Identification of Persistent Discontinuities on a Granitic Rock Mass Through 3D Datasets and Traditional Fieldwork: A Comparative Analysis

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Abstract. Geologists and engineers traditionally characterise rock slopes through laboratory tests and data captured during fieldwork and further cabinet work. They find, however, difficulties in capturing data in terms of safety, objectiveness and reliability. However, the continuous improvement of remote sensing techniques is changing the rock slope stability analysis. Light Detection and Ranging (LiDAR) and Structure from Motion (SfM) derived datasets comprise 3D point clouds that represent the studied ground surface. This data permits the geometric analysis and the extraction of the number of discontinuity sets affecting the rock mass, and their orientation, normal spacing and persistence. Despite the importance of persistence for characterising discontinuities, the user must previously decide on the field whether a discontinuity is persistent or non-persistent. Contrarily, the use of 3D datasets enables the establishment of objective criteria during the characterisation of rock masses. In this work, we present a comparative analysis of the persistence of a rock slope in Braga (Portugal). An experienced engineer analysed the discontinuities. Besides, the rock slope was digitised through the SfM technique, enabling the analysis and extraction of their discontinuity sets. The results showed that despite the aid of the 3D point clouds, the fieldwork still plays a key role in the field recognition and discontinuities characterisation. However, the use of 3D point clouds provides objective information to enhance the analysis of a rock slope.

Keywords: Discontinuity · Persistence · Remote sensing · SfM

1 Introduction

Rock masses are volumes of rock that lie under the Earth's surface. Besides, rock masses compose the surface jointly with soils. Civil and mining engineering works must deal with the rock masses in terms of stability (roads, cuts, reservoirs, tunnels, etc.) and resources extraction (mining). Their behaviour depends on the intact rock characteristics along with the presence and characteristics of the discontinuities.

The latter term refers to any separation in a rock mass that presents low or almost zero tensile strength [1], and its characterisation is a key factor for the stability of rock slopes. In 1978, the International Society for Rock Mechanics (ISRM) suggested various methods for the discontinuity. These suggestions considered that data were captured during the field work and consequently limited by human capabilities and available tools (compass, measure tape, etc.). Since then, computer machines and electronic tools have seen rapid development in terms of sensor characteristics, memory and processing. Remote sensing instrumentation, such as Light Detection and Ranging (LiDAR) or Terrestrial Laser Scanning (TLS), and digital photogrammetry, such as Structure from Motion (SfM), enable the rapid acquisition of millions of points with high accuracy and precision. These techniques are nowadays a hot topic among the scientific community [2]. Not only geomorphologists, engineers and geologist use the data derived from these tools, but also students exploit it because of its versatility and the usability by non-experts.

The data derived from remote sensing techniques comprises digital files that contain the coordinates $[X, Y, Z]$ of the surface points. The size of this data may range from miles of points (a poor and sparse point cloud) to hundreds of thousands of millions of points (several high-resolution registered scans). Besides, the points can also provide much more information. TLS instruments capture the coordinates of the points and record the returned energy to the sensor or intensity [I]. However, recent TLS instruments can capture imagery information estimating the true colour of the points by the captured photos. The colour is recorded by the combination of red, green and blue colours $[R, G, B]$. SfM processes do not record the intensity as they employ photos instead of a laser. As the photos are used, they directly provide the point colour and they can easily process the textures [3] Other researchers have focused on the multispectral or hyper-spectral information [4, 5], enabling the identification of lithologies or environmental applications [6, 7].

The discontinuity extraction from a rocky slope consists of the quantitative (geometric) and qualitative (descriptions) study of the planes exposed in an outcrop. Other techniques such as Ground Penetrating Radar (GPR) could be considered but are out of the scope of this study.

The traditional method consists of the preliminary identification of the planes, which is a subjective process since the user decides what is a discontinuity on the surface. Then, the user captures orientations using a compass. Note that the number and location of the measurements depend on the decisions of the users. Besides, environmental conditions, site conditions and personal situation of the user may affect the collected data. The user may also collect additional information of each discontinuity [8, 9]: weathering degree, Joint Compressive Strength (JCS), normal spacing, persistence, waviness and roughness, presence and composition of fillings, presence of water. Despite problems of subjectivity, this method allows the user to use the know-how obtained with the experience of previous years.

