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Determination of Slope Stability Safety Factor based on the Slope Mass Rating (SMR) Method and Linearity Analysis of Discontinuity Conditions and Orientations using Linear Regression Machine Learning: a Case Study of the Breksi Cliff Area, Yogyakarta

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Abstract

The Tebing Breksi area is a geotourism of ancient volcanic remains in the Southern Mountains in the Semilir Formation that existed in the Oligocene-Miocene, but not many have discussed the rock mechanic's side. The observation is conducted in Sambirejo, Prambanan, Sleman Regency, in the Special Region of Yogyakarta. Slope stability study by assessing slope kinematics and rock mass classification using the SMR Method, which assumes that the slope is in a state of failure, and this method evaluates whether the forces and moments acting on each slice are in equilibrium. The data used are slope geometry data, lithology description, and Rock Mass Rating classification data taken along the scanline. Kinematic analysis of the slope is obtained based on the stereographic projection results using Dips and rock slope quality and stability analysis based on RMR and SMR parameters. The RQD value of the slope is 99.94% in the excellent category, and the RMR value obtained is 77 in the good category. The kinematic analysis shows the mass movement that will occur as a toppling avalanche orientated at 46.05%, so the SMR value is 73 in the good category. The heatmap and linear regression analysis between conditions and discontinuity orientations with respect to RMR-SMR values indicate a varied linear relationship, with some variables showing positive correlation and others showing negative correlation. From these results, the existing rock slope has greater than 1 safety factor value, which states that the slope is included in a stable category or rarely has the potential for landslides.

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1. Introduction

Rock-mass is a structure of rock that occurs naturally that really importants in research of rock mechanic that relates into engineering constructions design such as tunnels, road cut, or dam (Hudson and Harrison, 1997, in Juhari et al., 2021). Therefore, slope stability parameters for each construction must be carefully considered to enhance safety.

Slopes are topographic conditions commonly encountered in civil engineering works. Slopes may occur naturally or be artificially created for specific purposes (Abramson et al., 2001, in Pangaribuan and Pangaribuan, 2022). Natural slopes are formed in various locations such as natural embankments, riverbanks, and other areas due to natural processes that play a direct role. Slope stability is an important aspect that must be evaluated to obtain a safe factor of safety for both researchers and professionals working in the field of geotechnical engineering. Slope instability can be identified by several factors, including the conditions of discontinuity planes and the presence of groundwater (Nalgire et al., 2020).

In general, natural slopes exhibit good stability when supported by favorable rock mass conditions. However, in certain cases, natural slopes may experience changes in slope geometry, loss of rock mass strength, and the development of structural features. Weathering and erosion processes affecting exposed rock masses also contribute to changes in discontinuity conditions, which in turn reduce the overall quality of the rock mass.

Human activities also play a significant role as stability parameters. At the study location, some local residents conduct small-scale mining to utilize the rock materials available on the slope for their needs. This activity results in changes to the slope geometry and surface conditions. It is important to understand that slope cutting tends to reduce rock stability; in other words, the potential for rock slope failure or landslides increases significantly.

The study area is located approximately 1 km east of the Breksi Cliff tourist site, within Sambirejo Village, Prambanan District, Sleman Regency, Special Region of Yogyakarta, Indonesia.

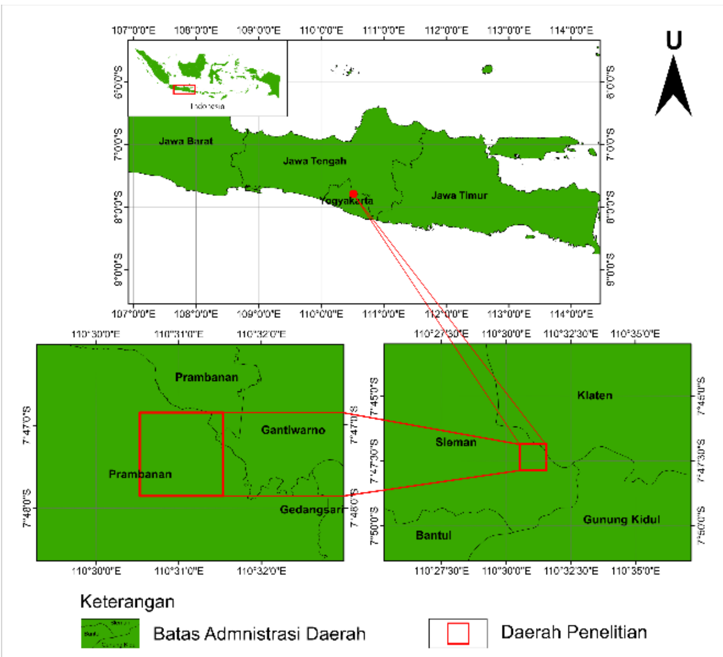

Figure 1. Location of Research Area

The objective of this study is to evaluate slope stability using the Slope Mass Rating (SMR) method, supported by Rock Mass Rating (RMR) parameters, in order to identify potential slope failure modes and to estimate the slope safety factor at the study area. The results are expected to contribute to a better understanding of slope stability conditions and to support hazard mitigation efforts in the future.

This study focuses on data interpretation, identification of relationships among variables, and assessment of potential trends based on the available dataset. Statistical models are required as part of the data analysis process. Common approaches for statistical modeling include clustering, classification, regression, and dimensionality reduction (Janssens, 2015). In this research, a linear regression–based machine learning model is applied to examine the relationships between discontinuity orientation and condition parameters and the resulting RMR–SMR values. Heatmap visualization is used to explore correlations among the analyzed variables.

