

Application of LiDAR technology for the assessment of mechanical scaling conditions in underground mines and tunnels



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ABSTRACT

Mechanical scaling consists of removing hazardous and loose rock from surfaces, following excavation by blasting. Mechanical scaling using heavy machinery involves scraping surfaces systematically to effectively cover most of the excavation and mitigate risks associated with loose materials. Quality control and performance assessment of mechanical scaling rely primarily on visual observations, which are subjective by nature. Assessing the impact of any changes in the mining process (e.g. drill pattern, new machinery) on mechanical scaling requirements and quality, is not trivial due to a lack of objective assessment criteria. The following article aims to introduce LiDAR survey applications for the assessment of mechanical scaling. Three different surface quality assessment methods are presented based on the analysis of point clouds obtained through LiDAR scanning. The methods provide an attempt at quantifying mechanical scaling quality, scale instability potential following mechanical scaling, and expected wear and tear on a mechanical scaler based on surface roughness. The methods were applied to different excavations across K+S Windsor Salt mining operations and on an open source tunnel point cloud.

RÉSUMÉ

Le processus d'écaillage mécanique consiste à sonder les parois d'une excavation rocheuse afin d'enlever le matériel endommagé posant un risque de relâchement non prévisible. La machinerie lourde opérée pour effectuer cette tâche est en général utilisée de façon large et uniforme enfin de sonder la grande majeure partie des parois rocheuses. L'analyse de la performance de l'écaillage, ainsi que l'estimation de l'effort requis se base principalement sur des observations visuelles et subjectives. L'impact de changements dans la méthode de minage (e.g. patrons de forages, nouvelle machinerie) est donc particulièrement difficile due au manque de subjectivité des analyses. Le présent article introduit diverses applications d'analyse de la qualité de l'écaillage mécanique à l'aide d'arpentage au LiDAR. Trois méthodes sont présentées basés sur l'analyse de nuage de points afin de quantifier la qualité de l'écaillage. Les méthodes proposées se concentrent sur le potentiel de glissement, la qualité de l'écaillage, et le degré d'intensité de l'écaillage nécessaire en lien avec la machine utilisée.

1 INTRODUCTION

Mining and tunneling operations are defined by cyclical and repeated processes. The typical mining cycles for conventional operations include drill and cut phases, explosives loading and blasting, ground control and material loading and hauling. Figure 1.1 illustrates a typical mining cycle for underground exploitations.

Ground control processes can be sub-divided into two primary categories: artificial support and surface scaling. Artificial means for ground control support include mechanical or grout anchored bolts, screen or mesh, support plates, and expansion bolts. Scaling of excavation surfaces relies on power tools or chisel bars which are used to sound surfaces and remove potentially hazardous material loosened by the blast.

In large underground operations such as room and pillar mines, mechanical scaling represents a resource intensive and time consuming component of the excavation process. In some instances, mechanical scaling can represent as much as 50% of the mining cycle. Great efforts are therefore invested to optimize the quality and efficiency of mechanical scaling, while ensuring safe active workings.

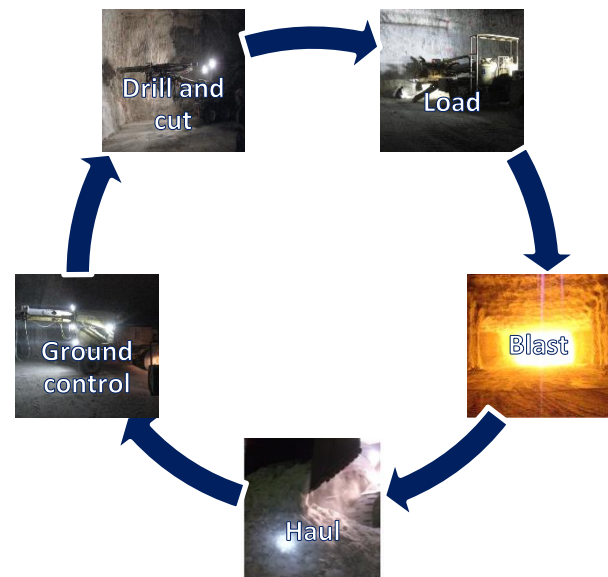


Figure 1.1: Typical operation cycle for large scale underground mining processes.

Mechanical scaling in underground excavations is intended to remove rocks that have been loosened by blasting vibrations and structural relief. The process plays a key role in mitigating roof fall hazards and must be performed systematically after each blasting event. Scaling can be greatly impeded by uneven surfaces that result from improper blast design or unaccounted for geological features. Rough surfaces will tend to cause accentuated wear and tear on mechanical scalers and increase the process time. The optimization of scaling requirements and conditions therefore present significant potential value.

