ISSN: 04532198
Volume 62, Issue 03, April, 2020

Low-wall Slope Stability Analysis Using Planar Surface and 3D Simplified Janbu Method

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Abstract— PT X has a pit slope geometry design until the end of 2020, which requires slope stability analysis in order to optimize mineable coal reserves and safety of mining operations. The low-wall slopes are the focus of this research which hypothetically has a potential for planar failure. This study uses planar surface failure analysis method, which is validated by the 3-dimensional Simplified Janbu method. The results showed safety factor value is 1.09 or unstable slope conditions on the analysis of planar surface, while the 2/3-dimensional Simplified Janbu method provided a safety factor value is 1.12 and 1.05. Besides that, the prediction potential volume of slope failure from the analysis of the Simplified Janbu method is 2.478.130 m^3.

Keywords— Pit Plan, Low-Wall, Planar Failure

1. Introduction

PT X is a coal mine with a PKP2B business agreement acquired from an open pit method located Sembakung and Sesayap Hilir sub-districts, and Nunukan and Tana Tidung districts, North Kalimantan. In carrying out its mining operations, it designed a mine slope to use till the end of 2020. In open pit coal mining, slopes consists of 2 sides, namely the high-wall and low-wall. A previous research on the same location has also been carried out with regard to the methodology for measuring geotechnical risk [1] and determining the slope stability of open pit coal mine using the 3-dimensional finite element method [2]. In addition, studies on the slope stability analysis of open pit mine have been sequentially conducted since 2018 [3] - [6].

Hypothetically low-wall has a potential for planar failure, which is the direction of the slope parallel to the slope of the rock layer.The study was conducted on a low-wall considering this location has the most potential for failure, so it needs to be analyzed with the appropriate method. The method used in this study uses a planar surface failure approach [7] compared to the "Simplified Janbu 2d & 3D" limit equilibrium method [8].

2. Methodology

2.1. The Limit Equilibrium Method

The limit equilibrium method (LEM) is divided into the slice and non-slice. The slope slice is analyzed by dividing the slope into several slices and analyzing its various equilibrium forces and moments, while the non-slice is analyzed for weak areas with the potential to cause landslides in the slope. Furthermore, the stability of the mine slope is determined by the value of the safety factor (SF).

According to the general definition, safety factor (SF) is the ratio of resisting forces to mobilized force (Figure 1). The determination of the analytical method used depends on the assumption and type of slope failure.

Furthermore, the circular failure used is suitable on moment balance, while other types of slope failure are more suitable on force balances.

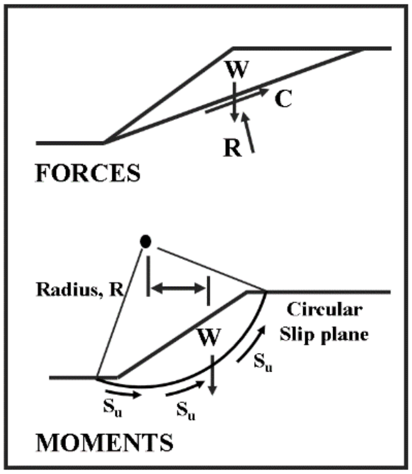

Figure 1. Force equilibrium and inclined plane moment

$$FK = \frac{Shear\ strenth}{Shearing\ stress} \quad (1)$$

The following guidelines are used as a reference in determining the appropriate methods for different types of slope failure:

1. For long slope with homogeneous rock lithology and failure surface plane is parallel to the slope face, the "Infinite Slope" analysis method is preferred.
2. For shallow, with long planar failure surface that are not parallel to the slope face, the 3D simplified Janbu analysis method is suitable.
3. For planar failure, the "Block Analysis" method is suitable in determining the value of the safety factor and the critical location of the slip. In addition, the "General Limit equilibrium (GLE)" is used for better accuracy.
4. For surface that tends to form an arc circle, the "Simplified Bishop" analysis method is suitable.
5. For slip surfaces by irregular shape, the appropriate slice methods are "Janbu’s GPS," “Spencer’s," "Morgenstern-Price," or "Sarma’s”.

