

## Characterization of Rock Slope Discontinuities by Three-Dimensional Image Restitution

Caracterización de discontinuidades en macizos rocosos mediante restitución de imágenes tridimensionales

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**ABSTRACT:** Fractured rock masses characterization requires systematic work to capture the most relevant properties of discontinuities in the field to build computational models that reflect such discontinuous nature. The quality and quantity of geological and geotechnical information obtained from field surveys is essential and highly relevant to proper characterization of rock masses. However, field workers often face challenges in gathering sufficient information on rock slopes, such as difficult access areas or unsafe slope stability conditions. In such cases, conventional compass and tape surveys require extrapolation of the information from the sampled areas to the entire slope surface, creating uncertainty about the representativeness of the data to reflect the spatial variability of discontinuities on the slope surface. It is therefore necessary to consider non-conventional methods such as restitution of three-dimensional images acquired with a short-range terrestrial photogrammetry system. This paper presents several case studies of rock masses in different regions of Colombia, where this technique has been successfully used to characterize discontinuities in mining and road slopes where field data collection using traditional methods was very difficult. Image analysis was used to identify the number of sets of discontinuities, to determine the geometric characteristics of each set, and to obtain an appropriate computational spatial representation of the slopes.

**KEYWORDS:** Rock slope, discontinuity characterization, short-range photogrammetry, 3D elevation model, image restitution.

### 1 INTRODUCTION.

Rock masses are often discontinuous media whose mechanical response may depend on the relative size of discontinuities to the magnitude of the slope. In these cases, the stress-strain behavior, the kinematics of eventual failure or instability, the permeability and durability are influenced by the geometric configuration of discontinuities, that can be very complex, depending on rock genesis and stress history.

Proper characterization of rock slopes requires systematic work to capture the most representative properties of discontinuities in the field (Dershowitz et al., 1985; Heliot, 1988; Wei et al., 2022). Conventional compass surveys use window or scanline sampling through subjectively selected areas of the slope, and the measured information is usually extrapolated to un-sampled areas. To overcome this limitation, data collection is complemented by using a piece of a powerful, wide-ranging equipment to extract a greater amount of data in a relatively short time (Cleveland and Wartman, 2006; Haneberg, 2008; Sturzenegger and Stead, 2009; Tannant, 2015), and for characterizing areas that are difficult or unsafe for

field workers to access (Menegoni et al, 2020; Jaboyedoff et al, 2012).

For this study, different rock slopes in Colombia were selected, and the field information was collected using a short-range terrestrial photogrammetry system (SRS) consisting of a calibrated camera, a range pole as a reference to scale photos, and the software (see Figure 1). The camera calibration requires determining camera settings parameters that describe the image formation inside the camera (focal length, focus or aperture), which means defining the interior camera orientation (Gaich et al, 2006). Then, 3D images from a calibration target are generated to correct the lens distortion (Gaich et al, 2004).

A pair of georeferenced and overlapping images is taken from the slope. The manufacturer recommends a distance from the camera standpoints to the slope face should range from 12% to 20% (Gaich et al, 2004). This ratio is verified as the 3D image is generated. Then, the 3D reconstruction is carried out by intersecting a viewing ray from a point in the first image with its corresponding counterpart in the second image (Gaich et al, 2004),

which defines the 3D location of that point. Afterward, a triangular mesh is generated by connecting the 3D points, which leads to the 3D image.



Figure 1. System components. Calibrated camera (left); Range pole (center); software (right).

