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Andesite Slope Stability Analysis Using Rock Mass Rating (RMR) and Slope Mass Rating (SMR) in Gunung Batu and Graha Puspa Areas, West Bandung Regency, West Java, Indonesia

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Preliminary communication

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Abstract

The susceptibility of West Java to landslides, coupled with its high population density, prompts research into landslide potential in the region. Notably, Gunung Batu and Graha Puspa in West Bandung Regency feature substantial andesite slopes situated along the Lembang fault and serve as tourist attractions. This study aims to assess the stability of these slopes using rock mass rating (RMR) and slope mass rating (SMR). The analysis integrates methods like rock mass classification (RMR), kinematics analysis, and empirical slope stability analysis (SMR), drawing on data obtained from uniaxial compressive strength (UCS) tests and scanline surveys. The andesite slopes exhibit RMR values ranging from 74 to 81, indicating good to very good rock mass quality. Design parameters and engineering properties are identified, including rock mass cohesion and internal friction angle, suggesting safe cut slope angles. Specific slopes are found susceptible to toppling or wedge failures. SMR values range from 72 to 96, categorizing the slopes as class I-II, indicating stability and a low probability of failure. Minor reinforcement options like scaling, toe ditch, fence, and spot bolting are proposed. Considering West Java's seismic and rainfall risks, the study recommends further modelling to incorporate variations in seismic acceleration and water content. The method would yield safety factors and cut-off values under different slope conditions, enhancing the understanding and management of landslide risks in the region.

Keywords:
andesite slopes; Gunung Batu; Graha Puspa; RMR; SMR

1. Introduction

Indonesia has a high susceptibility to landslides. There were 1,056 landslide events in 2021, which resulted in 340 deaths, 5,903 people displaced, and 1,349 houses damaged (**PVMBG, 2022**). As many as 60% of the landslide events were on Java Island. One area in Java Island that has a high susceptibility to landslides is West Java (**Sugianti et al., 2014**). Several factors, including geological structure, slope geometry, earthquakes, rainfall, and human activities can cause landslides. The West Java area has an intricate geological structure, high rainfall, infrastructure with many human activities, and the potential for earthquakes (**Raghuvanshi, 2019**). Considering these aspects, it is imperative to research the stability of current slopes in West Java to mitigate the potential risks associated with landslides.

The Lembang fault is an active fault that moves by 1.95 – 3.45 mm/year and has the potential to cause earthquakes measuring 6.5 – 7 Mw (**Daryono et al., 2019**). Earthquakes of considerable magnitude can cause slope instability within their radius of influence. Gunung Batu and Graha Puspa areas, located in West Bandung Regency, West Java, are densely populated areas and tourist spots that attract many visitors. In both areas, there are andesite cliffs/slopes located in the path of the Lembang fault. Andesite in both locations has enough discontinuities that can trigger slope failure. Landslides can inflict material losses and cause casualties. Slope stability analysis is essential for reducing these risks.

The objective of this study is to determine the empirical stability of the andesite slopes in Gunung Batu and Graha Puspa using RMR and SMR. Analysis of rock mass quality and slope stability using RMR and SMR is often done because it is convenient for decision-making (**Basahel and Mitri, 2017; Sari, 2019; Siddique et al., 2020; Sarkar et al., 2021; Kundu et al., 2022; Yeh et al., 2022; Zerradi et al., 2023**). Both methods are used to empirically assess slope stability based on geological and geotechnical conditions in the location concerned. RMR is one of the classifications to assess the quality of rock mass quantitatively using a parameter rating system (**Bieniawski, 1989**). This method provides rock mass

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Figure 1: Research location map (after **Google Maps, 2024**)

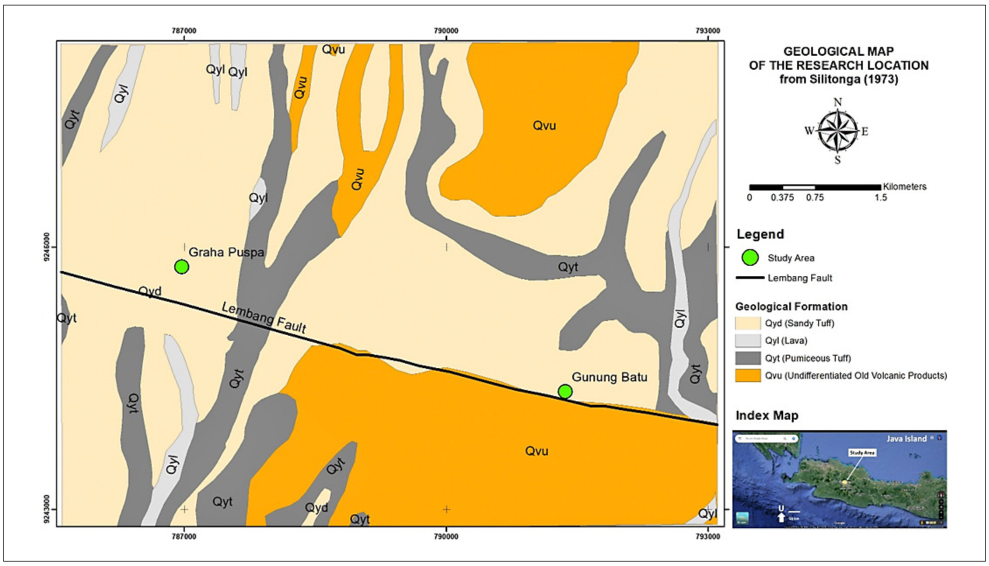

Figure 2: Geological map of the research location (after **Silitonga, 1973**)

classification based on uniaxial compressive strength (UCS), rock quality designation (RQD), discontinuity spacing, discontinuity conditions, and groundwater conditions. SMR is a classification to assess slope stability using basic RMR values, adjustment factors related to slope and discontinuity relationships, and correction factors related to excavation methods (**Romana, 1985**).

The research data were obtained from the results of the UCS test and scanline survey. Both data are used to obtain the RMR value. Discontinuity data obtained from scanline surveys were kinematically analysed with *Dips* software (**Rocscience, 2002; Sari, 2019; Yeh et al., 2022; Zerradi et al., 2023**). Kinematics analysis is performed to estimate the type of potential slope failure. The RMR values and the results of subsequent kinematics analysis are used to obtain the SMR values. RMR and SMR values can be used as a preliminary guide to identify rock slope stability. Based on the RMR and SMR values, several empirical parameters and recommendations can be obtained that are useful for engineering design on the slope concerned.

2. Research location

The area of Gunung Batu and Graha Puspa is physiographically located in the Bandung zone (**van Bemmelen, 1949**), which is a depression between several mountains. This zone is the peak of the western Java anticline that collapsed after the uplift and was filled with young volcanic deposits. Based on the distribution of the re-

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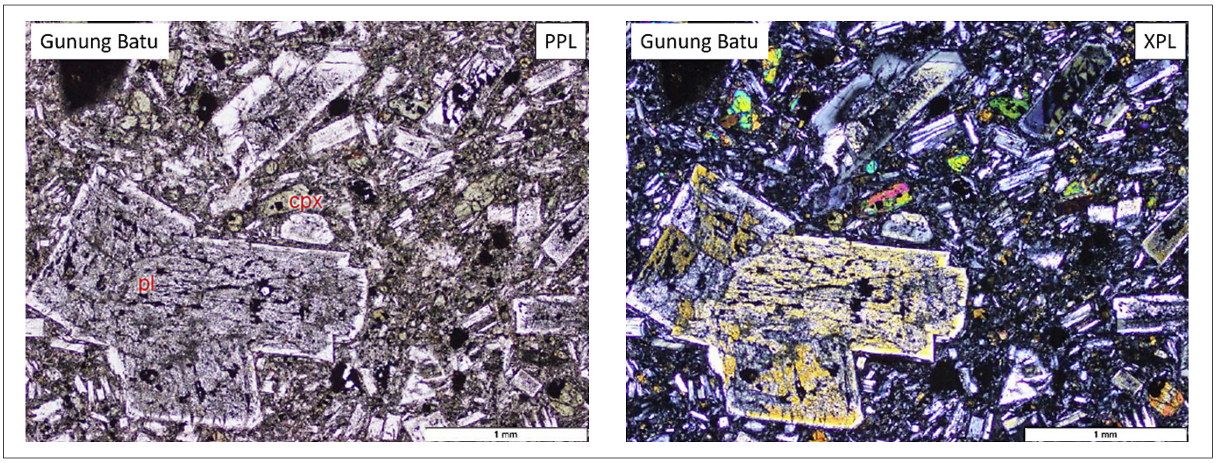

Figure 3: The section shows a seriate texture with gradually coarse to fine phenocrysts with a fine-sized ground mass rich in plagioclase microlites. The sieve texture and zoning can be seen in plagioclase, which has a tabular habit and a predominance of euhedral crystal forms. PPL: parallel-nicol; XPL: cross-nicol.