2.2 Limit Equilibrium Method 3D

The development of geotechnical risk management methodologies in Indonesia were established in 2009 starting with geotechnical data characterization research [9], probabilistic analysis for slope stability [10] - [12], and the analysis/evaluation of geotechnical risk in open mines [13] & [14]. Analyzing the stability of the 3-dimensional slope is part of the risk measurement analysis aimed at determining the probability of landslides and predicting its volumes.

The 3-dimensional model is a refined version of the 2-dimensional by projecting the skid plane into a column and determining the resultant force, as well as the moment based on the x, y, and z directions. The equilibrium force and moments acting on the overall column mass are used to determine the following 3 possible direction of the slip plane:

1. The column moves in the same direction

2. The column moves towards one another
3. The column moves in the opposite direction

For the 3-dimensional analysis, the mass potential of the slip plane is divided into several columns. Cheng and Yip [8] stated the equation of the Simplified Janbu method deduced from the Morgenstern-Price method to obtain a safety factor value of 3-dimensional analysis.

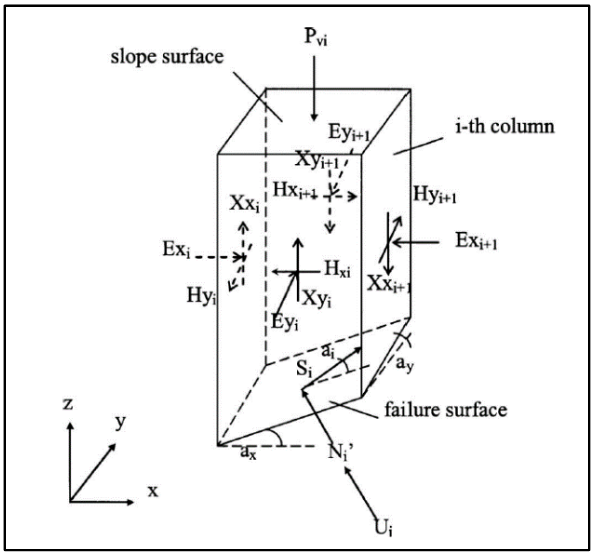

Figure 2. 3-dimensional column

a_i is space angle for sliding direction with respect to the projected x – y plane, a_x, a_y are base inclination along x and y directions measure at the center of each column, E_{xi}, E_{yi} are inter-column normal forces in x and y directions, respectively, H_{xi}, H_{yi} are lateral inter-column shear forces in x and y directions, N'_i , U_i are effective normal and base pore watery force, P_{vi}, S_i is vertical external force, and base mobilized shear force, and X_{xi}, X_{yi} are vertical inter-column shear force in plane perpendicular to x and y directions.

With the mohr-coulomb collapse criteria, the safety factor is determined using the following equation:

$$F = \frac{S_{fi}}{S_i} = \frac{C_i + N'_i \tan \phi'_i}{S_i} \quad \dots\dots (2)$$

where Sfi is ultimate resultant shear force available at the base of column I, N is the effective base normal force, Ci is c Ai and c and ii are effective, cohesive strength and the base area of the column. The base shear force Si and normal base force Ni are expressed as the components of forces with respect to x, y, and z directions for column i (Huang & Tsai (2000), and Huang et al (2002).

$$S_{xi} = F_1 S_i, S_{yi} = F_2 S_i, S_{zi} = F_3 S_i \quad \dots\dots (3)$$

$$N_{xi} = g_1 N_i, N_{yi} = g_2 N_i, N_{zi} = g_3 N_i \quad \dots\dots (4)$$

where f_1, f_2, f_3 and g_1, g_2, g_3 = unit vectors in the direction of Si and Ni. The projected shear angles a’ = same for all columns in the x – y plane in the present formulation, and by using this angle, the space shear angle ai found for each column as stated by Huang and Tsai (2000).

