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Photogrammetry for recording rock surface geometry and fracture characterization

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ABSTRACT: Rock surface geometry and rock fractures are important initial data for rock engineering and mining projects. Traditionally the field data has been obtained manually with hand-held tools to perform point-like measurements. Photogrammetry-based methods of acquiring geometry over large areas became a useful tool in characterization of rock surfaces over the last few decades mostly due to developments with UAV based and GPU accelerated photogrammetry. In this paper, we describe the usage of photogrammetry applied to recording of rock surface geometry and fracture characterization. The method is used to produce the required initial data for rockfall analysis, to measure the roughness of rock joints, and to create virtual training environments to practice rock mass characterization. The rockfall analysis was tested using a 122 m long rock cut. The roughness measurements were tested on a 2 m long rock sample and compared to manual measurements. The virtual learning environment was tested with 20 students and 10 staff members. The presented method performed successfully in each case. The method improves accessibility, speeds up and reduces subjectivity of rock mass characterization.

1 INTRODUCTION

1.1 *State-of-the-art*

Parameters describing the geological structures are very important initial data for any geoengineering project. All established methods for the design of geoengineering projects require the knowledge of geo-structural parameters, such as the orientation, size, frequency, and surface geometry of discontinuities. Additionally, geo-structural parameters are a part of the standardized selection of geotechnical parameters for quantitative rock mass characterization (e.g., Q-system by Barton et al. (1974); RMR by Bieniawski, (1989)). The interpretation of structural features usually is reliant on the previous experience and knowledge of the person performing mapping (Jones et al. 2004; Gaich et al. 2003). Furthermore, Houghton et al. (2015) report that a typical error is that the student is recording the field data but not understanding it.

The conventional method of tunnel mapping involves visual inspection and manual mapping of structural information using a geological compass, profilometer and measurement stick. The main advantages of automatic mapping are (1) ability to map inaccessible rock faces (2) no time limitation due to excavation work cycle and (3) removal of the human factor, such as prior experience, motivation or bias (Gaich et al., 2003). Multiple researchers have proposed semi-automatic and automatic mapping methods by laser scanning or digital photogrammetry (e.g., Mah et al. (2011); Lee et al. (2013); Riquelme et al. (2014); Gallant and Marshall (2016); Thiele et al. (2017); Chen et al. (2018); Mastrorocco et al. (2018))

Concerning the training of outcrop and tunnel mapping using virtual reality, several researchers have proposed similar concepts. Hurst (1998) suggested the use of computer visualization techniques and realistic simulations for the teaching of geology. Saini-Eidukat et al. (2002) developed web-based software for virtual geological mapping and interpretation designed to teach the students the basics of geologic concepts and practicing the decision-making and problem-solving skills required in field mapping. Kelly and Riggs (2006) developed a virtual environment for practicing certain geological mapping skills before the students go into the field. The virtual practices resulted in increased student performance, better spatial understanding of the problem and more confidence in the field. Argles et al. (2015) developed an interactive virtual geologic field practice in a 3d virtual world, where students can practice fieldwork tasks with real-data. Houghton et al. (2015) describe the Virtual Worlds Project, which was aimed for teaching and practicing of basic geological mapping skills in a virtual environment. Mastrorocco et al. (2018) demonstrated the use of a non-immersive desktop Virtual Reality model to map discontinuities. The quality of the virtual mapping compared well with the field measurements.

1.2 *Photogrammetric recording of rock surfaces and rock joints*

Mechanical Properties of Rock Joints (KARMO) research project was conducted in 2014-2018 at Aalto University in Finland. The objective was to develop a non-destructive method to record rock surface geometry and carry out fracture characterization using photogrammetry. In KARMO I (2014), the feasibility of using a combination of photogrammetry and 3D printing to create a replica of the observed geometry was tested (Yorke, 2014 and Korpi, 2016).

After a successful feasibility test, in KARMO II (2015-2016), the usage of photogrammetry of joint surface roughness as the basis of 3D printing mold and producing numbers of mortar replica samples for shear testing were examined (Kallio, 2015 and Tolvanen, 2015). As a result, a method to produce replicas using photogrammetry was published (Uotinen et al., 2015).