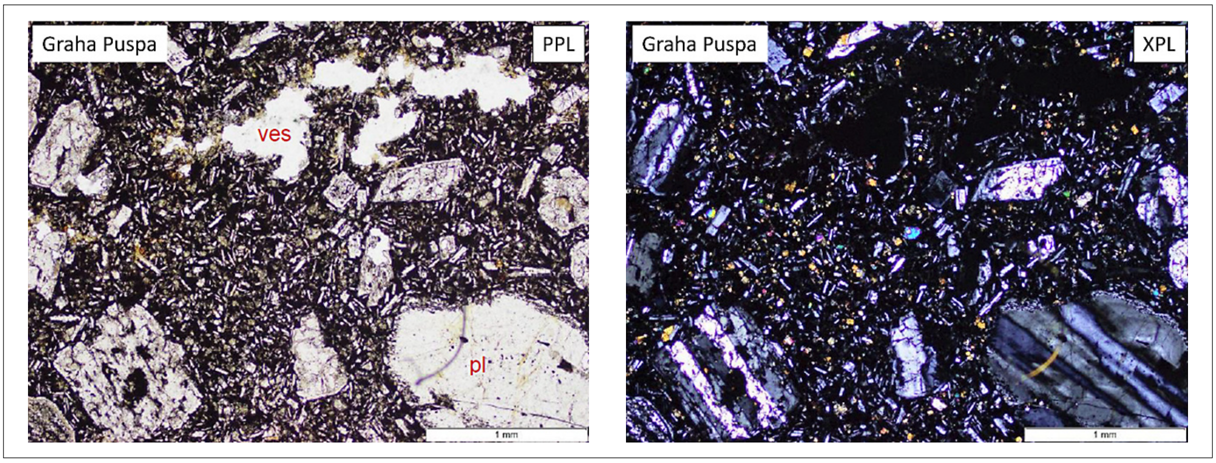

Figure 4: The section shows a vesicular texture, plagioclase phenocrysts with a sieve texture, as well as a groundmass consisting of plagioclase microlites, pyroxene, opaque minerals, and volcanic glass. PPL: parallel-nicol; XPL: cross-nicol.

gional structure of Java (**Pulunggono and Martodjojo, 1994**), the research location is in a region controlled by a west-east structure known as the Java pattern. The Java pattern structures were formed 32 million years ago. The Lembang fault that crosses the study site is one example. The research location map can be seen in **Figure 1**.

According to the geological map of Bandung quadrangle (**Silitonga, 1973**), the research location is composed of sandy tuff from Mount Tangkuban Perahu with the following description: brown, containing very coarse hornblende crystals, very porous; also red-weathered lahar, lapilli layers, and breccia (see **Figure 2**). There is also a dyke-type andesite intrusion in the Gunung Batu area (not mapped on the geological map), which is located between the eastern and western segments of the Lembang fault and shows a displacement of about 300 m (**Junursyah and Agustya, 2017**). Based on the results of dating with the K-Ar method, it is known that the andesitic rocks of Gunung Batu were formed 510,000 years ago (**Sunardi and Koesoemadinata, 1997**). The andesite dyke is the object studied in this paper.

Based on the results of the rock thin section descriptions in this study, it is known that the andesite in Graha Puspa has a slight difference from that in Gunung Batu. The rocks in Gunung Batu are pyroxene andesite (olivine-bearing), which has porphyritic (phenocryst:groundmass = 60:40), hypocrystalline, and seriate textures (see **Figure 3**). The rocks in Graha Puspa are andesite which has porphyritic (phenocryst:groundmass = 40:60), hypocrystalline, and sieve textures (see **Figure 4**). There are vesicular structures in the thin section and sheeting joints on the andesite slopes at Graha Puspa. Based on microscopic and macroscopic observations, andesites in Gunung Batu are interpreted as shallow intrusions, while andesites in Graha Puspa as lava.

3. Methods

There are five methods used in this study, namely the UCS test, scanline survey, rock mass classification (RMR), kinematics analysis, and empirical slope stability analysis (SMR).

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Figure 5: Outcrop conditions of andesite slopes in each section (GB: Gunung Batu, GP: Graha Puspa)

Table 1: RMR parameters and their ratings (**Bieniawski, 1989**)

No	Parameters		Range of values						
1	Strength of intact rock	Point load index (PLI)	>10 MPa	4-10 MPa	2-4 MPa	1-2 MPa	UCS is preferred		
		Uniaxial compressive strength (UCS)	>250 MPa	100-250 MPa	50-100 MPa	25-50 MPa	5-25 MPa	1-5 MPa	<1 MPa
	Rating		15	12	7	4	2	1	0
2	Rock quality designation (RQD)		90-100%	75-90%	50-75%	25-50%	<25%		
	Rating		20	17	13	8	3		
3	Spacing of discontinuities		>2 m	0.6-2 m	0.2-0.6 m	0.06-0.2 m	<0.06 m		
	Rating		20	15	10	8	5		
4	Condition of discontinuities		Very rough surfaces, not continuous, no separation, unweathered wall rock	Slightly rough surfaces, separation <1 mm, slightly weathered walls	Slightly rough surfaces, separation < 1 mm, highly weathered walls	Slickensided surfaces or gouge 5 mm thick or separation 1-5 mm, continuous	Soft gouge >5 mm thick or separation >5 mm, continuous		
	Rating		30	25	20	10	0		
5	Groundwater condition	Inflow per 10 m tunnel length (L/m)	None	<10	10-25	25-125	>125		
		Ratio of joint water pressure to major principal stress	0	<0.1	0.1-0.2	0.2-0.5	> 0.5		
		General description	Completely dry	Damp	Wet	Dripping	Flowing		
	Rating		15	10	7	4	0		

3.1. Uniaxial Compressive Strength (UCS) Test

The procedure used in this test refers to the standard of the International Society for Rock Mechanics (ISRM) (**Ulusay and Hudson, 2007**). There were three rock block samples taken from the study site (one block from Gunung Batu and two blocks from Graha Puspa). The rock block samples are then prepared into cylindrical core rocks with a height-diameter ratio (L/D) of 2-2.5. The test is carried out with a compressive strength machine connected to a load-logging computer to which the machine is applied. The UCS value will be used as one of the RMR parameters.

