Using open-source software for extracting geomechanical parameters of a rock mass from 3D point clouds: Discontinuity set extractor and SMRTool

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ABSTRACT: New 3D data acquisition techniques allow to obtain geometrical information of exposed rock masses. This information can be used to characterize some geo-mechanical parameters of rock slopes, allowing users to remotely obtain information. Recently, many researchers have been working on the extraction of geo-mechanical parameters of rock masses using 3D point clouds, such as the number of discontinuity sets and their orientations, the normal spacing and the persistence. In this contribution we use two novel open source programs: (1) Discontinuity Set Extractor (DSE) aids to analyse 3D point clouds detecting the number of discontinuity sets, classifying each point with its discontinuity set and plane equation and calculating their normal spacing; and (2) SMRTool calculates the geo-mechanical quality of a rock slope by means of the Slope Mass Rating (SMR) index. In order to illustrate the use of the two software programs, we analyse the geo-mechanical quality a slope placed in the National route N-332 in El Campello (Alicante, Spain), in the named Flysch sequence of Alicante, using 3D point clouds. The 3D point cloud was analysed using the previously mentioned open-access tools. Their use allowed to extract the discontinuity sets, normal spacing and persistence using a software which code can be inspected and improved without cost. Moreover, it allows to reproduce the full analysis process using the same method parameters.

1 INTRODUCTION

Rock mass classification systems are well known tools which are useful for characterizing rock mass properties, in order to assign an "index of quality" for stability purposes. These tools are used worldwide by geo-mechanical engineers in the design or pre-design stages of civil or mining projects. The quality assessment of a rock slope, through the geo-mechanical classification, is calculated using certain parameters. These parameters are usually acquired through time-consuming field investigation techniques: geological compass for obtaining discontinuity orientations, tape measurements for discontinuity spacings or persistence and roughness analysis by local examinations. Sometimes, fieldwork campaigns can be affected by several restrictions, being well known examples, such as, safety issues in active rockfall areas, possible access limitations and intensive work requirements in highly fractured rock masses. More recently, several attempts have been made to determine the rock mass quality using remote sensing data or digital pictures.

The use of remote techniques allows for the acquisition of three dimensional information of the terrain with high accuracy and high spatial resolution. Three-dimensional datasets coming from both techniques are widely used for landslide investigations (Abellán et al., 2014). Moreover, the scientific community is showing an exponentially growing interest in the study of the extraction of several parameters influencing rock slope stability, including rock mass discontinuity orientations (Riquelme et al., 2014b) and other rock mass parameters: spacing between discontinuities (Riquelme et al., 2015), discontinuity persistence (Umili et al., 2013) and roughness (Sturzenegger & Stead, 2009).

In this work, the Slope Mass Rating (subsequently called SMR) quality index of a rock slope is calculated using a 3D dataset, which was acquired using a 3D laser scanner. The discontinuity sets are extracted using the open source software Discontinuity Set Extractor (Riquelme et al., 2014b). The results obtained allow the analysis of the normal spacing (Riquelme et al., 2015) and the persistence. The basic Rock Mass Rating index (subsequently called

RMRb) (Bieniawski, 1989) is calculated considering the derived parameters using the 3D datasets, along with those calculated with the fieldwork data. Finally, the SMR index is calculated using the open source tool SMRTool (Riquelme et al., 2014a).

2 METHODOLOGY

2.1 *Data acquisition*

The data acquisition of the slope's surface consists on the collection of information during the fieldwork, along with the acquisition of millions of points. This process is performed through the use of remote sensing techniques. The use of this instrumentation allows to align the point cloud vertically respect to the global reference system. As a result of this, the dip of the discontinuity planes could be correctly extracted. The point cloud can also be properly oriented to the north, although, this last step is not mandatory when working on a relatively sloped-discontinuity reference system (Riquelme et al., 2016).