In KARMO III (2017-2018), the accuracy of the method on rock samples was examined (Sirkiä, 2015). The photogrammetric method was applied for open pit mines (Iakovlev et al., 2016) and for ground support design (Sirkiä et al., 2016). As experimental validation, large scale shearing tests for rock joints up to 2 m long were carried out in the laboratory with CNL configuration and displacement resetting (Dzugala, 2016; Dzugala et al., 2017; Uotinen, 2018) following the ISRM recommendations for shear testing (Muralha et al., 2014). As the final step, it was explored if the laboratory tests could be partially replaced by numerical shear tests (Kivivirta, 2017). The final results of the KARMO I-III will be published during the year 2019.

Based on inventions filed during KARMO, a startup company Fractuscan Ltd was launched to provide the method commercially for mine and infrastructure operators. The photogrammetric method was also applied for training purposes in research projects MIEDU (Mining Education and Virtual Underground Rock Laboratory), KAVI (Visualization of Rock Mass Quality in Rock Engineering Projects) and EDUROCK (Virtualization of the Rock Sample Collection of Aalto University). The virtual reality environment was tested with students and actual learning outcomes with reception from the attendees were measured (Jastrzebski, 2018)

2 METHODOLOGY

2.1 *Fracture surface roughness characterization by photogrammetry method*

The method was tested on a 2 m x 1 m Kuru gray granite slab pair which had a mechanically induced synthetic tensile crack between the slabs. Measurement of both bottom and top rock joint surfaces were done prior to shear testing and once after all the shearing stages. The joint surface roughness was measured in three equidistant lines using a plastic profilometer with a tooth width of 1.3 mm and photogrammetry methods. The profiles were surveyed with a 20 cm long profilometer and the two 10 cm halves were compared with the Barton and Choubey, 1977 reference profiles by Alireza Baghbanan. A photograph of each profilometer measurement was taken and two 10 cm curves were digitized using the Jenks natural breaks optimization method. The slopes of the resulting curves were compared to the slopes of the reference profiles to determine the best-fitting JRC profile.

Photographs were taken using a Canon EOS 5DS R camera and a Canon EF 35 mm F/2 IS USM objective. Most photos were taken at close range with small translation movements and large overlaps. Between the linear series, the camera angle was changed vertically (pitch) from 30 to 80° and horizontally (yaw) from -45 to +45°. Some of the pictures were taken at a different sensor angle (roll) from 0 to 45° to reduce sensor bias (Figure 1, left). The images were processed to a point cloud using VisualSFM software 0.5.25 using default settings (Wu, 2007; Wu et al., 2011; Wu 2013). The resulting cloud was cleaned up, cropped and meshed in CloudCompare 2.5.5.2 (Figure 1, right). Digital line profiles were then extracted with 10 cm subsections to compare with the manual measurements.

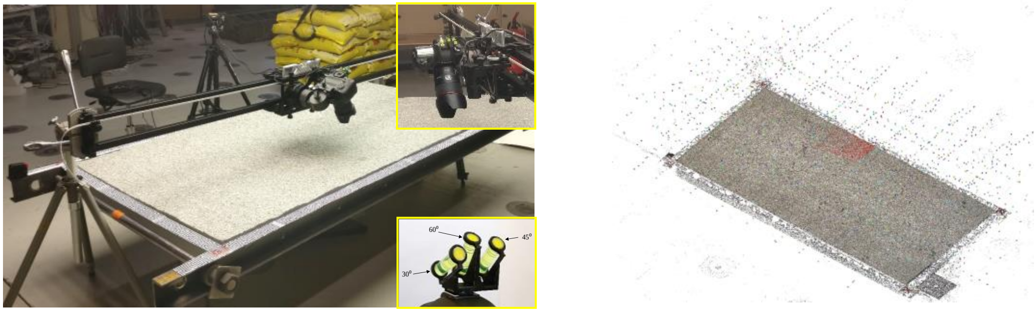

Figure 1. Motorized slider track, photography in 60˚ angle and installed balanced gauges (left); 3D coarse reconstruction of the rock sample and camera locations in VisualSfM (right)

2.2 *Tunnel digital twin and high-quality rock wall photogrammetric reconstruction*

The digital close-range photogrammetry was used to digitize a 100 m long section of Underground Research Laboratory Tunnels (URLA) located in the Otaniemi campus of Aalto University in Espoo, Finland. The tunnel is located approximately 20 m below the surface in granitic rock and is used in teaching geological and geotechnical mapping of rock walls. The goal of the photogrammetric reconstruction was to produce two 3D models to be utilized in VUTE (Virtual Underground Training Environment) a Virtual Reality (VR) system designed at Aalto University for enhancing the teaching of the geo-structural mapping of rock walls (Jastrzębski, 2018). VUTE consisted of two 3D models. The first model was a digital twin of the mapping tunnel used as the main virtual environment for the VR exercise. The second model was a 10 m long section of the mapping wall with higher quality for mapping in the VR.

