Applications of the Structure from Motion photogrammetric technique to solve geotechnical problems at different scales

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ABSTRACT: The Structure from Motion (SfM) photogrammetric technique has been widely used, due to its ease of use and low cost, as an excellent alternative for remote 3D rock mass characterization. This technique uses only the information obtained from the digital images acquired with a regular camera to generate very high-resolution 3D models. However, this technique is widely influenced by environmental and physical conditions (degree of luminosity, distance to the target, geometry, etc.) of each case. In this work, we present our previous experiences, from a micro-scale application (in the laboratory) for small-scale roughness analysis, to a large-scale application (in the field) for the characterization of long slopes using drones. For each application, different methodologies have been proposed, adapting the SfM technique and developing innovative solutions. The obtained results confirm the applicability of SfM to efficiently solve rock engineering problems at different scales and under different conditions.

Keywords: Structure from Motion, photogrammetry, rock roughness, rock characterization, UAVs.

1 INTRODUCTION

The multi-scale characterization of rock masses –from intact rock to rock joints, to rock masses– is important in rock mechanics and rock engineering, and several methods have been proposed for such task, such as the suggested by ISRM Commission on Standardization of Laboratory and Field Tests (1978). More recently, efficiency and safety reasons have promoted more advanced characterization technologies –such as photogrammetry or LiDAR– to obtain 3D models of rock joints or rock masses, which can be employed as a basis for engineering characterization of rock joints and rock masses and, hence, to solve rock engineering problems at different scales. This article explores the use of the Structure from Motion (SfM) technology to that end, and it presents recent examples of SfM application to (i) characterize rock joint roughness at the laboratory scale; to (ii) characterize roughness at field scale to solve rock slope stability problems; and (iii) to characterize rock slopes at a larger scale, and to estimate their associated risks.

2 THE STRUCTURE FROM MOTION TECHNIQUE

The Structure from Motion (SfM) technique (Snavely et al. 2008) has recently emerged as an efficient alternative to other methodologies, such as traditional photogrammetry. SfM is a "remote low-cost" measurement technique —note that only a reasonably good camera is needed— that minimizes the time the operator needs to be in the field, however, if the methodology is effectively designed for the case, the amount of information acquired is significantly higher than the one obtained by other high-cost remote or manual methods. This is because SfM can overlap multiple photographs, whose information allows one to compute the orientation parameters of the camera, hence avoiding the need to calibrate it that was inherent to traditional photogrammetry. As discussed in Garcia-Luna et al. (2019), to conduct such 'auto-calibration process', the SfM algorithm (i) identifies multiple key-points in each 2D image; (ii) matches them in overlapping images; and (iii) uses an iterative bundle adjustment algorithm to estimate the camera parameters for every image, so that the 3D positions of such key-points are computed and an initial disperse 3D point cloud is generated. Then, (iv) a high-density 3D point cloud is constructed using Multi-View Stereo (MVS) techniques –or techniques that use the stereo correspondence between points located in more than two images–; and, (v) the point cloud can finally be scaled and oriented within a reference system using (at least three) ground control points (GCPs), or points that can be recognized in the photos, and whose coordinates in the system are known. However, the way in which the 3D point cloud is obtained typically depends on the scale at which one is working, as discussed in the example cases presented below.

3 APPLICATION EXAMPLES

This section discusses several application examples, conducted at different scales.

3.1 Characterization of rock joint roughness in the laboratory

Rock roughness is a crucial aspect of rock joint strength, typically considered in rock joint strength criteria, through quantification of the Joint Roughness Coefficient (JRC; see Barton & Choubey (1977) for details), although there are other approaches to characterize joint roughness, such as statistical and fractal approaches (e.g., Maerz et al. 1990; Stigsson and Ivars 2019). This section discusses how to develop joint profiles using SfM so that joint roughness can be quantified (at both 'large' or 'waviness' scale; and 'small' or 'smoothness' scale) using the spectral frequencies of its profile (García-Luna et al. 2020). In particular, we focus on the 3D characterization techniques that measure joint roughness using digital photogrammetry and digital image processing (Unal and Unver, 2004), as shown by previous successful applications in the laboratory and in the field (Wernecke and Marsch, 2015; Tatone and Grasselli, 2013). In this case, images are obtained with a AF-S DX NIKKOR 18-55 mm F/3.5-5.6G VR lens mounted on a Nikon D5200 DSLR camera with 24 MP, installed on a professional Manfrotto tripod, using remote-control cordless shooting and lights from opposite sides of the samples, which are placed against an opaque dark background (see Figure 1).

