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Detection of geometric properties of discontinuities on the Špičunak rock slope (Croatia) using high-resolution 3D Point Cloud generated from Terrestrial Laser Scanning

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Abstract. Rock mass characterization is a very important part of engineering geological investigation. For a better understanding of the rock mass behaviour, it is crucially important to obtain as much as possible information about the discontinuity network, especially about orientation and the number of dominant discontinuity sets. The traditional methodology includes field mapping which dominantly produces a limited amount of data and consequently only a rough estimate about discontinuity network. To increase the number of measurements and to eliminate orientation bias, rock mass on the Špičunak rock slope in Gorski kotar, Croatia, was analysed using a combination of 3D Point Cloud and Textured Mesh Model generated from 3D Point Cloud by Poisson surface reconstruction. Both models were obtained from Terrestrial Laser Scanning. Two considerably different parts of a rock slope, with different weathering conditions and different degrees of fracturing were mapped. Discontinuities were mapped in the field and on the models using manual mapping techniques and semi-automated methods. Manual mapping on a 3D Point Cloud and Textured Mesh Model was done by Compass plugin and by Trace a polyline tool in Cloud Compare software version V2.12 and semi-automated mapping methods were done by Discontinuity Set Extractor and qFacet Fast Marching plugin for Cloud Compare software version V2.12. This study was used to show how the application of different methodologies, for the detection of geometric properties of discontinuities, influences the result. Statistical analyses were performed on the collected data to determine differences in the accuracy between the mapping techniques. Manual mapping on the 3D Point Cloud and high-resolution Textured Mesh Model showed good agreement with field measurements, apart from the higher number of discontinuities mapped by remote sensing methods. On the other hand, significant deviations were found between manual and semi-automated mapping techniques. Semi-automated methods did not correctly detect certain discontinuities, especially bedding planes that are perpendicular to a rock face. Also, semi-automated methods overestimate the number of discontinuity sets, especially in a highly weathered and highly fractured rock mass. These differences between methods can influence kinematic analysis results. Based on the results, an appropriate methodology was proposed to utilize the advantages of both manual and semi-automated methods. The proposed approach presents a powerful tool to accurately map and measure discontinuity orientation with results comparable to the field measurements.

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1. Introduction

Rock mass characterisation includes the acquisition of discontinuity network data. It is crucial to obtain accurate discontinuity data, especially about orientation and a number of discontinuity sets. Orientation and the number of dominant discontinuity sets significantly influence potential instability mechanics and represent the most critical parameters for any structural analysis [1]. Traditional field survey methodology includes acquiring a limited amount of data and consequently only a rough estimate about discontinuity network. Remote sensing methods can be applied to increase the collected discontinuity orientation data set and eliminate orientation bias [2]

Over the last twenty years, the application of remote sensing in geosciences has advanced significantly, especially in structural geology and rock mechanics [3-6]. To date, a large number of remote data collection methods have been developed with the primary goal of producing high-resolution 3D Point Clouds. Two methods stand out in the field of the engineering geological mapping of near-vertical rock slopes and tunnel excavation fronts: laser scanning (LS), digital photogrammetry (DP). Laser scanning methodology produces high-resolution and high-density 3D Point Clouds but with the limitation of much complex survey methodology and at a higher price [7,8]. Because of the accessibility of survey equipment, lower overall survey expense and much faster data acquisition for digital photogrammetry, it is used more often [9]. It was concluded in [8] that both techniques have their advantages and disadvantages, and accessibility is the first factor to consider when choosing an appropriate Point Cloud acquisition method. If Terrestrial Laser Scanning (TLS) is accessible, it should be used to provide a more accurate and higher-density Point Cloud.

In this study, a high-resolution Point Cloud was acquired using TLS, and structural analysis was performed using manual mapping technique and semi-automated methods. In addition, two considerably different parts of a rock slope, with different weathering conditions and different degrees of fracturing, were analysed and compared to field measurements.

2. Study Area

The investigated rock slope is located on the state road D3 (Goričan-Rijeka) in Gorski kotar region, Croatia. The vertical to subvertical rock slope has a total length of more than 300 meters. Part of the rock slope was reinforced and protected with a combination of shotcrete and rock bolts, and protective wire nets. The remaining part of the 160 meter needs to be inforced, and this section is the subject of this research.

