Characterization of joint roughness using close-range UAV-SfM photogrammetry

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Abstract. The Structure from Motion (SfM) photogrammetric technique has emerge as an efficient alternative for remote 3D rock mass characterization, compared to laser scanner (LiDAR) or stereoscopic photogrammetry, due to its economy and ease of use. In a similar way, the recent development of the drone-based technology has turn UAVs (“Unmanned Aerial Vehicles”) in a more accessible device for field applications in geotechnical engineering; allowing the acquisition of high quality images from a safe distance and without the need to establish direct contact with the rock mass. However, the close distance applicability of UAV-SfM photogrammetry has not yet been investigated in detail to characterize joint roughness at close range (<10 m). In this work we employ the SfM technique for the generation of 3D models of the joint surfaces from aerial images taken at a relatively short distance from the slope (10, 7.5, 5, and 2.5 m). Roughness profiles are extracted from the 3D data, and their $Z_2$ statistical parameter is used to estimate the Joint roughness coefficient (JRC). Finally, the JRC value of those profiles -obtained with the UAV-SfM approach- have been compared with those obtained with traditional measurements based on manual methods. The proposed methodology is applied to a real case in an ancient open-cast mine in Northern Spain. The results obtained at different distances are compared to analyze the potential of UAV-SfM photogrammetry to develop accurate close-distance models. Results show that it is not necessary to get too close to the slope in order to get the best results, as this may cause overestimation of the JRC value.

1. Introduction

Joint roughness is one of the main factors considered in the joint strength criteria [1, 2] and the JRC (Joint Roughness Coefficient) is the most commonly used methodology to quantify rock surface roughness on field applications. However, since its determination is often performed by manual methods (that need direct contact to the rock joint) and visual comparison (that can be very subjective), many authors aim to correlate this coefficient with other statistical parameters that can be objectively quantified [3, 4]. In that sense, Structure from Motion (SfM) technology has recently emerged as an efficient alternative for remote 3D rock mass characterization, becoming even more versatile when combined with Unmanned Aerial Vehicles (UAVs). For instance, Tomás et al. [5] have recent applied this technology using a heavyweigt professional drone (DJI Matrice 600) for semiautomatic identification of discontinuities sets of a rocky railway cutting. Moreover, Erhardt et al. [6] have used a compact portable drone (DJI Mavic Pro) for digital mapping and kinematic analysis of landslides in Alpine terrain, comparing field measurements made with compass to digitalized discontinuity measurements using manual, semi-automated and automated techniques. Similarly, Salvini et al. [7]
have studied the applicability of 3D digital point clouds, employing *medium weight professional drone* (Aibot X6), to determine discontinuity surface roughness characteristic in a quarry slope using images taken from a distance higher than 10 m. However, the close distance (<10 m) applicability of UAV-SfM approach has not been yet investigated in detail to characterize joint roughness.

This paper presents our results on the use of the SfM photogrammetry technique, in combination with aerial images taken at a relatively short distance to quantify joint roughness in a rock slope. Our main purpose is to analyze the potential of UAV-SfM approach as a field tool for close-range roughness analysis. To that end, we built several 3D models with photographs taken at different distances from the slope, and extracted their \( Z_2 \) statistical parameter to estimate the Joint roughness coefficient (JRC). Finally, these JRC values have been compared with manual measurements based on traditional methods.

2. Application example

2.1. Description of the analysis area
The slope analyzed is placed in an ancient open-cast mine, located in Caldas de Luna, in Norther Spain. The rock mass is made out of a massive carbonated series, formed by bioclastic limestones, micritic boundstone limestones and breccias (Carboniferous). The slope selected has approximately 9 m high and 7 m wide.

2.2. Application of the SfM technique

2.2.1. Reference template and GCPs. In contrast to other remote techniques, such as Laser scanner (LiDAR) or conventional threoscopic photogrametry, the SfM approach generates 3D models without scale or orientation, placing them inside an arbitrary scene. Therefore, in order to correctly analyse the geometry and location of the slope it is necessary to use Ground Control Points (GCPs) inside the scene. In this work, 3 types of GCPs have been used: (i) Control points, (ii) Check points and (iii) Isolated points. The first two types are incorporated into a portable orientation template and they will be used to scale, orientate and validate the 3D models. The isolated points are place directly on the rock surface, marked with a permanent marker, and will define the position –start and end– of the roughness profiles that will be further analyse.

