ASEAN Engineering Journal

Full Paper

ASSESSMENT OF ROCK MASS QUALITY AND ROCKFALL POTENTIAL EVALUATION FOR RECLAMATION OF A QUARRY

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Article history
Received
5 March 2023
Received in revised form
3 September 2023
Accepted
23 September 2023
Published online
29 February 2024

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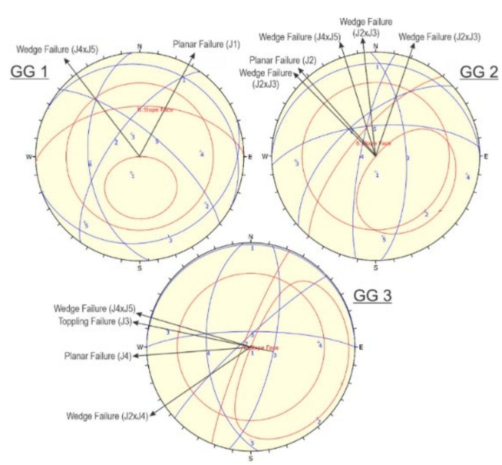
Graphical abstract



Abstract

In order to make an informed decision about implementing sustainable and efficient development during land reclamation in an area deemed geohazard-prone, thorough geological input is necessary. Quarry areas are vulnerable to slope failure and rockfalls, making it imperative to evaluate rock slopes for quarry reclamation. For this reason, researchers in Kinta Valley, Malaysia, set out to evaluate the slopes GG1, GG2, and GG3 at a defunct quarry. To evaluate the rock mass classification, the Rock Mass Rating (RMR) and Slope Mass Rating (SMR) systems were utilized, and the analyzing rock block's trajectory was using a rockfall analysis. The kinematic stability analysis was also performed to identify possible failure mechanisms. In order to assess the site's suitability for urban development, the rockfall scenarios were conducted. The SMR scaled from moderate to very good, while the RMR ranked the rock mass quality as good to very good. For all three of the slopes analyzed, the kinematic stability analysis pointed to the possibility of various failures (toppling, planar and wedge). According to the rockfall trajectory analysis, the rock block could roll as far as 5 metres from the base of the slope. For this reason, the study advised creating a buffer zone of 20 metres or more away from the rock slope as a means of protection against the geohazard of rockfall.

Keywords: Slope Mass Rating, Rock Mass Rating, Quarry Reclamation, Rock Slope, Rock Mass Classification

1.0 INTRODUCTION

Due to its rapid economic expansion, Malaysia has joined the ranks of the world's top-performing nations. The demand for undeveloped land to build on has skyrocketed due to rapid urbanization in major cities [1]. As a result, a diminishing supply of land considered secure and immune to geohazards exists. Geohazardous land areas are a desirable alternative for development because of their stable bedrock and level surface, both of which are necessary to construct building foundations [2,3]. Former quarries are now being used for farming [4], storing water for reservoirs [5], geotourism [6] and infrastructure [7]. Abandoned and hazardous quarry sites have been repurposed into other developed areas, breathing new life into the neighbourhood and raising its economic value [8].

Quarrying for aggregate resources often creates precarious slopes with the possibility of collapse on a slope [9,10]. Exposed cliffs and boulders are common features of the high, rocky slopes that once served as quarries. Due to the area's unsafe and risky condition, a thorough geological investigation is needed. Each slope's potential geohazards must be identified before any land reclamation or development can take place [11]. Geologists often use rock mass classification to evaluate a slope's stability and the ground's state below it.

Subterranean digging, tunnelling, and hillside building have used rock mass classification systems in the decades beginning in the '70s. It has also been widely used to study rock formations using the classification system for engineering and building purposes. Rock Mass Rating and Slope Mass Rating are two of the most well-known methods of classifying rock masses used in construction. First proposed in [12], the RMR classification system has seen updates in [13], [14], 1974, 1975, and 1976. Enhancements were made because of a more thorough appreciation of the value of each variable in managing the rock mass's stability. When it comes to major construction projects, the 1989 classification system is one of the most widely used tools available [15]. Meanwhile, [16] introduced the SMR, which builds on the RMR principle to evaluate slope stability by considering discontinuity and slope orientation as well.

