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Application of a Comprehensive Rock Slope Stability Assessment Approach for Selected Malaysian Granitic Rock Slopes

(Pengaplikasian Pendekatan Penilaian Kestabilan Cerun Batu Komprehensif untuk Cerun Batu Granit Malaysia yang Terpilih)

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ABSTRACT

In Malaysia, rock slope stability analysis has been largely confined to kinematic analysis with rock mass rating systems as assessment tools for stability analysis. While this method addresses the fundamental issues of rock slope stability including identifying potential failure modes, an information gap still exists between geologists and engineers in designing proper mitigation measures for rock slopes. This paper aims to address this issue by incorporating several methodologies, including kinematic analysis, slope mass rating and the Barton-Bandis criterion for the limit equilibrium method. Four rock slopes with potential instabilities namely KSA, KSB, LHA, and LHB were studied. KSA and KSB were located near Kajang, Selangor while LHA and LHB were located near Rawang, Selangor. Each slope exhibits multiple potential failures, with attention given on sliding-type failures in planar or wedge form. A slope mass rating value was assigned to each potential failure based on rock mass rating$_{basic}$ *and the slope mass rating based on readjustments for discontinuity orientation and excavation method. Factor of safety from limit equilibrium method show potentially unstable blocks and failed blocks (Factor of Safety <1.00) with confirmation on site. Water filling of discontinuity apertures plays an important role in destabilizing rock blocks, especially in wet conditions experienced in Malaysia's tropical climate. Several geometries are identified as potentially unstable due to low slope mass rating (Class V) and factor of safety of <1.2, such as planar J5 and wedge J2*J5 at KSA, wedge forming with sets J3, J4 and fault plane at KSB, planar J2 at LHA, and wedge J3*J4 at LHB. Stabilization structures such as rock bolts can be better designed with the determined factor of safety values coupled with relevant geological and geotechnical inputs. In this comprehensive rock slope stability assessment approach, limit equilibrium method serves as a useful method in analyzing rock slope stability to complement kinematic analysis and stability ratings often used in Malaysia.*

Keywords: Factor of safety; limit equilibrium method; rock slope stability; slope mass rating

ABSTRAK

Di Malaysia, sebahagian besar analisis kestabilan cerun batuan adalah tertumpu pada analisis kinematik dan diguna bersama dengan sistem perkadaran jasad batuan sebagai alat penilaian dalam analisis kestabilan. Walaupun kaedah ini dapat menangani isu-isu asas kestabilan cerun batuan dengan mengenal pasti ragam kegagalan yang berpotensi berlaku, jurang maklumat masih wujud antara geologi dengan jurutera dalam reka bentuk langkah-langkah mitigasi untuk cerun batuan yang lebih baik. Makalah ini bertujuan untuk mengatasi masalah ini dengan menggunakan beberapa kaedah iaitu analisis kinematik, perkadaran jasad cerun dan kriteria Barton-Bandis dalam kaedah had keseimbangan. Empat cerun batuan yang berpotensi tidak stabil dinamakan KSA, KSB, LHA dan LHB telah dikaji. KSA dan KSB terletak berhampiran Kajang, Selangor manakala LHA dan LHB terletak berhampiran Rawang, Selangor. Setiap cerun menunjukkan beberapa potensi kegagalan, terutamanya kegagalan jenis gelongsor dalam bentuk satah atau baji. Nilai perkadaran jasad cerun setiap potensi kegagalan telah ditentukan berdasarkan perkadaran jasad batuan$_{asas}$ *dan perkadaran jasad cerun yang berasaskan penyelarasan orientasi ketakselanjaran dan kaedah pengorekan. Faktor keselamatan yang diperoleh daripada kaedah had keseimbangan telah menentukan bongkah yang berpotensi tidak stabil dan gagal (Faktor Keselamatan <1.00) dan telah mendapat pengesahan di lapangan. Pengisian air dalam bukaan ketakselanjaran memainkan peranan penting dalam ketidakstabilan bongkah batuan, terutama dalam keadaan basah pada iklim tropika Malaysia. Beberapa geometri yang berpotensi tidak stabil telah dikenal pasti kerana mempunyai perkadaran jasad cerun yang rendah (kelas V) dan faktor keselamatan <1.2, seperti satah J5 dan baji J2 * J5 di KSA,* *baji yang terbentuk daripada set J3, J4 dan satah sesar di KSB, satah J2 di LHA, dan baji J3 * J4 di LHB. Struktur penstabilan seperti bolt batuan dapat direka bentuk dengan lebih baik hasil gabungan nilai faktor keselamatan dengan input geologi dan geoteknik yang berkaitan. Dalam pendekatan penilaian kestabilan cerun batuan yang menyeluruh ini, kaedah had keseimbangan berfungsi sebagai kaedah yang baik yang diguna bersama dengan analisis kinematik dan perkadaran kestabilan dalam penganalisisan kestabilan cerun batuan yang sering digunakan di Malaysia.*

Kata kunci: Faktor keselamatan; kaedah had keseimbangan; kestabilan cerun batuan; perkadaran jasad cerun

INTRODUCTION

Rock slope stability analysis for slopes controlled by geological discontinuities is primarily based on kinematic analysis to identify potential failures (Hoek & Bray 1981; Markland 1972; Wyllie & Mah 2004). Further development allows usage of ratings such as Slope Mass Rating (SMR) (Romana 1985) and Q-slope (Bar & Barton 2017) to determine the stability of rock slope. In Malaysia, SMR approach was adopted by Rafek et al. (2019) and Razib et al. (2018) in cut slope stability assessment. SMR also was adopted in cave stability assessment (Goh et al. 2019; Serasa et al. 2020). However, where the stability is influenced by potential sliding along a plane (as in planar and wedge failure), the limit equilibrium method allows the study of forces acting along the plane. A comprehensive study to determine the Factor of Safety (FOS) of a potential failure via limit equilibrium method allows proper mitigation design to be made in a cost-effective and safe manner. Rahim et al. (2019) conducted probabilistic analysis on planar type rock slope based on FOS. Intensive weathering experienced by tropical countries such as Malaysia have contributed to a thicker soil stratum, which means rock slope excavations are unlikely in lowland areas. However, rapid developments have encroached hilly areas, which means more slope excavations are required. Resulting rock slopes often lack proper stabilization measures, leading to failures attributed to geological discontinuities.