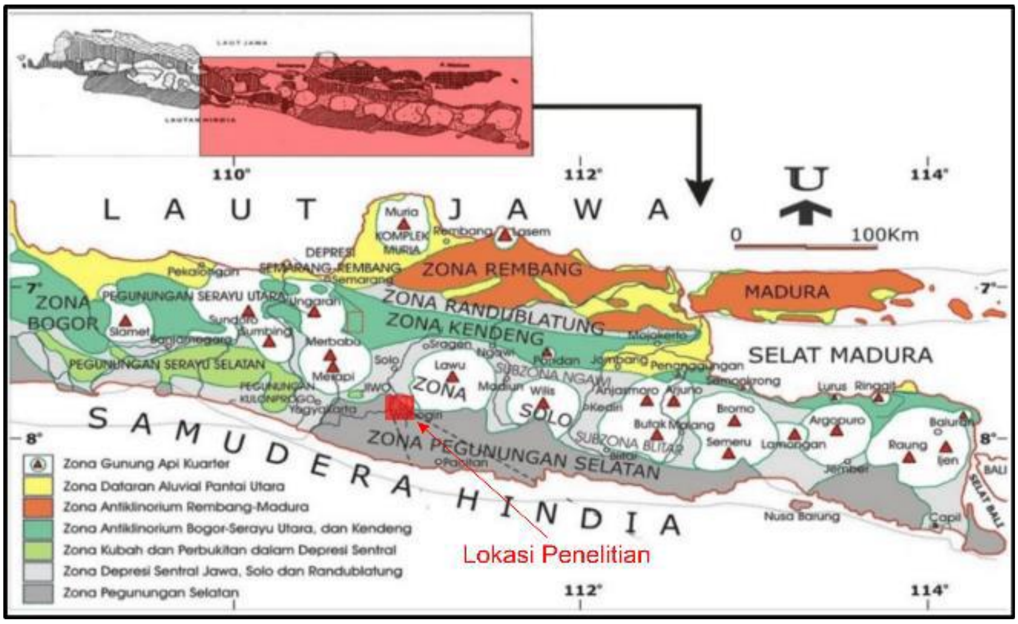

Figure 2. Eastern Part of Java Island's Physiography (Van Bemmelen (1949) with modification from Kusumayudha (2019) in Sudrajat (2021)

Regional Geology

The geological conditions of Indonesia are highly dynamic due to the interaction and collision between the Australian Plate and the Pacific Plate beneath the Eurasian Plate. The convergence of these plates has resulted in the activation of volcanic arc systems, which are capable of generating earthquakes. The increased ground vibrations associated with tectonic activity induce stress within rock masses on slopes, potentially triggering slope failures or landslides.

Tectonic activity has produced diverse physiographic zones and various morphological features, including valleys, plains, hills, and mountain ranges. According to Van Bemmelen (1949), the study area is located within the Southern Mountains Zone. Regionally, the geomorphology of the Southern Mountains is known as the Seribu Mountains, characterized by critical limestone hills that are barren and experience persistent water scarcity, particularly in the central part. The northern section, known as the Gunung Sewu Cone Hills, is bordered by two depressions: the Wonosari Depression to the west and the Baturetno Depression to the east. The northern boundary of this ridge is marked by a steep escarpment extending from the Parangtritis area northward, turning eastward south of Prambanan, and continuing to the Wonogiri area.

The landform of the study area consists of structural hills, with morphographic characteristics dominated by hilly terrain. The morphometric slope conditions range from moderately steep to steep, and the relief is characterized by moderately to strongly undulating hills.

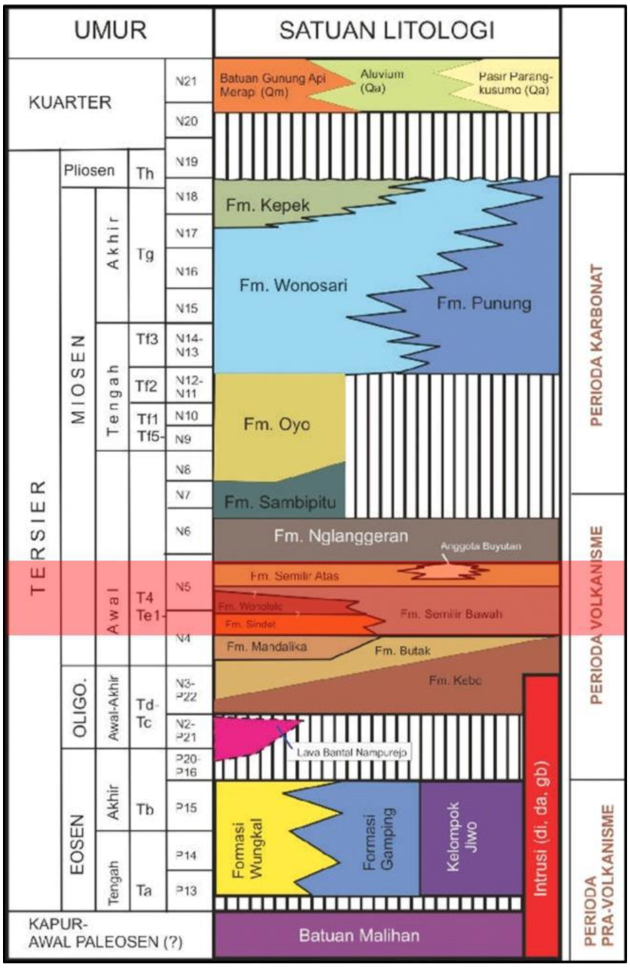

Figure 3. Stratigraphy of Southern Mountain (Surono, 2009)

According to the Geological Map of the Surakarta Sheet, the study area is situated within the Semilir Formation. The Semilir Formation consists of volcanic rocks produced by acidic volcanic eruptions, predominantly composed of lapilli tuff and tuff, with local intercalations of clastic sediments, particularly in the lower part of the formation. The lower part of the formation (Lower Semilir Formation) is dominated by lapilli tuff with interbeds of tuff and tuffaceous claystone, tuffaceous sandstone, and pumice breccia.

