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Calculation the Spacing of Discontinuities from 3D Point Clouds

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Abstract

The influence of discontinuities on the mechanical behavior of rock masses, demands a detailed knowledge about the geometrical properties of the existing discontinuity network. Traditional measurement techniques provide a rough knowledge about a discontinuity network but are also prone to bias. To increase the reliability of discontinuity models, remote sensing techniques like Close-Range Terrestrial Digital Photogrammetry (CRDTP) are increasingly applied for rock mass characterization. This research contributes to the trend of automatic rock mass characterization and focuses on the analysis of a digital surface model. This paper proposes a method to identify discontinuity sets in a point cloud and calculate the spacing of the sets. The discontinuity sets are semi-automatically identified with the open-source software DSE (Discontinuity Set Extractor). The program analyzes the density distribution of the point normal vectors in combination with a co-planarity test. The subsequent calculations apply DBSCAN to cluster and assign the points in the point cloud to singe discontinuity sets. After identifying the different discontinuity sets, the sub-members of each discontinuity set are again searched with DBSCAN in Matlab® (The Mathworks Inc.) and exported as a structure map to calculate the normal spacing between the single members of each set with ShapeMetriX3D Analyst. The point cloud is generated with CRTDP, using the digital mapping tool ShapeMetriX3D (3GSM GmbH), which is also used to validate the results of the calculations.

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1. Introduction

There hardly exists a rock mass without three or more different discontinuity sets. Hence, it is of crucial importance in rock engineering to have a profound knowledge about the discontinuity network within a rock mass, since present discontinuities, like bedding planes, joints or cracks, represent the weak zones, which separate singular

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polyhedrons of competent rock blocks and control failure mechanisms. Furthermore, discontinuities influence the mechanical properties and the behavior of rock masses.

Geotechnical engineers traditionally acquire this data by geological and geotechnical surveys, which combine visual and manual technologies to characterize rock masses. The most common tool is a geological clino-compass to directly measure the dip and dip direction of discontinuities. This method can be extended by scan lines and mapping windows which reduce the inherent bias of a single measurement. But traditional geotechnical data acquisition is nonetheless limited in accessibility, geological or geotechnical knowledge, time and scale. The results are often subjective rather than objective and therefore not reproducible [1, 2].

Remote sensing techniques and analyzing digital surface models have become a well-established technique in rock mass characterization over the last decades to extract geometrical and geotechnical information about discontinuities. These techniques start to replace traditional mappings for the following reasons [2, 3]:

1. Reproducible and objective results
2. Reduced time for data acquisition
3. Variable degree of detail
4. Safe investigation of inaccessible or time restricted areas
5. Possible automatization of the mapping process

Remote sensing techniques, like Terrestrial Digital Laser Scanning (TDL) or Close-range terrestrial digital photogrammetry (CRTDP) provide high resolution 3D surface models consisting of thousands of points with point distances less than few millimeters. Digital data also opens the way for an automation of the characterization process, so that geotechnical significant features can be recognized faster and more reliable [4–6].

After identifying discontinuity sets, one of the main difficulties in rock mass characterization is the estimation of the spacing and persistence of a discontinuity set in the investigated rock face. For this, many models consider infinite persistent discontinuities, which might lead to a too close spacing and underestimate the actual block size distribution in the rock mass [7]. This paper focuses on an approach to automate the digital mapping of a rock face by processing the point cloud data attained by CRTDP. It suggests a way to identify discontinuity sets and analyse the data with the digital mapping tool ShapeMetriX3D (©3GSM GmbH) in respect to an analysis of the spacing and length of the joint traces on a projected joint trace map.

2. Methodology

This paper is divided into two parts. In the first part, the different discontinuity sets in a rock face are identified using the open source software DSE. In the second part, the spacing for each discontinuity set is calculated with the commercial software ShapeMetriX3D Analyst (SMX Analyst). The results are validated by comparing the results (dip direction (DD)/dip (D) and mean trace length (TL)) to a complete manual mapping of the rock face with SMX Analyst. The single features of the manual mapping are clustered with the clustering algorithm implemented in SMX Analyst.