For the tunnel model, 1725 photos were taken with Canon EOS 5DS R camera and Canon 14 mm f/2.8 L II EF USM objective. The photographed surface was illuminated using three Aputure Amaran HR672C LED panels and three 2x 50 W LED panels with 4500 K color temperature and 3750 lm/led light output (EAN 6430058412328). The camera was fixed on a tripod and the photos were taken with 60 % overlap between the subsequent photos (Figure 2). Digital Photo Professional 4 software was used to even out the lighting and improve contrast.

For the wall section model, 369 photos were taken with Canon EOS 5DS R camera and Canon 14 mm f/2.8 L II EF USM and Canon 35 mm f/1.4 L II USM objectives. The camera settings used were the same as for the tunnel reconstruction, except that the tunnel was illuminated with 60 units of 2x 58 W fluorescent tube lights with color temperature 4000 K and 5250 lm/tube luminosity installed in the roof (EAN 6435200006738). The photos were also taken from a shorter distance to the wall to capture the fine details of the rock surface (Figure 3).

Next, two 3D photogrammetric models were created using Agisoft Metashape Professional 1.5.0 software. The reconstruction quality was set to Medium due to a large number of photos used. The 3D models were decimated to 8 million faces to enable smooth display performance in VR. To achieve the high resolution of textures, both models were split into six overlapping parts and textured using the default settings with a texture size of 16k. The final step was to load the 3D models and texture files into Unity 2017.3.1f1 real-time game engine that was used to create the VUTE system. The textures were compressed to 8k due to Unity import limitations.

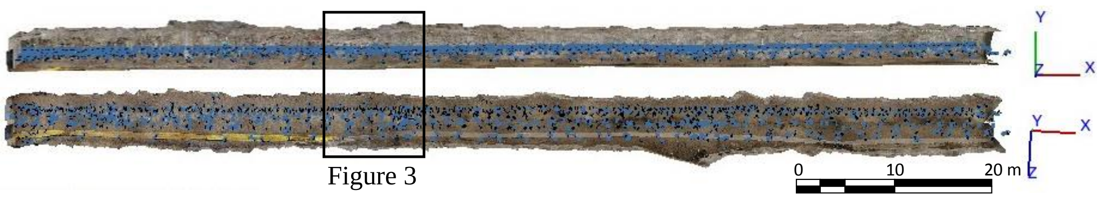

Figure 2. Textured 3D model of the tunnel with camera locations side view and top view.

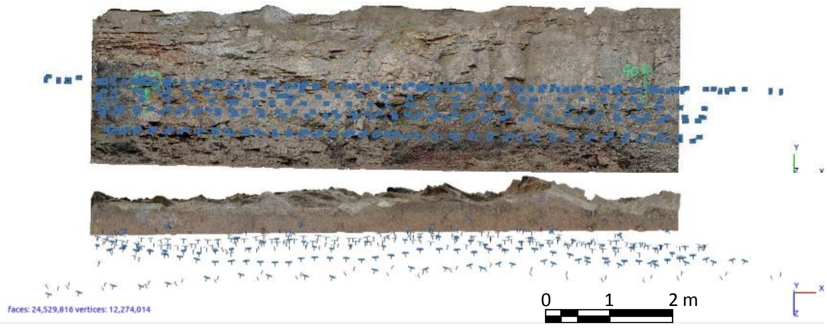

Figure 3. Textured 3D model of the mapping rock wall section with camera locations side and top view.