2.2 *Discontinuity set extraction*

The use of remote sensing techniques allowed to obtain the points of the surface (Fig. 1a). In this work the open source software Discontinuity Set Extractor was used (subsequently called DSE). This software analyses each single point of the dataset, searching its nearest neighbours and calculating the best fit plane of this subset. The coplanarity of this subset of points is analysed, and, if it is enough planar, its normal vector's pole is calculated in a stereonet (Fig. 1b). After this process is performed for the full dataset, the density of poles is analysed, and a density function is obtained through the kernel density estimation technique (Fig. 1c).

The analysis of this density function allows to identify the planar orientations of the surface. Using a supervised process, where the user inspects the classified point cloud, the discontinuity set orientations are extracted (Figs. 1d). Then, every point is assigned to its corresponding discontinuity set (Fig. 1e and f). Finally, a cluster analysis is performed using the DBSCAN algorithm (Ester et al., 1996). Consequently, for each discontinuity set, it is obtained the group of points members of a exposed plane (subsequently called cluster). These clusters are members of a planar outcrop, and thus, it is possible to calculate the plane equation of that plane (Eq. 1).

$$A \cdot x + B \cdot y + C \cdot z + D = 0 \quad (1)$$

The software DSE allows to set the normal vector (A, B, C) of all clusters, members of a discontinuity set, equal to the normal vector of its corresponding mean orientation. In this case, each cluster will have a different parameter D, which locates the plane in the 3D space. Conversely, it is also possible to calculate the normal vector of each cluster independently, but in this case the cluster planes might not be parallel. As a result of this, each point member of the dataset is labelled with the following information: (1) the discontinuity set, (2) its cluster or exposed plane and (3) the plane equation of its corresponding plane.

2.3 *Normal spacing analysis*

After the rock slope surface is classified with its corresponding discontinuity sets and clusters, it is possible to analyse the normal spacing of each discontinuity set. In this work, the normal spacing is measured between two exposed planes that are linked following certain criteria (Riquelme et al., 2015). In this case, it was assumed that discontinuities were non-persistent, and each cluster of points is linked to its nearest cluster. This principle can be seen in Figure 2. The normal spacing was calculated as the mean of all the normal distances measured between linked clusters.

2.4 *Persistence*

Persistence is related to the areal extent or size of a discontinuity within a plane. The ISRM recommends to make efforts to measure the discontinuity lengths in the direction of dip and in the direction of the strike (Barton, 1978). Using 3D point clouds, this information can be extracted from the planar surfaces, but not from traces unless the user supervises the process and inspects digital images.

In this work the persistence of each discontinuity set was calculated in both directions. It is worth noting that planar discontinuities can be exposed by various outcrops. Its persistence could be measured: (1) considering the size of each single outcrop as its persistence, or (2) merging its corresponding clusters in one single dataset. This process was performed merging those clusters that presented the same D parameter (Eq. 1).

The process consists of a transformation of the system reference, where the direction of the dip corresponds to the new axis X' and the direction of the strike corresponds to the new axis Y'. Therefore, the normal vector of the cluster corresponds to the axis Z. After this transformation, each cluster can be projected on the plane $OX'Y'$. Then, the persistence can be measured on the direction of the dip direction and in the direction of the strike as $|x_{max} - x_{min}|$ and $|y_{max} - y_{min}|$ respectively.

2.5 *Slope Mass Rating calculation*

SMR geo-mechanical classification, which can be very useful as a tool for the preliminary assessment of slope stability. As the application of the RMR system to slope is not easy to date, the SMR system provides adjustment factors to the RMR_b (Romana, 1993). In