Currently published rock slope stability analysis in Malaysia applies kinematic analysis (Jaapar 2005; Madun & Omar 2001) standard approach in identifying potential failures but are lacking in the engineering results required by the design engineer. On the other hand, the design engineer's application of an engineering approach in rock slope stability analysis may have inadequate geological considerations. This study explores a more comprehensive method in assessing rock slope stability utilizing the limit equilibrium method and geological considerations for selected Malaysian rock slopes.

MATERIALS AND METHODS

A total of 4 localities with potential instabilities were selected for the study namely KSA, KSB, LHA and LHB located along highways. KSA and KSB were located along a stretch of Kajang SILK Highway near Kajang town while LHA and LHB were located within LATAR Highway near Rawang township. The locations are shown on map in Figure 1. This study ranges from data acquisition on site, kinematic analysis, slope stability rating and to the Factor of Safety (FOS) determination. The workflow for this study is shown in Figure 2.

GEOLOGY OF STUDY AREA

The greater Kuala Lumpur area, also known as Klang Valley, is composed of Paleozoic sedimentary and metamorphic strata known as Hawthornden Schist, Kuala Lumpur Limestone and Kenny Hill Formation (Gobbett 1964). These strata form the undulating topography which mostly involves soil slopes. The intruding Mesozoic granite (Bignell & Snelling 1977) forms the hilly and mountainous terrain that flanks the eastern and northwestern part of the Klang Valley (Figure 3). Development in hilly granite areas involves cut slopes which uncovered multiple rock slopes, especially for road and residential area development.

All localities in this study are within granite which is part of the Main Range Granite characterized by its typical medium to coarse grained biotite granite (Cobbing et al. 1992). However, the slopes of LHA and LHB exhibit a slightly different texture, with finer mineral grains as compared to the typical properties. Both slopes exhibit slightly (Grade I-II) to moderately weathered (Grade III) rock masses.

DISCONTINUITIES CHARACTERIZATION AND ANALYSIS

Scanline and photogrammetry methods were deployed to measure the orientation and properties of discontinuities at site. The Scanline method involves measuring tape spread

