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Engineering geology consideration for low-wall stability analysis in open-pit coal mine

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Abstract In low-wall stability analysis, there are many geological factors that must be considered; therefore, in determining the method and parameters, real conditions in field must be taken into consideration. This paper examines what factors need to be considered in low-wall stability analysis, including condition of the study area. The analysis method used in this study was back analysis on a low-wall slope where failure occurred, by collecting all the details of geological conditions and performing finite-element-based stability analysis to break down the contribution of each factor. This method is expected to provide detailed information about geological condition that may be a contributing factor to slope stability analysis. The result showed that physical and mechanical properties, slope length, bed thickness, bedding ratio, lithology type, and aquifer type need to be considered. These considered conditions become important factors in the analysis, especially in determining suitable slope stability method as well as evaluating reasonable results of low-wall stability analysis. Comprehensive slope stability analysis may help improving quality of slope to be optimal. The result of this analysis can be implemented for layered sedimentary rocks with low mechanical properties.

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Keywords Low-wall · Coal mining · Bedding ratio · Bedding contact · Depressurization

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).

Many practices of slope stability analysis are carried out using limit equilibrium method with slip surface as normal circular which intersects the bedding plane. Some detailed geological conditions such as bedding ratio, bed thickness, and geohydrological condition have not been included in the parameters of slope stability analysis. Landslides are controlled by material heterogeneity due to structure of bedding plane and fracture in surface deformation zone (Cheng et al. 2018) which form a weak layer. This layer will control the occurrence of landslide at

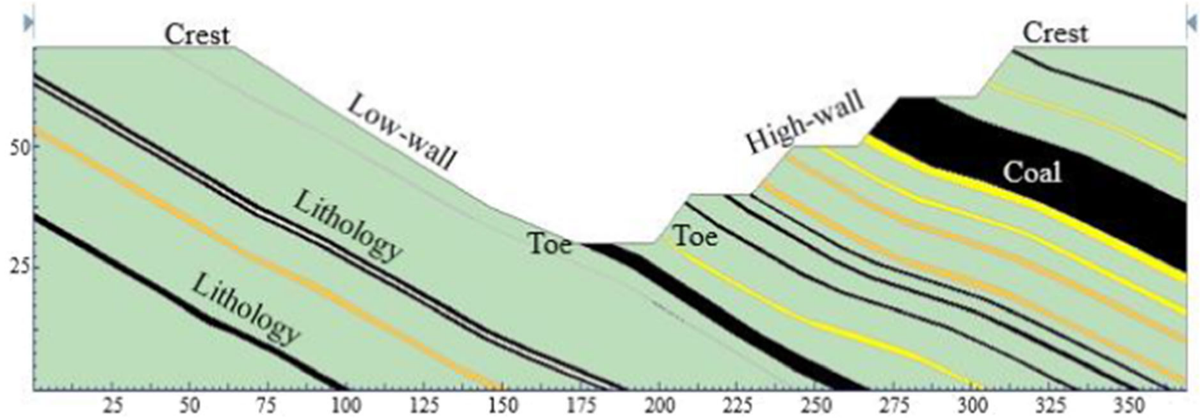

Fig. 1 Low-wall and high-wall of coal open-pit mine

weak zone (Stead and Eberhardt 1997; Alejano and Juncal 2010; Ning et al. 2011; Havaej et al. 2014; Hertelé et al. 2015; Yu et al. 2015; Sun et al. 2019). Landslide mechanism is formed due to kinematics of structural plane (Imber et al. 2003; Uenishi 2015; Smith 2018). Landslides will depend on friction in slip surface that passes through weak layer (Bahrani and Tannant 2011). Fluid can cause a complication through hydrogeological processes and mineralization (Carter et al. 2015). This study discusses in detail the factors that affect low-wall slope stability based on exploring the details of geological conditions in the landslide occurred at low-wall.

Coal deposits are associated with sedimentary rocks that have rock bedding. In fore-arc basin, coal deposits and rock lithology have low mechanical properties. 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 (Supandi 2014). 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 (Supandi 2014). 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, as shown in Fig. 2 (Supandi and Hidayat 2013). 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) (Sulistijo and Kusumo 2013).

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).

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.

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.

In some cases, 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.

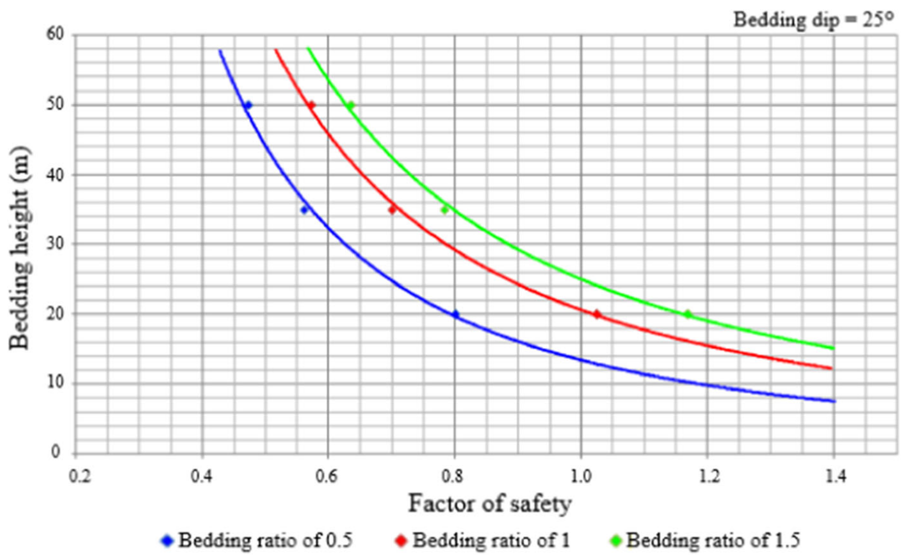

Fig. 2 Relationship between factor of safety and bedding ratio in the same slope geometry (Supandi and Hidayat 2013)

