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Rock slope discontinuity extraction from 3D point clouds: Application to an open pit limestone quarry

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Abstract: Discontinuities dominantly play a key role in the mechanical, hydraulic, and deformational behaviors of rock masses, frequently impose significant influence on the stability of rock slopes. Thus, it is important to have a profound knowledge on the discontinuity network in rock engineering. This paper focuses on the identification of plane within 3D point clouds using the Discontinuity Set Extractor (DSE) program in MATLAB® (The Mathworks Inc.). The 3D point clouds were generated using the Agisoft PhotoScan Professional digital photogrammetry software (version 1.1.6) from photos captured via UAV method. To verify the plane identification, the photogrammetric results were compared with the manual mapping generated using the scanline method. Rosette plot for both methods revealed discontinuities set of similar direction but different in quantity. The most dominant discontinuities orientation was in the NNW-SSE direction at N330° - N340°, while the least dominant orientation took place in the E-W direction at N080° - N090°. The reliability of the discontinuity models was enhanced using the Structure from Motion (SfM) technique.

Keywords: Open pit quarry, discontinuity, Point clouds, UAV

INTRODUCTION

Open pit mining is a commonly implemented mining method in quarrying industry. The advantages of this method are larger minerals and ore yield, flexible planning along with pit progress, greater tonnage for each blast, and most importantly, creates less pollution compared to other typical mining methods. However currently in Malaysia, only a few open pit quarries are still in operation. Having said that, the open pit mining method also demonstrates certain limitations. These include excessive overburden removal, backfilling, and dumping in excavation areas. Thus, the design of benching system is crucial for this particular type of mining method. Moreover, frequent activities of blasting and excavation at slope surfaces will introduce problems in slope stability due to discontinuities . In comparison, the instability of open pit slope is different than the implications from civil works, where the excavation of an open pit is more extensive and prone to rock falls. Generally, the slope for an open pit mine is designed and constructed as steep as possible to avoid the uneconomical excavation of waste rock.

On the other spectrum, natural factors such as variation in rock mass conditions, rock slope material characterization, face angle, and also discontinuity orientation impose significant effects on the stability of rock slope. Discontinuity refers to most types of joints, weakness zone, bedding planes, fault, and schistocity planes of a rock mass with low or zero tensile strength (ISRM, 1978). Such that, fractures and discontinuities in rock masses are the most significant hydrogeological features that allow the storage and movement of fluid through them. In rock mechanics and mining, specifically, discontinuity itself affects the rock mass properties, therefore, it is important to comprehensively understand discontinuities in details.

Slope stability problems due to all the above mentioned factors have attracted major concerns from researchers and practitioners, and consequently, several techniques and methods for slope stability evaluation have been proposed. Some of these methods are kinematic analysis, limit equilibrium, numerical modeling, and empirical methods (Basahel & Mitri, 2017).

The characterization of rock masses requires the acquisition of information, which was traditionally collected by means of fieldwork, using a compass and a tape. Traditional methods for acquiring discontinuity data in field include the scanline survey and cell mapping (Priest, 1993; Nicholas & Sims, 2001). The sampling process involves a manual survey performed by an operator directly on the rock mass (ISRM, 1978). In a scanline survey, fracture data is garnered along a line on a rockface. For cell mapping, the dominant structures (joint sets, faults, etc.) on a rockface are first identified and the average information (orientation, spacing, length, etc.) is then measured for each geological structure. Scanline surveys provide thorough information on individual fractures in each set that can be used in probabilistic design, whereas cell mapping only gives average information about each joint set. Nevertheless, the collection of fieldwork data is time-consuming, and the data quality may be affected by the user's experience (Slob *et al*., 2010). The results are often subjective rather than objective and therefore are not reproducible (Gaich *et al*., 2006, Kemeny & Post 2003). In addition, rockfaces are often unsafe due to loose rock structure at the base of slopes, leading to potential rockfall of blocks. Getting an access to rockfaces is often difficult or impossible. Considering the operators' safety during a slope stability survey and the problems related to direct access to slopes, many researchers have proposed non-contact methods, namely, procedures which allow one to perform a trace survey on a representative rock mass via image scanning or a digital model.