The upper part of the formation (Upper Semilir Formation) is mainly composed of tuff with intercalations of lapilli tuff, tuffaceous sandstone, and pebbly sandstone, and is interpreted to have formed during the Early Miocene, coinciding with a period of intense volcanism (Surono, 2009). In the Breksi Cliff area, the presence of microfossils has also been identified, indicating that this formation was deposited in a submarine environment (Van Gorsel, 1987, in Siti Umiyatun et al., 2019).

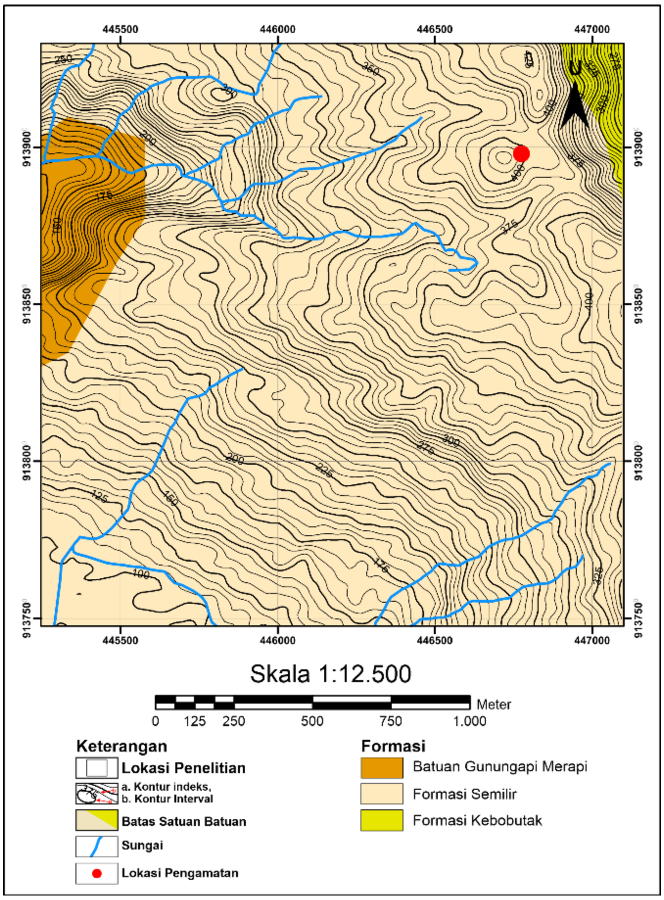

Figure 4. Regional Geology of Research Area

2. Materials and methods

Describe where and how you obtained your data. Explain the criteria and methods used for selecting samples. List any tools or instruments used to collect data.

Outline the overall design of your study. Detail the step-by-step procedures followed during the experiment. Mention any software tools or programs used for data analysis. Discuss any potential limitations or biases in your study. Cite any established methods followed.

The methodology applied in this study consists of several stages, as follows:

Literature Review

A comprehensive review of previous studies related to slope stability analysis for the determination of safety factor values, RMR–SMR classification, the application of machine learning in identifying linear relationships among variables, and the regional geology of the study area was conducted. This review provides the basis for problem formulation by integrating the above aspects and for developing an appropriate analytical approach.

Data Collection

Data collection was carried out through direct field observations, which included the following activities:

i. Field Description

Documentation of field conditions, including location, date, time, weather conditions, and rock descriptions based on physical (megascopic) characteristics.

Figure 5. Tuff rock outcrop

ii. Slope Geometry Measurement

Measurement of slope geometry, slope azimuth, slope angle (inclination), and slope dip direction was conducted using a measuring tape and a geological compass.

iii. Scanline Survey

Scanline surveys were performed by laying a measuring tape along discontinuity-bearing paths on the slope surface to observe and measure discontinuity characteristics.

iv. Field Documentation

Field documentation consisted of photographic records of the slope and rock exposures along the scanline paths.

v. Discontinuity Data Classification

Discontinuity data were grouped into sets or families based on the orientation of discontinuity planes to support weighting in the RMR and SMR classifications.

a. RMR parameters were obtained from scanline measurements, including rock strength, discontinuity conditions, and groundwater conditions.
b. SMR parameters were derived from discontinuity orientation and attitude relative to the slope, as well as the slope excavation method, which in this study corresponds to a natural slope condition.

Data Analysis

Data analysis involved the calculation and weighting of the Rock Mass Rating (RMR) using the five parameters proposed by Bieniawski (1989), namely: the orientation of discontinuity planes, intact rock strength, Rock Quality Designation (RQD), spacing of discontinuities, discontinuity conditions (including persistence, aperture, roughness, infilling, and weathering), and groundwater conditions. Adjustments related to discontinuity orientation were subsequently applied to the RMR weighting to estimate slope conditions.