2.1. The model

The model represents a blocky rock mass in a tunnel face (Fig. 1). The width of the investigated rock face adds up to 11.61 m with a height of 6.45 m and a depth of 1.87 m. The surface has a total area of 84 m². The total number of computed points is 158.5 k. The mean distance between the singe points is 2 cm. The x-direction points towards East and y to North. Z references the height. The camera used for the outcrop imaging was a calibrated SLR Nikon D300 with a focal distance of 12 mm. The model has been generated with a novel SMX-tool “MultiPhoto” using the structure from motion approach. The model is not geo-referenced, since it represents a fictive case for testing purposes. The orientation of the investigated tunnel face is ~ 000°/90°.

Fig. 1. Coloured 3D model of the investigated rock face calculated by the SMX-tool “MultiPhoto”.

2.2. Identification of discontinuity sets with DSE

DSE is an open source software (available on GitHub.com), which semi-automatically derives geometrical information of discontinuity sets from 3D surface models. The program is based on a density-based analysis of the deviation of point normal vectors to identify the single structure sets and assign points in the point cloud to them. Since it is semi-automatically, the user still has the full control over the results [5].

The normal vectors were calculated considering the 15 nearest neighbors of the central point with a maximum allowable deviation in a subset of points (tolerance, ε) to consider them lying in a plane of 0.2 according to [5]. The deviation of the angles of the principal vectors must be higher than 10°. Only principal poles with a clear increase in the density distribution were included in the calculations by manual selection. The maximum angle between the normal vectors of an assigned point to the normal vector of the principal pole was set to 20°. The standard deviation (σ_{erij}), as a testing parameter for merging two clusters, was set to 1.5 (default value). Planes consisting of less than 10 points were excluded.

2.3. Calculation of the Spacing and Trace Length

The identified discontinuity sets and their relating points in the point cloud are processed further with Matlab respectively SMX Analyst to calculate the spacing of the single discontinuity sets and their trace lengths. For the calculation, the sub-members of each plane have to be identified in advance basing on the discontinuity identification of DSE. The sub-members were identified by the spatial deviance of the singe points within one set. Again the identification and clustering of points in one sub-member plane was done using the DBSCAN [8]. Again, the minimal number of points was set to 10, epsilon was set to 0.2. For each identified sub-member plane, the mean normal vector has been computed by fitting a local plane through a central point and its surrounding 15 neighboring points using the Matlab-function *pcfitplane*. The border-points of each sub-member are detected using the Matlab-function *boundary* with a shrink factor of zero. Doublets were erased with the function *unique*. This procedure had to be done in order to extract only the border points, which span the specific plane in the SMX model and exclude inlier points which would distort the planar extension. The coordinates of the boundary points of each single sub-member were written into a file with their own local orientation, to process the data from the vector analysis with SMX Analyst.

The spacing is calculated by the mapping-tool “Multiple Scanline” in SMX Analyst. The tool projects the sub-members of each discontinuity set on a local reference plane perpendicular to the mean plane orientation of one set and creates a 2D trace map for each set. The approach also considers non-persistent discontinuities. Furthermore, Multiple Scanline also provides values for the trace lengths. The resulting discontinuity traces are then analyzed according to:

- the number of joint traces
- the joint frequency [1/m]
- the mean, maximum and minimum spacing [m]
- the standard deviation [m]

3. Results

3.1. Identification of Discontinuity Sets with DSE

In total, six different discontinuity sets have been identified with DSE. Figure 1(a) shows the single points according to their assigned discontinuity set (DSE-I to VI), symbolized by the different colors. Figure 2(b) shows the stereographic projection (lower hemisphere) of the density deviations of the plotted point normal vectors. Table 1 shows the calculated values for the dip direction and dip angles for each discontinuity set. In total 95378 points were classified, 63113 points have not been assigned.