The acquisition of 3D information through photogrammetric techniques has long been applied by geoscientists; most notably owing to their capability to visualize the Earth's surface and extract topographic data from stereo aerial photographs (Birdseye, 1940). With the integration of fundamental principles of photogrammetry with powerful algorithms from the computer vision community, collections of overlapping images can be automatically processed to quickly extract the relative 3D coordinates of millions of surface points (Lowe, 2004). Therefore, the only specialized resource required for the acquisition of 3D data through photogrammetric techniques is accessible and suitable software which depends on computer skills and requirements, and is available through both commercial and open-source alternatives. Among the free open-source commercial software that can easily be found and are user-friendly include PhotoScan, Acute3D, PhotoModeler, and 3DF Zephyr Pro.

The basic principle of photogrammetric entails the possible calculation of unique three-dimensional (3D) location of a set of given points from two overlapping photographs, relative to the cameras. In 'normal' photogrammetry which has evolved through surveying, remote sensing communities, and engineering, early estimations are usually derived by providing additional control data, such as the positions of known control points in images, prior to processing. This procedure permits error estimations (e.g., the accuracy of the control measurements) and a real-world coordinate system to be placed from the outset.

For rock slope discontinuity extraction, there are a few remote sensing techniques being developed and commercialized at the moment, such as 3D laser scanning or Structure from Motion (SfM) (Abellan *et al*., 2016). SfM technique allows the acquisition of millions of points of a surface with high accuracy, and the surface of a rock slope is digitalized using this dataset. As this dataset represents the surface of the rock slope, it may allow the identification and extraction of the existing discontinuity sets, its orientations, the normal spacing, the persistence and the roughness, as well as if the point cloud has enough quality (Riquelme *et al*., 2018). At this current moment, only discontinuity orientation and dip direction information can be extracted using this software (Riquelme *et al*., 2018).

Other method of identifying rock geological structures is 3D laser scanning, using instrument such as Terrestrial Laser Scanner (TLS). It allows high speed acquisition of coordinates (X, Y, and Z) of points of a surface (more than 222,000 measurements per second) from a considerable distance (up to 6,000 m). However, the cost of data acquisition of this instrument is currently expensive. TLS needs the use of a specific high specification computer to run all the analysis needed. In contrast, SfM only requires the use of a regular digital camera and a computer to process all digital photographs, but its precision is only limited by the camera resolution (James & Robson, 2012). Overall, this technique is much cheaper than TLS and is more suitable for educational sector.

This study focuses on the extraction of the discontinuity data sets of rock slope in an open pit quarry using 3D point clouds, obtained using the SfM technique. Unmanned Aerial Vehicle (UAV) was used to capture photos required for this technique. UAV method has been widely used for photogrammetric mapping of geological structures (Vasuki *et al*., 2014).

STUDY AREA

The study area covers the land of Hume Cement Quarry Sdn. Bhd. which is located in Gopeng, Perak at latitude of 4°23' North and longitude of 101°5' East. Figure 1 shows the location of the study area covering the central part of Peninsula Malaysia. The land of the quarry is geologically formed on the north part of Kinta Valley which represents various forms of limestone formation. Most of the limestone formation in Malaysia involves the process of karstification which yields a complex tectonic structure (Zabidi *et al*., 2016). The study area also covers part of the Kanthan Limestone bedrock in Kinta Valley. Kanthan Limestone generally comprises of locally prominent host rocks such as phyllite, slate, shale, and sandstone. Locally, the Kanthan Limestone at the quarry site is predominantly made up of massive and thin-bedded varieties with grayish white and black carbonaceous patches/spots. Moreover, fine-grained