$$a_i = \tan^{-1}\{\sin\theta_i/[\cos\theta_i + (\cos a_{yi}/\tan a' \cos a_{xi})]\} \quad (5)$$

$$\theta_i = \cos^{-1}\{\sin a_{xi} \cdot \sin a_{yi}\} \quad (6)$$

ayi and axi are defined in figured 2. Considering the vertical and horizontal force equilibrium for the ith column in the z, x, and y directions produces the following equations:

$$F_z = 0 = N_i g_{3i} + S_i f_{3i} - (W_i + P_{vi}) = (X_{xi+1} - X_{xi}) + (X_{yi+1} - X_{yi}) \quad (7)$$

$$F_x = 0 = S_i f_{1i} - N_i g_{1i} - H_{xi} + H_{xi+1} = E_{xi+1} - E_{xi} \quad (8)$$

$$F_y = 0 = S_i f_{2i} - N_i g_{2i} - H_{yi} + H_{yi+1} = E_{yi+1} - E_{yi} \quad (9)$$

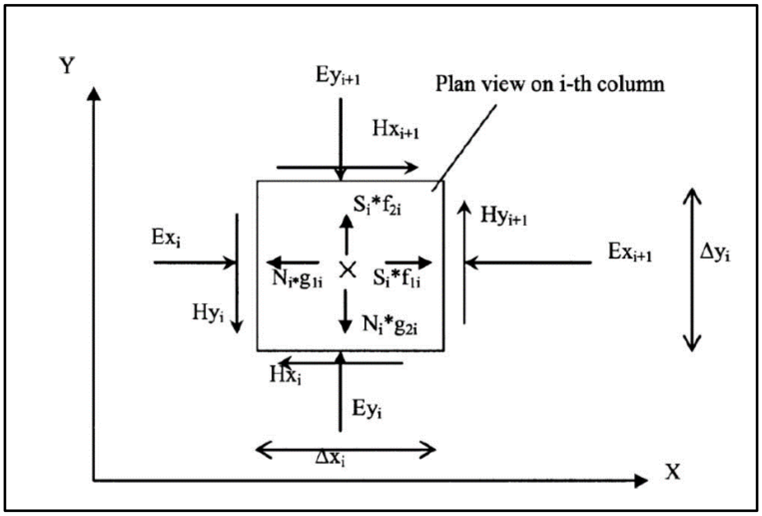

Figure 3. Force equilibrium in columns

Considering the overall force equilibrium in x-direction internal force E cancels out.

$$-\sum H_{xi} + \sum N_i g_{1i} - \sum S_i f_{1i} = 0 \quad (10)$$

considering overall force equilibrium in the y-direction

$$-\sum H_{yi} + \sum N_i g_{2i} - \sum S_i f_{2i} = 0 \quad (11)$$

The directional safety factor Fx and Fy is determined as follows:

$$F_x = \frac{\sum[C_i + (N_i - U_i)\tan\phi_i]f_{1i}}{\sum Nig1i - \sum Hxi}, \quad (0 < F_x < \infty) \tag{12}$$

$$F_y = \frac{\sum[C_i + (N_i - U_i)\tan\phi'_i]f_{2i}}{\sum Nig2i - \sum Hyi}, \quad (0 < F_y < \infty) \tag{13}$$

Formulation 3D simplified Janbu's methods by considering the force equilibrium equations and neglecting the inter-column vertical and horizontal shear forces.

$$A_{xi} = \frac{\{C_i + [(W_i - P_{vi})/(g_{3i} - U_i)]\tan\phi_i\}}{1 + (f_{3i}\tan\phi_i/g_{3i}F_{sx})} \tag{14}$$

$$A_{yi} = \frac{\{C_i + [(W_i - P_{vi})/(g_{3i} - U_i)]\tan\phi_i\}}{1 + (f_{3i}\tan\phi_i/g_{3i}F_{sy})} \tag{15}$$

$$F_{sx} = \frac{\sum A_{xi}(f_{1i} + f_{3i}g_{1i}/g_{3i})}{\sum(g_{1i}/g_{3i})(W_i + P_{vi})} \tag{16}$$

$$F_{sy} = \frac{\sum A_{yi}(f_{2i} + f_{3i}g_{2i}/g_{3i})}{\sum(g_{2i}/g_{3i})(W_i + P_{vi})} \tag{17}$$

For 3D asymmetric Janbu's method, at the force equilibrium point, the directional factors of safety, F_{sx}, and F_{sy} are equal to each other. Under this condition, the global factor of safety Ff based on force is determined as follows:

$$F_f = F_{sx} = F_{sy} \tag{18}$$

The safety factor is also used in vertical and 3D force equilibrium to achieve the simplified Janbu's method.