Investigated slope generally strikes SW-NE, and it is located on the hillslope dipping towards NW. The orientation of the slope is predominantly towards NW and subordinately towards SW. The slope angle was analysed using Strahler morphometric units [10], and the rock slope was classified into four categories based on the corresponding slope angle. Analysis has shown that the majority of the rock slope has an angle greater than 54° with an average value of 72°. Moreover, the height of the studied slope ranges between 8 and 22 meters, and as well as the slope angle increases going from the NE to the SW.

The investigated rock slope is located near the fault and transgressive contact between Upper Triassic deposits and Permian deposits. According to the Basic Geological Map of Croatia [11] and the results of geological field mapping, it was determined that rock slope is composed of the Main dolomites. The Main dolomite forming the rock mass is moderately strong to strong with uniaxial compression strength around 60 MPa and grey to reddish-brown in color. Colour is strongly dependent on the degree of weathering. The rock mass is very blocky to blocky - disturbed with GSI values ranging from 45 to 60 [12]. The dolomites have visible bedding planes with an average spacing between 10 – 100 cm.

Based on the results of the field survey, two considerably different parts of the rock cut (zones Z1, and Z-2) with different weathering conditions and different degrees of fracturing (Figure 1), were chosen for further analysis using remote sensing methods.

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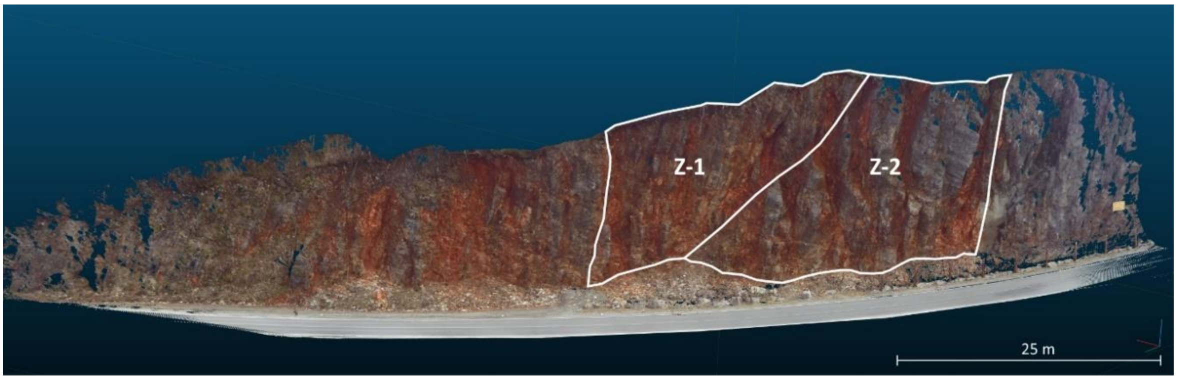

Figure 1. 3D Point cloud of the investigated rock slope with two highlighted engineering geological zones analyzed in this study

3. Methodology

3.1. Terrestrial Laser Scanning (TLS)

The Terrestrial Laser Scanning (TLS) was undertaken in April 2016 as a part of a Master Thesis at the Faculty of Civil engineering, University of Rijeka [13]. Terrestrial Laser Scanning was done using Faro Focus 3D s120 panoramic laser scanner equipped with a high-resolution 70 MPx camera which allows collecting RGB information for each measured point. The TLS system used in this study has the possibility to capture data at a pulse rate of 976 000 points/s with a surface point accuracy of 2 mm, 360° horizontal and 305° vertical field of view and scanning range between 0.60 and 120 m. Scanning was carried out from eight scanning positions at a 10 m distance from the rock face. Final Point Cloud, presented in Figure 1, has approximately 43 million points in the .e57 file with an average point density of 2181 points/m^2. The model has a total length of 140 meters and a maximum height of 28 meters. In addition, the final point cloud was used to generate a textured mesh model using Poisson surface reconstruction proposed by [14].