Furthermore, the rockfall analysis method is utilized in order to trace the rock's path. Rockfall is an example of a landslide, which occurs when rocks are hurled at high speeds [17]. Previous research [18, 19, 20] has covered the ground regarding the possibility of rockfall in former quarry areas. Impacts can be lessened by implementing mitigation strategies, and this assessment of rockfall potential is crucial to this process. Accidents affecting infrastructure and people can be avoided if the potential for rockfall is identified in advance.

This study evaluated the rock slope for infrastructure development by utilizing the RMR and SMR. Other than classifying the rock mass, the rockfall analysis was also conducted in a defunct former quarry. Within the quarry area, the research focused on three different slopes. The slopes were ranked according to how stable and likely they were to collapse. Rockfall scenarios were simulated using input data on rock material properties further to assess the site's suitability for urban development.

2.0 METHODOLOGY

2.1 Study Area

The study took place at Gunung Ginting in Kinta Valley, Perak, Malaysia. Gunung Ginting can be found at 4°36'52.01"N, 101°7'55.13"E on a GPS device. In the past, several quarries operated there, harvesting aggregate for use in various manufacturing processes. Nonetheless, after some time in operation, the company closed the quarry. As can be seen in Figure 1, unstable slopes were a direct result of quarrying activities. Slope locations GG1, GG2, and GG3 have been designated.

A large portion of the Kinta Valley city is enclosed by karst topography. The metamorphic process partially transformed the limestone bedrock beneath the Kinta Valley into marbles. In addition to limestone, the calcareous and arenaceous series, granite, and alluvium can be found in the study area [21]. Middle Devonian or early Middle Permian fossils have been found in Kampar's Western region, while the limestone is thought to date back to the Carboniferous period [21, 22]. In Kinta Valley, the prevalence of micritic limestone in the form of thin layers led scientists to conclude that the limestone formed in sedimentary environments like the incline of a large platform [21].

Geological mapping of structural features has also revealed structures of the isoclinal and overfolded Kinta Valley's eastern rocks due to the action of tectonic anomalies [21]. Four distinct deformational episodes occurred from the Permian to the Neogene [24]. The lithological distribution of Ipoh and the surrounding area is presented in Figure 2.

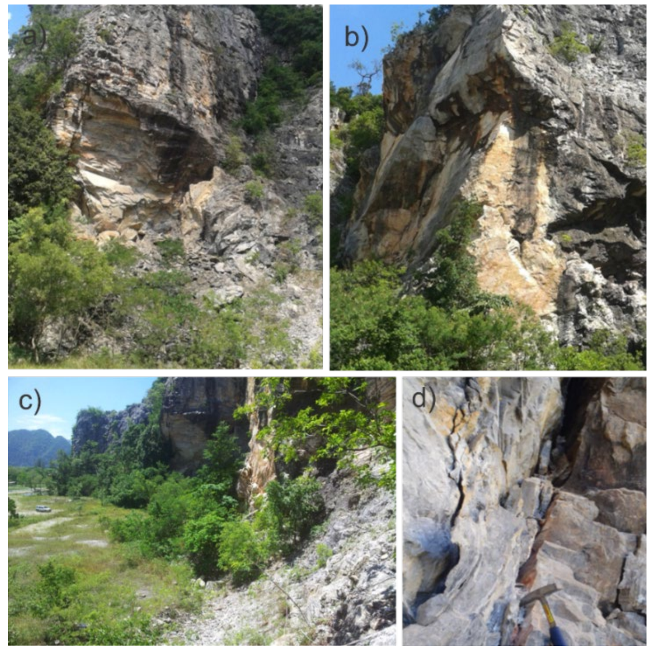


Figure 1 The state of the rocks in the area of research: a) wedge failure at slope GG2 leaves a visible scar, b) a planar failure was possible due to the nearly vertical cliff's presence of a highly joint persistence set whose orientation was parallel with the slope face, c) picture of the quarry rock slope as a whole, and d) sets of major joints that have a width opening but no filling material.