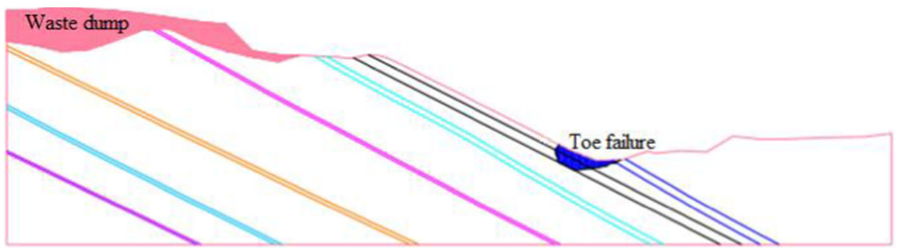

Fig. 3 Landslide at low-wall due to toe failure

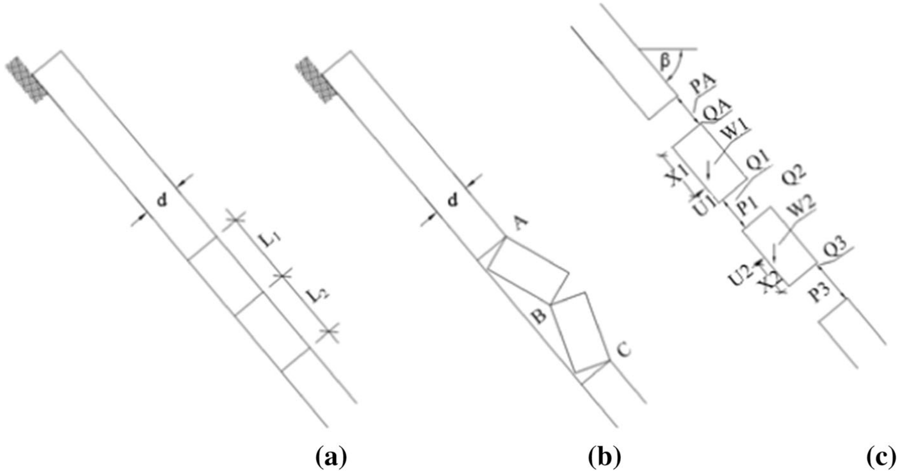

Fig. 4 Inaccurate application of rigid-and-jointed bed for low-wall stability (Giani 1992)

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 (Sulistijo and Kusumo 2013).

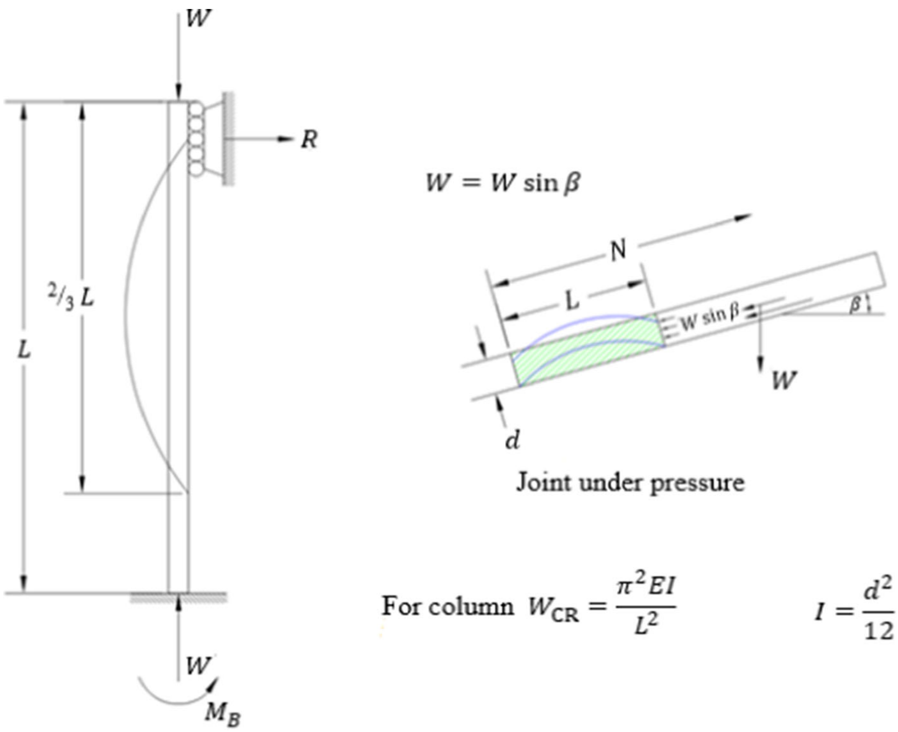

Fig. 5 Buckling concept at low-wall (Giani 1992)

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. The landslide is relatively thin and only on surface.

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.

