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Integration of UAV photogrammetry and kinematic analysis for rock slope stability assessment

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Abstract: Rock slope excavation is unpreventable due to some location of infrastructure development must cut through rock hills. Therefore, an appropriate rock slope characterization should be carried out in order to prevent any possible failure. Recent advancement of drone technology has enabled the preliminary assessment on geotechnical characterization to be done in a short period of time. This paper mainly focuses on extraction of orientation and discontinuity features from drone imagery through the application of photogrammetry for rock slope stability assessment. Kinematic analysis is a method used to analyze the various modes of potential rock slope failures such as planar sliding, wedge sliding and flexural toppling that occur due to the presence of unfavorable oriented discontinuities. A drone was used to capture images from aerial and sideways, then imported to photogrammetry software to be processed. The output of the photogrammetry which is the dense cloud point would then be imported into a cloud compare software for the kinematic analysis. The orientations of discontinuities that has been extracted from the rock slope using CloudCompare software was imported into Rocscience Dips Version 7.0 software. The kinematic analysis feature of this software provides a quick check for various rock slope stability failure modes on a stereonet plot, such as planar sliding, wedge sliding and flexural toppling with just input on slope orientation, friction angle and lateral limits, before selecting the failure modes. By using discontinuity data, the kinematic analysis shows that the rock slope has 15.40% risk for planar sliding, 7.16% for wedge sliding and 1.33% for flexural toppling. Hence, the use of UAV as a tool in rock slope characterization is reliable because it can provide valuable preliminary information on rock slope stability assessment.

Keywords: UAV photogrammetry, rock slope stability, kinematic analysis, sensitivity analysis

INTRODUCTION

Manmade rock slopes are mainly created by construction of highways and roads, mining pits and quarrying. In Malaysia, some of the construction works were carried close to unstable rock slope faces (Abdullah *et al.,* 2015). Failure of a rock slope is a catastrophe, therefore it should be identified and stabilized at the preliminary stage. This is very important to avoid any loss of human life, vehicles, and infrastructures due to the rock mass wasting process. In some cases, this is unavoidable because the chosen site for the proposed construction is most strategic compared to other locations. Preliminary assessment of the rock slope can prevent many problems from occurring and able to provide some preliminary predictions on the stability of the excavated rock slope (Majeed & Bakar, 2015). Rock slope failures is primarily controlled by the orientation of the discontinuities such as joints, faults, beddings and also the angle of hillslope and direction (Li *et al.,* 2009). To assess the occurrence of potential failure, the orientation of discontinuities is determined. In this study, orientation of discontinuities was extracted with the use of photogrammetry process by using an Unmanned Aerial Vehicle (UAV) digital image to identify the geological planes.

There has been a constant improvement in the use of remote sensing technology for monitoring of natural hazards. A significant improvement in the field of remote sensing technology is particularly the use of an UAV for mapping and monitoring slope failures (Razak *et al.,* 2011). Recent advancement of new technology in UAV have made it possible to utilize unstructured digital images to produce low cost three-dimensional data. Structure from Motion (SfM) methods have been a breakthrough in modern photogrammetry method due to its new algorithm called feature matching (Sweeney *et al.,* 2015). It extracts high quality and accurate spatial data using an affordable consumer grade digital camera or UAV (Micheletti *et al.,* 2015). A SfM workflow generates X, Y and Z positions of point cloud through the process of bundle adjustment to provide the desired output such as dense point cloud, 3D model, orthophoto and Digital Surface Model (DSM).

This paper presents a stability assessment of rock slope using kinematic analysis using the geological planes extracted from the photogrammetry output which is dense point cloud. It is very useful for a risk assessment process and for initial indication of the probability of failure. The kinematic analysis method was implemented in this study to analyze the slope stability where it uses stereographic projection principles and applies them in rock slope stability assessment. Kinematics refers to the motion of bodies without any reference to the forces which cause them to move (Goodman, 1989). Kinematic analyses focus on the probability of failures due to the formation of day lighting wedges or planes of sliding. This analysis depends on the brief evaluation of rock mass structure and geometry of existing discontinuity sets that may contribute to block instability (Keaton, 2007). This assessment may be carried out by means of stereographic projection plots, that are drown by hand using a stereo net or by a computer program

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such as open Stereo program and Dips from Rocscience (Zainalabideen, 2016). Kinematic model studies may be beneficial in anticipating the most likely pattern of slope failure when multiple sets of discontinuity planes intersect in an oblique angle (Goodman, 1989).