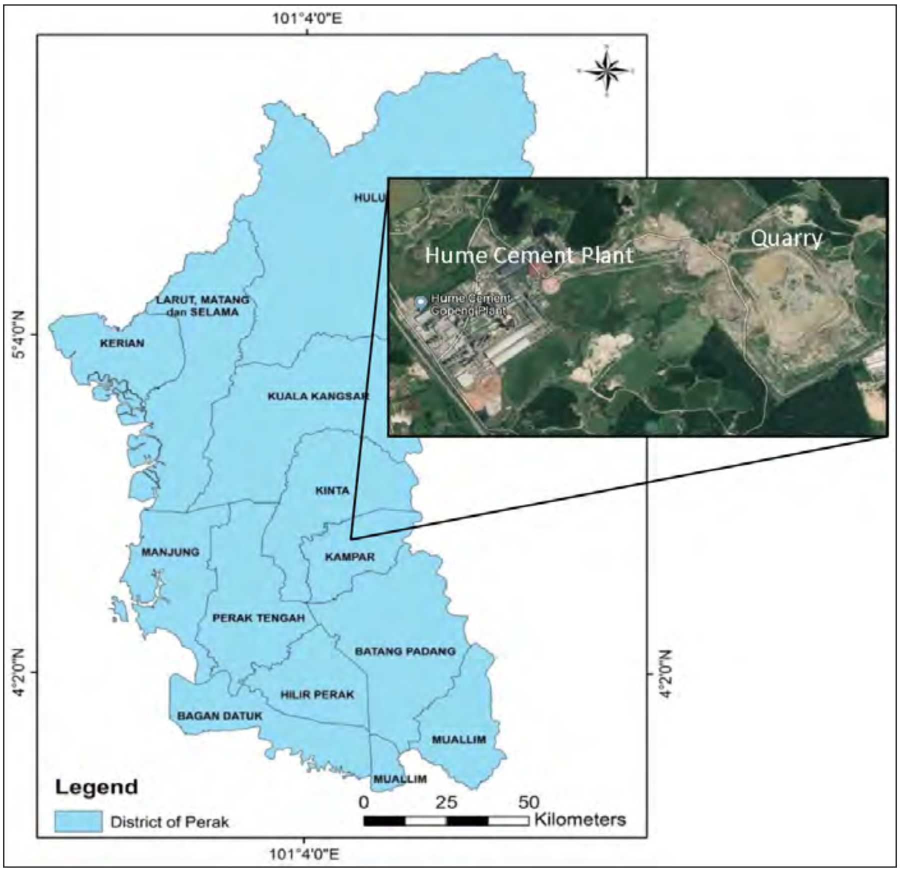

Figure 1: Location of the study area.

limestone is common and in places, it is intercalated or associated with carbonaceous (fissile) phyllite/schist. 4 m thick of massive fine-grained dolomite with creamy to pinkish white coloration was observed around the central part of the quarry area in the N-S direction. Structurally, this limestone formation is generally massive and interbedded in places as observed in many outcrops (Zabidi *et al*., 2016). Based on observation, Hume cement quarry rock faces are generally made up of yellow to yellowish brown, massive to highly bedded, and heavily jointed limestone rock strata.

METHODOLOGY

In order to produce 3D point clouds for the rock slope for this study, photos of the rock slope surfaces were taken via UAV method specifically by using DJI Phantom 4 Pro drone. The drone is built with a 20-megapixel camera, sufficient for photogrammetry method application as specified by certain recommendations (James & Robson, 2014). During the photos acquisition, overlapping photographs taken from different positions allow each feature in the overlapping area to be defined by a unique 3D position. After the evidence of the geological data was taken, the raw photos were processed and converted into a 3D model using the Agi PhotoScan software. Using this software, the raw photos were required to be primarily aligned before the location marker coordinates were placed. Following this, dense cloud was produced and the mesh and orthophoto were retrieved for further analysis.

Figure 2 shows the rock slope of the study area in 3D model. Upon performing a photogrammetry, it is recommended to test the quality of the model in terms of accuracy to emphasize more on the detailed analysis related to the coordinates of the model. Considering that a photogrammetry requires users to read the point cloud produced from photogrammetry method, users have to be precise in order to acquire accurate data and results.

After building the 3D model, analysis was carried out by analyzing the discontinuities set on the rock mass model generated by Discontinuities Set Extractor program (DSE) in MatLab. The input of this method is the 3D point clouds whereby each point has previously been classified by an assignment to a discontinuity set and to an aggregation of a point belonging to the same discontinuity plane, termed as a cluster. DSE is developed to calculate the cluster plane discontinuity set orientation with the best fitting plane (Riquelme *et al.*, 2015).

Figure 3 shows the discontinuity plane set extracted from DSE program in MatLab. In order to visualize the discontinuities plane, Cloud Compare software was used.

