Bulletin of the Geological Society of Malaysia, Volume 67, June 2019, pp. 83 – 90
DOI : https://doi.org/10.7186/bgsm67201910

Probabilistic analysis of potential planar-type rock slope failure of selected Malaysian rock slopes

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Abstract: Quantification of rock slope stability analysis in Malaysia has generally been limited to the traditional methods of Rock Mass Rating (RMR) or Slope Mass Rating (SMR). While these methods represent a means to convey message from geologists to engineers, they can be confusing especially in designing slope stabilization efforts. The limit equilibrium method which is widely used worldwide has only seen limited application for rock slope stability analysis in Malaysia. This paper discusses the limit equilibrium method using Factor of Safety (FOS) from deterministic calculations to probabilistic analysis. Four rock slopes in Klang Valley (L1, L2, L3 and L4) with potential and failed planar failures have been selected for FOS calculation. In this study, Barton's equation has been selected in favour of the Mohr-Coulomb method due to the availability of Joint Roughness Coefficient (JRC) data. A deterministic calculation in dry conditions shows that FOS values range from 1.08 to 2.34 which indicates stable conditions. However, introduction of water into the discontinuities (50% filling) reduces the FOS value from 0.80 to 1.89 while 100% filling of water inside discontinuities further reduces the FOS value to the range from 0.00 to 0.55. The results indicate the importance of water in influencing the FOS calculations. Probabilistic analysis uses normal distribution of parameters measured at the field except for water content in which an exponential distribution is assumed. The probabilistic FOS analysis shows probability of failure ranging from 4.83% to 44.80% whereby the slope with highest likelihood of failure is at L1. Estimated block weight shows median mass value between 0.07 tonne/m to 1.30 tonne/m. The establishment of FOS and probability of failure values will help the engineers better to design adequate stabilization structures if needed.

Keywords: Factor of safety, probability of failure, planar failure, rock slope

INTRODUCTION

Rock slope stability analysis has been done extensively in Malaysia, involving rock slopes in residential area, highways and quarries (Tajul & Nizam, 2001; Abd Rasid Jaapar, 2005; Aziman & Husaini, 2001). These studies were limited to identification of the potential failure via kinematic analysis without being able to quantify the risk posed. Several studies incorporated quantification of the rock mass and developed modified rock mass quantification methods (Ismail, 2014) but were still unable to quantify the risk posed by specific failure. Works on limit equilibrium method to determine Factor of Safety on local rock slopes can only be attributed to Radhi *et al*. (2008).

Deterministic analysis on planar failure to establish the Factor of Safety (FOS) has been developed over the years by several researchers with notable works done by Barton (1976) and Hoek & Bray (1981). Deterministic analysis method by Barton (1976) was adopted in this study due to the lack of established local rock discontinuities cohesion (c) values apart from works of Goh *et al*. (2014) needed for the Mohr-Coulomb method. Probabilistic analysis of FOS value involves the Monte Carlo method in generating random data for the study. Various works have been done to quantify the uncertainty of analysis results (Casagrande, 1965; Einstein & Beacher, 1983; Whitman, 1984) and recent efforts by El-Ramly *et al.* (2002) and Park et al. (2005) helps in developing the probabilistic analysis of FOS to determine the Probability of Failure. Figure 1 shows the example of planar failure scar at slope L3 in Rawang.

MATERIALS AND METHODOLOGY

Four localities of rock slopes namely L1, L2, L3 and L4 were chosen in the Klang Valley area. L1 and L2 slopes are located in the Kajang area. Slopes L3 and L4 are located in the vicinity of Rawang town. All localities are man-made rock slopes which were blasted for construction purposes. While none of the localities experienced large-scale planar failure, smaller scale scars and blocks from

Figure 1: An example of planar failure scar at Slope L3 in Rawang. The scar was estimated to be 2 m wide and 3 m high with smooth releasing planes at the sides.

planar failure have been identified. The workflow for this study is presented in Figure 2.