Increasing in safety factor of 'closed' joint ends cases compared with the 'open' counterparts on small scale slopes shows that support measures such as bolting and wire meshes, which essentially force exposed joint ends to move together, are effective (Hammah et al. 2009). The modelling in Hammah et al. (2009) also shows that the efficiency of such support decreases as slope height increases and suggests to consider other stabilization methods for large slope. Buckling failure may be reproduced by considering this variability. Back analyses of failure mechanism that were carried out by Silva and Lana (2014) shows that it leads to representative values of the in-situ stress state and the normal and shear stiffness modulus of the foliation discontinuities. Alejano and Juncal (2010) analysed different failure mechanisms to evaluate footwall slopes stability using the numeric code UDEC. These results were then contrasted against limit equilibrium method (LEM) to determine the use of UDEC as a valid tool in analysis of footwall slope. For cases where the footwall slope failure took place through complex mechanisms, UDEC was performed. Seeing that the rock mechanical behaviour obeys the statistical damage model, Liu et al. (2016) studied the effect of the rock mechanical parameters n and ε_0 on the slope CBH (critical buckling height). Results of the study confirms the effectiveness of rock strength on the slope CBH.

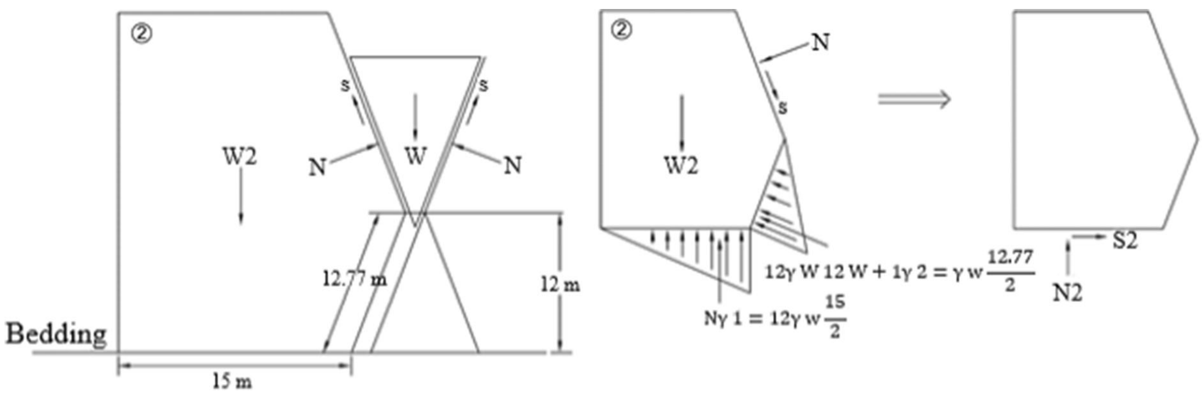

Fig. 6 Unfavourable joint mechanism (Giani 1992)

Maximum of the slope CBH will be resulted if the rock is supposed to be a linear elastic body without failure in Euler's method. Proper application of empirical methods begins with a step of reviewing the failure mode of laboratory testing samples and using the real intact rock uniaxial compressive strength value. The most critical and challenging step for rock mass strength estimation is understanding the pit floor rock mass characterization. It is easy to miss identification of floor shear and weak ground due to sparsely spaced exploration holes and limited floor trenches in coal mines. Concisely, the default material strength values should not be blindly applied to any rock mass condition from aspects of either safety or cost reduction and productivity increase (Li et al. 2016). Clastic sedimentary rocks in the Warukin Formation have low hardness (Supandi and Hartono 2020) and the rocks will degrade when exposed to the surface (Supandi et al. 2018). With this condition, clastic sedimentary rocks, especially claystone, have limited engineering properties, and type of clay mineral must be considered before choosing construction material (Supandi et al. 2019; Ballantyne 2003). Large scale low-wall failure causes considerable disruptions to mining associated with a loss of production, damaged infrastructure, and the potential loss of life (Vangsness 2020). Depressurization is indispensable in pit optimization and pit design (Waterhouse et al. 2008). Numerical modelling in slope stability analysis for optimizing mine slope is more convincing in the result of slope stability analysis (Suratha 2007).

2 Materials and Methods

The method used in this study is back analysis on landslide that occurred at low-wall of a coal mine. Back analysis was carried out by identifying 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 identified by detailing slope material, identifying contact zone, calculating bedding ratio, and mapping structure seen after the landslide; while geohydrological component was identified 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.

Back analysis was carried out by collecting all the details of geological condition in the landslide to model its mechanism during the analysis. Some of the concerned geological conditions are not limited to stratigraphy, bedding contact, bedding ratio, geohydrology, rock mass, and slope geometry. Mechanical properties were determined based on laboratory tests or the result of back analysis on the landslide. The analysis used a method that can adjust to the behavior of the landslide. The SRF, stress, and strain, as well as the slip surface pattern were evaluated according to the actual conditions in the field. The analysis diagram can be seen in Fig. 7 below.

2.1 Study area

The study area was in Batulaki Block, Tanah Bumbu Regency, South Kalimantan, Indonesia. Landslide at the low-wall of Batulaki pit had slope geometry of 28°, height of 65 m, and lithology dominated by mudstone. The toe of the slope was used as a sump for draining mine water with water depth of about 9 m from final elevation (Fig. 8). The coal seam extends from north to south with a dip direction to the east. The study area is the western part of Sembamban syncline. The topography is low hills with several rivers and creeks found around the study area (Fig. 9). From the drilling data, a stratigraphic profile is obtained, showing a distressed aquifer where the sandstone bed is between the impermeable mudstone beds. The distressed aquifer can be a problem for low-wall stability, therefore, stabilization is necessary in line with mining activity.