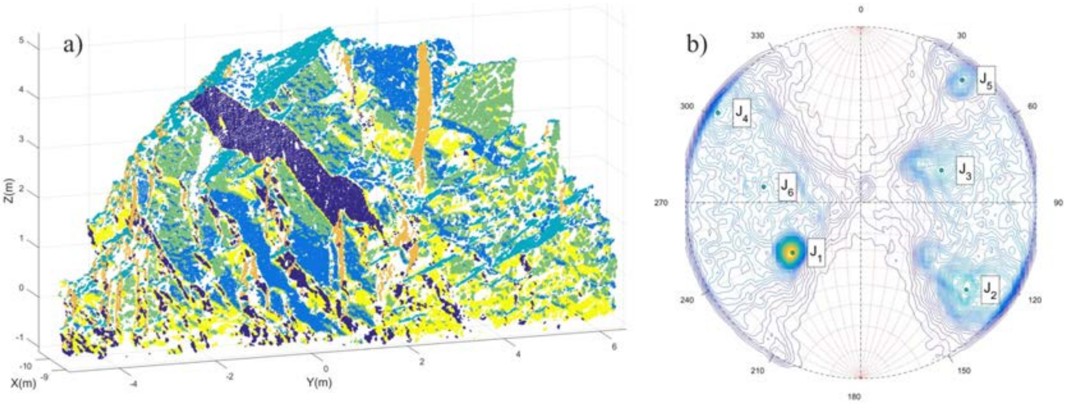

Fig.2. (a) assigned points in the investigated cloud coloured by their specific discontinuity set; (b) Density deviation as a contour plot with isolines each 1.25 % of the plotted point normal vectors in a stereographic projection (lower hemisphere) and identified principal poles (J_1 to J_6) of the discontinuity sets.

Table1. Dip direction and dip angles of the principal poles of each identified discontinuity set with the relating number of considered point normal vectors and the number of the assigned sub members.

Structure Set ID	DD [°]	D [°]	number of assigned points over the total number of points [%]
I	53.90	51.50	8.91
II	309.39	75.83	12.46
III	248.33	52.70	10.25
IV	122.04	87.73	15.38
V	219.70	84.32	7.60
VI	99.16	58.69	10.51

3.2. Calculation of the Spacing and Trace Length

The joint trace map for each discontinuity from DSE, as they are projected by SMX Analyst, are shown in Fig. 3. Table 2 shows the calculated values (mean ± standard deviation and maximum value) for the spacing of each discontinuity set, the mean trace lengths (mean ± standard deviation and maximum value) and the discontinuity frequency. DSE-V shows the highest mean value for the spacing (1.22 ± 0.89 m, max. 3.68 m), however, the maximum spacing is reached in DSE-III. DSE-II shows the longest trace lengths (0.77 ± 1.02 m, max. 4.01 m). A sub-member of DSE-I has the maximum trace length of 5.17 m. The most frequent discontinuity set is DSE-IV (1.76 1/m).