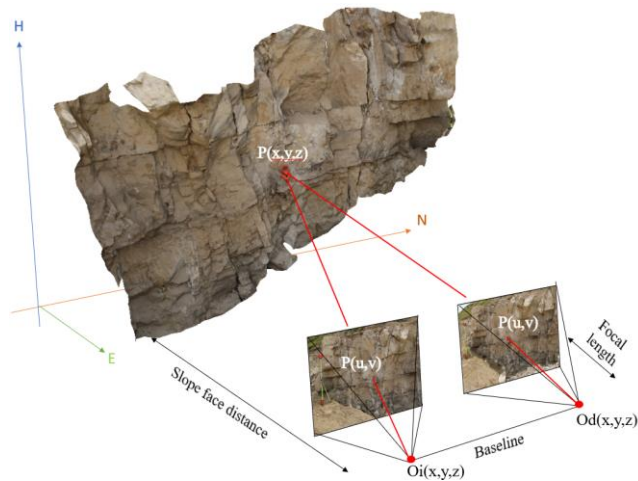


Figure 2. Overlapping image capture.

From the 3D model, the geometric characteristics of the discontinuities are extracted, the number of sets are identified, and their computational spatial representation is achieved. This allows the spatial variability of discontinuities within the slope surface to be properly represented in order to build computational models that reflect the discontinuous nature of the rock mass (Crosta, 1997; Bonilla-Sierra et al., 2015; Hernandez-Carrillo and Beltrán, 2019; Buyer et al., 2020).

This paper is organized as follows: Section 2 presents a detailed description of each case study and the respective characterization obtained with the unconventional image restitution-based methodology used in this work. Section 3 provides the most significant conclusions related to the advantages of these alternative methods to complement the geotechnical information for rock discontinuities characterization, as well as the special considerations and limitations identified, based on our experience.

## 2 CASE STUDIES

### 2.1 El Pedregal – sandstone quarry

This is a sandstone quarry located in Cundinamarca, the central region of Colombia (see Figure 3). The rock mass is part of the Une Sandstone Formation and is in a monocline with dips between 18° and 30°. The slope is located along a 1500m scarp on the monocline's east side. The surveyed slope is 270m long and 25m high.

Figure 4 shows the lithological sequence consisting of interbedded sandstone, and shale layers. The sandstone layer is utilized as aggregate for concrete in this region, and nowadays, active mining activity is carried out on this site. A joint set controls the slope face, and the excavation is perpendicular to the bedding dip direction.

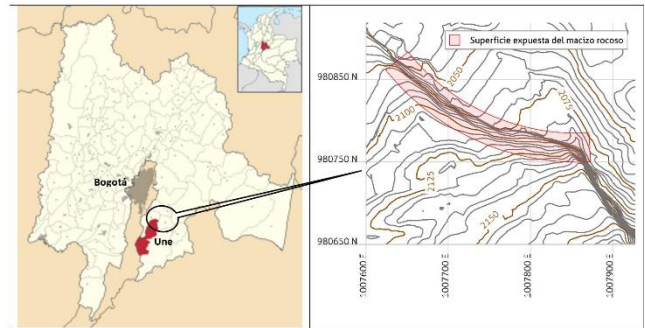


Figure 3. El Pedregal mine location

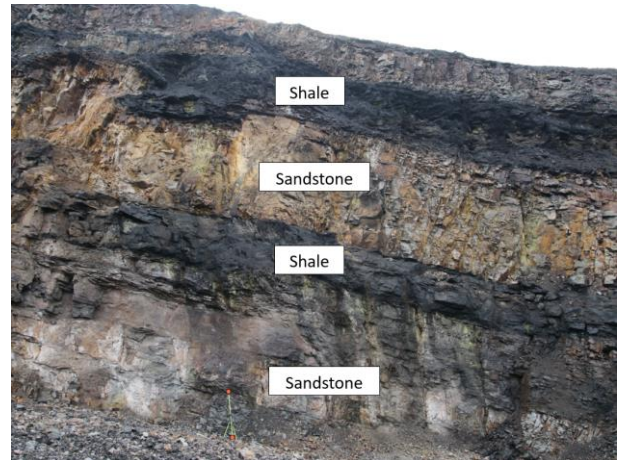


Figure 4. El Pedregal mine. Exposed lithological sequence.

