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Enhancement of Point Cloud Data for Rock Slope Stability Analysis

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Abstract

Unmanned aerial vehicle (UAV) photogrammetry offers a safe and efficient alternative to manual rock mass characterization in hazardous terrain. This study evaluates quality control measures, compares the discontinuity of accuracy data with and without Ground Control Points (GCPs), and performs kinematic a stability analysis of a sedimentary rock slope. Using a GPS-integrated drone and GNSS coordinates, a high-resolution 3D model was generated in Agisoft Metashape, and discontinuity orientations were extracted using CloudCompare. Results indicate that optimal UAV camera angles and an image overlap of 60%–80% are critical for achieving high model fidelity. Incorporating GCPs significantly improved accuracy; the mean percentage differences in dip direction decreased from 5.21%–22.01% (without GCPs) to 1.66%–10.06% (with GCPs). Comparative analysis with manual scanline surveys demonstrated strong agreement, successfully identifying stable conditions, as well as wedge and planar failures modes. These findings underscore the necessity of GCPs in UAV-based mapping for reliable kinematic rock slope assessment.

INTRODUCTION

Rock slope stability holds a critical role in construction projects such as housing development, highways, dams, and other projects. Even though the significance of morphology in slope has been acknowledged by engineering geology, integrating structural geology mapping and theory into all phases remains a major problem. To identify the stabilization or destabilization of the rock slope, Salmanfarsi et al. [1] recommended geologists need to study geological structures such as folds, faults, and discontinuities.

The morphological properties of a rock slope can be assessed using a variety of approaches. It consists of geometric such as slope angle, height, surface inclination, surface morphology such as texture, roughness, weathering features, and structural features such as discontinuities. These data cooperatively determine the response of rock slope to gravitational forces, weathering, and external factors, requiring the characterization necessary for stability analysis and engineering design consideration. The morphological properties of a rock slope can be evaluated using either a conventional or an advanced method. The most common conventional way is to conduct a scanline survey by Stead

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& Wolter [2]. This method was enhanced from the standardized approach for estimating the rock mass quality of a rock slope by drawing a horizontal line across the outcropped rock surface and examining the discontinuity parameters introduced by Priest & Hudson [3]. However, this conventional method has several major downsides, including sample problems, accessibility, human errors which depend greatly on the geological experience of the investigators, and safety concerns as been highlighted by Kong et al. [4].

Another approach to identifying morphological properties is advanced methods that use advanced remote techniques such as digital photogrammetry by using Unmanned Aerial vehicles (UAV), which provides a fast and extensive data collection. Photogrammetry is a technology that allows for quantitative measurements and reconstruction of the geometry of solid structures using pictures and other image data. It is a subfield of remote sensing that was traditionally established as a fundamental tool in geodesy and topography but has broad applications in these areas [5-11]. The UAV, usually known as a drone, provides capabilities that conventional methods, such as scanline surveys, cannot. The studies by Kong et al. [4] and Li et al. [12] also highlighted the advantages of using drones for geological engineers to access inaccessible rock slope areas, thus enabling more comprehensive investigations. The combination of this advanced method and the conventional methods increased the characterization of the rock slope.

The kinematic analysis of rock slopes is a crucial aspect in geotechnical engineering, particularly in assessing the stability and potential failure mechanisms in jointed rock masses. At its core, kinematic analysis focuses on potential rock slope failures, which include planar sliding, wedge sliding, and toppling failures, predominantly using stereonets and graphical methods [13-14]. Few studies also incorporate other methods concurrently with kinematic analysis such as proposing a probabilistic kinematic analysis for risk management in engineering projects [13] utilizing joint plane mapping and rock mass classification [15], and fused inclinometer data and numerical modelling to assess deformation caused by excavation processes [16].

This research focuses on using the advanced method which is unmanned aerial vehicles (UAVs) in photogrammetry for sedimentary rock slope stability profile together with the quality control of the photogrammetry data obtained. Conventional methods such as scanline survey have also been performed to validate the results of discontinuities data from the rock slope surface. The potential mode of failure of the rock slope has also been analyzed by conducting kinematic stability analysis. The results of the analysis then be used to facilitate the necessary mitigation measures for the safety of surrounding infrastructures.

METHODS

Study Location

In the study area, the major rock formation is Kubang Pasu Formation which is characterized by thickly bedded sandstone and mudstone as seen in Figure 1 based on the study conducted by Maslinda et al. [17]. The study was performed at Bukit Chondong, Beseri, Perlis, Malaysia with the coordinate of N 6.55299°, E 100.23647°, the east of the Maktab Rendah Sains Mara (MRSM). Chondong is a small steep hill forming part of the N-S trending Chuping Hills in central Perlis. The area was a quarry which exposes the uppermost of the Kubang Pasu Formation.