2.3 Planar Surface Failure Method

Planar failure on the slope surface occur assuming there is a layer of rock or soil with the strength that is relatively weaker to the layer underneath. Furthermore, on slopes with discontinuity plane cut the slope face and have its direction oriented towards the slope face. Stability analysis on the surface slides is determined by its geometry and shear strength parameters of the constituent materials.

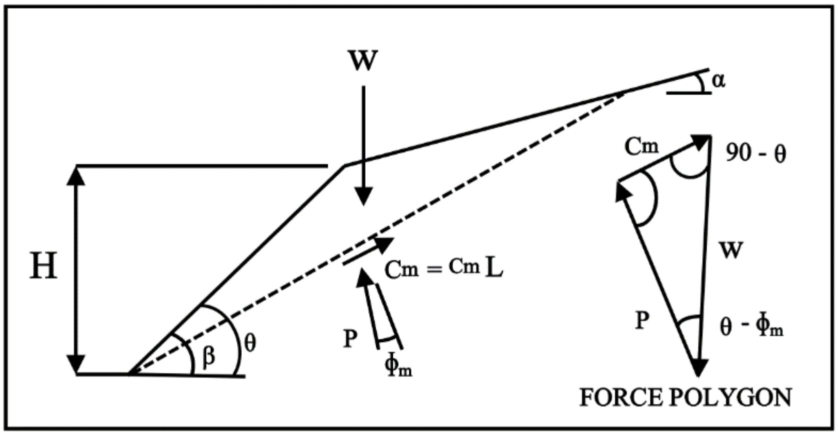

Figure 4. Analysis of field avalanche

$$L = \frac{H}{\sin\beta} \text{ X } \frac{\sin(\beta-\alpha)}{\sin(\Theta-\alpha)} \tag{19}$$

$$W = \frac{1}{2}\gamma H^2 [\frac{\sin(\beta-\Theta)}{\sin^2\beta} \text{X} \frac{\sin(\beta-\alpha)}{\sin(\Theta-\alpha)}] \tag{20}$$

$$N = W\cos\Theta \tag{21}$$

$$S_m = W\sin\Theta \tag{22}$$

With L = weak surface length, W = material weight, N = normal force, and Sm = shear strength. Assuming the value of the safety factor is related to the drive cohesion value, Fc, and the friction angle in the drive Fϕ then the shear strength of the drive is as follows:

$$C_m = \frac{c}{F_c} \tag{23}$$

$$\text{Tan}\ \phi_m = \frac{\tan\phi}{F_\phi} \tag{24}$$

$$S_m = C_m L + W\cos\Theta\tan\phi_m \tag{25}$$

With Cm = drive cohesion, and ϕm = friction angle in drive. Substituting the driving force calculation using the "Mohr-Coulomb" criterion, the following relationship is obtained:

$$C_m = \frac{W}{L} [\sin\Theta - \cos\Theta\tan\phi_m \tag{26}$$

$$C_m = \frac{\gamma H^2}{2L} \frac{\sin(\beta-\Theta)}{\sin^2\beta} [\sin\Theta - \cos\Theta\tan\phi_m] \tag{27}$$

$$C_m = \frac{W}{L} [\sin\Theta - \cos\Theta\tan\phi_m] \tag{28}$$

From the above equation, the value of the safety factor is calculated in stages as follows:

1. Assume the value of the safety factor is related to the friction angle in the drive, Fϕ
2. Calculate the value of the friction angle in the drive ϕm
3. Calculate the value of Cm
4. Calculate the safety factor (FK), Fc = c/cm
5. Repeat steps 1 to 4 until F = Fc