The result of laboratory analysis on the stratigraphy of slope rock is shown in Table 1. Samples were obtained based on drilling that had been carried out before mining activity. The drilling activity reached a depth of 150 m with a core size of HQ (70 mm).

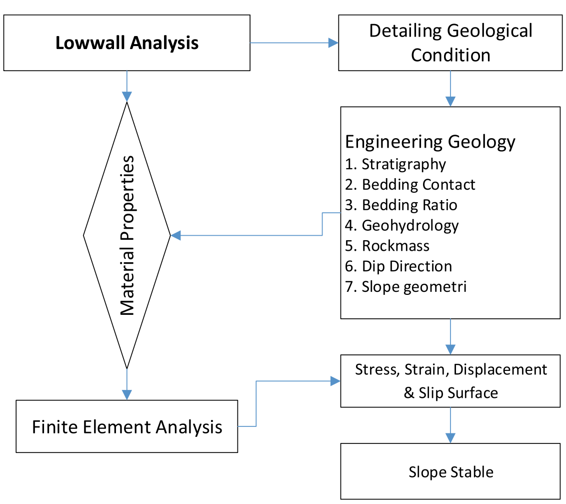

Fig. 7 Diagram of analysis

3 Result and Discussion

Based on the method that has been described, geotechnical analysis was carried out in detail, from geotechnical exploration, logging, sampling, mapping of discontinuous plane, aquifer identification, stability analysis, to geological concern related to the slope stability. The analysis was able to:

3.1 Identify the Details of Slope Rock Bedding

Planning geotechnical investigation, especially for low-wall area, requires more detailed planning. Full core drilling was carried out to determine the slope stratigraphy, to do sampling for laboratory tests, and to depressurize the area planned for low-wall formation. The drilling point should be placed at 2 points, near the sub-crop and in the down dip direction according to the pit depth plan. With this method, it is expected to obtain the bed correlation and the detailed geometry of slope bedding (Fig. 10). Samples for laboratory testing was taken for every variation of lithology, including for thin layer that was possible for laboratory testing. Laboratory testing was performed at least by triaxial test and uniaxial test.

3.2 Identify the Weak Zone

Rocks identification must be done in detail, including the identification of thin layers which have high plasticity. The thin layer is a weak zone that can trigger slip surface presence. This weak zone was used as a basis in calculating bedding ratio where the thickness of rock bedding was calculated based on the perpendicular distance between a weak zone and the next weak zone. Physical and mechanical properties of weak zone were determined by carrying out laboratory tests based on samples that were possible to be taken or performing back analysis. The layer must be identified because although it has a thickness of only a few centimeters, it has a considerable influence. Figure 11 shows the weak zone of mudstone bed that has a relatively high plasticity and the block where plane failure occurred at low-wall that was controlled by weak plane which is the contact between rock bedding.

Fig. 8 Failure at low-wall of an open-pit mine

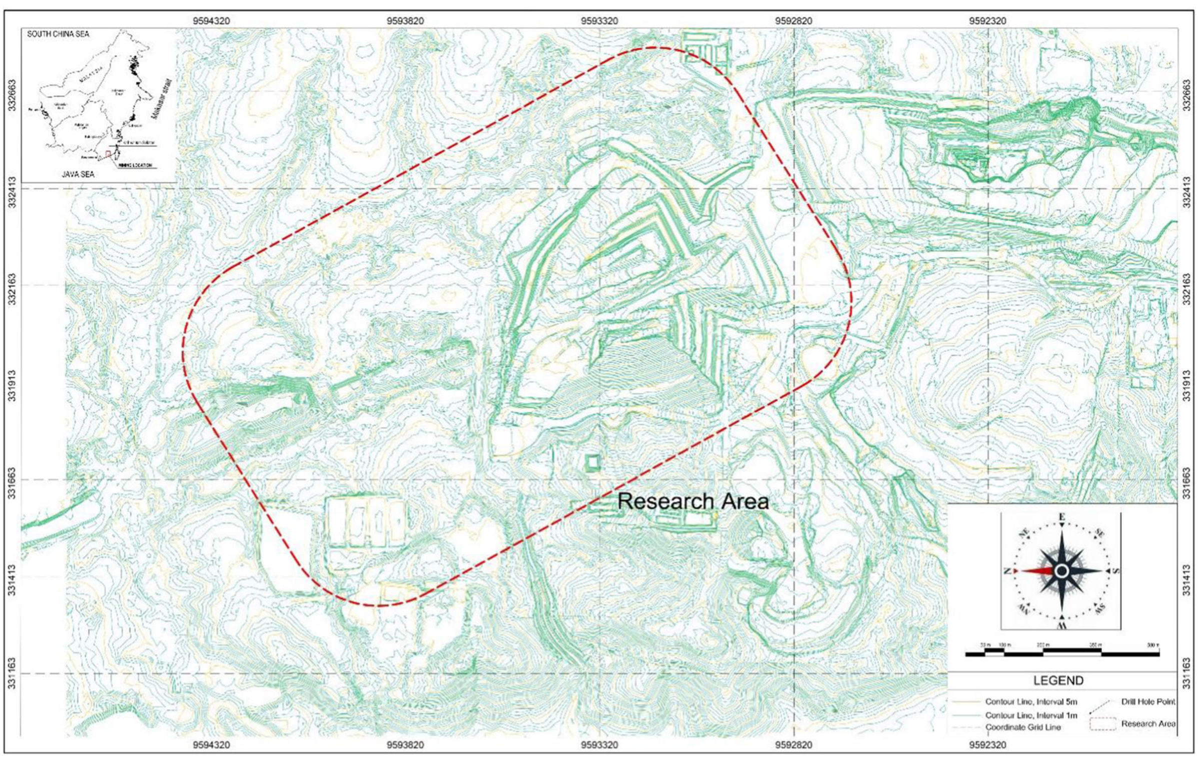

Fig. 9 Research area at Batulaki Pit, South Kalimantan, Indonesia

Table 1 Material properties for low-wall stability analysis in open pit coal mine