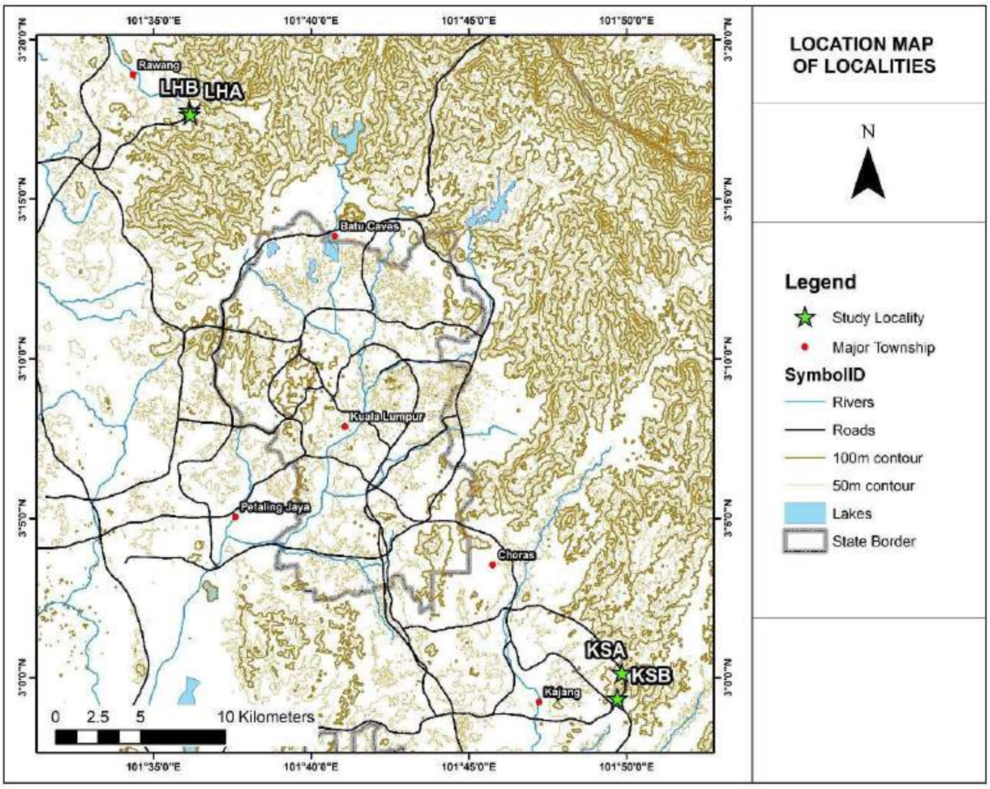


FIGURE 1. The location of study localities within Klang Valley

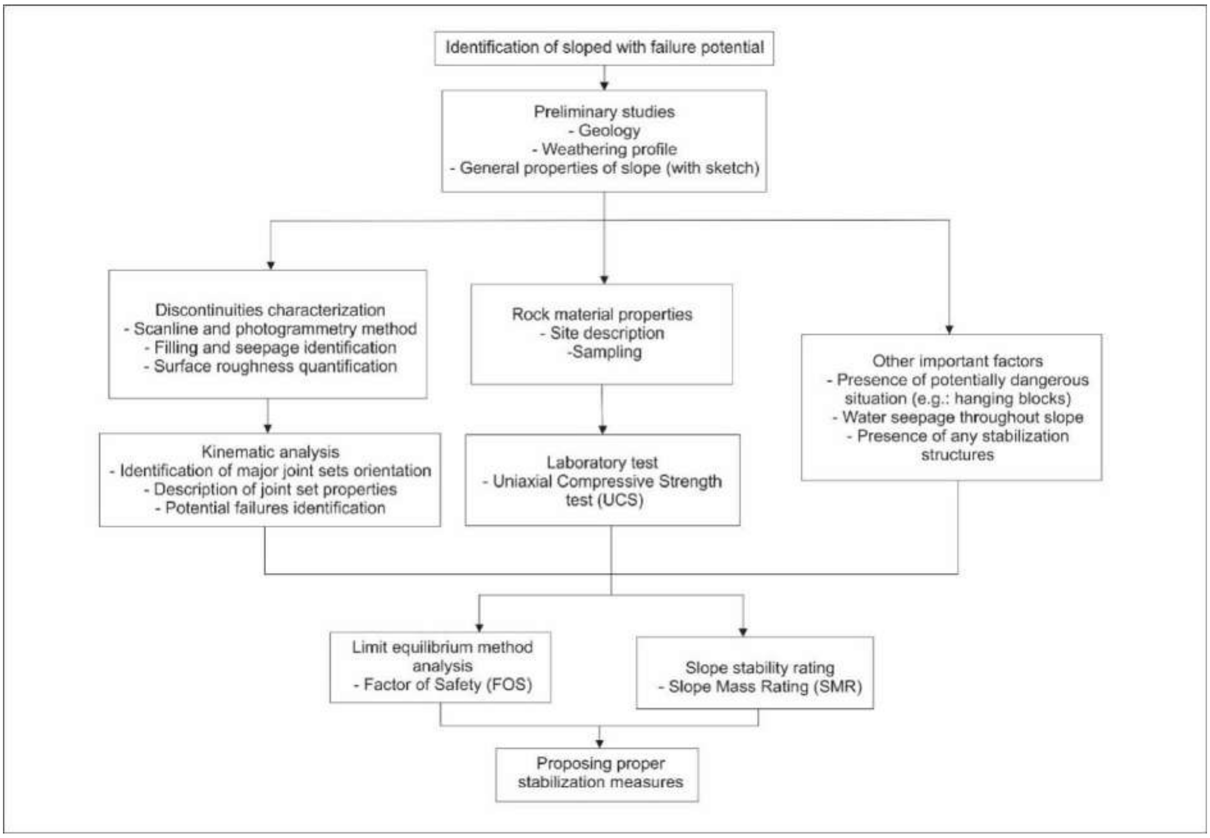


FIGURE 2. The workflow chart of slope stability analysis in this study

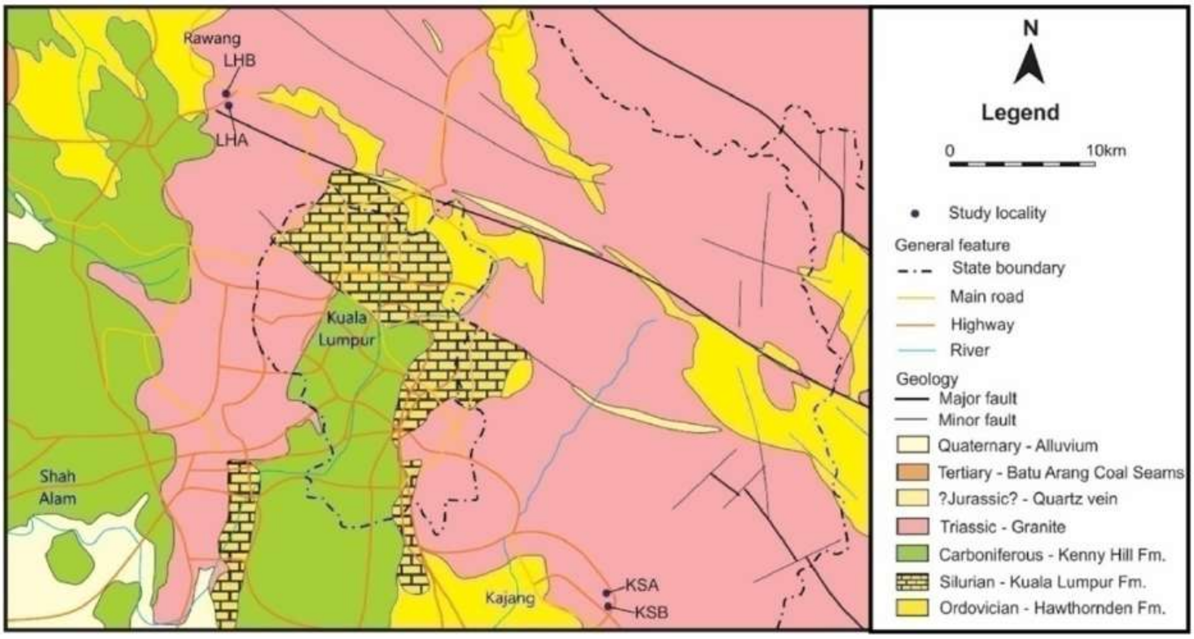


FIGURE 3. Geology of the study area (Kuala Lumpur, Malaysia, and surrounding region) (Jabatan Mineral dan Geosains Malaysia 2015)

across a rock slope, with any discontinuity crossing the line recorded (Brady & Brown 2006; International Society for Rock Mechanics 1981; Priest & Hudson 1976). Parameters of a discontinuity include spacing, orientation, length, roughness, and Joint Roughness Coefficient (JRC). The JRC value was recorded using a profiler based on recommendations by Barton and Choubey (1977).

Photogrammetry method served as a supplement towards the scanline method. Models generated from photogrammetry help to visualize the potential failure, estimating the size and volume of unstable blocks. Although the mesh and point cloud model generated from a photogrammetric data is capable of rebuilding the slope in 3-Dimensional manner, some limitations persist including the determination of JRC and filling of a discontinuity. Example of point cloud imagery is shown in Figure 4. Photogrammetry used in this study employs photographs of slope taken with over 60% overlaps between them. The extensive overlaps allow 3D depth to be gauged. *Agisoft* software was used to generate the

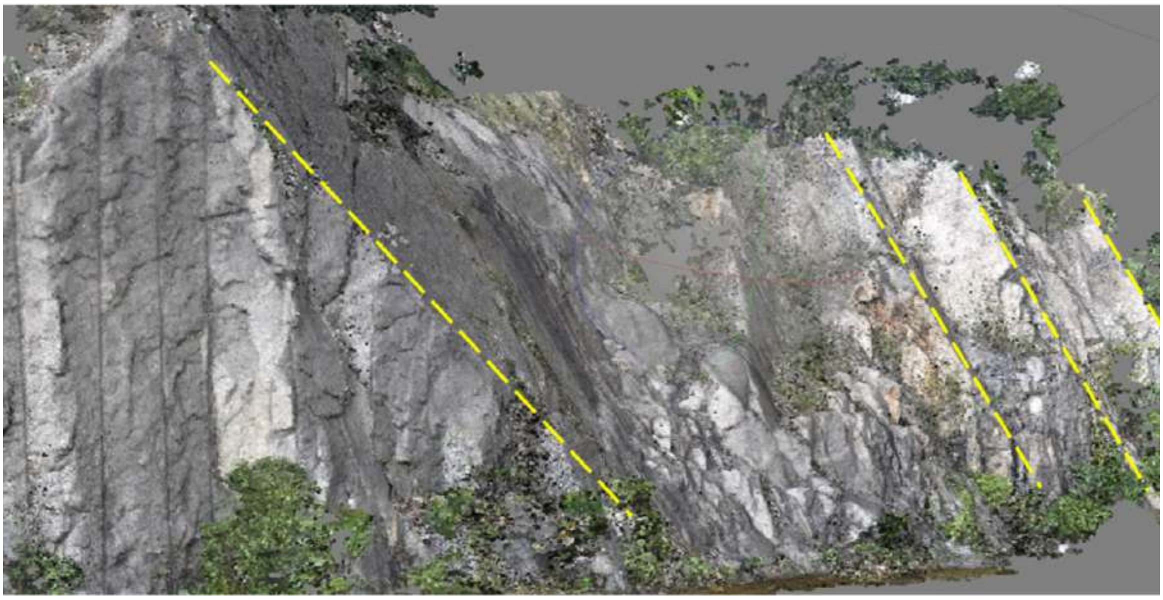


FIGURE 4. The point cloud model obtained from photogrammetry survey of Slope KSA, showing signs of relic planar failure as shown in yellow dashed lines

