Three dimensional slope stability analysis of open pit limestone mine in Rembang District, Central Java

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Abstract. PT X is a limestone mine located in the district of Rembang, Central Java, which plans to expand and dig deeper. To ensure that the slope is stable, geotechnical study is needed. However, if it is done in 2 dimensional (2D) the result might not always be representative. This research was conducted to determine the stability of single slope using three dimensional limit equilibrium method (3D LEM). The data was collected by doing geotechnical mapping of the drill core sample and conducting laboratory test of rock samples, i.e. the test of physical and mechanical properties of rocks. The result shows that there is a significant difference between 2D and 3D FoS. The volume of sliding is also presented.

Keywords : Factor of Safety, 3D Limit Equilibrium Method, Volume of failure, Limestone.

1. Introduction

Risk of slope failure is the multiplication between the failure probability (FP) against the consequences (avalanche volume, damage/loss of equipment or company assets, rehabilitation costs, fatality rate, and environmental damage). Risk management needs to be done to ensure that the potential risks of a mining operation can be controlled and measured. Research related to avalanche risk has been carried out by [9]; [15]; [17]; [16]; [18]; [10]; [11]; [12]; [7]; and [14]. If we want to reduce the risk the only key is actually at the FP itself. The higher the FP, the higher the risk.

In an overall slope design, PT X's limestone mine, in Rembang district, Central Java Province requires a stable and optimum single slope design. By using rock mass strength data acquired from geotechnical structural mapping in drilling activities the slope can then be assessed. Before analyzing the overall slope, the single slope must first be confirmed stable because if it is not stable, the overall slope must not stable either.

These days the needs and pressure to analyze a slope 3 dimensionally is more sounds. This is because 2D analysis assumes that the width of slope is infinitely wide so then it neglects 3D effect. [5] stated that in most of the cases the width to height ratio is not sufficiently long and varies perpendicular to the slide movement. Therefore, 3D analysis is considered important to be done to produced the representative FoS. Moreover, in 3D analysis the volume of failure can also be estimated while 2D analysis cannot. If the volume can be determinated, it can be useful as one of the considerations in giving failure prevention recommendation.

One of the most common methods usually used to analyze the stability of slopes is limit equilibrium method (LEM). In this research, the FoS of those lithologies were calculated with various angles of single slope so the optimum single slope could be determined. The analyzes were done in 2D and 3D. The comparison between 2D and 3D result of this research makes the need for 3D analysis more felt.

2. Methodology

2.1. 3D Limit Equilibrium Method

In 2D analysis a mass failure is defined based on the slip surface line in a sectional slope that will be divided into slices. Unlike 2D analysis, in 3D analysis a mass failure is discretized into columns. 3D LEM method is actually the extended formula from 2D LEM methods (Bishop, Janbu, Morgenstern-Price) in 2 orthogonal directions. [6] introduced the extended formula of Morgenstern-Price for 3D analysis that was also reduced to Bishop and Janbu methods. The formulations below are the summarized formulations of Bishop method reduced from Morgenstern-Price method used in this research to get the 3D FoS. Futher details about the derivations of it can be directly referenced in [6].

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

$$\theta_i = \cos^{-1}\{\sin a_{xi} \cdot \sin a_{yi}\} \quad \text{(II.2)}$$

$$F_{my} = \frac{\sum\{\{K_{yi}[f_{1i}RZ_i + f_{3i}RX_i]\}\}}{\sum(W_i + P_{vi})RX_i + \sum N_i(g_{1i}RZ_i - g_{3i}RX_i)} \quad \text{(II.3)}$$

$$F_{mx} = \frac{\sum\{\{K_{xi}[f_{2i}RZ_i + f_{3i}RY_i]\}\}}{\sum(W_i + P_{vi})RY_i + \sum N_i(g_{2i}RZ_i - g_{3i}RY_i)} \quad \text{(II.4)}$$

$$F_{mz} = \frac{\sum[K_{zi}(f_{2i}RX_i - f_{3i}RY_i)]}{\sum N(g_{2i}RX_i - g_{1i}RY_i)} \quad \text{(II.5)}$$

$$K_{yi} = \frac{\{C_i + [(W_i + P_{vi})/(g_{3i} - U_i)]\tan\phi_i\}}{1 + (f_{3i}\tan\phi_i/g_{3i}F_{my})} \quad \text{(II.6)}$$

$$K_{xi} = \frac{\{C_i + [(W_i + P_{vi})/(g_{3i} - U_i)]\tan\phi_i\}}{1 + (f_{3i}\tan\phi_i/g_{3i}F_{mx})} \quad \text{(II.7)}$$

$$K_{zi} = \frac{\{C_i + [(W_i + P_{vi})/(g_{3i} - U_i)]\tan\phi_i\}}{1 + (f_{3i}\tan\phi_i/g_{3i}F_{mz})} \quad \text{(II.8)}$$

$$n_i = \left\{\frac{\pm\tan a_{xi}}{J}, \frac{\pm\tan a_{yi}}{J}, \frac{1}{J}\right\} = \{g_1, g_2, g_3\} \quad \text{(II.9)}$$

$$s_i = \left\{\begin{matrix}\frac{\sin(\theta_i - a_i)\cdot\cos a_{xi}}{\sin\theta_i}, \frac{\sin a_i \cdot \cos a_{yi}}{\sin\theta_i}, \\ \frac{\sin(\theta_i - a_i)\cdot\sin a_{xi} + \sin a_i \cdot \sin a_{yi}}{\sin\theta_i}\end{matrix}\right\} = \{f_1, f_2, f_3\} \quad \text{(II.10)}$$

$$J = \sqrt{\tan^2 a_{xi} + \tan^2 a_{yi} + 1} \quad \text{(II.11)}$$

Where N_i, U_i = effective normal force and pore pressure force on column base; S_i = mobilized shear force on column base; a_i = space shear angle; a' = projected shear angle; E_i = intercolumn normal force; X_i = intercolumn vertical shear forces; H_i = intercolumn horizontal shear forces; P_{vi} = vertical external force; RX_i, RY_i, RZ_i = lever arms; W_i = column weight; n_i, s_i = unit vectors

The direction of sliding (a_i) can be determined by changing the projected shear angle (a') with certain interval until F_{mx}, F_{my}, and F_{mz} values become the same as each other.