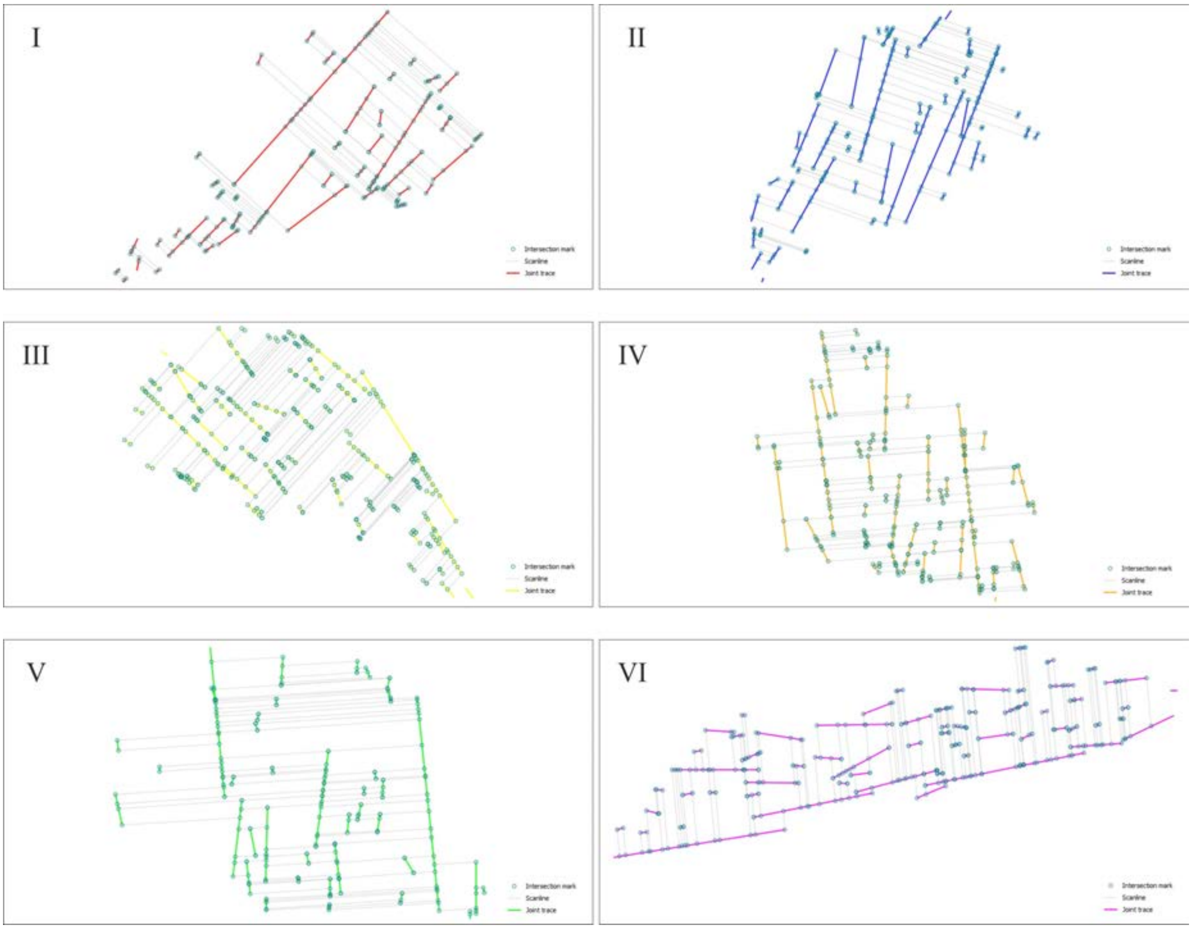

Fig. 3. Trace maps of the detected discontinuities (DSE-I to VI) with DSE, calculated by SMX Analyst (coloured lines) with the projected scan lines (grey lines) and the intersections (dots).

Table 2. Calculated spacing, trace length and frequency values for the discontinuity sets identified with DSE and calculated with SMX Analyst.

Set ID	No. of Joint Traces	Mean Spacing [m]	Max. Spacing [m]	Mean TL [m]	Max. TL [m]	Frequency [1/m]
DSE-I	43	0.72 ± 0.52	3.34	0.62 ± 0.91	5.17	1.40
DSE-II	50	0.78 ± 0.58	2.74	0.77 ± 1.02	4.01	1.28
DSE-III	69	0.81 ± 0.68	4.34	0.53 ± 0.75	4.54	1.24
DSE-IV	53	0.57 ± 0.40	1.65	0.69 ± 0.92	4.27	1.76
DSE-V	38	1.22 ± 0.89	3.68	0.65 ± 0.9	4.51	0.82
DSE-VI	60	0.61 ± 0.38	2.26	0.57 ± 0.73	3.47	1.63

3.3. Discontinuity Mapping with SMX Analyst

Figure 4 shows the mapping results from SMX Analyst. Figure 4(a) shows the mapped discontinuities in the investigated tunnel face, whereas Fig. 4(b) plots the mapped point normals (stereographic projection, equal angle). In total, five different discontinuity sets could be mapped. Table gives the dip direction and dip angles with their cone of confidence, spherical aperture and degree of orientation of the single discontinuity sets as well as the number of mapped sub-members.

Table 3. Dip direction and dip angles with their cone of confidence, spherical aperture and degree of orientation of the mapped discontinuity sets (SMX-I to V) with the relating number of the assigned sub members.

