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Application of Photogrammetric and The Scanline Survey Approaches for Rock Slope Stability Analysis

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Abstract

The stability of rock slopes in quarries is a critical concern, particularly in light of the constant threat of collapse posed by ongoing blasting activities. These slopes have been assessed and analysed using a variety of approaches, including traditional field surveys and modern remote sensing techniques. Despite advancements, doubts persist regarding the accuracy and reliability of photogrammetry compared to conventional methods, despite its capability to gather vast amounts of data efficiently. This study focused on utilising both scanline surveys and photogrammetry to gather discontinuity information on rock slopes. An Unmanned Aerial Vehicle (UAV) was employed to capture visual images, from which orientation and discontinuity features were extracted. Agisoft Metashape software facilitated the creation of a detailed 3D point cloud model. Subsequently, CloudCompare was used to process the photogrammetric outputs, enabling the extraction of geological planes, which is crucial for assessing kinematic stability and identifying major discontinuity sets within the slope. The stability analysis of the rock slope was performed using PLAXIS 3D, employing both the Jointed-Rock and Mohr-Coulomb models to determine Factors of Safety (FoS). Structural failure scenarios were simulated by reducing ϕ/c parameters and applying uniform vertical loads. Analysis of dip angle and dip direction data acquired from dense point clouds using the CloudCompare compass plugin demonstrated reliability, with differences of less than 20%. The findings from scanline surveys and photogrammetry methods indicated comparable stability and a low risk of failure, as indicated by FoS values remaining above the permissible minimum threshold for stability assessment.

1. Introduction

The stability of rock slopes at quarries and mining sites is crucial because activities such as blasting and excavation can create weak points in the rock [1]. The stability of the rock depends on its shape and features, such as cracks and faults. To assess stability and risks, various methods are employed to examine these features. There are two primary methods for achieving this: traditional and advanced approaches [2]. Traditional methods, such as scanline surveys, utilise basic tools but have limitations. They are often challenging and hazardous to perform in high or hard-to-reach areas and can be time-consuming and costly.

The site investigation is somewhat biased, hazardous, time-consuming, and expensive [3]; therefore, advanced methods utilise remote sensing technologies, such as drones, which facilitate the collection of detailed data about rock slopes [4]. This approach enables more effective analysis and helps prevent damage to infrastructure by monitoring and managing geohazards more efficiently.

However, conventional methods remain the preferred approach for measuring the stability of a rock slope, and some people continue to question the accuracy and validity of the photogrammetry method. This study was conducted to evaluate the numerical stability assessment of rock slopes using digital photogrammetry and the scanline survey approaches. The roles of discontinuities were evaluated to determine their influence on the slope stability assessment of a rock slope. The extraction of orientation and discontinuity features from visual images can be captured by a low-cost UAV through the application of photogrammetry for assessing rock slope stability. To achieve this, the drone was flown to capture multiple overlapping images of the rock slope surface and Agisoft Metashape software was used to generate the 3D dense point cloud model.

The photogrammetry data were imported into CloudCompare to identify geological features and assess the stability of rock slopes. For this task, the FACET and Compass plugins can be used. While FACET has been commonly used in past studies, this study employed the Compass plugin to analyse rock slope models. The dip and strike data from both CloudCompare and a scanline survey were then imported into Stereonet 11 for further analysis. This involved plotting the dip and strike to create a diagram of discontinuities and joint sets. By analysing these, the potential failure modes of the rock slope were determined. Finally, the results from the CloudCompare data (gathered via UAV photogrammetry) were compared with scanline survey data to confirm their accuracy in characterising rock slopes.

There are limitations to assessing rock slope stability using the Limit Equilibrium Method (LEM) alone [5]. Several studies have compared beforehand the results of slope stability analyses using the LEM and FEM methods [6]-[10]. In this scenario, applying numerical approaches such as the Finite Element Method (FEM) enables engineers to conduct more comprehensive rock slope stability evaluations. In this study, FEM numerical methods were used to assess the numerical stability of a rock slope. The Factors of Safety (FoS) value of the rock slope was evaluated using PLAXIS 3D geotechnical software, which employed FEM analysis. Since FEM uses soil stress-strain behaviour for slope stability modelling, this study also contains an overview of the general behaviour of jointed rock material. The basic properties of the rock were also determined in the laboratory to meet the parameters required [11].

