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Workflow for discontinuity set characterization in rock masses using 3D digital outcrop models derived from UAV survey in an iron ore mine slope

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ABSTRACT: The rapid development of unmanned aerial vehicle (UAV) technology has enabled numerous open pit and underground mining companies to leverage this tool for slope stability assessment and the construction of geotechnical models. The use of aerophotogrammetry techniques with UAVs enables geotechnical and geological engineers to work in a safe and agile manner, maintaining a safe distance from hazardous areas. These techniques can identify the orientation of discontinuities in the rock mass, which is vital in evaluating slope stability. Moreover, new semi-automatic extraction techniques for discontinuities in rock masses allow aerophotogrammetric models to be utilized in geomechanical characterization in a more accessible and efficient way. With the use of 3D point cloud analysis software, the primary sets of discontinuities in a rock mass outcrop can be identified, measured, and utilized in various applications. This study presents a methodology for constructing three-dimensional models of a mine slope and utilizing them to determine the primary orientations of discontinuity sets using images captured through UAV survey. The method comprises four primary steps: (i) UAV flight and image capture, (ii) 3D point cloud construction using SfM technique, (iii) detection and measurement of discontinuities, and (iv) statistical data analysis.

1. INTRODUCTION AND OBJECTIVES

The collection of structural data is a critical task in characterizing rock masses and evaluating slope stability in mining. Traditionally, this task is carried out manually using a geologist's compass, exposing the technical team to various risks. Additionally, many areas are inaccessible to the team, resulting in data gaps.

With the advancement of aerial surveys using unmanned aerial vehicles (UAV) and the structure from motion (SfM) image processing technique, 3D point clouds (3DPC) can be generated from RGB images taken by UAVs, as described by Francioni et al. (2019). This 3DPC can be used in various applications, such as terrain analysis, slope stability, and hazard monitoring, which can reduce risk exposure and provide crucial information to the technical team, as discussed by Papathanassiou et al. (2020).

Previous works have extensively tested semi-automatic and manual techniques for extracting discontinuities in 3DPC (Lato and Vöge, 2012; Dewez et al., 2016; Menegoni et al., 2021; Bordehore et al., 2017), and numerous case studies have been published in scientific literature. Although this technique is not intended to replace conventional methodologies, it can complement them by acquiring data with lower risk exposure and in previously inaccessible areas.

This study presents the results of two surveys conducted in an open-pit iron ore mine to obtain structural data from the slopes within the mining area. Due to operational difficulties in stopping access roads for conventional surveys and accessing natural slopes, UAVs were employed to carry out the surveys.

The first survey (Site A) focused on an access road slope in the process plant's surroundings, aiming to semi-automatically detect the orientation and spacing of the primary discontinuity in the rock mass, corresponding to the bedding of the rock. The second survey (Site B) aimed to identify the primary points susceptible to rockfall on a natural slope adjacent to the mining pit area, where local overhangs are observed. In these areas, the orientations of the primary discontinuities influencing the formation of blocks with inadequate support for the overlying rock mass were manually identified in the 3DPC.

2. STUDY SITE

The study was conducted at an open-pit iron ore mine owned by Anglo American in the city of Conceição do Mato Dentro, Minas Gerais, Brazil (Fig. 1). The mine pit stretches approximately 6.6 km in the North-South direction and is situated in compact and friable itabirites of the Serra da Serpentina Group (Rolim, 2016).

Two sites were chosen for the surveys. Site A is located on an access road to the mine's process plant. The survey was conducted on a slope excavated in rock, composed of compact, well-deformed itabirites. Site B, located in the mine pit's southern portion, is a natural slope consisting of itabirites with higher degrees of weathering, making it more friable and susceptible to the formation of blocks and overhangs.

