APPLICATION OF PHOTOGRAMMETRY FOR DETERMINATION OF VOLUMETRIC JOINT COUNT AS A MEASURE FOR IMPROVED ROCK QUALITY DESIGNATION (RQD) INDEX

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ABSTRACT. Rock quality designation (RQD) index, provides a general indication of rock mass quality and is widely used in many rock mass classification systems. From the literature review, it is concluded that the RQD methodology has several limitations and one of them is highlighted in this paper with the help of stochastic analysis with Monte Carlo simulation. The purpose of this paper is to improve the results of the RQD index through volumetric joint count (Jv) from accessible surface areas or when drill cores are not available. In this paper, we introduce a low-cost photogrammetric method for rock slope reconstruction with scaled and oriented 3D point cloud, ideally suited for geomechanical analysis. As an outcome, the 3D point cloud is then used to detect the discontinuity sets and to, define their orientation, normal spacing and persistence. Results are then used to calculate the number of joints per m^3, which is then used as input in the empirical correlation between the RQD index and the Jv. The main advantage of the proposed methodology is that it is completely based on open-source software.

Key words: RQD index, volumetric joint count, photogrammetry, discontinuity sets

Introduction

The rock mass varies with the evolution of the geological environment, producing complex structures with two components: intact rock and discontinuities (Palmström, 2001). To obtain information about the joint properties of the rock mass it is necessary to perform visual observations in the field or on drill cores (if available). The methodology according to which the observations are made has a great impact on the quality of the data used in the calculations and evaluations. The presence of joints in the rock mass, divides it into blocks that contribute to the stability and the mechanical behaviour of the rock structure (Palmström, 2005).

RQD is a critical index that is based on core recovery procedure for quantifying the degree of rock mass jointing (Vavro et al., 2015). The assessment of RQD is a crucial aspect for mineral excavation and is widely used for evaluating the stabilities of the rock masses. However, the methodology of the traditional RQD can yield inaccurate assessments due to limitations within the methodology itself (Haftani et al., 2016; Pells et al., 2017; Chen et al., 2018; Chen and Yin 2019). These limitations can influence the results within the classification systems where the RQD is used, such as Rock Mass Rating (RMR) system, Q-system, and Qslope-system.

The volumetric joint count (Jv) measurements take into account all the joints in a three-dimensional rock mass and is a useful measure about the number of joints in a unit volume of rock masses (Palmström, 2001). The volumetric joint count can give much better characterisation for the degree of rock mass jointing.

The literature review point to the fact that the estimation of RQD with low value of error is crucial for engineering assessments. In this regard, several methods have been created to overcome the limitations inside the traditional RQD methodology, such as the weighted joint density (WJD) (Palmström, 1995, 1996), Modified WJD (Haftani et al., 2016), Volumetric joint count (Jv) (Palmström, 1982, 1985), Modified blockiness index (Bz) (Chen et al., 2019) and Improved Rock Quality Designation (RQDi) (Azimian, 2016).

In the last years, the use of remote sensing techniques for rock mass characterisation has increased dramatically. Lidar scanning and digital photogrammetry techniques have been used to create 3D models for stability analysis and joint properties of the rock mass.

Buyer and Schubert (2017) proposed a method to identify discontinuity sets in a point cloud, generated from photogrammetry and calculate the spacing of the joint sets. Kim et al. (2013) presented photogrammetry based methodology to provide 3D models for estimation of the Joint Roughness Coefficient (JRC) values. Macciotta et al. (2020) used the photogrammetric techniques combined with discrete fracture network models to reliably estimate the rock fall block volumes. Francioni and coauthors (2019) proposed a new method of using photogrammetry for creation of scaled and georeferenced 3D models from rock slopes. The obtained 3D models from the proposed approach have been validated against a laser scanning point cloud and the advantages and limitations of the proposed method are highlighted.

Recent literature review and the rapid development in the field of digital photographing and development of 3D point clouds, encouraged the authors to present methodology for determination of volumetric joint count through photogrammetry. In the development process of the presented methodology the authors used open-source software. The focus of this study is the implementation of free open-source software to analyse the results obtained from the point cloud data for the purpose of improving the results of the RQD index through volumetric joint count. The procedure that was followed in this study is shown in Figure 1.

Methods

Limitations of traditional RQD methodology

The RQD was first introduced in 1963 by Deere to provide a quantitative estimate of rock mass quality from drill core logs. RQD is defined as the percentage of the total length of core pieces longer than 10 cm (Li) to the total length of the core run (L):

$$RQD = \frac{\sum L_i}{L} * 100\ [\%] \quad (1)$$

Several limitations in the RQD methodology emerged from a substantial bibliographical review, expressed as follows (Haftani et al., 2016; Pells et al., 2017; Chen et al., 2018; Chen, Yin 2019):