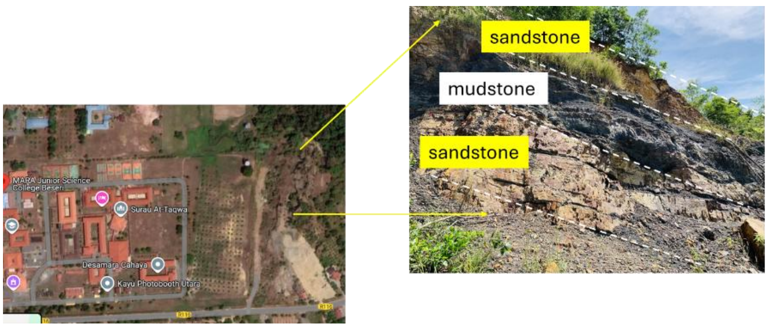


Figure 1. Bukit Chondong, Beseri, Perlis, Malaysia, with the Interbedded of Sandstone and Mudstone

Photogrammetry Survey by using UAV

The photogrammetry method is focusing on capturing high-resolution images by using drones namely DJI Spark for obtaining accurate data. Figure 2 shows the general process of UAV mapping conducted by Maes [18]. While planning for the flight, few factors should be considered, such as flight height, horizontal overlap, flight direction and viewing angle. The study also highlights the importance of sufficient area for flying the drone to capture images of the rock slope surface. Furthermore, the rock slope surface also must be exposed so that the discontinuity is visible and can be seen clearly. This study adopted flight route planning from Kong et al. [19] as a reference. A total of 943 images were taken with a varied flight height from 6–20-meter above the ground and the distance between the surface of the slope with the drone is 5 meters. Figure 3 shows the drone flight path and the three different zones for this study, Alpha, Beta, and Theta respectively.

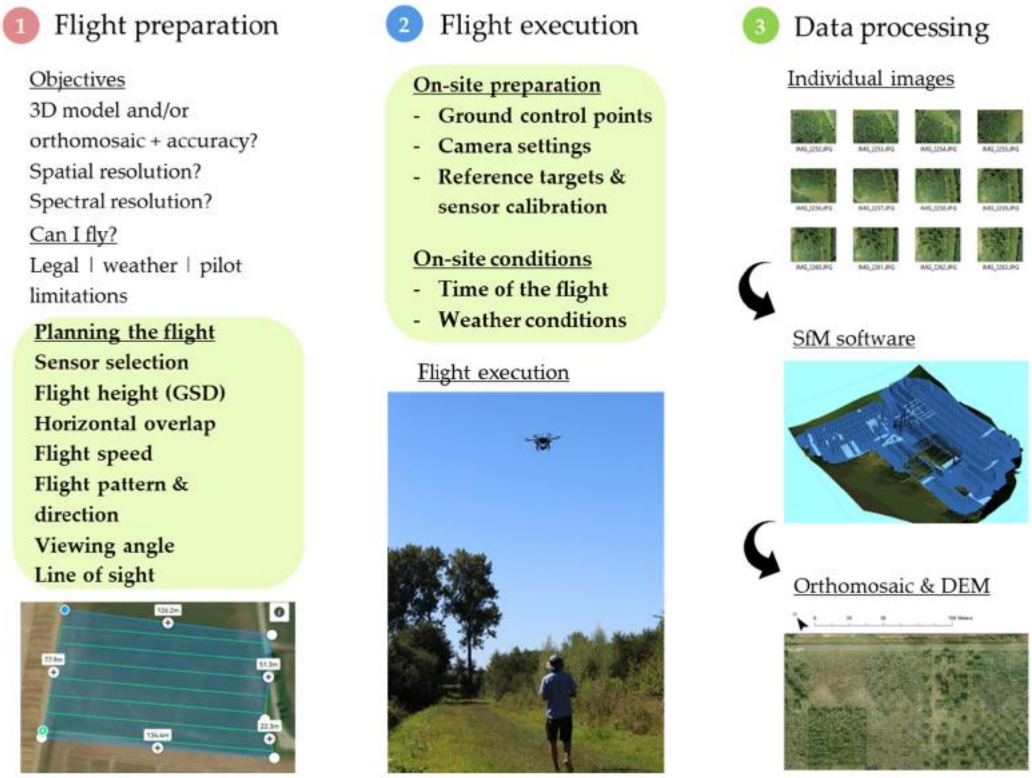


Figure 2. Overview of the UAV Mapping Process by Maes [18]

(a) (b)

Figure 3. Photogrammetry Survey: (a) Drone Flight Path, (b) Three Divided Zones

Figure 4. Ground Control Point (GCP) marked on the Slope Surface

Before starting to capture images, three locations had been chosen for marking Ground Control Point (GCP) due to three zones being separated for the sedimentary rock slope. Table 1 shows the coordinates reading of each GCP in longitude, latitude, and altitude by using GNSS Viewer apps from mobile phone. GNSS Viewer (Global Navigation Satellite System, i.e, GPS, Glonass, Beidou, Galileo, IRNSS) displays current GNSS information as reported by the built-in GNSS unit of phone (or tablet). The GCP will be marked by using spray with different colour from the rock slope so that we could identify the location of GCP from the images taken based on Tung et al. [20]. Red colour has been chosen for this site and the GCP were marked as symbol alpha, beta and theta, this mark was shown as Figure 4.