2. Methodology

FYS Quarry Sdn Bhd was selected as the study site, as shown in Fig. 1(b). The quarry is situated at 5°22'47.4"N 100°28'53.9"E on Jalan Berapit, Bukit Mertajam, Pulau Pinang, depicted in Fig. 1(a). Managed by FYS Marketing Sdn Bhd, the quarry is located approximately 300 meters from a medium-density residential area to the west.

Rock blasting occurs on a weekly basis, making the rock slope vulnerable to geohazards such as rockslides. These blasting activities create new joint sets, known as blasting-induced discontinuities, which can weaken the rock mass by introducing new cracks and widening existing ones, increasing the risk of rockfalls. To protect workers and equipment, it is crucial to ensure the slopes at the quarry remain stable. Proper rock slope characterisation and mitigation measures are essential to prevent dangerous events and maintain stability.

(a) (b)

Fig. 1 *Site Location - (a) Map of the Central Seberang Perai District, Pulau Pinang; and (b) FYS Quarry location*

2.1 Rock Characterisation Tests

Some rock characterisation tests were conducted to understand the rock's physical, geological, and strength properties. The rock properties, along with the formulas from previous studies, are used to determine the dynamic and modulus properties of the rock using numerical analysis. Rock boulders, each about 300 x 250 x 200 mm in size, were collected from the study area. According to [12], a geological hammer was used to break these rocks into the sizes needed for the point load test.

At the lab, the rock blocks were cut into specific sizes using a rock masonry machine. Five samples were prepared for basic friction angle tests, and two additional samples were prepared for the Brazilian test. The dynamic and modulus properties were determined using correlations from earlier research. Table 1 summarises the formulas used for determining these properties.

Table 1 *Summary of formula used for the rock characterisation tests*

No	Parameters	Formula/Correlation used	Sources
		Geological Properties	
1	Weathering Grade	e Weathering Classification System – N values	Schmidt rebound hammer
		Dynamic and Modulus Properties	
2	Basic friction angle, φ_i	φ_i = median βi =1,...,5	[13]
3	Density of the rock, ρ	$\rho = w/V$	[14], [15]
4	Unit weight of the rock, γ	26 - 27 kN/m^3	[16]
5	Shear modulus, G	$G = E/2\,(1+V)$	[10]
6	Bulk modulus, K	$K = E/3\,(1+2V)$	[10]
7	Cohesion, c_i	$c = \frac{1}{2}(\sigma_c.\sigma_t)^{1/2}$	[17]
8	Young's modulus, E	E_t = 0.3793 (UCS) + 11.928 E_s = 0.3699 (UCS) +11.805	[18]
9	Poisson's ratio, v	$v = \frac{1}{2}(1 - \sin\varphi)$	[17]
		Rock Engineering Properties Testing	
10	Uniaxial Compression Strength, σ_c	UCS = (20, ... ,25) I_{s} 50	[11], [19]
11	Tensile strength, σ_t	$\sigma_t = 0.636\,P/D_t$	[20]

2.2 Geological Plane Extraction

Geological planes were extracted using CloudCompare and a scanline survey, and then analysed to determine rock slope discontinuity orientations, which were correlated with kinematic analysis in Stereonet 11. First, point cloud data from Agisoft Metashape was imported into CloudCompare, which uses the Compass plugin. This plugin helps analyse rock models by measuring and organising geological data. It has two modes: Compass Mode for measuring orientations and thicknesses, and Map Mode for outlining geological units. In this study, Compass Mode was used to manually measure planes in virtual space. The Compass Plugin plane distances based on the point cloud vertices. Fig. 2 illustrates the workflow in CloudCompare.