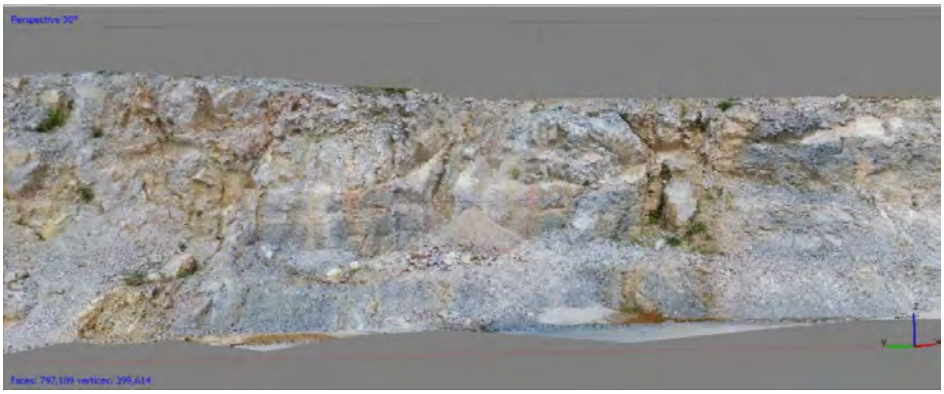

Figure 2: Modeled study area by Agisoft Photo Scan.

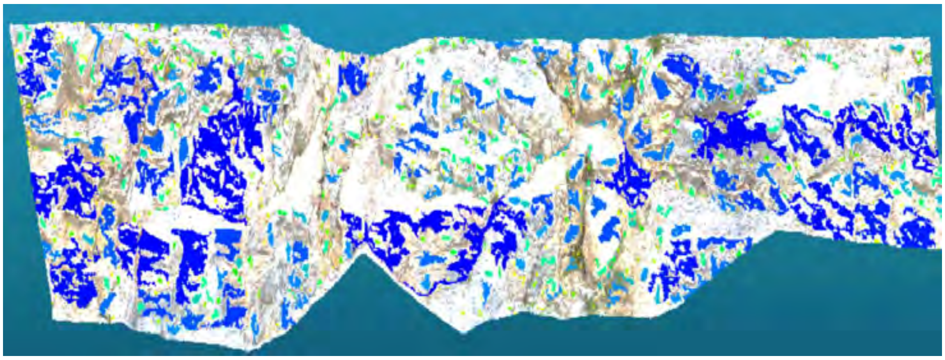

Figure 3: Example of discontinuity joint set (DS4) generated from DSE program and Cloud Compare.

Figure 4: The studied rock slope.

Manual mapping was carried out at the rock slope within 55 m length and 15 m height below the ramp road to pit, prior to results verification from the 3D point cloud analysis. The rock slope is as shown in Figure 4. Then, the dip and dip direction of the rock slope face was taken using clinometer instrument and was recorded in a data sheet. Scan line mapping technique was also employed to identify several requirements for Rock Mass Rating (RMR) analysis such as the condition of ground water, the spacing of the discontinuities, surface condition, location sketching, and also rock quality designation (RQD) value.

RESULTS

Based on the analysis from DSE program, ten discontinuity sets labeled as DS1 to DS10 were found at the rock slope. Table 1 shows the results from the DSE program. According to Table 1, DS1 is considered as the major discontinuity on the rock slope with the highest

Table 1: Results from photogrammetry mapping.

Discontinuity Joint Set	Dip Direction (°)	Dip (°)	Number of Cluster	Number of Points	Density	%
DS1	237.52	34.49	495	430294	4.0755	31.79
DS2	241.26	80.17	876	252696	0.9131	18.69
DS3	65.32	88.21	597	175798	0.6382	13.00
DS4	170.31	89.44	145	47771	0.4902	3.55
DS5	195.75	87.94	707	41223	0.3743	3.11
DS6	28.49	86.95	829	94509	0.3528	7.03
DS7	185.19	76.54	583	80926	0.2802	6.00
DS8	4.18	88.77	295	27113	0.2497	2.02
DS9	33.11	66.35	442	42415	0.2432	3.15
DS10	321.01	65.5	217	49348	0.1893	3.69

percentage of points (31.79%) oriented at 237.52° and 34.49° dip-dip direction. Furthermore, the pole density plot for DS1 as portrayed in Figure 5 compliments the result in Table 1.

Figure 6 shows the Rosette plot for the major direction of discontinuities from both photogrammetry and scanline mapping. The most dominant direction is N330° - N340° on NNW-SSE. Meanwhile, the least dominant discontinuities orientation occurred in the E-W direction at N080° - N090°. The main difference between both Rosette diagrams is the quantity of discontinuity set extracted. Photogrammetry mapping produces a larger number of orientations of discontinuity clusters compared to scanline mapping technique. Photogrammetry could simply extract more data from the rock slope including its orientation, direction, and dip direction. However, in terms of direction of the major plane of discontinuities, both techniques demonstrated identical direction comparable to one another.