Rock slope surveying has been carried out in this mine since 1997, and structural information has been collected by compass and tape. However, gathering the structural information has been challenging, given the slope height and the constraints imposed by the mine operation and safety requirements. Hence, the time

available for this task is limited. Hence, an SRS is suitable to collect such information.

To implement SRS, the slope was divided into 12 stations. At each station, a 3D image was constructed, and the geometric structural features were precisely measured. This data was then used to create a comprehensive 3D image, as shown in Figure 5, where three distinct joint sets are visualized, each identified by a unique color.

As a result, a robust dataset of joint orientation, separation, and length was obtained within one day of fieldwork and three days of processing time. Table 1 and Table 2 show a summary of the orientations measured by the SRS technique and the compass, respectively. The corresponding pole plots are shown in Figure 6.

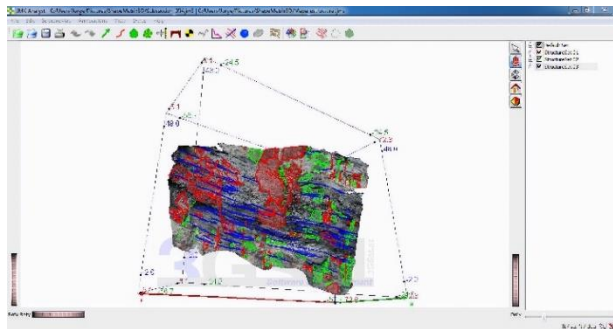


Figure 5. El Pedregal mine. 3D image reconstruction.

Table 1. El Pedregal mine. Summary of information on joints orientations measured with compass.

	Set 1	Set 2	Bedding
Number of measured planes	272	235	56
Dip direction (°)	152.68	58.93	288.23
Dip (°)	76.51	74.53	25.71

Table 2. El Pedregal mine. Summary of information on joints orientations measured with SRS.

	Set 1	Set 2	Bedding
Number of measured planes	657	732	521
Dip direction (°)	171.54	51.59	297.39
Dip (°)	86.20	80.43	15.07

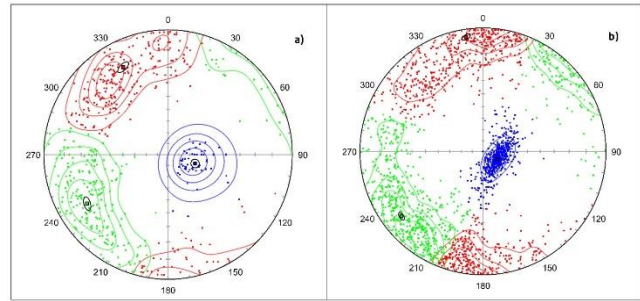


Figure 6. El Pedregal mine. Poles plot for the rock discontinuities orientation. Left: measured with compass. Right: measured with the SRS.

The first noticeable result is the amount of collected data; the number of planes measured is three times that measured by the compass (563 by compass and 1910 by SRS). The difference is more dramatic for the bedding planes, where I measured 521 orientations, while previous works gathered only 56 data on this plane. This result is significant from a practical point of view. From the author's experience, frequently, it is tough to position the compass properly on a bedding plane to measure its orientation because it is too small or unreachable.

Besides, the time required to perform the fieldwork is only one day, while the information collected with compass results from several field workdays since 1997. A comprehensive statistical analysis of additional information related to length trace (size, persistence) and separation (spacing) is presented in Peñuela et al. (2019). As main result, the authors highlight the agreement between the information collected by compass and SRS.

## 2.2 Road slopes – La Guajira, Colombia

The rock mass is located near Albania, La Guajira, Colombia (see Figure 7), within a Neogene sedimentary formation composed mainly of interbedded layers of medium-grained sandstone, shale, siltstones, and conglomerates.