2.3 Kinematic and Numerical Stability Analysis

The kinematic analysis was conducted using Stereonet 11 software to identify potential failure causes and the major joint sets of the rock slope. The orientations on stereonets can be discovered visually or by applying density contours to the stereonets, as described by Dewez et al. [21]. Stereonet 11 was used to quantify the chance of possible failure in the various forms of planar sliding, wedge, or flexural rock slope failure. For slope stability analysis, PLAXIS Software is used to analyse 3D rock slope stability. This software is used to calculate the FoS of 3D failure surfaces on rock slopes. The selected research area was divided into three zones: Zone 1 (5 m), Zone 2 (5 m), and Zone 3 (5 m). A 3D model of the rock slope was created in PLAXIS 3D prior to obtaining the FoS for the slope. The Mohr-Coulomb model is used for bedrock analysis, whereas the Jointed Rock model was employed for the rock slope using PLAXIS. Fig. 3 illustrates the workflow for assessing numerical stability in the PLAXIS software, while Fig. 4 displays the geometry of the 3D rock cut slope for each zone.

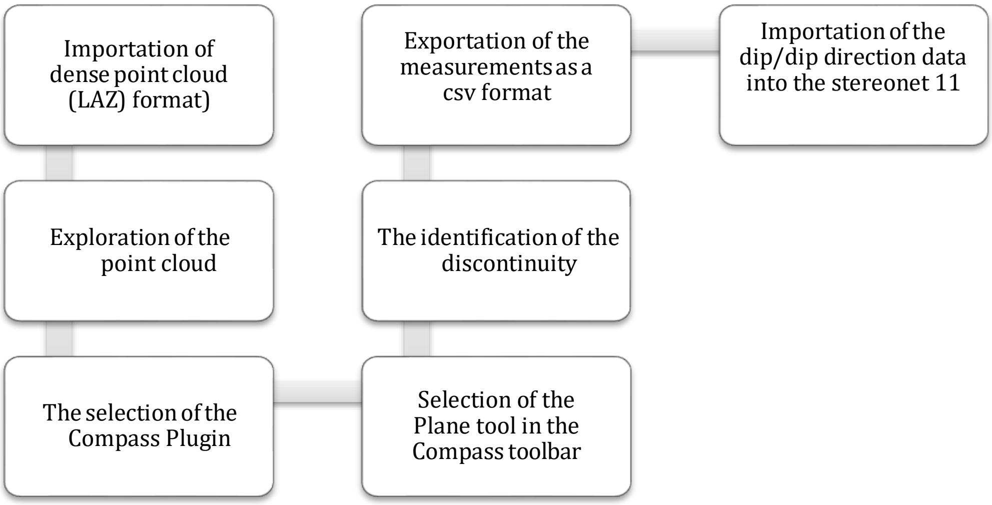


Fig. 2 *Workflow in CloudCompare software*

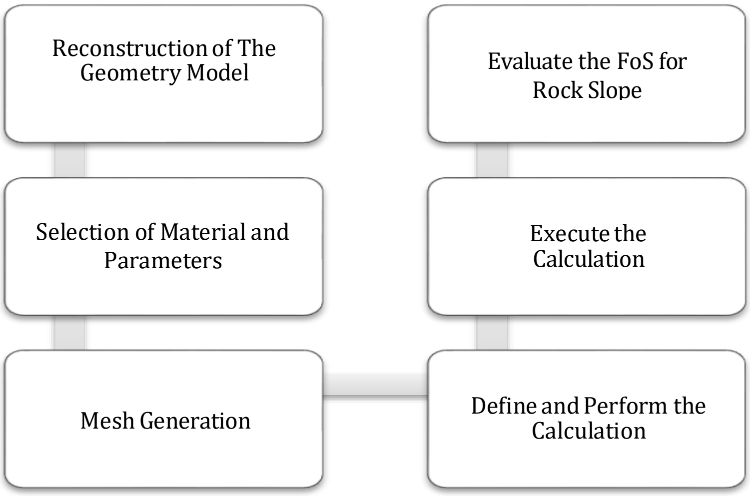
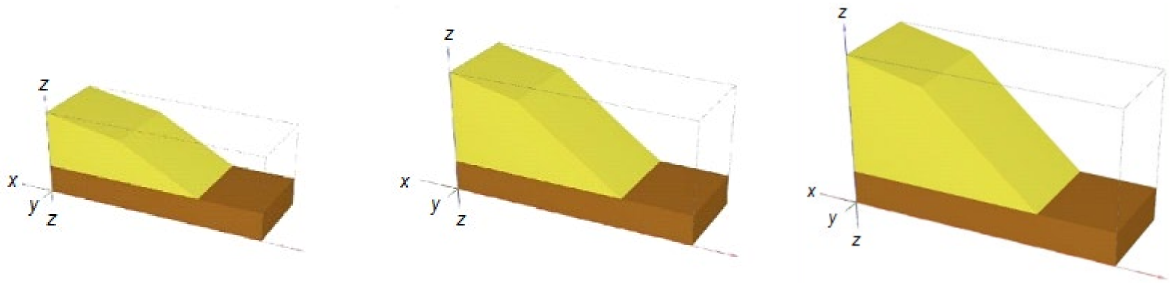


Fig. 3 *Workflow in PLAXIS 3D software*



(a) **(b)** **(c)**

Fig. 4 *The geometry of the 3D rock cut slope for each zone - (a) Zone 1; (b) Zone 2; and (c) Zone 3*

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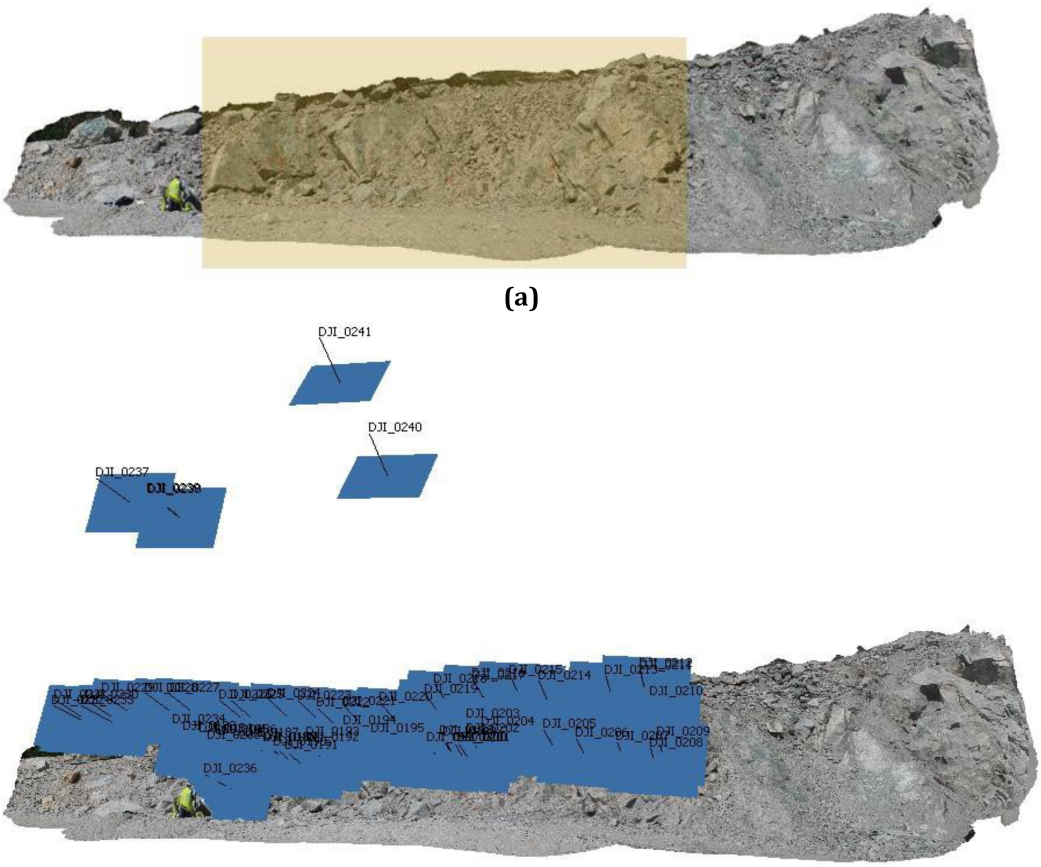
3. Result and Discussion