A rotary platform allows us to take many photographs in a short time, without re-focusing the camera and without problems due to vibration of the camera or shadows on the surface, so that the sample surface is fully covered with photographs that have a high degree of overlapping (approx. 95%). In addition, and to provide a scaling reference to the model, a template with a rectangular reference frame with known dimensions of 220 mm x 140 mm is used. This reference frame incorporates 38 GCP (one every 2 cm) along its boundaries, so that they can be recognized in the photographs and their (known) coordinates can be employed to scale the model and to set-up a horizontal (x-y) reference system later used in roughness analyses.

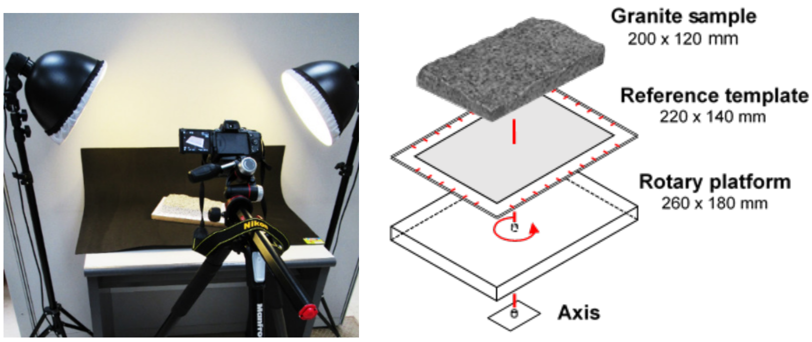

Figure 1. Illustration of photographic set-up to take photographs of rock samples at small scale, and with enough precision to be used in roughness analyses (García-Luna et al. 2020).

3.2 *Characterization of rock joint roughness in the field*

Joint roughness can also be obtained from rock joints outcropping in the field, with a similar workflow to the one employed for roughness characterization at the laboratory (see Figure 2), but with one main difference: as shown in Garcia-Luna et al. (2021a), a telephoto lens can be employed to quantify joint roughness in rock mechanics practice, so that pictures can be efficiently taken at a distance of several meters (>5m) from the rock joint of interest. For this application, the previous Nikon camera is employed, in conjunction with a AF-S DX VR NIKKOR 55-200 mm F/4.0-5.6G IF-ED telephoto zoom lens (equivalent focal length at 35 mm format: 82.5-300 mm). To study the influence of different camera settings and distances to the joints of interest, we developed two types of models using photographs taken with the same telephoto zoom lens but with different focal length (*f*): (i) a "General" (or G) model, that replicates a regular short focal length lens with *f* = 55 mm; and (ii) a "Telephoto" (or T) model, with *f* = 200 mm. Similarly, and as shown in Figure 3 we developed three models with photographs taken at 5, 10 and 15 m distance from the joint surface of interest; and a "Detailed model" (D) is also developed, for reference, using photographs taken at 1 m distance.