The use of 3D datasets enables the analysis of millions of points captured from the surface. This fact constitutes a radical change in the paradigm of the geometrical analysis because previous methods must be adapted. The extraction of the number and orientations of the discontinuity sets has been deeply studied [10–24]. The subsequent analysis focuses on the study of the normal spacing [25, 26], persistence [27] or roughness [28–32].
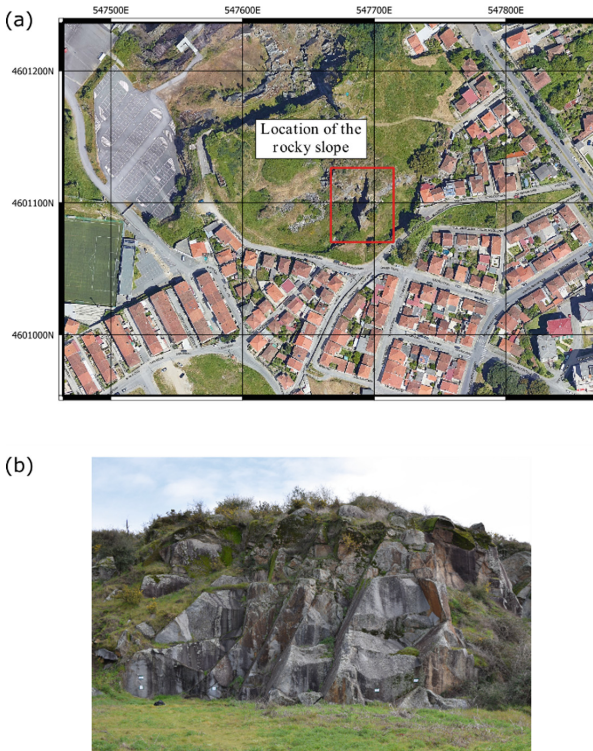
Fig. 1. (a) Location of the site, the location of the rocky slope is marked in a red frame; (b) view of the rocky slope.

In this study, a granite rocky outcrop is studied by an experimented geological engineer using traditional methods and by the analysis of a digital model captured using the SfM technique. In both approaches, the number of discontinuities is extracted along with their orientations, and the persistence is established. The comparison of the results leads to a discussion, where the advantages and disadvantages of both methods are shown.

2   Materials and Methods

2.1   Site Description

The rocky slope is in the granite's quarry of Monte Castro in Braga, Portugal. This quarry is next to the Municipal Stadium of Braga (see Fig. 1a). The size of the rocky slope is approximately 15 m width and 10 m height (see Fig. 1b). The exposed parallel planar surfaces represent all the discontinuity sets.

Observation of the discontinuities shows long persistence values and lack of rock bridges. This leads to the idea that perhaps these discontinuities are sheet joints [33].

2.2 Fieldwork

Two experienced geological engineers carried out a fieldwork campaign in July 2018. They used traditional methods to identify the discontinuity sets and to measure their persistence. First, they identified ten discontinuity sets (see Fig. 2). Second, they measured the orientations on what they considered planes (well defined as seen on Fig. 2) using a compass, and persistence values were measured using a tape. It is worth noting that in granites three discontinuity sets along with other secondary discontinuity sets are usually found. However, in this case, some discontinuities which seemed to have the same orientation crossed. Consequently, in this early stage of the study, it was decided to consider them as separate discontinuity sets.

Fig. 2. Identification of the discontinuity sets identified during the fieldwork.

2.3 Building the SfM Digital Model

The digital model of the rocky outcrop was generated using the software Agisoft Metashape [34]. To compare the results of the fieldwork and remote sensing work both models must be oriented with respect to the magnetic north and the vertical axis. Since we got the coordinates of the three first GCP using orientations captured with a compass, we can compare both results. We captured the 169 photos according to the method proposed by Jordá Bordehore et al. [35]. This method comprises the insertion of ground control points (GCP) defined using a local reference system.

The GCPs were printed targets fixed on the rock surface. The first GCP was considered as the origin and two close GCP coordinates were calculated using a compass and a tape. Four additional GCPs were inserted into the model using targets, and their distances were measured using a tape. These four GCPs only introduced distances in the SfM workflow, so their coordinates were not calculated. The errors of the coordinates and the errors of the distances inserted in the rest of the GCP are presented in Tables 1 and 2, respectively.

Table 1. Errors found in the GCP.

