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Comparative analysis of fragmentation sizes in LKAB's Kiirunavaara (Konsuln) mine

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ABSTRACT

Sublevel caving (SLC) is a widely used underground mass mining method, known for its efficiency and economic viability. However, like all caving methods, it requires specific geological conditions of the hanging wall, ore, and foot wall. A key result parameter is fragmentation. Fragmentation of the material coming from the draw point during mucking is dependent on the blasting and of the material in the caved zone and has a direct impact on operational costs, as it can affect ore recovery, increase transportation costs, and the subsequent processing of the ore. The presence of oversized rock fragments (boulders) will also delay operations, as extra time is required to handle the boulders. This study presents a comparative analysis of the fragmentation variations in different production levels in LKAB's Kiirunavaara Konsuln mine. The data consist of images of the trucks transporting the mucked material coming from blasted rings on the main haulage ramp. The images were filtered and the payload material in the trucks were categorized using a Quick Rating System (QRS) into one of five fragmentation classes (very fine, fine, medium, coarse, very coarse). A method to count the number of boulders in the trucks is under development, further method development as well as the calibration phase will be performed in future work. The results highlight the size variations in the material from the mine during a nine-month period. A method to measure the fragmentation and the number of boulders in an effective and reliable way would help in the process of improvement of the mining operation.

1 INTRODUCTION

Sublevel caving (SLC) is a large-scale mining method widely used in underground operations because of its high degree of mechanization, flexibility, simple mining structure, high mining rate, as well as, being considered as a safe method. (Cao et al., 2016; Zhao & Zhu, 2020). However, it requires specific geometrical conditions, including a steep dip and large vertical dimensions (Hamrin, 1982). The ore is drilled in a fan-shaped pattern and blasted to break it down into smaller fragments (Janelid & Kvapil, 1966). The fragmented ore caves due to stress and gravity (Hamrin, 1982; Brunton et al., 2010) and is excavated through draw points below the fans.

The process of rock blasting in SLC is complex, with diverging holes and inbuilt variations in specific charges that influence several factors. One factor is the fragment size (Hunter et al., 1990; Allen et al., 1999; Power, 2004; Brunton et al., 2010), that has a significant impact on the underground production and productivity. Danielsson et al. (2018) showed that in a Swedish SLC mine, a mid-range particle size distribution with a low amount of fine material provided the highest loading efficiency. Fine compacted material on the other hand, resulted in difficulties penetrating the muck pile. This increased the loading time and often resulted in material flowing closer to the blast plane, i.e., shallow draw (Power, 2004; Wimmer, 2012; Wimmer et al., 2015; Danielsson et al., 2018). In contrast, coarse material and boulders often cause gravity flow disturbances including blockages or arching. For SLC, the inherent increasing frequency of boulders with increasing excavation rate and its productivity consequences was demonstrated by Manzoor et al. (2023). Past investigations (Aler et al., 1996; Campbell & Thurley, 2017, Paluszny & Zimmerman, 2017; Amoah-Kyei et al, 2018) have found that in order to control and optimize the mining process it is important to evaluate the fragmentation.

A number of different principles and methods have been used to evaluate fragmentation. Paluszny and Zimmerman (2017) discussed several numerical modelling methods, including the finite element method (FEM), the discrete element method (DEM), and the extended finite element method (XFEM). Yi et al. (2017) drew on these numerical methods and used an LS-DYNA code to evaluate fragmentation in a SLC mine. Thurley (2013), Wimmer et al. (2015), and Campbell and Thurley (2017) implemented 3D imaging measurement as a method of fragmentation control.

Another method consists of visual estimates by counting the number of oversized fragments or by Quick Rating System (QRS) that is an observational 2D method where the fragmentation is compared with a set of pre-defined fragmentation images (Aler et al., 1996; Danielsson et al., 2017; Manzoor et al., 2021). Studies by Danielsson et al. (2017) and Manzoor et al. (2022) supported the use of QRS and concluded that the technique can be a reliable and less time-consuming method for large datasets, when implemented correctly.