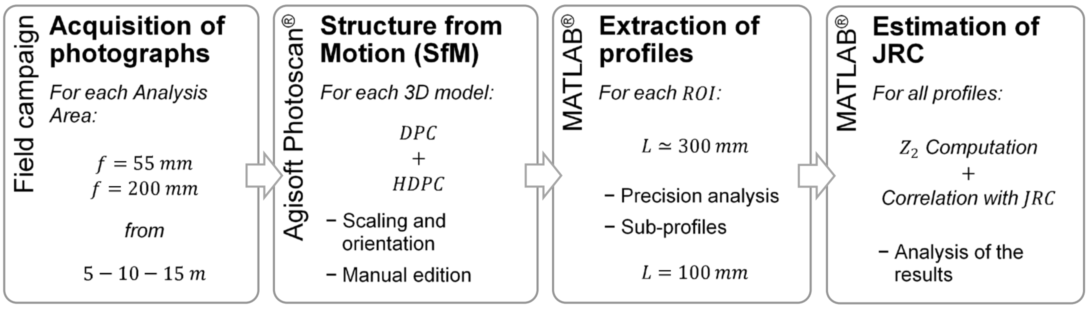

Figure 2. Flowchart of methodology to determine joint roughness using SfM technique with photos taken using a telephoto lens (Garcia-Luna et al. 2021a).

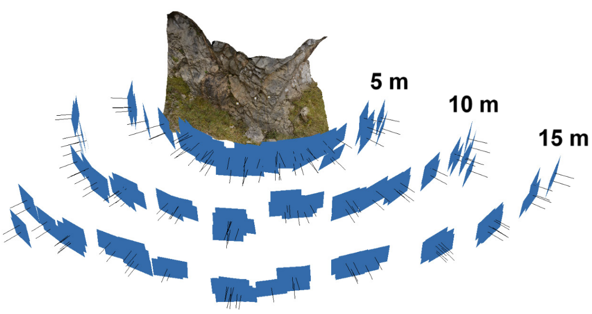

Figure 3. Camera positions for pictures taken with a telephoto lens (Garcia-Luna et al. 2021a).

After the SfM and roughness analyses are conducted according to the flowchart in Figure 2 (see Garcia-Luna et al. (2021a) for details) results show that (i) models generated with the telephoto lens provide a much closer match to the “Detailed model”, hence suggesting that they are preferrable to “general” models generated without the telephoto lens, and (ii) that JRC estimations using the telephoto lens model can be very similar to JRC estimations computed from the “Detailed” model, particularly for SfM models constructed from photographs taken at a closer distance (of, say, 5m; see Figures 4 and 5). In addition, this procedure can be employed for stability analyses of rock blocks against sliding (or wedge, among others) failure, for which the shear strength for the computed JRC is a crucial aspect of the analysis. In addition, since one has the 3D surface model of the joint, it is possible to compute the JRC associated to the expected failure direction. See Figure 6 and, for additional details, the discussion in García-Fernández et al. (2022).

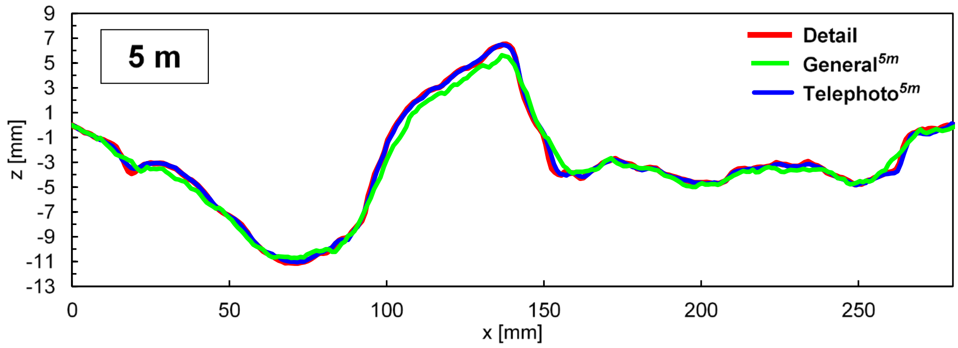

Figure 4. Comparison of joint profiles from SfM models using photographs taken at 5 m distance to the joint of interest with and without photo lens (Garcia-Luna et al. 2021a).