Inside the analysis area (described in section 2.1) a smaller region was selected, associated to a discontinuity plane which orientation is contained inside the plane formed by the surface of the slope (denoted as “region of interest”), where the roughness analysis will be conducted. On its face 6 isolated points have been installed, in “pairs”, that will help to define 3 profiles (\( \text{Prof}_1 \), \( \text{Prof}_2 \) and \( \text{Prof}_3 \)) of approximately 300 mm length (303, 300 and 295 mm), similar to Barton’s Comb length (see figure 1). These profiles have been evenly distributed on the plane surface and they follow the maximum slope line, with the purpose to analyse the value of the most critical roughness.

The portable orientation template used in this study is an improved version of the original one developed by the same authors in previous research [8, 9], and it allows to scale and orientate the model –in a single step– in a quick and easy way. This new template contains 9 GCPs (5 Control points and 4 Check points) drawn in a rigid base, with approximately 180 mm long and 180 mm wide, that is placed directly on the slope surface. The 5 control points define the position of two of the axis that create the plane (x, y), and from their local coordinates we are able to scale and orientate the model. The 4 Check points help to validate the precision of the former ones.
For the installation of the template, once an area with good adherence and high visibility has been selected, it is only necessary to follow the next steps: (i) ensure that its “reference line” is placed horizontally with the aid of spirit level, and then (ii) measure its orientation (Dip/Dip Direction) with a geological compass.

2.2.2. Equipment and flight planning. For the generation of the photogrammetric 3D models, a medium weight professional drone (DJI Inspire 1 PRO; model T600) was used in combination with a compact digital camera (Zenmuse X5; model FC550). The remote control of the aircraft was carried out manually, through the mobile application (DJI GO) operated from a Tablet (iPad 7th Generation Wi-Fi + Cellular 32 GB) installed directly on the controller (DJI C1) with the help of the included bracket. (Note that since the main objective of this study is to analyze the applicability of the UAV-SfM approach at close-range (<10m), the use of automatic flight modes at these working distances could increase the risk of accident, especially if the aircraft does not have an obstacle detection system.) Therefore, to make flight planning simple, and help the aircraft to better position once it is in the air, it was decided to install a series of references on the ground, as camera positions, marking with color aerosol some rock blocks (see figure 2).

In this way, a total of 20 ground references for the UAV or camera positions were defined by establishing 5 points per each analysis distance (10, 7.5, 5 and 2.5 m with respect to the slope surface).
2.2.3. Data acquisition. From each position, three photographs were taken keeping the drone at a constant height of approximately 3 m above the ground surface, varying only the angle of inclination of the camera. To that end, once the drone is positioned on the mark and with the camera gimbal in a horizontal position, the rotation of the central axis of the UAV was adjusted to ensure that the region of interest—defined by the position of the 6 insolated points—was framed and captured right in the center of the image. Subsequently, the angle of inclination of the camera was manually modified to take 2 new images: one in high-angle position and other in low-angle position. In this way, we made sure that the analysis area is always present in all photographs, ensuring 100% overlap between images. In total, 60 photographs were taken to make the models (3 images x 5 camera positions x 4 analysis distances).

All photographs were taken with the highest resolution available (16MP, 4:3; 4608 x 3456 px; JPEG format) using a fixed focal length of 15 mm (equivalent of 30 mm in 35 mm format) and automatic camera settings (normal program, spot metering mode, AF, aperture F/2.2, exposure time 1/1919.4" and auto ISO).

In the same way, as the objective of this work is to evaluate the advantages of the UAV-SfM technique compared to traditional methods, once the photogrammetric campaign was finished, the manual measurement of the 3 roughness profiles was carried out—using a Barton’s comb of 300 mm—to be able to capture the “real” geometry of the discontinuity “in the field”. (Therefore, to validate the methodology first, it was necessary to use an accessible area to obtain these manual measurements.)

2.2.4. Generation of the 3D models. For the generation of the 3D models, the professional version of the photogrammetric software Agisoft PhotoScan [10] was used. All models were developed selecting the highest “precision level” allowed by the program; “Highest” accuracy settings for the generation of the initial disperse point clouds (DPC) and “Ultra High” quality settings for the high-density points clouds (HDPC). Table 1 shows the computing times needed to generate the four completed 3D models (DPC + HDPC) that have been used in this work (one per each analysis distance). As can be observed, the longest processing time correspond to the second stage of the process (HDPC) and is directly related to the density (number of points) defined in the first stage (DPC). (Note that, by reducing the analysis distance, the resolution of the images increases, making it easier for the program to identify common points, thus increasing the density of the initial disperse point cloud.)