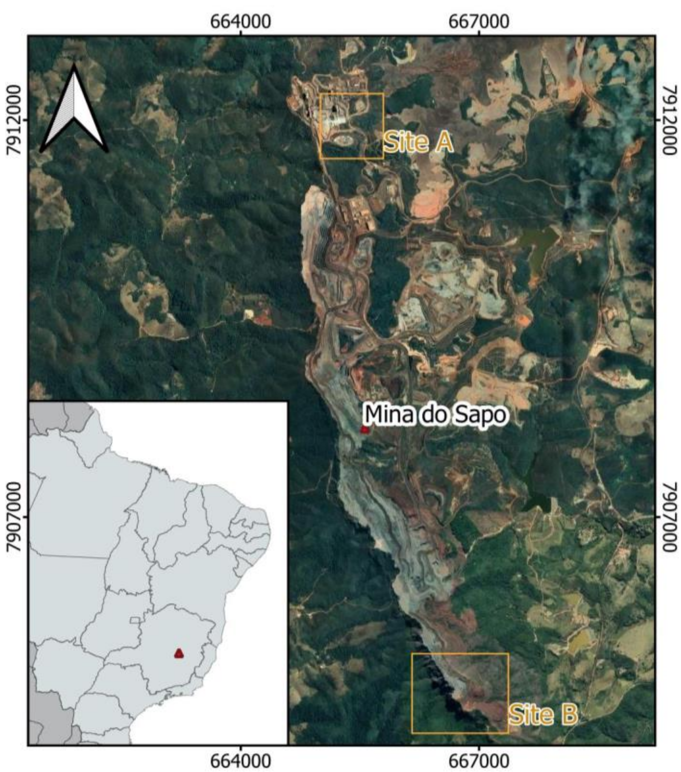


Fig. 1. Location of the Mine and surveyed sites.

3. METHODOLOGY

To conduct the study, high-resolution RGB images of the slopes were captured using a DJI Matrice 300 RTK quadcopter equipped with a Zenmuse P1, 45MP full-frame camera. The images were processed through the SfM technique using Agisoft Metashape® software to generate 3D point clouds of the slopes. CloudCompare® was used to filter vegetation, select points of interest, and standardize point density in the point clouds.

At Site A, oblique images were manually captured to represent the entire length of the slope, and the DSE® software was used to semi-automatically detect the orientation of discontinuities and calculate their average spacing.

At Site B, horizontal images were automatically captured to cover the mining pit slope area, and detailed oblique images were manually captured. The Compass Tool from CloudCompare® was used to manually measure the orientation of discontinuities, and other measurement tools were used to determine the dimensions of blocks subject to falls and generate topographic profiles.

The workflow for conducting the slope surveys using these tools is illustrated in the flowchart (Fig. 2).

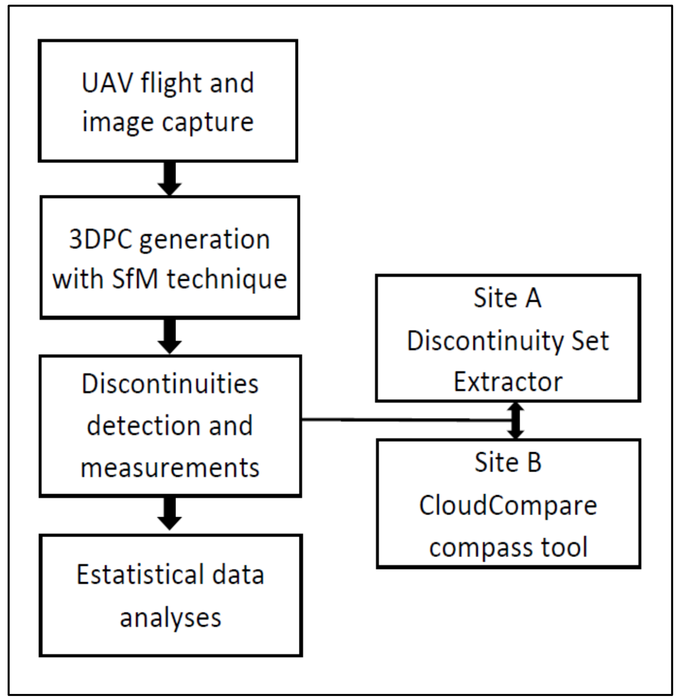


Fig. 2. General flowchart for the methodology used in the study.

