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Characterization of Rock Masses by Three-Dimensional Image Processing Technique

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Abstract. This paper presents an alternative to measuring structural features in rock masses. The procedure is based on the reconstruction of the slope surface from a stereoscopic pair of images, taken with a calibrated camera. Complementary, hardware elements for referencing in the field and a software for generating 3D images, measurements and assessments are used. Once the 3D image is generated, it is possible to measure the orientation, spacing and geometry of discontinuities, as well as to process the data to generate the pole stereo networks of the measured planes. Additionally, these poles can be classified by supervised clustering techniques, to define the most representative families of discontinuities in the rock mass and to generate separation statistics for each family. The methodology allows to collect information of the entire free face of the slope quickly, reducing the exposure of the field team to falling blocks risk. Also, orientation and average inclination measurements of planes are made, reducing the error related to local variations in the normal vectors to the planes. Finally, systematic collection of information allows generating a more reliable probabilistic description of discontinuities, compared to traditional methods.

Keywords. 3D image system, joint set, stereoscopy, dip angle, dip direction angle, spacing, uncertainty.

1. Introduction

The three primary sources of uncertainty in rock mechanics problems are the inherent spatial variability of properties, the error induced in measuring and the estimation of engineering properties and inaccuracies in modeling [1].

The first two sources can be handled by improving the data collection process. More observations will not reduce the uncertainty but will improve the characterization of such variability. On the other hand, involving alternative and reproducible methods for collecting observations on the rock mass will contribute to reducing the uncertainty linked to the second source of uncertainty, the measurement error.

With this framework, two alternatives were used in this paper to collect the information on joints geometry. First, the orientation of joint planes was measured by using compass and tape. Subsequently, a short-range stereoscopy system was used to gather information on rock joints structure.

The applied method integrates an extensive experimental plan in both, field and computer laboratory, to collect structural data such as orientation, persistence, and

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spacing of discontinuities in a rock mass taken as a case study. Likewise, an intensive work of data collection in the field was carried out by conventional methodologies using compass and tape, for comparative purposes validation. The results allow establishing the advantages of using unconventional techniques, in terms of quality and quantity of information, as well as efficiency in terms of time spent on field data collection. Through the semi-automatic analysis of three-dimensional images, geological mapping and objective characterization of discontinuities for geotechnical purposes were achieved. The technique discussed in this paper constitutes a powerful tool with significant potential for use in road and mining projects in Colombia.

2. Measuring rock mass structure

Information on joints geometry is collected based on information observed on the rock mass exposed areas or boreholes. In any case, an extrapolation from 1D or 2D information, into a 3D model is required to represent the rock mass adequately.

Probabilistic approaches for defining the joint sample sizes by scanline or window mapping were used [2]. This sampling error, which controls the quality of the mapping, arises from three different sources [3]:

- Sampling error: caused by non-representative information
- Estimation error due to statistical variation of samples
- Measurement error due to inaccurate measurement

The two main conventional techniques for collecting rock mass structure are boreholes and compass measurements. Boreholes provide information on joints geometry in depth, beyond the exposed area. However, this method of data collection is relatively expensive and time-consuming. Besides, given the small size of the sample, the information provided is very limited, and a proper interpretation of the information is required.

Conversely, the use of compass and tape for measuring information in outcrops and engineering rock slopes, provides an important amount of information at a much lower cost. However, by itself, it does not provide information on the evolution of geometry with depth, as it is the case of borehole data collection. Hence, a combination of both approaches is desirable.

In both cases, direct access to the observation area is required, which intermediately generates the following limitations:

- Limited access
- Time-consuming activity, which can be a drawback, especially in mining operations, where operation constrains access to slopes
- Measurements depend on the characteristics and experience of the staff; e.g., most measurements are taken up to the operator's height.

The above mentioned drawbacks have two main consequences. Results are biased, and reproducibility is not guaranteed [4].

In practice, the selection of sampling sector is conditioned by the availability of accessible outcrops and engineered slopes and depends upon expert opinion based on its interpretation of the geological conditions of the rock mass and the subjectivity for the selection of sampling points.

In order to overcome and reduce the uncertainty linked to the joints geometry sampling process, new technologies based on remote measurements have been developed [5].Image processing systems are a relatively new approach to characterize rock mass joint geometry, overcoming the above mentioned limitations.