STUDY AREA

The study area is located near Timah Tasoh, Kuala Perlis where the site has uncovered rock slope outcrops. The study area coverage is 27,700 m^2 as shown in Figure 1. The exact location of the study area is at a latitude of 6.428794 and longitude of 100.143884. Rock slopes were excavated for construction of open channel to bypass the water from Timah Tasoh dam, where the project purpose is to prevent flooding in Perlis.

METHODOLOGY

A small quadcopter which is DJI Phantom 4 Pro mounted with a 20-megapixel camera was used to capture the images. Waypoints were created to allow the drone to capture images accordingly to cover the required region. A total of 234 images were taken from the top and side views of the rock slope outcrops. The flying height was fixed at 70 m throughout the drone fly. Agisoft photoscan version 1.4.1 was used to process the imagery, the software runs through an algorithm called Structure from Motion (Sfm) which is able to detect features in the image for bundle adjustment. Sfm is a photogrammetric method that uses overlapping images to create 3D surface models. Ground controls have also been deployed at the site to make sure the photogrammetry process is able to generate accurate and reliable outputs. The outputs from photogrammetry process are 3D model, 3D dense point cloud, orthophoto and Digital Surface Model (DSM). Workflow of Agisoft is briefly explained by Lucieer *et al.*, 2014 and in the manual published by Agisoft (Agisoft LLC, 2016). Dense point cloud from the photogrammetry process is then imported into a freeware called CloudCompare. FACET is a plugin introduced by Dewez *et al.* (2016) to perform geological plane extraction, the facets can be exported in the format Comma-Seperated-Variable (CSV) ASCII file and shape files for kinematic analysis in other software. In this study, Dips Version 7.0 software from Rocscience was used to perform the kinematic analysis. Figure 2 summarizes the research methodology in the form of a flowchart.

Kinematic analysis is a method used to analyze the various modes of potential rock slope failures such as planar sliding, wedge sliding and flexural toppling that occur due to the presence of unfavorable oriented discontinuities. Discontinuities are geologic breaks such as joints, faults, bedding planes, foliations, and shear zones that can potentially serve as failure planes (Lucieer & Robinson, 2010). Different types of slope failure are associated with different geological structures and the structural patterns should be identified when examining pole plots in the stereonet as illustrated in Figure 3. Kinematic analysis is based on Markland's test as described by Hoek & Bray (1981). According to the Markland's test, a planar failure is likely to occur when a discontinuity dips in the same direction (within 20°) as the slope face, at an angle less than the slope angle but greater than the friction angle along the failure plane. A wedge failure may occur when the line of intersection of two discontinuities forming the wedge-shaped block plunges in the same direction as the slope face and the plunge angle is less than the slope angle but greater than the friction angle along the failure plane. A toppling failure may happen when a steeply dipping discontinuity is parallel to the slope face (within 30°) and dips into it (Yoon *et al.*, 2002).

Rocscience Dips Version 7.0, a graphical and statistical analysis of orientation data software, was utilized to analyse and visualise the orientation data exported from CloudCompare software. The orientation data is presented in

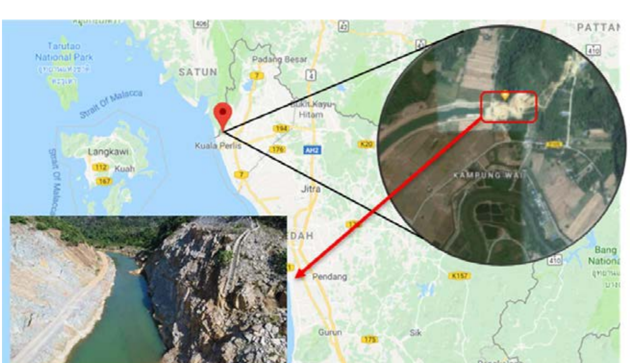

Figure 1: Location of the study area and site overview (latitude, longitude: 6.428794, 100.143884) (Source: Google Map).