Figure 1.2 presents the picture of a mechanical scaler used at the underground room and pillar salt mine Ojibway (K+S Windsor Salt), located in Windsor Ontario. The long and retractable boom is complemented by a pick used to scrape and remove rocks. Scaling strokes are performed at approximately 50 centimeter horizontal spacing intervals, and over the full vertical length from the roof to the floor.



Figure 1.2: Mechanical scaler cleaning the surface of a pillar after a blast at the Ojibway mine (Windsor, Ontario, Canada). The room is approximately 6 meters in height and 13 meters in width.

Surface quality assessment in the context of mechanical scaling primarily applies to two situations: the estimation of mechanical scaling efforts, and identification of ground control hazards. Assessing the quality of a surface for mechanical scaling purposes (both before and after) often relies on subjective visual assessments and provides very little quantitative and comparable information. Ghasemi et al (2012) presented an empirical guideline to assess roof fall risks in room and pillar coal mines. In their proposed risk model, surface quality is assessed based on roughness and size of outlying lumps.

The following article presents an evaluation approach for blasted and scaled surfaces based on the concept of surface roughness measured using LiDAR technology. The objective of the conducted work is to provide an objective, reproducible and partly automated methodology, to assess surface quality, to improve mechanical scaling efficiency and ground control of hazards. The proposed assessment also aims to provide a quantitative comparison basis for changes in the mining cycle that could potentially adversely affect

surface quality and scaling requirements (e.g. different type of explosives, new drilling pattern).

Three different surface assessment methods are proposed here based on surface roughness. The workflows have been developed using point cloud surveys obtained in a room and pillar salt mine located in Nova Scotia, Canada. The assessment methods are subsequently tested on an open-source point cloud of an underground hard rock tunnel.

Underground terrestrial laser scanning (TLS) was used to obtain three-dimensional point clouds of the surfaces of interest. Laser scanning has gained widespread popularity in the field of geological engineering during the last two decades. Researchers have developed processing tools to help engineering tasks such as the prediction of rock slope failure (Lato, et al., 2009; Kromer, et al., 2015), and automated identification and characterization of rock mass discontinuities (Lato, et al., 2009; Vögue, et al., 2013; Vazaio, et al., 2017). Fekete et al. (2010) listed a concise summary of various applications for LiDAR technology in conventional drill and blast tunneling operations. Other authors have used point clouds collected from LiDAR to characterize blasting conditions (Aubertin, et al., 2017; Aubertin, et al., 2018) and the resulting muckpile fragmentation (Campbell & Thurley, 2017).

2 SITE DESCRIPTIONS

2.1 Pugwash mine

The Pugwash mine, Nova Scotia, Canada, is operated by the Canadian mining company K+S Windsor Salt. Rock salt is extracted from the mine at a depth of approximately 1300 feet. Rooms of 55 feet wide by 60 feet high are excavated by two successive horizontal passes of 30 feet high. Conventional drilling and blasting is used to break the rocks. Mechanical and hand scaling is performed following the haulage of the broken rock to ensure safe ground control conditions in active workings. Little to no roof support is installed in the main workings except at critical locations where periodic rework is considered impossible.

Recent work on drilling and blasting practices at the Pugwash mine emphasized the need to quantify scaling requirements before it takes place, and mechanical scaling quality once it is performed. Two different point cloud sets from Pugwash were used and processed for the present work. Both were obtained using a FARO Focus X-130 (FARO Technologies Incorporation, 2014) at its 1/8th resolution setting, achieving 13 millimeters spacing per 10 meters radial distance from the scanner location. Settings also included repeatability (quality setting) with three measurements averaged for every point.

The first scan was collected from an unscaled and recently blasted location. The second scan was collected at a location recently scaled mechanically and manually.

This second point cloud is meant to serve as a point of reference for scaling quality.

2.2 Open source tunnel data set

A third point cloud set was obtained from the Rockbench open-access data-set (Lato, et al., 2013). The scan set is from an underground tunnel, under construction, located in Oslo, Norway. A FARO Photon 120 was used to survey the location. Point spacing is less than 1 centimeter for the section of interest. The tunnel point cloud was obtained from two different scan positions, relatively close to the face and at the same stage of development. Positioning of the scans was performed using FARO SCENE software (FARO, 2016). Positioning and registration of the scans were performed using the Cloud Compare software and its built-in registration algorithm.