Geology of the study area

The Klang Valley area consists of several metasedimentary Paleozoic successions starting from Dinding Schist, Hawthornden Schist, Kuala Lumpur Limestone, Kenny Hill Formation and finally the Triassic intrusion of Granite (Figure 3). Rock slopes in the area generally consist of cut rock slopes in Grade I – II granite which forms hilly areas flanking the Klang Valley to the east and western side except for several rock slopes within slightly to moderately weathered schist or metasedimentary rocks. Limestone cliffs are restricted to the Batu Caves area. Major structural feature in the area is the Kuala Lumpur fault trending WNW – ESE manner.

All localities in this study are located in the granite province. The granite in the area is recognised as the Kuala Lumpur Pluton of the Main Range Batolith (Cobbing *et al.*, 1992). Granitic rocks of localities L1 and L2 consist of medium to very coarse biotite grained granite while L3 and L4 lithology are made of fine-grained biotite granite with feldspar megacrystals. Locally, intense shear zones are absent on the rock slopes although several fault planes can be recognised among the discontinuities.

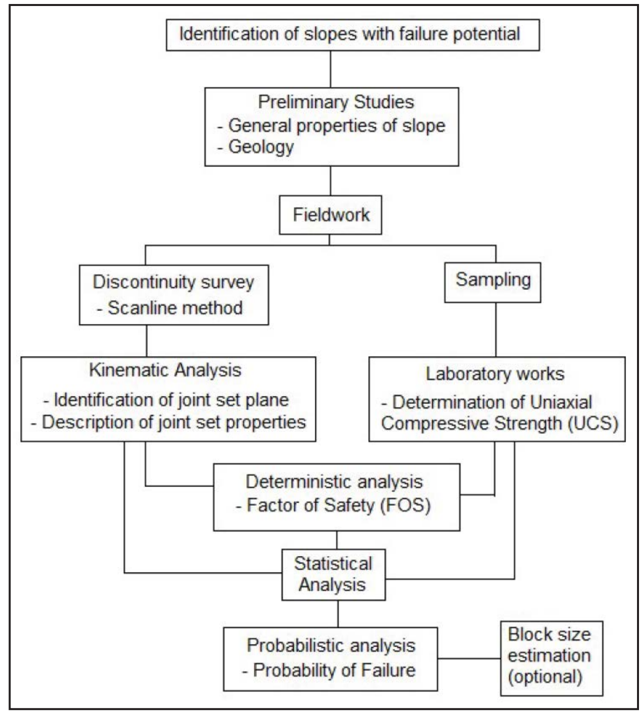

Figure 2: Work flow to obtain the probability of failure in this study.

Data acquisition

A total of 4 localities were selected for the analysis namely L1, L2, L3 and L4 (Figure 4). Discontinuity data was acquired using the scanline method (Priest & Hudson, 1976) during the discontinuity survey. The method comprises of systematic recording of discontinuity parameters including the orientation, length, aperture, water content, roughness and the Joint Roughness Coefficient (JRC) as suggested by ISRM (1981). The JRC data

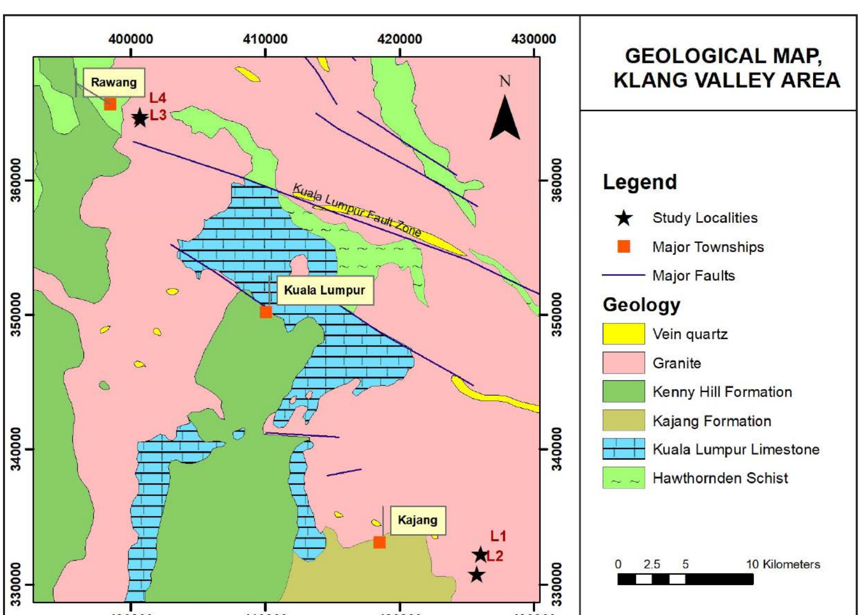

Figure 3: The geology of the Klang Valley area. The slope localities (L1, L2, L3 and L4) are located nearby Kajang and Rawang, with both areas falling within granite province (Mineral and Geoscience Department Malaysia, 2014).