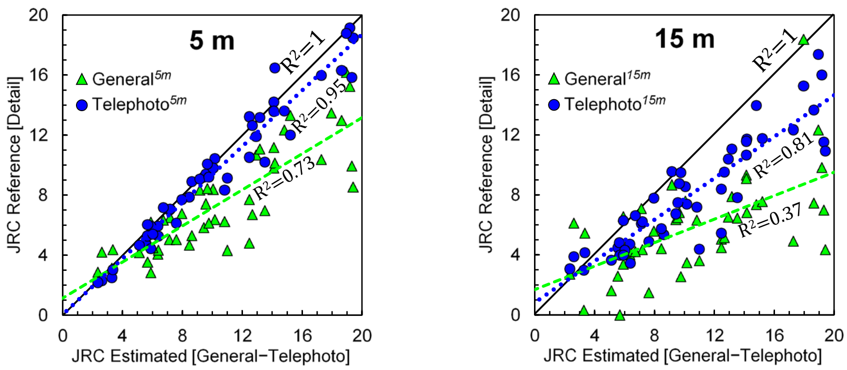

Figure 5. Comparison of JRC estimates using SfM models from photographs taken with different distances to the joint of interest (Garcia-Luna et al. 2021a).

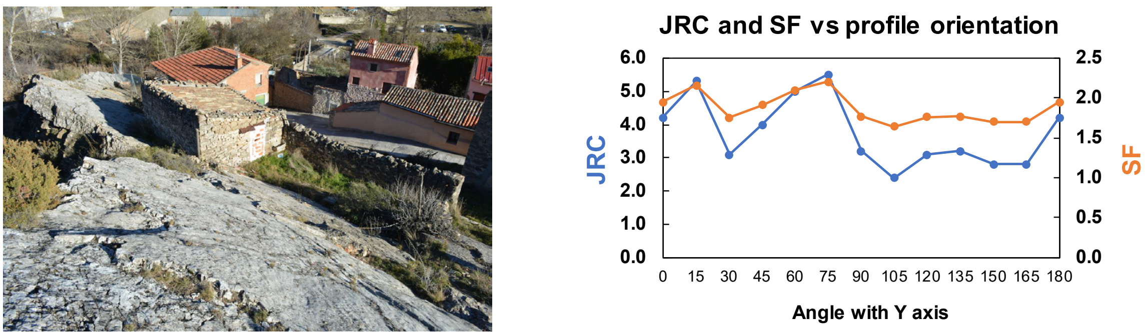

Figure 6. Example of application of the use of SfM models to estimate JRC of a sliding plane, and of the associated stability analyses conducted (modified from García-Fernández et al. 2022).

3.3 *Characterization of rock masses for risk analyses*

The SfM approach can also be employed to efficiently characterize long rock-slopes, in which stability or risk analyses –such as the Rock Hazard Rating System, or RHRS (Pierson et al. 1990), among others– are to be conducted. To that end, one can integrate a photographic camera within an Unmanned Aerial Vehicle (UAV), or use the camera that many UAVs incorporate, to take the pictures needed for SfM characterization of the slope, and then employ the resulting 3D point cloud to (i) identify discontinuity planes; or (ii) to compute geometric features needed for the specific risk system of interest (e.g., in RHRS, geometric features of the slope and of the road; and/or specific rock mechanics features, such as discontinuity spacing, RQD, or persistence, among others) (see Figure 7). In our experience, a set-up with a medium weight professional drone (DJI Inspire 1 PRO; model T600, combined with a compact digital camera Zenmuse X5 model FC550; or a DJI Inspire 2 with a Zenmuse X5S camera, possibly incorporating a Panasonic LUMIX G Vario PZ 14-42 mm F/3.5-5.6 ASPH telophoto lens) can provide the photographic quality required for this task if an appropriate flying pattern is employed. To that end, one can use flights with "manual" or "programmed" remote control of the aircraft, 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 flying patterns too close to the slope may impose a risk to the aircraft, especially if it lacks an obstacle detection system; see Garcia-Luna et al. 2021b for details.)

Figure 7. Example of application of the use of SfM models constructed with photographs taken from an UAV, and of how to use them to identify geometrical slope features, or to identify joints within the slope.