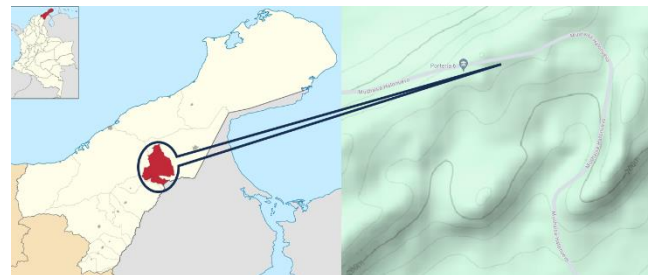


Figure 7. La Guajira road slopes location

In this case, three rock slopes were surveyed: two are private roads, while the third is public. On the private road, it is not allowed to collect information directly from the slope face, given the hazard

of frequent rockfalls. Therefore, the most suitable alternative to collect the structural information was the SRS system.

Figure 8 shows a 3D reconstruction of one slope in Sector 1. The collected information is summarized in Table 2. Two and three joint sets were identified by k-means clustering adjusted according to the field observations. On the other hand, Figure 9 illustrates a fold identified in Sector 2. This is an interesting structural feature that can be fully captured by this sort of technique.

Table 3 summarizes the rock joint orientations in the three surveyed sectors. Sector two was divided into subsectors since different structural features were clearly defined. In this case, robust data sets with 1321 orientations were measured during two days of fieldwork and five days of information processing. Given the restrictions imposed on the private road, the geotechnical designer was pleased to get such robust information for designing the mitigation for rockfalls.

The corresponding pole plots are displayed in Figure 10. The joint sets defined from these plots coincide with the trends identified during the fieldwork. This work was supervised by an experienced geologist, who approved the data yielded by the SRS. In this case, a statistical analysis to compare the information collected manually and by SRS was not possible, because of the mentioned access constraints.

Table 3. Road slopes, La guajira. Summary of information on discontinuity orientations measured with SRS.

Sector	Set	Max Eigenvector		
		Dip	Dip direction	N
1	Set 1-Bedding	164.9	40.63	131
	Set 2	216.43	82.3	105
	Set 3	332.29	75.65	173
2-North	Set 1-Bedding	273.23	50.33	301
	Set 2	104.34	63.5	48
2-South	Set 1-Bedding	308.22	47.05	237
	Set 2	136.49	51.75	65
	Set 3	70.33	85.29	38
3	Set 1-Bedding	203.59	25.92	30
	Set 2	312.26	67.73	127
	Set 3	87.69	86.99	96

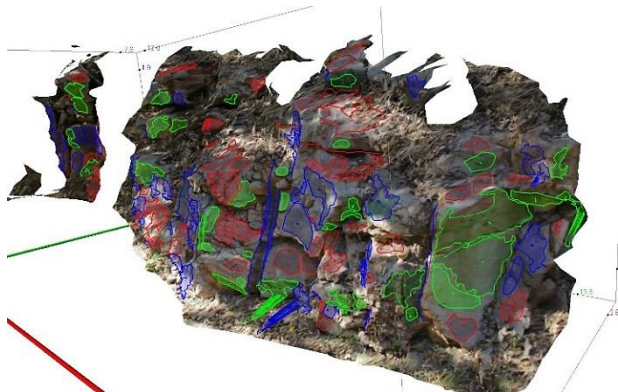


Figure 8. Road slope. Sector 1. 3D reconstruction and planes measured.

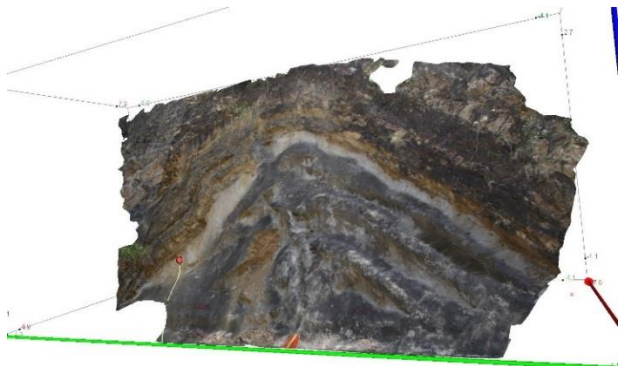


Figure 9. Road slope. Sector 2. 3D reconstruction of a fold identified.