Structure Set ID	DD [°]	D [°]	Cone of Confidence [°]	Spherical Aperture [°]	Degree of Orientation [%]
SMX-I	45.13	59.45	6.42	17.46	91
SMX-II	123.19	65.40	7.90	21.41	86.67
SMX-III	219.88	86.64	5.70	18.05	90.40
SMX-IV	311.63	73.82	5.00	18.02	90.43
SMX-V	236.07	36.32	5.75	23.31	84.34

The cone of confidence defines a region around the calculated mean orientation, which delimits the deviation of the true mean orientation for a predefined confidence level of 95 %. The spherical aperture represents the spread of orientations around the mean value of the structure set. The degree of orientation is the normalized measure of the alignment of orientations in one set [9].

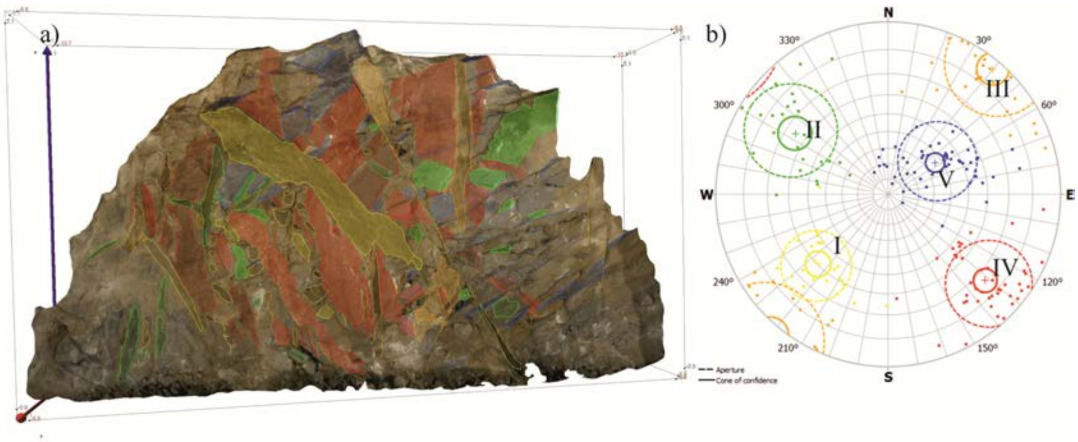

Fig. 4. (a) Mapped tunnel face of the investigated rock mass; the colors represent the single identified discontinuity sets (SMX-I to V); (b) shows the stereographic projection of the lower hemisphere and the plottet normals of the mapped planes.

Table 4 lists the calculated values for the spacing (mean ± standard deviation and maximum value) as well as the joint trace length (mean ± standard deviation and maximum value) and the joint frequency of the manually mapped discontinuities. SMX-3 shows the highest spacing with 1.34 ± 1.38 m (max. 5.73 m). SMX-IV is the discontinuity set with the highest frequency (1.49 1/m) and has also the longest trace lengths (0.59 ± 0.75 m, max. 3.80 m).

Table4. Calculated spacing, trace length and frequency values for the discontinuity sets manually mapped and calculated with SMX Analyst.

Set ID	No. of Joint Traces	Mean Spacing [m]	Max. Spacing [m]	Mean TL [m]	Max. TL [m]	Frequency [1/m]
SMX-I	25	0.78 ± 0.47	2.21	0.43 ± 1.01	4.95	1.28
SMX-II	25	0.69 ± 0.63	2.73	0.47 ± 0.44	1.88	1.45
SMX-III	33	1.34 ± 1.38	5.73	0.57 ± 0.52	2.68	0.74
SMX-IV	42	0.67 ± 0.59	2.92	0.59 ± 0.75	3.80	1.49
SMX-V	53	0.78 ± 0.89	4.08	0.48 ± 0.43	1.74	1.28