However, QRS may be affected by the experience and judgement of the person making the assessment (Babaeian et al., 2019). Nevertheless, in Wimmer et al.'s (2015) study, QRS showed similar results when different people oversaw the classification, and overall results were similar to those obtained by more advanced 3D image analysis. Disadvantages of using 2D images for fragmentation control include distortion of the images and particle delineation errors, as defined by Thurley et al. (2015)

The purpose of this study is to present an overview of the fragmentation of the material coming from an SLC mine. QRS is selected for fragmentation classification due to the large volume of data to be processed. The purpose is also to test the possibility of using the images from QRS for boulder identification and counting.

2 METHODOLOGY

This research is based on a literature review, data acquisition from filming the mine trucks used for transportation of the mucked material, data processing, including data filtering and analysis, and fragmentation classification using QRS. The data in the form of raw images was retrieved from LKAB's Konsuln mine in Kiruna. The images were taken in 2023 and correspond to trucks carrying the fragmented material coming from the mine. The steps taken to carry out the fragmentation study are shown in Figure 1 and are described in detail in the following sections.

Figure 1 Research steps.

2.1 Case Study

Konsuln is located south of the Kiirunavaara ore body (LKAB, 2023a) and became a test mine in 2018 (SUM, 2023). Even though the mine serves as a test mine, it is also used for production and contributes between 1.8 and 2.4 million tons/year to the overall ore production at LKAB's mine operation in Kiruna. Figure 2 shows the mine layout.

The mine has currently four production levels: 436, 486, 536, and 565. Trucks haul the ore from the production areas to the surface, along the main ramp.

Figure 2 Konsuln Mine layout (modified from LKAB, 2023b).

2.2 Test Set-Up

To capture the fragmentation of the mucked material from the draw points, a camera (Hikvision, model iDS-2CD7A46G0-IZHSY) was mounted in the roof of the main ramp. A schematic layout of the camera set-up is shown in Figure 3. The location was chosen, as it was a section of the ramp that allowed access to the computer installation on the site without disrupting the traffic of the trucks coming to the surface. To improve the quality of the video, additional lights were installed beside the camera (Figure 3).