3. Data Analysis

Data collection's location of material properties in 3D single slope stability analysis is at PT X, Rembang village, Central Java Province. The data were obtained from geotechnical drilling activities by using rock mass characterization method. In obtaining strength parameters in the calculation of RMR, a uniaxial compressive strength test was carried out with a sample in the form of core HQ, to determine the unit weight value of the physical properties and to determine the strength of intact rock using uniaxial compressive strength test and triaxial compressive strength test because the limestone in that location is categorized as primary limestone. The geometry of the single slope was 4,67 m berm long, 10 m in height, 10 m in width and slope angles 60^0, 65^0, 70^0, 75^0, and 80^0. Material properties for high grade are unit weight 20.6 kN/m^3, cohesion 170 kPa, internal friction angle 53.0 degrees and tensile strength 2500 kPa and for low grade unit weight 20.5 kN/m^3, cohesion 120 kPa, internal friction angle 46.9 degrees and tensile strength 2250 kPa. For 2D analysis, the results were adopted from [13].

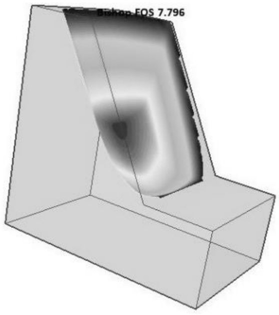

Figure 1. 3D LEM Slope Stability Analysis Result.

Table 1. 2D and 3D Analysis Result.

Lithology	Slope Angle (°)	2D FoS (Prakoso, 2018)	3D FoS
HG	60	6.36	7.796
	65	5.87	7.493
	70	5.41	7.088
	75	4.97	6.5
	80	4.49	6.536
LG	60	4.64	5.696
	65	4.3	5.326
	70	3.98	5.08
	75	3.63	4.806
	80	3.28	4.761

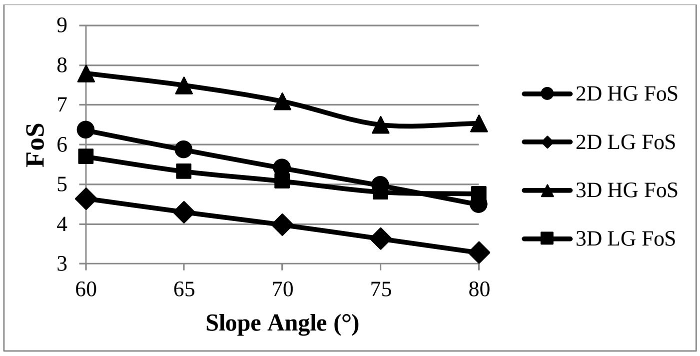

Figure 2. 2D and 3D FoS Trendlines Between FoS and Slope Angles Variety.

Based on Table 1, in every simulation the slope is stable though the slope angle has been increased to 80°. Therefore, the optimum single slope angle is determined. Both 2D and 3D analysis results show declining trends. The FoS also tends to be smaller with the increasing slope angle.
As seen in the result before, the 2D analysis produced smaller FoS than 3D analysis. This shows that the 3D effect really affects the FoS because the difference between 2D and 3D FoS is significant. This results support the past researches that stated 3D FoS is higher than 2D FoS that was summarized by [2] and [1] and stated in [8]. The only researches that stated 3D FoS is smaller than 2D FoS are Hovland (1977), Chen dan Chameau (1983), Thomaz and Lovell (1988), dan Seed, dkk. (1990), but in those researches there were significant potential inaccuracies involved as stated in Albataineh (2006) and Akhtar (2011).

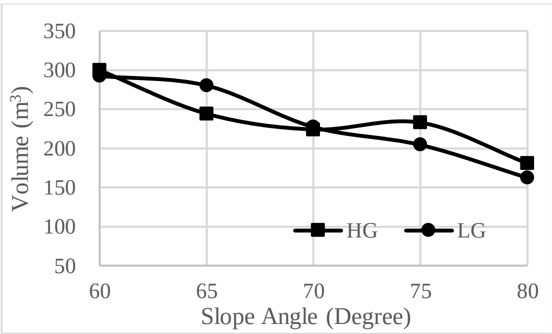

Figure 3. Slope Angle and Volume of Sliding Chart.

Figure 9 shows that the volume of sliding decreases along with higher slope angle, because of the circular slip surface or area which affected by the slide gets smaller.

4. Conclusion

a. The optimum single slope angle for each lithology is at 80° with 3D HG FoS and 3D LG FoS value 6.536 and 4.761 respectively.
b. 3D FoS is found to be higher than 2D FoS in LEM and it is because of the existence of 3D effect that affects the FoS. The difference between 2D and 3D FoS is also significant. Thus, 2D analysis is not always representative.
c. The estimated volume of sliding generated from 3D LEM for HG and LG are 181 m^3 and 163 m^3 respectively with the trends go downward.

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