Finally, once the four 3D models are generated, they are scaled and oriented in Agisoft PhotoScan (using relative local coordinates) with the aid of the five control points included in the orientation template. Table 2 shows the average errors (x, y, z) of these points resulting from the comparison between their real “known” coordinates and those “estimated” by the 3D digital model. Similarly, the differences provided by the four Check points are also listed. As shown in table 2, in all cases, the generated 3D models have mean errors less than 0.5 mm.

| Models | DPC          | HDPC        |
|--------|--------------|-------------|
|        | Accuracy     | Time        | Points   | Accuracy | Time        | Points   |
| 2.5 m  | 1 m 22 s     | 16,348      |           | 10 h 8 m 30 s | 41,285,668 |
| 5 m    | Highest      | 1 m 32 s    | 13,077    | 7 h 43 m 53 s | 41,080,948 |
| 7.5 m  | 1 m 43 s     | 8,867       | Ultra-High| 5 h 24 m 26 s | 39,147,903 |
| 10 m   | 2 m 2 s      | 7,200       |           | 3 h 51 m 18 s | 35,822,793 |
Table 2. Average errors (x, y, z) of GCPs included in the orientation template.

| Models | GCP  | X error (mm) | Y error (mm) | Z error (mm) | XY error (mm) | Total (mm) | Image (pix) |
|--------|------|--------------|--------------|--------------|---------------|-------------|-------------|
| 2.5 m  | Control | 0.089        | 0.127        | 0.119        | 0.155         | 0.196       | 0.286       |
|        | Check   | 0.190        | 0.280        | 0.499        | 0.338         | 0.603       | 0.285       |
| 5 m    | Control | 0.133        | 0.153        | 0.181        | 0.203         | 0.272       | 0.292       |
|        | Check   | 0.317        | 0.104        | 0.494        | 0.334         | 0.596       | 0.278       |
| 7.5 m  | Control | 0.073        | 0.214        | 0.126        | 0.226         | 0.258       | 0.263       |
|        | Check   | 0.147        | 0.118        | 0.424        | 0.188         | 0.464       | 0.230       |
| 10 m   | Control | 0.316        | 0.174        | 0.152        | 0.391         | 0.391       | 0.244       |
|        | Check   | 0.425        | 0.179        | 0.201        | 0.503         | 0.503       | 0.210       |

Figure 3. Visual comparison, for roughness profiles $Prof_1$ (a), $Prof_2$ (b) and $Prof_3$ (c), between the “reference profiles” (generated by manual methods) and the “comparison profiles” extracted from the 3D models (generated at 2.5, 5, 7.5 and 10 m distances).
2.3. Roughness analysis

2.3.1. Extraction of profiles. Finally, after generating, scaling and orienting the 3D models, the four resulting HDPC have been exported to MATLAB [11] to extract the roughness profiles using the relative coordinates of the six isolated points and its normal vector to create the cut plane. For the extraction of the “reference profiles” Barton’s comb field photographs have been exported to AutoCAD and manually digitalized. Therefore, once the extraction process is finished, a total of 15 roughness profiles have been achieved: 3 “reference profiles” obtained from manual methods and 12 “comparison profiles” obtained from 3D models. Figure 3 shows a visual comparison between these profiles.

As shown in figure 3, the profiles developed from the models generated at a shorter distance (red line and blue line) fit the reference profiles (black solid line) much better than the profiles generated at a greater distance (green line and yellow line); indeed, this last two, tend to smooth the joint surface and delete the main asperities of the reference profiles.