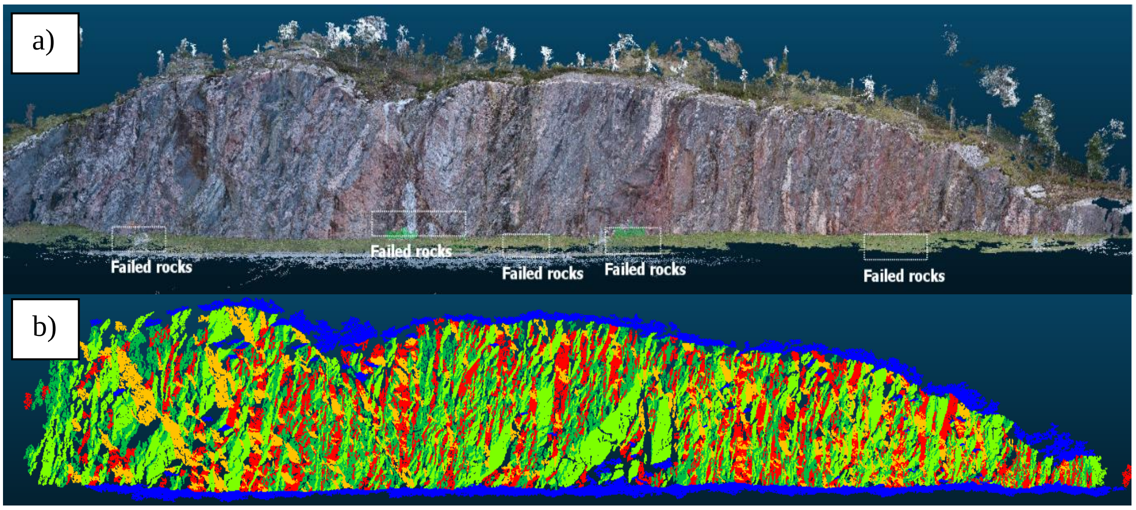

Figure 4. Location of observed rockfall (a) and automatically detected joint sets (b).

2.3 *Photogrammetric method of rock wall recording*

The drone-based aerial photogrammetric recording method for rock walls was tested on site scale by capturing a 122 m x 15 m roadside rock cut. UAV with a stabilized camera was deployed to capture 3224 images of the site. The photos were taken over a time of 3 h 45 min mainly from 3-5 m distance from the rock wall. The location of the already fallen rocks was noted (Figure 4a). The images were processed to a point cloud and the discontinuity sets were extracted using the Discontinuity Set Extractor (Riquelme et al., 2014). The resulting automatically identified joint sets were used to determine block formation locations (Figure 4b). This data and the cross-section geometry were used as initial data in rockfall analysis.

3 RESULTS

3.1 *Scale and stress effects on evaluated fracture surface roughness*

The results of the 60 JRC measurements for the 2 m x 1 m rock slab are shown in Figure 5 with manual JRC measurements using profilometer, with single profilometer photographs and with digital curves. Manual measurements have the highest scatter and the digital curves have the least scatter. The majority of the measurements fall in the 6-12 JRC range with the mode 8-10. The digital curves give higher JRC readings than the single photograph analyses.

The performance of both digital methods was compared to the manual measurements (Figure 6). The single photograph method and hand method give the same result 21 out of 60 times and only rarely is the method off by more than one JRC range of 2 units (Figure 6, on left). The digital curve method gives the same answer as the manual result 16 out of 60 times and at times the result can be off by several JRC ranges (Figure 6, on right). Interestingly, the single photograph method and the digital curve method also give the same result every third time (20 of 60).

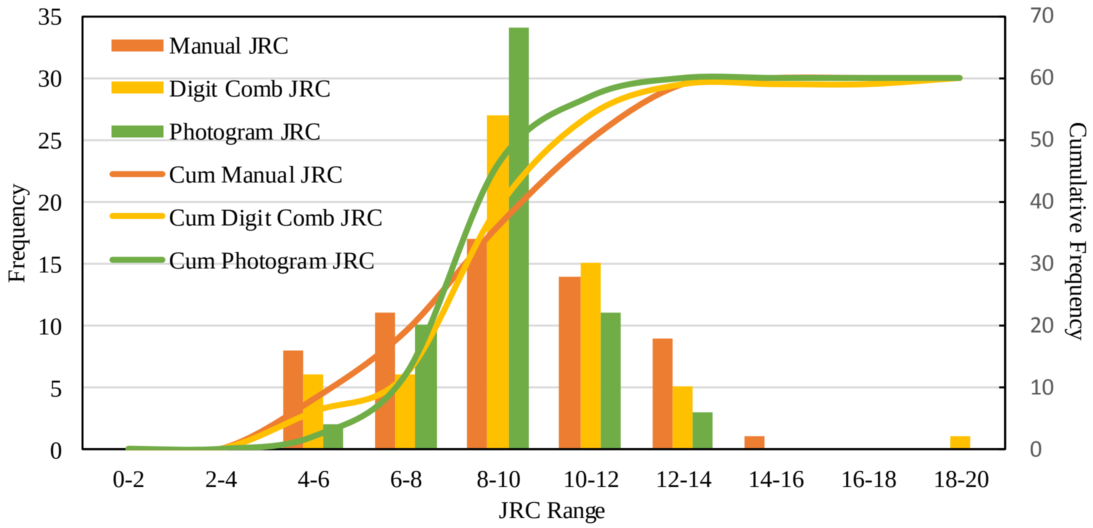

Figure 5. JRC measurement results using the manual profilometer (red), single photograph (yellow) and digital curve (green) photogrammetry methods.

