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A Preliminary Assessment of Rock Slope Stability in Tropical Climates: A Case Study at Lafarge Quarry, Perak, Malaysia

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Abstract

The stability analysis of rock slopes is a complex task for the geotechnical engineers due to the complex nature of the rock mass in a tropical climate that often has discontinuities in several forms, and consequently, in several types of slope failures. In this work, a rock mass classification scheme is followed in a tropical environment using the Rock Mass Rating (RMR) and Geological Strength Index (GSI) combined with the kinematic investigation using the Rocscience Software Dips 6.0. The Lafarge quarry is divided into ten windows. In the RMR system, the five parameters uniaxial compressive strength (UCS), rock quality designation (RQD), discontinuity spacing, discontinuity condition, and groundwater conditions are investigated. The RMR values range from 51 to 70 (fair to good rock mass), and the GSI values range from 62 to 65 (good to fair rock mass). There is a good and positive correlation between RMR and GSI. The kinematic analysis reveals that window A is prone to critical toppling, window H to critical wedge-planar failure, and window G to critical wedge failure. From the results obtained, it can be concluded that the kinematic analysis combined with the rock mass classification system provides a better understanding to analyze the rock slope stability in a tropical climate compared with considering the rock mass classification system individually.

1- Introduction

A preliminary assessment of the rock slope stability is a crucial part of determining the design for a variety of engineering projects [1]. Considering rock slope in most quarries is susceptible to instability due to the variability in the rock mass condition at the site, intensive weathering in tropics, and seismic activities [2]. The sub-surface geological features such as the existence of joints, folds, and properties of rock play an essential role in the instability of rock slopes [3]. Moreover, the rock slope stability may also be influenced by height, material characteristics, face angle, and rock joint orientation.

The slope stability problems have attracted paramount concerns from the researchers, and consequently, various frameworks, methods, and criteria have been proposed in order to evaluate the slope stability. These techniques can be categorized, i.e. limit equilibrium method, numerical modelling, empirical methods, and kinematic analysis. The limit equilibrium method identifies the potential failure mechanism by assessing the driving and resisting forces that drive a factor of safety for a geotechnical structure [4]. Numerical modelling is used in more complex slope geometries, where other methods fail to represent the behavior of the slope. This method yields a factor of safety for a slope based on the stress distribution behavior and displacement [5 and 6]. The kinematic analysis is employed to predict the possible slope failure that depends on the discontinuity orientation (wedge, planar, and toppling) using the stereographic projection technique [7 and 8]. Discontinuities are mechanical planes of weakness in rock mass such as bedding planes, fractures, shear zones, joints, and foliation that can potentially assist failure [9]. The empirical

methods are auspicious tools for the systematic assessment of the rock slope stability, and they are created on the basis of the empirical relations between the rock mass properties and the geotechnical engineering applications [1].
The rock mass classification systems are the backbone of the empirical design and are extensively employed in the geotechnical field due to their simplicity and the limited data required [10]. However, these classification systems are primarily introduced in order to evaluate the stability of underground openings and tunnels [11]. These systems are introduced using the significance of parameters; each parameter has a weighting factor using numerical values. The weighting factors are substitute into an empirical formula to get the absolute rating values of rock mass [12]. These rating values help in a decision related to the design of underground structures [13]. Although the empirical classification systems are standardized for assessment of the geotechnical structure stability, few classification systems have been implemented in the rock slope stability assessment [14]. Discontinuities and characterization parameters in rock mass are the backbones of the rock mass classification systems, i.e. discontinuity condition, spacing and persistence, groundwater condition, unconfined compressive strength (UCS) and rock quality designation (RQD), infilling material, discontinuity roughness, discontinuity aperture size, and weathering [15].
The researchers have been working over the years to introduce new methods to estimate the rock slope stability. Basahel and Mitri [1] have developed a number of classification systems to evaluate the rock slope stability against the explored rock mass conditions in rugged terrain. He has revealed that slope mass rating (SMR) can be an appropriate technique for the slope stability assessment but can be further enhanced by adding the slope height parameter. Mohamed and Bayram [16] have employed SMR to perform a preliminary rock slope assessment in Turkey and have concluded that the SMR classification scheme can be effectively used for the failure classification. Ansari, Sharma [17] have assessed the rock slope in Himalayan for a possible failure using the kinematic investigation and the empirical analysis. According to RMR, GSI, SMR, and Q_{slope} provide a better perception to investigate the slope instability with a simple and prompt approach in a hilly region. Sujatha and Thirukumaran [18] have investigated a road cut slope in India using RMR, SMR, and continuous slope mass rating (CSMR), and the results obtained have shown that the SMR results are conservative, while CMSR provides a better perception for creating the spatial database.
In this work, the two rock mass classification systems RMR and GSI were chosen to evaluate the rock slope stability. The stability assessments for rock slope were conducted in a tropical climate, and the results obtained were compared. Furthermore, the kinematic analysis was employed to evaluate the potential mode failure. In Malaysia, most of the quarries deal with a slope that has varied dip angle relying on the joint and fault orientation. The higher the slope angle, the more deposit can be extracted. However, the safety working area must not be neglected by the management. Therefore, the slope stability studies are crucial to maximize the slope angle, while producing a safe working area.