2.4 The Simplified Janbu 2D Method

This method assumes no shear force works between slices and ignores the equilibrium moment. However, it calculates the horizontal and vertical force equilibrium at each slice. The vertical force balance in the slices are as follows:

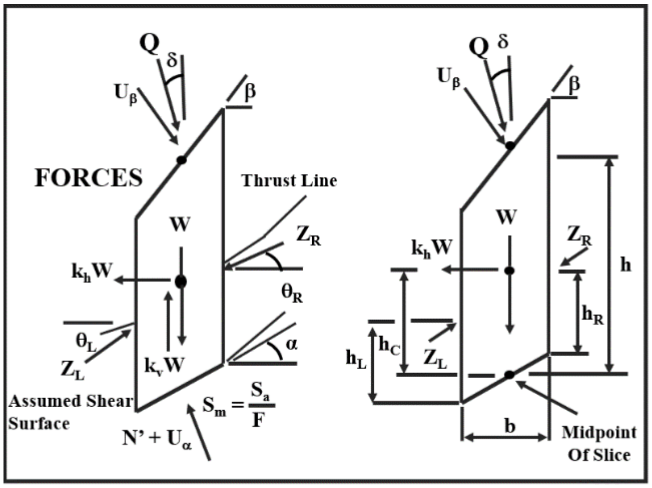

Figure 5. 2-dimensional slices

$$\Sigma Fv = (N' + U\alpha)\cos\alpha + Sm\sin\alpha - W(1 - Kv) - U\beta\cos\beta - Q\cos\delta = 0 \quad \ldots\ldots (29)$$

$$N' = \frac{-U_\beta\cos\alpha - S_m\sin\alpha + W(1 - K_v) + U_\beta\cos\beta + Q\cos\delta}{\cos\alpha} \quad \ldots\ldots (30)$$

$$Sm = \frac{C + N'\tan\phi}{F} \quad \ldots\ldots (31)$$

With N ' = normal force, and Sm = shear strength of the material, C is cohesion, and ϕ is the friction angle in the material. Substituting the above equation produces the following:

$$N' = \frac{1}{m_\alpha}\left[W(1 - k_v) - \frac{C\sin\alpha}{F} - U_\alpha\cos\alpha + U_\beta\cos\beta + Q\cos\delta\right] \quad \ldots\ldots (32)$$

$$m\alpha = \left[\cos\alpha\ \frac{\tan\alpha\tan\phi}{F}\right] \quad \ldots\ldots (33)$$

The horizontal force equilibrium on the slices are as follows:

$$\Sigma Fh = \Sigma\ [(N' + U\alpha) \sin \alpha + W\,Kh - U\beta \sin \beta\ ] - \Sigma[\ Q \sin\delta + \frac{C + N' \tan \phi}{F} \cos \alpha] = 0 \quad \text{.......................................} (34)$$

$$\Sigma\ [(N' + U\alpha) \sin \alpha\ +\ W\,Kh\ -\ U\beta \sin \beta\ -\ Q \sin\delta]\ =\ \Sigma\ [\ \frac{1}{F}(C + N' \tan \phi) \cos \alpha\ ] \quad \text{.............................} (35)$$

Then obtained the value of the safety factor for each slice, F,

$$F\ =\ \frac{\Sigma[C + N' \tan \phi] \cos \alpha}{\Sigma A4 + \Sigma\, N' SIN\ \alpha} \quad \text{...} (36)$$

$$A4\ =\ [\ U\alpha \sin \alpha\ +\ W\,Kh\ -\ U\beta \sin \beta\ -\ Q \sin\delta\ ] \quad \text{...} (37)$$

The "3D Simplified Janbu" method is the most suitable slice method used to determine the level of stability of a slope on a low-wall, in accordance with the potential slides that occur in the field avalanche.

3. Results and Discussion

3.1. Rock Properties and Data

Table 1 shows the input parameter statistical data obtained from the laboratory tests results of the physical and mechanical properties of rocks. It also shows the basic statistical analysis by determining the means and standard deviations assumed to be normally distributed. Based on the mechanical properties value, the weakest rocks are mudstone and carbonaceous clay.