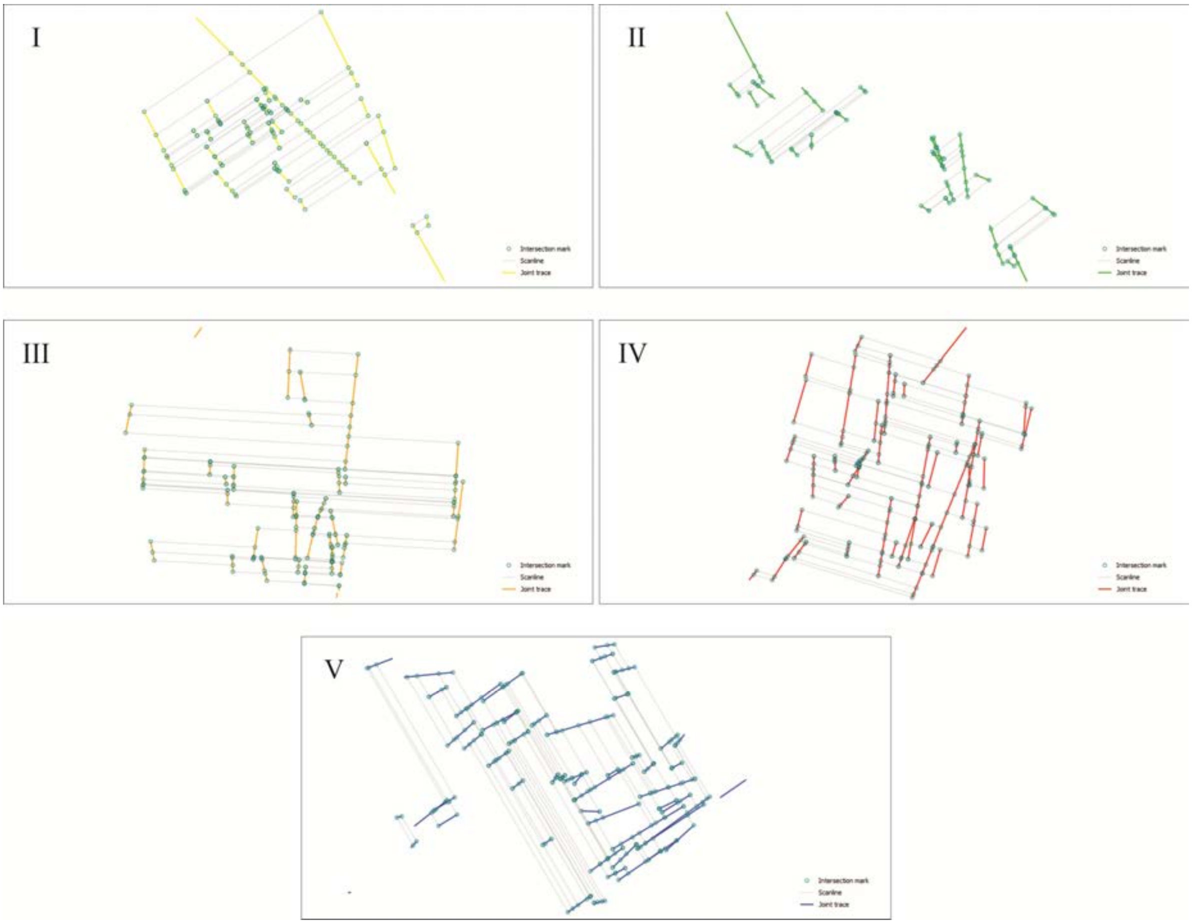

Fig. 5. Joint trace maps of the manual mappings (discontinuity set SMX-I to V) projected with SMX Analyst (coloured lines) with the projected scan lines (grey lines) and the intersections (dots).

4. Discussion

Comparing the stereographic projections of the results from DSE with those from the manual mapping, the following connections can be concluded and the values for the orientation, the spacing and the trace lengths compared (Tab. 5). The discontinuity set DSE-VI has no corresponding partner at the sets from the manual mapping.

Table 5. Absolute differences between the results from the discontinuity detection with DSE and the manual mapping with SMX Analyst.

Set ID DSE	Set ID SMX	$\lvert\Delta_{DD}\rvert$ [°]	$\lvert\Delta_{D}\rvert$ [°]	$\lvert\Delta_{mean\ SP}\rvert$ [m]	$\lvert\Delta_{max\ SP}\rvert$ [m]	$\lvert\Delta_{mean\ TL}\rvert$ [m]	$\lvert\Delta_{max\ TL}\rvert$ [m]
DSE-I	SMX-I	8.77	7.95	0.06	1.13	0.19	0.22
DSE-II	SMX-IV	2.24	2.01	0.11	0.18	0.18	0.21
DSE-III	SMX-V	12.26	16.38	0.03	0.26	0.05	2.8
DSE-IV	SMX-II	1.15	22.33	0.12	1.08	0.22	2.39
DSE-V	SMX-III	0.18	2.32	0.12	2.05	0.08	1.83