3.2. Remote sensing based analysis

To increase the number of measurements and to eliminate orientation bias, studied rock mass was analysed using a combination of the high-resolution 3D Point Cloud and Textured Mesh Model generated using Poisson surface reconstruction. Discontinuities were mapped on both models using manual mapping technique and semi-automated methods. Manual mapping on a 3D point Cloud was done by Compass tool [15] and by Trace a polyline tool in Cloud Compare software version V2.12 [16]. Semi-automated mapping methods were carried out by Discontinuity Set Extractor v3.0 [17,18] and qFacet Fast Marching Algorithm plugin [6] for Cloud Compare software version V2.12.

3.2.1. Manual mapping of discontinuities in Cloud Compare. The Manual mapping of discontinuities on the 3D Point Cloud, and Textured Mesh Model, with the Compass tool is used to determine the orientation of planar surfaces represented by a group of points in the form of dip and dip direction [15]. When determining the orientation of the discontinuity, it is necessary to determine its surface visually and by using the function Plane tool, select the radius within which all points are used to calculate the orientation of the best-fit plane using the least-squares method. For more precise measurements, it is possible to change the size of the circle within which the plane is approximated. For the obtained orientation values to be representative, a large number of measurements were performed. Furthermore, the orientation of those discontinuities visible only as traces are determined using the function Trace a polyline. Then, the specified function is used for selecting the start and endpoint of the plane trace, and the algorithm draws the trace and sets the best-fit plane for which orientation is calculated. The number of performed measurements depended on the size of the engineering geological zone, the number of discontinuity sets, and the exposure of discontinuity planes, and it varied from 100 to 350 measurements per zone. The measured orientations are used to determine the dominant sets of discontinuities in the next step.

This analysis of discontinuity sets was performed in the Dips v7.0 software by RocScience [19]. In this study, discontinuities were grouped into sets based solely on orientation. The determined discontinuity orientations showed correspondence to those measured in the field and were taken as reference values.

3.2.2. Semi-automated mapping of discontinuities in Discontinuity Set Extractor (DSE). The primary purpose Discontinuity Set Extractor is to semi-automatically derive planes and associated sets of discontinuities and determine their orientation in space from 3D point clouds obtained by either laser scanning or digital photogrammetry [17]. The analysis consists of several steps which include the determination of the number of nearest neighbours for every point, a coplanarity test and calculation of the normal vector for each discontinuity plane, semi-automated discontinuity identification using Kernel Density Estimation Analysis [20], statistical analysis, and finally, cluster analysis. In addition, it is mandatory to assign values to several calibration parameters.

Since the input parameters of the analysis are highly susceptible to subjective assessment, it is necessary to determine optimal parameters values. Testing of various input parameters was performed on a separate part of the investigated rock slope with clearly visible discontinuity surfaces. Resulted optimal input parameters are listed in the Table 1.

Table 1. Input parameters for Discontinuity Set Extractor (DSE)

Input parameters	Value
Number of nearest neighbours, knn	30-100
Tolerance for the co-planarity test, η_{MAX}	0.2
Kernell Density Estimation parameter, n	6
Angle between normal vectors of discontinuity planes, γ	20°
Number of discontinuity sets, N	5 - 10
Cone for point alignment, γ_1	20°
Cluster distribution threshold, k	2

3.2.3. Semi-automated mapping of discontinuities using qFacet FM algorithm. In a second step, a similar process was carried out using qFacet Fast Marching algorithm proposed by [6] included in open-source software Cloud Compare V2.12. The proposed methodology is based on subdividing initial high-resolution 3D point cloud into sub-cells using least square fitting algorithm and computing elementary planar objects which are later aggregated into polygons according to a planeity threshold [6]. Generated polygons are represented by their dip and dip direction and can be exported in ASCII file and later reported on a stereographic projection.

Input parameters of the analysis using qFacet Fast Marching algorithm include octree level, maximum distance of points, minimum points per facet and maximum edge length. As previously mentioned in the analysis using DSE, input parameters are highly susceptible to subjective assessment, and it is necessary to determine optimal parameter values. Special emphasis should be placed on maximum distance parameter. This criterion is used to estimate whether a facet is still flat enough after merging a new patch or not [6]. Testing of various input parameters was performed on a separate part of the investigated rock slope with clearly visible discontinuity surfaces. Resulted optimal input parameters are listed in Table 2.