point cloud. One of the advantages of the point cloud model is to allow a more accurate measurement of any identified geometry.

Kinematic analysis was done to determine the major discontinuity sets and potential mode of failures on site. The potential failures were identified based on Hoek and Bray (1981) and the Markland Test (Markland 1972). Emphasis was given to planar and wedge type potential failures, in which potential sliding might occur on the known discontinuity plane.

SLOPE MASS RATING (SMR) SYSTEM

The Rock Mass Classification System used in this study is Slope Mass Rating (SMR) (Romana 1993, 1985). The rating system is based on the Rock Mass Rating (Bieniawski 1989, 1975) with a system of rating readjustments based on the discontinuity orientation and dip, slope orientation and dip as well as slope excavation method. Therefore, each potential failure has its own SMR rating that provides information on its stability.

LIMIT EQUILIBRIUM METHOD ANALYSIS

The Limit equilibrium method (LEM) calculates the forces acting along a potential failure plane, which can be translated into the Factor of Safety (FOS). Several shear strength criteria are available for this method such as Mohr Coulomb, Patton (Patton 1966), Barton-Bandis (Barton & Bandis 1990), and Hoek-Brown (Hoek & Brown 1988). Barton - Bandis criterion (Barton 1976; Barton & Bandis 1990) was the most suitable for the prevailing site conditions. *Dips v6.008* was used to plot the stereonet diagram, while *RocPlane v3.0* and *Swedge v5.0* was used for the stability analysis. Joint Roughness Coefficient (JRC) serves to quantify the discontinuity of surface roughness. FOS calculation using the Barton - Bandis equation is shown as follow:

$$FOS \quad = \frac{\sigma tantan\,(\varphi_r + JRC\ log_{10}\left(\frac{JCS}{\sigma}\right))A}{W sinsin\,\psi_p} \qquad (1)$$

where the respective parameters are shown in Table 1.

TABLE 1. Parameters and data acquired for FOS calculation via Barton - Bandis criterion

Parameter	Explanation	Data source	Remarks
σ	Normal force	Based on weight of block; $\sigma = Wg\ cos\ cos\ \psi_p$ * W = weight of block * ψ_p = failure angle dip	- In planar failure calculations, the plane is assumed as parallel to slope face, weight is expressed as tonne/m - In wedge failure calculations, weight is based on block size, normal force acting on two planes
JRC	Joint Roughness Coefficient	Measurement on site using comb	- Mode of JRC value selected for respective joint set
JCS	Joint wall strength	Schmidt hammer rebound test on discontinuity surface	- UCS lab test results
A	Potential failure surface area	Calculated geometrically based on measured length on site	- Based on photogrammetry results
ψ_p	Potential failure plane dip angle	Based on identified discontinuity set from kinematic analysis	- Based on photogrammetry results and field data acquisition
φ_r	Residual friction angle	Based on published value for granite	- Goh et al. (2014)

Results and Discussion

ROCK SLOPE DESCRIPTION AND DISCONTINUITIES CHARACTERIZATION

Four slopes were selected for this study. General description of the slopes is shown in Table 2. Figure 5 shows the image of slopes in this study.

TABLE 2. General characteristics of rock slopes examined in the study

Slope Locality	Dip	Dip Direction	Nature of slope	Height	Geology	Remarks
KSA	76 °	N 40 ° E	Cut slope	15 m	Medium – Coarse grained biotite granite	Blocky rock slope with overhangs
KSB	72 °	N 128 ° E	Cut slope	10 m	Medium – Coarse grained biotite granite	Rock slope with recent failure
LHA	72 °	N 305 ° E	Cut slope	30 m	Fine grained granite	Heavily jointed rock slope with failed blocks
LHB	72 °	N 135 ° E	Cut slope	30 m	Fine grained granite	Heavily jointed rock slope with failed blocks

FIGURE 5. Field photo for Slope KSA, KSB, LHA, and LHB. All slopes studied were granite rock cut slopes

KINEMATIC ANALYSIS AND POTENTIAL FAILURES

The results of stereonet plots of kinematic analysis based on discontinuity data for each slope are shown in Figure 6. Multiple potential failures were identified on each slope based on kinematic analysis. In this study, the potential failure orientations are identified from the stereonet plots, but the individual potentially failed geometry profiles are extracted from the point cloud model, along with its dimension. The potential failures were observed on site, with multiple failed geometry being observed in several slopes. The resulting FOS calculation will be compared with site conditions for confirmation. Table 3 shows the discontinuities sets identified on the rock slopes, while Table 4 shows the potential mode of failures identified from kinematic analysis.