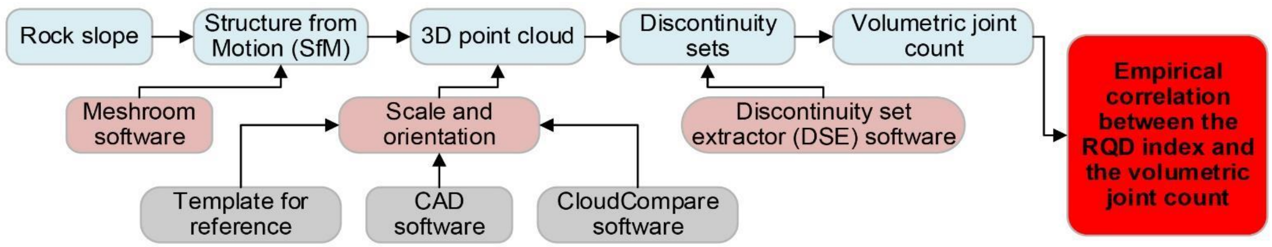

Fig. 1. Flowchart of the proposed methodology to evaluate the volumetric joint count as a measure for improved RQD index

- For example, RQD = 0 % where the distance between the joints in the drill cores is 9 cm or less, while RQD = 100 % where the distance between the joints is 11 cm or more, see Figure 2a).
- The traditional RQD methodology does not give any information about the quality of core pieces smaller than 10 cm in length.
- The RQD value is anisotropic and sensitive to the orientation of joint sets and dependent on the direction of the borehole (Figure 2b).

By emphasizing the limitations in the RQD methodology, the calculations made need to be used with caution because they may often lead to inaccuracy or errors. Literature review from several authors point out that in practice the RQD methodology values tend to be either high or low (often above 70% or below 10 to 20 %) in most rock engineering projects (Harrison 1999; Hack 2002). This statement was tested by the authors using a Monte Carlo simulation (Adjiski et al., 2019). Figure 3 shows the model used for the Monte Carlo simulation.

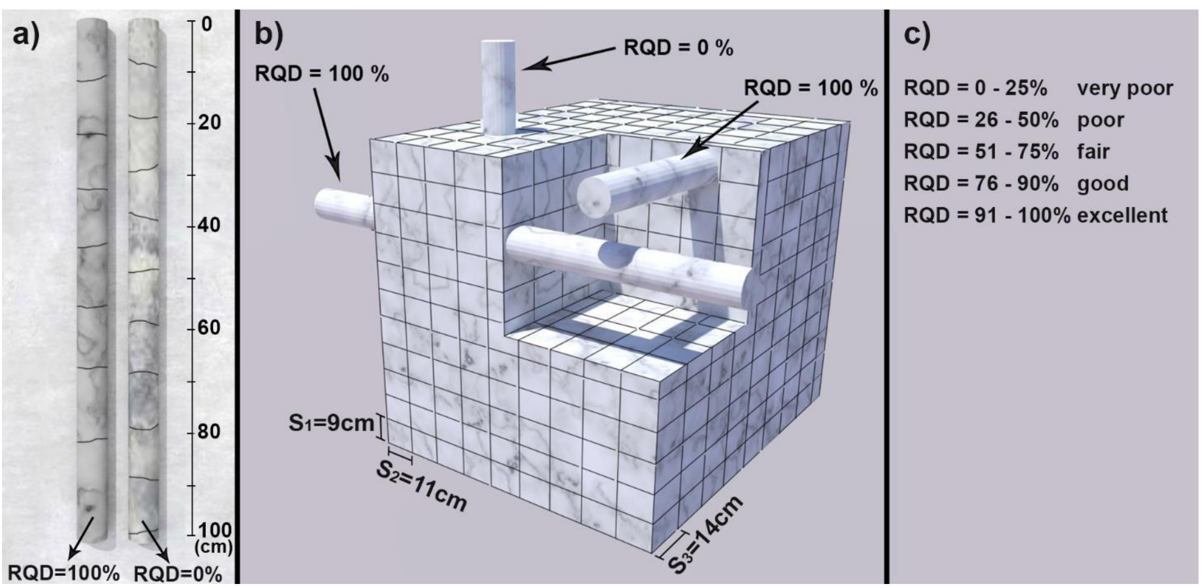

Fig. 2. a) Limitations in the traditional methodology can generate different RQD values even due to a small change in the size of core sticks, b) Sensitivity and dependence of RQD values on drilling direction of the borehole, c) RQD index classification values of rock mass

Table 1 shows the RQD (%) results from the Monte Carlo simulation models for each of the generated fracture frequency in 100 cm drill core length. For the purpose of this paper, 10 000 simulations were performed for each of the generated fracture frequency and the results were grouped into RQD values from 0 to100 (%) with 10% increments.

Figure 4 shows the graphical display in the form of a histogram, in which all RQD (%) values of the Monte Carlo simulation models are grouped into percentage frequency ranges. The results show that more data are in the range above 75 % or below 25 % which is close to the statement from several authors about the tendency of the RQD values to be either high or low in most rock engineering projects.