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Table 2: Design parameters and engineering properties based on RMR values (after **Bieniawski, 1993; Waltham, 2002**)

No.	Parameters/properties of rock mass	RMR				
		81-100	**61-80**	**41-60**	**21-40**	**≤20**
1	Classification	Very good	Good	Fair	Poor	Very poor
2	Cohesion (MPa)	>0.4	0.3-0.4	0.2-0.3	0.1-0.2	<0.1
3	Internal friction angle (°)	>45	35-45	25-35	15-25	<15
4	Safe cut slope (°)	>70	65	55	45	<40

Table 3: SMR parameters and their ratings (**Romana, 1985**)

Parameters	Case of slope failure		Very favourable	Favourable	Fair	Unfavourable	Very unfavourable
F_1	P	$\lvert\alpha_j-\alpha_s\rvert$	>30°	30-20°	20-10°	10-5°	<5°
	W	$\lvert\alpha_i-\alpha_s\rvert$					
	T	$\lvert\alpha_j-\alpha_s-180°\rvert$					
	Value		0.15	0.40	0.70	0.85	1.00
F_2	P	β_j	<20°	20-30°	30-35°	35-45°	>45°
	W	β_i					
	Value (P/W)		0.15	0.40	0.70	0.85	1.00
	Value (T)		1.0	1.0	1.0	1.0	1.0
F_3	P	$\beta_j-\beta_s$	>10°	10-0°	0°	0-(-10°)	<-10°
	W	$\beta_i-\beta_s$					
	T	$\beta_j-\beta_s$	<110°	110-120°	>120°	NA	NA
	Value		0	-6	-25	-50	-60
F_4	Method of excavation		Natural slope	Pre-splitting	Smooth blasting	Normal blasting or mechanical excavation	Poor blasting
	Value		+15	+10	+8	0	-8

P: planar failure; W: wedge failure; T: toppling failure; α_s: slope strike; α_j: joint strike; α_i: trend of intersection line; β_s: slope dip; β_j: joint dip; β_i: plunge of intersection line

3.2. Scanline Survey

A scanline survey was conducted to record the physical properties of rock masses and discontinuity properties contained in rock outcrops (**Hudson, 1989; Ulusay and Hudson, 2007**). The survey was carried out by stretching a wire tape with a certain distance on an outcrop and then collecting data on the physical properties of rock masses and discontinuity properties passed by the tape. Physical properties of rock mass recorded include colour, grain size, type, structure, block size, and degree of weathering. Discontinuity properties recorded include type, dip, dip direction, persistence, aperture, nature of filling, strength of filling, surface shape, groundwater flow, and spacing. Both types of properties will then be used as parameters in determining the RMR value.

The scanline survey was carried out on natural slopes composed of slightly weathered andesite at elevations of 1200-1300 masl. The slope sections in Gunung Batu are coded GB-01, GB-02, and GB-03, while the slope sections in Graha Puspa are coded GP-01, GP-02, and GP-03. Andesite slopes in Gunung Batu generally face north, while in Graha Puspa, some andesite slopes face north, and some face east. The condition of andesite outcrops on each slope can be seen in **Figure 5**.

3.3. Rock Mass Rating (RMR)

RMR uses a parameter condition rating system (rocks in good condition have high rates while rocks in poor condition have low rates) (**Bieniawski, 1989**). Five basic parameters are components of RMR, namely UCS, RQD, discontinuity spacing, discontinuity conditions, and groundwater conditions (see **Table 1**). The summation of the average rates of the five parameters is called the basic RMR value. RMR values range between 0 and 100, 0 for very poor rock conditions and 100 for very good rock conditions. From 0 to 100, RMR values are divided into five rock quality classes, each of which has different design parameters and engineering properties that are useful as a reference in carrying out engineering on the rock mass (**Bieniawski, 1993; Waltham, 2002**) (see **Table 2**).

3.4. Kinematics Analysis

Discontinuity data obtained from the scanline survey were then analysed for kinematics with *Dips* software

Table 4: Slope stability classes based on SMR values (**Romana, 1985**)

Slope Description	SMR				
	81-100	**61-80**	**41-60**	**21-40**	**≤20**
Slope class	I	II	III	IV	V
Rock mass quality	Very good	Good	Normal	Bad	Very Bad
Stability	Completely stable	Stable	Partially stable	Unstable	Completely unstable
Failure type	No failure	Some block failures	Planar along some joints and many wedges	Planar or wedges	Big planar or soil-like or circular
Probability of failure	0	0.2	0.4	0.6	0.9

Table 5: Recommendations for slope reinforcement based on SMR values (after **Romana et al., 2003**)

SMR	Slope sub-class	Recommended reinforcement
91-100	Ia	None
81-90	Ib	None, scaling is required
71-80	IIa	(None, toe ditch, or fence), spot bolting
61-70	IIb	(Toe ditch or fence nets), spot or systemic bolting
51-60	IIIa	(Toe ditch and/or nets), spot or systematic bolting, spot shotcrete
41-50	IIIb	(Toe ditch and/or nets), systematic bolting/anchors, systematic shotcrete, toe wall and/or dental concrete
31-40	IVa	Anchors, systematic shotcrete, toe wall and/or concrete (or re-excavation), drainage
21-30	IVb	Systematic reinforced shotcrete, toe wall and/or concrete, re-excavation, deep drainage
11-20	Va	Gravity or anchored wall, re-excavation

Less popular reinforcements are given in brackets.

(**Rocscience, 2002**). Kinematics analysis seeks to identify the potential failure mode that could occur on the slope under investigation (**Hoek and Bray, 1981**; **Wyllie and Mah, 2004, Sari, 2021**). *Dips* software can display the direction of slope and discontinuities on a stereonet so that potential failures that can occur in the configuration of these discontinuities can be analysed. The RMR value that has been obtained previously, along with the results of kinematics analysis, is then used as SMR parameters.

3.5. Slope Mass Rating (SMR)

SMR is derived from the basic RMR coupled with adjustment factors related to discontinuity-slope relationships and correction factors related to excavation methods (**Romana, 1985**) (see **Table 3**). The SMR ranges from a minimum of 0 to a maximum of 100. 0 for completely unstable slopes (0.9 probability of failure) and 100 for completely stable slope conditions (0 probability of failure). From 0 to 100, SMR values are divided into five slope quality classes, each of which has a description of rock mass, stability, failure type, failure probability, and reinforcement recommendations that can be used on the slope concerned (**Romana, 1985; Romana et al., 2003**) (see **Tables 4** and **5**).

4. Results and discussion

There are five UCS test results (one in Gunung Batu and four in Graha Puspa) (see **Table 6**). The UCS value of the andesite at both locations ranges from 130-170 MPa. Based on the average UCS of laboratory test results, andesite in Gunung Batu and Graha Puspa is included in the category of very strong rocks (100-250 MPa) (**Bieniawski, 1979; ISO 14689:2017**).

According to the ISRM (**Ulusay and Hudson, 2007**), a scanline survey is considered representative if the scanline length is 10-50 times the average discontinuity spacing. This statement can be interpreted to mean that the number of representative discontinuities in a scanline survey is 10-50. In this case, the scanline survey conducted by the researcher has met the requirements. The plunge of the scanline is arranged in such a way that

Table 6: The results of the UCS tests

No.	Sample Code	Location	Lithology	σ_c (MPa)
1	Blok 01/UCS-01	Gunung Batu	Andesite	143.27
2	Blok01-GP/UCS-01	Graha Puspa	Andesite	134.96
3	Blok02-GP/UCS-02	Graha Puspa	Andesite	171.60
4	Blok03-GP/UCS-03	Graha Puspa	Andesite	165.63
5	Blok04-GP/UCS-04	Graha Puspa	Andesite	158.68

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Table 7: Summary of the scanline survey at the study location (GB: Gunung Batu, GP: Graha Puspa)

Section	X	Y	Slope Dip	Slope Dip Direction	Scanline Plunge	Scanline Trend	Scanline Length (m)	No. of Fractures	Discontinuity Spacing (m)	
									Mean	Standard Deviation
GB-01	791304.046	9244219.992	67°	N2°E	5°	N272°E	9.5	25	0.38	0.47
GB-02	791292.856	9244214.641	72°	N332°E	7°	N242°E	17.2	43	0.40	0.48
GB-03	791278.071	9244209.046	81°	N32°E	18°	N302°E	16.8	62	0.27	0.30
GP-01	787238.809	9245211.761	80°	N30°E	17°	N120°E	11.65	33	0.35	0.40
GP-02	787238.962	9245201.182	75°	N70°E	12°	N160°E	8.7	32	0.27	0.43
GP-03	787240.814	9245189.745	70°	N110°E	5°	N200°E	25	67	0.37	0.28

makes it easier for researchers to make as many discontinuity measurements as possible. The position and length of the scanline, as well as the number and spacing of discontinuities on each slope, can be seen in **Table 7**.