Kinematic analysis was conducted using Rocscience Dips v7 software through stereographic projection to analyze discontinuity planes and to identify potential modes of slope failure. The calculation and weighting of the Slope Mass Rating (SMR) were determined based on two intersecting discontinuity planes identified in the stereographic projection during the kinematic analysis. The SMR correction factors include: (F1) the relationship between slope direction and discontinuity orientation, (F2) the dip angle of the discontinuity plane, (F3) the relationship between the dip angles of the slope and the discontinuity plane, and (F4) the slope excavation method.

Subsequently, slope stability modeling was performed using Rocscience Slide 6.0 software by incorporating slope geometry, natural unit weight of the rock mass, rock strength parameters, and groundwater table conditions to obtain the minimum factor of safety. The modeling results were then used to further evaluate slope stability. Lithological colors were applied to represent the rock units forming the slope, and potential failure mechanisms were illustrated using three-dimensional block modeling to describe the possible failure processes.

Linear Regression Machine Learning Analysis

Linear regression is a fundamental statistical and machine learning method used to identify linear relationships between one or more independent variables and a dependent variable. The objective is to determine the best-fit linear equation that represents the relationship among variables. Linear regression can be applied to analyze and predict relationships between two or more variables.

In this study, the Python programming language was used for data analysis and the development of linear regression models involving several variables. The variables examined for linear relationships include discontinuity orientation and discontinuity condition parameters in relation to RMR–SMR values. Heatmap visualization was also employed to compare correlations among the analyzed variables. The application of machine learning and heatmap visualization in this study serves as a preliminary analysis to evaluate linear correlation trends among variables based on field data. Variables that exhibit a positive linear relationship with RMR–SMR values are interpreted as contributing to increased slope stability, whereas variables showing negative linear relationships are interpreted as reducing slope stability.

Slope Reinforcement Recommendation

Slope reinforcement recommendations were developed based on the SMR classification system proposed by Romana et al. (2003) to minimize the potential risk of slope failure.

3. Results and Discussion

Based on field measurements, discontinuity data were collected using a horizontal scanline with a length of 15 m, a scanline plunge of 15°, and a scanline azimuth of N230°E. This configuration was applied to obtain discontinuity planes oriented approximately perpendicular to the scanline direction. A total of 13 discontinuity planes (Joint_IDs) were identified, exhibiting varying conditions and classified into four discontinuity sets or families based on their relative orientations (Figure 6), as follows:

i. Joint Set A, with a relative north–south orientation, consisting of five joints;
ii. Joint Set B, with a relative northeast–southwest orientation, consisting of two joints;
iii. Joint Set C, with a relative east–west orientation, consisting of four joints;
iv. Joint Set D, with a relative northwest–southeast orientation, consisting of two joints.

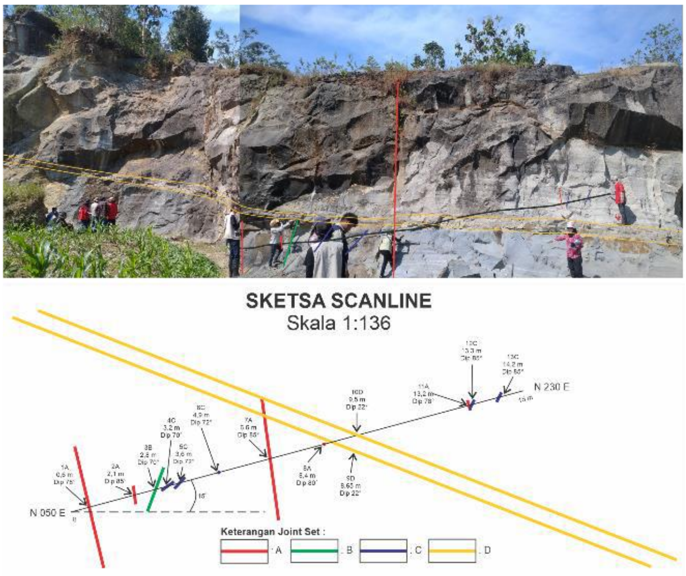

Figure 6. Outcrop photo and corrected scanline sketch

Table 1. RMR value data

Joint_ID	Intact_Rock_Strength	UCS(MPa)_Strength	RQD_Value(%)	Joint_Spacing_Value(m)	Joint_Length_Value (m)	Joint_Aperture_Value	Joint_Roughness_Value	Filling_Value	Wheathering_Value	Groundwater_Condition_Val	RMR_Value	RMR_Class	RMR_Category
1A	R3	25-50	99,94432	0,6	4	0,3	R	Clay	W2	Dry	72	II	Good
2A	R3	25-50	99,94432	1,5	0,6	0,1	R	Clay	W2	Dry	76	II	Good
3B	R3	25-50	99,94432	0,7	1,5	0	R	No Filling	W2	Dry	80	II	Good
4C	R3	25-50	99,94432	0,4	0,5	0	R	No Filling	W2	Dry	77	II	Good
5C	R3	25-50	99,94432	0,4	0,5	0	R	No Filling	W2	Dry	77	II	Good
6C	R3	25-50	99,94432	1,3	0,11	0	R	No Filling	W2	Dry	82	I	Very Good
7A	R3	25-50	99,94432	1,7	4	0	SM	No Filling	W2	Dry	74	II	Good
8A	R3	25-50	99,94432	1,8	0,1	0	R	No Filling	W2	Dry	82	I	Very Good
9D	R3	25-50	99,94432	0,2	22	0	SM	No Filling	W2	Dry	67	II	Good
10D	R3	25-50	99,94432	0,9	22	0	SM	No Filling	W2	Dry	72	II	Good
11A	R3	25-50	99,94432	3,7	0,35	0	SR	No Filling	W2	Dry	85	I	Very Good
12C	R3	25-50	99,94432	0,1	0,35	0	R	No Filling	W2	Dry	75	II	Good
13C	R3	25-50	99,94432	0,9	0,35	0	R	No Filling	W2	Dry	82	I	Very Good
										Rata-rata	77		