3.1 Rock Slope Exploration

The scanline survey and photogrammetry survey were used to collect the main field data. The photogrammetric findings are compared with a scanline survey method to validate the plane identification from the UAV photogrammetry method.

Based on the UAV photogrammetry, Fig. 5(a) shows the 3D textured point clouds created using Agisoft Metashape Photoscan software. This 3D model provided important data, including the dimensions of the rock slope, which were measured directly in Agisoft Metashape. These measurements were crucial for building the geometry model of the rock slope in PLAXIS software. The ruler tool in Agisoft Metashape was used to measure the height and distance of the 3D model.

Three key factors were considered during data capture: the angle of the photos, the overlap between photos, and the lighting on-site. Photos were taken from various angles to reduce distortion, as shown in Fig. 5(b). Typically, there was a 70% - 80% overlap between photos, consistent with previous studies. The 3D rock slope model was created with optimal lighting conditions in the morning to minimise shadows.



(a)

(b)

Fig. 5 *(a) 3D textured dense point cloud model; and (b) Camera position and orientation of the image capture by UAV*

From the scanline survey, a total of 8, 11, and 14 discontinuity orientations were identified in each zone. The dip angle and direction data from scanline surveys were imported into Stereonet 11 software to create structural plots and daylight envelopes. This was done to assess the kinematic stability of the rock slope in each zone. The resulting data are crucial for identifying major joint sets and potential failure zones on the slope.

3.2 Rock Characterisation Test

The rock slope parameters obtained from the rock characterisation tests were used as the input data into the PLAXIS Software to perform a numerical stability study on the rock slopes. Table 2 shows the summary results from the rock characterisation tests.

3.3 Geological Plane Extraction

In Zone 1, with a slope height of 3 meters, 32 discontinuities were identified (see Table 3). Zone 2, with a 5-meter slope height, had 39 discontinuities. Zone 3, with a 6-meter slope height, had 62 discontinuities. This shows that the CloudCompare Compass plugin effectively extracts and maps geological planes across the rock outcrop [22]. To verify and compare these results with scanline surveys, discontinuities were also examined in the lower part of the slopes. For this area, CloudCompare identified 9, 13, and 17 discontinuities in the three respective zones.

3.4 Comparison of Discontinuity Datasets

Table 4 shows that photogrammetry detected more discontinuities than the scanline survey. Specifically, photogrammetry identified 12.5% more discontinuities in Zone 1, 18.18% more in Zone 2, and 21.43% more in Zone 3 compared to the scanline survey. This is because discontinuities are more visible in photographs, making them easier to detect. The difference between the two methods is less than 20%, with discrepancies of 11.76%, 16.67%, and 19.35% for Zones 1, 2, and 3, respectively. Thus, photogrammetry using CloudCompare software provides reliable and accurate measurements. A difference of no more than 20% between scanline and photogrammetry data indicates that photogrammetry is a dependable method [23].