Table 1. Coordinates of Ground Control Point (GCP)

GCP	Longitude (m)	Latitude (m)	Altitude (m)
Alpha	100.236589	6.552633	28
Beta	100.236513	6.552785	36
Theta	100.236560	6.552692	34

Processing UAV Imagery Datasets

The image analysis procedure begins with the import of geotagged photos into a photogrammetry software called Agisoft Metashape Professional (64 bit). Images were stitched together to build 3D models of rock slopes. All the processes by using Agisoft Metashape software accuracy setting will be set as high for obtaining a quality of data. Figure 5 shows the step for using this software and Figure 6 shows the generated dense cloud and 3D textured model of the rock slope. There were 8 million points generated in the dense cloud. Two different datasets are produced from the same number of photographs: model without and with GCP. The dense point cloud generated and integrated with the ground control point (GCP) is then imported into an open-source software, CloudCompare, to extract the geological planes in the rock slope outcrop.

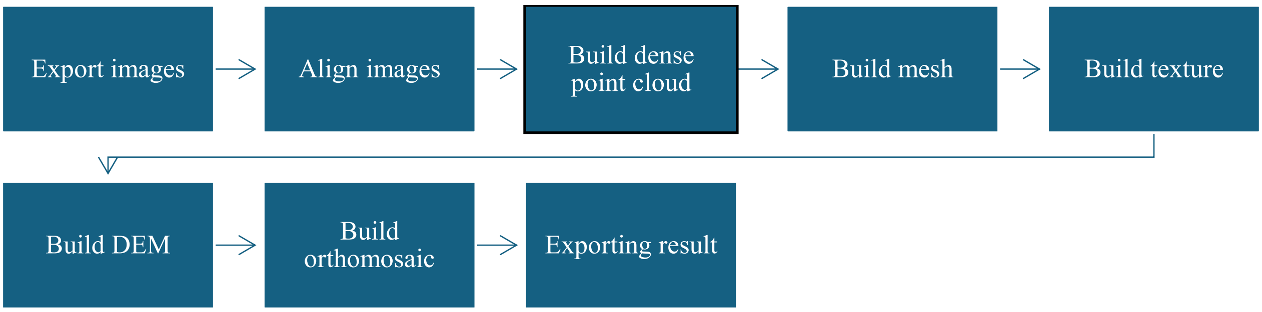
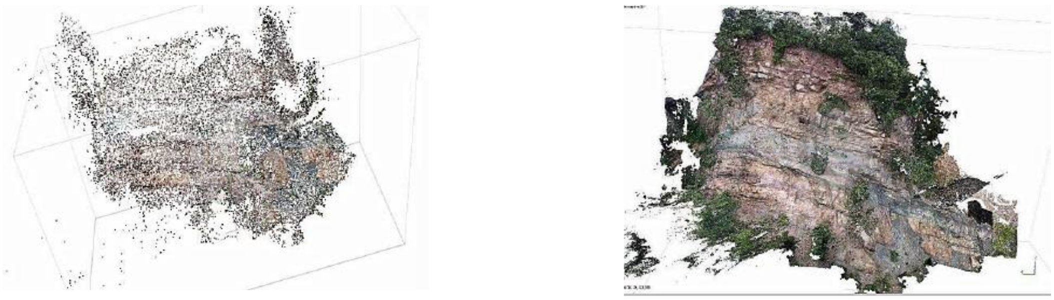


Figure 5. Overall Steps for using Agisoft Metashape Software



(a) (b)

Figure 6. Agisoft Metashape Software Outputs: (a) Generated aligned Images to a Point Cloud, and (b) 3D Textured Model

All the dip and strike measures will be taken at the lower region due to scanline survey can only access to lower region as shown in Figure 7. The data also will be measured and compare approximately 15 data due to each region only has 15 data obtained by using scanline survey. The data obtained from each region will be compared with and without GCP while scanline survey acts as baseline or benchmark. This is for obtaining the percentage difference for each zone. To obtain the percentage difference for with and without GCP, equation 1 was used.

$$Percentage\ difference, x1 = \sum \frac{total\ a - total\ b}{total\ b}\ x\ 100$$

Where:
x1 = Total percentage difference value of dip or dip direction for with and without GCP
a = Dip or dip direction with and without GCP
b = Dip or dip angle for scanline survey
*A total of 15 numbers of data
*Ignore negative sign

(a) (b) (c)

Figure 7. CloudCompare Software for Extracting Dip Angle and Dip Direction: (a) Zone Alpha, (b) Zone Beta, (c) Zone Theta

Discontinuity Orientation Acquisition by Scanline Survey Method

The scan-line technique has been the most often used method for performing a discontinuities survey as established in ISRM [21]. Since the study site chosen was accessible, this approach could be utilized to measure and gather data on discontinuity-related characteristics. According to Tung et al. [20], the slope must be between 30 and 100 metres long. In addition, according to Priest & Hudson [3], the length of the rock slope should be at least 10 to 50 times the average spacing of the discontinuities. The selected rock slope was separated into three zones, and dip and strike measurements were taken solely on the bottom area of the rock slope. The length of the slope of the research area was measured using a measuring tape. The plane orientation of every discontinuity was then assessed using a geological compass, as demonstrated in Figure 8.