The captured portion of the tunnel is over one hundred meters in length. Only the main active face was used as the relevant portion of the point cloud. The face exhibits a horseshoe shape and spans approximately 13 meters in width.

3 METHODOLOGY

The following section describes the methodology used and algorithms adapted to process the point clouds of interest.

3.1 Roughness coefficients

For the present work, surface conditions are assessed using a coefficient of roughness (RC). Roughness is defined simplistically here as the distance of a point p to the best-fit plane for points located within a sphere of radius r around p .

The best-fitting plane P for the set of points X defined by a sphere of radius r around point p is defined by its normal vector \vec{n} using the following equation:

$$\vec{n} \cdot p_0 + d = 0 \quad [1]$$

Where $\vec{n} = \langle a, b, c \rangle$ and d is a distance constant. p_0 represents any point p which satisfies equation 1. A best fit plane from a set of points X can be derived from minimizing the squares of the residuals along the plane's axis with the shortest span (i.e. the smallest angular difference with the resulting normal). Cramer's rule is used to solve the resulting set of equations (Fienen, 2005).

The roughness coefficient RC (m) for the point p is defined as the distance from $p = [x, y, z]$ to the best-fitting plane P .

$$RC = \frac{(ax+by+cz)}{a^2+b^2+c^2} \quad [2]$$

It is to be noted for this work that computations of roughness coefficient were limited to uninterrupted parallel surfaces. Two perpendicular surfaces (e.g. the roof and a wall) would need to be assessed separately.

From the definition of roughness outlined above, it can be seen that any analysis performed requires the arbitrary assignment of a radius r of measurements. The implications of the radius of measurements and some rationale behind parameter selection are discussed in Section 4.

3.2 Definitions of surface conditions

The conditions of a surface before and after mechanical scaling is reflected primarily by the mechanical effort (and resulting wear and tear) expended by the scaling machine, and the remaining lumps of rocks on the surface that can be considered as potential rock fall hazards. In the case of mechanical effort, the relevant dimension relates to the size of mechanical tools used to scale the surface. The chisel edge of a standard 1.2 meter (4 feet) aluminum scaling bar (illustrated in Figure 3.1) will detect significantly smaller roughness features on a surface, as opposed to a mechanical scaling pick as shown in Figure 1.2.

Mark and Iannacchione (2000) reviewed available data related to injuries caused in underground mines due to roof falls in United States. The study suggested that skin failure, defined by 0.6 meters (2 feet) pieces of rock, represents more than 95% of the injuries caused by roof and rib pillar failures. This value is used in future analysis when considering scale instability potential.



Figure 3.1: Pictures of a scaling bar, typically used to perform secondary scaling and sound surfaces for voids.

4 RESULTS AND ANALYSIS

4.1 Distance of interest

The roughness coefficient RC defined above is greatly influenced by the considered radius of measurement r (m). A small measurement radius will describe localised roughness created by surface asperities. A large radius of measurement will quantify point distances and relative roughness with respect to a plane closely resembling the overall surface.

Figure 4.1 shows point clouds from the Pugwash mine for a mechanically scaled surface. The point cloud is colored according to a scalar field for RC values as defined in the previous section. The figure shows RC computed for the same surface point cloud using three different r values. The three distributions for RC are summarized by the mean, RC_μ (m), standard deviation, RC_σ (m) and maximum value RC_{max} (m).

Figure 4.2 shows RC_μ , RC_σ , and RC_{max} , based on the considered r values for the scaled surface at Pugwash. It can be observed that the relevant statistical values representing the value of RC increases over the considered range of radius of movement. It can be understood, conceptually, that the theoretical maximum RC value will be achieved for the dimension r of the excavation. In the light of Figure 4., the question remains as to what radius of measurement should be used to provide consistent surface quality assessment.

Figure 4.1 presents the ratio of the maximum to mean roughness coefficient (RC_{max}/RC_μ) with respect to the radius of measurement r for the Pugwash scaled surface. It can be noted from Figure 4.1 that the influence of the radius of measurement on the ratio RC_{max}/RC_μ is inversely proportional, and eventually plateaus.