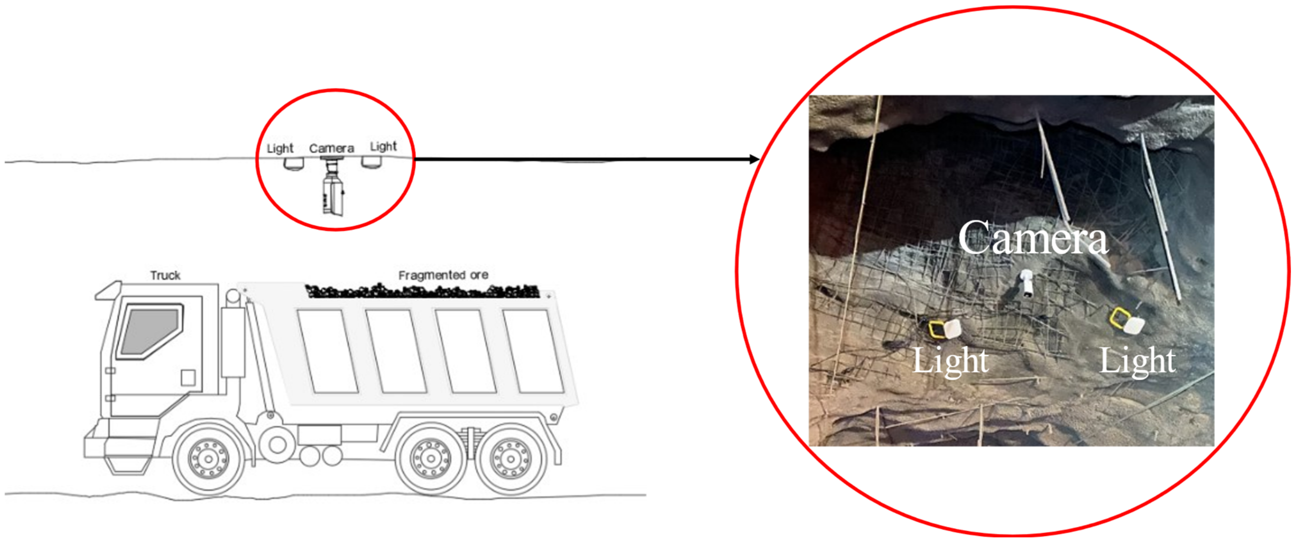

Figure 3 Schematic layout and on-site installation.

A short video of the truck bed was filmed for every passing truck. The video was then converted into images using the software XProtect® SmartView from Milestone System and downloaded and stored on a local computer.

Due to the long monitoring period, a Wi-Fi repeater, providing internet connection, was installed in the area for the camera set up. This provided easy access to the locally stored data and also allowed access to the camera software at all times allowing modification of video formatting specifications, if needed. TeamViewer software was used to access the on-site computer to download filtered images for fragmentation classification.

The camera recorded the trucks when they were leaving the mine. Every truck was tagged using a radio frequency identification (RFID) tag set on the windshield of the truck (see Figure 4). When a truck passed the area where the camera was mounted, the RFID triggered a sensor. The sensor collected the unique identification number of the truck, as well as the date and time for the truck passage. The time and truck number were logged using a TagMaster system. Due to the limited storage capacity of the TagMaster, the gathered information was downloaded every fourth day.

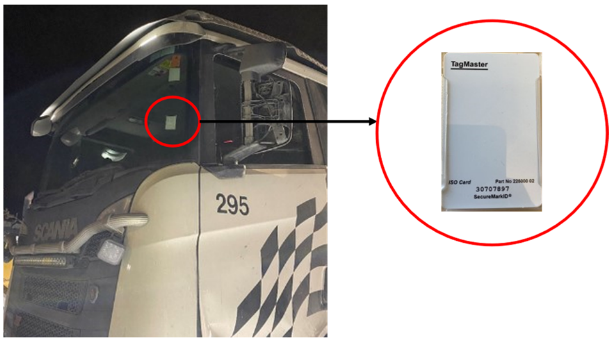

Figure 4 RFID tag mounted on a truck.

For back-up reasons, the truck number was also installed on the roof of the truck's cabin. These numbers helped when correlating the information from the RFID with what was visible in the video. An example of the number affixed to the truck's roof is shown in Figure 5. The fragmentation class for each truck's load was then connected to the truck's ID number.

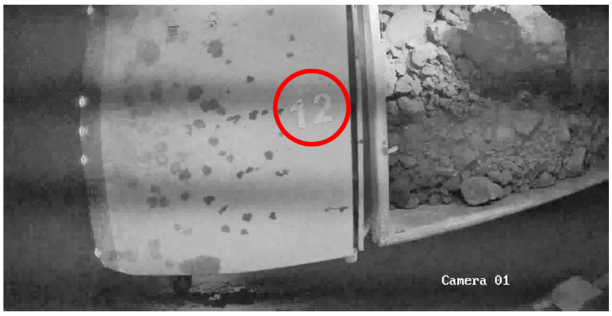

Figure 5 Truck number mounted on the roof of the truck.

2.3 Data Collection and Filtration

Images of the trucks carrying the fragmented material from the mine to the surface were taken over a period of nine months in 2023. The installed camera recorded a video every time a truck with an identity card was passing. Therefore, all trucks with an identity card passing the camera, both the filled trucks and the empty trucks, were included in the recordings.

Every week, the data was collected, and the best images of the truck's box with the material were selected from each video for fragmentation classification. Images of empty trucks or other types of vehicles were discarded. Filtering was done manually, selecting each individual image.