Label	X error [cm]	Y error [cm]	Z error [cm]	Total [cm]	Image [pix]
Target 1	−3.57042	5.05714	0.29312	6.19746	0.159 (39)
Target 2	2.26098	−3.2025	−0.0670916	3.92078	0.159 (25)
Target 3	1.30923	−1.85471	−0.225949	2.28146	0.125 (16)
Total	**2.55434**	**3.61804**	**0.217159**	**4.43419**	**0.152**

Table 2. Errors found in the GCP with scale bars.

| Label	Distance [m]	Error [m]
Target_1-Target_4	4.4053	0.00230377
Target_5-Target_5	2.81696	−0.00104203
Target_6-Target_7	1.95649	0.00149005
Total		**0.00169444**
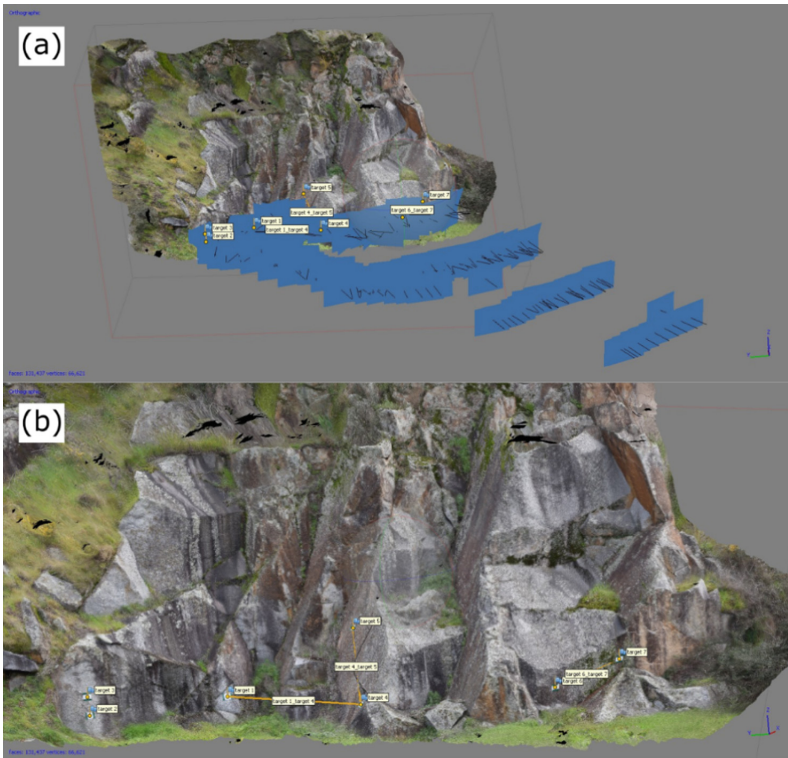
Fig. 3. (a) View of the 169 cameras; (b) textured model and location of the GCP.

To analyse the rocky slope, the vegetation was manually removed. Besides, the three-dimensional point cloud (3DPC) was subsampled setting the minimum distance between points to 1 cm. This step reduces the heterogeneity of density in the model and enhances the quality of the normal vector poles' density (Fig. 3).