Figure 8. Measurement of Dip Angle and Dip Direction by using Geological Compass

Potential of Orientation Failure

Rock slope stability analysis involves evaluating whether a rock slope will remain stable or fail under various conditions. This study conducting kinematic analysis by utilizing stereographic projection on UAV datasets. Kinematic analysis involves interpreting the spatial connections of geological discontinuities regarding the slope to assess the possibility of potential for the several types of rock slope failure such as planar sliding, wedge, or toppling failure. Stereonet 11, an open-source programme, was utilised in this study to evaluate the possible type of failure. For graphical kinematic analysis, Stereonets are used. Stereonets are circular graphs that are used to plot planes depending on their dip and strike orientations. On a Stereonet, discontinuity orientations can be represented as large circles, poles, or dip vectors.

The kinematic analysis approach begins with the drawing of discontinuity poles on a great stereographic circle. After identifying the individual discontinuity sets, the average or typical plane of discontinuity for each set was displayed. The friction circle = friction angle and slope face orientation strike and dip of the discontinuity are plotted to estimate the possible failure mode, and therefore the potential mode of failure able to be determined. Figure 9 shows the great circle of discontinuities produced by using Stereonet 11 software.

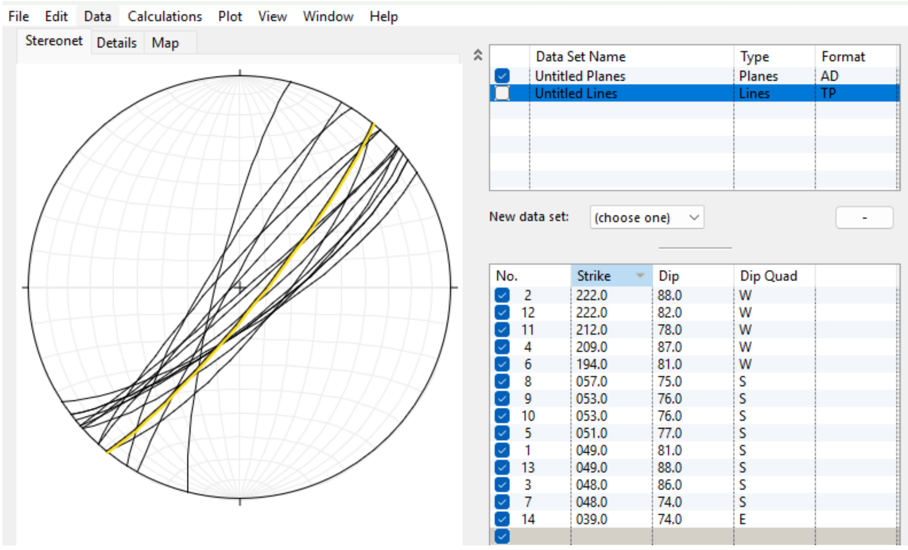


Figure 9. Stereonet Software for Determination of Potential Mode of Failure of the Rock Slope

RESULTS AND DISCUSSION

Quality Control Measures in Photogrammetry Method

From the study, two factors in survey considerations during capturing the data , which are the angle of image taken and overlapping between the images were observed and analyzed.

Angle Position of the UAV

The angle at which images are captured during data collection significantly influences the alignment process in developing the 3D model as highlighted by Maes [18]. Systematically capturing photos from multiple specific angles, rather than a single viewpoint, helps minimize distortion in the reconstructed model. Figure 10 illustrates the UAV image capture locations, where the blue squares represent the angles and positions used for data acquisition. This approach improves safety by providing better oversight of the surface of the slope.