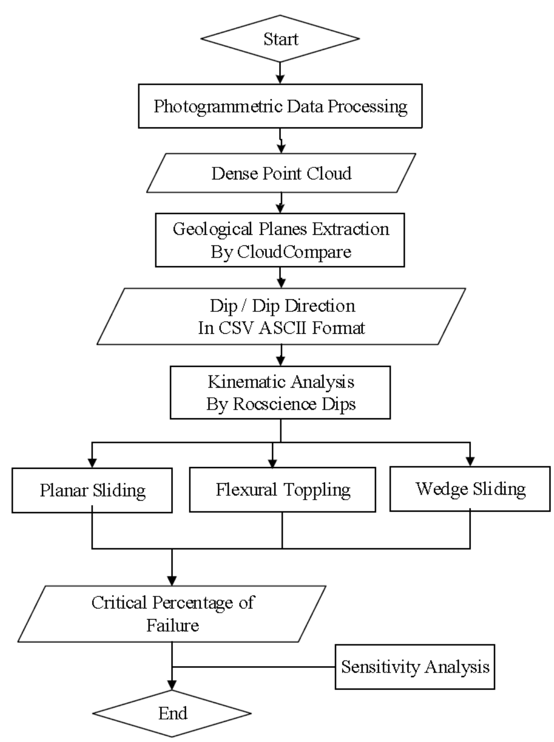

Figure 2: Flowchart of methodology.

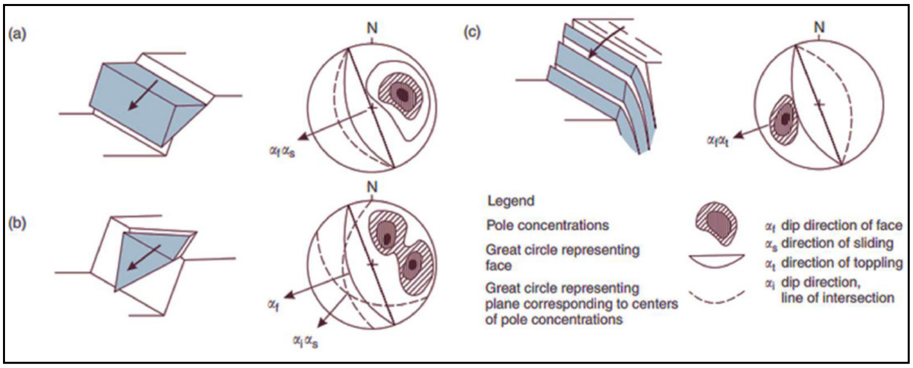

Figure 3: Slope failures and its stereonet (a) Planar sliding, (b) Wedge sliding and (c) Flexural toppling (Hoek & Bray, 1981).

the form of stereonet, also known as stereographic projection. It can be shown in many forms such as pole vector mode, dip vector mode, contour mode, 3D steoreonet and Rosette plot. Kinematic analysis feature provides a quick check for various rock slope stability failure modes on a stereonet plot such as planar sliding, wedge sliding and flexural toppling by just providing the slope orientation, friction angle and lateral limits and next select the failure modes. It can identify the critical percentage of potential movement of the rock blocks in various failure modes.

Creating a stereonet

The orientation of discontinuities that had been obtained from the rock slope using CloudCompare software was then imported into Rocscience Dips Version 7.0 software. There are many types of global orientation format such as dip/dip direction, trend/plunge, and strike/dip. In this study, the dip/dip direction orientation was utilized. Next, the traverse information was defined as it is used to group data units. The stereonet is then ready to be visualized and queried.

Adding set and plane

With the presented stereonet, add the plane of the slope. Next, add set to the stereonet based on the contour density concentration by clicking “sets from cluster analysis”. Sets are created to obtain mean plane orientations and set statistics of data clusters.

Kinematic analysis

Kinematic analysis was carried out by selecting the mode of failure: planar sliding, wedge sliding and flexural toppling and by inputting the kinematic properties. The statistical results are shown for each failure mode.