The analysis of the 3DPC followed the method proposed by Riquelme et al. [20]. The method is available in the open-source software Discontinuity Set Extractor (DSE) [36]. The method aids the identification of the discontinuity sets, the extraction of their orientations and classifies the 3DPC assigning a discontinuity set and a plane (cluster of points). This classification enables subsequent analysis: the normal spacing analysis [25] and the discontinuity persistence [27]. The DSE software offers both analysis.
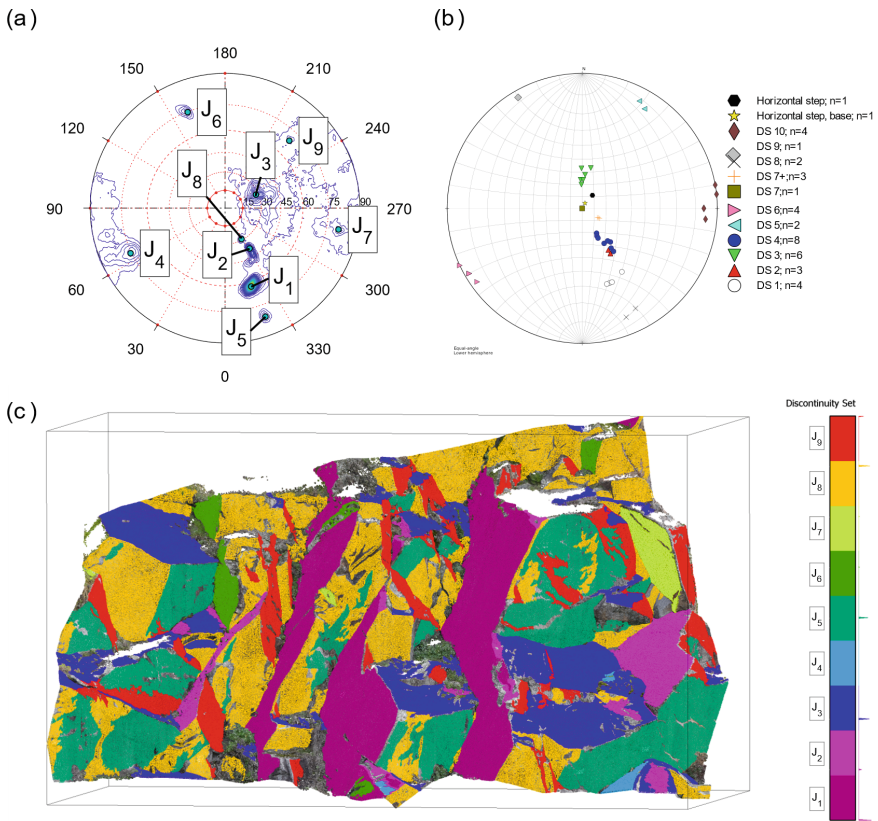
Fig. 4. (a) Stereonet obtained from the 3DPC; (b) stereonet of the fieldwork measurements; (c) 3DPC classified, one colour per discontinuity set. Non-coloured points (according the scale bar) are points not assigned to any DS.

3   Results

The Fig. 4 shows the analysis of orientations results. The discontinuity sets that were identified in the fieldwork were also extracted from the 3DPC. Figure 5 and Table 3 show the results of the persistence measured during the fieldwork and using the 3DPC.
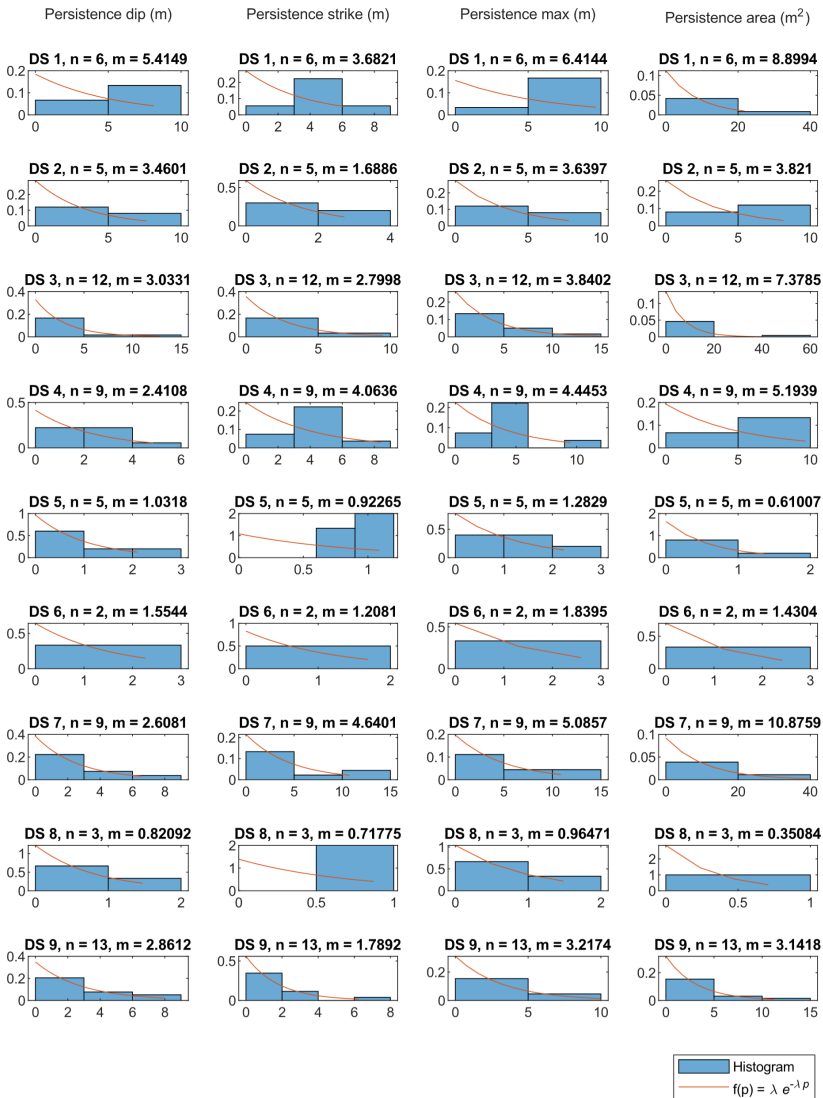