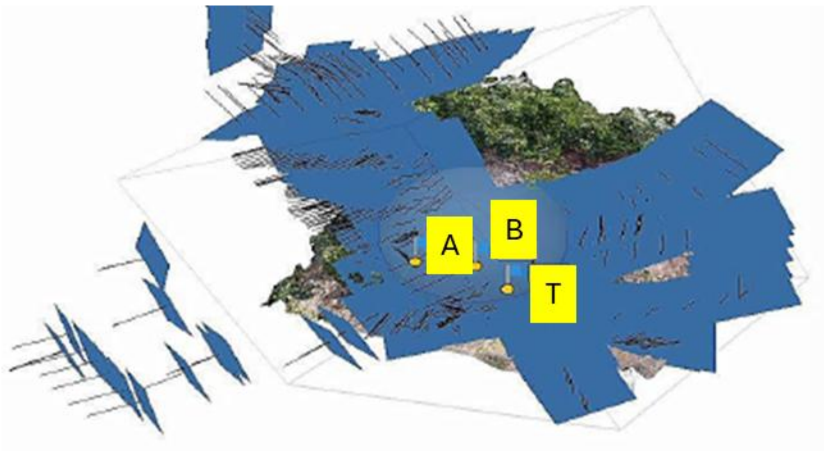
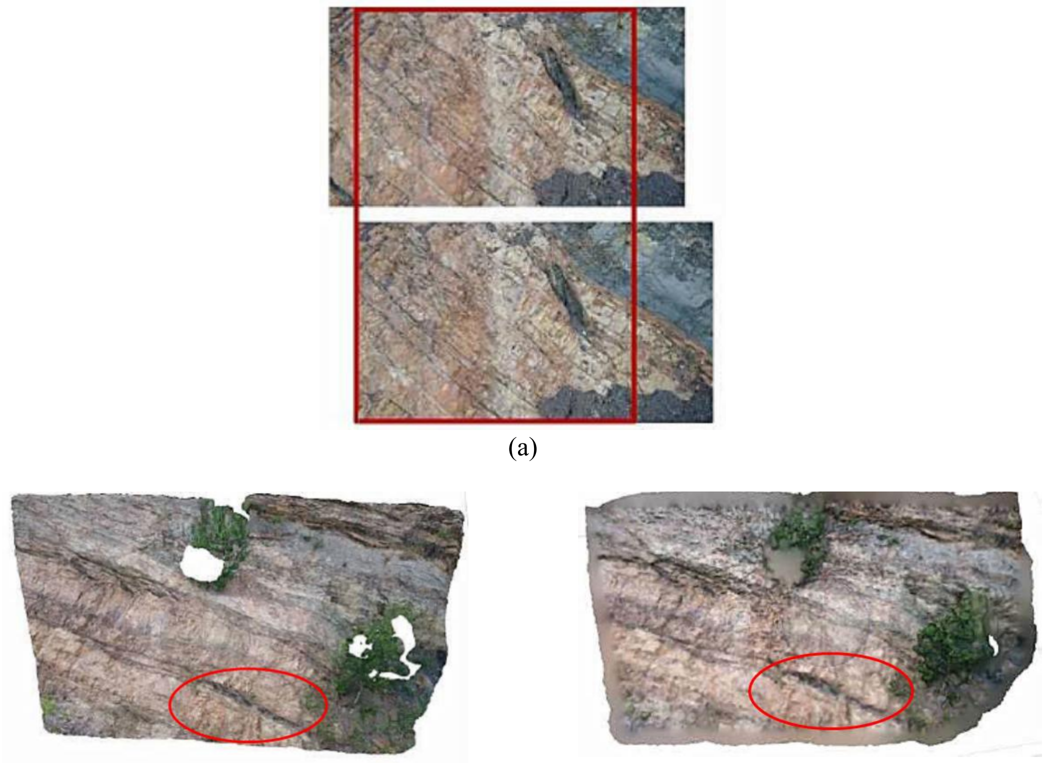


Figure 10. Different Angles and Positions of Photogrammetry Camera

Overlapping between Images

The vertical and horizontal overlap between photos is an important aspect in producing an accurate 3D model of the rock slope surface [18] . The pictures overlapped between 60% - 80% is known as stereoscopic overlap. However, due to imprecise texture in the image, photographs that overlap less than 60% may generate a poor-quality 3D model

[22]. This overlap is important because it results in at least 2 different picture perspectives of each object along the flight line [23]. Optimum overlap also ensures that the rock slope is mapped at the required scale with no voids, resulting in a clearer stereo model, minimizes geometric errors, and improves the accuracy of the point cloud, DEM , and orthomosaic. Figure 11 shows the example of overlapping between images, > 60% lapping and <60% lapping.



(a) (b) (c)

Figure 11. Quality of Images: (a) Overlapping between Images, (b) 80% Overlapping, (c) 60% Overlapping

Comparison of Number of Discontinuities Data Collected with GCP and without GCP

Before the results of the rock slope stability can be used in geohazard assessment, the application of photogrammetry must be evaluated. As a result, for each zone, a comparison was made between the results obtained by utilizing photogrammetry with GCP and without GCP, while scanline survey served as a baseline for the data. Scanline survey can only be assessed at the lower part of the slope due to its height; discontinuities were also chosen on the lower region of the slope using CloudCompare software. According to the comparison for zones alpha, beta, and theta, there is a difference in the value of dip and strike determined using photogrammetry with and without GCP. This may occur due to applying value of GCP during aligning the images and generating 3D slope model using Agisoft Metashape software.

