and coal with dips of about 7-9°. Counterweight was put on the toe of landslide material by back filling up the overburden material layer by layer, so that optimal buttress was obtained. Undercutting was carried out about 15 m from the buttress toe with an undercut depth of about 35 m, calculated from the elevation of buttress toe. The dip of undercutting slope was about 38°, therefore there was daylight due to the bedding dip of 9° (Fig. 7).

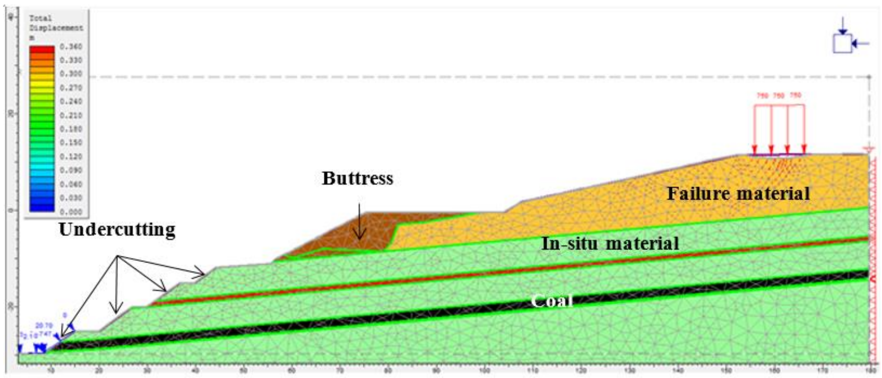

Fig. 7. Distribution of in-situ and failure materials.

Soft material at the toe of landslide material had been cleaned before the buttress construction. Removal of the landslide toe caused creeping on 1/3 part of the slope (after being submerged) but did not cause major failure (Fig. 8). Counterweight was formed at the toe of slope with a height of 15 m and a width of 25 m, and buttress dip of 17°. Undercutting formed a slope by cutting the bedding plane of in-situ rock on the low-wall side, causing daylight. Slope formation in the undercutting position was adjusted to the overall slope for undercutting.

Fig. 8. Excavation using box cut method at low-wall.

Analysis was performed to determine the stability of landslide material before the undercutting began. Stabilization of landslide material is required to know the impact on stability of undercutting that will be carried out. In general, the analysis was performed on:

i. Stability of landslide material with and without buttress.

ii. Slope stability of landslide material and undercutting with and without buttress.

The analysis shows that the landslide material had safety factor of 1.01 which indicated repose condition, and this was in accordance with the real condition where the slope dip of landslide material was formed naturally when landslide occurred (Fig. 9). Stress accumulation was found at the toe of slope with slip surface in the contact area between the in-situ material and the landslide material above it. This was in line with the characteristics of the location. Buttress construction increased the stability of landslide material to 1.08, but when undercutting was carried out, the slope stability changed to 1.03 (Figs. 10 and 11).

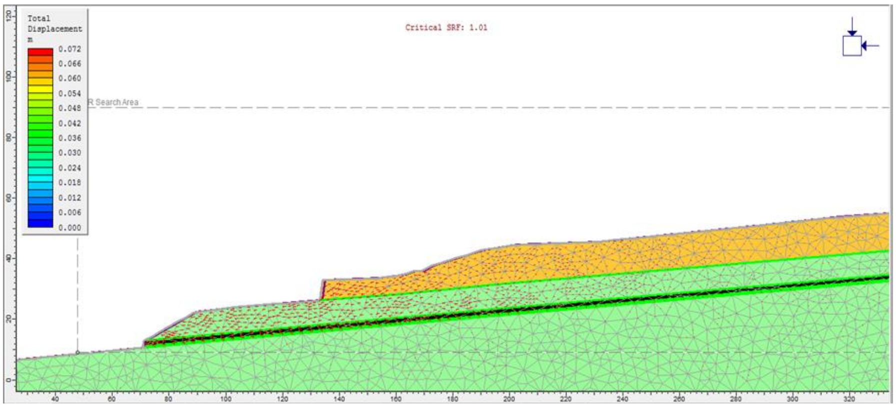

Fig. 9. Single step of in-situ and failure materials without buttress.