Fig. 5. Histograms of the discontinuity sets for persistence measured in the direction of dip, strike, maximum length within the convex hull and area.

Table 3. Persistence values measured during the fieldwork and using the 3DPC.

Family	Fieldwork			3DPC	
	Joint length [m]	Direction	Observation	Persistence [m]	Direction
1	>20	Max. slope	Crosses the slope	6,4	Max.
2	>10	Max. slope	≈DS 2 spacing	3,6	Max.
3	5	Max. slope	–	3,8	Max.
4	>5	Max. slope	–	4,5	Max.
5	>2	Max. slope	–	1,3	Max.
6	>7	Horizontal	–	1,8	Max.
7	>20	Horizontal	Crosses the slope	5	Max.
7+	5	Max. slope	Between DS 2 and 3	–	–
8	>20	Max. slope	Crosses the slope	1	Max.
9	>5	Max. slope	–	3,2	Max.
10	>4.5	Horizontal	–	–	–
Hor. step (base)	>2.2	Max. slope	–	–	–
Hor. step (top)	>2.2	Max. slope	–	–	–

4   Discussion

The fieldwork identified 10 discontinuity sets. Although most geologists and engineers may consider this figure excessive, there is a reason for this. The operators made a rigorous consideration during the fieldwork: if two discontinuity planes with similar orientation crossed in the outcrop; we consider both planes part of separate discontinuity sets. Figure 2 presents the adopted scheme.

The analysis of the 3DPC showed a sparse density of the normal vector's poles. To identify the precise values of the orientations, we used a high number of neighbours for calculating the normal vector (knn = 30). Besides, the resolution of the density function required the increase of the number of bins (from the general value 26 to 27).

In both stereonets, a set of discontinuity sets appeared following a path (see Fig. 4a): J5, J1, J2, J8 and J3. This difficult the analysis of the orientations. In the fieldwork's case, the operators analysed separately the measurements captured from selected planes. Therefore, there are no interferences. However, if we analyse the measurements of all the slope simultaneously, we may not identify the aforementioned set of discontinuity sets as they were. This is the case of the analysis using the 3DPC: somehow it is a blind analysis of the points and the user guides the software to achieve the results.

The persistence analysis shows variations between the fieldwork and the 3DPC. Some maximum values of the persistence are similar. However, others do not match. We can find the explanation in the 3DPC data. If we assume that the analysis only uses the geometric data, some information may be lost: small traces or visual trends in the outcrops. The used method to extract the persistence considers the extent of each plane (or cluster of points belonging to the same plane). The software can consider coplanar planes members of a discontinuity set and merge them into a single cluster. This implies that the persistence value increases. Despite the valuable information provided by the 3DPC, the fieldwork perception provides additional information that the digital data could not provide. However, digital datasets provide precision and access to areas where the operator could not access.

5   Conclusion

This study presents the analysis of a granite rocky slope in Braga (Portugal) using traditional fieldwork data and SfM-derived 3DPC. Several discontinuity sets presented close mean orientations, but the operators considered them as separate discontinuity sets because they crossed in the outcrop. Consequently, the 3DPC analysis required specific settings to provide precision to the analysis. The results and the stereonets showed high resemblance. The analysis of the persistence presented good correlation in some discontinuity sets. However, others presented differences because the field perception provides information that is hardly found in geometric digital data.

This study evidences the potential of low-cost techniques to analyse rocky slopes. In addition, it also shows that, despite the advances in the techniques, the engineers and geologists still require the fieldwork experience.

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