No.	Properties	Claystone	Mudstone	Sandstone	Soil	Coal	Weak zone
1	Friction angle (°)	45.31	27.792	40.96	13.55	24.57	13.00
2	Cohesion (kPa)	189.32	114.334	354.534	25.04	154.70	3.00
3	Tensile strength (kPa)	5.703E+03	7.676E+04	2.430E+04	2.635+03	8.604E+03	2.312+3
4	Young modulus (kPa)	6.823E+03	4.871E+04	1.848E+04	1.736+02	3.179E+04	2.341+03
5	Poisson's ratio	0.314	0.297	0.382	0.231	0.271	0.423

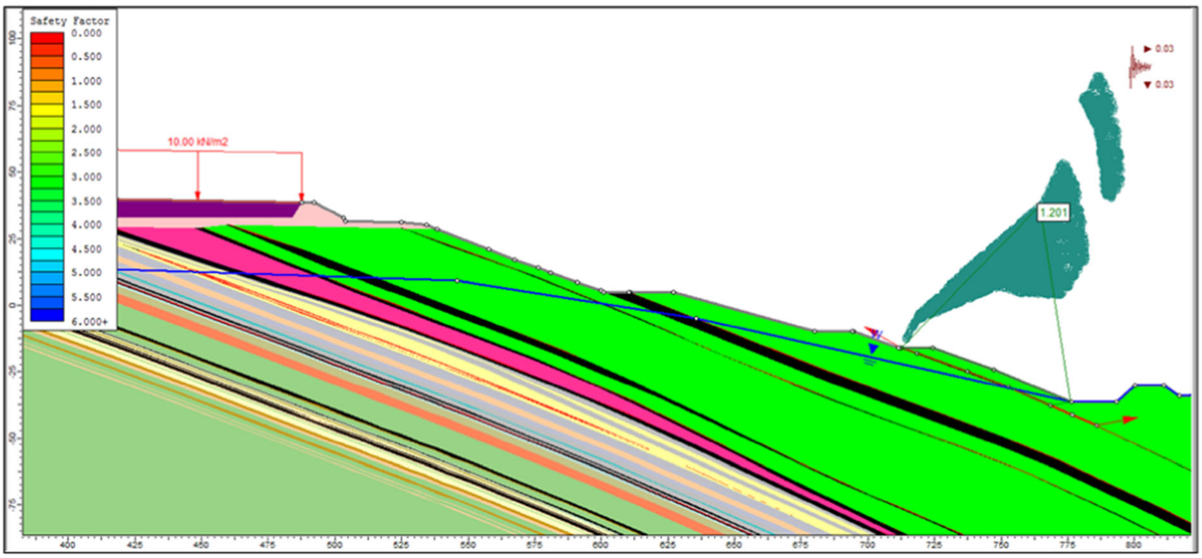

Fig. 10 Detailed stratigraphic model including weak layer. The thin black line is a weak layer in bedding contact

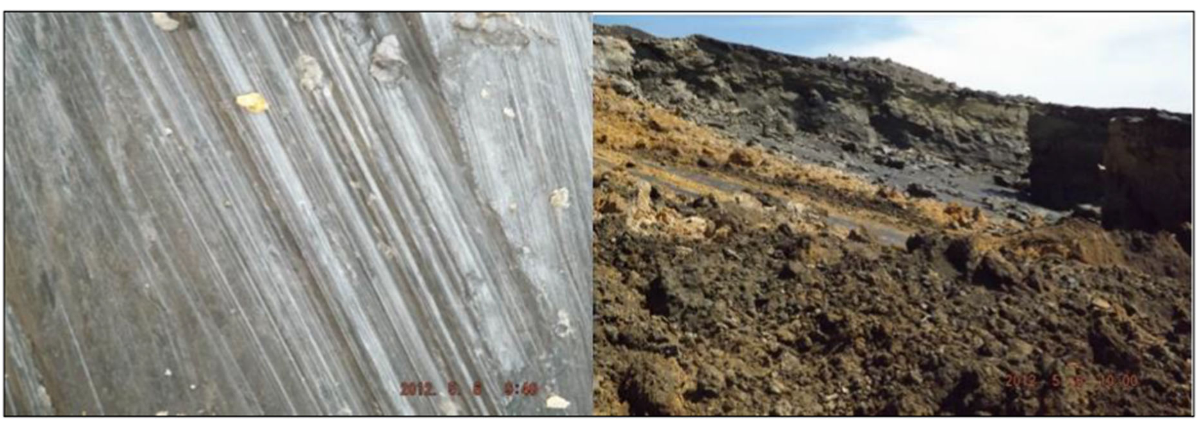

Fig. 11 Slip surface on weak plane (left) and landslide at low-wall controlled by weak plane (right)

3.3 Describe the Bedding Dip Including Weak Zone Control

Identifying weak plane must be continued by identifying continuity of the weak plane. Continuity in direction of strike and continuity in direction of dip can be used for detailed analysis on the correlation with the patterns of weak plane. Weak plane pattern in the form of rock bedding contact can also correlate with weak plane pattern due to joint or geological structure activity. In sedimentary rocks, continuity of weak plane follows distribution of rock bedding. Although the thickness is limited, it is necessary to do more detailed mapping.