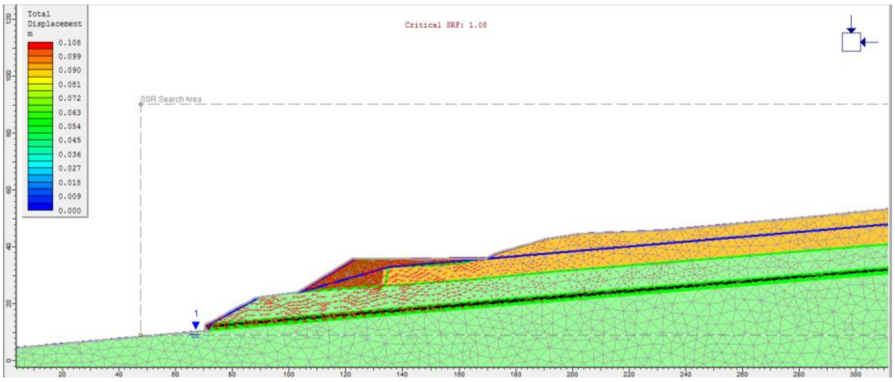

Fig. 10. Single step of in-situ and failure materials with buttress showing groundwater level to buttress.

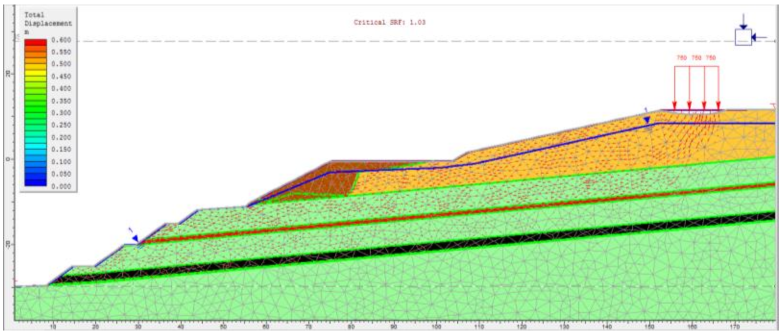

Fig. 11. Undercutting final design and showing distribution displacement.

Potential for landslide was found in the landslide material and in the discontinuous plane along the rock bedding which was a weak zone that controlled instability (Fig. 12). Material deformation occurred more in the landslide material and in the upper in-situ bed. Undercutting mining can be carried out with strict control to maintain the material properties at the top and in the in-situ material. The safety factor of 1.03 is a critical number, therefore, this should be utilized in undercutting mining. Surface water must also be managed to avoid either surface water flow into the landslide zone or infiltration to the contact zone between the in-situ and the landslide materials. If water gets into the contact zone, it will trigger slip surface along the contact zone. Heavy equipment in the landslide zone must also be restricted to keep the load stable. Heavy equipment activity in the landslide area can increase the material load, so the driving force becomes greater.

Slope monitoring system is also mandatory to obtain real condition of slope stability. The monitoring can use simple tool, considering the material has a high plasticity, so that the potential for sudden failure is quite small. Visual observation on drainage condition and buttress stability should also be regularly carried out during undercutting. With strict control, undercutting can be carried out safely and coal can be mined out properly. Coal reserves increased significantly based on the result of this analysis. When the mining was completed, the stability of undercutting and buttress were maintained (Fig. 13). The optimum monitoring tool can be selected by adjusting to the rock characteristics, in this case, the strain of rock mass. Accuracy level of the monitoring tool used adjusts to the rock mass strain. The selected monitoring tool is certainly different for high strain and low strain.

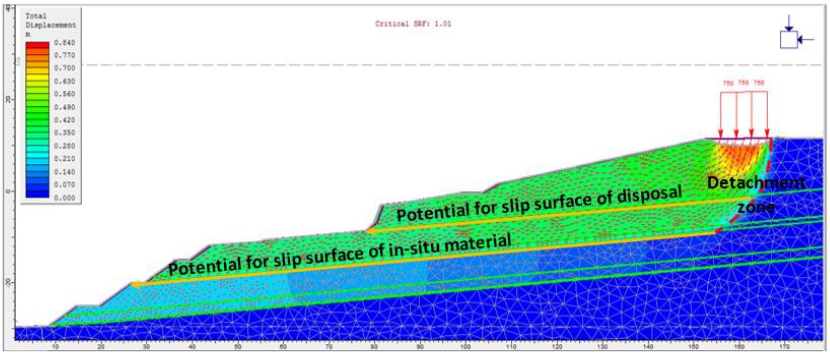

Fig. 12. Distribution of total displacement showing semi-circular pattern.