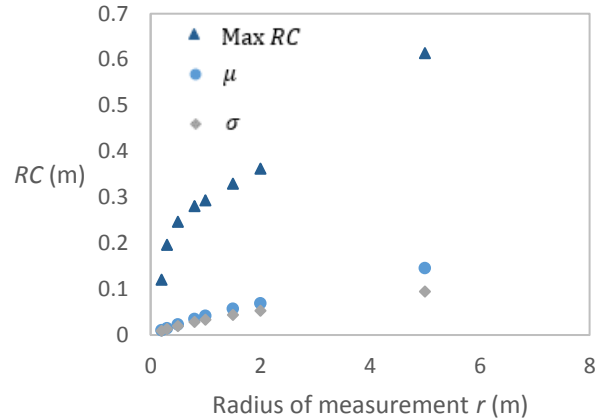


Figure 4.2: Mean, standard deviation and maximum value for the roughness coefficient based on considered radius of measurement

RC_{max}/RC_μ increases as the measurement radius r increases, with a fairly distinct inflection in the curve. It seemingly reaches a plateau after which r no longer seems to influence the considered ratio.

The abrupt decrease in RC_{max}/RC_μ observed for an increasing radius of measurement presents a useful indicator of the scale to be considered. As the radius of measurement for the coefficient of roughness increases, the best-fit plane within the considered sphere of radius r closely describes the overall surface considered. In Figure 4.1, the largest r considered is 17 meters, approximately the largest dimension for the surface, obtained from its diagonal. A radius of measurement of 25-30% of the surface span (between 4 and 5 meters) appears to represent a tipping point between localized RC associated with asperities and global roughness corresponding to the overall surface, in this case.

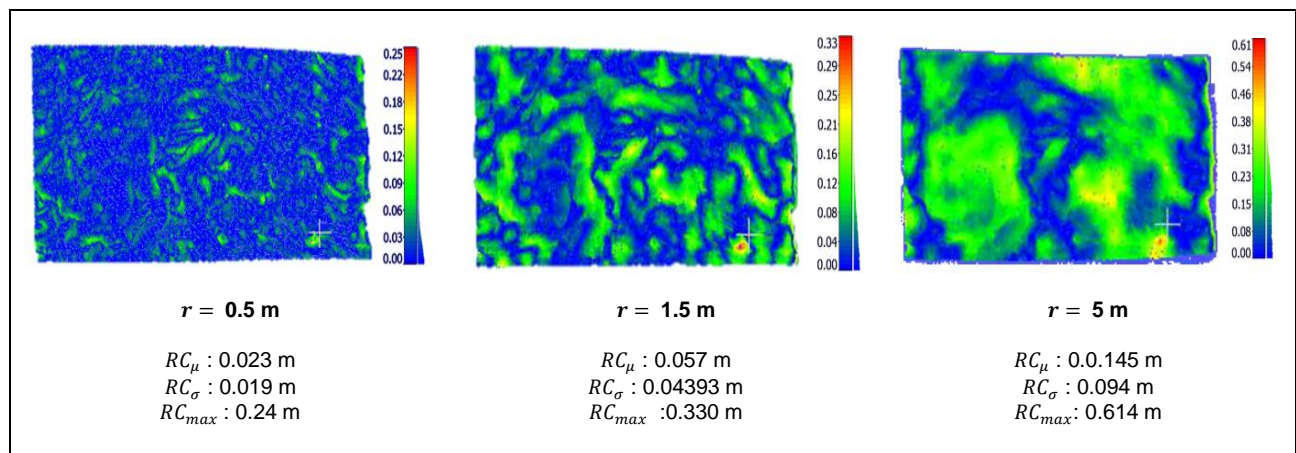


Figure 4.1: Point cloud of the scaled surface at the Pugwash mine. Point cloud scale factor and key indicators for surface roughness are based on measurement radius of 0.5, 1.5 and 5 meters. Face dimension is 18 meters wide by 9 meters high. Color scale is for RC (m) value with origin at 0

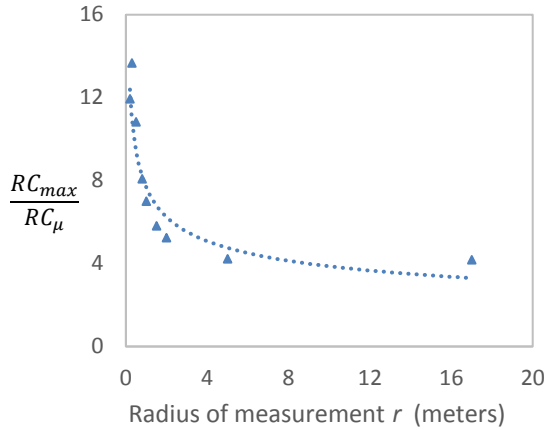


Figure 4.1: Ratio of maximum to mean roughness coefficient with respect to the radius of measurement, for Pugwash mine data

The point of inflection on the curve presents a repeatable way to describe surface roughness. It effectively quantifies the scale of asperities with respect to the overall surface. The smaller the radius of measurement at the tipping point, the smaller the size of the localized asperities relative to the overall surface morphology. A reduction in this point indicates an improvement in the scaling quality. The ratio of mean to maximum RC can be normalized by the surface span to provide a comparable term to quantify and compare roughness.