Table 2. Input parameters for *qFacet Fast Marching Algorithm.*

Input parameters	Value
Octree level	8
Maximum distance of points at 99% of standard deviation	0.06
Minimum points per facet	200-400
Maximum edge length	2

4. Results

Two homogeneous engineering geological zones, Z-1 and Z-2 were selected by field mapping and analyzed using remote sensing methods. Zone Z-1 was found to be moderately weathered in alternation with a very intensely weathered rock mass. Zone Z-2, on the other hand, is slightly weathered in alteration with moderately to slightly weathered rock mass. Structural analysis of engineering geological zones Z-1 and Z-2 was performed utilizing field mapping and remote sensing techniques using Cloud Compare, DSE and Cloud Compare qFacet Fast Marching algorithm.

4.1. Engineering geological zone Z-1

As shown in Table 3 and Figure 2a engineering geological field mapping resulted in the recognition of five discontinuity sets, four fracture sets (S1 – S4) and a bedding plane (S0). The manual mapping procedure using Cloud Compare also resulted in five discontinuity sets (red traces in Figure 2a) with minor deviations from field mapping results. Because a much greater number of measurements were performed using manual mapping in CloudCompare, those results were chosen as statistically representative and semi-automatic methods were compared to them. Figure 2b represents results of semi-automated mapping with Discontinuity Set Extractor (green traces) compared to manual mapping with Cloud Compare (red traces). Stereographic projection clearly shows that this approach generated only four fracture sets (S1-S4). Also, the most common discontinuity set, the bedding plane (S0), was not detected using this approach because it is mainly represented with just traces on a rock face. Furthermore, DSE has unnecessarily divided sets S1 and S2 into four different sets due to the impossibility of adequate classification of points in conditions of increased rock mass weathering and fracturing. Discontinuity set Sx was recognised using DSE, but a review of the 3D model revealed that it was noise in the data and it is not an actual discontinuity set.

Table 3. Discontinuity orientations in zone Z-1 obtained with different methods.

Structure set ID	Field survey (DD/D) [°]	Cloud Compare (DD/D) [°]	DSE (DD/D) [°]	qFacet FM (DD/D) [°]
S0	290/30	294/33	-/-	-/-
S1	86/80	84/81	68/75 (96/75)	89/85
S2	337/81	335/85	341/79 (163/75)	341/79(156/82)
S3	10/79	12/81	5/83	9/79
S4	117/83	120/83	118/82	122/76 (306/84)
Sx	-/-	-/-	320/59	309/51

In Figure 2c, results of semi-automated mapping using Cloud Compare qFacet Fast Marching Algorithm (green traces) compared to manual mapping with Cloud Compare (red traces) are presented. The orientation of discontinuities detected using this approach show high dissipation, and it was challenging to group them into discontinuity sets. Stereographic projection clearly shows that the semi-automated approach using qFacet Fast Marching algorithm generated four sub-vertical and vertical fracture sets (S1-S4). In the case of qFacet Fast Marching algorithm vertical sets S2 and S4 were unnecessarily divided into four sets due to the impossibility of adequate classification of points in conditions of increased weathering and fracturing of rock mass. On the other hand, the algorithm could not detect the most common discontinuity set, i.e., bedding plane (S0), because it is mainly represented with just traces on a rock face. Discontinuity set Sx was also recognised using this method.