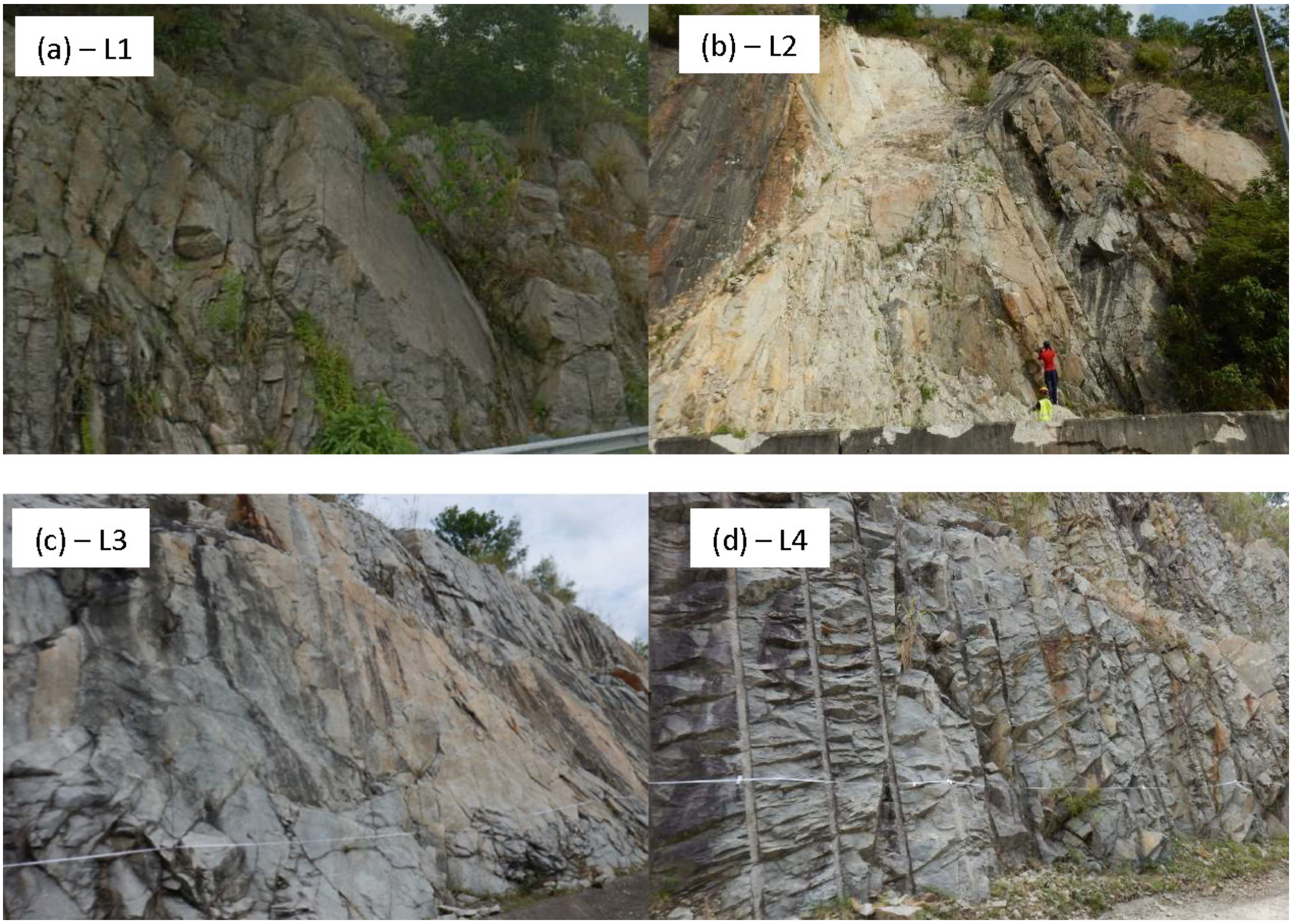

Figure 4: The rock slopes at localities L1 (a), L2 (b), L3 (c) and L4 (d) studied in this article.

was retrieved using a profiler as suggested by Barton & Choubey (1977).