3.4 Calculate the Bedding Ratio of Rock Bedding

Calculation of bedding ratio can be done after identification of weak plane done and well modeled. Bedding ratio was calculated perpendicularly between two weak planes and was calculated for the very top (crest) and the very bottom of the pit plan. Bedding ratio is a comparison between top bed thickness and bottom bed thickness. Bedding ratio is equal to 1 if the thicknesses of the top and the bottom are the same; less than 1 if the bottom is thinner than the top; and greater than 1 if the bottom is thicker than the top. The thicker the bottom, the more stable the low-wall because of the increasing stress. The thinner the bottom, the greater the stress received, thus, it may disturb the stability. Figure 12 shows a bed with a bedding ratio of less than 1 where the thickness of the toe was smaller than the crest, so the stress increased at the toe. This condition reduced the value of slope safety factor.

3.5 Map the Pattern of Discontinuous Plane

Mapping of discontinuous plane is more emphasized in the discontinuous plane in the form of geological structure which can be joint or fault. Measurement of discontinuous plane must be done in detail in terms of its density or position. Describing rock mass or discontinuous plane must also be done in detail which cannot be separated from the filling material, roughness, and water condition. Identification of discontinuous plane was carried out on all slope sections from the top to the bottom. The bottom part must get more attention because the accumulation of stress occurs in that zone, so a little of discontinuous plane can trigger stability. Figure 13 shows the existence of a weak plane on rock contact in the form of a thin layer of mudstone which is a controller in the occurrence of plane failure at low-wall. The block above the weak plane moved down the slope along the weak plane.

3.6 Identify the Type of Aquifer Found on the Slope

In analysis of low-wall stability, it is a must to identify the rock bedding especially which have high porosity. Vigilance needs to be increased if a bed that has high porosity is found between impermeable layers or