The discontinuity data were then plotted in stereonets in the *Dips* software to see their relative direction to slopes and in rosette diagrams to see the trend of structural orientation at the study site (see **Figures 6** and **7**). Based on stereonet plots, most slope sections (GB-01, GB-02, GB-03, GP-02, and GP-03) have discontinuities oriented in a direction opposite to that of the slope, which has the potential to cause toppling failure (**Hoek and Bray, 1981**). There is one slope section (GP-01) that has two intersecting discontinuities in front of the slope face that has the potential to cause wedge failure.

The second parameter required in RMR is RQD. In this study, RQD was calculated by the formula formulated by **Priest and Hudson (1976)** (see **Equation 1**). The required variable in this formula is the frequency of discontinuity (λ). The frequency of discontinuity is obtained by dividing the sum of discontinuities by the length of the scanline. Based on the results of RQD calculations, rock masses in Gunung Batu and Graha Puspa are included in the category of very good rocks (RQD 90-100%) (**Bieniawski, 1979**). The calculation of RQD at both study sites can be seen in **Table 8**.

$$RQD = 100\left(0.1\lambda + 1\right)e^{-0.1\lambda} \quad (1)$$

where:

RQD – rock quality designation (%),

λ – discontinuity frequency (the average number of discontinuities per meter).

The mean discontinuity spacings on slopes GB-01, GB-02, and GB-03 were 0.38; 0.40; and 0.27 m, respectively; while on slopes GP-01, GP-02, GP-03 were 0.35; 0.27; and 0.37 m. The discontinuity conditions used in RMR are persistence, aperture, roughness, nature of filling, and degree of weathering. All slopes are known to be dry except GP-02, which is humid due to water seepage through discontinuities. The rating results of all parameters are then summed to produce the basic RMR value. A compilation of all RMR parameters and their ratings can be seen in **Table 9**.

Based on the RMR calculation results, three slopes have good rock mass quality (GB-01, GP-02, GP-03), and three slopes with very good quality (GB-02, GB-03, and GP-01). RMR values can be used to estimate design parameters and engineering properties empirically (**Bieniawski, 1993; Waltham, 2002**) (see **Table 2**). Slopes with good categories can use the following design parameters and engineering properties: rock mass cohesion of 0.3-0.4 MPa, internal friction angle of 35-45°, and safe cut slope of 65°. Slopes with very good categories can use the following design parameters and engineering properties: rock mass cohesion >0.4 MPa, internal friction angle of >45°, and safe cut slope of >70°.

Next, kinematics analysis is carried out to determine the type of slope failure that has the potential to occur based on slope and discontinuity directions. The type of potential failure is confirmed by the stereonet model proposed by **Hoek and Bray (1981)** and some of the conditions summarized in **Wyllie and Mah (2004)**.

Apart from discontinuity data, several other data input into the kinematic analysis are slope dip and dip direction, friction angle of discontinuity, as well as lateral limit. The slope dip and direction were obtained from the results of the scanline survey. The friction angle of discontinuity is obtained from the estimate in J_a Table of Q System (**Barton, 2002**), taking the value 25° because the discontinuity at both locations tends to be empty, has not been altered, and only contains surface stainings. The lateral limit is obtained from the consensus of geotechnical experts (**Rocscience, 2002**), taken as a value of 20°.

Slopes GB-01, GB-02, GB-03, GP-02, and GP-03 indicate a potential toppling failure, while slopes GP-01 indicate wedge failure potential. Based on the conditions of **Wyllie and Mah (2004)**, only slope GB-01 and GP-01 meet the criteria for failure, temporarily concluding slope GB-01 and GP-01 have the potential to failure, and the other four slopes do not. Apart from these conditions, slope safety can also be seen from the safe cut slope parameters obtained from RMR (**Waltham, 2002**). Three slopes were declared unsafe because they had dips that exceeded the recommended safe cut slope, namely GB-01, GP-02, and GP-03. The results of the kinematics analysis of the six slopes, along with drone photos of the outcrops, can be seen in **Figures 8-13**.

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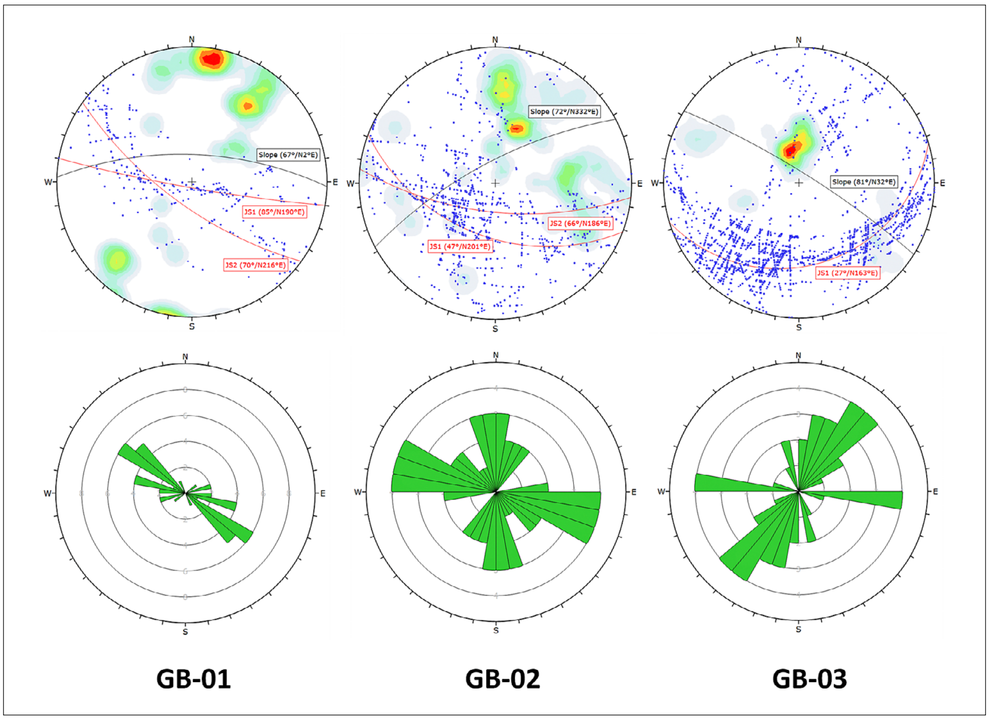

Figure 6: Stereonet and rosette diagrams depicting the direction and orientation of discontinuities in each slope at Gunung Batu

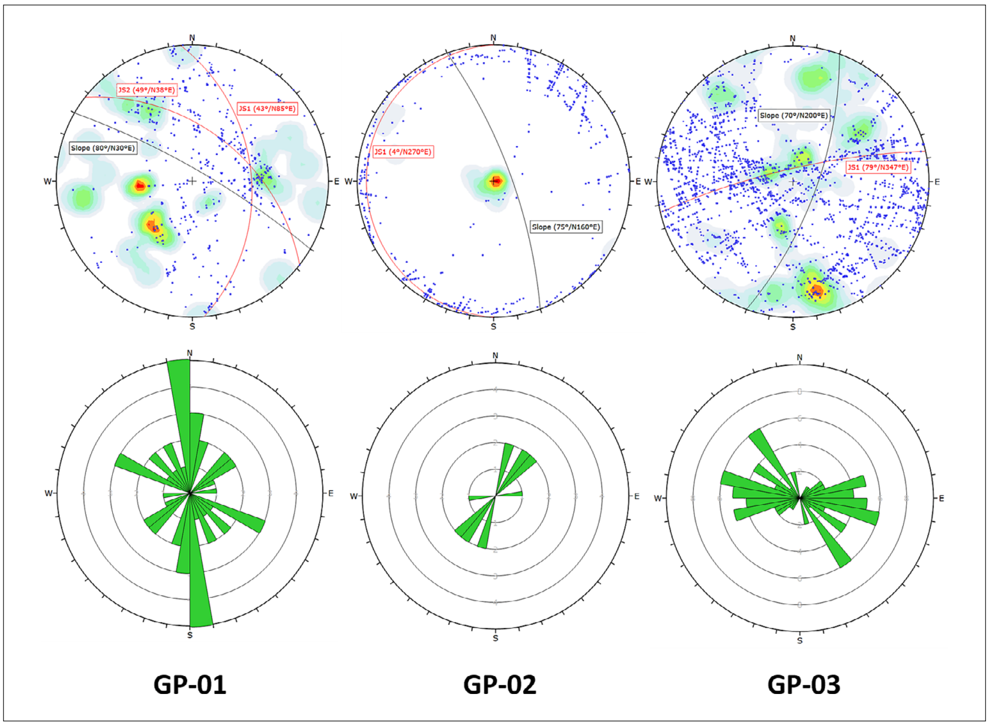

Figure 7: Stereonet and rosette diagrams depicting the direction and orientation of discontinuities in each slope at Graha Puspa