Bhreasail et al [6] developed a revision of the remote techniques available for geotechnical purposes, to be implemented in roads management in England, such as multispectral and hyperspectral images, Synthetic Apertura Radar Interferometry (InSAR) [7], passive microwave radiometry and cameras with motion sensors. Besides, there are several examples of applications of the laser with LIDAR [8], a combination of techniques [9–11], and comparative analysis [12].

As for photogrammetry applied to rock structure measurements [13] published a pioneering work to measure the roughness profile of rocks. Then, Topographical Survey Directorate of the Surveys and Mapping Branch, Department of Energy, Mines and Resources in Canada, carried out a research to measure joints geometry and slope face movements by using photogrammetry [14]. Subsequently, [15] utilized pictures taken from a setup of two cameras to compute the position of five points along a single discontinuity. With this information, the orientation of the plane is computed.

Several works have focused on the measurement of geometrical features of rock slopes by photogrammetry [16–19]. For hazard assessment [20], [21] for landslide mapping [22], and monitoring [23–25]. Information collected using photogrammetry has been used as input information for further geotechnical stability assessment [26–31].

Considering the need for developing more reliable models and introducing up-to-date technologies to daily engineering activity, this work resorts to ShapeMetrix3D that is a short-range photogrammetry system that builds a 3D image of the rock face based on two overlapping images, using the principle of stereoscopy. The system is based on the original work of Gaich, Fasching and Schubert [32] and then commercialized by the Austrian company ShapeMetrix3D.

Figure 1 shows the parts of the imaging system. It consists of a calibrated camera to capture the images, a range pole to scale the images, and processing software divided into components to construct the 3D image, normalize, trim and reference the image and perform the mapping. With this system, the current operation of the slope was characterized following the steps depicted in Figure 2. A detailed explanation of the procedure to generate a 3D rock slope face image and to measure rock slope structure is presented in [33].

Figure 1. Components of ShapeMetrix3D system. After [33].

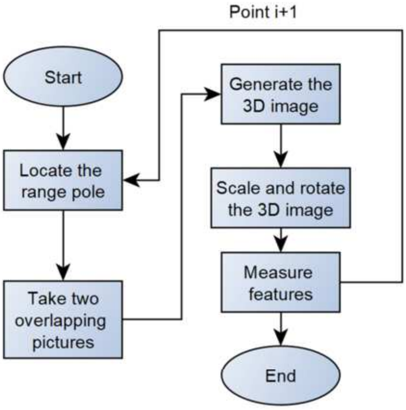

Figure 2. Procedure to characterize rock slopes structure by a short-range stereoscopy system.

3. Case Study

The 3D image system was utilized in El Pedregal quarry. This is a sandstone quarry situated in Une, Cundinamarca, Colombia. This mine is in a sedimentary rock mass, formed mainly by an alternation of sandstones and shales. The mine has been operated since mid 1990s to present. Holcim Colombia S.A. operated the mine until 2013, then Gravillera Albania S.A. took over control of the operation. Both companies have had a responsible follow-up program on geological and geotechnical aspects, according to Colombian legislation.

As for the geology, the mine is located on a sedimentary complex from Arenisca de Une formation. The rock mass is on a monoclinal dipping northwest with variable dip ranging between 18° and 30°. A 1500m length scarp bounds the east side of the monoclinal. On the north edge of the scarp is located the mine exploration. The main exploitation slope has approximately 270m length and 25m high.

The collection of information on joints geometry has been addressed using conventional compass measurements. In 1997 just a compass and approximate location were used. Then in 2011, the GPS location was added. Then in 2016, new information was collected following the same procedure.

In 2017 information was collected using ShapeMetriX3D. A civil engineer with experience in rock mechanics carried out this task assisted by a research assistant. As preparing task, the engineer took a training course in Graz, Austria for operating ShapeMetriX3D.

To acquire the images, the slope was divided into 16 regions. At each region, the range pole is located on one side of the measurement and two overlapping pictures are taken. Besides, within each region a reference line was surveyed to properly rotate the image.

Once pictures are available, the SMX ReconstructionAssistant software component interpolates the pair of photographs to construct a 3D image of the slope. Then, the SMX Normalizer scales and rotates the image, based on the range pole reference and the surveyed line respectively. Subsequently, traces and panes are measured using the JMX Analyst module of ShapeMetriX3D. Figure 3 depicts a 3D image already processed, where three joint sets were identified.