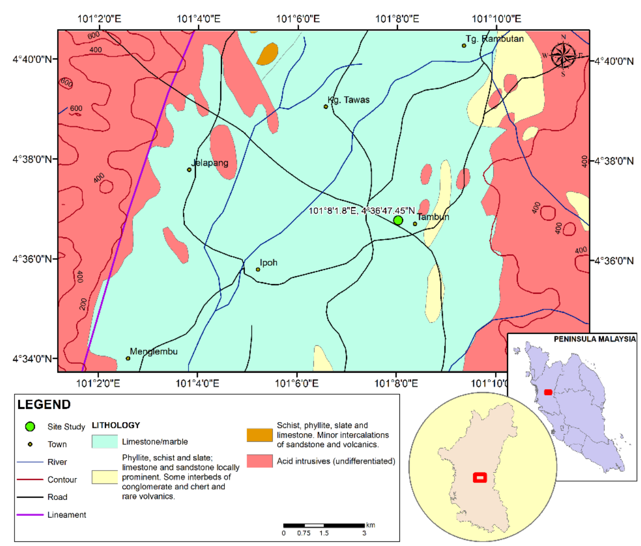


Figure 2 The geographical and geological layout of the Ipoh research area in Malaysia. The information comes from [25].

2.2 Rock Mass Classification

RMR was classified based on five parameters, which are the strength of intact material, rock quality designation (RQD), spacing of discontinuities, condition of discontinuities and groundwater. Detailed information on RMR parameters is shown in Table 1. Table 2 displays the guidelines for the discontinuity condition. Totalling the scores from all parameters, which can be between 0 and 100, yielded the RMR classification. According to [15], there are five distinct categories for rock mass characteristics.

In addition, the SMR relied on six variables, such as the strength of the rock material, the RQD, the spacing and conditions of the discontinuities, the state of the groundwater, and the adjusting factors(F1, F2, F3, and F4) (Table 3). Factors F1, F2, F3, and F4 were adjusted using the data in Table 2. The slope face orientation affects the joint orientation adjustment factors F1, F2, and F3. The excavation method requires a correction factor, denoted by F4. Equation 1 was used to calculate the SMR value.

$$SMR = RMR_{basic} + (F1 \times F2 \times F3) + F4 \quad (1)$$

An important factor in determining F1 is whether the slope face is perpendicular to the joint. F1 ranged from 0.15 to 1.0, while F2 depended on the joint plane's inclination angle. When the dip angle was less than 20 degrees and more than 45 degrees, F2 was 0.15 and 1.0, respectively. When a topple occurs, however, F2 equals 1, so this is an exception. F3 is the slope-to-joint-plane angle relationship (j-s). According to the RMR classification system, the value of F3 ranged from -60 to 0 and was correlated with the orientation of the joints. F4 is impacted by the excavation method used. F4 ranged from negative eight to plus fifteen.

Furthermore, SMR categorization calls for a kinematic evaluation of all three slopes. Through the graphical representation of the discontinuity means data for each set concerning the strike of the slope, it is possible to make inferences on the probable failure mechanism of the rock mass. As can be seen in Table 4, SMR was rated from 0 to 100 on a scale from most unstable to most stable.

Table 1 RMR system according to Bieniawski [15]

Parameters		Range of values						
Strength of intact rock material (MPa)	PLSI[1]	> 10	4–10	2–4	1–2	UCS was preferred at low range		
	UCS[2]	> 250	100–250	50–100	25–50	5–25	1–5	< 1
Rating		15	12	7	4	2	1	0
RQD[3] (%)		90–100	75–90	50–75	25–50	< 25		
Rating		20	17	13	8	3		
Spacing of discontinuities		> 2 m	0.6–2 m	200–600 mm	60–200 mm	< 60 mm		
Rating		20	15	10	8	0		
Condition of discontinuities (See Table 2)		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	Slicken-sided 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		
Ground water	Inflow/10 m tunnel length (l/m)	0	< 10	10–25	25–125	> 125		
	Joint water press/ Major principal (σ)	0	< 0.1	0.1–0.2	0.2–0.5	> 0.5		
	General condition	Completely dry	Damp	Wet	Dripping	Flowing		
Rating		15	10	7	4	0		

Table 2 Guidelines for the condition of discontinuities [15]

Persistence (m)	< 1	1–3	3–10	10–20	> 20
Rating	6	4	2	1	0
Aperture (mm)	None	< 0.1	0.1–1.0	1–5	> 5
Rating	6	5	4	1	0
Roughness	Very rough	Rough	Slightly rough	Smooth	Slicken-sided
Rating	6	5	3	1	0
In-filling (mm)	None	Hard filling < 5	Hard filling > 5	Soft filling < 5	Soft filling > 5
Rating	6	4	2	2	0
Weathering	Unweathered	Slightly weathered	Moderately weathered	Highly weathered	Decomposed
Rating	6	5	3	1	0

Table 3 Proposed SMR adjustment factors from [16,27].