The closest fitting show the orientation, spacing and trace length values of DSE-II with SMX-IV and DSE-V with SMX-III. In this two cases the number of identified planes and mapped features is also very similar. Thus, it can be said, on the one hand, the manual mapping detected almost all members of these discontinuity sets and on the other hand, the semi-automatic detection of the discontinuity sets comes very close to the results a geotechnical engineer would map, but with a reduced time effort to map these features. Nonetheless, there is a discrepancy of more than a meter in the maximum spacing of the mapped discontinuities of DES-V and SMX-III, which cannot be explained at this stage.

The second best fitting show the corresponding sets DSE-I with SMX-I. Obviously, the manually mapped features of SMX-I are very dominant in the rock face, but still, the analysis with DSE detected almost twice the number of planes. According to the number of sub-members, the orientation values for this discontinuity set might be more precise from DSE-I, than from SMX-I.

The corresponding discontinuity sets DSE-III with SMX-V and DSE-IV with SMX-II show big differences in either the orientation values or the spacing resp. trace lengths. In the case of the first corresponding pair, the density plot (Fig-b) does show an increased density accumulation around 238°/43°, but DSE allocated the principal pole of this set to the higher density which lies around 248°/53°. Fig-b does not show this accumulation of orientation values but a larger scattering of the orientations. Since SMX Analyst calculates the mean of all elements in one structure set, the resulting principal pole is influenced by first the k-means cluster results and second the existence of outliers, which can be seen in the values for the cone of confidence and the spherical aperture for SMX-IV: Although the data show significant differences in the orientation, the cone of confidence is relatively high. Both techniques identified more than 50 single planes, which is also shown in the similar frequency values ($f_{DSE-III}$ = 1.24 1/m, f_{SMX-V} = 1.28 1/m). The big differences of the second mismatching correspondence (DSE-IV/SMX-V) might be explained by DSE-VI. If during the manual mapping more than 25 elements could have been mapped, the sixth discontinuity set like DSE-VI might also have occurred in the manual mapping results. The relatively high spherical aperture and low cone of confidence of SMX-V indicates this as well. In this case SMX-II (25 elements) stands between DSE-IV (53 elements) and DSE-VI (60 elements) and again, the results from DSE seem to be more reliable. With this in mind, it is up to the observer, which result – manual mapping or semi-automatic clustering with DSE – provides the better results.

Another discontinuity set, which was neither identified by DSE (due to exclusion) nor the automatic clustering routine in SMX Analyst, can be suspected by a close look on Fig-b in the region of 309°/53°. This minor structure can still have a huge influence on the global stability of the rock face if it intersects with other discontinuities in an unfavorable way. To detect these features confidently is one of the key qualifications, an automatic discontinuity detection has to fulfill.

The absence of orientations in the ranges of 000°± 20°/80°± 10° and 180°± 20°/80°± 10° (Fig-b) can be ascribed to the orientation of the investigated tunnel face and the absence of (sub-)parallel structures to this orientation.

5. Conclusion

In this work, a method to identify discontinuity sets in a blocky rock mass using the open source software DSE is applied. The software gave good results which were comparable with the manual mapping of the same rock face with SMX Analyst. Three of five identified discontinuity sets of the analysis with DSE showed a reasonably good match with the manual mapping results. One discontinuity set, identified with DSE could not be found by the manual mapping, however, the number of mapped features was considerably less than the elements from DSE, which implies that the feature might exist although it does not show up in the manual mapping results.

Furthermore, the spacing and trace length of the single discontinuity sets was computed by transferring the results from DSE into SMX Analyst. A main advantage of this method is that unlike the method for calculating the spacing of non-persistent discontinuities according to [7], this approach can handle the problem of unlinked and spatial distributed discontinuity planes. It is not necessary, to fix the plane orientation of each planar sub-member, like with the application to calculate the spacing, implemented in DSE, where the planar equations must currently be fixed which does not meet the definitions of [10] and [11] for persistence and spacing.

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