RQD (%)	Geotechnical quality
<25	Very poor
25-50	Poor
50-75	Fair
75-90	Good
90-100	Excellent

Figure 7. RMR Classification (Deere and Deere, 1988, in Siswanto and Anggraini, 2018)

Parameter/properties of rock mass	Rock mass rating (rock class)				
Rating	100-81	80-61	60-41	40-21	<20
Classification of rock mass	Very good	Good	Fair	Poor	Very poor
Average stand-up time	10 years for 15 m span	6 month for 8 m span	1 week for 5 m span	10 h for 2.5 m span	30 min for 1 m span
Cohesion of the rock mass	>400 kpa	300-400 kpa	200-300 kpa	100-200 kpa	<100 kpa
Friction angle of the rock mass	>45°	35-45°	25-35°	15-25°	<15°

Figure 8. RMR Classification (Bienawski, 1989, in Siswanto and Anggraini, 2018)

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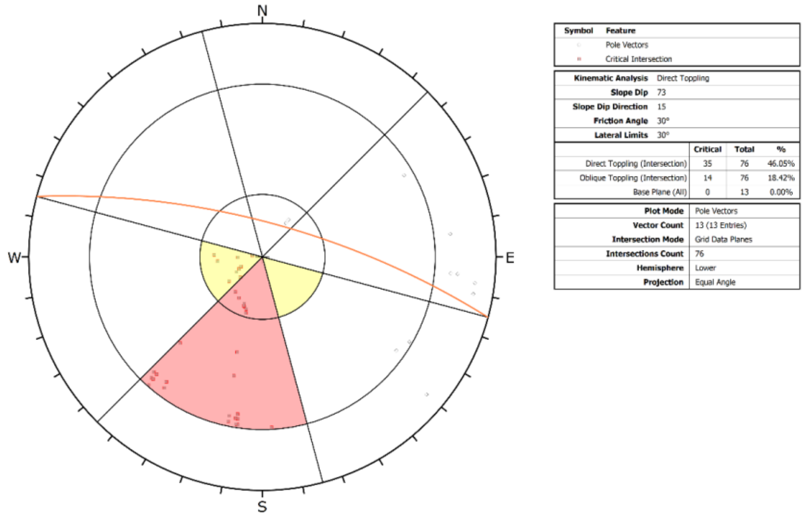

Figure 9. Kinematic Analysis of slope failure with software Dips v.7

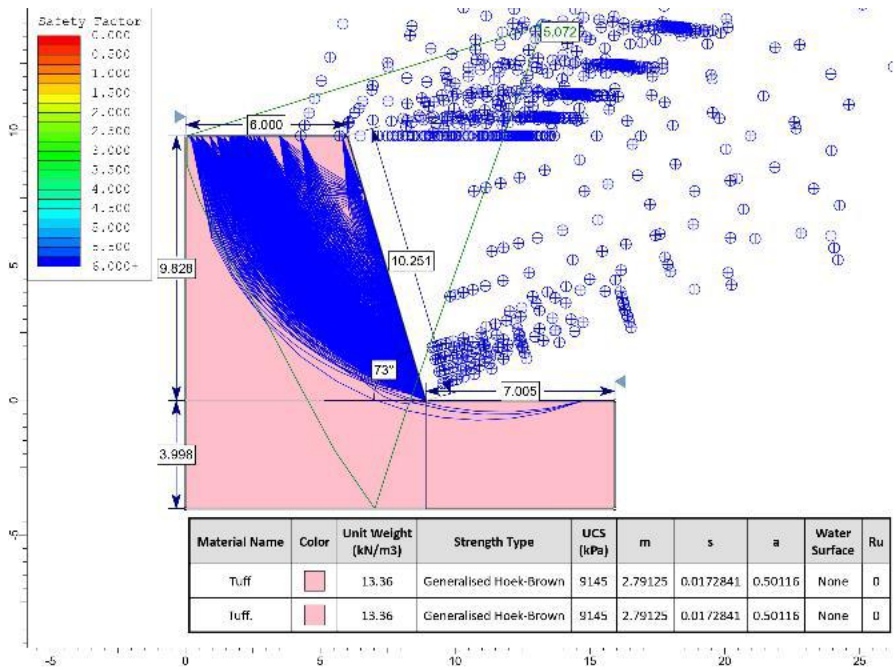

Figure 10. Slope stability analysis and factor of safety value of research area

The RQD value of the slope is 99% (Table 1), which falls within the excellent quality class. This value is close to 100%, indicating very good rock mass quality in the study area (Figure 7.

Based on Table 1, the average RMR value of the slope is 77 (Table 1), corresponding to Class II rock mass quality within the range of 61–80. This class is characterized by an estimated stand-up time of approximately 6 months for an 8 m span, rock mass cohesion values ranging from 300 to 400 kPa, and friction angles between 35° and 45° (Figure 8).

Slope geometry data collected in the field include a slope azimuth of N195°E, slope direction of N015°E, slope angle of 73°, slope height of 9.6 m, and slope width of 6 m. These parameters were used for kinematic analysis, SMR calculation, and slope modeling to determine the slope factor of safety.

The kinematic analysis indicates that the dominant failure mode is direct toppling, accounting for 46.05% of the analyzed orientations (Figure 10). This failure mode involves forward rotational movement of one or more rock blocks about a pivot point located beneath the rock mass, driven by gravitational forces and/or by thrust forces from adjacent rock blocks, as well as by forces induced by water pressure within rock discontinuities (Figure 9).