2. Studied area

The preliminary study was carried out at the Lafarge quarry. Associated Pan Malaysia Cement Sdn Bhd. (Lafarge Group) operates the quarry, located at Batu 13 1/2, Jalan Kuala Kangsar, 31200 Chemor, Perak Darul Ridzuan, Malaysia (see Figure 1). Geologically, in the vicinity of the Lafarge quarry, almost the whole sequence of the Kanthan limestone formation is exposed. The discovery of the Kanthan limestone Silurian-Devonian suggests that the Kanthan limestone is the unit of Kinta valley limestone bedrock. The Kanthan limestone is partly interfingering with the slate, phyllite, sandstone, and shale deposited locally prominent. In addition, some of the sparse volcanic, chert, and interbeds conglomerate are in places.
The quarry slope (outcrops) is comprised of relatively massive and thin-bedded black and greyish-white carbonaceous spots/patches and fine-grained limestone. Similarly, about 4 m thick, cream to pinkish white-colored, fine-grained dolomite is deposited in the N-S direction in the quarry center associated with carbonaceous schist/phyllite.
Structurally, karstified, massive, and inter-bedded limestone is underlain in the quarry faces. The karstified limestone range varies from few centimeters to huge massive rock bodies. After the limestone deposition, a tectonic event led to folding, and a wavy line of limestone also inter-bedded with the fine-grained carbonaceous shale. This karstified limestone interbeds generally, striking in the N-S trending, coinciding with the local complex geological structure of Peninsular Malaysia. However, the experienced local and

moderate scale deformation resulted in folding and faulting in place.

3. Rock mass classification systems for slope

As stated earlier, two rock classification systems along with the kinematic analysis were used in this work. Rock mass rating (RMR) is based on the weighting scores of the basic parameters; hence, this case study was evaluated with the fundamental RMR values.

3.1. Rock mass rating (RMR)

RMR was developed by Bieniawski (1973-1989) to appraise the stability of the underground geotechnical structures. Correspondingly, RMR is one of the most popular classification systems employed to assess the rock slope stability. The parameters on which RMR is based are the followings: (1) uniaxial compression strength (UCS) of intact rock, (2) rock quality designation (RQD), (3) discontinuity spacing, (4) discontinuity condition (5), and groundwater condition. This is termed as the basic RMR system; it provides the weighting values in the range of 0-100 [19]. The RMR system is modified for several times; for the rock slope stability evaluation, a new parameter known as the discontinuity orientation has also been introduced [13]. In this work, the modified RMR system was used to evaluate the slope stability.

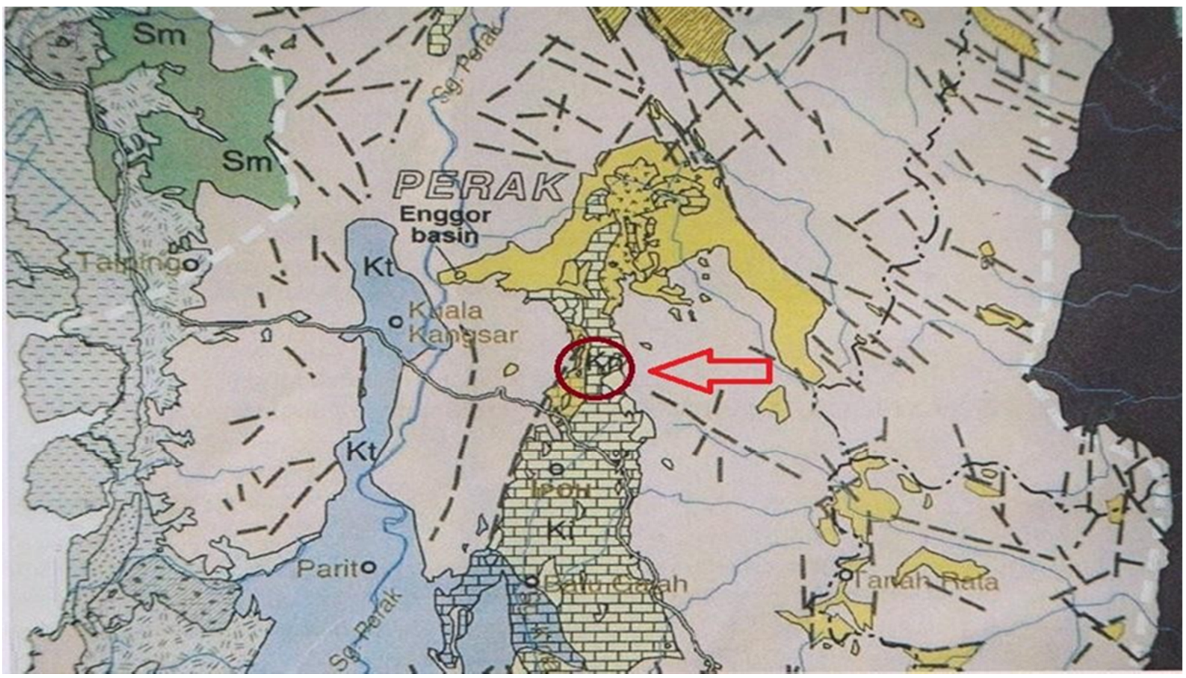

Figure 1. Location of the Kanthan rock formation, where the limestone quarry is located near Chemor, Perak (light yellow) (after technical report Kanthan, 2012).

3.2. Geological strength index (GSI)

Hoek and Brown have proposed a method by estimating the strength values of jointed rock mass based on interlocking and surface conditions of blocks [20]. This method was further modified to appraise the poor quality rock masses and a method known as GSI was established [21]. This method is based on the actual data collected from the site investigation such as lithology (physical characteristics), structure, and discontinuity condition [21]. As discussed earlier in this paper, two rock mass classification systems were employed in combination with the kinematic analysis in order to assess the rock slope stability.

4. Results and Discussion

In this work, a cement quarry was selected to investigate the slope stability using two classification systems. Window mapping is a technique used by various researchers to record the geological information and the discontinuity characteristics at the rock slope face. The quarry is divided into ten windows at an interval of 30 m for each section (see Figure 2).