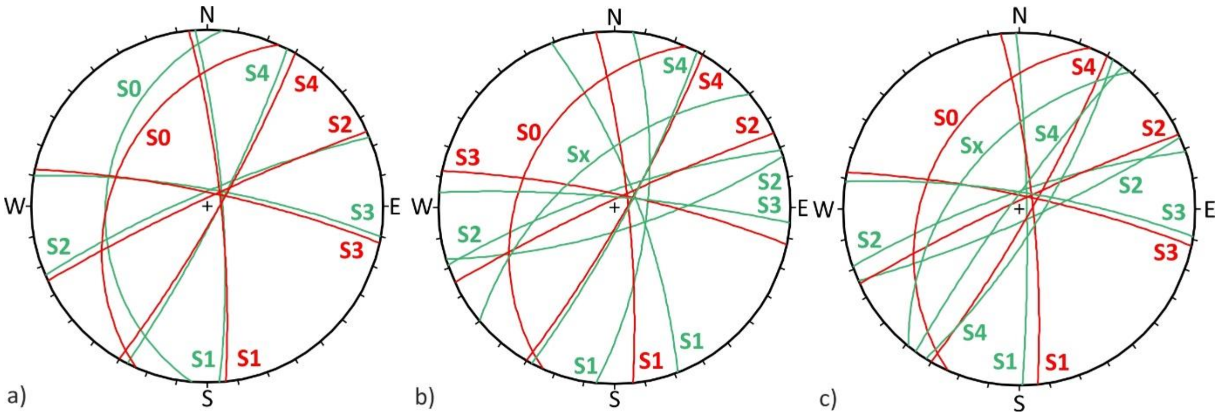

Figure 2. Stereographic projection (lower hemisphere and equal area) of the traces of the discontinuities for zone Z-1: a) field survey (green traces) and Cloud Compare (red traces); b) Cloud Compare (red traces) and DSE (green traces); c) Cloud Compare (red traces) and qFacet FM algorithm (green traces)

4.2. Engineering geological zone Z-2

As shown in Table 4 and Figure 3a engineering geological field mapping resulted in recognition of six discontinuity sets, five fracture sets (S1 – S5) and a bedding plane (S0), as shown in Figure 4a represented with green traces. The manual mapping procedure using Cloud Compare, also resulted in six discontinuity sets (red traces in Figure 3a) with minor deviations from field mapping results as shown in Table 4 Because a much greater number of measurements was performed using manual mapping in Cloud Compare, those results were chosen as representative and semi-automatic methods were compared to them.

Figure 3b represents results of semi-automated mapping with Discontinuity Set Extractor (green traces) compared to manual mapping with Cloud Compare (red traces). Stereographic projection clearly shows that this approach generated only five fracture sets (S1-S5). Also, the most common discontinuity set, the bedding plane (S0), was not detected using this approach because it is mainly represented with just traces on a rock face. Discontinuity set Sx was recognised using DSE, but a review of the 3D model revealed that it was noise in the data and not an actual discontinuity set.
Results of the structural analysis of engineering geological zone Z-2 are presented in Table 4.

Table 4. Discontinuities orientation in zone Z-2 obtained with different detection methods.

Structure set ID	Field survey (DD/D) [°]	Cloud Compare (DD/D) [°]	DSE (DD/D) [°]	qFAcet FM (DD/D) [°]
S0	285/33	300/35	-/-	-/-
S1	77/79	80/82	80/80	95/80
S2	332/85	331/83	331/83	345/81
S3	3/77	1/74	2/72	6/79
S4	117/82	119/82	121/81	148/82
S5	32/85	30/86	211/88	43/77
Sx	-/-	-/-	315/54	295/49

In Figure 3c, results of semi-automated mapping using Cloud Compare qFacet Fast Marching Algorithm (green traces) compared to manual mapping with Cloud Compare (red traces) are presented. The orientation of discontinuities detected using this approach show high dissipation, and it was challenging to group them into discontinuity sets. Stereographic projection clearly shows that the semi-automated approach using qFacet Fast Marching algorithm generated five sub-vertical and vertical fracture sets (S1-S5). On the other hand, bedding plane (S0) was not detected. Discontinuity set Sx was

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also recognised, but a review of the 3D model revealed that it was noise in the data, same as with DSE mapping.