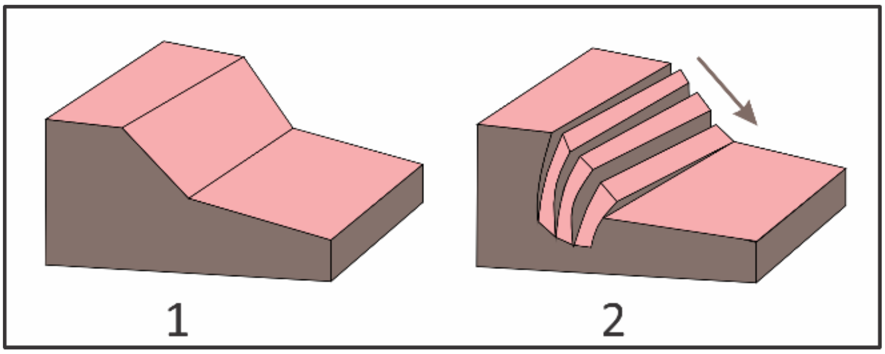

Figure 9. 3D block model of slope stability with Toppling failure type.

Numerical modeling using Rocscience Slide 6.0 (Figure 10) indicates a factor of safety (FoS) value of 6 for the studied slope. Based on the factor of safety classification proposed by Bowles (1989, in Denni, 2021), slopes with FoS values greater than 1 (FoS > 1) are classified as stable or as having a low potential for failure. The analysis was performed using the generalized Hoek–Brown failure criterion (Hoek, 2019).

The calculated SMR value is 73 (Table 2), which falls within Class II and is categorized as Good rock mass quality, with a dominant toppling failure mode. The studied slope exhibits relatively stable conditions, with the potential for failure involving some rock blocks. Occasional support may be required, and recommended support measures include the installation of rock bolts (anchor bolts), although in some cases no additional support may be necessary.

Heatmap visualization illustrating the relationship between discontinuity orientation variables and RMR–SMR values is presented in Figure 13. The discontinuity strike direction shows a positive correlation with RMR values of 53% and with SMR values of 20%. This correlation pattern is consistent with the machine learning model results shown in Figures 14(a) and 14(b), which indicate a positive linear relationship. Higher discontinuity strike direction values are associated with higher RMR values, while slope stability (SMR) shows a slight increase.

The discontinuity dip direction variable also exhibits a positive correlation with RMR values of 53% and SMR values of 20%. This relationship is consistent with the linear regression results presented in Figures 14(c) and 14(d), indicating a positive linear trend. As the dip direction of discontinuities increases, RMR values tend to increase, accompanied by a slight increase in slope stability (SMR).

The relationship between discontinuity strike and slope strike (F1) shows a positive correlation with RMR values of 53% and SMR values of 20%. This pattern corresponds with the linear regression results presented in Figures 14(e) and 14(f), indicating a positive linear relationship. Higher F1 values are associated with increased RMR values, while slope stability (SMR) shows a modest increase.

Furthermore, the relationship between discontinuity dip and slope dip (F3) exhibits a positive correlation with RMR values of 59% and SMR values of 27%. This relationship is consistent with the linear regression results shown in Figures 14(g) and 14(h), which also indicate a positive linear trend. Higher F3 values are associated with increased RMR values and a slight increase in SMR-based slope stability.

Table 2. SMR data value

Joint_ID	Slope_Azimuth	Slope_Dip	Landslide_Type	Strike_J-S_F1	Slope_Dip_F2	Dip_J-S_F3	Slope_Type_F4	SMR	SMR_Class	SMR_Category
1A	15	73	Toppling	68	1	151	Natural Slope	68,25	II	Good
2A	15	73	Toppling	82	1	158	Natural Slope	72,25	II	Good
3B	15	73	Toppling	45	1	143	Natural Slope	76,25	II	Good
4C	15	73	Toppling	110	1	143	Natural Slope	73,25	II	Good
5C	15	73	Toppling	105	1	145	Natural Slope	73,25	II	Good
6C	15	73	Toppling	105	1	145	Natural Slope	78,25	II	Good
7A	15	73	Toppling	85	1	158	Natural Slope	70,25	II	Good
8A	15	73	Toppling	80	1	153	Natural Slope	78,25	II	Good
9D	15	73	Toppling	19	0,4	93	Natural Slope	68	II	Good
10D	15	73	Toppling	19	0,4	95	Natural Slope	72	II	Good
11A	15	73	Toppling	80	1	151	Natural Slope	81,25	I	Very Good
12C	15	73	Toppling	115	1	158	Natural Slope	71,25	II	Good
13C	15	73	Toppling	115	1	158	Natural Slope	71,25	II	Good
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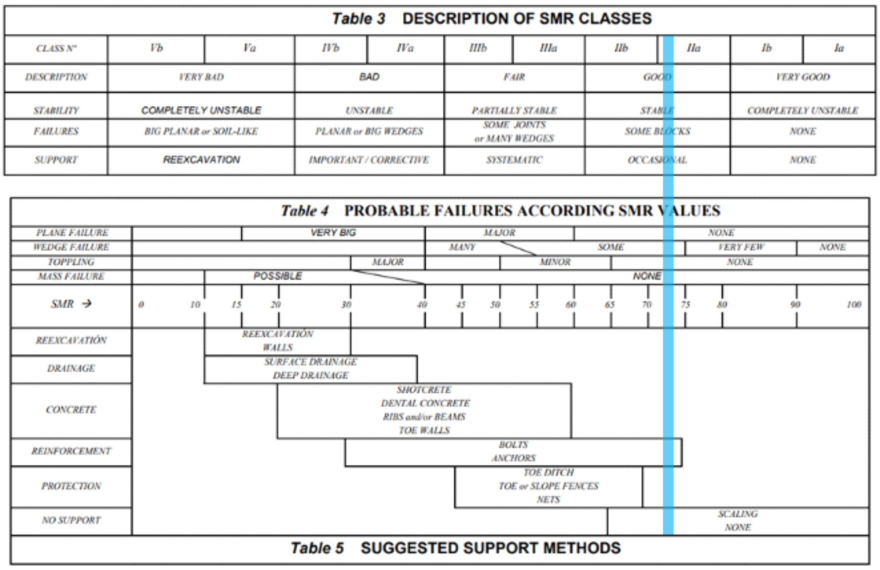