Several issues were encountered during the data collection process resulting in significantly fewer data for some months. In some cases, power shortages disconnected the system, and the system had to be restarted to regain functionality. In the sixth month of the study, water came in contact with the Wi-Fi repeater, and access to the system was lost for around three weeks. In some cases, the system had pre-planned restarts that went unnoticed, leading to loss of data for some days. To minimize system downtime, the connection to the system was checked twice a day. If the system was down, measures were taken to get it going again. Another known reason for a low number of trucks in some months was pre-planned low production due to a vacation period.

In total, over a million images were filtered, but after discarding images with nothing on them or images showing empty trucks or other vehicles passing, 25,253 images remained for analysis. An example of a truck's footage is shown in Figure 6. The frame showing most of the truck's box was used for fragmentation classification, and the rest of the frames were discarded. In this sequence of frames, the one used for fragmentation classification was frame 4. Frames 1-3 and 5-6 were discarded because the box was only partially visible, and the classification might not be entirely correct if those frames are used.

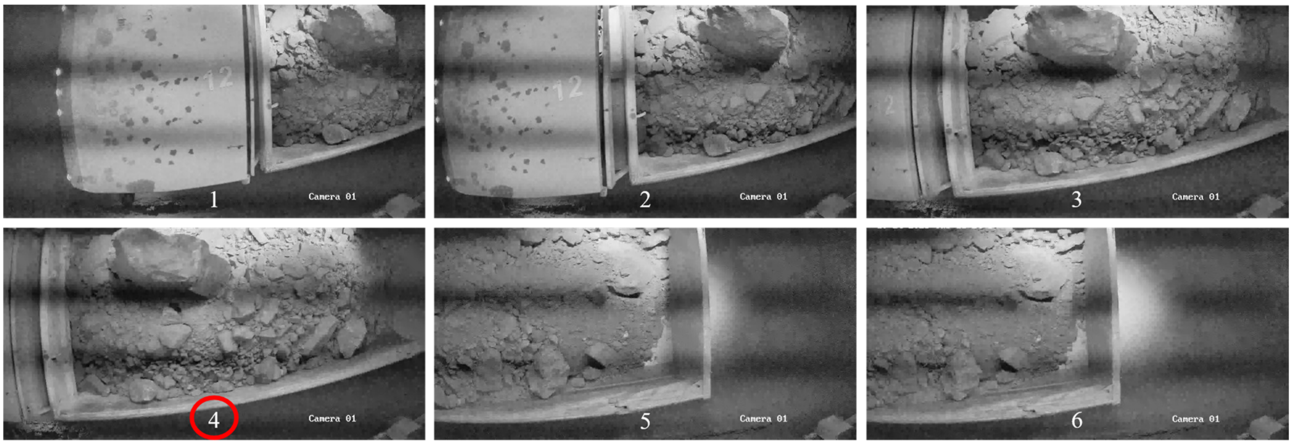

Figure 6 Sequence of truck captured by the camera.

Given the conditions in the mine, which include poor lighting, a confined environment and the presence of dust, the quality of the images captured was less than ideal. One more thing affecting the quality was the “fish-eye” effect that was produced due to the fact that the distance between the camera and the passing trucks was small (around 2 metres). This created a problem in the quality of the images, giving the box a curvature and increasing the distortion on the material inside the box. Although extra lights were installed, the area for the set-up could not be fully illuminated creating some shadows in the images. These shadows can be seen in the form of dark stripes in most of the images.

2.4 Data Analysis using QRS

For the QRS analysis, the image analysis software package Split Desktop was used to identify the median fragment size (X_{50}) of the reference class images (Figure 7). All collected images were then sorted by week and then compared with the reference images to classify the fragmented payload into one of five fragmentation classes.