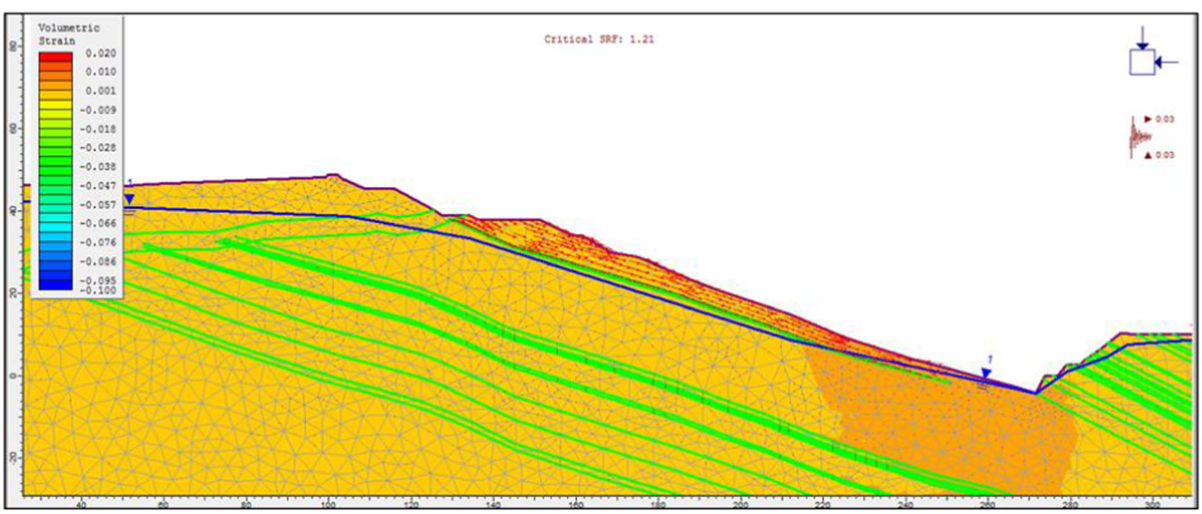

Fig. 12 Bedding ratio and strain behavior at low-wall cross section

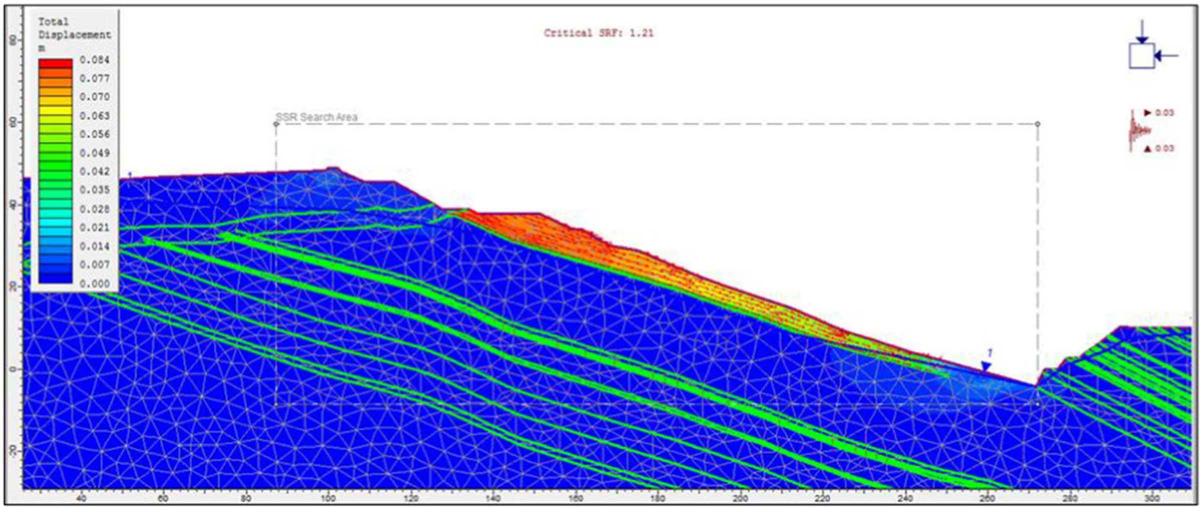

Fig. 13 A discontinuous plane on contact plane that controlled displacement in rock bedding

distressed aquifer is found. The distressed aquifer can have aquifer stress in the form of water or air. If the impermeable layer at the top has a limited thickness and pressure continues to increase, buckling will occur. To avoid this, depressurization may be carried out before forming low-wall slope. Depressurization can be done at several points at low-wall with target of distressed aquifer layer. When there is pressure from the distressed aquifer, it will release pressure from the formation which usually appears artesian water pressure. Water will continue to come out of the formation until the pressure in the formation decreases (Fig. 14). The more the depressurization point, the faster the formation pressure will decrease.

3.7 In Analysis

Based on the consideration of geological conditions previously described, the low-wall stability analysis must be carried out by using finite element method or plane model for limit equilibrium method. Figure 15 shows the result of back analysis on the landslide at low-wall using finite element method with the movement towards the toe. This can be corroborated by the distribution of stress pattern occurred in rock mass which shows the stress pattern leading to the toe (Fig. 16). Limit equilibrium method can be carried out as long as the thickness of slope bed is homogeneous or the equilibrium plane only occurs in one bed. Calculation of stress especially at the toe area must be

Fig. 14 Depressurization (red dot) and the aquifer stress causing artesian (bottom left)

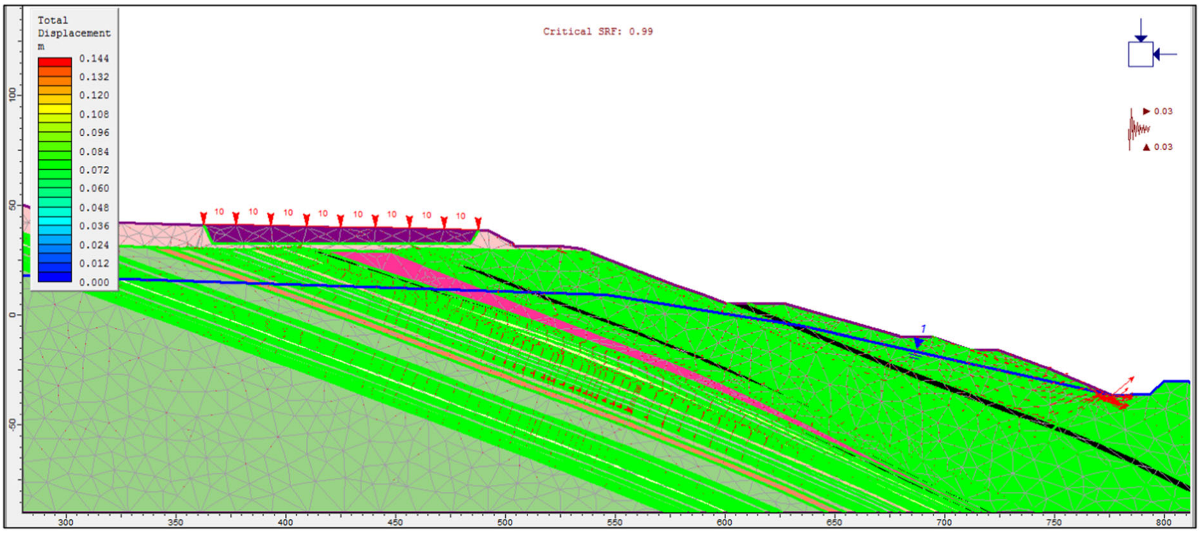

Fig. 15 Displacement pattern on the low-wall cross section after stabilization. The direction of displacement was still at the toe