Figure 2. The map showing Lafarge quarry with all windows.

The process used in this work can be categorized into two phases. In the first phase, a detailed geological mapping and laboratory testing was conducted. For the laboratory testing, the samples were obtained from each window, and the point load test (PLT) was used to analyze UCS and RQD of the rock mass. The information was measured, observed, and recorded. In the second phase, the data through geological mapping and laboratory testing was analyzed and interpreted to obtain the RMR and GSI values. The data from geological mapping was also analyzed using the Rocscience Software Dips 6.0 to evaluate the potential mode of failure.

4.1. Rock mass rating (RMR)

The results obtained from the RMR system (see Table 1) reveal that the windows A, B, C, E, F, G, H, I, and J) have the RMR values in the range of 62–70, and are classified as "good rock." Window D has an RMR value of 51, and is classified as "fair rock."

4.2. Geological strength index (GSI)

GSI was calculated for all windows based on Marinos and Hoek (2000), and the results obtained were tabulated in Table 1. The two essential parameters rock or block structure and surface condition were observed at the slope wall in order to determine GSI for the rock slope. Both parameters required a carefully and thoroughly observation to estimate the GSI values.

Table 1. Total RMR for each window.

Window	Total RMR (%) rating	Rock mass classes
A	65	Good rock
B	62	Good rock
C	70	Good rock
D	51	Fair rock
E	65	Good rock
F	65	Good rock
G	62	Good rock
H	65	Good rock
I	70	Good rock
J	65	Good rock

4.2.1. Rock structure or block size

Generally, all windows were carefully observed to ascertain the structure of the rock mass. Discontinuity orientation, discontinuities spacing, number of discontinuities, and discontinuities persistence were taken into consideration in determining the rock structure. All of these properties are a volumetric expression of the discontinuity density and important as an indicator of the rock mass quality. Throughout the observation of the rock wall, the rock structure can be classified as blocky, which can be described as well-interlocked undisturbed rock mass comprising the cubical blocks produced by three intersecting discontinuity sets.

4.2.2. Surface condition

The surface conditions of the quarry could be classified as very good, good, fair, poor, and very poor, and were observed during the geological mapping. From the observation of the surface conditions, some of it could be classified as good, while the others were classified as good to fair (see Table 2). On average, the surface condition could be described as rough to smooth. Some of the surfaces were also iron-stained and slightly weathered.

Table 2. GSI results according to the window.

Window	Structure	Surface condition	GSI value
A	Blocky	Good, slightly weathered, iron stained	65
B	Blocky	Good, slightly weathered, iron stained	65
C	Blocky	Good, slightly weathered, iron stained	65
D	Blocky	Good to fair, smooth slightly weathered	62
E	Blocky	Good, slightly weathered, iron stained	65
F	Blocky	Good to fair, smooth slightly weathered	62
G	Blocky	Good to fair, smooth slightly weathered	62
H	Blocky	Good to fair, smooth slightly weathered	62
I	Blocky	Good, slightly weathered, iron stained	65
J	Blocky	Good, slightly weathered, iron stained	65

4.3. Kinematic analysis

The kinematic analysis was conducted in order to evaluate the rock slope stability on the exposed rock slope in a quarry of Lafarge cement (APMI), Chemor, Perak. The geometric data from the geological mapping was analyzed using Rocscience 6.0. The kinematic analysis of the data was simultaneously carried out within the window by window segments (see Table 3). The mode applied while entering the data was the dip/dip direction. A total of 423 discontinuity site data was measured and analyzed. This data was compiled as a key to generate the contour of the stereonet diagram. The data also gives the discontinuity direction pattern. The kinematic analysis was carried out for all windows in order to predict the sliding potential and all the failure modes.

Table 3. Critical failure analysis of rock slopes.

Window	Plane failure (%)	Wedge failure (%)	Flexural toppling (%)	Risk tendency
A	3.70	0.00	40.74	Toppling-critical
B	0.00	9.94	1.85	Low
C	0.00	13.36	18.37	Low
D	2.44	13.78	12.20	Low
E	2.23	28.03	0.00	Wedgeless critical
F	0.00	19.40	0.00	Low
G	4.74	34.03	0.00	Wedgeless critical
H	42.55	52.64	0.00	Wedge-planar critical
I	2.33	19.95	0.00	Low
J	12.12	30.17	3.03	Wedgeless critical

4.3.1. Failure Modes

The planar and plane sliding failure modes for many rock slopes are generally in the order of 2.23–52.64%. The critical limit was recorded at 40.74% at window A (see Figure 3). The results obtained show that window A has a high tendency for toppling failure to occur. The tendency for the wedge sliding failure was also critical at window H. The critical limit for the wedge sliding mode recorded by window H was 52.64% (see Figure5) and the plane sliding recorded for window H is 42.55% (see Figure 4). Other windows could be considered as less critical (less than 30%) except for window G, which was located at the side of window H with a tendency of 34.03% for the wedge sliding mode to occur.

For the flexural toppling sliding mode, the range was around 3.74–40.74% with only a particular window showing the value inside that range. Window A had a high tendency for the flexural toppling sliding mode to happen with a value of 40.74%. Window H and window A are discussed due to the critical condition and tendency for failure to happen.

For window A, the density of high concentration was located at 160° near the south region. There were also present other concentrations in the same direction but with a different angle. The maximum density in the contour was 28.85%. As discussed earlier, window A has a high tendency for the flexural toppling failure to happen. From the kinematic analysis of the flexural toppling failures, 11 sets of discontinuities from 27 lied in the critical zone for the flexural toppling failure to happen. That makes 40.74% of discontinuities lying in the critical zone and can be considered as critical (more than 30).