Using QRS, which is a comparative visual method for fragmentation classification, means that the issues regarding the quality of the picture did not affect the classification itself. Since the classification was done manually, problems such as the curvature of the box and particle delineation were of little consequence. However, it must be stated that problems such as bad lightning and blurriness in some pictures did pose some issues. For these cases the judgment of the individual behind the analysis was considered. Overall, the classification was done with caution to minimize the misclassification of the material.

The classes used in this study were very fine, fine, medium, coarse, and very coarse, and are referred to as Classes 1, 2, 3, 4, and 5, respectively. The range of sizes and X_{50} used for this study are shown in Figure 7.

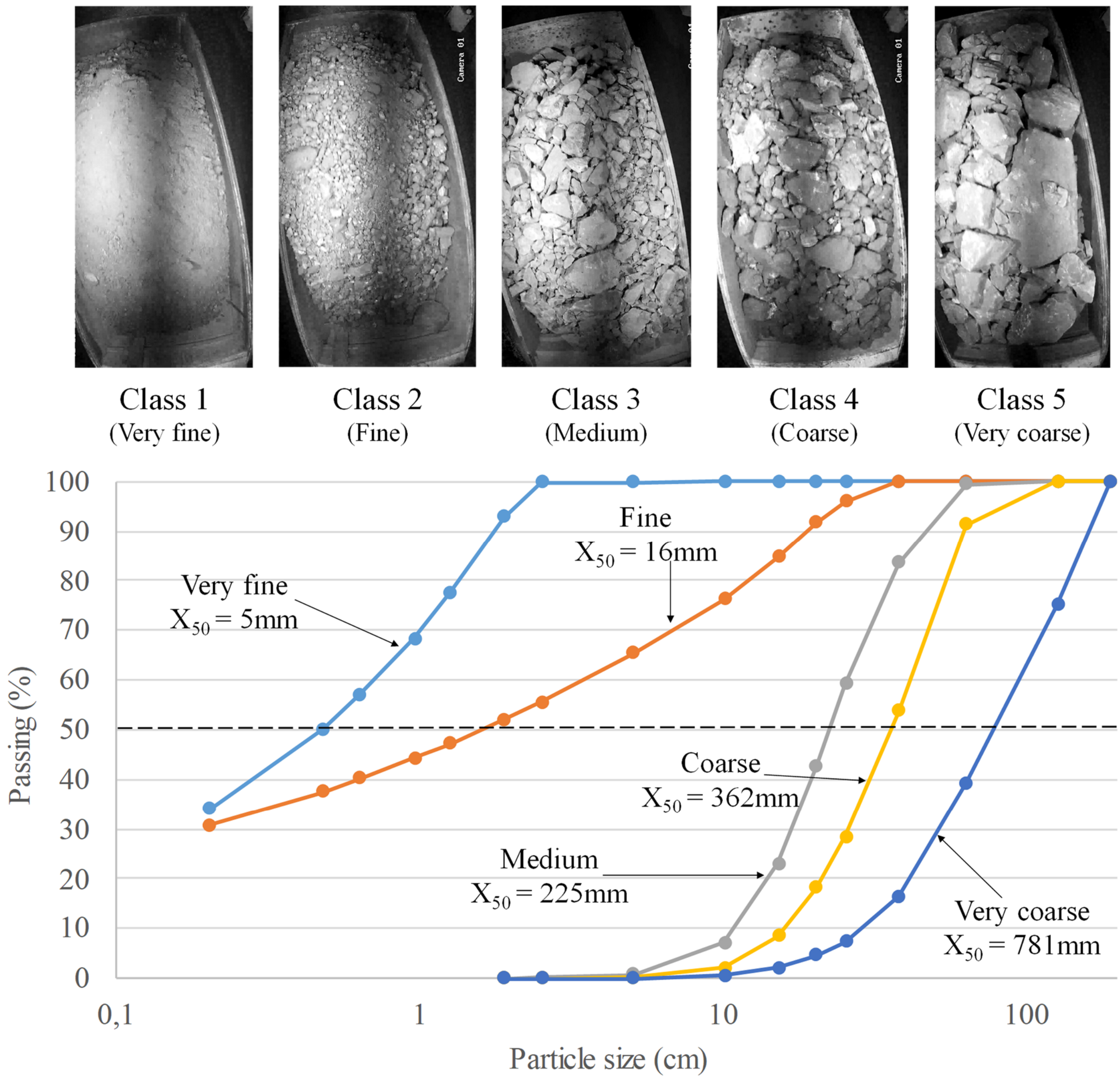

Figure 7 Fragmentation analysis using Split-Desktop and reference images.