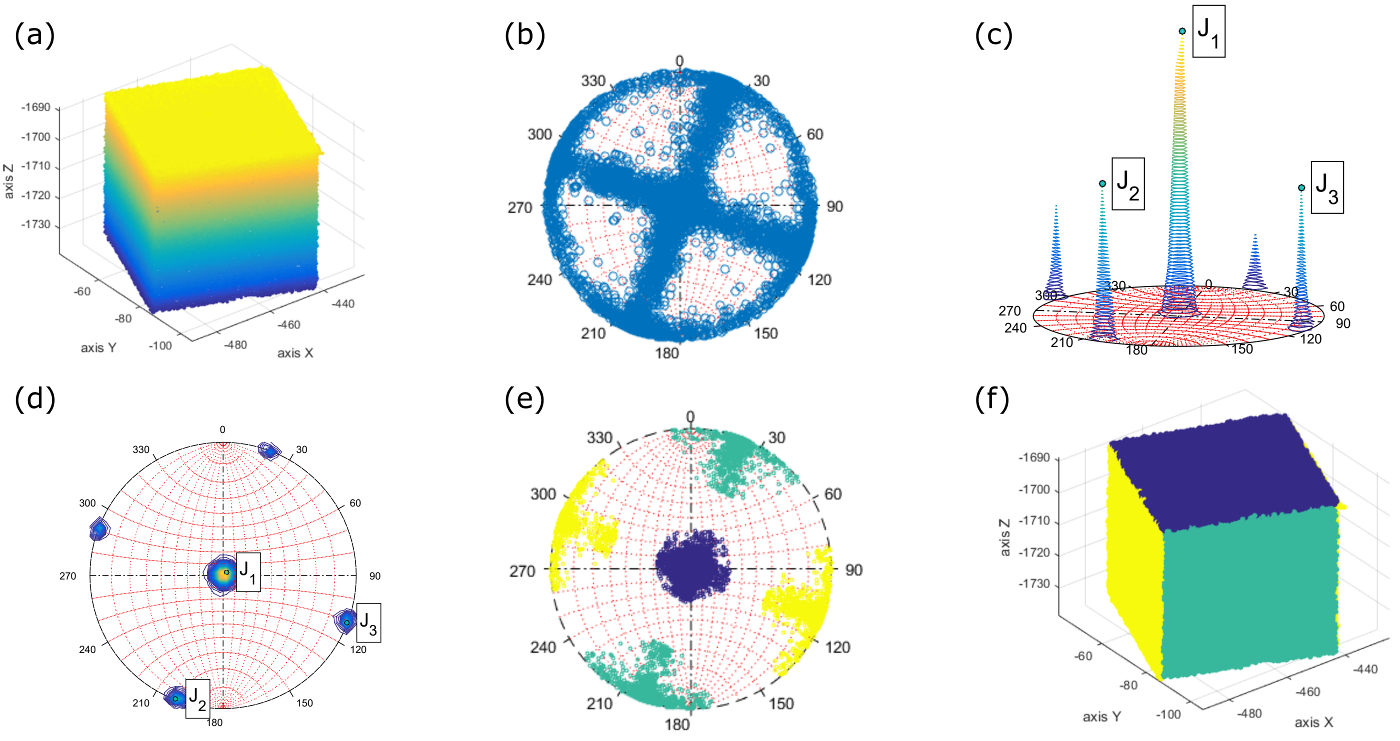

Figure 1. Extraction of the discontinuity sets of a cube through its point clouds. (a) Depiction of the point cloud; (b) poles of the normal vectors associated to each point, depiction in a stereonet; (c) and (d) density of all poles; (e) poles assigned to a discontinuity set; (f) depiction of the point cloud, where each point is coloured depending on its assigned discontinuity set.

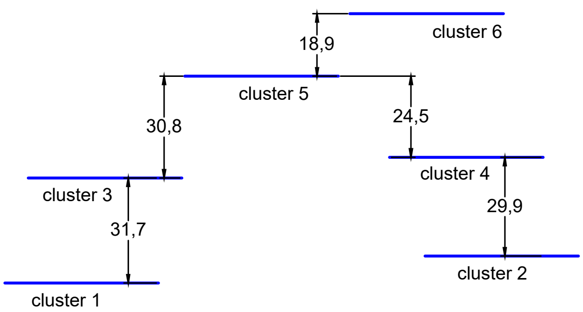

Figure 2. Establishment of the relations between clusters for the normal spacing calculation.

this work, for each discontinuity set, the RMR_b index was calculated using some information extracted from the 3D point clouds. Nevertheless, some parameters require other information that is not suitable of being extracted from the previous data (Riquelme et al., 2016). As a result of this, these parameters were obtained during the fieldwork in a second phase.