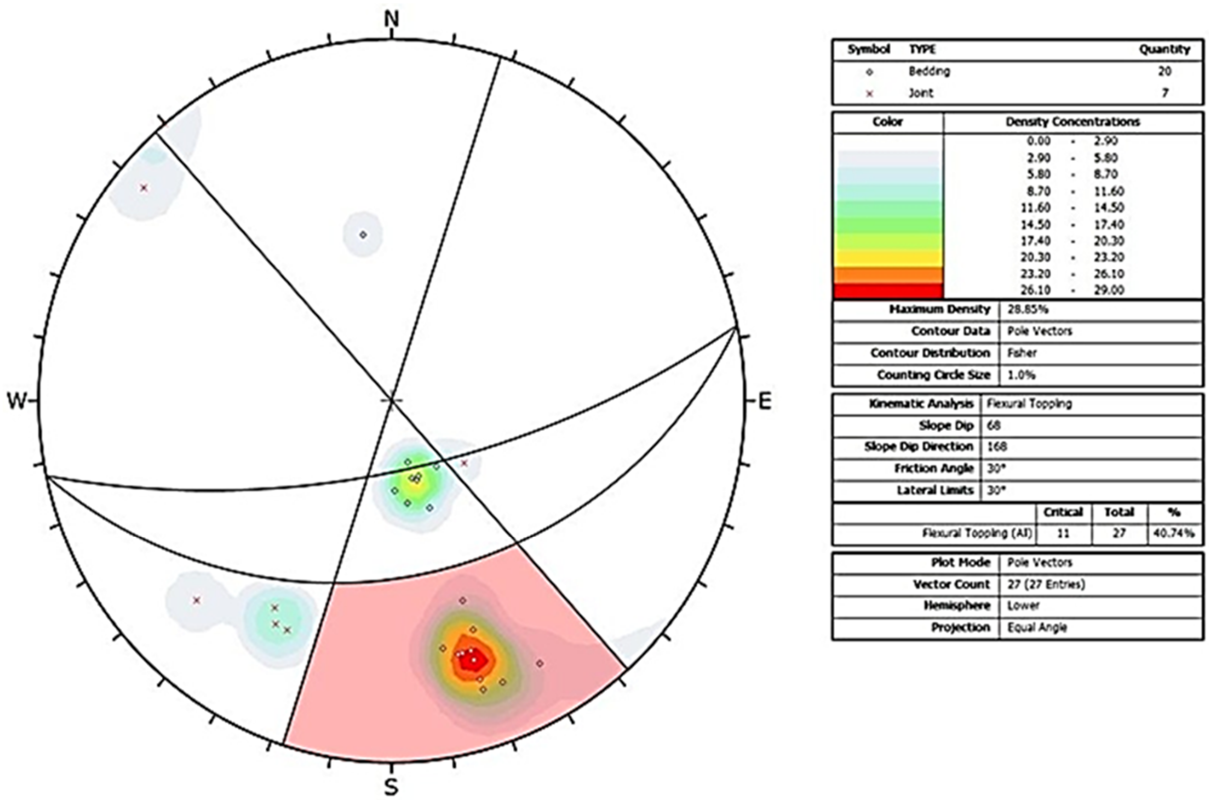

Figure 3. Flexural toppling failure for window A.

From the wedge failure contour generation by the kinematic analysis, it was found that 568 of the total intersection lying in the critical zone was susceptible to wedge failure. As we know, wedge failure tends to happen when two discontinuities intersect with each other. From the contour generation, we know that there are 1079 of the intersection of discontinuities present. However, only 52.64% of them lied in the critical zone with tendency for the wedge failure to happen (see Figure 5). From the contour, 52.64% (more than 30%) could be considered as the critical condition. Window H is required to be inspected regularly because the tendency for the failure to happen is high. The presence of the wet surface conditions (reduced rock mass shear strength, which is susceptible to deteriorate due to the moisture content) may increase the critical level of failure.

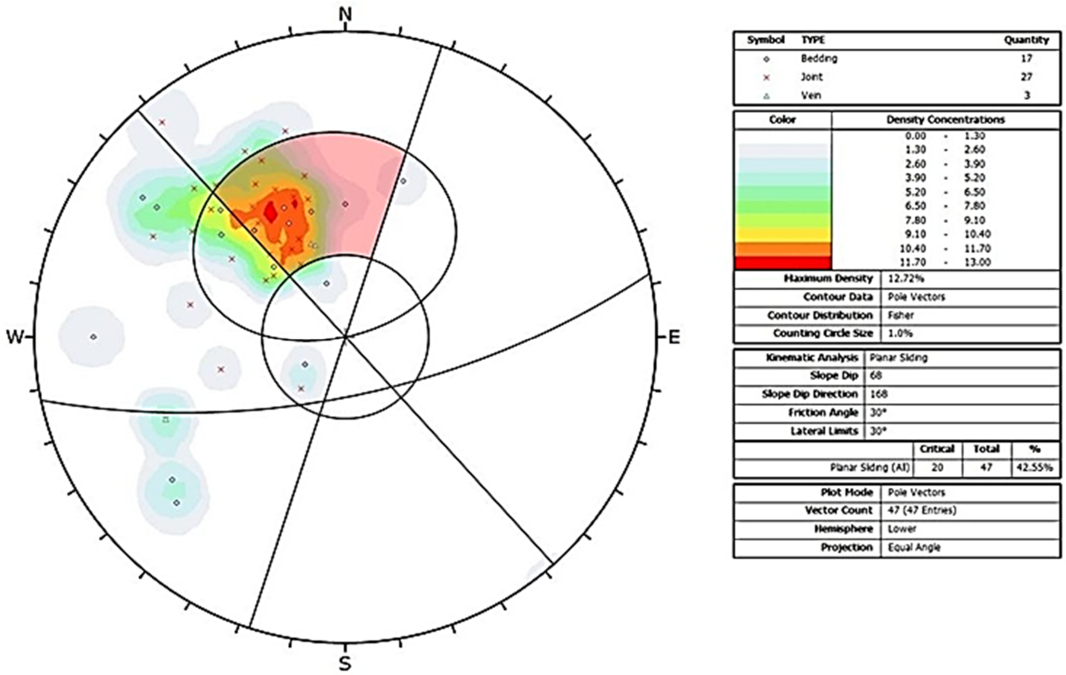

Figure 4. Stereographic projection showing the potential for plane failure for window H.