Based on the discontinuity data, the Rock Quality Designation (RQD) and spacing of the joint set can be calculated from field measurements. The JRC data can be utilised to estimate the friction angle of the discontinuity plane (Goh *et al*., 2012; Goh *et al*., 2014). Laboratory analysis were also done to obtain the Uniaxial Compressive Strength (UCS) of the rock samples.

Deterministic calculation of planar failure

Factor of Safety (FOS) is a ratio of the resisting force over driving force in a specific block. If the driving force exceeds the resisting force, FOS value will fall under 1.00 which indicates failure. Deterministic calculation for planar-type failure based on the Barton's equation (Barton, 1976) given as Equation 1:

$$FOS = \frac{\sigma \tan(\varphi_r + JRC\ log_{10}\left(\frac{JCS}{\sigma}\right))A}{W \sin \psi_p} \qquad \text{...Equation. 1}$$

Whereas;

σ = Normal force upon failure plane expressed as

$$\sigma = Wg \cos \psi_p \qquad \text{...Equation. 2}$$

JRC = Joint roughness coefficient
JCS = Joint wall strength
A = Area of failure surface
W = Weight of block
ψ_p = Dip angle of plane
φ_r = Residual friction angle
g = gravitational constant (9.807 ms^{-2})

According to Hoek & Bray (1981), one of the assumption made in planar failure analysis is that both sliding surface and tension crack strike parallel to the slope. Therefore, the equation can be expressed in 2-dimension as Equation 3;

$$FOS = \frac{\sigma \tan(\varphi_r + JRC\ log_{10}\left(\frac{JCS}{\sigma}\right))\ L}{A \sin \psi_p} \qquad \text{...Equation. 3}$$

Whereas the normal force, σ is also transformed in 2-D, expressed as Equation 4;

$$\sigma = A\, \gamma_r g \cos \psi_p \qquad \text{...Equation. 4}$$

L = Length of sliding plane in cross-section (perpendicular to slope face)
γ_r = Density of rock

And the area, A in equation 3 and 4 refers to the cross-sectional area of the failure block perpendicular to the slope face (Figure 5).

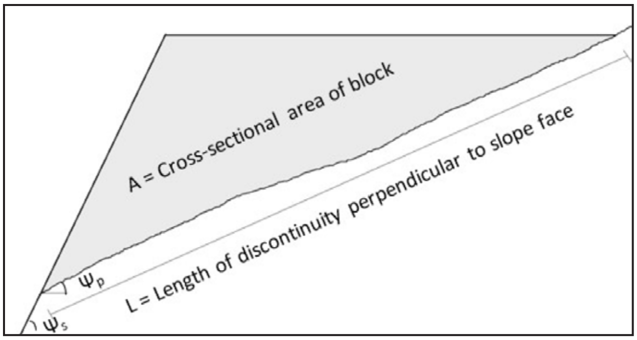

Figure 5: Parameters for calculation in Equation 3.

As the calculation for the planar failure is in 2-dimension, the exerting forces (resisting and driving) must be expressed in terms of tonnes/m. The calculations were done in an EXCEL spreadsheet. Deterministic calculations are only valid for a specific set of conditions according to the data input. In real-time situation, the data varies even for discontinuities from the same set, with certain parameters such as water content can be dynamic due to weather influence. Therefore, FOS value over 1.0 does not guarantee absolute stability of the block especially with values close to 1.0. Priest & Brown (1983) suggested the optimal FOS value for rock slope must be at least 1.25.

Probabilistic calculation of planar failure

Probabilistic method is a solution to address the fluctuation in these variables. Different scenarios are recreated using different random values to produce unique FOS values. Even though the deterministic analysis of a particular scenario indicates a stable plane, a slight change in the variables could lead to failure.