Table 1. Statistical data input parameters for slope stability analysis

Lithology	**Specific Weight (kN/m^3)**		**Cohesion (kPa)**		**Angle of internal friction (Degrees)**	
	Average	**Std. Dev**	**Average**	**Std Dev**	**Average**	**Std. Dev**
Mud stone	20,6	2,8	60	4	18,1	2,2
Sandstone	22,5	3,1	123	9	30,1	3,7
Muddy Sandstone	21,1	2,4	72	7	21,9	2,7
Silt Stone	20,6	2,5	90	11	22,6	2,9
Lumping Sandstone	22,1	2,7	95	6	26,4	3,3
Carbonized Clay Stone	21,2	3,2	37	3	14,01	1,9
Coal	13,5	1,8	195	21	43,1	4,7

3.2 Weighting Rock Properties Data

Table 2 below is a weighting data of the rock property values obtained by using an average approach to the thickness function that is owned by each layer of rock formed on the slope. The study of the weight value effect of rock properties on the degree of slope stability is read in more detail in Kemal et al (2019).

Table 2. Data weighting properties for slope stability analysis

Lithology	**Specific Weight (kN/m3)**		**Cohesion (kPa)**		**The angle of internal friction (Degrees)**	
	Average	**Std.Dev**	**Average**	**Std.Dev**	**Average**	**Std.Dev**
Full Composite	20,7	5,1	83,1	20,7	23,1	5,7

3.3. Janbu Simplified 2D Analysis Results

The Janbu Simplified method is used with the slip surface Cuckoo Search and surface type non-circular dimensions to determine the safety factor of slope stability on low-walls with the rotational slice equilibrium (LEM).

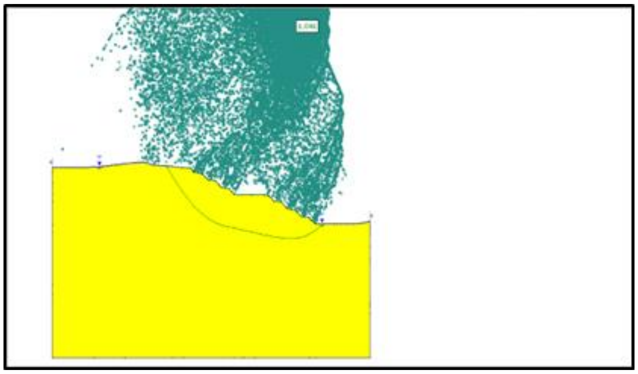

Figure 6. Simplified Janbu analysis 2D

The 2-dimensional analysis was carried out to validate the results of the 3-dimensional analysis, in accordance with the SF value to the low-wall cross-section is 1.05.

3.4. Janbu 3D Simplified Analysis Results

The 3-dimensional limit equilibrium method (MKB) analysis approach is a refinement of the 2-dimensional used to determine FK values, landslide potential locations, and the estimated volume of slope failure. According to Azizi et al. (2019), for slip surfaces due to the Grid Search, the 3-dimensional analysis is ineffective, and the number of points determines the accuracy. In addition, Cuckoo Search and ellipsoid are used to determine its analysis.

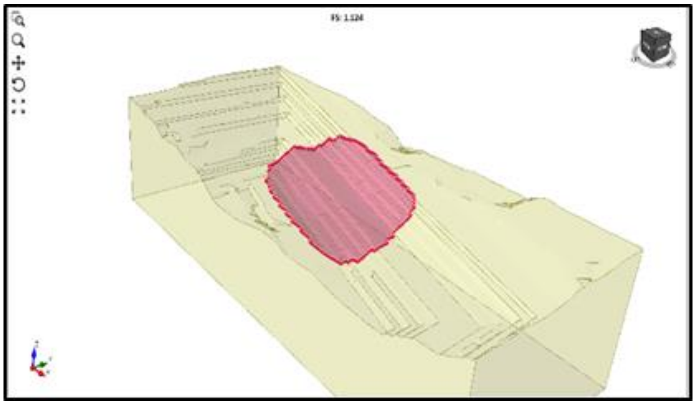

Figure 7. Simplified 3D analysis of Janbu

The results of the analysis of the stability of the 3-dimensional slope on the low-wall slope provided a SF value of 1.12 in the most critical zone with predicted landslide volumes of 2,478,130 m3 in the direction of the southern avalanche (Figure 6).