The following six slopes were analysed for empirical stability using SMR. SMR values are obtained from the basic RMR values (RMR_b), F_1, F_2, F_3, and F_4 (see **Equation 2**) (**Romana, 1985**). RMR_b is the RMR value obtained from five parameters as done in the previous section. F_1, F_2, and F_3 are adjustment factors related to slope and discontinuity directions. F_4 is the correction factor related to the excavation method. Recapping the parameters and SMR values of each slope can be seen in **Table 10**.

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Table 8: RQD calculation results

Section	n	l (m)	λ	RQD
GB-01	25	9.5	2.63	97.07
GB-02	43	17.2	2.50	97.33
GB-03	62	16.8	3.69	94.63
GP-01	33	11.65	2.83	96.65
GP-02	32	8.7	3.68	94.66
GP-03	67	25	2.68	96.97

n: number of discontinuities, l: scanline length, λ: discontinuity frequency

$$SMR = RMR_b + \left(F_1.F_2.F_3\right) + F_4 \tag{2}$$

where:

SMR – slope mass rating,

RMR_b – basic rock mass rating,

F_1, F_2, F_3 – adjustment factor related to the directions of slope and discontinuity,

F_4 – correction factor related to the excavation method.

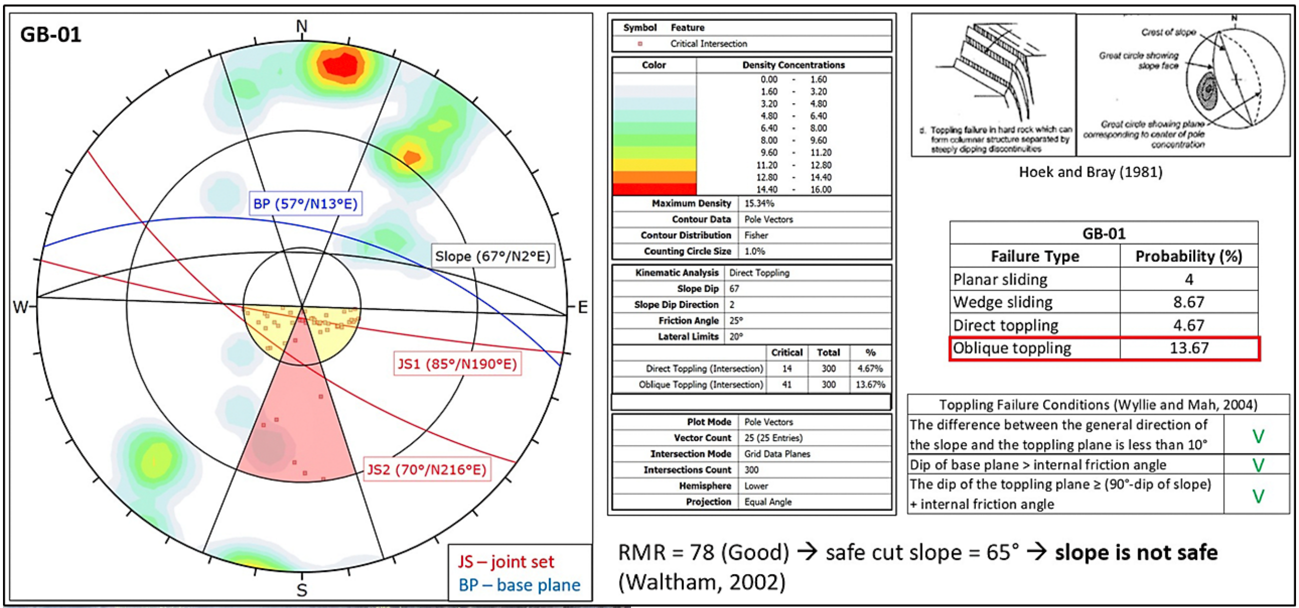
Based on SMR calculations, all slopes at the study site are included in class I (SMR 81-100) except slope

Table 9: RMR calculation results

Section	Rock Strength		RQD		Discontinuity Spacing		Discontinuity Condition		Groundwater Condition		RMR	
	Value (MPa)	Rating	Value (%)	Rating	Value (m)	Rating	Description	Rating	Description	Rating	Value	Class
GB-01	143	12	97.07	20	0.38	10	Persistence <1 m, aperture 1-5 mm, rough, hard filling <5 mm, slightly weathered	21	Dry	15	78	Good
GB-02	143	12	97.33	20	0.40	10	Persistence 1-3 m, aperture 0.1-1 mm, rough, none, slightly weathered	24	Dry	15	81	Very Good
GB-03	143	12	94.63	20	0.27	10	Persistence 1-3 m, aperture 0.1-1 mm, rough, none, slightly weathered	24	Dry	15	81	Very Good
GP-01	157	12	96.65	20	0.35	10	Persistence 1-3 m, aperture 0.1-1 mm, rough, none, slightly weathered	24	Dry	15	81	Very Good
GP-02	157	12	94.66	20	0.27	10	Persistence 1-3 m, aperture 0.1-1 mm, rough, hard filling <5 mm, slightly weathered	22	Damp	10	74	Good
GP-03	157	12	96.97	20	0.37	10	Persistence 1-3 m, aperture 0.1-1 mm, rough, hard filling <5 mm, slightly weathered	22	Dry	15	79	Good

Table 10: SMR calculation results

Section	Failure Type	RMR_b	F_1	F_2	F_3	F_4	SMR	Class	Stability
GB-01	Toppling	78	0.85	1	-25	15	72	II	Stable
GB-02	Toppling	81	0.15	1	-6	15	95	I	Completely Stable
GB-03	Toppling	81	0.15	1	0	15	96	I	Completely Stable
GP-01	Wedge	81	0.15	0.85	-60	15	88	I	Completely Stable
GP-02	Toppling	72	0.40	1	0	15	87	I	Completely Stable
GP-03	Toppling	79	0.15	1	-25	15	90	I	Completely Stable