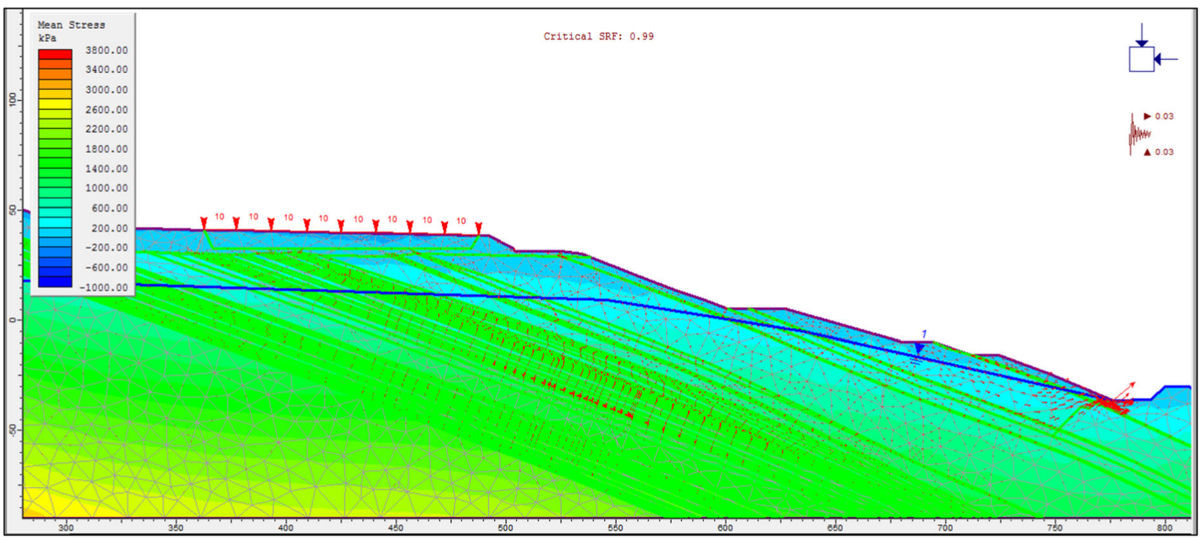

Fig. 16 Stress pattern on the low-wall cross section with the direction of stress at the toe

done to ensure that the concept of stress occurs in the analysis process. Weak zone determination at the time of analysis must be done with parameters that can refer to the results of the laboratory analysis or based on back analysis. Even though the thickness is thin and only a few centimetres, separate layer must be made. Identification of aquifer stress needs to be done to ensure that the bed thickness is able to withstand the stress from the bed as well as from the aquifer. When all parameters have been considered, the optimum slope height is modelled for each bed, so formation of the low-wall slope geometry can be performed.

3.8 Optimization

With the geological conditions in mind, analysis of low-wall can be done using finite element method by considering the weak zone and bedding ratio. Low-wall height modelling for each bed with a specific dip can be done to get the optimum low-wall geometry. If there is a distressed aquifer on low-wall, then

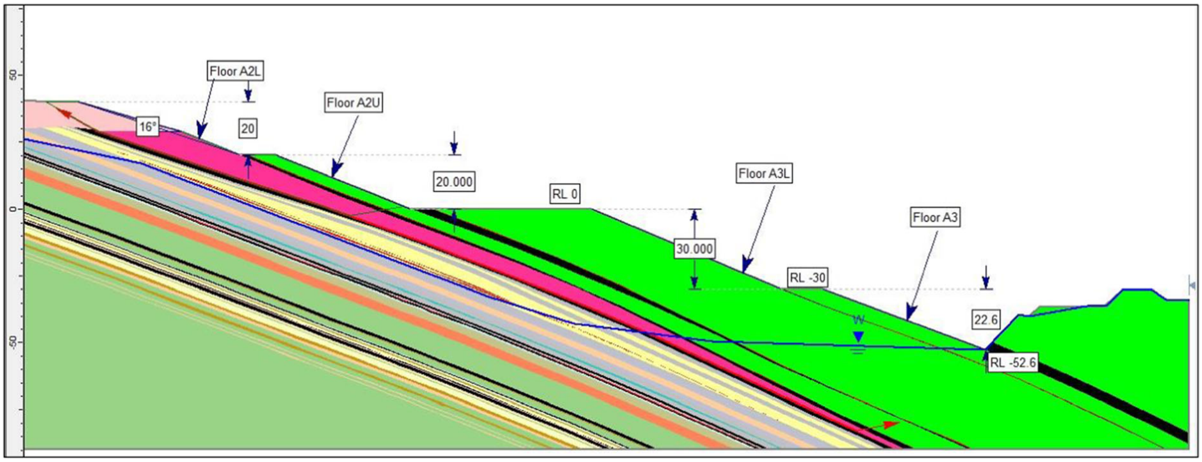

Fig. 17 Geometry of the low-wall slope after being analysed by considering the geological aspects

depressurization must be done to reduce the aquifer stress on the bed above it.

a. Analysis using finite element method
b. Simulating bedding ratio
c. Simulating the effect of bedding dip on the rock bedding
d. In connection with the point c above, the length of the bed is simulated to obtain the optimum height of the low-wall geometry in each bed
e. Depressurization needs to be done especially to release aquifer stress which has the potential to trigger buckling

Based on the explanation above, for the low-wall geometry, it is a must to pay attention to the detailed geological aspects and the dip of single slope at the low-wall following the dip of bedding contact or rock bedding. To obtain the optimum geometry, it can be done by using the optimum height of each bed, so the optimum height will be different for each bed. Figure 17 shows the optimum geometry of the low-wall based on back analysis result where the bed thickness has a different geometry.

4 Conclusion

In geotechnical analysis, it is mandatory to consider the geological conditions at each location starting from lithology, bedding contact, bedding, structures, and geohydrology. The analysis method must also be chosen relevant to the rock mass behaviour, so the landslide mechanism can be analysed according to the actual conditions. Based on the result and discussion, analysis of low-wall must be carried out with detailed planning so that it is able to identify the geological conditions. Geological conditions cannot be separated from the condition of lithology, stratigraphy, aquifer, and weak plane between beds. Identification of discontinuous plane pattern must be done to ensure the kinematics of a bed. In high stress zones, condition of discontinuous plane has a significant role in stability of low-wall slope. Calculation of bedding ratio after modelling a 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 bed. Depressurization is required to reduce aquifer stress due to the presence of distressed aquifer. The dip of single slope on low-wall is the same as the dip of rock bedding, but the height of the slope can adjust to the height of each bed.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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