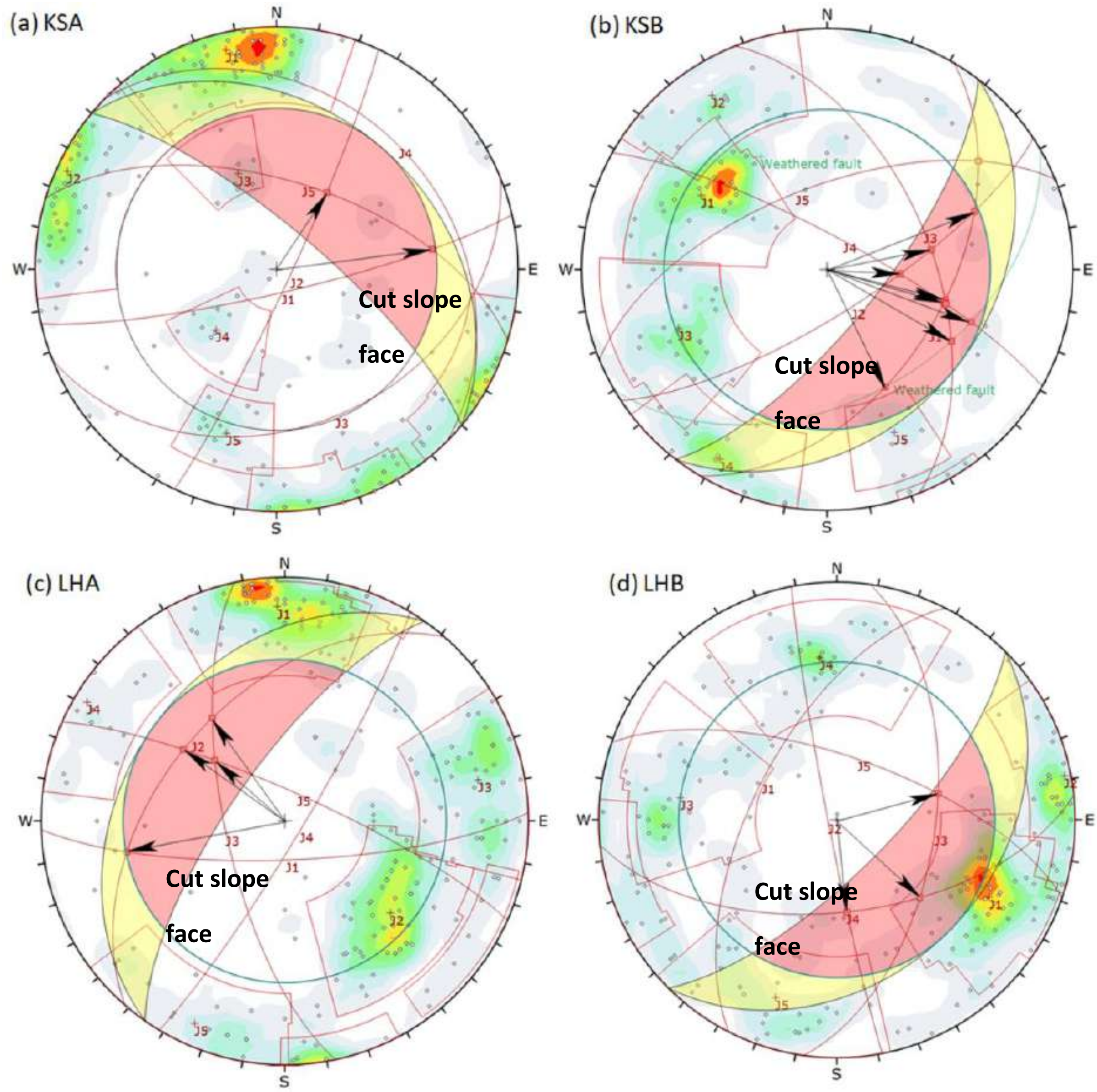


FIGURE 6. Kinematic analysis based on discontinuities for respective slope. Stability of slope KSA (a) was influenced by presence of set J5 forming potential planar, or as wedge when intercepted with J1. Slope KSB (b) shows multiple potential wedge failure, with most of them attributed to presence of a weathered fault. The wedge failure was observed in the field, sliding along fault plane with multiple vertical discontinuities contributed to failure. Slope LHA (c) exhibits a potential planar failure (joint set J2) and multiple wedges with J2 as sliding plane, also observed in the field. For slope LHB (d), multiple potential wedge failures were also identified. Table 4 shows the list of potential failures for the respective slopes

TABLE 3. Discontinuities sets and its respective properties for each slope in this study

Slope	Set	Dip direction / dip	Length, m	Aperture, mm	Filling	JRC	Water	Remarks
KSA	J1	167 °/82 °	1.5 – 3	<2	Colored	3	Damp	
	J2	115 °/85 °	0.5 – 3	<2	Clean	5	Damp	
	J3	158 °/35 °	0.5 – 1	<2	Clean	7	Damp	
	J4	45 °/29 °	0.5 – 2	6 – 20	Colored	9	Dry	
	J5	17 °/60 °	5	6 – 20	Colored	5	Damp	Failure Plane
KSB	J1	121 °/50 °	0.5 – 3	<2	Clean	5	Dry	
	J2	147 °/75 °	0.5 – 2	<2	Clean	9	Dry	
	J3	68 °/55 °	0.5 – 3	<2	Clean	9	Dry	
	J4	29 °/79 °	0.5 – 5	2-6	Clean	11	Dry	
	J5	338 °/62 °	0.5 – 5	<2	Colored	9	Dry	
	F	150 °/45 °	10	50	Clay	3	Damp	Fault contributing to wedge failure
LHA	J1	178 °/77 °	0.5 - 3	<2	Clean	5	Dry	
	J2	311 °/48 °	0.5 - 2	<2	Clean	5	Dry	
	J3	258 °/70 °	0.5 - 2	<2	Clean	9	Dry	
	J4	121 °/84 °	0.5 - 2	<2	Clean	9	Dry	
	J5	24 °/80 °	1 – 2	<2	Clean	5	Dry	
LHB	J1	297 °/61 °	0.5 - 4	<2	Clean	9	Dry	
	J2	259 °/87 °	0.5 - 2	<2	Clean	9	Dry	
	J3	98 °/56 °	0.5 - 3	<2	Clean	9	Dry	
	J4	174 °/58 °	0.5 - 3	<2	Clean	9	Dry	
	J5	19 °/68 °	0.5 - 2	<2	Clean	7	Dry	

*JRC – Joint Roughness Coefficient, value obtained based on mode value for each set

TABLE 4. List of potential failures on each slope identified via kinematic analysis

Slope	Potential planar failure	Remarks	Potential wedge failure	Remarks
KSA	J5	Observed on site as scars (failed), set J2 act as releasing plane	J2*J5, J1*J5	-
KSB	J1	Observed instead as releasing plane from the back of wedge failure	J1*J3, J1*J4, J2*J3, J2*J4, Fault*J1, Fault*J3, Fault*J4	Multiple sets form a composite wedge failure, primarily sliding along the weathered fault plane
LHA	J2	Observed as scars on site (failed geometry)	J1*J2, J2*J3, J2*J5, J3*J5	Small wedges observed with fallen rock blocks in rock ditch
LHB	-	-	J2*J4, J3*J4, J3*J5	Small wedges observed with fallen rock blocks in rock ditch