Table 2 *Summary results from the rock characterisation tests*

No.	Parameters	Value	Unit	Sources
		Geological Properties		
1	Weathering Grade	Grade II (Slightly weathered rock)	-	Schmidt rebound hammer
		Dynamic and Modulus Properties		
2	Basic friction angle, φ_i	35°		[13]
3	Density of the rock, ρ	2.69 g/cm^3		[14], [15]
4	Unit weight of the rock, γ	26 kN/m^3		[16]
5	Shear modulus, G	21.42×10^6 kN/m^2		[10]
6	Bulk modulus, K	29.79×10^6 kN/m^2		[10]
7	Cohesion, c_i	16.27 kN/m^2		[17]
8	Young's modulus, E	51.83×10^6 kN/m^2		[18]
9	Poisson's ratio, v	0.20		[17]
		Rock Engineering Properties Testing		
10	Uniaxial Compression Strength, σ_c	105.21×10^3 kN/m^2		[11], [19]
11	Tensile strength, σ_t	10.07×10^3 kN/m^2		[20]

Table 3 *Number of discontinuity orientations obtained using photogrammetry survey*

Zone	Entire slope	Lower region
1	32	9
2	39	13
3	62	17

Table 4 *Number of discontinuities obtained using photogrammetry and scanline survey*

Zone	From scanline survey	From photogrammetry survey	Percentage difference (%)
1	8	9	11.76
2	11	13	16.67
3	14	17	19.35

3.5 Kinematic Analysis

Table 5 shows that scanline and photogrammetry surveys recorded 8 and 9 discontinuities, respectively. Both methods identified four main joint sets with similar great circles. In the critical zone (the shaded area), the scanline survey's joint sets J1 and J3 intersected, suggesting a risk of wedge failure in Zone 1. Planar failure was also possible in the scanline survey's joint set J4, which crossed the critical zone. The shaded triangle indicated a risk of toppling failure if the major joint set fell within it, as seen in the scanline survey's J2. In photogrammetry, J3 and J4 also showed a pattern for wedge failure. The contoured plots, which utilised photogrammetry, were centred on the southwest and northeast.

Table 5 *Comparison of kinematic analyses plots for Zone 1*

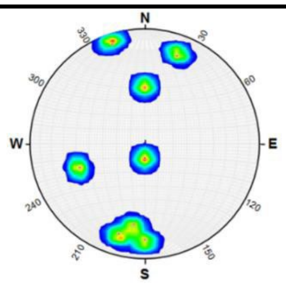
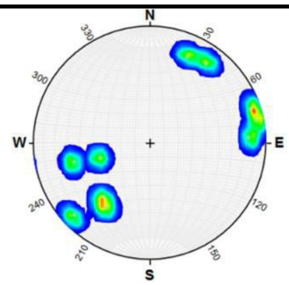
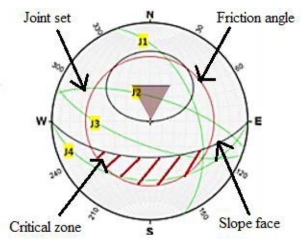
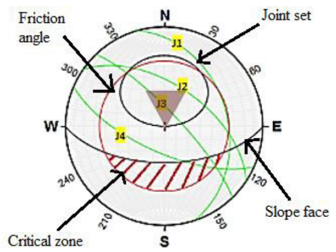
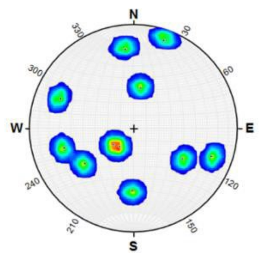
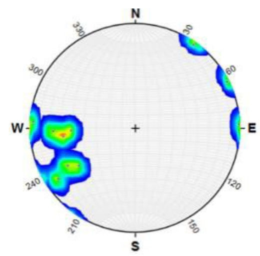
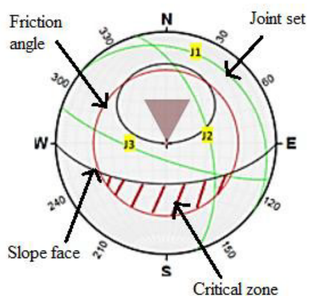
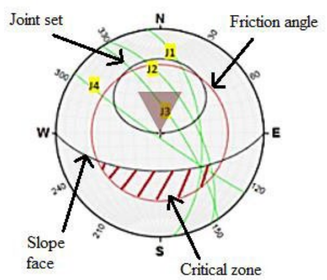
Parameters	Scanline survey	Photogrammetry survey
Contour plot of discontinuities		
Major joint set with friction angle plane		
Values of Major Discontinuity Sets (Strike/Dip)	J1 - 340°/ 50° J2 - 286° / 70° J3 - 110° / 70° J4 - 90° / 40°	J1 - 343°/ 36.2° J2 – 304.5°/ 56° J3 – 316.2°/ 78.1° J4 – 113.9°/ 68.4°