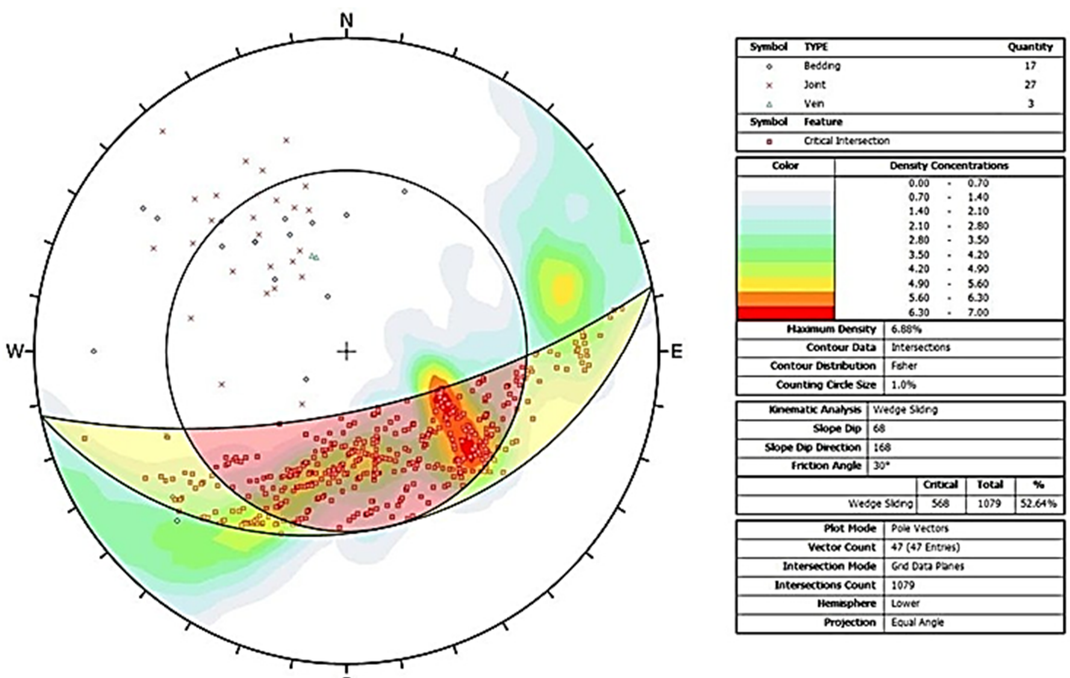

Figure 5. Stereographic projection showing the potential for wedge failure for window H.

The overall window is the overall data that represents the whole slope being studied, and this means that all the data from all windows is being entered to create the contour of stereonet and rose diagram. From the rose diagram for the overall window (see Figure 6), we could see that the direction of the discontinuities for the overall slope dominantly was at 150-160˚ in direction. This could happen due to the presence or appearance of joint sets in the same direction. The highest concentration of the discontinuities was located at 230–250˚ near the southwest region. Two contours could be seen in the west region. It can be caused by the same discontinuity location but slightly different in the dip reading.

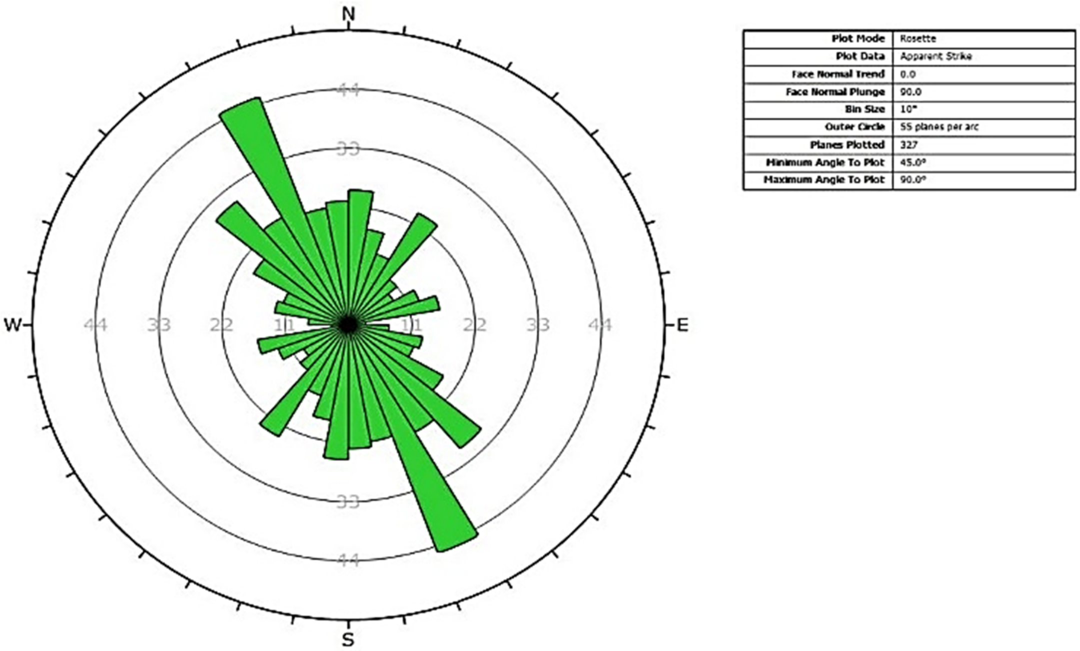

Figure 6. Rose diagram for all windows showing the discontinuity directions.