4. RESULTS AND DISCUSSION

4.1. Site A

In the survey conducted at Site A, a manual flight was carried out to capture oblique RGB images of the slope using the UAV (Fig. 3, A). The images were processed using Agisoft Metashape® to generate a point cloud containing 83 million points. The point cloud was prepared in CloudCompare® by selecting the lower bench of the slope for discontinuity detection. The Subsample Tool was used to reduce the number of points in the point cloud to 10 million, ensuring a uniform distance between points.

The resulting homogeneous 3DPC of the lower bench of the slope was processed in the software DSE® for semi-automatic detection and measurement of the orientation of the main discontinuity present in the rock mass, corresponding to the bedrock plane. During this process, a new 3DPC was generated that only contains points considered coplanar and belonging to the bedrock plane (Fig. 3, B).

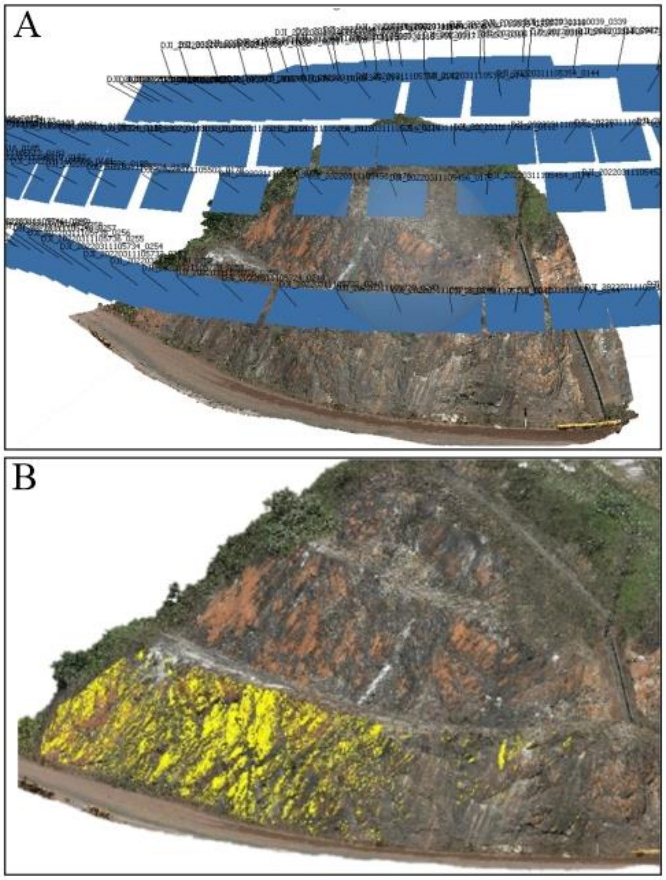


Fig. 1 - A) UAV locations for images capture. B) Colored 3DPC of the slope, merged with the point cloud generated in DSE® for the discontinuity set S1 (in yellow).

To perform statistical analysis on the data obtained from the DSE software, the normal vectors to the points of the cloud were plotted in a stereogram (Fig. 4, A), allowing for the observation of their distribution around the point with the highest density of poles. The user could then define the acceptable limit of deviation in the direction of the normal vectors with respect to the density peak for this discontinuity. This process helped to identify the region that encompasses all the poles belonging to this foliation, which is shown in a new stereogram (Fig. 4, B).

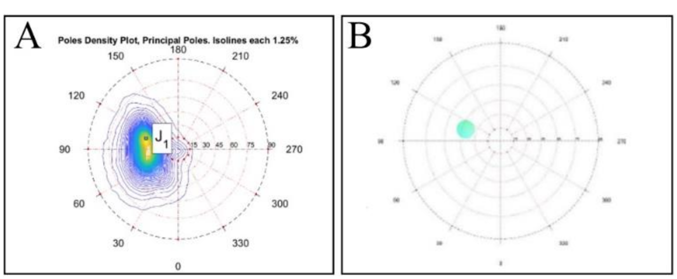


Fig. 4. A) Stereogram with orientation of the normal vectors to the points of the original 3DPC generated in the UAV survey. B) Stereogram with a delimitation of the region that contains 95% of the dataset classified in the point cloud.