TABLE 5. The RMR_{basic} and SMR for each slope

Slope	Average UCS	RQD	Spacing	Cond. of disc.	Ground-water	RMR_{basic}	Potential failure	Total Re-adjustment	SMR	Class
KSA	42 MPa	68%	60 – 200 mm	-	Dry	62	J5	-26	36	IV
							J1*J5	-5	57	III
Rating	5	14	8	20	15		J2*J5	-47	15	V
KSB	74 MPa	73%	60 – 200 mm	-	Dry	58	J1	-51	7	V
							J1*J3	-29	29	IV
							J1*J4	-24	34	IV
Rating	7	15	8	13	15		J2*J3	-11	47	III
							J2*J4	-15	43	III
							F*J1	-29	29	IV
							F*J3	-47	11	V
							F*J4	-30	28	IV
LHA	95 MPa	96%	200-600 mm	-	Damp	71	J2	-54	17	V
							J1*J2	-12	59	III
Rating	9	19	10	21	12		J2*J3	-20	51	III
							J2*J5	-49	22	IV
							J3*J5	-42	29	IV
LHB	88 MPa	80%	200-600 mm	-	Damp	66	J2*J4	-9	57	III
							J3*J4	-60	6	V
Rating	8	16	10	20	12		J3*J5	-9	57	III

Note: UCS - Uniaxial Compressive Strength, RQD - Rock Quality Designation

SLOPE MASS RATING (SMR)

Slope Mass Rating (SMR) was deployed to rate the stability of the rock slopes. The rating system utilizes the RMR_{basic} from observations and measurements of the slope in general with modification from potential failure planes. SMR serves as a general rating in identifying potentially unstable blocks on slopes. Resulting SMR rating shows values ranging from Class III (40-60) which can be considered as partially stable to Class V (0-20) which is extremely unstable. The difference in rating for each type of failure resulted from differences in geometry including the dip and dip direction of potential failure. Table 8 shows the SMR rating for each slope in this study. Based on SMR rating, each slope exhibits classification between Class III (partially stable) to Class V (highly unstable) slope. For slope KSA, the lowest rating is 15 (Class V) due to wedge formed by intersection between discontinuities sets J2 and J5. At slope KSB, lowest ratings are 7 and 11 (Class V) due to potential planar failure J1, and wedge formed by intersecting fault plane (F) and J3. At slope LHA, lowest rating is 17 (Class V) due to potential planar failure of set J2. Slope LHB exhibits lowest rating at 6 (Class V) sue to wedge formed by intersection between J3 and J4. All lowest SMR rating geometries for each slope show scars due to past failures. Based on SMR rating, all slopes have Class V geometries which means they can be highly unstable. However, the severity of the condition also depends on the dimension of the block and nature of the failure (is it widespread?) itself in which SMR fails to capture.

TABLE 6. Parameter input for limit equilibrium analysis using Barton - Bandis criterion for each potential failure on each slope

Slope	Potential failure	Parameter Input					
		Normal Force, σ (kN)	Joint Roughness Coefficient, JRC	Joint wall strength, JCS (MPa)	Failure surface area, A (m^2)	Potential failure plane dip angle,	Residual friction angle,
KSA	P J5	57.76	5 (J5)	42.00	6.15	60 °	34.1°
	W J1*J5	181.43	3 (J1), 5 (J5)	42.00	13.38	35 °	
	W J2*J5	43.94	5 (J2), 5 (J5)	42.00	9.68	59 °	
KSB	PJ1	43.54	9 (J1)	74.00	4.33	50 °	34.1°
	W J1*J3	1.67	9 (J1), 9 (J3)	74.00	1.43	49 °	
	W J1*J4	1.50	9 (J1), 11 (J4)	74.00	1.39	49 °	
	W J2*J3	4.51	9 (J2), 9 (J3)	74.00	2.68	54 °	
	W J2*J4	0.20	9 (J2), 11 (J4)	74.00	0.36	65 °	
	W F*J1	3.53	3 (F), 9 (J1)	74.00	2.07	45 °	
	W F*J3	118.66	3 (F), 9 (J3)	74.00	13.75	41 °	
	W F*J4	1050.33	3 (F), 11 (J4)	74.00	52.09	37 °	
LHA	P J2	22.85	9 (J2)	95.00	3.02	48 °	34.1°
	J1*J2	1.08	5 (J1), 9 (J2)	95.00	0.46	34 °	
	J2*J3	0.39	9 (J2), 9 (J3)	95.00	0.52	47 °	
	J2*J5	0.49	9 (J2), 5 (J5)	95.00	0.54	48 °	
	J3*J5	4.81	9 (J3), 5 (J5)	95.00	1.92	59 °	
LHB	J2*J4	1.47	9 (J2), 9 (J4)	88.00	1.38	58 °	34.1°
	J3*J4	4.81	9 (J3), 9 (J4)	88.00	5.53	50 °	
	J3*J5	0.10	9 (J3), 7 (J5)	88.00	0.03	54 °	

SMR gives a rating and general recommended stabilization measures for the potential failure, without detailing the forces acting along the potential failure plane, and FOS value which is useful for design of structures. The rating is used to give a general idea of slope condition. This limitation is addressed using the Limit Equilibrium Method in determining FOS value.