Nevertheless, the concentration was a little low compared with the first concentration mentioned before. The maximum density of concentration present was 5.71%. A total of 180 sets of bedding and 229 sets of joints were recorded. There were also present 8 sets of calcite veins and 6 sets of faults that made the total data being recorded as 423 sets of discontinuities.

For a failures mode, we go through the planar sliding failure first. For a planar sliding failure (see Figure 7), from the contour generation by the kinematic analysis, it was found that a total of 30 sets (7.09%) of discontinuities occurred within the critical zone susceptible to the planar sliding failure.

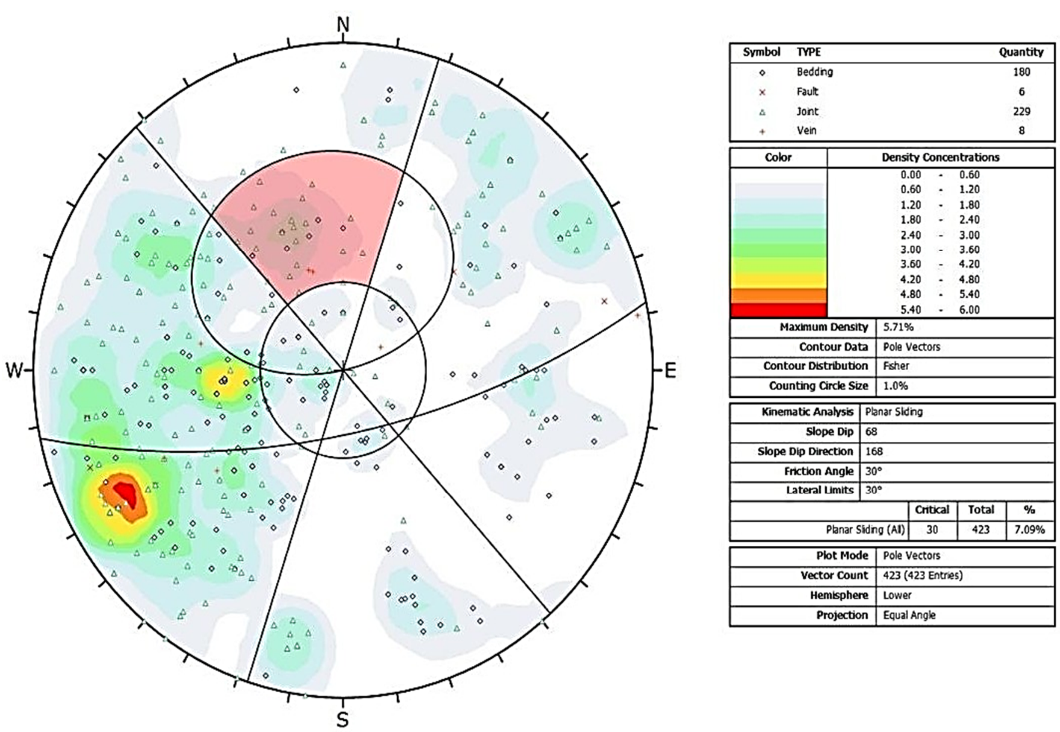

Figure 7. Planer sliding failure for overall windows.

From the wedge failure contour (see Figure 8) generation by the kinematic analysis, 20690 of the intersection was present in the critical zone for the wedge failure to happen. Notably, the wedge failure tends to happen when two discontinuities intersect with each other. From the contour generation, we know that there are 89105 of the intersection of discontinuities present. However, only 23.22% of them are located in the critical zone that tend for the wedge failure to happen. From the contour, 23.22% (< 30%) can be considered as a less critical condition. However, the presence of wet surface conditions (i.e. reduced rock mass shear strength, which is prone to deteriorate as a result of moisture content) may increase the critical level of failure.

Lastly, the kinematic analysis of the flexural toppling failures (see Figure 9) was generated by the software. 27 sets of discontinuities lied in the critical zone, being susceptible to the flexural toppling failure. That makes 6.38% of discontinuities lying in the critical zone. The requisite for flexural toppling failure to occur, a plane is required with a dip less than the friction angle of that plane or any infilling material that may be present and a dip direction out of the slope.