Sensitivity analysis

A slight change in the kinematic properties such as orientation, friction angle and lateral limits will affect the critical percentage of the potential failure of the rock slope. A sensitivity analysis can be carried out to determine its effect by inputting a range of values of orientation, friction angle and lateral limits. Graphs were plotted to show the effects of the changes to the critical percentages of the rock slope failure. The probability of failure was kept in between 25% since the maximum percentage of failure is 15.40%.

Table 1: Critical percentage of failure on different failure modes.

Failure Mode	Critical Percentage (%)
Planar Sliding	15.40
Wedge Sliding	7.16
Flexural Toppling	1.33

RESULTS AND DISCUSSION

Kinematic analysis was conducted to determine the failure modes of the rock slope by interpreting the stereonet. There are three types of failure modes; plane sliding, wedge sliding and flexural toppling. The variables that contribute to the probability of failure are slope orientations, friction angle and lateral limits. The critical percentage of rock failure based on different failure modes is summarized in Table 1. Since rock slope is heterogeneous, sensitivity analysis was also conducted to check on the maximum percentage of failure probability. Rock heterogeneity is the main concern because the sample collected for laboratory analysis may not represent the whole rock slope material.

Planar sliding kinematic analysis

The stereonet presented in Figure 4 is about planar sliding kinematic analysis failure mode in pole vector mode. It is mainly to check for sliding resistance on a single plane. The great circle of the slope plane is displayed with orientation 40°/175° dip/dip direction. The friction angle of the rock slope is 30°. From Figure 4, the region highlighted in red is the critical zone for planar sliding where it is inside the daylight envelope and outside the pole friction cone. Any pole falling within daylight envelope is kinematically free to slide if frictionally unstable. On the other hand, any pole falling outside of the pole friction cone represent planes which dip steeper than the friction angle and can slide if kinematically possible. All poles that are plotted in the region in red are representing a risk of planar sliding. With respect to all poles, the probability of failure is 3.66% where 254 out of 2933 poles are in the critical region. Contrarily, for the joint set which is circled in red, 252 out of 1636 poles are in the critical region. The risk of the occurrence of planar sliding is about 15.40%. This indicates that a sliding failure along any single joint plane is likely to occur in the geological plane having dip direction of 175°.

Wedge sliding kinematic analysis

Figure 5 depicts the stereographic projection of wedge sliding kinematic analysis failure mode. Multiple joints can form wedges which can slide along the line of intersection between two planes. The great circle of the slope plane is displayed with orientation 40°/175° dip/dip direction. The friction angle of the rock slope is 30°. The key elements of the wedge sliding kinematic analysis are slope plane, plane friction cone and intersection plotting. The slope plane defines the day lighting condition for intersections. Any intersection point which plots outside the pit slope great circle satisfies the day lighting condition. The plane friction cone is the angle measured from the equator of the stereonet. The primary critical zone for wedge sliding is the crescent shaped area inside the plane friction cone and outside the slope plane which is highlighted in red. Any intersection points that plot within this zone represent wedges which satisfy frictional and kinematic conditions for sliding. On the other hand, the secondary critical zone, highlighted in yellow in Figure 5, is the area between the slope plane and a plane inclined at the friction angle.

Wedges do not necessarily slide along the line of intersection of two joint planes. Wedges can slide on a single joint plane, if one plane has a more favorable direction for sliding than the line of intersection. In this case, the second joint plane acts as a release plane rather than a sliding plane. This can occur in either the primary or the secondary critical region. Critical intersections which plot in the secondary