Figure 11. SMR classification (Romana et al., 2003, in Romana et al., 2015).

Figure 12. Heatmap direction of discontinuity with RMR-SMR value

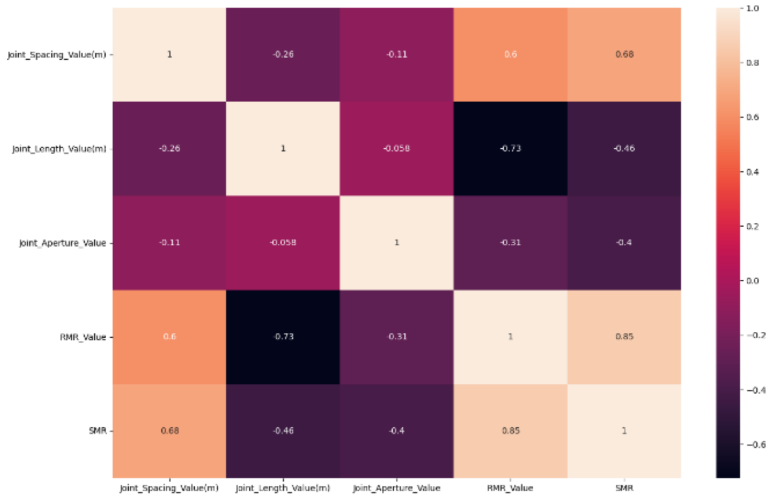

Figure 13. Heatmap condition of discontinuity with RMR-SMR value

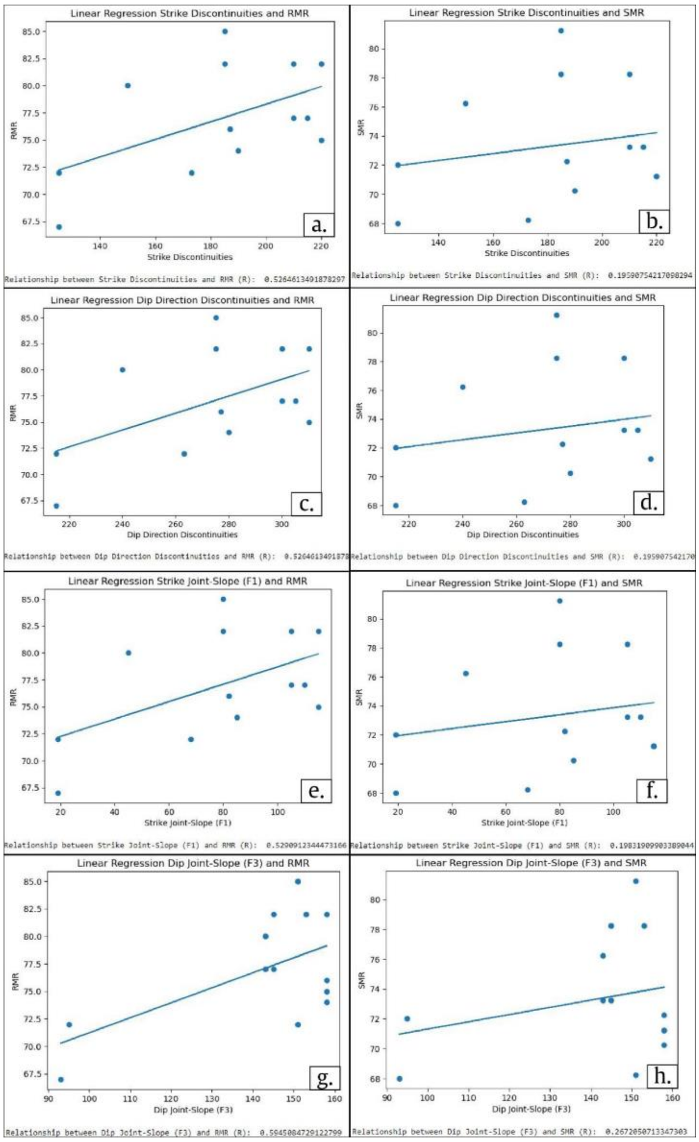

Figure 14. Machine Learning discontinuity direction with RMR-SMR value

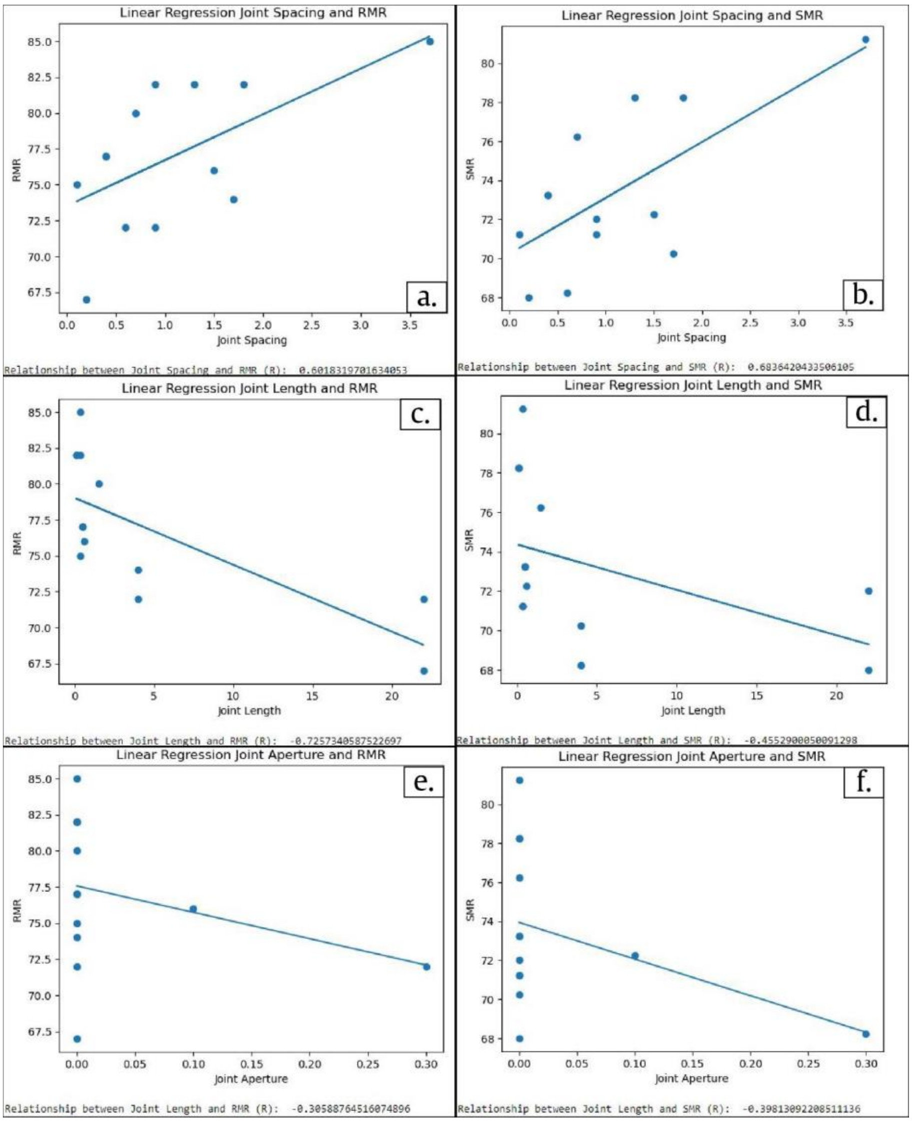

Figure 15. Machine Learning for condition of dinscontinuity with RMR-SMR value

Heatmap visualization of the relationships between discontinuity condition variables and RMR–SMR values is presented in Figure 15. Discontinuity spacing shows a positive correlation with RMR values of 60% and SMR values of 68%. This correlation pattern is consistent with the linear regression model results shown in Figures 17(a) and 17(b), indicating a positive linear relationship. Increasing discontinuity spacing is therefore associated with improved slope stability.

Discontinuity persistence (length) exhibits a negative correlation with RMR values of 73% and SMR values of 46%. This relationship corresponds with the linear regression results shown in Figures 15(c) and 15(d), which indicate a negative linear trend. As discontinuity persistence increases, slope stability tends to decrease.

Discontinuity aperture also shows a negative correlation with RMR values of 31% and SMR values of 40%. This relationship is consistent with the linear regression results presented in Figures 15(e) and 15(f), indicating a negative linear relationship. Larger discontinuity apertures are therefore associated with reduced slope stability.

4. Conclusions

Based on the results of this study, the average RMR value of the investigated slope is 77, which corresponds to Class II according to the RMR classification system. Kinematic analysis based on slope geometry indicates that the dominant potential failure mode is toppling. The calculated