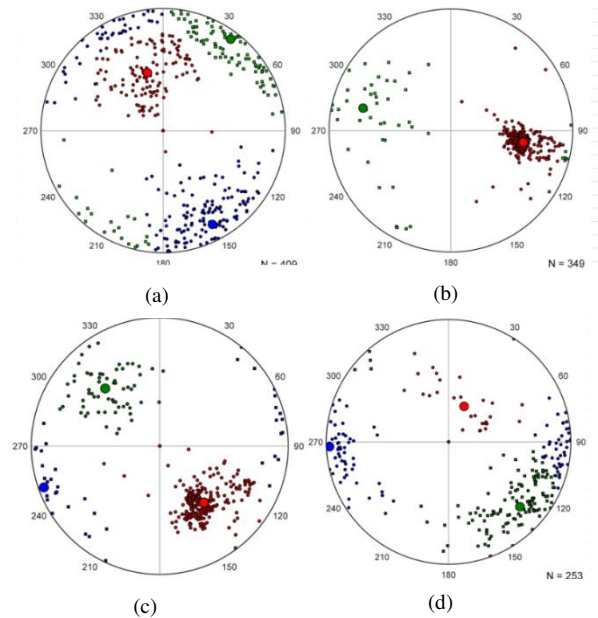


Figure 10. Poles plot for the rock discontinuities orientation. Information collected in the three road surveyed sectors. (a) Sector 1, (b) Sector 2-North, (c) Sector 2-South (d) Sector 3. Set 1-Bedding (in red); set 2 (in green) and Set 3 (in blue)

### 3 CONCLUSIONS

This section summarizes the main advantages and limitations identified in this work, of using 3D image restitution to characterize rock slope discontinuities.

#### Advantages:

- Detailed 3D models were obtained by restoring the images, which facilitate the measurement of the geological-geotechnical parameters of interest.
- Parameters such as spacing, frequency, direction, azimuth, dip, clustering, persistence, size, and shape of discontinuities, can be determined from the 3D model.
- The SRS allows measuring areas of slopes that are very difficult to access, either because of height or restrictions imposed by the companies involved.
- The technique used allowed sampling and measuring the entire area of the slope, thus obtaining a good representation of conditions in the field.
- The system has allowed obtaining very robust databases with a large amount of quality information to ensure objectivity and repeatability.
- The SRS significantly reduces field personnel's exposure to potential rockfalls or slides.
- Digital images are permanently available for analysis, validation, or comparison with subsequent measurements.
- During fieldwork, little or no impact has been generated on vehicular traffic.
- The equipment is lightweight, making it easy to assemble, disassemble and transport.

#### Considerations and limitations:

- There are several conditions that hinder the measurements on the images, such as: the presence of vegetation on the slope or obstacles in the line of acquisition of the images, weather and environmental conditions of cloudiness, precipitation, or low luminosity.
- As with any field data collection method, good georeferencing accuracy is required.
- For stereographic restitution, it is necessary to use photographic pairs taken at the same time.
- Determining parameters such as discontinuity roughness, aperture, and infill requires complementary techniques.

### 4 ACKNOWLEDGEMENTS

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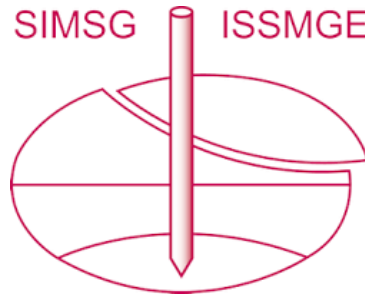
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