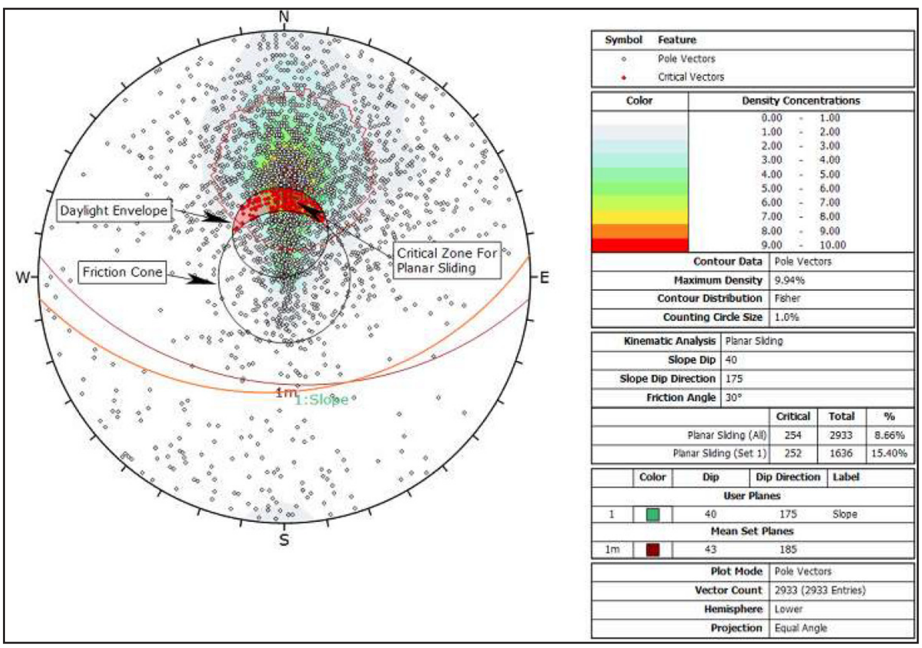

Figure 4: Stereonet of planar sliding kinematic analysis.

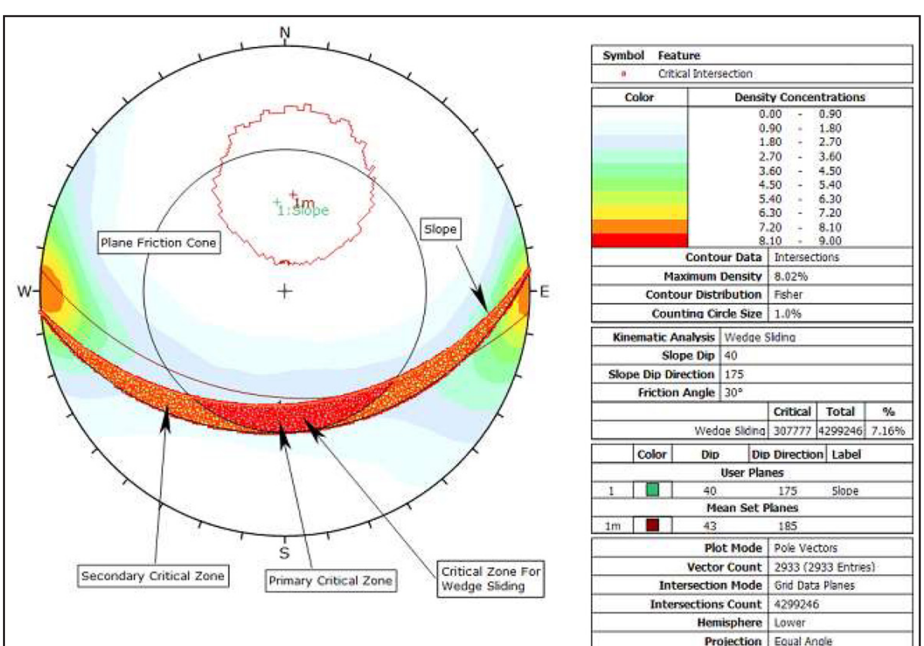

Figure 5: Stereonet of wedge sliding kinematic analysis.

critical zones always represent wedges which slide on one joint plane. In this region, the intersections are actually inclined at less than the friction angle; nonetheless, sliding can occur on a single joint plane which has a dip vector greater than the friction angle. Moreover, the intersection contours based on the intersection of all planes are displayed in Figure 6. Since, the contours fall outside the critical zone for wedge sliding, it renders a preliminary indication that wedge sliding is not a problem for this slope orientation. In this rock slope, out of 4299246 intersections, there are 307777 intersections fall into the critical zone. This indicates that wedge sliding is not a great concern for this slope orientation as the critical intersection is merely 7.16%. Figure 6 depicts all the plane intersections of the rock slope in the stereonet. It can be deduced that the number of critical intersections is relatively small compared to the total number.