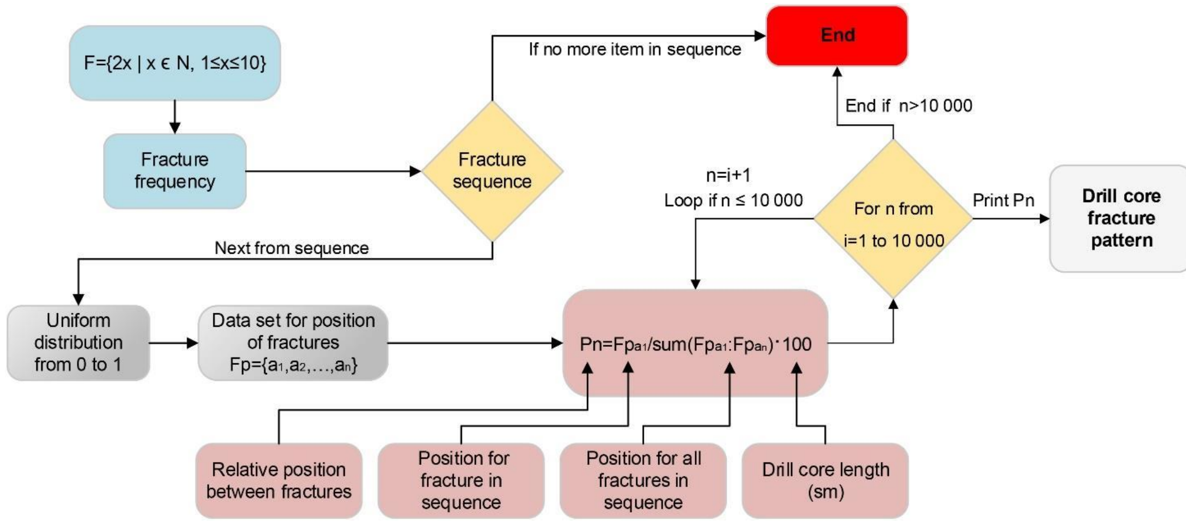

Fig. 3. Monte Carlo simulation models for the generation of uncertainty in fracture frequency parameters of drill core to evaluate the RQD index

Table 1. *Results from the Monte Carlo simulation models*

		RQD (%)									
		0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
Fracture frequency=2	Nº	0	0	0	0	0	0	0	0	0	10000
	%	0	0	0	0	0	0	0	0	0	100
Fracture frequency=4	Nº	0	0	0	0	0	0	0	3	511	9486
	%	0	0	0	0	0	0	0	0.03	5.11	94.86
Fracture frequency=6	Nº	0	0	0	0	0	0	4	339	3287	6370
	%	0	0	0	0	0	0	0.04	3.39	32.87	63.7
Fracture frequency=8	Nº	0	0	0	0	0	22	391	2421	4953	2213
	%	0	0	0	0	0	0.22	3.91	24.21	49.53	22.13
Fracture frequency=10	Nº	0	0	0	2	87	645	2421	4091	2406	348
	%	0	0	0	0.02	0.87	6.45	24.21	40.91	24.06	3.48
Fracture frequency=12	Nº	1	6	64	336	1151	2525	3324	2072	493	28
	%	0.01	0.06	0.64	3.36	11.51	25.25	33.24	20.72	4.93	0.28
Fracture frequency=14	Nº	71	215	738	1865	2595	2458	1529	481	47	1
	%	0.71	2.15	7.38	18.65	25.95	24.58	15.29	4.81	0.47	0.01
Fracture frequency=16	Nº	911	1066	2014	2605	2036	948	357	60	3	0
	%	9.11	10.66	20.14	26.05	20.36	9.48	3.57	0.6	0.03	0
Fracture frequency=18	Nº	3411	1810	2046	1665	770	242	52	4	0	0
	%	34.11	18.1	20.46	16.65	7.7	2.42	0.52	0.04	0	0
Fracture frequency=20	Nº	6504	1560	1096	623	184	33	0	0	0	0
	%	65.04	15.6	10.96	6.23	1.84	0.33	0	0	0	0

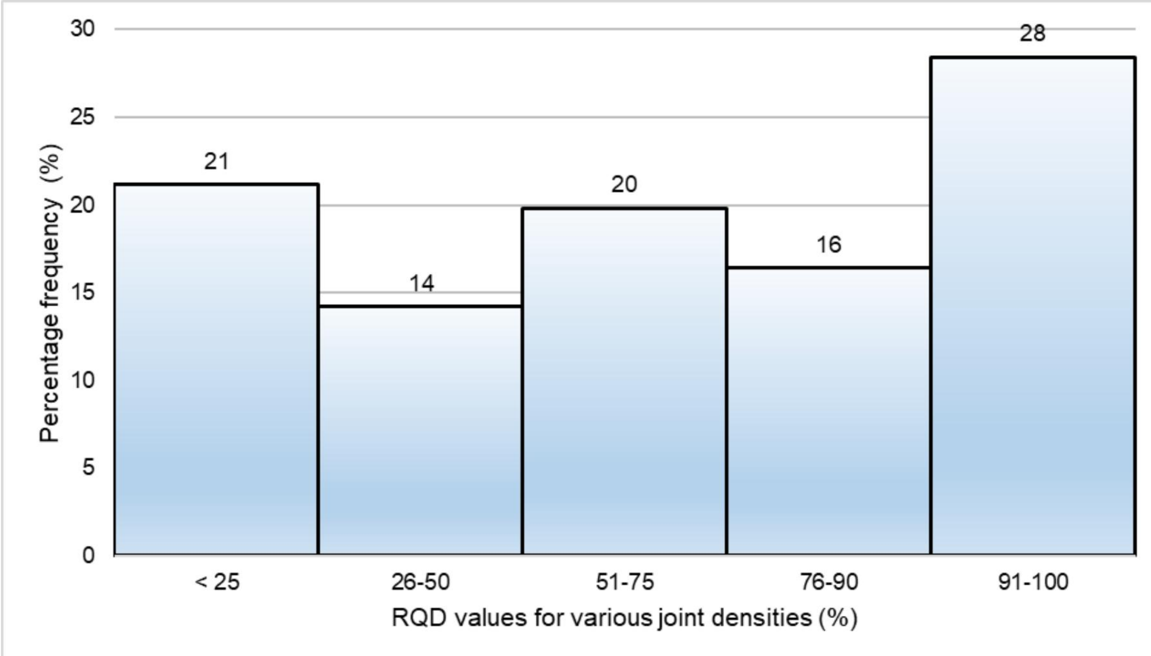

Fig. 4. Percentage frequency from the values of the Monte Carlo simulation models