The calculation of the SMR index was performed using the open source tool SMRTool (Riquelme et al., 2014a). The required inputs are (1) the orientation of the slope, (2) the excavation method and, for each discontinuity set: (3) the orientation of the discontinuity and (4) the RMR_b value. This software allows the automatic calculation of the adjustment factors, which depend on its possible modes of failure. In addition to this, it calculates the corresponding wedge for each couple of discontinuity sets, and if its failure is possible or not, depending on the slope orientation.

The software automatically calculates the possible mode of failure, but no kinematic analysis is performed. It is depicted the relation between the dip directions: when the angle between these vectors is minor than 90°, the possible mode of failure is planar, but if not, the possible mode of failure is toppling (Romana, 1993). In order to understand the mode of failure and its affection to the SMR index, a conceptual cross section is depicted by the SMRTool, where the discontinuity set intersects the slope in a cross section of the slope (Fig. 3). In this figure, only the relation between the dip of the slope and the dip of the discontinuity set is considered. Finally, the auxiliary angles A, B and C are calculated, and then, the adjustment factors F_1, F_2 and F_3. Finally, the SMR index is easily calculated by the equation 2.

$$SMR = RMR_b + F_1 \cdot F_2 \cdot F_3 + F_4 \qquad (2)$$

3 CASE OF STUDY

This case of study analyses a rock slope excavated in limestones located in El Campello (SE Spain). During the fieldwork, three orthogonal discontinuity sets were identified. The most visible discontinuity set was the bedding plane, which was not horizontal but dipped 30° to the East. The second and the third discontinuity sets were sub-vertical. The detailed visual inspection, along with those measurements taken with compass during the fieldwork, showed that it was likely to be more than three discontinuity sets. Nevertheless, the steep surface did not allow to perform the data collection under safe conditions.