Adjustment factors	Very favourable	Favourable	Normal	Unfavourable	Very unfavourable
Planar failure $\vert\alpha j-\alpha s\vert$ Topple failure $\vert\alpha j-\alpha s-180^{o}\vert$ Wedge failure $\vert\alpha i-\alpha s\vert$	> 30°	30-20°	20-10°	10-5°	< 5°
F1	0.15	0.40	0.70	0.85	1.00
$\vert\beta j\vert$	< 20°	20-30°	30-35°	35-45°	> 45°
F2 for planar/wedge failure	0.15	0.40	0.70	0.85	1.00
F2 for topple failure	1.00	1.00	1.00	1.00	1.00
Planar failure $\vert\beta j-\beta s\vert$ Wedge failure $\vert c\ \beta i-\beta s\vert$	> 10°	10-0°	0°	0-(-10°)	< -10°
Topple failure $\vert\beta j+\beta s\vert$	< 110°	110-120°	> 120°	-	-
F3	0	-6	-25	-50	-60
Excavation method	Natural slope	Pre-splitting	Smooth blasting	Blasting or mechanical	Deficient blasting
F4	+15	+10	+8	0	-8

Note: αj = dip direction of the discontinuity; αs = dip direction of the slope; αI = dip direction of the intersection line of two sets of discontinuity; βj = discontinuity dip; βI = angle of the plunge of the intersection line of two sets of discontinuity; βs = slope dip

Table 4 The classification system for SMR by [16]

Class	V	IV	III	II	I
SMR value	0-20	21-40	41-60	61-80	81-100
Condition of rock mass	Very poorly rock	Poorly rock	Fairly rock	Good rock	Very good rock
Stability	Very unstable	Unstable	Slightly stable	Stable	Very stable
Failure	Big planar or soil-like	Planar or a big wedge	Some joints and many wedges	Some block	None failure
Possibilities of failure	0.9	0.6	0.4	0.2	0

2.3 An Evaluation of Rock Falls

The slope of the quarry rock was poorly constructed. Direct evidence of the damage caused by excessive and careless blasting at rock excavation sites. The dispersed mass of broken rock was also widespread. The size and form of the loose, unstable blocks varied. GeoRock, a two-dimensional (2D) programme, was used to analyze rockfalls for this study. The program was partly developed in response to the Colorado Rockfall Simulation programme. Size, shape, mass, and initial velocity of boulders, energy loss at impact as measured by Rn and Rt values, and roughness coefficient value were all inputs in GeoRock 2D software.

2.4 Field Studies And Data Processing

Essential geological tools like compasses, hammers, and measuring tape were used to complete the field mapping. The line scan method proposed in [28] was used to collect field data at the three slope site areas. Joint alterations, hydrogeological conditions, hydrology, inclination of slopes, orientation of discontinuities and their properties (openings, conditions, and roughness) were all gathered from the field mapping. The discontinuities survey form was used to record data from the field for systematic analysis. RMR and SMR classifications used the collected data as their input. In addition, a scanning line survey of discontinuity data was incorporated into the slope kinematic analysis [29] to help identify a likely failure mechanism. The slope kinematic analysis is a helpful method for determining the likelihood of failure. The rock samples of intact material were collected for a uniaxial compression strength to establish the rock's strength [30]. DHR2000 model, a uniaxial compression machine from UTS company, was used in conducting the intact rock material strength testing. Experiments were performed on cylindrical specimens having a diameter of 54 mm, whereby a loading rate ranging from 0.5 to 1.0 MPa/s was applied. Using the formula [31], the RQD value can be calculated.

3.0 RESULTS AND DISCUSSION

3.1 Rock Mass Classification

Analysis of the discontinuity condition based on field survey and laboratory test results revealed that most openings in the geological structures were narrow and slightly undulating. Nothing was flowing out from along the plane, and there was no sign of filling material. Rock strength values varied from 5.10 MPa to 10.59 MPa, and discontinuity spacing for the three slopes ranged from 0.21 m to 0.33 m. Tabular data (Table 5) reveals that RMR_{basic} gave a total rating of 82, 80, and 87 to slopes GG1, GG2, and GG3, respectively. The RMR_{basic} classification showed that the strength of the rock mass was evaluated as good to very good generally.