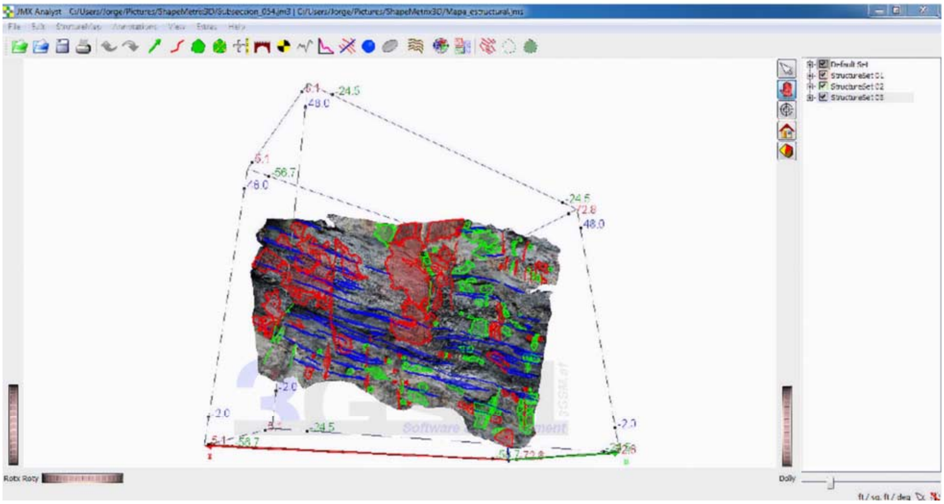

Figure 3. 3D image of the rock slope already processed.

4. Results

In the following, a description of the information collected using ShapeMetrix3D is presented, as well as a comparison with the results obtained by the traditional compass technique.

One of the first noticeable differences has to do with the area measured by the remote system. Here, the entire area can be mapped, which ranges between 150m^2 and 450m^2 depending on the region, while with the compass up to 2m high was reachable, which means that only 13% of the area is sampled.

Orientations measured by using the compass and the remote system are depicted in Figure 4. Poles diagrams show similar trends, in which there are three joint sets: one for the bedding (blue) and two steep joint sets (green and red). Orientations were clustered using a k-means algorithm and mean orientations are presented in Table 1.

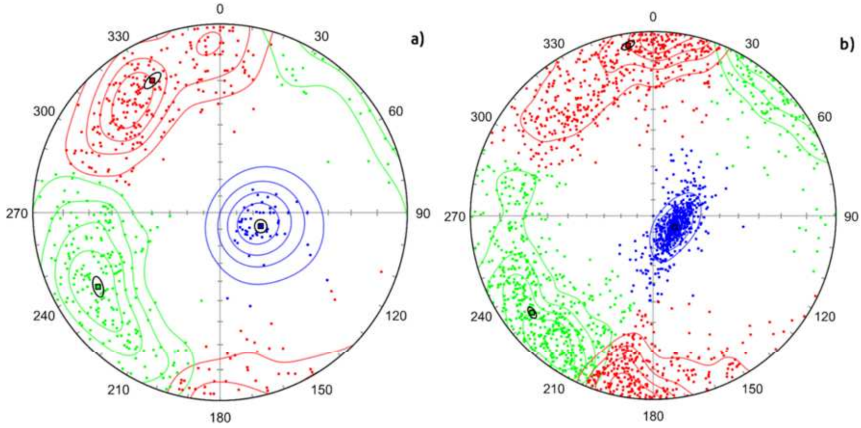

Figure 4. Pole diagrams measured with a) compass and b) ShapeMetrX3D system.

With the 3D image system, 2152 orientations were measured, which represents an increment of 91% on the number of planes, compared with the information collected manually, during the field campaigns in 1997, 2011 and 2016 altogether. This is the result of reaching a larger area, which makes the process more efficient.

Table 1. Joint sets defined by k-means algorithm for both compass and ShapeMetriX3D techniques.

Technique	Parameter	Set 1	Set 2	Set 3 (Bedding)
Compass	Number of planes	272	235	56
	Dip direction (°)	152.7	58.9	288.2
	Dip (°)	76.5	74.5	25.7
ShapeMetriX3D	Number of planes	657	732	521
	Dip direction (°)	171.5	51.6	297.4
	Dip (°)	86.2	80.4	15.1

Other than the amount of information collected, it is important to highlight how the information is distributed among the different joint sets. For the compass, most of the data (90%) belong to joint sets 1 and 2, and only 56 poles were measured on the bedding.