Figure 4.2 presents the relationship between RC_{max} / RC_{μ} , and the radius of measurement r normalized by the surface's span. The Pugwash scaled surface is compared to the Pugwash unscaled surface, and the open source tunnel.

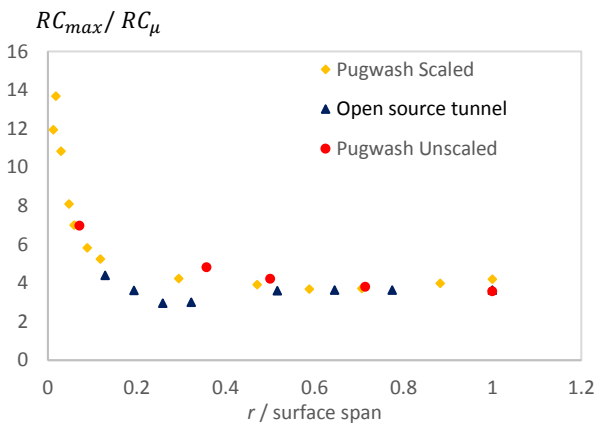


Figure 4.2: Maximum to mean roughness coefficients with respect to the radius of measurement for the Pugwash scaled and unscaled surfaces and the open source tunnel point cloud.

It can be observed that the Pugwash scaled, the open source tunnel, and the Pugwash unscaled face respectively transition from a local to global roughness measurement at a r value equivalent to 0.3, 0.5, 0.85 (normalized by the surface span).

4.2 Mechanical scaling effort assessment

The assessment of mechanical scaling requirements must be related to the machinery used to perform the task. The mechanical scaler considered for the Pugwash mine is assumed to have a scaling motion range of approximately 2 meters per pass. Critical lumps adversely affecting the mechanical scaling process, because they are difficult to remove, are defined here as 10 centimeters. based on site experience at the mine.

Figure 4.3 below shows the unscaled surface at Pugwash with roughness coefficient computed for a measurement radius of 1 meter (2 meters diameter, i.e. approximately the scaling range of motion). The scalar field is limited to red for RC values above 10 centimeters, and blue for the rest. A cross-section of the surface is illustrated on the right side of the figure to highlight the different color representations.

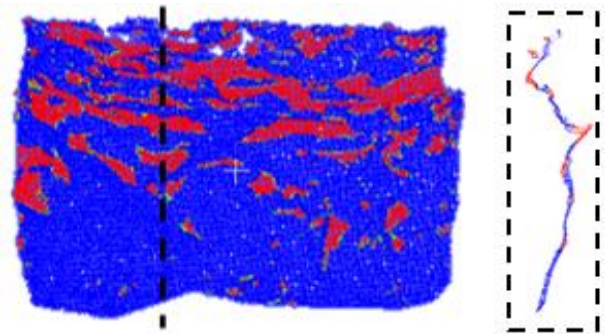


Figure 4.3: Pugwash unscaled surface point cloud with roughness coefficient scalar field based on a one-meter measurement radius. Color scheme adapted to showcase roughness above 10 centimeters in red, and the remaining portion in blue.

The mechanical scaling assessment performed for the Pugwash mine relies on the definition of a scaling effort rating to provide an objective and quantifiable perspective. The effort rating is defined as the fraction (%) of the surface below the identified threshold: in this case 10 cm. A higher rating therefore indicates to a surface that will cause less wear and tear on the scaling equipment used.

Table 4.1 presents the effort rating for the three different excavations considered as part of this work, and for 2 meters range of motion (i.e. 1-meter radius of measurement).

Table 4.1: Mechanical scaling effort rating for the point cloud surfaces considered.

Point cloud	Effort rating (%)
Pugwash unscaled surface	72.5
Pugwash scaled surface	94
Open source tunnel	68.1

It is important to note that the dimensions of the mechanical scaling device and its relevant critical dimension are site-specific. The fraction of the surface above the defined threshold provides a measure of surface quality that can be used to compare surfaces, defined here as the mechanical scaling effort rating.