The same information used to calculate RMR_{basic} was applied to the problem of calculating SMR. Table 6 displays the information regarding the set of discontinuities and the orientation for each GG1, GG2, and GG3 slope. F1, F2, and F3 adjustment factors were computed using the discontinuity orientation data plotting. Figure 3 displays the kinematic analysis results for a slope. The data suggest that possible wedge and planar failures occurred on slopes GG1 and GG2, while additional toppling failures occurred on slope GG3. In addition, quarrying activities formed the GG1 and GG2 slopes; hence, F4 was rated at 0, and the GG3 slope was rated at 15. Table 7 displays the results of the computations for the adjustment factors F1, F2, F3, and F4, while Table 8 displays the SMR value for the slopes GG1, GG2, and GG3.

In general, the comparison between RMR and SMR ratings does not exhibit much differentiation, with the exception of slope GG2 and slope GG3 (Figure 4). The RMR value corresponding to the wedge-1 and planar-1 failures seen at slope GG2 is reported as 80. However, it is noteworthy that the SMR value exhibits a significant decrease, reaching a value of 29. A similar pattern may also be observed for the wedge-1 failure at slope GG3, where the RMR value decreases from 87 to 51 for SMR. The variability in the slope GG2's slope value can be attributed to the almost parallel alignment between the slope orientation and the orientations of both wedge and planar failures. Therefore, it has an impact on the F1 score. The F1 score for both failed cases is 0.85, resulting in a much lower overall SMR value as compared to RMR.

Table 5 Application of RMR to categorizing rock masses in the study area

Parameters	GG1		GG2		GG3	
	Value	Rating	Value	Rating	Value	Rating
Point load test (MPa)	6.67	12	5.10	12	10.59	15
RQD (%)	94	20	91	20	96	20
Discontinuities spacing (m)	0.25	10	0.21	10	0.33	10
Ground water condition	Dry	15	Dry	15	Dry	15
Conditions of discontinuities	Discontinuities length of 0.46 m, tight, surface roughness smooth and undulating, no in-filling, unweathered	25	Discontinuities length of 3.55 m, tight, slightly undulating, no in-filling, unweathered	23	Discontinuities length of 0.85 m, tight, slightly undulating, no in-filling, unweathered	27
Total rating for RMR_{basic}	82		80		87	
Class Classification of rock mass	I Very good		II Good		I Very good	

Table 6 Major set of discontinuity orientation.

Slope	Slope face orientation	Major discontinuities set	
		Dip direction/dip	Types of discontinuities
GG1	358/50	028/14	Bedding
		305/66	Joint
		160/19	Joint
		265/49	Joint
		040/71	Joint
GG2	310/70	360/12	Bedding
		318/60	Joint
		087/66	Joint
		281/78	Joint
		355/66	Joint
GG3	292/84	180/00	Bedding
		317/83	Joint
		102/72	Joint
		266/55	Joint
		360/78	Joint

Table 7 Discrete method based on Romana [27] used for SMR classification of rock slopes at the study area.

Slope	Mode of failure	RMR	F1	F2	F3	F4	SMR
GG1	Planar-1	82	0.15	0.15	-60.00	0	81
	Wedge-1	82	0.15	0.70	-60.00	0	76
GG2	Wedge-1	80	0.85	1.00	-60.00	0	29
	Wedge-2	80	0.15	1.00	-50.00	0	72
	Wedge-3	80	0.15	1.00	-60.00	0	71
	Wedge-4	80	0.15	0.85	-60.00	0	72
	Planar-1	80	0.85	1.00	-60.00	0	29
GG3	Wedge-1	87	0.85	1.00	-60.00	15	51
	Wedge-2	87	0.15	1.00	-60.00	15	93
	Toppling-1	87	0.70	1.00	-25.00	15	84
	Planar-1	87	0.40	1.00	-60.00	15	78