In this particular case, the software defined the region that encompasses 95% of all poles and assigned a dip/dip direction orientation of 108°/32° to this foliation.

After determining the orientation of the main discontinuity observed in the slope, the Spacing Calculation Tool was utilized to measure the average spacing between the discontinuity planes. This is a critical factor in assessing the quality of the rock mass and its susceptibility to landslides. To perform this calculation, the points belonging to the coplanar region highlighted in Fig. 4, B and belonging to the same discontinuity, were exported to a new classified point cloud. The average spacing of the discontinuity was determined using the Spacing Tool of the DSE® software (Fig. 5). The tool considers both the full persistence condition and non-persistent condition to perform this calculation (please refer to Riquelme et al., 2015 for a detailed description). For the full persistent condition, the spacing was calculated to be 0.37 m, and for the non-persistent condition, the spacing was calculated to be 0.59 m.

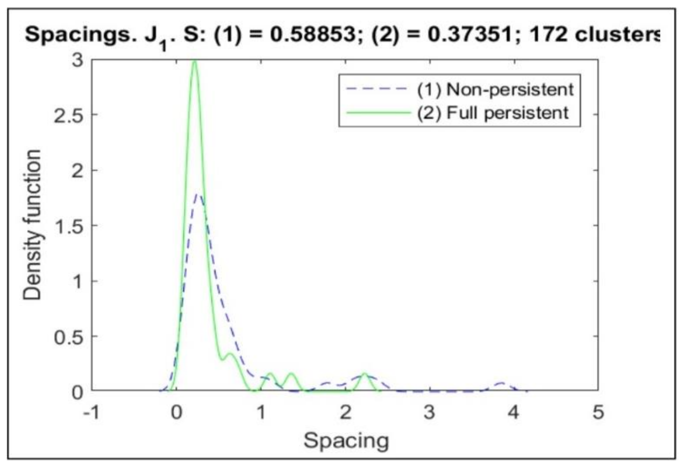


Fig. 5. Spacing calculation for the S1 foliation in DSE®.

4.2. Site B

At Site B, two aerial surveys were conducted. The first survey was performed automatically, covering a larger area of interest (Fig. 6, A), while the second survey was done manually, focusing on the portion where structural measurements were made in detail (Fig. 6, B). Both surveys were processed separately using Agisoft Metashape® software, resulting in a 3D point cloud of the general survey and a denser point cloud with more details of the area of interest. The two point clouds were then merged in CloudCompare® software to perform the analysis (Fig. 6, C).

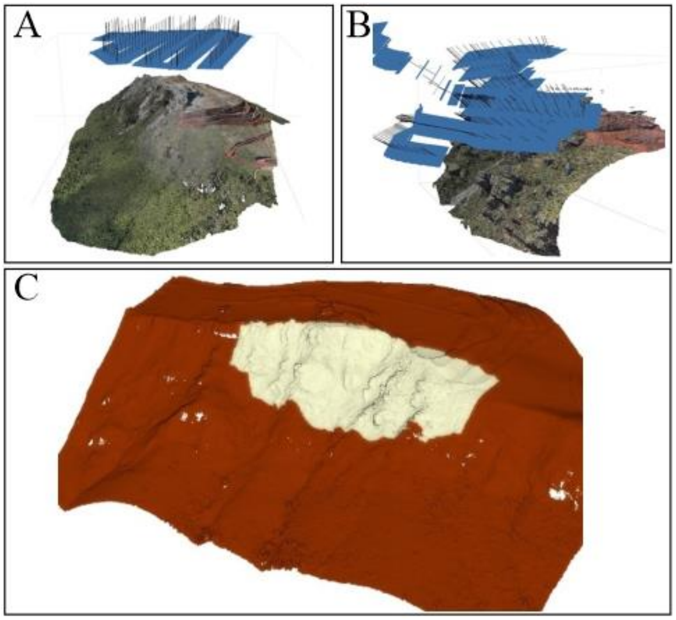


Fig. 6. A) UAV location for image capture in automated flight. B) UAV location for image capture in the manual flight. C) Composition of the general and detail 3DPC. In yellow the detailed manual flight, and in brown the general automated flight.