FACTOR OF SAFETY (FOS) - DETERMINISTIC ANALYSIS

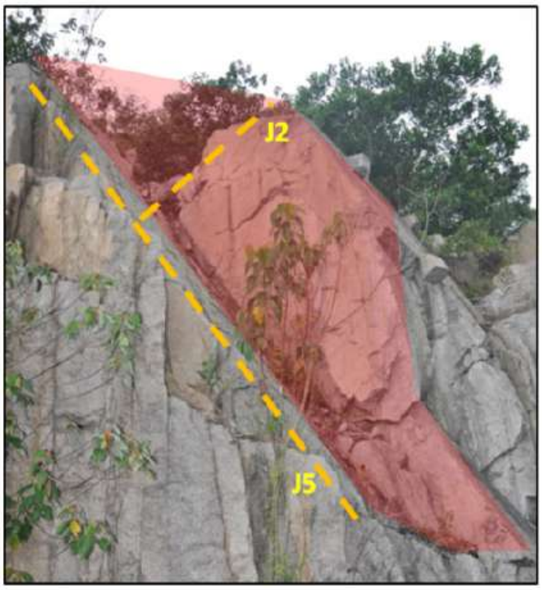
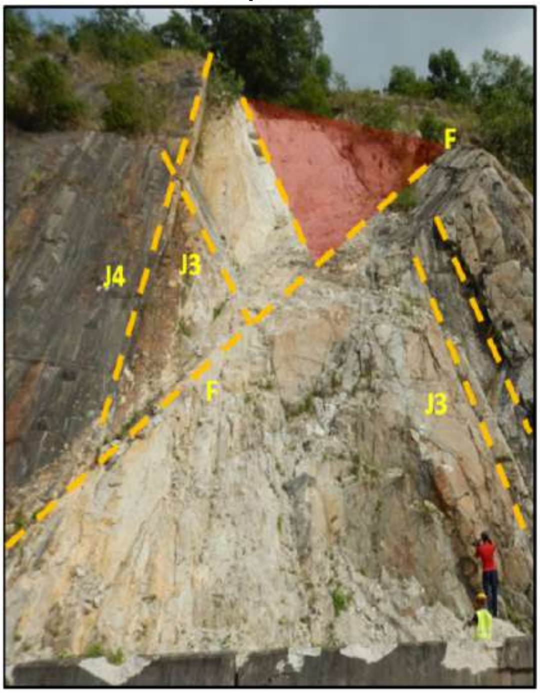
FOS calculation for rock slope stability analysis was made using Barton - Bandis criterion. The parameters involved were either obtained from site measurements, laboratory tests, and published data. The input parameters used in this study are shown in Table 6. Resulting FOS values range from 0.00 to 8.07. FOS value below 1.00 should indicate a failed geometry, with value equal to or greater than 1.00 as stable. However, marginal FOS must be treated with caution as environmental changes might reduce the FOS value. Estimated block weight in tons is calculated to assist in designing proper mitigation methods.

TABLE 7. List of FOS values calculated based on Barton - Bandis criterion

Slope	Potential Failure	SMR Rating	Factor of Safety, FOS			Estimated block weight, tons	Remarks
			0% water	50% water	100% water		
KSA	P J5	36	1.08	0.80	0.00	6.90	Major planar failure
	W J1*J5	57	8.07	7.50	4.63	6.98	No observed failure
	W J2*J5	15	0.75	0.67	0.00	13.15	Major wedge failure
KSB	J1	7	1.13	0.92	0.25	0.35	Small planar blocks
	J1*J3	29	2.31	2.03	0.15	1.27	Small blocky wedge
	J1*J4	34	2.31	2.27	0.16	1.31	Small blocky wedge
	J2*J3	47	2.16	1.71	0.07	0.44	Small wedge failures
	J2*J4	43	2.24	1.66	0.65	0.24	Small wedge failures
	F*J1	29	1.01	0.92	0.25	1.88	Small blocky wedge
	F*J3	11	1.04	0.99	0.60	5.77	Major wedge failure
	F*J4	28	1.37	1.30	0.93	20.07	Major wedge failure
LHA	J2	17	1.20	0.99	0.37	0.29	Planar failure observed
	J1*J2	59	2.72	2.49	0.66	0.03	Small wedge failures
	J2*J3	51	4.36	4.08	2.12	0.25	No observed failure
	J2*J5	22	2.89	2.63	0.80	0.03	No observed failure
	J3*J5	29	2.34	1.98	0.18	0.06	Small wedge failures
LHB	J2*J4	57	1.07	0.85	0.00	0.01	Small wedge failures
	J3*J4	6	0.84	0.78	0.31	3.04	Medium-sized wedge failures observed
	J3*J5	57	1.85	1.55	0.00	0.31	Small wedge failures

However, an important parameter in slope stability analysis – water content – varies greatly with weather, especially in wet tropical climates. Therefore, three conditions were established; when the discontinuities were filled with 0% water (dry), 50% water (wet) and 100% filled with water (saturated condition). Although the discontinuities may appear dry during site observation on a sunny day, they may become saturated with water during heavy downpour which changes the dynamic forces acting upon any potential failure block. Table 7 shows the influence of water content in discontinuities towards FOS value.

TABLE 8. Summary of rock slope stability analysis

Slope	Summary
Slope KSA  An example of potentially unstable block that sits on top discontinuity set J5, this block may require rock bolts stabilization.	**Potential Failures:** Planar J5, Wedges J1*J5, and J2*J5 **SMR Rating:** RMR_{basic}: 62, Lowest SMR rating at 15 (Class V) due to the presence of wedge J2*J5. Failed wedge is shown as red area. **Major stability concerns:** Instabilities caused by potential failure along plane set J5 with marginal FOS that may fail with increased presence of water in discontinuities. Discontinuity set J2 may contribute as releasing planes, or as wedge along the intersection line. **Recommended mitigation measures:** Active Rock bolts to increase the FOS of unstable block primarily of wedge J2*J5 and planar J5. Loose blocks can be removed via scaling.
Slope KSB  The major wedge failure due to presence of fault plane, and discontinuities sets J3 and J4.	**Potential Failures:** Planar J1, Wedges J1*J3, J1*J4, J2*J3, J2*J4, F*J1, F*J3, and F*J4. **SMR Rating:** RMR_{basic}: 58, Lowest SMR rating at 7 (Class V) due to potential planar failure J1. Another potential failure with very low SMR rating is wedge F*J3 (Rating – 11, Class V). The failure associated with wedge F*J3 is shown as red area. **Major stability concerns:** Major wedge failure observed primarily due to presence of a fault plane (F). Multiple unstable blocks still sit on the plane, bound by discontinuity sets J3 and J4 with marginal FOS value that may fail with increased water filling. **Recommended mitigation measures:** Scaling on loose blocks, Active rock bolts on potentially unstable blocks especially on top of fault plane. Rock ditch with barrier should be installed to trap rock falls from smaller wedges.

Slope LHA

Slope LHA with multiple discontinuities sets, generally exhibit blocky nature, but no major failure observed.

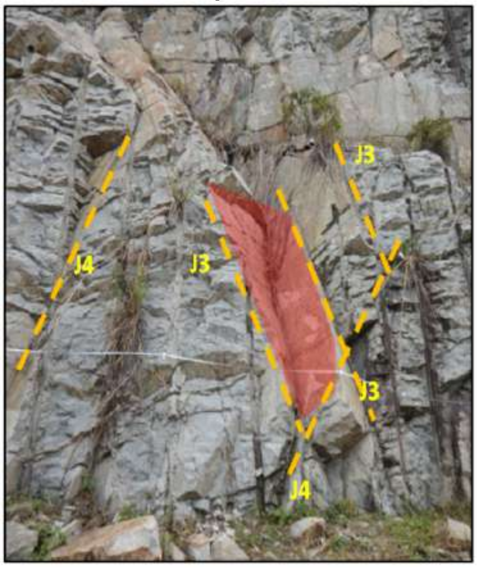
Potential Failures:
Planar J2, Wedges J1*J2, J2*J3, J2*J5, and J3*J5.