Volumetric joint count

Palmström (1982, 1985) described the volumetric joint count (Jv) as a useful measure of the degree of joints intersecting a volume of rock mass. Volumetric joint count is a 3D measurement for the density of all the joints and it can be measured from the joint set spacings within a volume of rock mass as (Palmström, 2001):

$$J_v = \frac{1}{S_1} + \frac{1}{S_2} + \frac{1}{S_3} + \ldots \tag{2}$$

where, S_1, S_2, S_3 are the average spacings for the joint sets. In his research Palmström (2001) also mentioned that random joints could be included by using the following expression:

$$J_v = \frac{1}{S_1} + \frac{1}{S_2} + \frac{1}{S_3} + \ldots + \frac{N_r}{5} \tag{3}$$

where N_r is the number of random joints and for the random joints spacing the experience indicates that this can be set to S_r = 5 m.

Palmström (1982) in his research suggested that, when drill cores are not available but surface exposures or exploration adits with discontinuity traces are visible and accessible, the RQD index can be estimated from the number of discontinuities per unit volume. The suggested relationship can be estimated by using the following expression:

$$RQD = 115 - 3.3J_v \tag{4}$$
$$(RQD = 0 \; for \; J_v > 35, and \; RQD = 100 \; for \; J_v < 4{,}5)$$

where, Jv is the sum for all joint (discontinuity) sets known as the volumetric joint count. Palmström (2005) in his latest research, stated that this empirical correlation (Equation 4) was deficient and recommended a new equation to give a better average correlation between RQD and Jv:

$$RQD = 110 - 2.5J_v \tag{5}$$
$$(RQD = 0 \; for \; J_v > 44, and \; RQD = 100 \; for \; J_v < 4)$$

Given the foregoing it can be concluded that RQD is a directionally dependent parameter closely related with the borehole orientation and the use of the volumetric joint count can significantly reduce this directional dependence.

Structure from motion photogrammetry

Structure from motion (SfM) is a photogrammetric technique which utilises a series of 2D overlapping images to reconstruct 3D surface models (Francioni et al., 2019). SfM technique can be used to create point cloud based 3D models of objects with consumer grade digital cameras. The advances in this photogrammetric technique, together with the advances of computers, digital cameras and unmanned aerial systems (UAS) have now made it feasible to be able to generate 3D models without expensive equipment.

In this research we propose a SfM photogrammetric technique to create a high resolution 3D rock slope model. The studied slope with a length of around 25 m and height of up to 15 m was selected for this study and is located in an open pit mine in N. Macedonia.

For the purpose of this model a total of 281 images were acquired to cover the rock slope with overlapping images. The images were captured using a Canon 450D camera with 50 mm focal length.

The overlapped images from the survey were processed using the open-source software Meshroom (2020), which resulted in a model that contains a dense point cloud with 7 105 230 points.

The process of georeferencing the model will be the subject of another study, since this model will represent a case for testing purposes. The proposed SfM methodology generates point clouds without scale or orientation, i.e. arbitrary reference system. However, to obtain discontinuity characteristics (orientation, spacing, persistence) from this model, it is still necessary to have an object of known geometry as a reference scale and orientation (García-Luna et al., 2019).

This methodology involves the use of ground control points (GCPs) for scaling, located on the slope and providing a reference during the creation of the 3D model (Figure 5a).

The GCPs utilised in this research is an Ethylene Vinyl Acetate (EVA) foam square with targets at the four corners and in the middle (Figure 5b). To correctly orient the generated 3D point cloud with SfM the three EVA templates have been positioned on the slope to provide the necessary reference and a geological compass is used to measure the dip and dip direction of the EVA template and also the inclination of the base of the EVA template. An important note to keep in mind is that the EVA templates must be located and oriented within the research scene before any photograph is taken.

The next step is to use the open-source software CloudCompare (2020) to scale and orient the point cloud in relation with the EVA templates. The presented methodology is shown in Figure 6 where we highlighted the necessary steps of this procedure.