Table 2. Mean Percentage Difference between with and without GCP for Each Zone

Zone / Percentage Difference	With GCP		Without GCP	
	Dip Angle	Dip Direction	Dip Angle	Dip Direction
Alpha	0.07	3.05	2.08	5.21
Beta	4.77	1.66	6.31	5.82
Theta	0.96	10.06	5.37	22.01

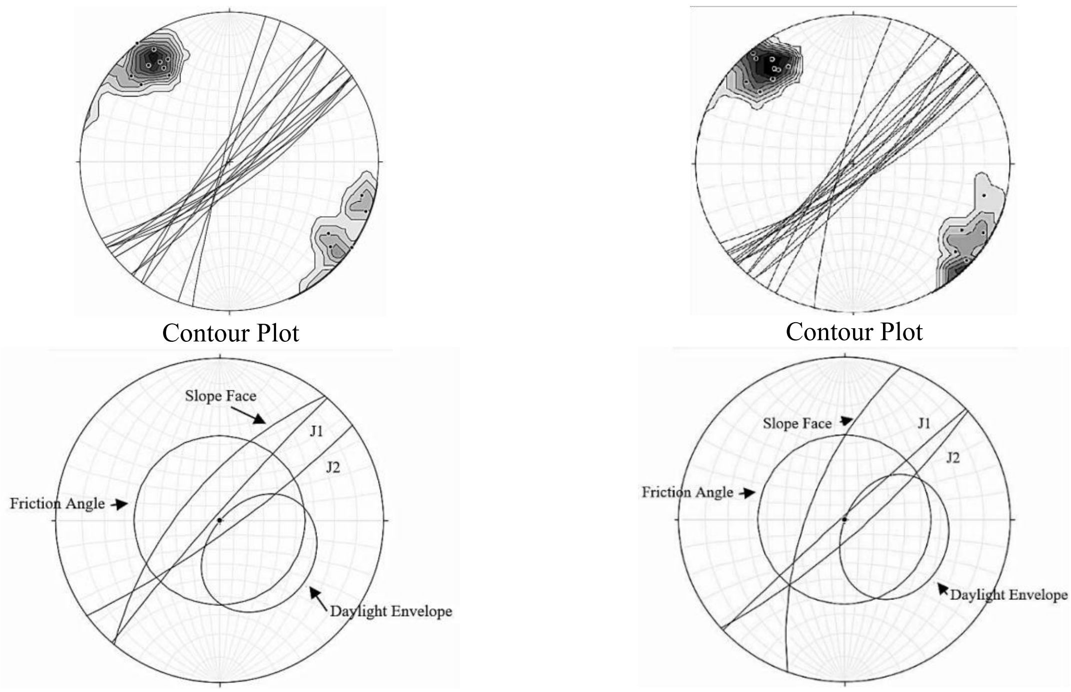
Based on the data collected at zone alpha, mean percentage difference of the discontinuities for GCP (0.07% & 3.05%) is lesser than without GCP (2.08% & 5.21%). From the results obtained we could identify that by applying GCP it increases the accuracy of the 3D model generated in this zone. Meanwhile, based on the data collected at zone beta, the mean percentage difference of the discontinuities for with GCP (4.77% & 1.66%) is lesser than without GCP (6.31% & 5.82%). From the result obtained we could determine that by using GCP it increases the accuracy of the 3D model generated on this zone. Next, based on the data collected at zone theta, the mean percentage difference of the discontinuities for with GCP (0.96% & 10.06%) is less than without GCP (5.37% & 22.01%). From the result obtained we could determine that by using GCP it increases the accuracy of the 3D model generated on this zone where the accuracy of GCP can improve more than 50% discontinuities data. The mean percentage difference of the discontinuities by using photogrammetry for with and without GCP as tabulated in Table 2. Results obtained from this study aligned with the study by Ridha et al. [24] that incorporate the three GCPs in different positions for soil slope stability analysis.

Kinematic Analysis of Rock Slope

Kinematic slope stability analysis is used to assess the potential for failure mechanisms such as planar (dip-slope) failure, which involves sliding along a single discontinuity plane (e.g., bedding), and wedge failure, which occurs along the line of intersection between two discontinuity planes (e.g., bedding and fault). The kinematic stability of a slope is governed by the geometric relationship between the orientations of these discontinuities and the slope face. In this study, a reference internal friction angle of 35° was applied, as recommended by Matheson [25]. A comparative analysis was conducted between the results derived from the manual scanline survey and the photogrammetry-based mapping to evaluate differences in failure mode prediction and structural feature identification. The degree of agreement and variation between these two methods was assessed zone by zone, providing insights into the tolerance and reliability of photogrammetric techniques as a complementary tool in geological structure mapping for slope stability assessment.

Kinematic Analysis at Zone Alpha

In this zone, two major joint sets (J1 and J2) were identified, characterized by high joint intensity in specific areas, as illustrated in the discontinuity contour plot. All discontinuity sets fall within the friction cone region, and no daylighting failure was observed. Additionally, no critical intersections between J1 and J2 were detected within the potential failure zone, indicating that Zone Alpha remains in stable condition. The results of the kinematic analysis for Zone Alpha are presented in Figure 12.