Probabilistic analysis of the planar failure involves the generation of random data using the Monte Carlo Simulation. Random data involves several randomized input parameters including dip angle, length, and the JRC value of the failure plane. The dip direction is constant throughout analysis due to the assumption that slope face and failure planes are parallel. The generation of random data, however is based on the statistical analysis obtained from the discontinuity survey upon each slope. Probabilistic calculation is done using the *RocPlane* software.

10000 number of iterations were made in this probabilistic analysis. Each iteration indicates unique random conditions that produce specific value of FOS. The final product of the probabilistic analysis is the percentage of total FOS value which falls below 1.00 over total result. The percentage is called the probability of failure.

RESULTS

Slope properties

Four different slopes were selected in this study. All slopes exhibit proof of failures that occurred in the past including scars and blocks. Table 1 shows the properties of the selected slopes.

Kinematic analysis

Kinematic analysis was done on each of the rock slope. Markland test (Hoek & Bray, 1981) was used to identify the potential planar failure planes. The prerequisite for a potential planar failure is that $\psi_s > \psi_p > \varphi$ which means the failure plane must dip greater than the frictional angle but less than the slope dip. The critical area is marked as the shaded area in the equal-area projection of the data. Figure 6 shows the stereonet build for each of the slopes.

Discontinuity properties for deterministic and probabilistic calculation

Parameters for deterministic analysis were based on the mean value for a given set while parameters for probabilistic analysis includes the mean, standard deviation, relative minimum and relative maximum. The values for orientation (dip & dip direction), length, and JRC were obtained from the discontinuity survey. JCS values were obtained from the point load test and Schmidt hammer rebound test from both material sample and upon the rock wall. All parameters were projected in normal distribution except water presence. Residual friction angle, φ_r is assumed at 34.1° for Grade II granite (Goh *et al*., 2014) based on weathering grade assessment on site. Table 2 shows the properties of discontinuities with potential planar failure on respective slopes.

Water content is randomly generated exponential manner (Pathak & Nilsen, 2004) which the highest probability is dry condition. This coincides with the condition of field discontinuities that were mostly dry but due to the tropical condition, probability of water seeping into the discontinuities still exist.

Table 1: General properties of rock slopes in the study area.

Slope Locality	Dip	Dip Direction	Nature of slope	Height	Geology	Remarks
L1	76°	N 40° E	Man-made slope	8 m	Medium – Coarse grained biotite granite	Blocky rock slope with overhangs
L2	57°	N 128° E	Man-made slope	10 m	Medium – Coarse grained biotite granite	Rock slope with recent failure
L3	70°	N 335° E	Man-made slope	30 m	Fine grained biotite granite	Heavily jointed rock slope with failed blocks
L4	70°	N 128° E	Man-made slope	30 m	Fine grained biotite granite	Heavily jointed rock slope with failed blocks

Deterministic analysis

Deterministic analysis was done using the mean values of data from the discontinuity survey and laboratory test. Based on the results, every potential planar failure remains stable although the block plane at L1 does not meet the safety value of FOS>1.25 for safe rock slope (Priest & Brown, 1983). However, at 50% of water infilling inside the plane, the value falls with blocks at L1 and L4 having failure. FOS value when the plane is 100% filled with water shows that every plane has failure. Table 3 shows the deterministic FOS value for each potential planar failure.

Probabilistic analysis

Probability of failure

Parameters from Table 1 were used for the probabilistic analysis for the Factor of Safety (FOS). All potential