Fig. 13. Mining was completed using under-cutting method without any instability issue.

Based on the analysis result, undercutting can be applied out by considering detailed geological aspects of the area, and the analysis should pay attention to the aspects. Undercutting method will be decrease stripping ratio (SR) and increasing economical aspect. Consequence of undercutting is increasing geotechnical risk, but the risk can reduce by implementation some geotechnical consideration and close monitoring during operation. This kind of analysis is few due to the data limitation and the difficulty in verification. This research combines the collected data which are quite detailed, complete, in accordance with the standards of each process, and also has the opportunity to be implemented in field as the verification of calculation. A series of processes in collecting, testing, and analysing the data in detail is the novelty in this research, in particular in the case of a coal mine that has low mechanical properties.

4. Conclusions

Undercutting mining can be carried out by paying attention to the detailed aspects of geological condition. The analysis result using finite element method shows a critical safety factor, but with strict control of slope stability variables, undercutting activity can still be carried out. The analysis identified details of geological condition such as lithology, stratigraphy, aquifer, and weak zone between beds. Identification of discontinuous plane pattern must be done to ensure the kinematics of a bedding. In high stress zone, the condition of discontinuous plane has a significant role in stability of low-wall slope. Calculation of bedding ratio after modelling weak plane is highly recommended so that at the time of analysis, it will be close to the real field condition. Finite element method is recommended for low-wall stability analysis even though limit equilibrium method is still possible if circular pattern only occurs in one bedding. Depressurization is required to reduce aquifer stress due to the presence of distressed aquifer.

Nomenclatures

A	Discontinue Upper part (Fig. 4), m
B	Discontinue Middle part (Fig. 4), m
C	Discontinue Middle part (Fig. 4), m
d	Thickness of discontinue layer (Figs. 4 and 5), m
E	Elasticity (Fig. 5), -
I	Area of buckling ($d^2/12$) (Fig. 5), m^2
L	Length of Buckling (Fig. 5), m
$L1$	Length of upper block (Fig. 4), m
$L2$	Length of bottom block (Fig. 4), m
M_B	Coupling movement (Fig. 5), degree
N	Force (Figs. 5 and 6), N
$N2$	Secondary Force (Fig. 6), N
PA	Pressure upper part (Fig. 4), kPa
$P1$	Pressure middle part (Fig. 4), kPa
$P3$	Pressure bottom part (Fig. 4), kPa
QA	Movement upper part (Fig. 4), m
$Q1$	Movement middle part (Fig. 4), m
$Q2$	Movement Bottom part (Fig. 4), m
R	Resistant Force (Fig. 5), N
S	Shear stress (Fig. 6), kPa
$U1$	Pore pressure upper block (Fig. 4), Psi
$U2$	Pore Pressure second block (Fig. 4), Psi
W	Weight of Block (Figs. 5 and 6), Ton
W_{CR}	A total weight of block ($(\pi^2 EI)/L^2$) (Fig. 5), ton
$W1$	Weight block upper block (Fig. 4), ton
$W2$	Weight block bottom block Figs. 4 and 6), ton
$X1$	Length shear block upper block (Fig. 4), m
$X2$	Length Shear block bottom block (Fig. 4), m

Greek Symbols

β	Angle of shear block (Figs. 4 and 5), degree.
γ	Unit Weight (Fig. 6), gr/cm^3

Abbreviations

ASTM	American Society for Testing and Materials
CBH	Critical Buckling Height
SR	Stripping Ratio

References

1. Canbulat, I.; Hoelle, J.; and Emery, J. (2013). Risk management in open cut coal mines. *International Journal of Mining Science and Technology*, 23(3), 369-374.
2. Hidayat, H. (2013). The impact of geometry bedding toward slope stability in coal mining. *Proceedings of the Fourth International Symposium of Geotechnical Safety and Risk*. Hong Kong, China, 559-562.