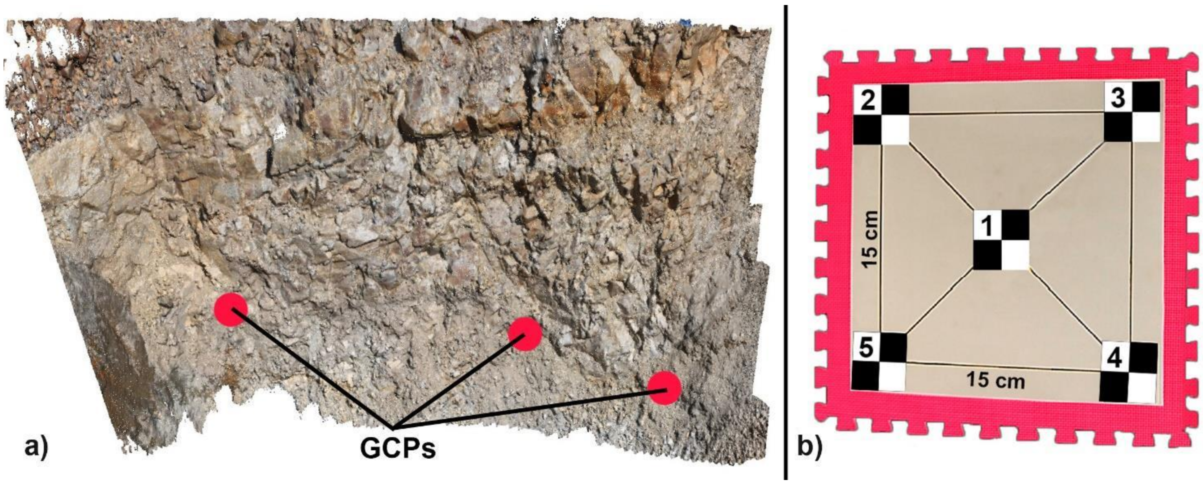

Fig. 5. a) Point cloud 3D model generated with Meshroom and marked position for GCPs b) EVA template used for GCPs

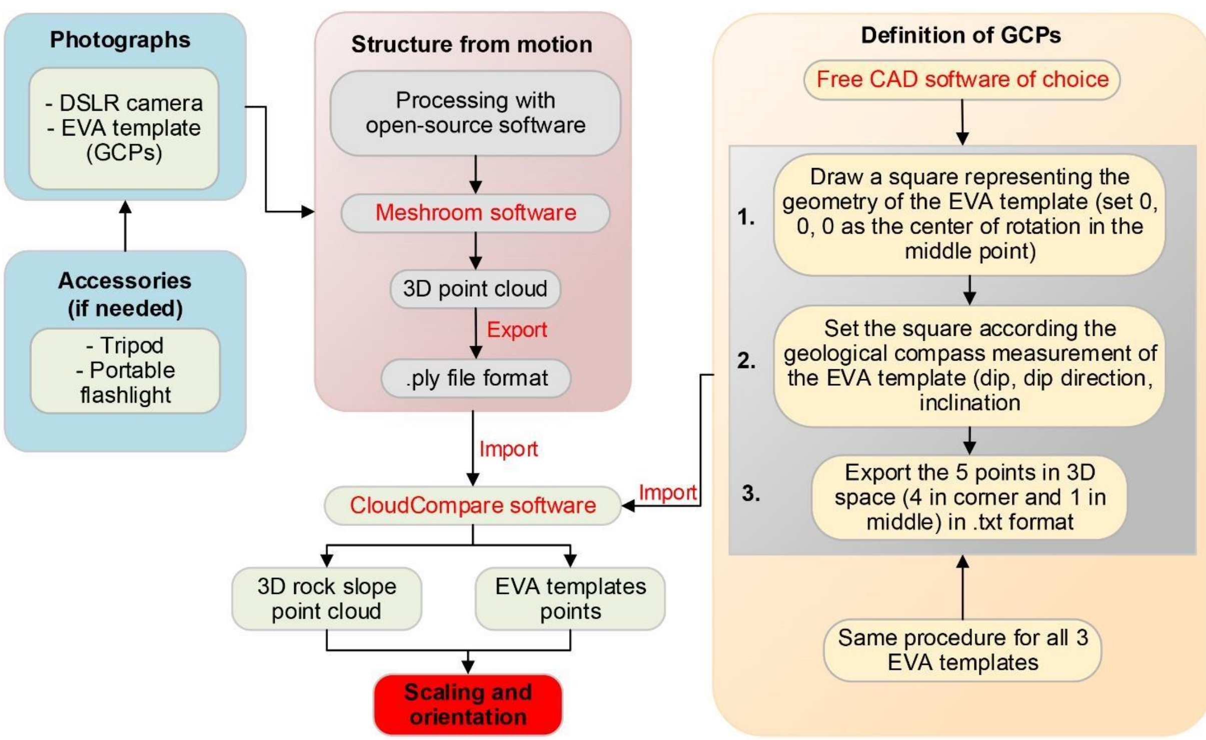

Fig. 6. Flowchart of the SfM methodology for creating properly scaled and oriented point cloud from the rock slope

Identification and analysis of discontinuity sets with DSE software

One of the most important parameters in rock engineering is to have knowledge about the discontinuity network within a rock mass. This information is of crucial importance to locate the discontinuities, bedding planes and joints which influence the behaviour and mechanical properties of rock masses.

For this purpose, the DSE (available on GitHub.com) an open-source software is introduced to identify the different discontinuity sets in a rock face from previously developed 3D point cloud (Riquelme et al., 2014; Papathanassiou et al., 2020).

This software analyses each single point within an unorganised 3D point cloud, searching its knn (k-nearest neighbours algorithm) and calculating the best fit plane of this subset.

The methodology behind the software is shown in Figure 7.