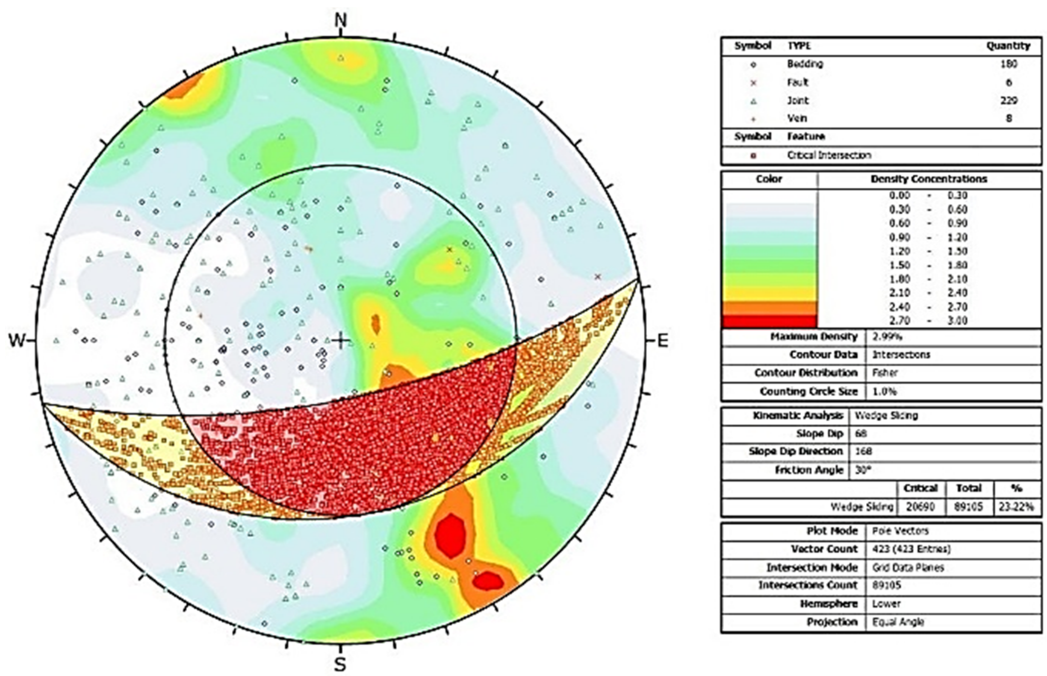

Figure 8. Wedge sliding failure for overall windows.

The original concept of GSI has been presented by [22], which is divided into twenty categories based on the geological mapping (discontinuity characteristics and visual impression). This system was modified by [23] and [24] by adding new parameters for the laminated/foliated rock masses. Further, Marionos and Hoek (2001) have presented a special GSI system for the heterogeneous rock masses. After that, it was also modified by Sonmez and Ulusey (1999) to the very poor and block rock masses. However, in this research work, we used [21] because their presented system was applied to the field characteristics.

RQD plays an important role in the rock mass classification but it is not valid for poor to block rock masses (due to the difficulty in the calculation, and often gives zero values). In this work, the RMR system was used for the rock mass classification due to the quarry containing the rocks with fair to good quality. The Kanthan quarry slope was divided into 10 windows, and was studied using the RMR and GSI systems. The RMR values in this research work ranged from 62 to 70, and the GSI values ranged from 62 to 65. RMR and GSI had a good positive correlation (shown in Figure 9), revealing that RMR increased with an increase in GSI. However, for a soft rock, the RMR and GSI values tend to reduce, while it increases for the hard and massive rocks. The regression model for RMR and GSI are presented in Figure 9. The regression model was trained using the data collected from the RMR and GSI classification systems, and the optimal equation obtained for the prediction of GSI was given in Figure 10.

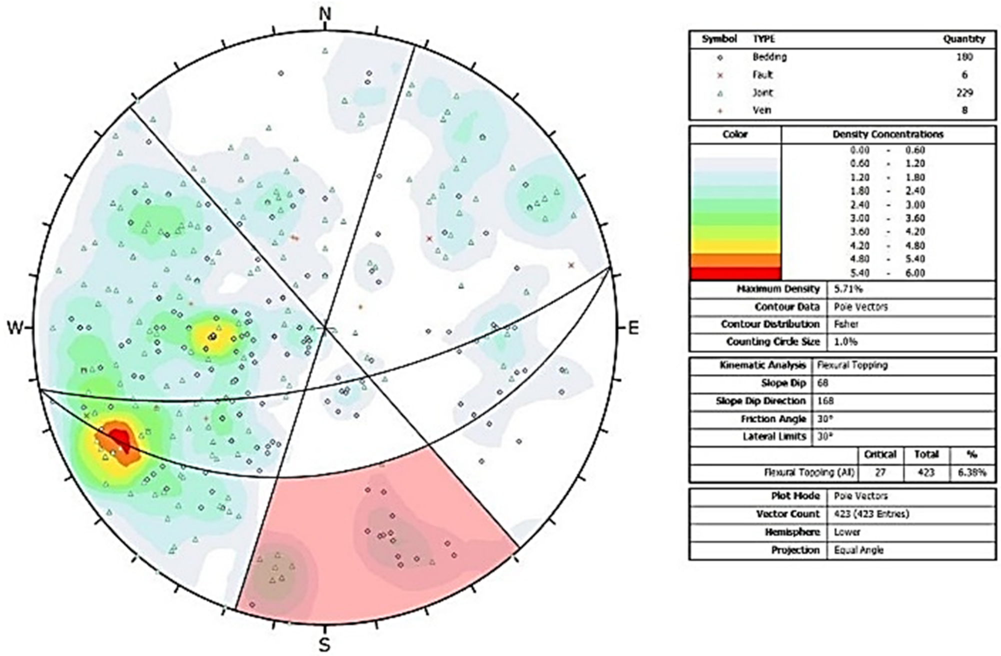

Figure 9. Flexural toppling failure mode for overall windows.