This bias is less evident for ShapeMetriX3D, where data are evenly distributed: 35% of the information belongs to joint set 1, 38% to joint set 2 and 27% to bedding. The difference in the information distribution has to do with the drawbacks to measure bedding planes because most of them are traces that cannot be directly measured by the compass.

Table 2 and 3 summarizes trace length and spacing results respectively. A minimum trace length of 0.30m was considered in both, the conventional and the remote techniques. The first evident result is the amount of information collected. For the nonconventional technique 1810 measurements of length were collected, while 465 for the tape. As for spacing, this difference is even more dramatic; 5338 orientations were measured by ShapeMetriX3D and just 408 by tape. Moreover, as orientations, spacing, and trace length measurement are evenly distributed when collected by ShapeMetriX3D, as shown in tables 2 and 3.

Table 2. Trace length for joint sets computed from both tape and ShapeMetriX3D techniques.

Technique	Parameter	Set 1	Set 2	Set 3 (Bedding)
Compass	Number of measurements	233	225	7
	Mean (m)	1.91	1.66	0.93
	Standard dev. (m)	2.61	1.68	0.73
ShapeMetriX3D	Number of measurements	590	721	499
	Mean (m)	1.16	1.03	2.71
	Standard dev. (m)	0.93	0.93	1.97

The difference in the number of measurements between the two techniques is explained by the larger area measured with ShapeMetriX3D. When information was collected by tape, the sampled area was constrained by the operator's height, while with ShapeMetrix3D the entire slope height was measured, which makes the persistence and separation measured by the remote technique more reliable.

Table 3. Spacing for joint sets computed from both tape and ShapeMetriX3D techniques.

Technique	Parameter	Set 1	Set 2	Set 3 (Bedding)
Compass	Number of measurements	205	200	3
	Mean (m)	0.26	0.32	0.58
	Standard dev. (m)	0.33	0.35	0.65
ShapeMetriX3D	Number of measurements	1690	2098	1550
	Mean (m)	1.77	1.40	1.28
	Standard dev. (m)	2.63	2.13	1.75

5. Conclusions

In this work, a short-range stereoscopy technique (ShapeMetriX3D) for collecting remotely structural information from a rock mass has been utilized. Results were compared with the traditional compass and tape technique.

One of the main advantages is the possibility of doing remote measurements, which makes accessible the whole exposed rock mass face (slope or outcrop). In conventional compass measurements, the access is constrained by the operator ability to access and measure exposed planes. Hence, a larger area is mapped using the short-range stereoscopy technique.

Consequently, the amount of collected information by the 3D image system is larger compared to the compass. Specifically for case studied in this project 9058 measurements were gathered with ShapeMetriX3D, including 1910 orientations, 5338 spacing, and 1810 trace length records, while with compass and tape 1436 data were measured distributed in 563 orientation, 408 spacing, and 465 length records.

Aside from the bias induced by access restriction, the remote system reduces bias generated by preference to measure only clearly exposed planes, the ability to measure traces orientation directly from the slope face, and changes in mean slope orientation in the same exposed plane.

Besides, it reduces the fieldwork time required to collect the information, which means less time for the operator to be exposed to an eventual slope instability event, rock fall or an accident, the latter is crucial in mining activities.

Regarding orientations, mean joint set orientation measured with ShapeMetriX3D and compass are consistent, despite the difference in the amount of evidence. This validates the applicability of this 3D image technique for measuring rock mass structure features.

The 3D image technique allows having reproducible and objective measurements of joint planes spacing, based on the normal distance between planes, using the same algorithm over and over. Besides, it allows sampling the entire slope, improving the representativeness of measured trace length and separation.

The comparative advantages of the short-range stereoscopy make it a suitable technique to be implemented in routine geomechanical applications for rock slope design in Colombia when rock faces are exposed. However, it does not replace the traditional methods and sound professional judgement.

Finally, once the image is generated, it is available at any time. Hence, additional measurements or assessment may be carried out without going back to the site. Besides, it allows the geotechnical engineer to have a close and detailed view of the rock slope, which improves his/her understanding of the rock slope potential behavior.

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