Table 6 *Comparison of kinematic analyses plots for Zone 2*

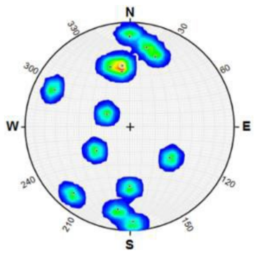
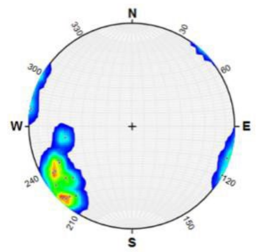
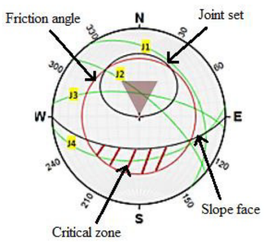
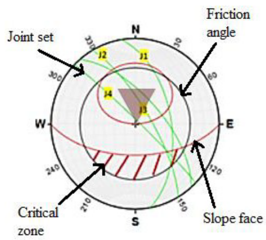
Parameters	Scanline survey	Photogrammetry survey
Contour plot of discontinuities		
Major joint set with friction angle plane		

Values of Major Discontinuity Sets (Strike/Dip)	J1 - 308°/ 18° J2 - 344° / 58 ° J3 - 109° / 78°	J1 - 353.1°/ 57.8° J2 - 330.5° / 62.3 ° J3 - 125° / 86.7° J4 - 326.3° / 76.2°

The total number of discontinuities recorded for the scanline survey was 11, and 13 for the photogrammetry method. There is a difference in the number of major joint sets recorded in Zone 2. Table 6 shows that scanline surveys had three major joint sets and photogrammetry had four major joint sets. J2 and J3 in the scanline survey great circles indicate that the probability of wedge failure would happen in zone 2. For photogrammetry, there were two major joint sets that meet in the critical zone: J1 and J3, and J2 and J4. Because of these intersections, the slope in zone 2 would experience wedge failure. According to the contour plot in kinematic analysis, the photogrammetry contour plots were more concentrated in the west direction, but the scanline survey had a scattered distribution.

There was a total of 14 discontinuities for scanline surveys and 17 discontinuities for photogrammetry. There were four main joint sets in both the photogrammetry and scanline surveys. The major joints, J2 and J4, from the scanline method intersect in the critical zone, and this could result in wedge failure, as indicated in Table 7. On the other side, the photogrammetry great circle revealed huge possibilities for wedge failure. J1 and J4 were two significant joint sets that connected in the critical zone. The contoured plots in the scanline survey were very scattered in the north and south areas, but for photogrammetry, the contoured plots were focused on the southwest side.

Table 7 *Comparison of kinematic analyses plots for Zone 3*

Parameters	Scanline survey	Photogrammetry survey
Contour plot of discontinuities		
Major joint set with friction angle plane		
Values of Major Discontinuity Sets (Strike/Dip)	J1 - 324°/ 32° J2 - 310° / 72 ° J3 - 278° / 69° J4 - 83° / 49°	J1 - 350°/ 54.8° J2 - 329.3° / 75 ° J3 - 318.4° / 64.6° J4 - 313.8° / 86.6°