SMR value of 73 also falls within Class II and is categorized as Good rock mass quality, with a toppling-type failure mechanism, indicating relatively stable slope conditions.

Numerical modeling results indicate a factor of safety of 6, which is greater than 1 (FoS > 1) and therefore classifies the slope as stable or as having a low probability of failure. Discontinuity orientation variables, including strike direction, dip direction, the relationship between discontinuity strike and slope strike, and the relationship between discontinuity dip and slope dip, show positive correlations with slope stability indicators (RMR–SMR). Discontinuity condition variables indicate that discontinuity spacing has a positive correlation with slope stability, whereas discontinuity persistence and aperture exhibit negative correlations with slope stability.

Based on the SMR classification, the studied slope can be considered moderately stable; however, occasional support may still be required. Recommended support measures include the installation of rock bolts to minimize the potential risk of slope failure in the future.

5. Competing interests

The authors declare that they have no competing interests.

6. Author's contributions

Maulana Putra Adiningrat conceived the study, developed and tested the linear regression machine learning model, performed the slope stability and SMR analyses, interpreted the results, and wrote the original draft of the manuscript. Naspuria Gita Marpaung contributed to data acquisition, discontinuity orientation analysis, and assisted in data interpretation and manuscript revision. Hannah Roselynne Chang contributed to methodological refinement, validation of the analysis, and critical review of the manuscript. All authors read and approved the final manuscript.

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