This process needs extensive computer power and because of this, a small area from the point cloud is selected. The selected part for the DSE analysis that has an area of 8.5∗8.5 m and contains a point cloud with 1 113 250 points is shown on Figure 8.

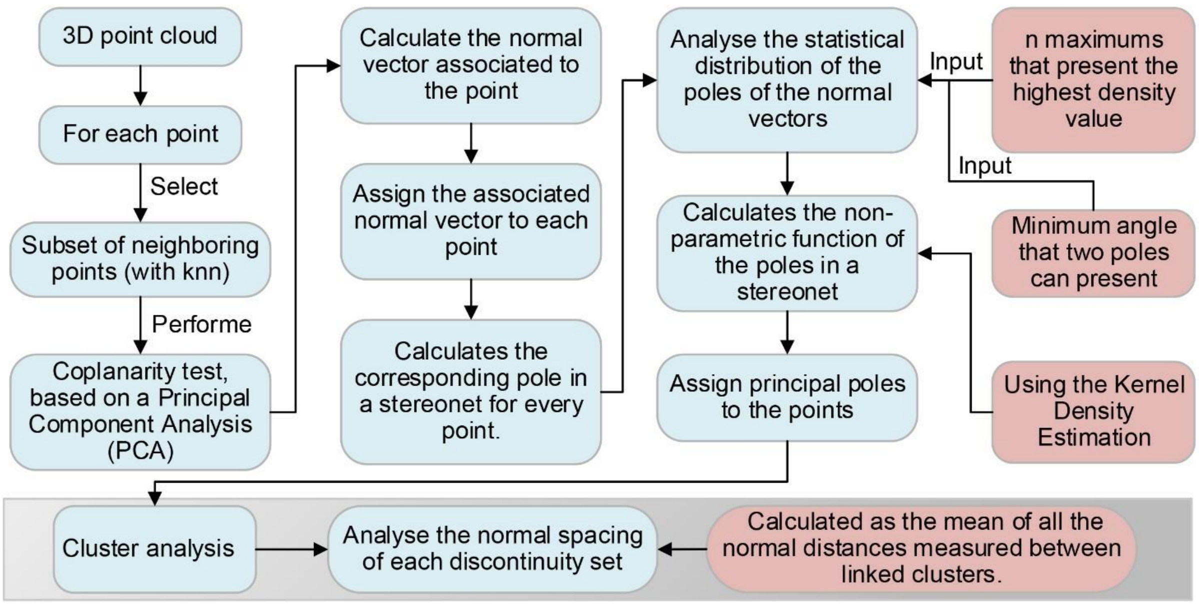

Fig. 7. Step by step methodology for application of DSE open-source software

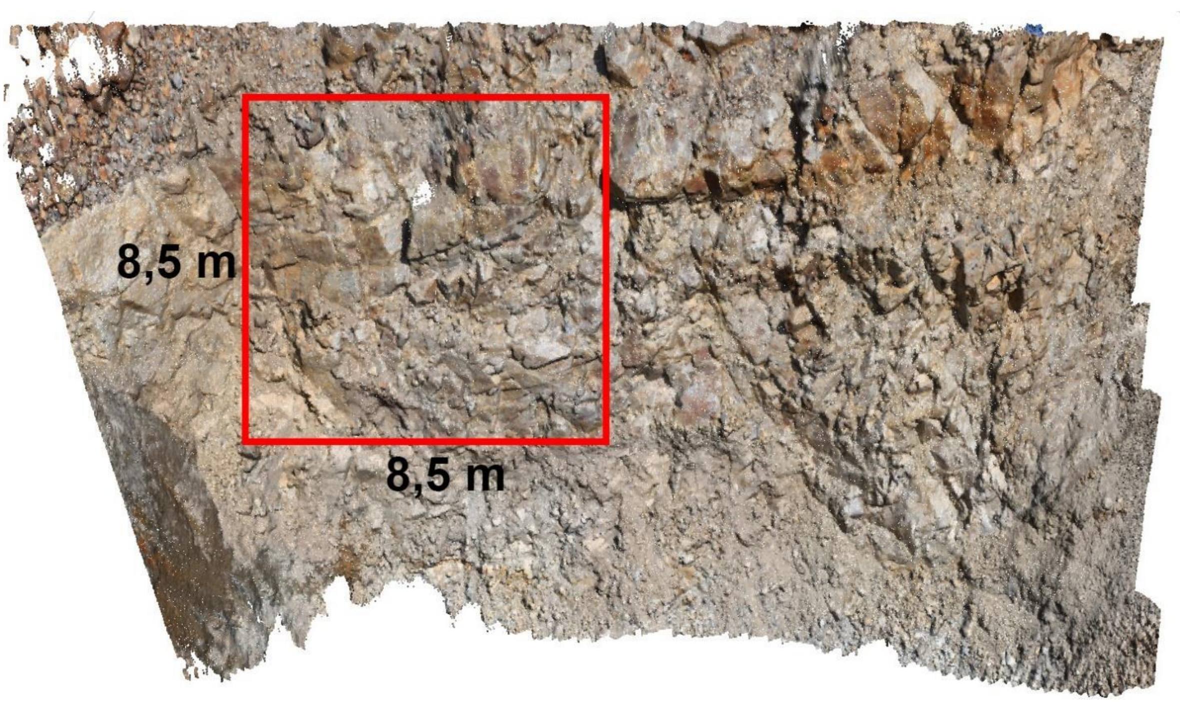

Fig. 8. Selected area for DSE analysis from the point cloud

Results and discussion

In order to estimate the volumetric joint count and use its value for empirical correlation with the RQD index, the generated point cloud was analysed by applying the previously mentioned methodology (Figure 1).