Flexural toppling kinematic analysis

The stereonet of flexural toppling kinematic analysis is shown in Figure 7. The key elements of flexural toppling analysis using pole vectors are slope plane, slip limit plane and lateral limits. The great circle of the slope plane is displayed with orientation 40°/175° dip/dip direction. The friction angle of the rock slope is 30°. Planes won't topple if they cannot slide with respect to one another. Goodman. (1989) states that for slip to happen, the bedding normal must be inclined not as much steep than a line inclined at

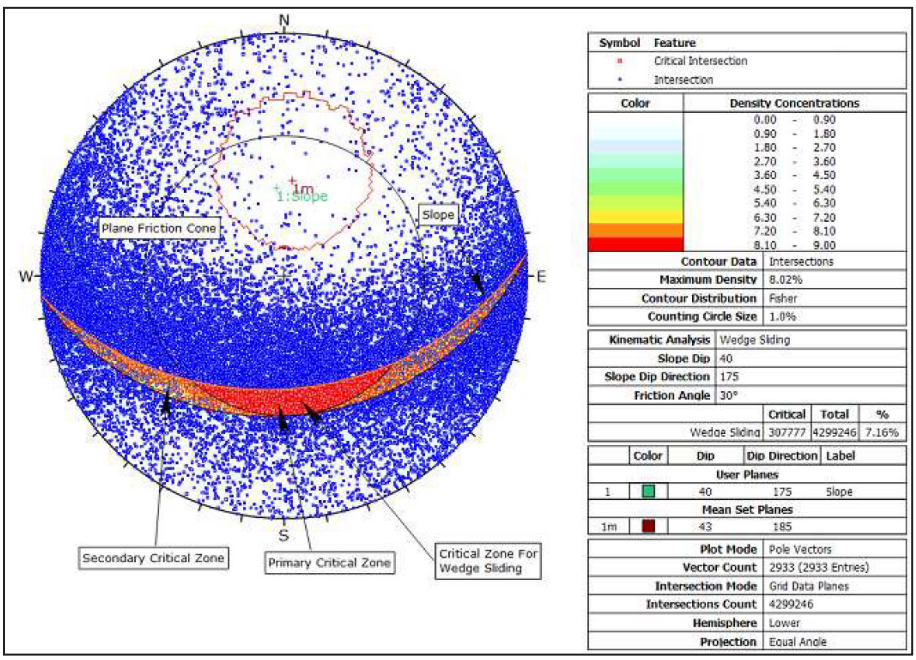

Figure 6: Stereonet of wedge sliding (with all plane intersections in blue).

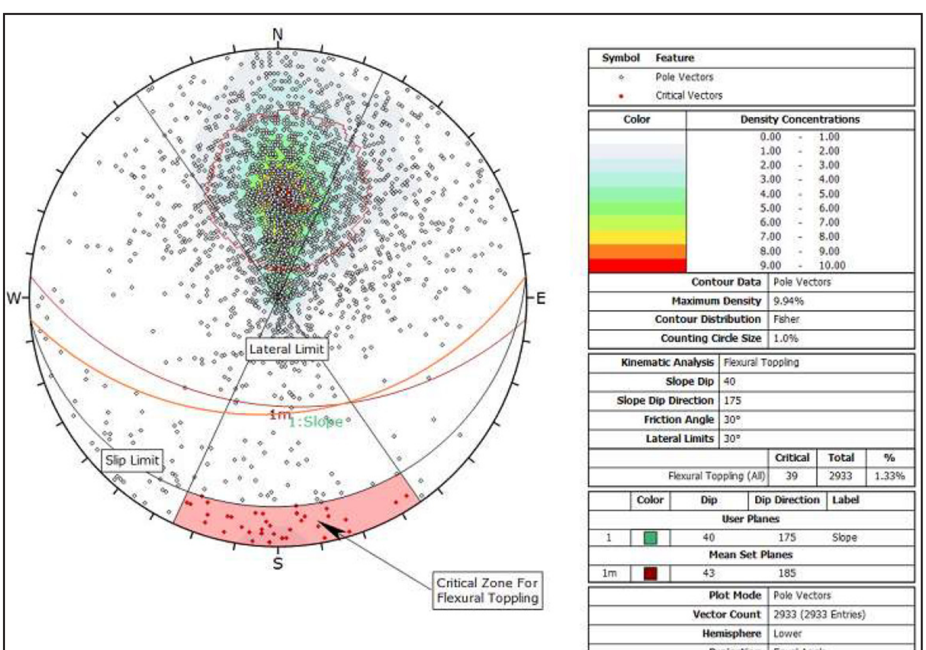

Figure 7: Stereonet of flexural toppling kinematic analysis.