Three points with overhangs were observed and selected for manual measurement of the orientation of the discontinuities using the Compass Tool in CloudCompare® (see Fig. 7A). Length measurements of the blocks were also taken in the 3DPC and displayed in the detailed image of this point (see Fig. 7B). The discontinuity orientations obtained through manual measurements are shown as green arrows in the point cloud (see Fig. 7C).

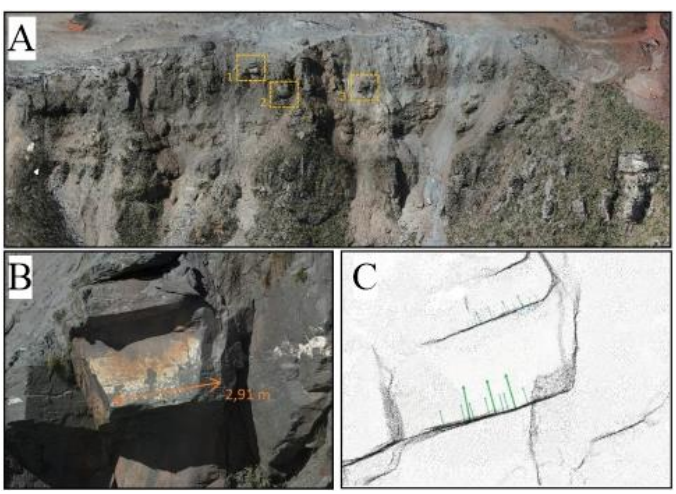
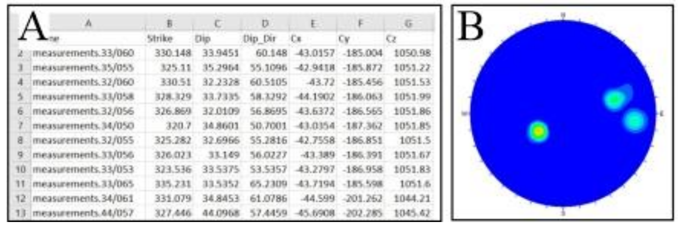


Fig. 7. A) Orthomosaic of the studied slope, with indication of the 3 measurement points. B) Detail image of point 1, with the length of the block face. C) 3DPC with indication of the measurements of the orientations performed in CloudCompare®.

Altogether, 50 structural measurements were collected at the three selected points and exported in .csv format (Fig. 8, A). To perform statistical analysis on the measured orientations, the data was plotted in a stereogram using the software Dips® (Fig. 7, B). The results showed an average dip/dip direction orientation of 63°/41° for the S1 set and 262°/66° for the J1 set.



	A	B	C	D	E	F	G
	ne	Strike	Dip	Dip_Dir	Cx	Cy	Cz
2	measurements.33/060	330.148	33.9451	60.148	-43.0157	-185.004	1050.98
3	measurements.35/055	325.11	35.2964	55.1096	-42.9418	-185.872	1051.22
4	measurements.32/060	330.51	32.2328	60.5105	-43.72	-185.456	1051.53
5	measurements.33/058	328.329	33.7335	58.3292	-44.1902	-186.063	1051.99
6	measurements.32/056	326.869	32.0109	56.8695	-43.6372	-186.565	1051.86
7	measurements.34/050	320.7	34.8601	50.7001	-43.0354	-187.362	1051.85
8	measurements.32/055	325.282	32.6966	55.2816	-42.7558	-186.851	1051.5
9	measurements.33/056	326.023	33.149	56.0227	-43.389	-186.391	1051.67
10	measurements.33/053	323.536	33.5375	53.5357	-43.2797	-186.958	1051.83
11	measurements.33/065	335.231	33.5352	65.2309	-43.7194	-185.598	1051.6
12	measurements.34/061	331.079	34.8453	61.0786	-44.599	-201.262	1044.21
13	measurements.44/057	327.446	44.0968	57.4459	-45.6908	-202.285	1045.42