3.6 Numerical Stability Analysis

The factor of Safety (FoS) is the ratio of the resisting force to the driving force in a particular block. The purpose of determining the FoS value is to determine the rock slope's vulnerability to geohazards. The major discontinuity sets of dip and dip direction data that were collected during the Kinematic analysis in Stereonet Software (using the data obtained from Scanline and Photogrammetric data), were used to calculate the FoS for all the 3D rock slopes. The FoS value was determined by using Eq. (1) and by generating a graph $\sum Msf$ versus |u|.

$$\text{FoS} = \frac{\sum_i^n Resisting\ Moment\ (i)}{\sum_i^n Driving\ Moments\ (i)} \quad (1)$$

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The FoS value will drop below 1.00 when the driving force exceeds the resisting force, indicating failure. However, the minimum acceptable FoS of the local and global stability for the unreinforced slopes is 1.3 [24]. This is consistent with the acceptability criteria for the jointed rock slopes that were mentioned by Priest et al. [25]. Hence, the rock slope is sufficiently stable if its FoS value is more than 1.3.

The Factor of Safety (FoS) values are 4.12 for Zone 1 and 2.99 for Zone 3 (see Table 8). In Zone 2, two FoS values were obtained from the photogrammetry survey due to two intersecting major joint sets in the critical zone: 3.34 (Set 1) and 3.99 (Set 2). All these FoS values exceed 1.3, indicating that the rock slopes are stable and unlikely to collapse. Slopes with FoS values between 1.0 and 1.3 may require stabilisation; however, since all values are above 1.3, no stabilisation measures are necessary based on UAV photogrammetry [26]. The scanline survey also confirms that the rock slopes are stable. Thus, unless additional loads or changes occur, no further mitigation is needed. The percentage difference between scanline and photogrammetry results is small in Zone 1 and slightly larger in Zones 2 and 3.

Table 8 *Comparison of FoS values from scanline and photogrammetry survey*

Zone	FoS value			Percentage Difference (%)	
	Scanline Survey	Photogrammetry Survey			
1	3.87	4.12		6.26	
2	2.90	3.34 (Set 1)	3.99 (Set 2)	14.10	31.64
3	2.18	2.99		31.33	

4. Conclusion

This study investigated the impact of discontinuities on slope stability using both traditional (Scanline Survey) and advanced (Photogrammetry Survey) methods at the FYS quarry in Bukit Berapit, Bukit Mertajam, Pulau Pinang. Due to access issues, scanline surveys were unable to measure discontinuities on the upper parts of the slope.

The study found that the dip angle and direction data from the dense point cloud, obtained using the Compass plugin in CloudCompare, were accurate, with method differences of less than 20% (11.76% for Zone 1, 16.67% for Zone 2, and 19.35% for Zone 3). Both methods indicated similar failure risks in the lower slope region, indicating that photogrammetry is a reliable method for assessing geohazards. The results suggested a potential for wedge failure in all three lower slope zones. With Factor of Safety (FoS) values above 1.3, the slopes are considered stable and unlikely to fail. Future research should focus on improving photogrammetry techniques to enhance accuracy and image quality.

For rock property assessments, direct tests are preferred over indirect tests, such as the point load test, which may be less accurate, especially for weak or weathered rocks. Current numerical analysis software has limitations, struggling to accurately model rock faces and display all joints and discontinuities. To improve stability assessments and data accuracy, using software without these limitations is recommended. Advanced tools, such as Rocscience Slide3, RS3, or FLAC3D, should be considered for more complex rock slopes. This research is particularly valuable for landslide mitigation in earthquake-prone areas, such as Japan and Indonesia.

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Conflict of Interest

The authors declare that they have no conflict of interest regarding the publication of this paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***Study conception and design:*** *Syifaa Nadia Zulkifli, Nurul Ainain Mohd Salim;* ***Data collection:*** *Syifaa Nadia Zulkifli;* ***Analysis and interpretation of results:*** *Syifaa Nadia Zulkifli, Nurul Ainain Mohd Salim;* ***Draft manuscript preparation:*** *Syifaa Nadia Zulkifli, Nurul Ainain Mohd Salim, Diana Che Lat. All authors reviewed the results and approved the final version of the manuscript.*

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