A point cloud is constructed with the open-source software Meshroom from the overlapping photos taken from the rock slope. The point cloud was then scaled and oriented with specially developed EVA templates with known dimensions and was used as GCPs (Figure 5 and 6).

In order to detect the discontinuity sets from the point cloud the studied area was analysed by the open-source software DSE. For this purpose, supervised classification of discontinuity sets was performed in the DSE software applying the methodology shown in Figure 7.

The method behind the DSE software is to assign a set to every point from the point cloud if the angle between the principal plane and the points normal is less than a specified threshold value. The parameters used in the DSE are as follows:

- number of nearest neighbours (knn) = 30;
- tolerance= 0.2;
- number of bins = 64;
- minimum angle that two poles can present = 300;
- maximum number of principal planes = 10;
- minimum angle between the normal vector of a discontinuity set and the normal vector of the point (cone) = 30.

Once the sets with the points members are extracted, for every cluster of points which is a member of a plane the software calculates the planes' equations for every surface. This result is then used for calculation of the normal spacing and the persistence inside the DSE software.

As a result, four main discontinuity sets have been semi-automatically extracted and identified with the DSE software. Figure 9a shows the point cloud with single points symbolised by the different colours according to their assigned discontinuity set (from 1 to 4). Figure 9b) shows a lower-hemisphere stereographic projection of the density of the normal vectors poles and its corresponding principal poles based on DSE software.

The results presented in Table 2 show the mean dip direction and dip angles for each discontinuity set and their characteristics.

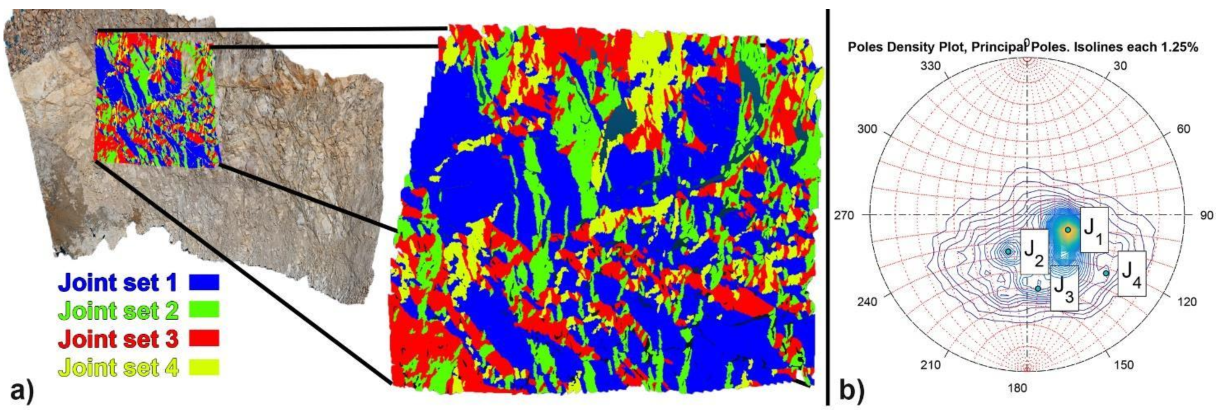

Fig. 9. a) Point cloud where each point is coloured by their specific discontinuity set b) Stereographic projection of the normal vector density plot and its corresponding principal poles

Table 2. *Discontinuity sets main properties obtained with DSE from the 3D point cloud*

Discontinuity set ID	Dip direction	Dip	Density	Number of assigned points to a discontinuity set over the total number of points (%)
Joint set 1	290.53	31.25	11.57	40.16
Joint set 2	26.58	29.75	2.27	18.51
Joint set 3	351.34	50.84	1.73	17.62
Joint set 4	307.02	64.10	0.79	12.77

The results from the normal spacing shown in Figure 10, are calculated as the mean value of all the normal spacings for each joint set, and based on the geological judgment from the 3D point cloud model, the joint set is considered as non-persistent.

The mean values of the four joint set spacings are measured as J_1 = 0.22 m, J_2 = 0.25 m, J_3 = 0.19 m and J_4 = 0.21 and with the Equation (2) suggested by Palmström (2001), the number of joints per m^3 (Jv) is calculated as follows:

$$J_v = \frac{1}{0.22} + \frac{1}{0.25} + \frac{1}{0.19} + \frac{1}{0.21} = 18.57\ joints/m^3 \quad (6)$$

Taking into account the correlation between RQD and the volumetric joint count (Jv) proposed in Equation (5) by Palmström (2005), the RQD index when drill cores are not available is calculated as follows:

$$RQD = 110 - 2.5 * 18.57 = 63\% \quad (7)$$

RQD index of the analysed rock mass in this paper is computed as 63% and this value according to Deere (1963) belongs to the "fair" classification (Figure 2c).