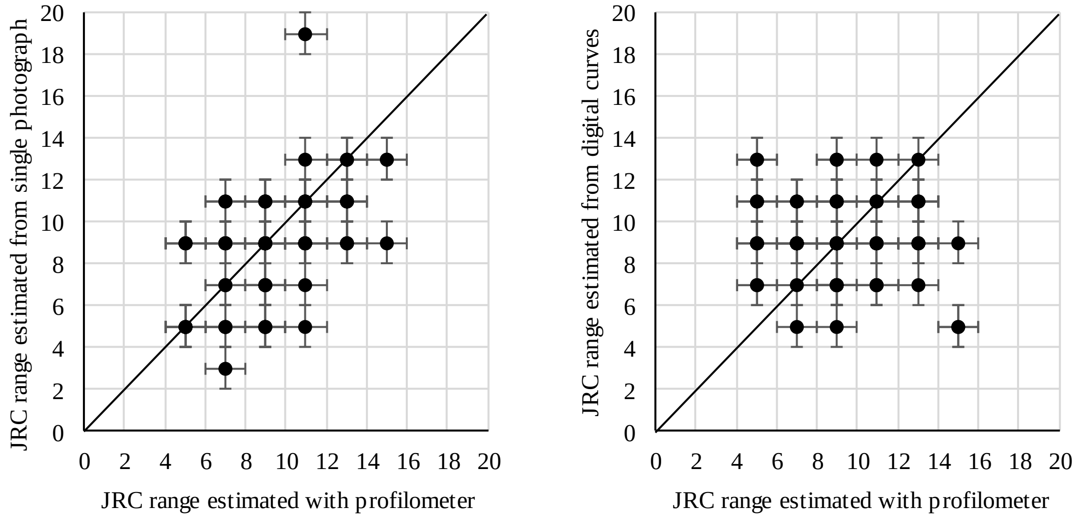

Figure 6. Comparison of the JRC measurement results from a single photograph and manual profilometer (on left) and digital curves and manual profilometer (on right).

3.2 *Tunnel digital twin and VUTE experiment results*

As a result of the photogrammetric reconstruction, two 3D models were obtained. The tunnel model consisted of 58 million faces reconstructed from a dense point cloud of 291 million points and the wall section model consisted of 24 million faces reconstructed from a dense cloud of 122 million points. Both models were decimated to 8 million faces and imported into Unity for implementation into VR. Figure 7 compares the real tunnel, photogrammetric model, and the tunnel in VR.

Figure 7. Comparison of the tunnel (a), photogrammetric model (b) and virtual reality environment (c). Source: Youtube-video https://youtu.be/8Zxtotw_vyg (1 min 18 s)

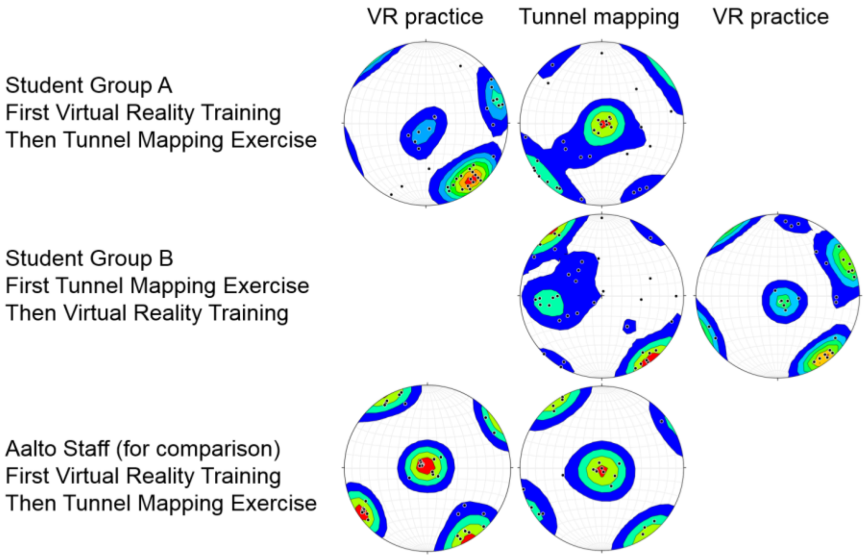

Figure 8. The results of the geological mapping test in Virtual Underground Training Environment.