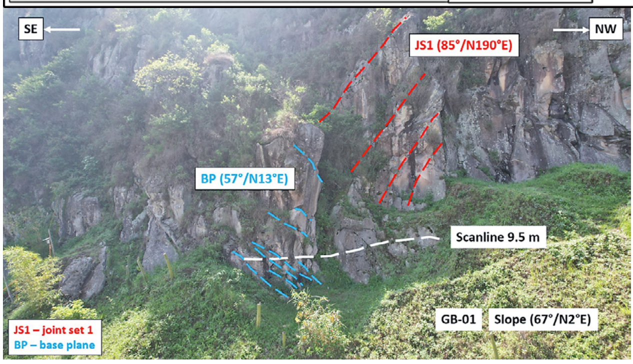
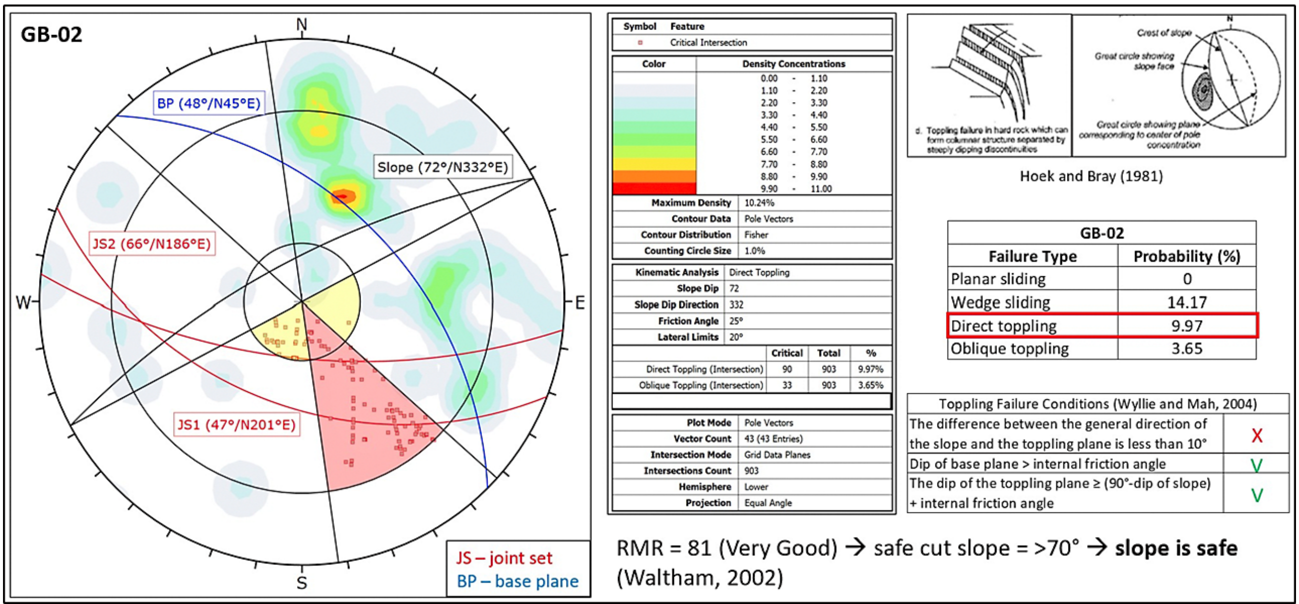


Figure 8: Kinematic analysis results and drone photo of section GB-01



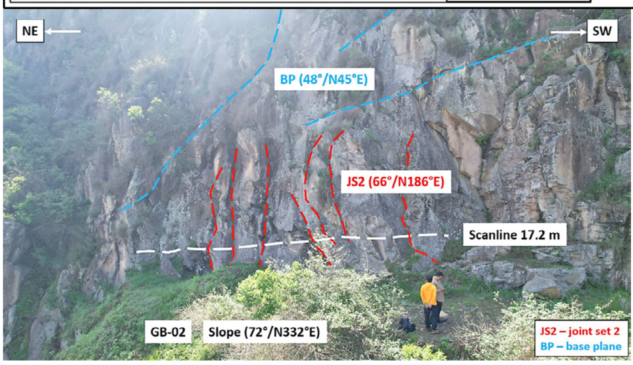
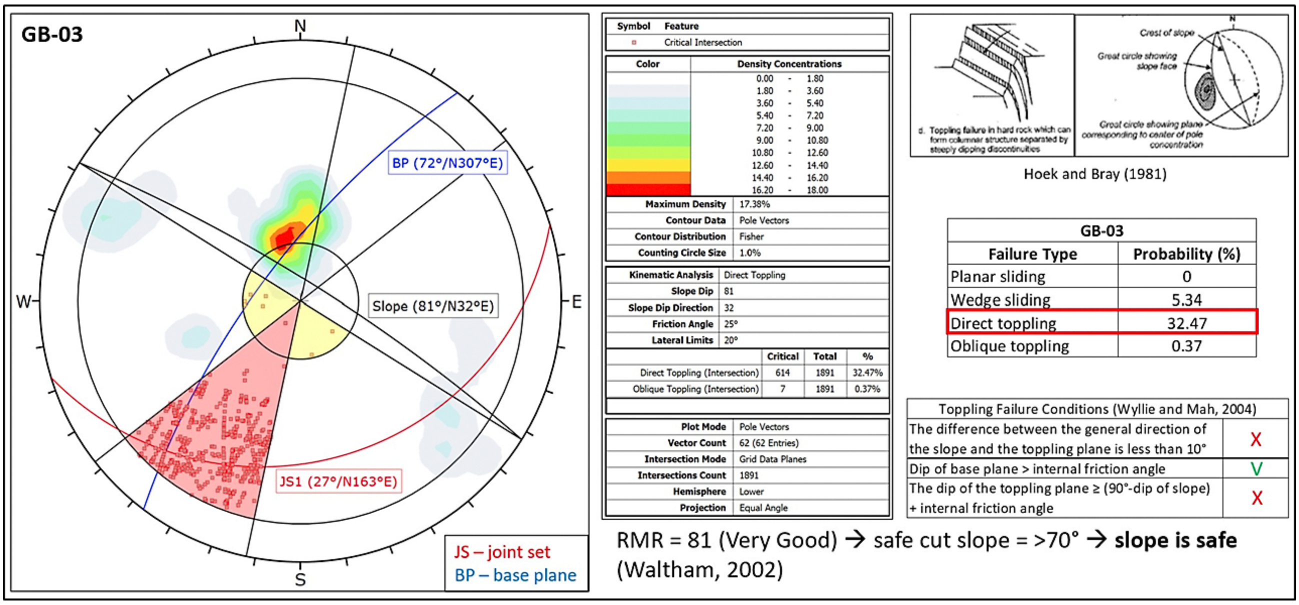


Figure 9: Kinematic analysis results and drone photo of section GB-02



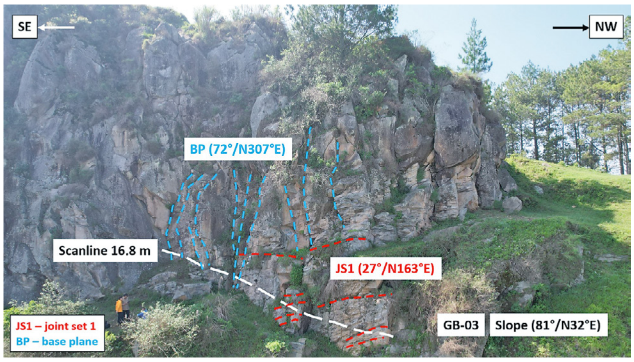
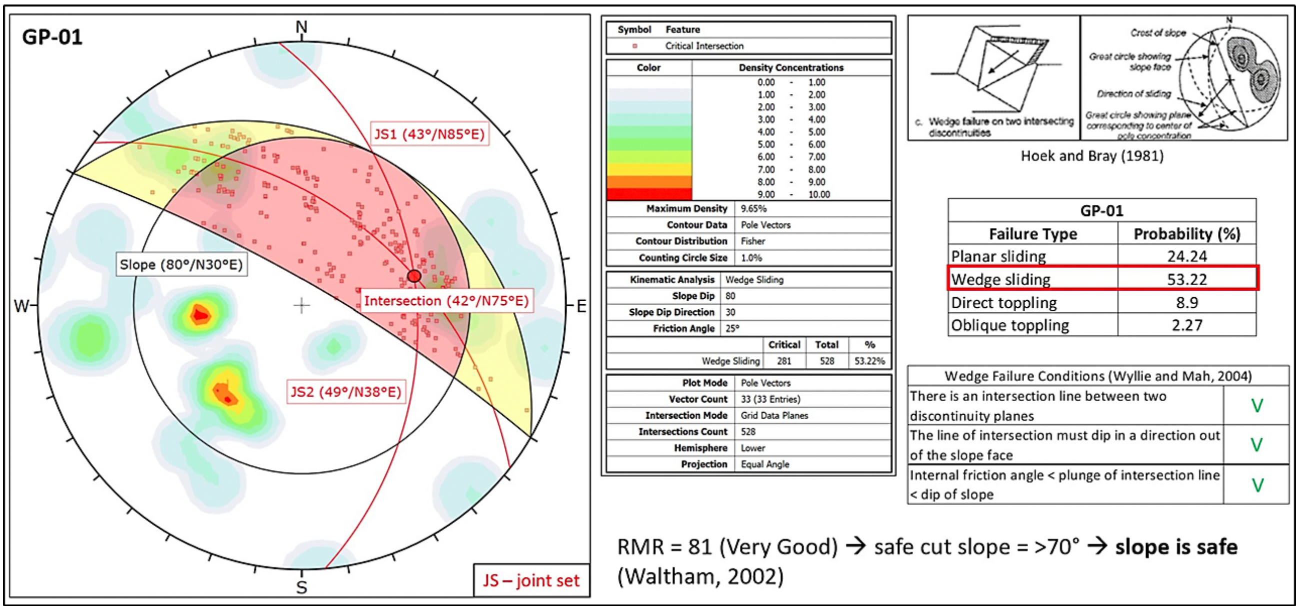