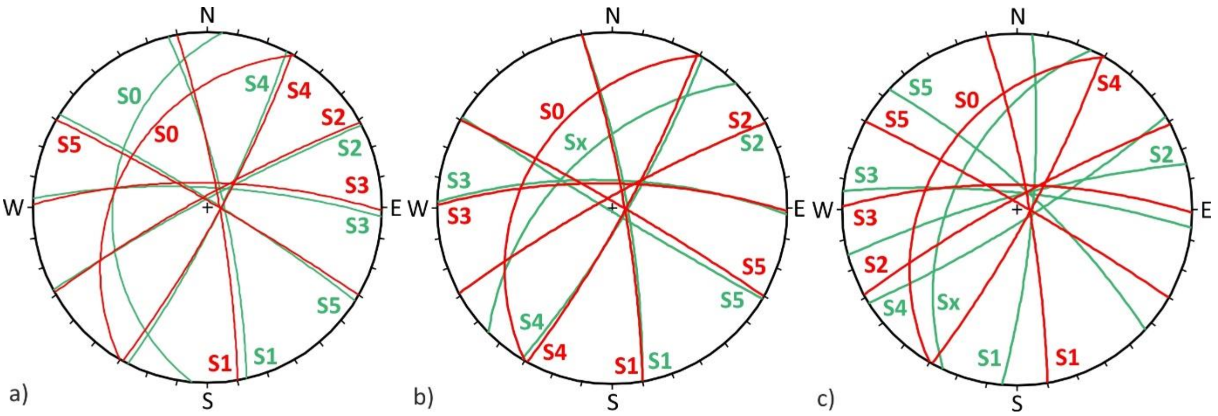

Figure 3. Stereographic projection (lower hemisphere and equal area) of the traces of the discontinuities for zone Z-2: a) field survey (green traces) and Cloud Compare (red traces); b) Cloud Compare (red traces) and DSE (green traces); c) Cloud Compare (red traces) and qFacet FM algorithm (green traces)

5. Discussion and Conclusion

The innovative application of remote sensing methods using high-resolution 3D point clouds presents a step forward in engineering geological rock mass investigation. Since rock mass is characterized by very complex 3D geometry and complex structural relationships, it is necessary to collect data on discontinuities in an objective and representative way, which results in a realistic engineering geological model of the rock mass. Traditional methods for rock mass mapping performed either in one (scanline mapping) or in two dimensions (window mapping) are too subjective, time-consuming, and usually result in a small amount of data collected [21].

Structural analysis of dominant discontinuity sets and their orientation were performed by manual mapping using open-source software Cloud Compare V2.12 and two semi-automated methods for discontinuity detection: Discontinuity Set Extractor [17] and qFAcet Fast Marching Algorithm [6]. Analysis pointed out certain discrepancies between these methods, predominantly in the number of discontinuity sets identified, and in the orientation values obtained. Manual mapping using Cloud Compare Compass plugin mapping is much more time consuming than semi-automated methods, but on the other hand, faster and can obtain much more measurements of structural characteristics than with filed mapping. Furthermore, it gives much more accurate results due to a higher number of discontinuity orientation measurements. The identification of discontinuities in this way requires an understanding of the engineering geological and structural characteristics of the research area. Additionally, with the manual method, it was possible to map discontinuities that are visible only as traces on the surface of the rock slope which was not the case with semi-automated methods. Semi-automated methods produce best results on ideal rock masses with maximum tree orthogonal sets of discontinuities and fresh to slightly weathered rock mass conditions. That is why results of semi-automated methods should be thoroughly validated in order to determine their accuracy in the conditions of highly weathered and fractured rock masses as was the case in the study area. The results of semi-automated methods depend on precisely defined input parameters. Geologist doing the structural analysis using semi-automated methods needs to be very experienced with the methodology to adapt input parameters to the conditions of the rock mass. Furthermore, semi-automated methods such as DSE and qFacet Fast Marching Algorithm emphasize the number of those discontinuities that are clearly visible and represented with planar surfaces, while underestimating those that are less visible on the rock slope.

Semi-automated methods used in the research resulted in a considerable amount of noise, which most often represents the surface of the rock slope or debris cover. This is especially significant for very intensely weathered rock mass in engineering geological zone Z-1. On the other hand, results obtained in engineering geological zone Z-2 show relatively good agreement with manual mapping methods, since the rock mass is less weathered and fractured. For obtaining better results in highly weathered rock mass it is recommended to use semi-automated methods, especially DSE, as an aid in manual mapping of discontinuities since the resulting coloured point cloud speeds up manual mapping and emphasizes discontinuity surfaces. In this way, the advantages of both methods are exploited for obtaining valid results which can be used as an input data for kinematic analysis.

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