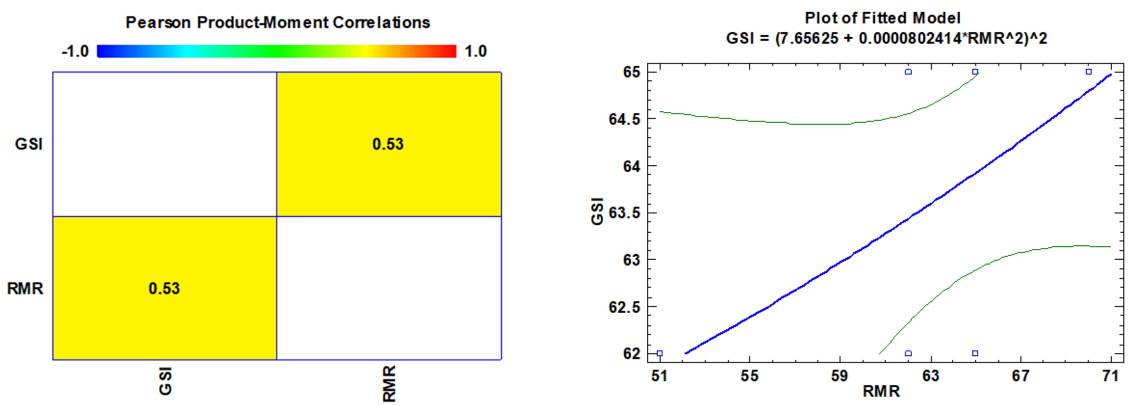

Figure 10. Correlation and regression between and RMR and GSI.

The kinematic analysis is a method used to evaluate the potential type of failure. In this work, the kinematic analysis was also carried out, combined with RMR and GSI. According to GSI and RMR, the quarry contains blocky, good to fair, and slightly weathered rocks.

Nevertheless, the kinematic analysis revealed that the windows A, G, and H were critical for failure. Hence, the rock mass classification system gives a sound knowledge about the characteristics of the slope but the results are limited to the classification. On the other hand, the kinematic analysis provides a detail for the failure mode. According to RMR, window A comprises "good rock," and it is good to slightly weathered concerning GSI but the kinematic analysis of window A is prone to critical toppling failure. The cases of windows G and H were embodied "good rock" as reported by RMR and "good to fair" as indicated by the GSI system, while according to the kinematic analysis, window G is susceptible to the critical wedge failure and window H is vulnerable to critical wedge-planar failure.

5. Conclusions

The objective of this work was to evaluate the stability of the studied slope and identification of the significant parameters that can influence the rock slope stability. The rock mass classification system was used to evaluate the stability of the rock slope. Furthermore, the kinematic analysis was carried out using the Rocscience Software Dips 6.0

to determine the tendency of failure to happen. The Rock Mass Rating (RMR) classification system comprises six parameters that identify the influence of the rock mass on the stability of the geotechnical structures. The focus of the RMR classification system was on the strength of intact rock materials, RQD, discontinuity spacing, discontinuity condition, groundwater condition, and discontinuity orientation. All of these parameters were observed, measured, and analyzed. In the RMR classification scheme, the rock mass classes were determined from the total rating for the results of the parameters obtained.

The RMR analysis obtained from each window showed that all windows, except for window D, could be classified into good rock, and window D was classified as fair rock. The RMR rating for window D was different due to the presence of water seepage at the slope face. As for the GSI classification scheme, the GSI value depends on the structure and surface condition of the discontinuities. The GSI value for each window was almost the same with only a slight difference in the range of 55-70. The GSI classification scheme requires much experience to make a precise judgment in the evaluation. Besides, the RMR classification scheme depends on six parameters compared to the GSI classification system, which considers only two parameters. From the correlation, it could be indicated that there was a positive and good correlation between RMR and GSI.

The kinematic analysis revealed that windows A, G, and H were prone to a different mode of failure, while according to RMR and GSI, these windows comprised a good to fair rock. Overall, it could be concluded that the kinematic analysis combined with rock mass classification provided a better understanding of the condition of rock slopes. Therefore, this work revealed that the rock mass classification system combined with the kinematic analysis was suitable for a rock slope stability assessment considering the weathering conditions as well as the severe weathered conditions in tropics.

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ارزیابی مقدماتی پایداری شیب سنگ در آب و هوای گرمسیری: مطالعه موردی در معدن لافراژ، پراک، مالزی

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چکیده:

تحلیل پایداری شیروانی‌های سنگی به دلیل طبیعت پیچیده توده‌ی سنگ در آب و هوای استوایی که اغلب موجب ایجاد ناپیوستگی‌هایی با شکل‌های مختلف می شود همواره برای مهندسین با پیچیدگی‌هایی همراه بوده است. در این پژوهش، یک طرح طبقه‌بندی توده سنگ در یک محیط گرمسیری با استفاده از رتبه‌بندی توده سنگ (RMR) و شاخص مقاومت زمین شناسی (GSI) همراه با تحقیقات حرکتی با استفاده از نرم افزار Rocscience Dips 6.0 دنبال می‌شود. معدن سنگ لافارژ به ده پنجره تقسیم شده است. در سیستم RMR، پنج پارامتر مقاومت فشاری تک محوره (UCS)، تعیین کیفیت سنگ (RQD)، فاصله ناپیوستگی، وضعیت ناپیوستگی و شرایط آب زیرزمینی بررسی می شود. مقادیر RMR از 51 تا 70 (توده سنگ خوب) و مقادیر GSI از 62 تا 65 (توده سنگ خوب) متغیر است. بین RMR و GSI همبستگی مثبت و خوبی وجود دارد. تجزیه و تحلیل حرکتی نشان می‌دهد که پنجره A مستعد سقوط بحرانی، پنجره H به شکست گوه مسطح بحرانی و پنجره G به شکست گوه بحرانی است. از نتایج به دست آمده، می توان نتیجه گرفت که تجزیه و تحلیل حرکتی همراه با سیستم طبقه بندی توده سنگ درک بهتری برای تجزیه و تحلیل ثبات شیب سنگ در یک آب و هوای گرمسیری در مقایسه با در نظر گرفتن سیستم طبقه بندی توده سنگ به صورت جداگانه فراهم می‌کند.

کلمات کلیدی: پایداری شیب، درجه بندی توده سنگ، طبقه بندی توده سنگ، شاخص مقاومت زمین شناسی، تجزیه و تحلیل حرکتی.