Figure 10: Kinematic analysis results and drone photo of section GB-03



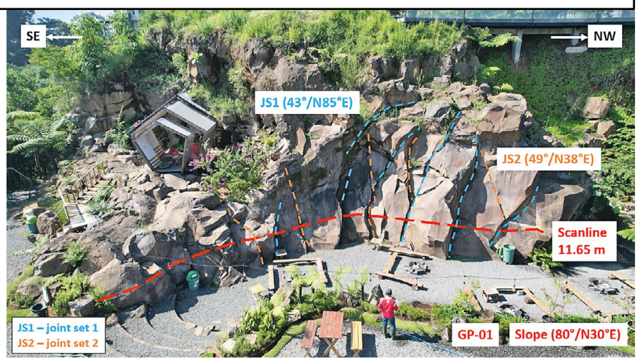


Figure 11: Kinematic analysis results and drone photo of section GP-01

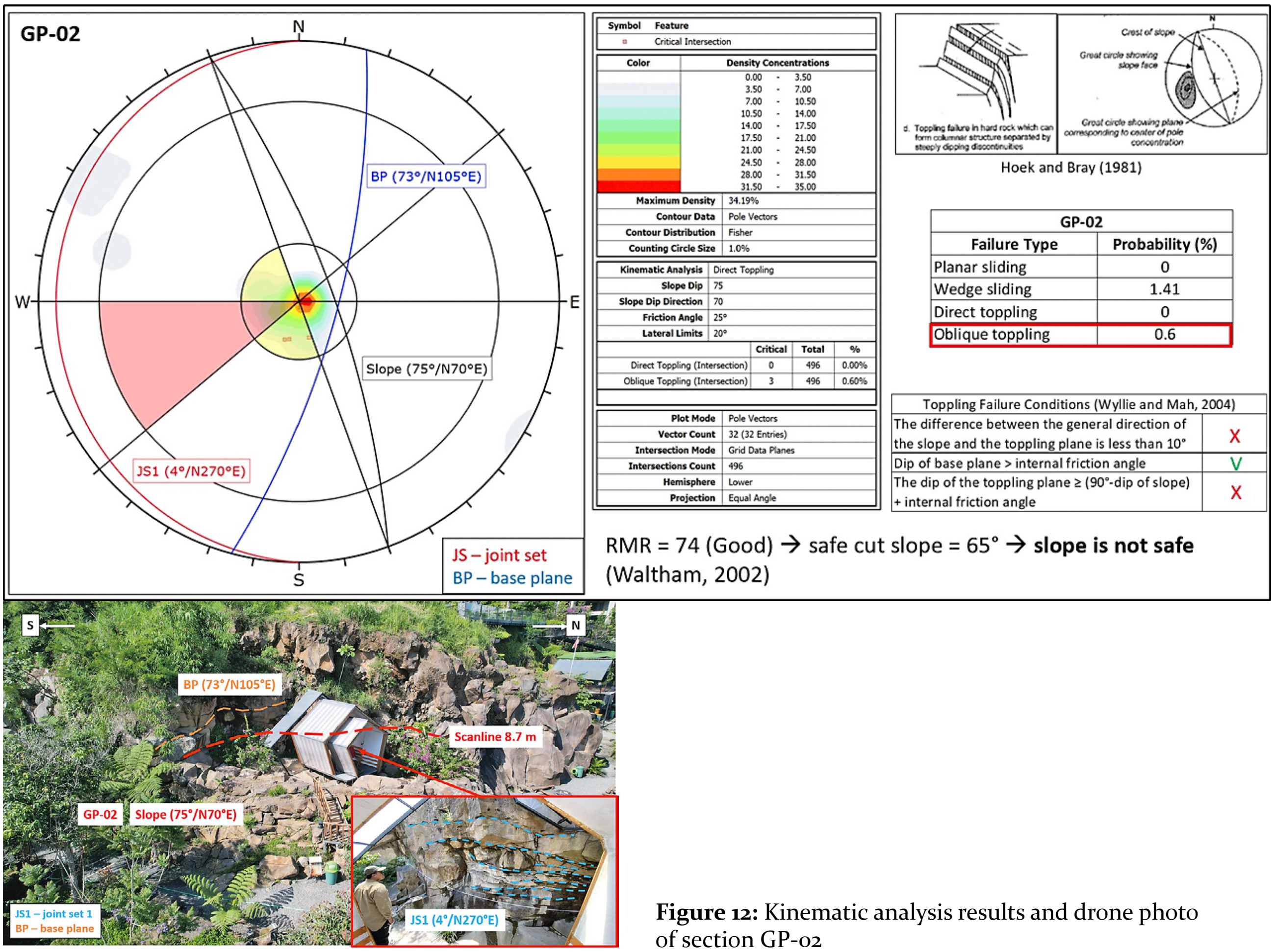


Figure 12: Kinematic analysis results and drone photo of section GP-02

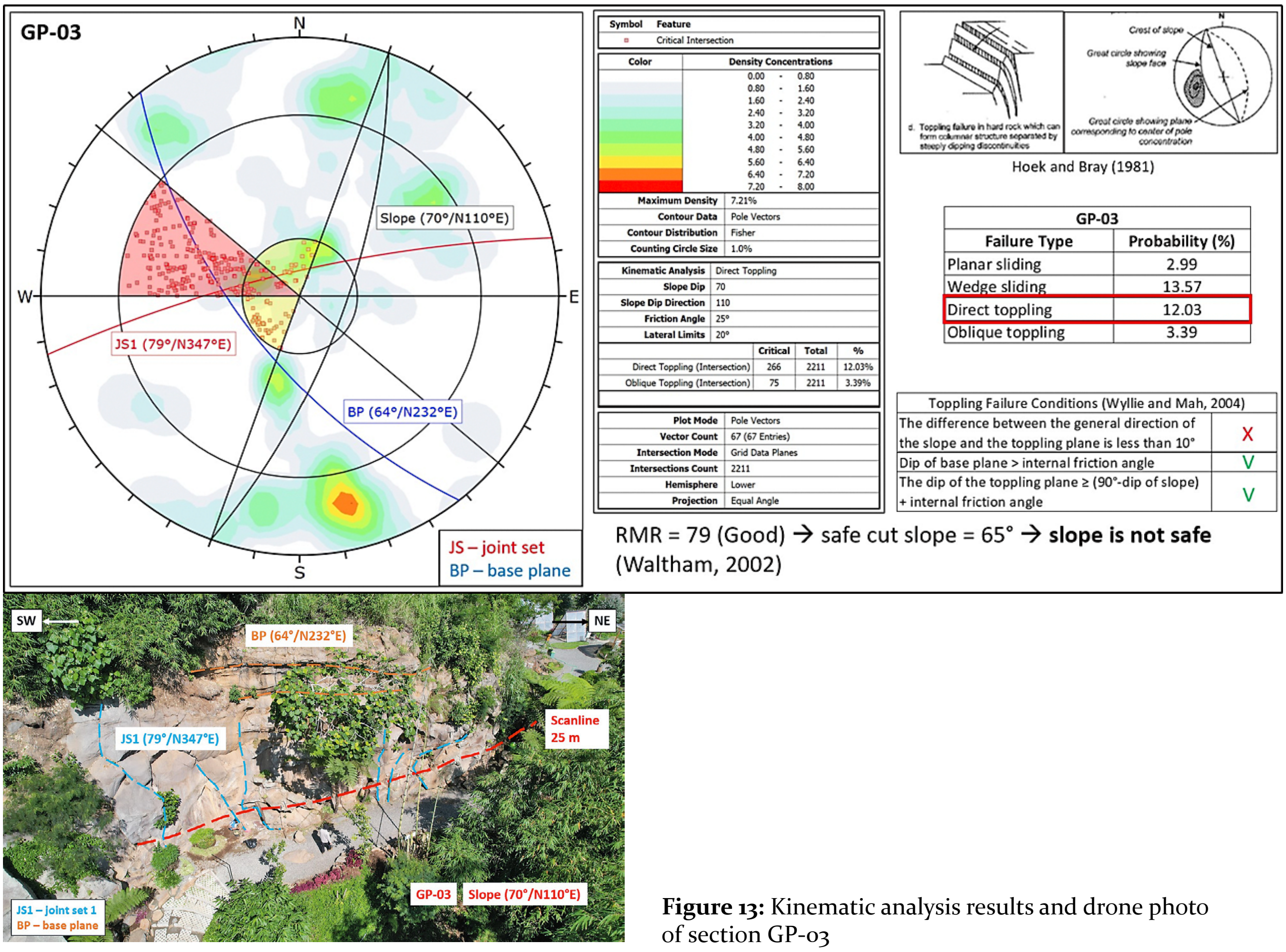


Figure 13: Kinematic analysis results and drone photo of section GP-03

GB-01, which is included in class II (SMR 61-80) (see **Table 4**) (**Romana, 1985**). Class I slopes are very stable, have no potential for failure, and the probability of failure is zero. Class II slopes are stable, have block failure potential, and have a failure probability of 0.2. SMR values can also be used to estimate slope reinforcement recommendations required for each slope subclass (see **Table 5**) (**Romana et al., 2003**). On slope GB-01, which is included in subclass IIa (SMR 71-80), reinforcement can be applied in the form of a toe ditch, fence, or spot bolting. On slopes of GP-01, GP-02, and GP-03, which belong to subclass Ib (SMR 81-90), can be applied reinforcement in the form of scaling. Slopes GB-02 and GB-03, belonging to subclass Ia (SMR 91-100), do not require any reinforcement.

On slopes GB-02, GP-02, and GP-03, there are inconsistencies between the probability of failure and the kinematic model taken. These three slopes have a greater probability of wedge failure than toppling failure, but the kinematic model used is toppling failure. This thing occurred due to the stereoplot of the three slopes does not reflect the potential for wedge failure (**Hoek and Bray, 1981**). When tested with wedge failure software, no wedge failure occurred on the three slopes. It should be noted that *Dips* software determines the dominant failure probability only based on the density concentration of the discontinuity, so the potential failure type must also be confirmed by the configuration between the slope and the discontinuity as well as field observations. Cases like this can be used as a lesson that kinematic analysis must be re-examined with basic knowledge of slope failure theory, not just believing in the failure probability results in the software.

Three slopes are declared unsafe based on the safe cut slope recommendation (**Waltham, 2002**) but are declared safe by SMR, namely GB-01, GP-02, and GP-03. This contradiction is understandable because the safe cut slope recommendation is obtained from the RMR value, which is a reflection of the quality of the rock mass (only referring to five parameters, as previously explained). SMR already accommodates RMR as well as adjustment factors related to the orientation of slope and discontinuities in the form of parameters F_1, F_2, and F_3. The orientation of slope and discontinuity greatly determine the favorability of slope stability. Thus, the SMR value shows more convincing slope stability conditions because it has integrated more contributing factors.

5. Conclusions

Andesite slopes in Gunung Batu and Graha Puspa have RMR values of 74-81 which are included in the category of good-very good rock mass. The design parameters and engineering properties that can be applied to andesite slopes at both sites are as follows: rock mass cohesion of 0.3-0.4 to >0.4 MPa, internal friction angle of 35-45 to >45°, and safe cut slope of 65 to >70°. Slopes GB-01, GB-02, GB-03, GP-02, and GP-03 have the potential for toppling failure, while slope GP-01 has the potential for wedge failure. Andesite slopes in Gunung Batu and Graha Puspa have SMR values of 72-96 which are included in class I-II slope categories. Slopes with this category