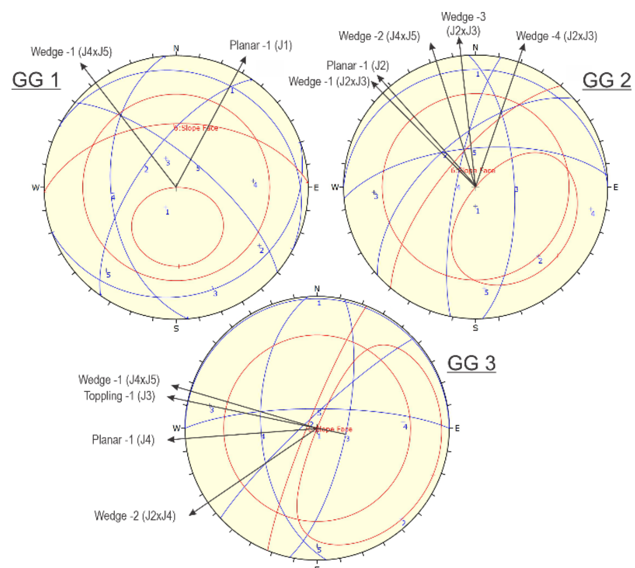


Figure 3 The kinematic stability analysis for slopes GG1, GG2, and GG3 indicates that the failures can occur in three different modes: as a wedge, as a planar failure, or as a toppling failure.

Table 8 SMR value for respective slope in the study area

Slope	Mode of failure	SMR	Class	Condition of rock mass	Stability of rock mass	Possibilities of failure
GG1	Planar	81	I	Very good	Very stable	0
	Wedge	76	II	Good	Stable	0.2
GG2	Wedge	29	IV	Poor	Unstable	0.6
	Wedge	72	II	Good	Stable	0.2
	Wedge	71	II	Good	Stable	0.2
	Wedge	72	II	Good	Stable	0.2
	Planar	29	IV	Poor	Unstable	0.6
GG3	Wedge	51	III	Fair	Slightly stable	0.4
	Wedge	93	I	Very good	Very stable	0
	Toppling	84	I	Very good	Very stable	0
	Planar	78	II	Good	Stable	0.2

3.2 Rockfall Evaluation

According to Table 9, twenty different simulated rockfall scenarios were run using information on the properties of rock materials as input. The characteristic of the limestone block used in the simulation refers to the suggestion value by [32]. Locations at the rock slope's head, centre, and toe were used in the simulations of rockfalls. The size of the rock block used in the simulation was determined from the spacing of discontinuities from the scan line mapping. According to the results of the discontinuity survey, the most dangerous rock size was determined to be 3m by 3m for the maximum and 1m by 0.21m to 0.33m for the minimum.

Table 10 displays the results of the rock fall investigation, according to results from the simulations, including the greatest possible roll distances for each of the three GG slopes (GG1, GG2, and GG3) measured 5, -4, and 3 metres. It was also discovered that the fragmentary rock slopes assisted in keeping that solid mass of rock from sliding down the slope. A ditch width (W) of 6 metres and a ditch depth (D) of 1.23 meters have been proposed and implemented in the rockfall model to account for the fact that most slope angles were greater than 76 degrees and slope heights were between 60 and 90 metres.

Table 9 Characteristics of rocks used in simulations of rock falls

Parameters	Value
Rock density	2600 kg/m^3
Elastic modulus	5 GPa
Velocity for X-axis	3 m/s
Velocity for Y-axis	-3 m/s
Terminal velocity	0.01 m/s

Table 10 An overview of 20 runs through the GeoRock simulation programme simulating rockfall on slopes of GG1, GG2, and GG3

Slope	Rock block dimension (m)	Max rolling distance (m)	Starting location for block rolling
GG1	1 x 0.25	5	Upper slope
	3 x 3	5	
	1 x 0.25	5	Mid slope
	3 x 3	5	
	1 x 0.25	-2	Toe slope
	3 x 3	2	
GG2	1 x 0.21	-7	Upper slope
	3 x 3	-7	
	1 x 0.21	-7	Mid slope
	3 x 3	-7	
	1 x 0.21	-4	Toe slope
	3 x 3	-4	
GG3	1 x 0.33	-5.5 (with vegetation) -0.5 (without vegetation)	Upper slope
	3 x 3	-5.5 (with vegetation) -0.5 (without vegetation)	
	1 x 0.33	-0.5	Mid slope
	3 x 3	-0.5	
	1 x 0.33	3	Toe slope
	3 x 3	3	

According to the RMR analysis, the sum of the values for rock in all three slopes is classified as the very good and good categories. Later SMR analysis revealed that the quality of rock masses from class I (extremely stable) to class IV (moderately unstable) (unstable). Three slopes were found to be very stable, five were found to be stable, one was found to be slightly stable, and two were found to be unstable, according to the SMR analysis. Figure 5 compares the SMR and RMR for the investigated slopes, showing the differences between the GG1, GG2, and GG3 classifications. Based on the data provided, one slope had a lower SMR value than the others, but this was not always the case. There was no statistically significant difference in overall rating (less than 10).