Joint Set J1: Peak Orientation = 54° / 81°
Joint Set J2: Peak Orientation = 221° / 86°
Slope Face = 220° / 70°

(a)

Joint Set J1: Peak Orientation = 48° / 88°
Joint Set J2: Peak Orientation = 227° / 78°
Slope Face = 220° / 65°

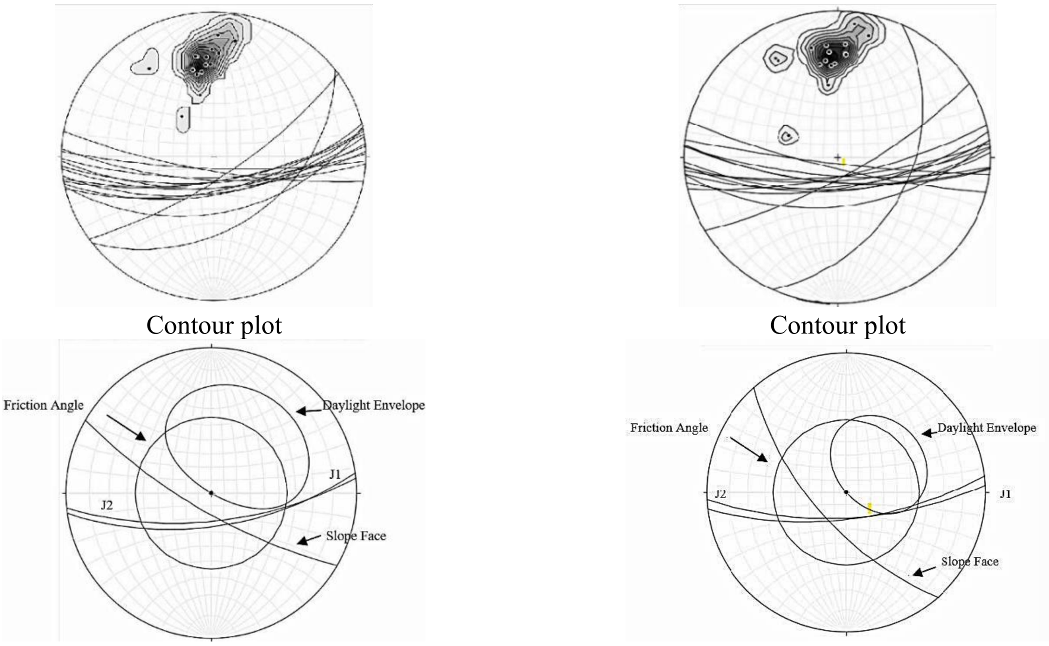
(b)

Figure 12. Comparison of Contour Plot and Major Joint Set for Zone Alpha, (a) Scanline Survey, (b) Photogrammetry

Kinematic Analysis at Zone Beta

In this zone, a total of 15 discontinuities were identified and plotted based on the photogrammetry survey. Three major joint sets were recognized, with high joint intensity observed in specific areas, as illustrated in the discontinuity contour plot. All discontinuity sets fall within the friction cone region, and no daylighting failure was detected.

However, an intersection between joint sets J1 and J2 was observed in the critical zone, indicating a potential for wedge failure in Zone Beta. The results of the kinematic analysis for Zone Beta are presented in Figure 13.