3. Supandi (2014). Determination material properties on bedding contact at the low-wall part of coal mine. *Proceedings of International Society for Rock Mechanics and Rock Engineering EUROCK*. Vigo, Spain, 229-233.
4. Sulistijo, B.; and Kusumo, A.D. (2013). Stabilitas low wall. *Proceedings of TPT XXII PERHAPI*. Yogyakarta, Indonesia, 345-355.
5. Supandi (2021). Engineering geology consideration for low-wall stability analysis in open-pit coal mine. *Geotechnical and Geological Engineering*, 39, 3815-3828.
6. Liu, H; Wang, G; and Huang, F. (2016). Methods to analyze flexural buckling of the consequent slabbed rock slope under top loading. *Mathematical Problems in Engineering*, 2016, 3402547.
7. Bahrani, N.; Tannant, D.D. (2011). Field-scale assessment of effective dilation angle and peak shear displacement for a footwall slab failure surface. *International Journal of Rock Mechanics and Mining Sciences*, 48(4), 565-579.
8. Uenishi, K. (2015). Dynamic dip-slip fault rupture in a layered geological medium: broken symmetry of seismic motion. *Engineering Failure Analysis*, 58(2), 380-393.
9. Ning, Y.J.; An, X.M.; and Ma, G.W. (2011). Footwall slope stability analysis with the numerical manifold method. *International Journal of Rock Mechanics and Mining Sciences*, 48(6), 964-975.
10. Sun, C.; Chen, C.; Zheng, Y.; Zhang, W.; Liu, F. (2019). Numerical and theoretical study of bi-planar failure in footwall slopes. *Engineering Geology*, 260(2019), 105234.
11. Havaej, M.; Stead, D,; Eberhardt, E.; and Fisher, B.R. (2014). Characterization of bi-planar and ploughing failure mechanisms in footwall slopes using numerical modelling. *Engineering Geology*, 178(2014), 109-120.
12. Giani, G.P. (1992). *Rock slope stability analysis*. Rotterdam: A.A. Balkema.
13. Hammah, R.E.; Yacoub, T.; and Curran, J.H. (2009). Variation of failure mechanisms of slopes in jointed rock masses with changing scale. *Proceedings of the Third CANUS Rock Mechanics Symposium*. Toronto, Canada, 3956.
14. Alejano, L.R.; and Juncal, A.S. (2010). Stability analyses of footwall slopes in open pit mining. *DYNA*, 77(161), 61-70.
15. Silva, C.H.C.; and Lana, M.S. (2014). Numerical modeling of buckling failure in a mine slope. *Revista Escola de Minas*, 67(1), 81-86.
16. Supandi; and Hartono, H.G. (2020). Geomechanic properties and provenance analysis of quartz sandstone from the Warukin formation. *International Journal of GEOMATE*, 18(66), 140-149.
17. Supandi; Zakaria, Z.; Sukiyah, E.; and Sudradjat, A. (2018). The correlation of exposure time and claystone properties at the Warukin formation Indonesia. *International Journal of GEOMATE*, 15(52), 160-167.
18. Supandi; Zakaria, Z.; Sukiyah, E.; and Sudradjat, A. (2019). The influence of kaolinite-illite toward mechanical properties of claystone. *Open Geosciences*, 11(1), 440-446.
19. Vangsness, T.A. (2020). *Shear strength characterisation of in-pit mud to ensure low wall stability*. PhD Thesis, School of Civil Engineering, The University of Queensland.