At the same time, there were situations where the SMR value was too low and was classified as poorly stable, even though the RMR classification showed a good value. The unfavourable discontinuity plane orientation influenced the SMR value to be lower than the RMR. During the study, no slopes were found to be wet, which raises the possibility that their stability would worsen in water availability, particularly during the tropics' rainy season. As defined by SMR, unstable slopes were those in danger of a slope collapse brought on by either natural or anthropogenic causes (such as prolonged rainfall or slope erosion). Slopes with SMR values between 40 and 60, considered fairly stable, also showed evidence of a forthcoming risk of experiencing slope failures.

When analyzing rock falls with blocks of varying sizes, we found that the longest recorded trajectories were 5, -4, and 3 metres, respectively. When the value is negative, the rock block's trajectory does not continue down the slope but rather stops at the base of the slope. Due to a scattering of rocks and vegetative cover at the slope's base, formed regarding quarrying activities, the rock block's trajectory has halted at the foot of the slope. These gravel mounds demonstrated the efficacy of using rocks as small as gravel in rockfall prevention systems by absorbing the bounce energy of rock blocks.

The simulations also demonstrated that the starting position has no bearing on the final trajectory distance for a given rock block of any size. When measuring the rockfall of the GG1 slope starting from its topmost slope, the difference in height between the largest and smallest blocks was 5 m. The slopes GG2 and GG3 followed the same pattern. Rock mass and rock trajectory analysis indicates that an appropriate mitigation method is needed for development proposals in this area. Buffer zones should be used cautiously and forethought to prevent unintended damage to developed areas and their inhabitants from geological hazards. The buffer zone was recommended to be at least 20 meters from the rock face. This is four times further than the farthest the rock could have travelled on its trajectory.

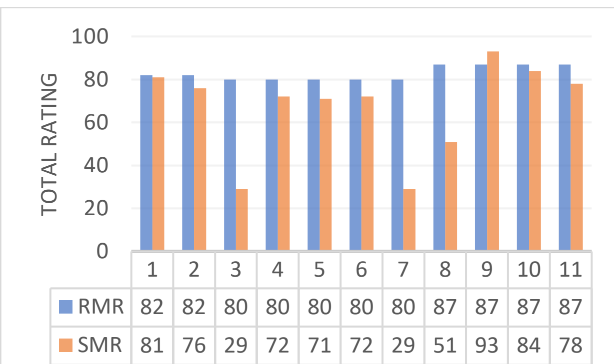


Figure 4 This study's comparison of RMR and SMR values.

4.0 CONCLUSION

This study's findings highlighted the importance of having comprehensive geological data before beginning the reclamation process at defunct quarries. Almost vertical in nature, the steep slopes of the abandoned quarry featured uneven, rough surfaces covered in loose rock blocks. As a means of evaluating the risk of rock slope failure, it was necessary to determine the rock mass classification and the potential for rockfall. Slope kinematic analysis also showed that the potential slope failures are planar, wedge, or toppling. Moreover, the RMR system's analysis of the rock bodies' quality indicated that they fell into the good and very good categories. When evaluating rock bodies, SMR may yield a low stability value if discontinuities have an unfavourable orientation. Therefore, this research's results can be applied to prioritizing slopes that have been identified as critical and thus necessitating extra care during the implementation of mitigation works. This research showed that a systematic approach can be effective, especially when dealing with a large area and needing to develop suitable mitigation measures.

Acknowledgement

Funding for this study came from the FRGS grant scheme (FRGS/1/2020/WAB07/UMK/03/1) provided by the Ministry of Higher Education Malaysia. Appreciation also goes to the Faculty of Earth Science, Universiti Malaysia Kelantan, for supporting this research.

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