The analysis applied to the open source tunnel is based on the Pugwash conditions and does not account for the machinery used or the geological settings. It is impossible to surmise any site specific conditions for the open source tunnel, other than inferring that a similar mechanical scaling equipment used at Pugwash would incur increased wear and tear on the tool at the tunnel site.

4.3 Scale instability potential

Scale instability potential is defined here based on Mark and Iannacchione's (2000) definition of a critical size of 60 cm lumps. In this analysis, 30 centimeters is selected as a scalar field threshold for the roughness coefficient (i.e. half block protruding). In contrast to the mechanical scaling effort, scale instability potential is defined as an absolute assessment, assuming that any identified lumps must be removed when identified.

Figure 4.4 shows the point cloud for Pugwash's scaled surface with a binary scalar field showcasing sections above the defined threshold value.

4.3.1 Comparison sites

Figure 4.5 presents the open source tunnel point cloud with the same applied algorithm. The open tunnel point cloud was analysed here to showcase the potential to reproduce the methodology and exercise.

It is noted that no further assessment of the face condition is made by the author of this paper. Any actual hazard related assessment would require knowledge of site specific conditions such as geotechnical parameters and geological structures. Authors of this paper refrain from making any hazard related assumptions or recommendations.

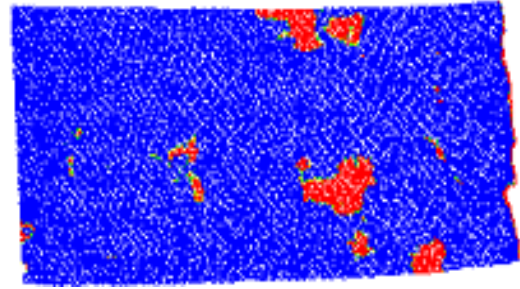


Figure 4.4: Scale instability potential for Pugwash scaled surface

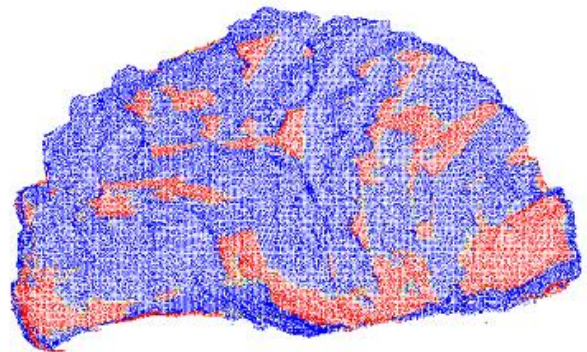


Figure 4.5: Rock fall hazard assessment for the open source tunnel point cloud.

5 DISCUSSIONS AND CONCLUSION

Mechanical scaling represents a major component of the mining cycle in underground room and pillar mines. An attempt was made in this work to quantify and assess objectively the quality of mechanical scaling and the expected efforts on the machine based on surface roughness. Three different approaches were proposed to systematically assess surface quality from point clouds. These methods can be summarized as follows:

1. *Roughness scale transition*: the radius of measurement for surface roughness where the surface's overall orientation takes precedence over local asperities. A smaller transitional radius of measurement relates to a smoother surface.
2. *Mechanical scaling quality rating*: fraction of the surface below a mechanical impedance threshold. The threshold depends on the equipment used for scaling. A surface with high rating relates to less wear and tear on the machine.
3. *Scale instability potential*: systematic and objective perspective to determine zones that may require additional consideration based on predetermined empirical dimension (regulatory or site specific).

The three methods summarized above were applied to an open source point cloud of an underground tunnel. The tunnel subjected itself well to the implemented methodology, emphasizing the capacity to replicate the process on point clouds.

5.1 Limitations and future work

It is noted here that the methods above reflect systematic assessment methodology based on empirical evidence (e.g. size of protruding lump, dimensions of mechanical scaling equipment). Calibration based on equipment and operational conditions must be performed to identify appropriate radius of measurement.

Additional work must be performed to identify relevant dimensions for the respective thresholds used in methods 2 and 3. These represent inherent variables in the defined functions and will require additional investigation to properly quantify their influence and provide meaningful data.

The present work introduced algorithms providing the means to assess mechanical scaling conditions and requirements based on site specific features and empirical evidence. It is emphasized that any actual recommendations towards scaling improvements, mining method changes, and hazard detection requires an in-depth knowledge and understanding of the geological and geotechnical characterization of the deposit considered.

6 ACKNOWLEDGEMENTS

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