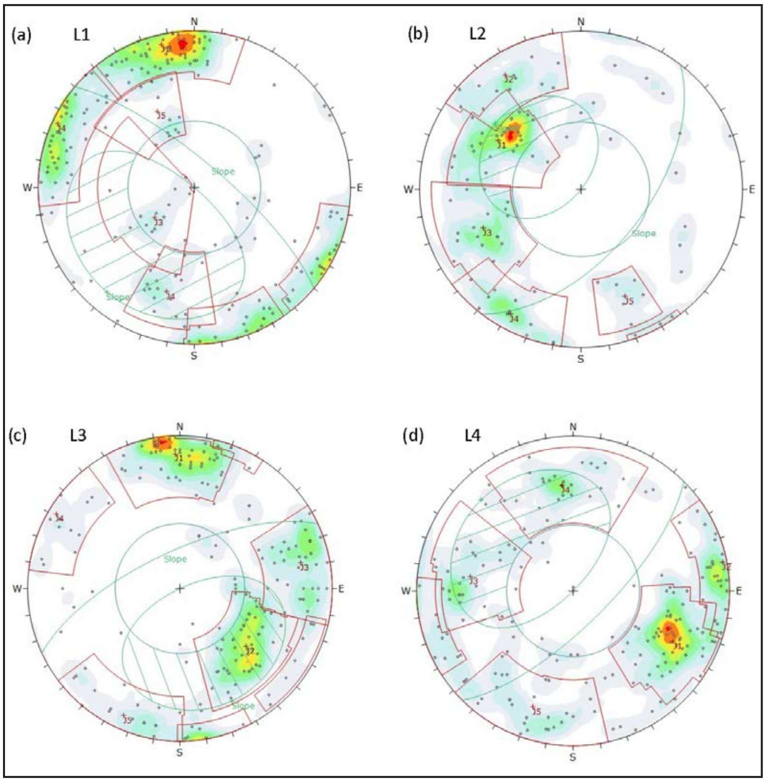

Figure 6: Stereonet diagram for kinematic analysis on rock slopes for each slope. (a)Stereonet diagram for Slope L1, shows discontinuity set J4 located in the shaded area of daylighting envelope and identified as potential planar failure. (b) Stereonet for Slope L2, shows discontinuity set J1 falls into the daylighting envelope and identified as potential planar failure. (c) Stereonet for Slope L3 shows discontinuity set J2 falls into the daylighting envelope and identified as potential planar failure. (d) Stereonet for Slope L4 shows discontinuity set J4 falls into the daylighting envelope and identified as potential planar failure.

Table 2: Parameters for each set with potential planar failure at each slope locality.

	Parameters	Dip	Dip Direction	Length (m)	JRC	JCS, MPa	Residual Friction Angle, φ_r
Set J4, Slope L1	Mean	58.38°	N 16.00° E	1.79	6.38	42.00	34.1
	Relative Min.	22.38°	12.00°	1.74	3.38	7.42	-
	Relative Max.	19.63°	12.00°	4.21	4.63	5.30	-
	Std. Dev.	11.71°	8.42°	2.13	2.90	5.41	-
Set J1, Slope L2	Mean	50.64°	N 122.40° E	1.39	10.60	62.58	34.1
	Relative Min.	28.64°	27.40°	1.29	3.60	2.24	-
	Relative Max.	19.36°	23.60°	3.61	6.70	2.25	-
	Std. Dev	11.79°	13.84°	1.45	2.58	3.16	-
Set J2, Slope L3	Mean	49.54°	N 309.92° E	0.91	10.44	85.56	34.1
	Relative Min.	19.54°	34.92°	0.79	7.44	0.31	-
	Relative Max.	20.46°	32.08°	4.19	8.56	0.30	-
	Std. Dev	9.62°	17.35°	0.87	4.00	0.43	-
Set J4, Slope L4	Mean	59.11°	N 173.85° E	0.94	7.48	64.48	34.1
	Relative Min.	21.11°	31.85°	0.84	4.48	25.67	-
	Relative Max.	20.89°	34.15°	2.06	9.52	18.88	-
	Std. Dev	10.56°	16.94°	0.82	3.25	23.03	-

planes have stable median FOS value (FOS>1). However, all potential planes have failure probability especially on joint J4 at L1 and J4 at L4 which are significantly higher. Every histogram plot shows a normal distribution of FOS value with variable standard deviation and mode values. The difference of the distribution is due to the variance in input data. Table 4 shows the probabilistic FOS values and failure probability for each slope. Histogram for probability of failure is shown on Figure 7.

Estimating probable failure block weight

Estimating the failure probability alone is insufficient without the estimation of probable failure block weight. By estimating the block weight, proper mitigation measures can be proposed for the rock slopes. Failure to estimate the block weight would either cause redundant protection measures which are costly or potentially disastrous underestimation. Table 5 shows the estimation of block weight of probable planar failure. Figure 8 shows the probable weight of block with its corresponding FOS value.

DISCUSSION AND CONCLUSION

Parameters of the discontinuities were measured on siteand analysed statistically. Random properties are generated based on the statistical results of the parameters (Mean, standard deviation, relative minimum and maximum).