have characteristics: stable-very stable, have the possibility of block failure to no failure, and the probability of failure is 0.2-0. Almost no major reinforcement is required. Several minor reinforcement options can be applied, such as scaling, toe ditch, fence, and spot bolting. The results of this study can be developed by modelling rock slopes so that safety factors are obtained that reflect slope stability with more certainty. Given that West Java Province has the potential for earthquakes and high rainfall, this rock slope modelling can also be expanded with variations in seismic acceleration and moisture content so the cut-off values of these two factors can be obtained to make sure that the slopes remain safe.

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SAŽETAK

Analiza stabilnosti kosine u andezitu pomoću RMR i SMR klasifikacija u područjima Gunung Batu i Graha Puspa, zapadna pokrajina Bandung, Zapadna Java, Indonezija

Podložnost Zapadne Jave klizištima, zajedno s velikom gustoćom naseljenosti, potiče istraživanje potencijala klizišta u regiji. Regije Gunung Batu i Graha Puspa u West Bandung pokrajini imaju znatne kosine u andezitima, smještene duž rasjeda Lembang, koje služe kao turističke atrakcije. Cilj je ove studije procijeniti stabilnost tih kosina korištenjem RMR i SMR klasifikacije. Analiza integrira metode kao što su klasifikacija stijenske mase (RMR), kinematička analiza i empirijska analiza stabilnosti kosina (SMR), oslanjajući se na podatke dobivene iz istraživanja jednoosne tlačne čvrstoće (UCS) i linija snimanja diskontinuiteta. Kosine u andezitima pokazuju RMR vrijednosti u rasponu od 74 do 81, što upućuje na dobru do vrlo dobru kvalitetu stijenske mase. Utvrđeni su projektni parametri i inženjerska svojstva, uključujući koheziju stijenske mase i kut unutarnjega trenja, koji upućuju na sigurne kutove nagiba usjeka. Utvrđeno je da su određene kosine podložne prevrtanju ili klinastom slomu. SMR vrijednosti kreću se od 72 do 96, kategorizirajući nagibe u klasu I-II, što upućuje na stabilnost i malu vjerojatnost sloma. Predlažu se manje mjere osiguranja kao što su micanje nestabilnih blokova s kosine, drenaža nožice, ograđivanje i točkasto sidrenje. Uzimajući u obzir seizmičke rizike i rizike oborina Zapadne Jave, studija preporučuje daljnje modeliranje kako bi se uključile varijacije u seizmičnosti i sadržaju vode. Metoda bi dala faktore sigurnosti i granične vrijednosti pod različitim uvjetima nagiba, poboljšavajući razumijevanje i upravljanje rizicima na klizištima u regiji.

Ključne riječi:
kosine u andezitima, Gunung Batu, Graha Puspa, RMR, SMR

Author's contribution

All authors of this paper are the main contributors. **Wira Cakrabuana** contributed as the first author of this paper, which was part of his thesis research. Wira conducted scanline surveys, drone photo taking, data processing, and paper writing. **Imam Sadisun** is Wira's thesis supervisor at the Institut Teknologi Bandung (ITB). **Indra Dinata** is an assistant of Imam who assists Wira in the thesis research process. This research is a development of the study of rock slope stability in the Lembang Fault Zone carried out by the Research Center for Geological Disaster, Badan Riset dan Inovasi Nasional (BRIN) under the leadership of **Adrin Tohari**, coordinator **Antonina Martireni**, and two research members, **Koko Hermawan** and **Hasan Atmojo**. From the BRIN research team, rock thin sections and UCS test results were obtained. **Hamzah Mahmud** assisted Wira in conducting a scanline survey and taking drone photos. **Ratika Nareswari** assisted Wira in describing the rock thin sections.