3.5. Planar Surface Failure Analysis Results

The value of safety factors on low-wall slopes was determined using the planar surface failure method and validated using the janbu slice which is simplified due to its excavation in the direction of the slope of the rock layer.

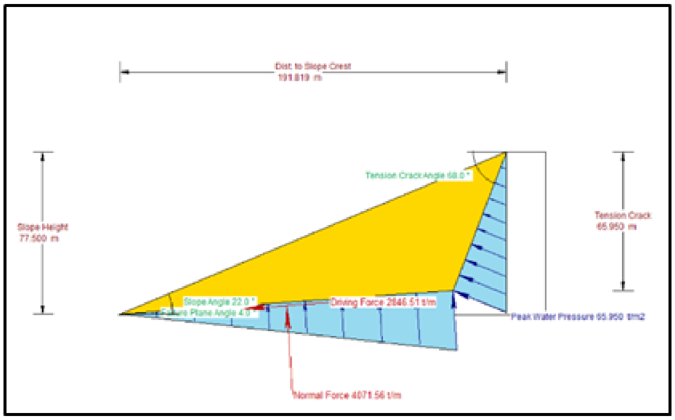

Figure 8. Planar failure geometry

This method is unable to model multi-seam, therefore it is necessary to weigh the value of rock properties in full. The actual slope geometry is adjusted to an overall angle of 220, height of 77.5-meters and discontinuity plane angle is 40 following the dip of the layer rock bed with water pressure conditions of 0.98t/m3 and fractures (tensional crack minimum FS Location), the results of the stability analysis on Low-wall slopes obtained SF values is 1.09.

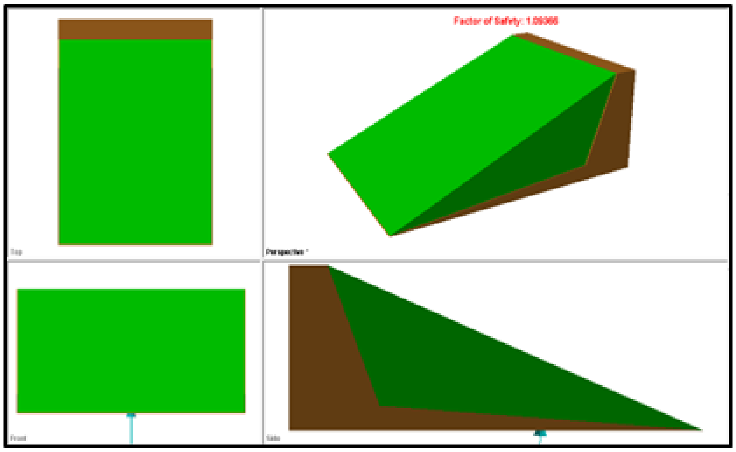

Figure 9. Planar failure surface analysis

4. Conclusion

Some of the conclusions obtained from the results of the study are as follows:

- The stability analysis using the Simplified 3D Janbu method show low-wall slopes in unstable conditions with SF value is 1.12 and predicted volume of slope failure is 2,478,130 m3.
- The stability analysis using the simplified 2D method of Janbu show a cross-section of low-wall slopes in unstable conditions with SF value is 1.05.
- The stability analysis using the "planar surface failure" method shows a cross-section of low-wall slopes in unstable conditions with SF value is 1.09.
- The difference in SF from the analysis of the "Planar Surface Failure" with the Janbu Simplified 2D method is 0.04, while the 3D is 0.07.

5. Acknowledgments

The authors are grateful to the PT X for facilitating the collection of field data. The authors are also grateful to the Mining Computation Laboratory of the FTKE Mining Engineering Study Program at Trisakti University for providing the software used in modeling the research data.

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