2.3.2. Estimation of JRC. To translate these differences in terms of JRC, and thus be able to analyze the potential of the SfM technique combined with UAV as short distance roughness analysis, in this work, we have used the correlations proposed by Li and Zhang [12] that correlate the statistical parameter $Z_2$ with the JRC coefficient:

\[ JRC = 55.7376 \cdot Z_2 - 4.1166 \] (1)

\[ Z_2 = \frac{1}{L} \cdot \frac{1}{N} \sum_{i=1}^{N-1} \left( \frac{z_{i+1} - z_i}{x_{i+1} - x_i} \right)^{\frac{1}{2}} \] (2)

Where

- $L$: Profile length
- $N$: Number of sampled points
- $x_i$, $z_i$: Coordinates of the sampled points

However, note that these expressions are only suitable for profiles with a specific range of $Z_2 \in [0.074 - 0.433]$ and with a certain length $L \in [72 - 119.6 \text{ mm}]$. Therefore, to follow these specifications, the 15 profiles under study have been previously divided, each one, into 3 sub-profiles of 100 mm, and rotated to match an horizontal plane. Thus, finally, 45 profiles have been used for roughness analysis; 9 “reference profiles” (3 profiles x 3 sub-profiles) and 36 “comparison profiles” (4 models x 3 profiles x 3 sub-profiles).

| Profiles | Section (mm) | Manual Measurements | 3D Models (2.5 m | 5 m | 7.5 m | 10 m) |
|----------|--------------|---------------------|------------------|-----|-------|-------|
| Prof_1   | 0 – 100      | 11                  | 13               | 9   | 7     | 8     |
|          | 100 – 200    | 12                  | 14               | 12  | 7     | 8     |
|          | 200 – 300    | 10                  | 19               | 9   | 15    | 11    |
|          | 0 – 100      | 8                   | 14               | 9   | 3     | 4     |
| Prof_2   | 100 – 200    | 11                  | 14               | 11  | 6     | 6     |
|          | 200 – 300    | 15                  | 17               | 14  | 9     | 9     |
|          | 0 – 100      | 8                   | 16               | 12  | 6     | 7     |
| Prof_3   | 100 – 200    | 20                  | 17               | 14  | 10    | 8     |
|          | 200 – 300    | 18                  | 16               | 20  | 13    | 7     |

$\bar{JRC}$

| $\bar{JRC}$ | 13 | 16 | 12 | 9 | 8 |

Table 3. JRC values calculated for all sub-profiles of the study area.
Table 3 lists the JRC coefficients of all sub-profiles computed using equation (1) and equation (2) and the average $\overline{JRC}$ coefficients per model considering the total discontinuity surface. These results make possible to compare (i) the results provided by the UAV-SfM 3D models obtained at different distances, with (ii) the reference values provided by the digitalized Barton’s comb profiles.

Table 3 shows that, in almost all cases, the 3D models generated at 5 m returned JRC values much closer to the reference values (obtained by manual methods) than the JRC coefficients obtained from the other 3D models (at 2.5, 7.5 and 10 m). Considering average $\overline{JRC}$ coefficients (last row in table 3), at 5 m distance the $\overline{JRC}$ coefficient is only 1 point below to the reference results; whereas at 2.5 m distance the $\overline{JRC}$ values are 3 points above. Additionally, when the analysis distance is increased (to 7.5 and 10 m), these differences also increase (with average differences of -4 and -5 points, respectively). These results indicate that, as the analysis distance rises above 5 m, the estimated JRC values tend to decrease; while as the analysis distance is reduced below 5 m, the estimated JRC coefficients tend to increase, overestimating the reference values.

Figure 4 shows graphically, for all sub-profiles and for each analysis distance, the comparison between (i) the reference JRC results generated by manual methods and (ii) the estimated JRC values obtained from the 3D models. As shown, the best fitting line (closer to the diagonal; $R^2 = 1$) is provided by the model generated at 5 m distance.

**Figure 4.** Comparison between the estimated JRC values of all sub-profiles extracted from the 3D models, and the reference JRC coefficients extracted from the digitalized Barton’s comb profiles.

3. Conclusions
In this work, we study the applicability of the Structure from Motion technique (SfM), combined with the use of Unmanned Aerial Vehicles (UAVs) at close-range, to characterize the joint surface roughness in a rock slope. The UAV-SfM approach was applied to generate 3D models of the discontinuity plane, from aerial images taken at a relatively short distance of the slope (2.5, 5, 7.5 and 10m). The reference JRC coefficients of the 3 studied profiles were obtained from digitalized Barton’s comb measurements. Roughness profiles were then extracted from these models and the Joint Roughness Coefficient (JRC) was estimated using the $Z_2$ statistical parameter and the correlation proposed by Li and Zhang [12]. The results show that the best adjustments are obtained working at a distance of 5 m from the slope; if we get closer, the JRC values tend to be overestimated, and if we increase it, JRC values tend to be underestimated.

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