CONCLUDING REMARKS

This article discusses several rock mechanics applications in which the SfM technique can be employed to characterize the 3D surface or rock joints or rock masses, in different engineering problems of interest and at different scales. In particular, and since the results can be greatly dependent on specific equipment set-ups, information is provided about equipment and camera configurations for each application, and about data capture strategies adapted. Results show that the SfM technique can currently provide, in an efficient way, enough 3D point cloud accuracy so that one can develop adequate estimations of roughness (and, hence, of joint strength), which can then be employed for stability analyses; and they also show that SfM provides an efficient tool for risk analyses of long rock slopes, in which an UAV can be employed for further efficiency while taking the photographs required.

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REFERENCES

Barton, N., Choubey, V. 1977. The shear strength of rock joints in theory and practice. *Rock Mechanics* 10 (1–2), pp. 1–54. DOI: 10.1007/BF01261801

García-Fernández, M. García-Luna, R., Senent, S., Jiménez, R. 2022. Caracterización de la rugosidad en taludes mediante técnicas fotogramétricas y su influencia en la estabilidad frente al deslizamiento. In: *X Simposio Nacional sobre Taludes y Laderas Inestables*, Granada, September 2022.

García-Luna, R., Senent, S., Jurado-Piña, R., Jimenez, R. 2019. Structure from Motion photogrammetry to characterize underground rock masses: Experiences from two real tunnels. *Tunnelling and Underground Space Technology* 83, pp. 262–273. DOI: 10.1016/j.tust.2018.09.026

García-Luna, R., Senent. S., Jimenez, R. 2020. Characterization of joint roughess using spectral frequencies and photogrammetric techniques. *Boletín Geológico y Minero* 131 (3), pp. 445-458. DOI: 10.21701/bolgeomin.131.3.007

García-Luna, R., Senent. S., Jimenez, R. 2021a. Using Telephoto Lens to Characterize Rock Surface Roughness in SfM Models. Rock Mechanics and Rock Engineering 54, pp. 2369-2382. DOI: 10.1007/s00603-021-02373-7

García-Luna, R., Senent. S., Jimenez, R. 2021b. Characterization of joint roughness using close-range UAV-SfM photogrammetry. In IOP Conference Series: Earth and Environmental Science 833 012064. DOI: 10.1088/1755-1315/833/1/012064

ISRM Commission on Standardization of Laboratory and Field Tests. 1978. Suggested Methods for the Quantitative Description of Discontinuities', International Journal of Rock Mechanics and Mining Sciences and Geomechanics 15, pp. 319-368. DOI: 10.1016/0148-9062(78)91472-9

Maerz, N., Franklin, J., Bennett, C. 1990. Joint roughness measurement using shadow profilometry. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts* 27 (5), pp. 329–343. DOI: 10.1016/0148-9062(90)92708-M

Pierson, L.A., Davis, S.A., Van Vickle, R. 1990. *Rockfall Hazard Rating System – Implementation Manual*, Federal Highway Administration (FHWA), Report FHWA-OR-EG-90–01, FHWA, U.S. Dep. of Transp.

Snavely, N., Seitz, S.M., Szeliski, R. 2008. Modeling the world from internet photo collections International *Journal of Computer Vision* 80 (2), pp. 189–210. DOI: 10.1007/s11263-007-0107-3

Stigsson, M., Ivars, D.M. 2019. A novel conceptual approach to objectively determine JRC using fractal dimension and asperity distribution of mapped fracture traces. *Rock Mechanics and Rock Engineering* 52 (4), pp. 1041–1054. DOI: 10.1007/s0060 3-018-1651-6

Tatone, B.S., & Grasselli, G. 2013. An investigation of discontinuity roughness scale dependency using high-resolution surface measurements. *Rock Mechanics and Rock Engineering* 46 (4), pp. 657-681. DOI: 10.1007/s00603-012-0294-2

Unal, M., & Unver, B. 2004. Characterization of rock joint surface degradation under Shear Loads. *International journal of Rock Mechanics and Mining Science* 41 (3), pp. 145-150. DOI: 10.1016/j.ijrmms.2004.03.033

Wernecke, C., & Marsch, K. 2015. Mapping rock surface roughness with photogrammetry. In *Proceedings of the ISRM Regional Symposium EUROCK 2015 - Future Development of Rock Mechanics*, Salzburg, Austria, 7–10 October 2015.