Fig. 8. (A) .csv format sheet of the orientations and the coordinates of each measure, together with the coordinates for each point of measure; (B) Stereogram of the measuments generated on Dips®

In addition to collecting orientation measurements at the three selected points, topographic profiles were generated to represent the surface relief and overhangs at these points (Fig. 9, A). These profiles were georeferenced and exported in .dxf format and can be visualized in several CAD software. The topographic profile of point 1 illustrates the main discontinuity sets involved in the overhangs (Fig. 9, B).

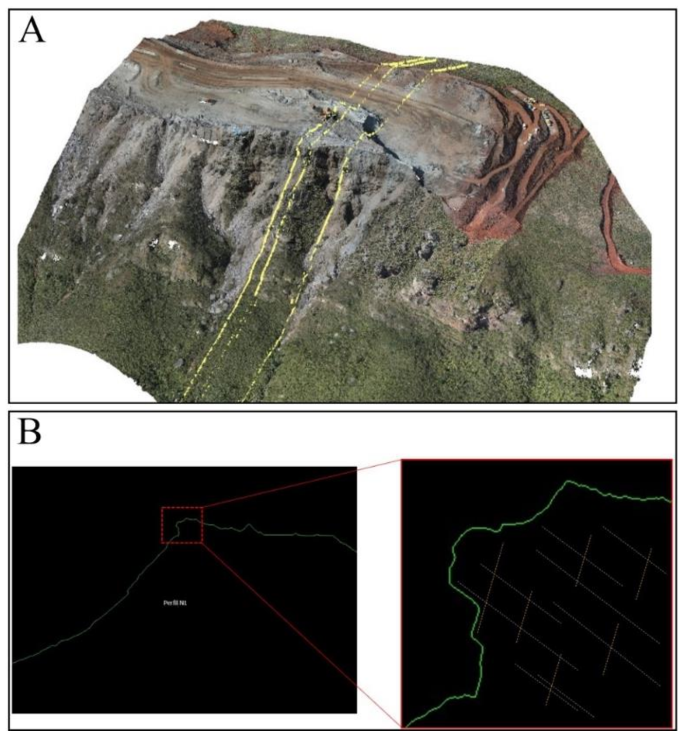


Fig. 9. (A) Cloud of points with the 3 topographical profiles generated by the measurement points of the structures. (B) Topographic profile of point 1 with representation of the structures identified in point 1.

5. CONCLUSIONS

Aerial surveys were conducted at two locations in the Mina do Sapo. At Site A, the primary orientation of the discontinuity in the rockmass was determined using an automated extraction method in the 3D point cloud (3DPC). Additionally, the average spacing for this discontinuity was calculated using the DSE software tool. The attitude of the discontinuity was found to be 108°/32°, and the spacing was 0.48 m (considering full-persistent and non-persistent methods).

This method proved capable of identifying and measuring the orientation and spacing of the discontinuity while reducing the time required for data collection in the field. This approach can be useful in areas where accessing the slope poses a risk to the team or when there are other access difficulties. The survey at Site A did not require stopping the access road and was completed in approximately 20 minutes.

At Site B, the average orientation of the discontinuities that formed the overhangs was determined by manually measuring the orientation in the 3DPC. Three points were selected for measurement, and the data was exported and analyzed in Dips software. The analysis revealed an average orientation of 63°/41° for the S1 set and 262°/66° for the J1 set. This method proved effective for determining the orientation of discontinuities at inaccessible measurement points where traditional compass surveys are not feasible. Furthermore, the coordinates of each measurement can be used to feed the geotechnical database of the team.

It is essential to note that the quality of the products generated using this technique depends on the quality of the image acquisition in the field. The drone's flight schedule and atmospheric conditions, such as humidity and clarity, can impact the product's quality. It is recommended to conduct flights close to noon to minimize the occurrence of shadows, which can affect the image quality.

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