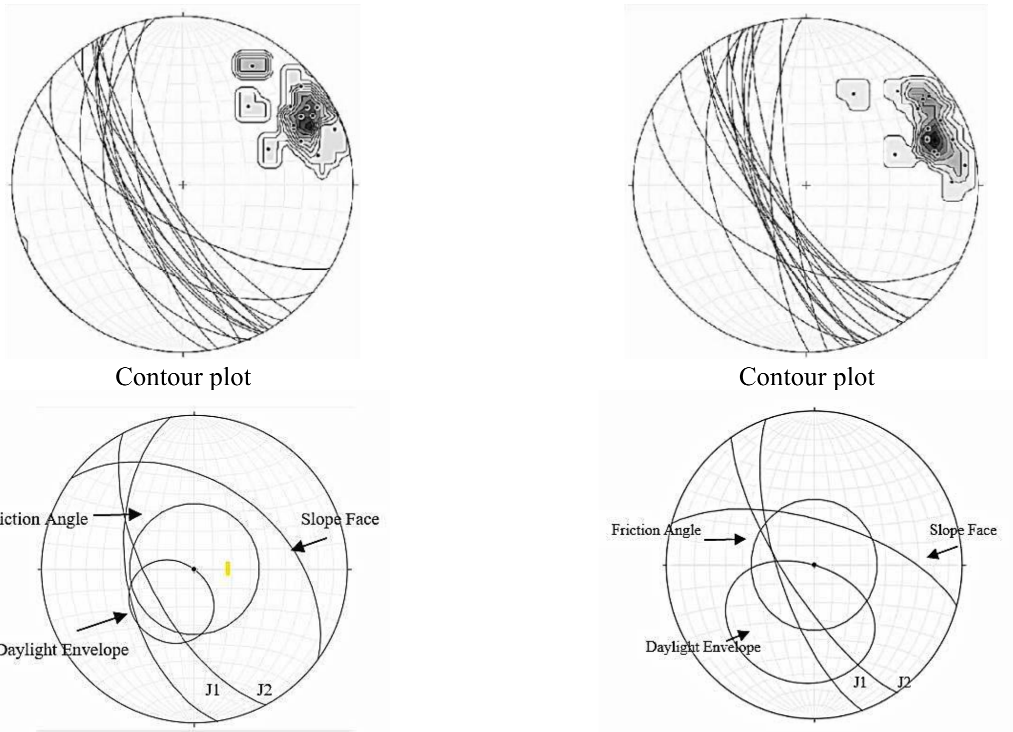


Joint Set J1: Peak Orientation = 82° / 64°
Joint Set J2: Peak Orientation = 84° / 68°
Slope Face = 135° / 75°
(a)

Joint Set J1: Peak Orientation = 90° / 70°
Joint Set J2: Peak Orientation = 82° / 70°
Slope Face = 140° / 70°
(b)

Figure 13. Comparison of Contour Plot and Major Joint Set for Zone Beta, (a) Scanline Survey, (b) Photogrammetry

Kinematic Analysis of Zone Theta



Joint Set J1: Peak Orientation = 171° / 53°
Joint Set J2: Peak Orientation = 152° / 65°
Slope Face = 295° / 65°
(a)

Joint Set J1: Peak Orientation = 161° / 70°
Joint Set J2: Peak Orientation = 146° / 74°
Slope Face = 285° / 75°
(b)

Figure 14. Comparison of Contour Plot and Major Joint Set for Zone

In this zone, a total of 15 discontinuities were plotted based on the results of the photogrammetry survey. Two major joint sets were identified, exhibiting high intensity in specific areas, as shown in the discontinuity contour plot. All discontinuities are located outside the friction cone region. Based on the stereonet analysis, the intersection of the two major joint sets (J1 and J2) lies within the critical zone, suggesting a potential failure mechanism. According to the photogrammetry data, Zone Theta is currently considered stable. However, the scanline survey indicates that the rock slope may be susceptible to planar failure. The detailed kinematic analysis for Zone Theta is presented in Figure 14.

The results from the manual scanline survey and photogrammetry analysis showed strong agreement in identifying potential failure mechanisms across the three zones. In Zone Alpha, no daylighting failure or critical intersections between joint sets were observed, indicating a stable condition. Zone Beta exhibited potential for wedge failure, with intersecting joint sets located within the critical zone. In Zone Theta, both methods consistently indicated susceptibility to planar failure. This consistency confirms the reliability of photogrammetry as a complementary tool for structural characterization in slope stability assessments.

CONCLUSIONS

Several quality control measures must be considered to obtain high-quality images for photogrammetry. One critical factor is ensuring sufficient image overlap, typically between 60% and 80%, known as stereoscopic overlap. This overlap is essential to avoid data gaps during image acquisition and to ensure that the rock slope is mapped at the required resolution, resulting in a more accurate and complete stereo model. In addition, capturing images from multiple angles, rather than from a single perspective helps reduce distortion and enhances the accuracy of the 3D reconstruction.

Achieving high accuracy in photogrammetric surveys for slope stability analysis also depends on the use of Ground Control Points (GCPs). By marking GCPs on the sedimentary rock slope, the camera alignment is improved, and the precise locations of key features can be georeferenced, thereby improving the accuracy of the 3D model. Results show that the percentage difference in discontinuity measurements between photogrammetry with GCPs and scanline surveys is significantly lower compared to photogrammetry without GCPs, confirming the benefit of GCP integration. For future studies, an alternative approach when GCPs cannot be used is either to use post-processed kinematics (PPK) or to combine real-time kinematics with oblique imagery.

Finally, the kinematic stability of the interbedded sedimentary rock slope was successfully analyzed using point cloud data generated from the photogrammetry survey. Geological planes were extracted using CloudCompare software, which provided the dip angle and dip direction of discontinuities for kinematic analysis. Validation of the results indicated that the predicted failure mode at the slope toe was consistent across both photogrammetry and manual methods, demonstrating that photogrammetry provides a reliable dataset for geohazard assessment and slope stability evaluation. Scalability remains a challenge, particularly in topographically complex regions. Incorporating larger UAV datasets can enhance the accuracy of the analysis, thereby further supporting slope stability analysis and disaster risk management. Other monitoring tools can also be incorporated such as Interferometric Synthetic Aperture Radar (InSAR) data to monitor slope stability [26].

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