SMR Rating:
RMR_{basic}: 71, Lowest SMR rating at 17 (Class V) due to potential planar failure J2. Failed block from planar failure is shown as red area.

Major stability concerns:
No major large-scaled potential planar or wedge failures observed on site. The identified potential failures are small-sized blocks that may contribute to rock falls. (Multiple fallen blocks at the foot of slope).

Recommended mitigation measures:
Scaling on loose blocks, rock ditch with barrier at bottom of slope to capture rock falls.

Slope LHB



Wedge failure on slope LHB due to intersection of joint sets J3 and J4.

Potential Failures:
Wedges J2*J4, J3*J4, and J3*J5.

SMR Rating:
RMR_{basic}: 66. Lowest SMR rating at 6 (Class V) due to potential failure J3*J4.The failed geometry is shown as red area.

Major stability concerns:
Several medium-sized potential wedge failures especially due to intersection between J3 and J4 with marginal FOS. Several scars indicate past failures of the wedge.

Recommended mitigation measures:
Active rock bolts on potentially unstable wedge block especially wedge J3*J4 to increase the FOS. Rock ditch with barrier to be installed to contain rock falls from smaller wedges.

IMPACT OF WATER IN SLOPE STABILITY

FOS calculations based on dry conditions and site observation may result in conflicting figures although other parameters were obtained from each specific site. This is due to the influence of water in discontinuities that reduce the resisting force acting along the failure plane during rainy conditions. A sensitivity analysis was done on several potential failures to determine the percentage of water in discontinuities at failure as shown in Figure 7.

The importance of water presence in affecting the stability of potential sliding failure of rock slopes requires the parameter to be considered in any stability analysis. Although the FOS in dry condition may exceed 2.00 which is considered as safe, gradual increase in water fill eventually lowers the FOS value. Therefore, existing potential failure with marginal FOS in dry conditions must be treated with caution. Mitigation measures that control the water build up inside the discontinuity system may reduce the risk of failure during rainy seasons.

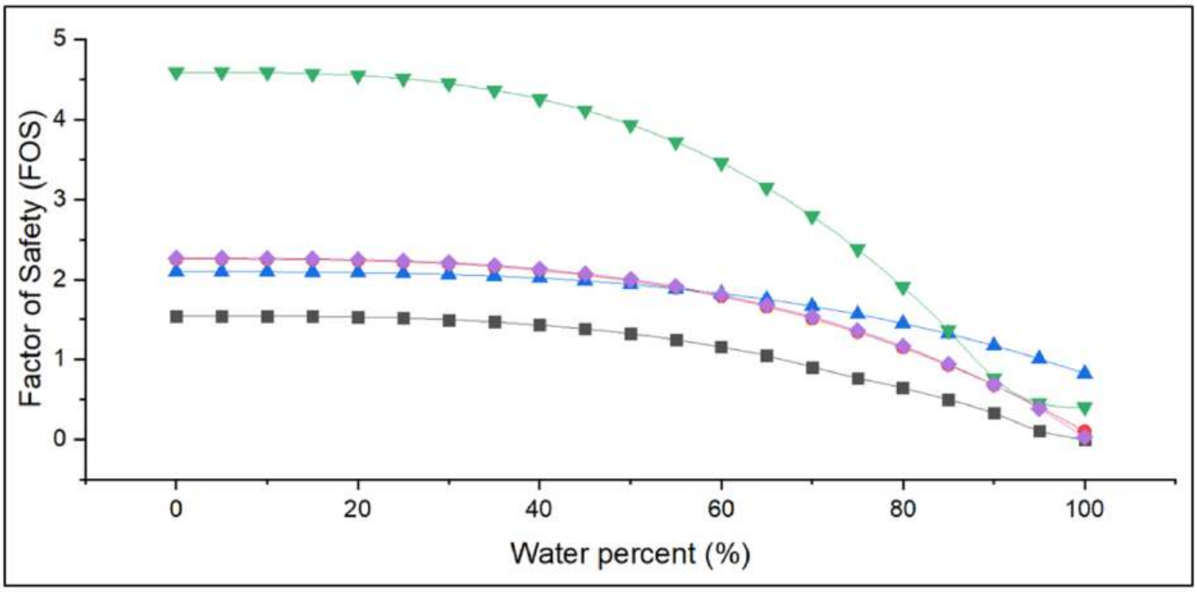


FIGURE 7. Sensitivity analysis to determine the percentage of water required to induce failure (FOS <1.00) as observed on site on several potential failures. The FOS values decrease as water percentage within the discontinuity increases, eventually falling below FOS=1. This highlights the need to consider water even in dry conditions, as Malaysia often experience torrential rains

CONCLUSION

This study incorporated several steps in rock slope stability analysis including kinematic analysis, Slope Mass Rating (SMR) and the LEM analysis based on Barton - Bandis criterion. Slopes KSA, KSB, LHA, and LHB were selected for the study. The summary of the rock slope stability analyses is shown in Table 8. Slope KSA exhibits a potentially unstable block due to intersection between discontinuities J2 and J5. Due to the size of the block, active rock bolting may be needed to secure the block in place. At slope KSB, a wedge newly failed during fieldworks, due to discontinuities sets J3, J4, and a fault plane. However, more potentially unstable blocks were identified, and shall be stabilized. At LHA and LHB, most potential failures and unstable blocks are relatively small, in which a rock ditch with a barrier can intercept them. However, there is a block identified at LHB that requires rock bolting in place.

The slopes had multiple potential failures that were quantified using FOS via limit equilibrium method. Low SMR rating may correspond with low FOS value although the result may differ in certain cases, but the correlation between the values is poor. This is due to different input for SMR and FOS, which translate into different output. Comprehensive analysis including FOS calculation helps in proper design of mitigation methods, including calculating proper capacity for rock bolts to increase the FOS of a potentially unstable block. The SMR values were used in the selection of the type of rock bolt (active or passive) to be installed. Water content in discontinuities play an important role in stability of a rock slope and should not be neglected in stability analysis especially in Malaysian wet tropical climate. Mitigation measures can be costly for some but addressing the potential failures (and other hazards) of a rock slope can avoid future tragedies that result in costly loss of lives and properties.

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