Table 3: Deterministic analysis on FOS value of potential planar failure.

Slope Locality	Joint Set	Slope Face Dip	Plane Dip	Plane Length, m	JRC	JCS, MPa	Block weight, tonne/m	FOS (Dry)	FOS (50% Water)	FOS (100% Water)
L1	J4	76.00°	58.38°	1.79	6.38	42.00	1.15	1.08	0.80	0.00
L2	J1	57.00°	50.64°	1.39	10.60	62.58	0.27	2.25	1.01	0.00
L3	J2	70.00°	49.54°	0.91	10.44	85.56	0.32	2.34	1.89	0.55
L4	J4	70.00°	59.11°	0.94	7.48	64.48	0.21	1.62	0.91	0.00

Table 4: Probabilistic analysis on FOS value of potential planar failure.

Slope Locality	Joint Set	Slope Face Dip	Plane Dip	Median FOS Value	Standard Deviation	Mode FOS Range	Probability of failure, %
L1	J4	76.00°	58.38°	1.06	0.57	0.8 – 1.0	44.80
L2	J1	57.00°	50.64°	2.54	1.11	2.0 – 2.2	4.83
L3	J2	70.00°	49.54°	2.07	0.83	1.8 – 2.0	6.59
L4	J4	70.00°	59.11°	1.36	0.65	1.0 – 1.2	24.97

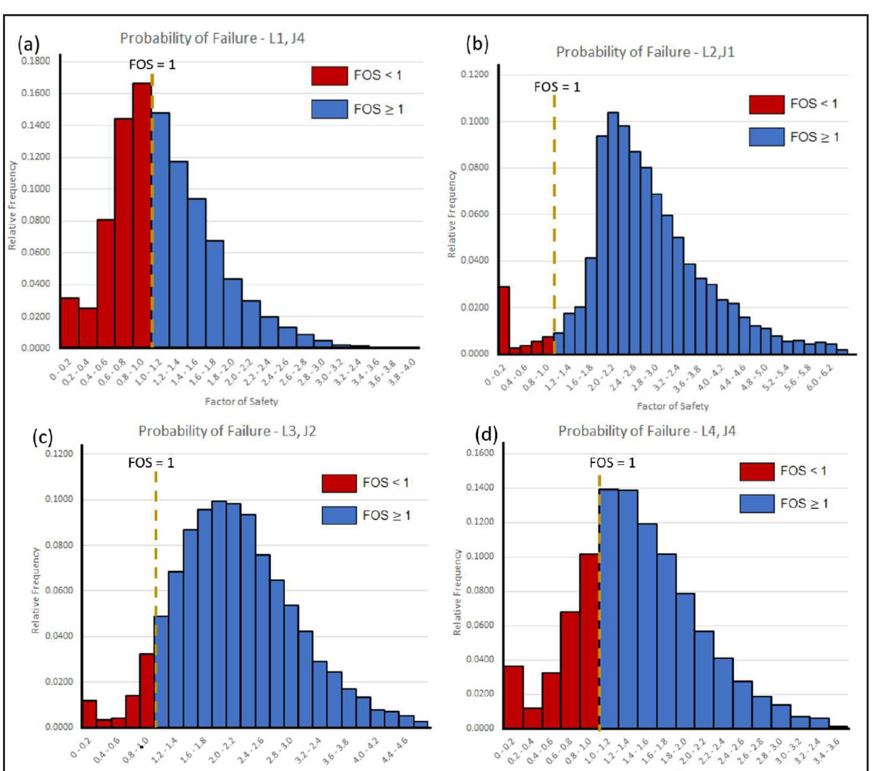

Figure 7: Probability of failure for potential planar failure on each of the slope. Probability of failure is characterized by the percentage of FOS value under 1.0. Red bar represents FOS values < 1 while blue bar represents FOS values ≥ 1.0. (a) Histogram for Slope L1 shows a mode of FOS 0.8 - 1.0 which is a failed state with Probability of Failure around 44.80%. Other slopes shows relatively lower probability of failure with 4.83% for Slope L2 (b), 6.59% for Slope L3 (c), and 24.97% for Slope L4 (d).