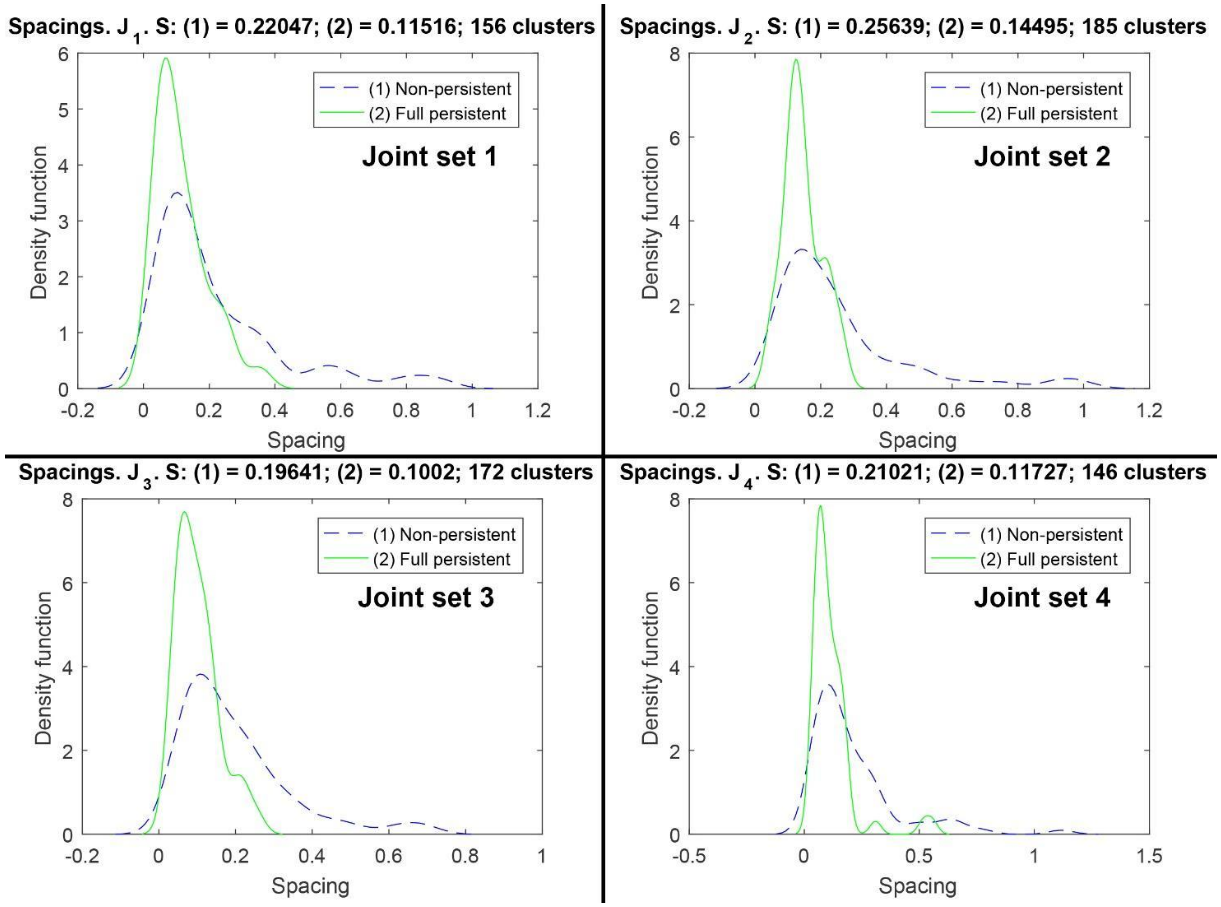

Fig. 10. Normal spacing of discontinuity sets extracted from the DSE

Conclusion

This study primarily aims to improve the results of the RQD index through volumetric joint count (Jv) when drill cores are not available or surface areas are visible and accessible. This work has also demonstrated that through the use of the proposed methodology, some of the limitations inside the traditional RQD index methodology will be avoided.

Using SfM methods and the availability of new high-resolution digital cameras and open-source software has led to a noticeable increase in the quality of engineering data that can be collected.

This research proposes a SfM photogrammetry method with the open-source software Meshroom for creation of a 3D point cloud of a rock slope located in an open pit mine in N. Macedonia. The method is based on the use of EVA templates of known geometry and orientation, located on the rock slope during the survey (Figure 5a, b). The EVA templates are used as GCPs which are then used to scale and orient the 3D point cloud with free CAD software of choice and the open-source software CloudCompare (Figure 6).

The oriented and scaled 3D point cloud obtained with the SfM methodology is then used for structural mapping of discontinuities with the open-source software DSE (Figure 7).

The DSE software gave good results for four main discontinuity sets and their mean orientations (Table 2). Additionally, the 3D point cloud was classified which allowed to perform additional calculations that include the normal spacing and the maximum persistence (Figure 10). The results are then used for calculation of the volumetric joint count (number of joints per m^3).

The geo-mechanical quantitative estimate of the rock mass is then performed with the empirical correlation proposed by Palmström (2005), between the RQD index and the volumetric joint count (Jv).

The proposed methodology has several advantages which include the following:

- equipment needed is relatively inexpensive;
- no need for advanced photographic skills for the SfM photogrammetry methodology;
- no need for expensive tools for scaling and orientation of the 3D point cloud;
- the used software in the presented methodology is under the open-source licenses (free).

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