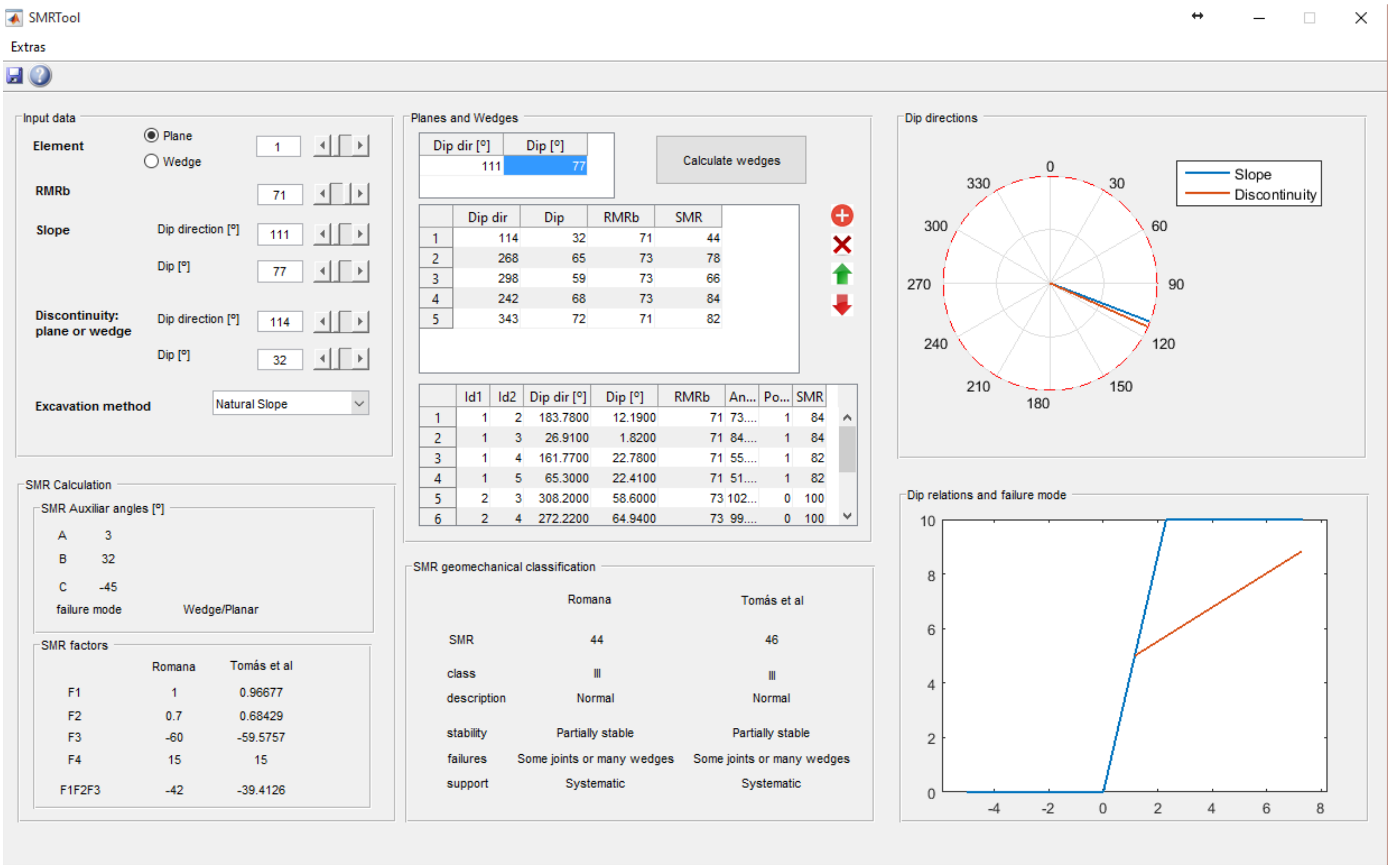

Figure 3. Capture of the SMRTool open source software.

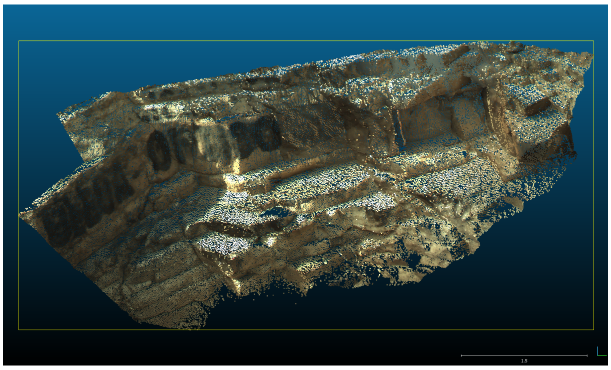

Figure 4. 3D point cloud of the analysed sector

The approximate size of the analysed area is $7 \times 3.5m$ (Fig. 4). The 3D dataset was acquired by a Leica C10 laser scanner on November 27th 2015. In order to reduce shadow areas, the data acquisition was performed in four separate stations. Three 6" planar targets were used as reference points and the point cloud was registered using data from a digital map (SIGNA http://signa.ign.es/signa/). The studied sector was subsampled, fixing a maximum distance between points of 1 cm, and obtaining a point cloud with 131 200 points.

4 RESULTS

The point cloud analysis showed that six discontinuity sets were detected. Figure 5a shows the 3D point cloud, where every classified point is coloured depending on its assigned discontinuity set. The orientation of each plane is shown in Table 1. The normal spacing was calculated assuming that the clusters were non-persistent. The persistence of each discontinuity set was calculated merging those clusters with the same parameter D, and the results are shown in Table 1. It is worth noting that the discontinuity set J_1 corresponds to the bedding plane, so it is reasonable to consider its persistence as very high, as it was observed during the field work. Therefore, it can be seen that the analysis of the persistence using this methodology is limited by the sector dimensions.

Table 1. Extracted discontinuity sets and main properties.