Table 5: Probabilistic analysis on probable weight of failed block.

Slope Locality	Joint Set	Slope Face Dip	Plane Dip	Probability of Failure, %	Median Probable Failed Block Weight, tonnes/m	Minimum Probable Failed Block Weight, tonnes/m	Maximum Probable Failed Block Weight, tonnes/m
L1	J4	76.00°	58.38°	44.80	1.30	$6.46 * 10^{-5}$	23.31
L2	J1	57.00°	50.64°	4.83	0.07	$2.51 * 10^{-5}$	3.97
L3	J2	70.00°	49.54°	6.59	0.25	$9.14 * 10^{-4}$	9.61
L4	J4	70.00°	59.11°	24.97	0.13	$2.06 * 10^{-5}$	4.95

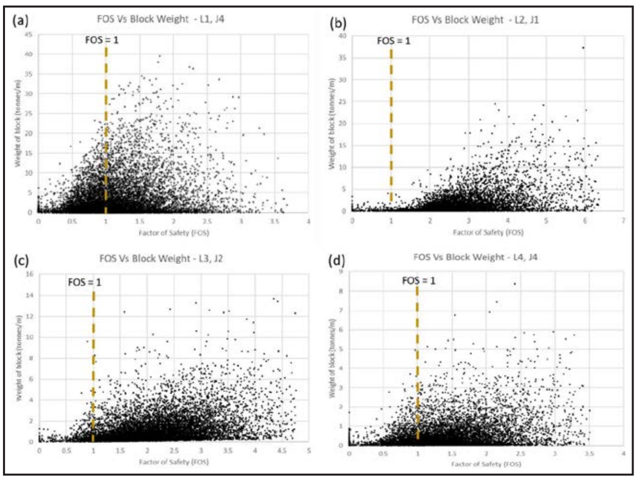

Figure 8: Scatter plot for the Factor of Safety (FOS) versus estimated block size. The failed blocks are plotted as points to the left of FOS = 1 line.

The Factor of Safety (FOS) of the potential planar failure identified from the Markland test was calculated using the Barton method to replace cohesion values in Mohr-Coulomb calculation.

Deterministic analysis for each of the potential planar failure localities reveals FOS value of 1.08 (L1), 2.25 (L2), 2.34 (L3) and 1.62 (L4) in dry condition. The introduction of water reduce the FOS value and may cause failure when filled with 50% and 100% of water. Therefore even in dry conditions, water influence should not be neglected especially in the tropical conditions experienced in Malaysia.

Probabilistic analysis shows the probability of failure at 44.80% (L1), 4.83% (L2), 6.59% (L3), and 24.97% (L4). Slopes L2 and L3 shows relatively high FOS value during deterministic analysis in dry conditions, but still exhibits probability of failure even though the value is relatively small. The situation occurred due to water content parameters inserted in probabilistic analysis strengthening the need to include water influence in limit equilibrium calculations. Estimated median failed block ranges from 0.07 t/m (L2) to 1.30 t/m (L1). The estimation of block size helps in proposing suitable mitigation measures on the rock slope that potentially fail.

Probabilistic analysis of planar failure is needed when a slope is known to exhibit planar-type potential failures by joint sets. Each joint set may not have uniform properties, making deterministic calculation inapplicable to multiple planar blocks even on the same slope. The study area exhibits several planar blocks that already failed while some of the blocks are still intact, proving the variations of properties that affect the FOS value.

Rock blocks with FOS>1.25 are considered stable based on Priest & Brown (1983) and extensive mitigation measures may deem unnecessary unless external forces such as additional load is expected which may change the outcome of FOS. Slope with FOS between 1.00 to 1.25 requires stabilization efforts under the knowledge of geotechnical engineer for suitable structures. The establishment of FOS value will help the engineers to design adequate structure to raise the FOS value which in turn will reduce the probability of inadequate or excessive and expensive slope stabilization design.

ACKNOWLEDGEMENTS

The authors wish to thank the laboratory staff of the Geology Programme, UKM. This work has been supported by the Government of Malaysia under the Fundamental Research Grant Scheme FRGS/1/2017/WAB08/UKM/02/1.

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Manuscript received 3 July 2018
Revised manuscript received 16 January 2019
Manuscript accepted 10 February 2019