an angle equal to the friction angle above the slope. This consequences in a "slip limit" plane which defines the critical zone for flexural toppling. This results in a "slip limit" plane which defines the critical zone for flexural toppling. Slip limit plane is based on slope angle and friction angle. The dip angle of the slip limit plane is derived from the subtraction of slope angle and friction angle which is 45 – 30 = 15. The dip direction of the slip limit plane is equal to that of the face (175 degrees). Lateral limits define the lateral extents of the critical zone with respect to the dip direction of the slope. The limit is set at 30 degrees as suggested by Goodman. The critical zone for flexural toppling is the highlighted region between the slip limit plane, stereonet perimeter and the lateral limits. Any poles in this region represent a risk of flexural toppling. From the legend shown in Figure 7 there are 39 out of 2933 poles fall into the critical zone which is having a probability of 1.33% for the occurrence of flexural toppling. This statistic shows that the flexural toppling is not a great concern for this slope orientation.

Sensitivity analysis

Sensitivity analysis was conducted to analyse the effects of slope dip angle, dip direction and friction angle on the critical percentage of each failure mode. The critical percentage of planar sliding, wedge sliding, and flexural toppling failure mode is presented and discussed in the methodology section with the mean of 40° for dip angle, 175° for dip direction and 30° for friction angle. However, changes in those values will alter the critical percentage of the failure modes. Hence, the range of slope dip angle from 20° to 60°, slope dip direction from 155° to 195° and friction angle from 10° to 50° with an interval of 5° were utilized in this analysis.

The x-axis is presented as percent of range. Since the interval used is five and the difference between the lower and upper limit is four there will be a plot in every 12.5% in x-axis. The critical percentage of planar sliding increases with increasing dip angle (Figure 8). At 70% of range which is a slope dip angle of 48°, the critical percentage of planar sliding has exceeded 20%. This indicates that there will be a 20% or more risk of occurrence of planar sliding. However, dip angle of 30° or less will have zero risk. On the other hand, slope dip direction is not significant in this failure mode. It maintains less than 10% from 155° to 195°. For friction angle, higher slope friction angle will induce safer and stable slope. There is 0% of occurrence of planar sliding if friction angle exceeds 40°. Contrarily, friction angle less than 30° will have a probability of failure at 10% or more.

The patterns of the graphs presented are like that of the planar sliding kinematic sensitivity analysis. The critical percentage of planar sliding increases with increasing dip angle (Figure 9). At 72% of range which is a slope dip angle of 49°, the critical percentage of wedge sliding has exceeded 20%. This indicates that there will be a 20% or more risk of occurrence of wedge sliding for dip angle of 49°. However, dip angle of 30° or less will have zero chance for the occurrence of planar sliding. On the other hand, slope dip direction is not significant in this failure mode. It remains less than 10% from 155° to 195°. For friction angle, higher slope friction angle will induce safer and stable slope. There is 0% of occurrence of planar sliding if friction angle exceeds 40°. Contrarily, friction angle less than 27° will have a probability of failure at 10% or more.

The critical percentage of flexural toppling increases with increasing dip angle (Figure 10). It reaches 2.4% when the dip angle is at the upper limit of 60°. On the other hand, the critical percentage increases when slope dip direction increases, reaching about 1.6% at 195°. For friction angle, higher slope friction angle will induce safer and stable slope. There is 0% of occurrence of flexural toppling when friction angle exceeds 40°. Contrarily, friction angle of 10° (lower limit) has a critical percentage of 2.4%. In short, flexural toppling is not a great concern for this rock slope because the critical percentage of failure is less than 2.5% at the upper limit of slope dip angle and lower limit of friction angle.