20. Waterhouse, J.; Crisostomo, J.; Nolan, D.; and Dutton, A. (2008). An integration of hydrogeology and geotechnical engineering for the design of the tutupan coal mine t100 low wall, South Kalimantan, Indonesia. *Proceedings of the Tenth International Mine Water Association*. Ostrava, Czech Republic, 81-84.
21. Suratha, I.G. (2007). Numerical modelling and slope stability analysis for optimizing open pit coal mine at Binuang South Kalimantan. *Indonesian Mining Journal*, 10(1), 1-9.
22. Rosengren, A.J.; Daquin, J..; Tsiganis, K.; Alessi, E.M.; Deleflie, F.; Rossi, A.; and Valsecchi, G.B. (2017). Galileo disposal strategy: stability, chaos, and predictability. *Monthly Notice of the Royal Astronomical Society*, 464(4), 4063-4076.
23. Ballantyne, S.; Nolan, D.; and Merry, M. (2003). Lowwall instabilities in coal mines in Indonesia from a geotechnical perspective. *Proceedings of Seminar Sehari Kemantapan Lereng di Pertambangan Indonesia III*. Bandung, Indonesia, 1-8.
24. Li, J.; Tucker, N.; and Todd, J.K. (2016). Impact of rock mass strength parameters on low wall stability assessment outcomes in open-cut coal mines. *Proceedings of the Fifth International Conference on Geotechnical and Geophysical Site Characterization*. Sydney, Australia, 1117-1122.

I would like to submit my review for the manuscript with tittle UNDERCUTTING MINING METHOD, WHY NOT? A GEOTECHNICAL CONSIDERATION FOR COALOPTIMIZATION. The paper needs further revision before accepted with some correction related;

No	Subject	Review
1	Research Question	Why the authors do this research and what is its importance and application
		It has been explained in the script about the background, so the writing of this script becomes interesting.
2	Novelty	A paper gives new ideas, derivations, applications that has been not studied before or little- or not indepth-studied
		It needs to be added the novelty research so it clearly distinguishes with the previous research.
3	Literature Review	To identify the research gap with recent references from 2010 onwards
		The existing references are in accordance with the topic of the paper, but the number of references is still very limited and needs to be added with new references so it can support the refinement of this paper. There are still 5 papers published before 2010 and it is recommended to add the references above 2015.
4	Research Methodology	Analytical, numerical or experimental or mixed. What is the contribution of the authors, assumptions and/or approximations used, description of apparatus and its limitations, steps of experiments, etc
		1. Detailing method to gathering sample shall be briefed on manuscripts 2. Standard of all laboratories test shall be mentioned in the manuscript
5	Quality of Research	And the depth and logic of the discussion.
		1. The value of poison ratio need to be check because the number is similar with various cohesion numbers. The value of young modulus need to check also. 2. The material properties need to be checked again because between weak layer material and disposal material does not seem to be not quite right, the material properties for weak zone should be smaller so that it can be as a weak field. If you look at the weak zone material properties with a cohesion of 10 KPa and Phi 30 degree is still called a weak field. ....?
6	Insight	Conveyed and recommendations that might be used by others for future work
		This manuscript does not explain in detail what the advantages and disadvantages are
7	English	Used effectively to communicate the ideas and easy to understand with least or no grammatical error or typos
		It needs to be checked by a linguist during the final draft of this manuscript.

REVIEW FORM

Title of paper: **UNDERCUTTING MINING METHOD, WHY NOT? A GEOTECHNICAL CONSIDERATION FOR COAL OPTIMIZATION**

For sections A & B, please tick a number from 0 to 5, where 0 = strongly disagree and 5 = strongly agree.

A. Technical aspects

	0	1	2	3	4	5
1. The paper is within the scope of the Journal.	☐	☐	☐	☐	☐	☑
2. The paper is original.	☐	☐	☐	☐	☐	☑
3. The paper is free of technical errors.	☐	☐	☐	☑	☐	☐

B. Communications aspects

	0	1	2	3	4	5
1. The paper is clearly readable.	☐	☐	☐	☑	☐	☐
2. The figures are clear & do clearly convey the intended message.	☐	☐	☐	☑	☐	☐
3. The length of the paper is appropriate.	☐	☐	☐	☐	☑	☐

C. Comments to the authors (You may use another sheet of paper.)

1. Number of references is limited, please add some reference.
2. Explanation about novelty has been not clear mentioned on the manuscript
3. Value of poison ratio and young modulus has bene wrong, need to check
4. Advantage and disadvantage have been not clearly explained on manuscripts.
5. Other review comment can check on separate file

D. Recommendation (Tick one)

1. Accepted without modifications. ☐
2. Accepted with minor corrections. ☑
3. Accepted with major modification. ☐
4. Rejected. ☐

E. Comments to the editors (These comments will not be sent to the authors)

Revision is highly recommended before accepted. Detail feedback can bee seen on separate file.