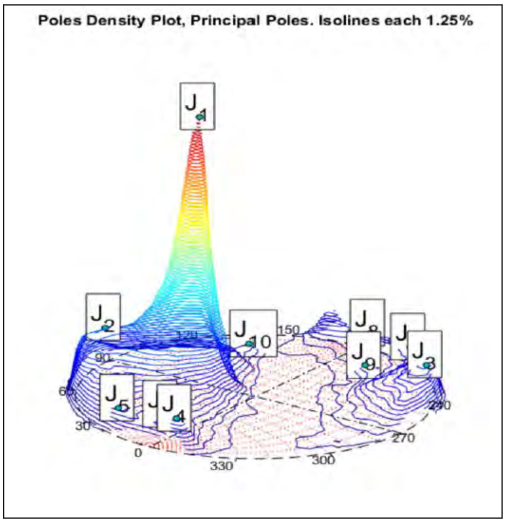

Figure 5: Pole density plot of ten joints set of discontinuity extracted from DSE program.

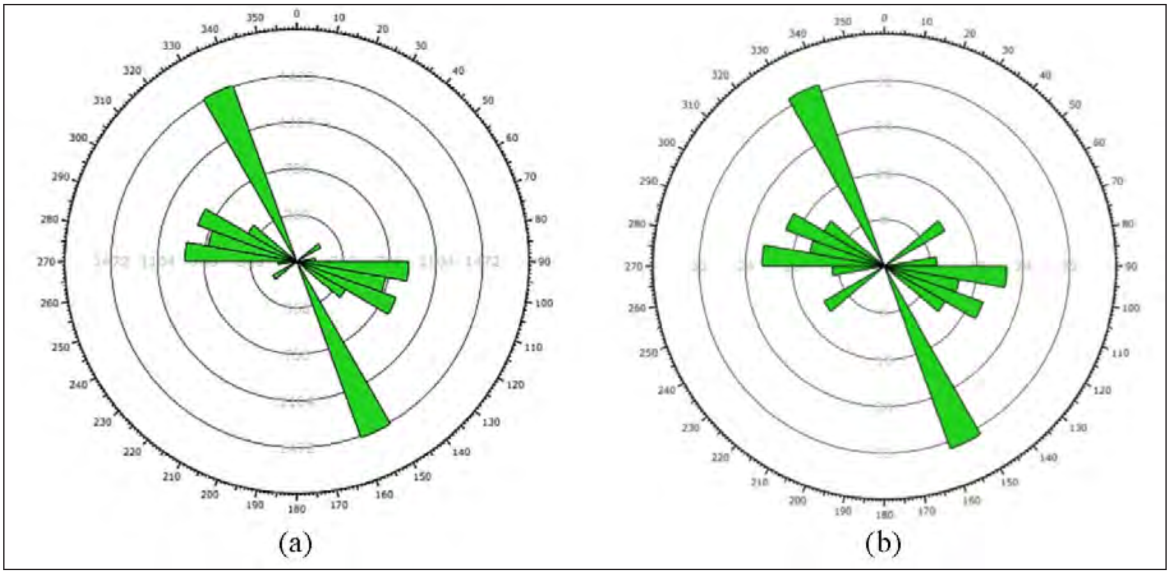

Figure 6: (a) Rosette plot by photogrammetry mapping, (b) Rosette plot by scanline mapping.

CONCLUSION

The main goal of the present work is to develop a workflow for extracting discontinuity sets using photogrammetry or SfM method. Besides, a few steps were considered in producing more accurate results which were then compared with manual scanline mapping. It was found that the methodology implemented has yielded reliable results. This method also provides safer, faster, and fewer bias outcomes by providing a good idea on the general discontinuity system at rock slope faces. However, several issues and limitations are present in this method. Firstly, the methodology only presents data on the most frequent plane orientation, exclusive of other characteristics information such as spacing, roughness, and persistence. These characteristics are important for a better understanding on the stability and quality of rock masses. Other than that, this workflow is nowhere from a complete automation, since several support programs are needed (Agisoft, MATLAB®, and Cloud Compare). A combination of all of the software into one complete software is deemed more practical for this method. It is safe to say that photogrammetry is a reliable technique for discontinuity mapping and analysis. Nonetheless, further study to automate the mapping process focusing on the reliability of the results is recommended to be done. The results can also be used to directly build a 3D numerical model of a rock mass.

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