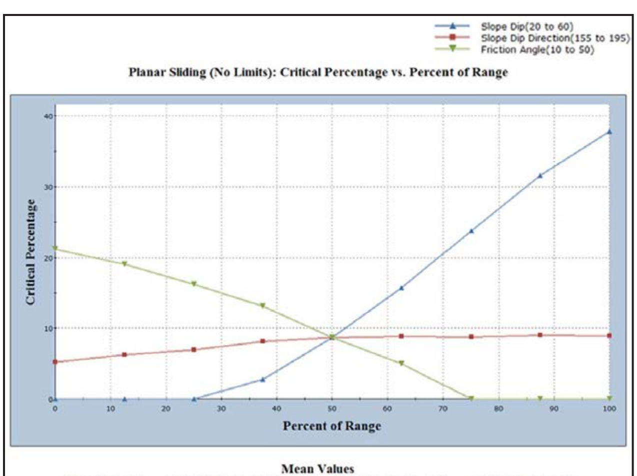

Figure 8: Kinematic sensitivity analysis for planar sliding failure mode.

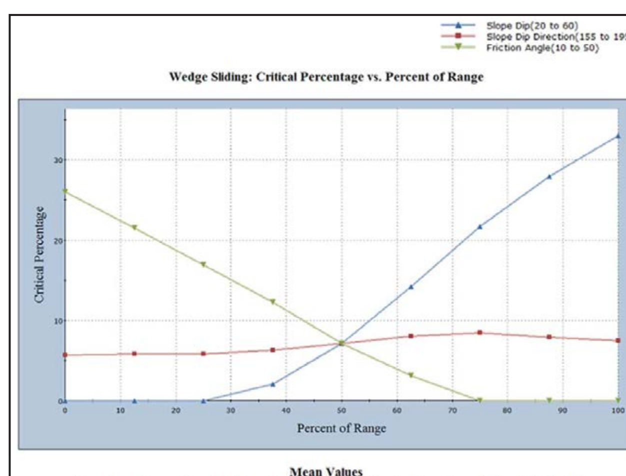

Figure 9: Kinematic sensitivity analysis for wedge sliding failure mode.

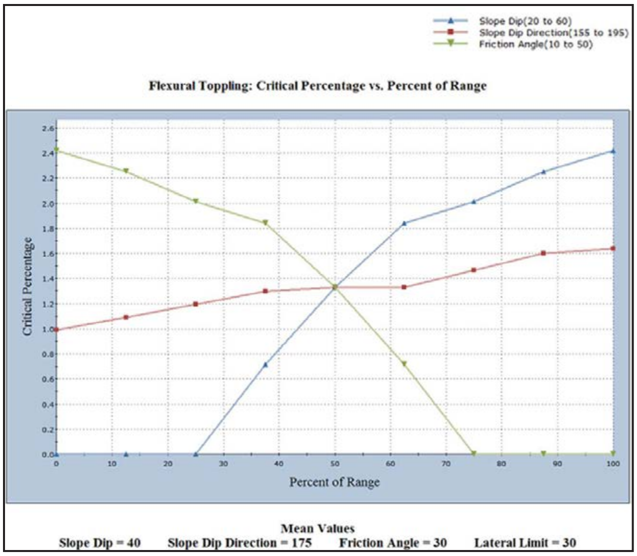

Figure 10: Kinematic sensitivity analysis for flexural toppling failure mode.

CONCLUSION

UAV photogrammetry is a great tool to preliminarily assess the rock stability for possible failure through kinematic analysis. A practitioner will be able to identify possible failure before carrying out further detail assessment. Geological planes extracted from the CloudCompare software provide 2 major discontinuity sets. By carrying out kinematic analysis in Dips 7.0 using the orientation data, it was discovered that the rock slope has higher probability of failure in the planer sliding failure mode (15.40 %) compared to wedge sliding (7.16 %) and flexural toppling (1.33 %). A sensitivity analysis was also carried out to identify the maximum value of each parameter that may affect the probability of failure. This study can be significant to understand the overall stability of the slope in a short period of time and is able to provide useful information regarding possible failures.

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