DS	Orientation	Normal spacing	Persistence (m) Dip dir	Persistence (m) Strike	Persistence (m) Max
J_1	114/32	0.272	1.653	4.083	4.083
J_2	268/65	0.249	1.490	3.516	3.516
J_3	298/59	0.181	1.287	2.783	2.783
J_4	242/68	0.380	3.234	2.498	3.234
J_5	343/72	0.315	0.995	1.733	1.733
J_6	326/57	0.407	1.203	1.805	1.805

The analysis of the classified point cloud (Fig. 5a) allowed us to note that J_5 and J_6 are usually contiguous. In addition to this, both orientations are very close, as it is shown in the density function (Fig. 5b). Moreover, the analysis of the normal spacing and persistence showed very similar results. As a result of this, it was decided to consider this effect as waviness, and therefore, the SMR calculation was performed considering only J_5. Concerning its persistence, it was observed as high persistence during the

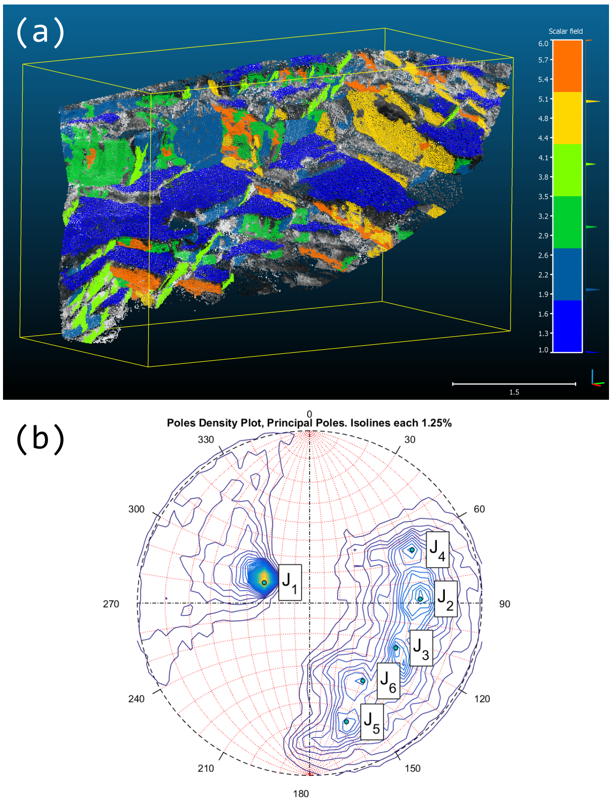

Figure 5. Extracted discontinuity sets. (a) 3DPC view where each point is coloured depending its corresponding discontinuity set; (b) Stereonet of the density of the normal vector's poles and its corresponding planes.

fieldwork.

The calculation of the RQD index was performed using the expression proposed by (Palmstrom, 2005) through the volumetric joint count J_v (Eq. 3). The visual inspection of fallen rocks showed shapes type block. Therefore, we used the expression proposed by Palmstrom (Eq. 4).

The RMR_b index was calculated for each discontinuity set, and their values are shown in Table 2. The calculation of the SMR index was performed for each discontinuity set and wedge. Table 3 shows the SMR values for each discontinuity set and for each wedge when its failure mode can occur.

$$J_v = \sum_{i=1}^{5} \frac{1}{Jv_i} = 19.02 \left(\frac{joints}{m^3} \right) \tag{3}$$

$$RQD = 110 - 2.5 \cdot 19.02 = 62.44 \tag{4}$$

5 DISCUSSION

The minimum SMR value was found when analysing the discontinuity set J_1. This discontinuity set corresponds to the bedding plane, and its failure mode is planar (Fig. 3). All other discontinuity sets showed a toppling failure mode. The SMR value of this discontinuity set was 44, and its SMR class is III, being described as normal.

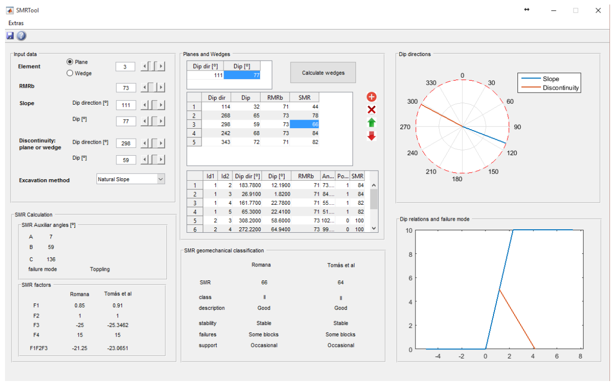

Figure 6. SMRTool screen capture of the analysis of J_3

The discontinuity sets J_2, J_3, J_4 and J_5 belong to classes I to II, being described as "Good" (stability "Stable") or "Very Good" (stability "Completely Stable") by the geo-mechanical classification SMR.