The VUTE VR system was tested on a group of 20 students divided into group A which was first doing the geological mapping in VR and then in the tunnel and group B which first did the tunnel and then VR. The students were measuring the dip direction, and dip angle of each joint set they identified. The performance of the students in both VR and real tunnel was compared to a control group of Aalto staff personnel with more experience in geological mapping. The results of the VUTE systems test are presented in Figure 8. It can be seen that the group A, which first used the VR had more consistent results with less error as compared to group B. A detailed description of the VUTE experiment can be found in Jastrzębski (2018).

3.3 *Photogrammetric method of rock wall recording*

The drone-based photogrammetric recording method for rock walls was tested on site scale by capturing a roadside rock cut. By processing the images taken, a point cloud with a ground sampling distance of 1 mm was created. See Figure 9 for the point cloud as well as the discontinuity sets and one cross-section profile that were extracted from the point cloud. In this case, the data was used to assess the risk of a dislodged block reaching the nearby road. Figure 10 shows one rockfall trajectory analysis with RocFall 7.004 software for a small block falling from just below the crest of the slope. As a result, the probability of a rockfall landing in the road area and distribution of safety factor defined as the distance traveled divided with the distance to the road can be extracted for each cross-sectional profile.

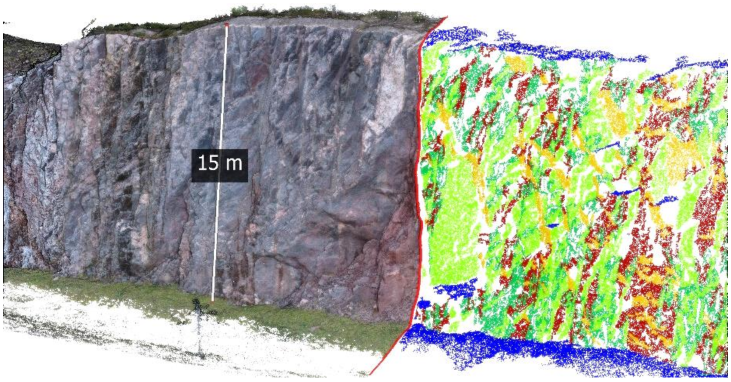

Figure 9. Point cloud (on left), one cross section with red color (in middle) and grouping by dip and dip direction (on right).

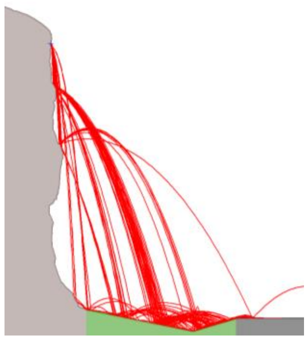

Figure 10. Possible trajectories of a rockfall event.

4 CONCLUSION

The usage of photogrammetry for the recording of rock surface geometry of rock cuts and fracture characterization of rock cuts was demonstrated using a 122 m long roadside rock cut. The resulting high-resolution point cloud had a ground sampling distance of 1 mm. Automatic discontinuity set extraction was used to determine likely locations where blocks may form. Rockfall analysis was used to determine the associated probability of failure and the factor of safety distribution. In conclusion, the proposed method can be used to produce the initial data required for risk assessment and rockfall analysis of rock cuts.

The photogrammetric method was used to scan a 100 m long section of an underground rock mapping teaching tunnel. The resulting dense point cloud was utilized to produce a virtual underground teaching environment (VUTE). The VUTE was tested using 20 students and 10 members of Aalto University staff. The task was to determine dip and dip direction for rock joints in a given area. The results show a reduction of scatter for students who received virtual reality training before tunnel mapping exercise.

Finally, the photogrammetric method was used to scan large rock joint laboratory samples with sizes up to 2 m x 1 m. While the high-resolution scanning can be used directly to obtain a directional roughness metric of the surface, here it was used to obtain an objective reading of JRC, which was then compared to subjectively obtained manual and single photograph readings. The initial result shows that the proposed methods produce realistic values, but as JRC is not defined explicitly, a large set of experts is needed for further validation.

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