It is worth noting to discuss why J_1, which is the less steep discontinuity, is classified as the most unsafe. The analysis of the adjustment factors, showed in Table 3, allows to identify that F_1 is equal to 1, which means that this discontinuity and the slope presents the highest parallelism (Fig. 3) and it is a very unfavourable situation. Moreover, the adjustment factor F_3, which refers to the probability that joints daylight in the slope face, is equal to -60. This is, once again, the most unfavourable case. As a result of this, J_1 presents the most unfavourable term $F_1 \cdot F_2 \cdot F_3$.

On the other hand, J_3 also presents a relevant parallelism (Fig. 6), so its adjustment factor F_1 is equal to 0.85, but as the possible failure mode is toppling, the most unfavourable value of F_3 is -25. As a result of this, the SMR value is not reduced as much as for J_1.

6 CONCLUSION

The geo-mechanical quality of a slope was analysed using 3D point clouds and data acquired during the fieldwork. The analysis of the 3D point cloud was performed using open source tools (DSE), which aided the user to identify the number of discontinuity sets and their mean orientations. Additionally, the 3D point cloud was classified, and each exposed plane was located. This allowed to perform to additional calculations: the normal spacing and the maximum persistence. Other parameters of the rock mass, such as the roughness, infilling, aperture, uniaxial rock strength, etc. required the fieldwork in order to their definition.

The geo-mechanical quality was assessed through the SMR index, using previous results, by means of the open source software SMRTool. This software automatically calculated the failure mode for each discontinuity set, their corresponding auxiliary angles and adjustment factors. Introducing the excavation method, the SMR index was calculated and the

Table 2. Calculation of the RMR_b for each discontinuity set. X_1 to X_5 are the corresponding parameters (Bieniawski, 1993).

Disc. Set	Separation [mm]	Rough.	Infilling	Weath.	RMR_b parameters X_1	X_2	X_3	X_{41}	X_{42}	X_{43}	X_{44}	X_{45}	X_5	RMR_b
J_1: 114/32	1 - 5	slightly	hard < 5	Unw.	12	20	10	0	1	3	4	6	15	71
J_2: 268/65	1 - 5	slightly	hard < 5	Unw.	12	20	10	2	1	3	4	6	15	73
J_3: 298/59	1 - 5	slightly	hard < 5	Unw.	12	20	8	4	1	3	4	6	15	73
J_4: 242/68	1 - 5	slightly	hard < 5	Unw.	12	20	10	2	1	3	4	6	15	73
J_5: 343/72	1 - 5	slightly	hard < 5	Unw.	12	20	10	0	1	3	4	6	15	71

Table 3. SMRTool report. Slope:(111/77).

plane/wedge id	dip dir [°]	dip [°]	RMRb	A [°]	B [°]	C [°]	failure	F_1	F_2	F_3	F_4	SMR	Class
J_1	114	32	71	3	32	-45	Planar	1	0.7	-60	15	44	III
J_2	268	65	73	23	65	142	Toppling	0.4	1	-25	15	78	II
J_3	298	59	73	7	59	136	Toppling	0.85	1	-25	15	66	II
J_4	242	68	73	49	68	145	Toppling	0.15	1	-25	15	84	I
J_5	343	72	71	52	72	149	Toppling	0.15	1	-25	15	82	I
W_{12}	184	12	71	72.78	12.19	-64.81	Wedge	0.15	0.15	-60	15	84	I
W_{13}	27	2	71	84.09	1.82	-75.18	Wedge	0.15	0.15	-60	15	84	I
W_{14}	162	23	71	50.77	22.78	-54.22	Wedge	0.15	0.4	-60	15	82	I
W_{15}	65	22	71	45.7	22.41	-54.59	Wedge	0.15	0.4	-60	15	82	I

slope was assessed as "Normal", being its stability described as "Partially Stable". Additionally, this software provided useful information for the understanding of the SMR index calculation.

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