2.5 Boulder Identification

Boulders are often a byproduct of the blasting of the production rings but can also origin from the upper caved zone or from the hanging wall. Due to this, they can be found alongside the material belonging to any of the fragmentation classes 1 to 5. In the Kirunavaara mine a boulder is defined as a block that exceeds the 1 metre size limit in any direction. In Konsuln the ore is loaded from the draw points directly to the trucks that haul the material to the surface, a strict limit size of 1m is therefore not required. Since boulders create problems further down the production chain, it is however useful to identify severe boulder problems.

In order to be able to identify and count the number of boulders an evaluation method is under development.

For testing the method of using the images from QRS for boulder count, data from one week was analysed. The number of boulders within the size limit of 1m, 1.3m and 1.5m were counted and compared. It was decided, based on the results, that for the developing and testing this method, a boulder was defined as any fragment that exceeded 1.3 metres in any direction (see Figure 8). For a test period of two months, all boulders visible in the images were identified and counted to see if this method could be used in a reliable way. The use of QRS allowed for a boulder count that could be carried out at the same time as the fragmentation classification.

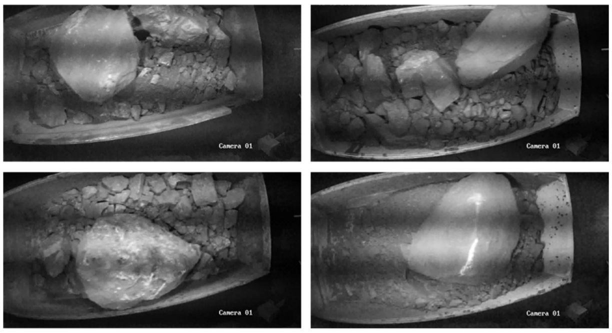

Figure 8 Example of boulder on truck's box.

Once an oversize fragment was identified, there was a need to determine whether it exceeded the size range previously settled. The earlier mentioned issues with distortion of the images and particle delineation errors when using 2D images were especially difficult to deal with when carrying the boulder count. There is a risk that the distortion of the images affects the size of what is shown in the image creating an incertitude when identifying a boulder. To counter this problem when implementing QRS for boulders, an additional set of scales were determined. This scaling system adjusted the size of the truck's box in different sections, see Figure 9.

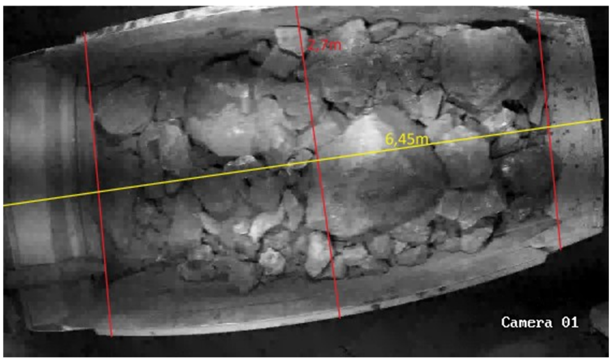

Figure 9 Scale system used for boulder counting.

Since the truck's correct length (6.45 m) and width (2.7 m) were known, the correct size of the boulder could be calculated based on the position of the boulder in the truck's box. As this is still an ongoing research, the future work will focus on calibrating the method to enhance its efficacy in determining the number of boulders using the available images.

3 BOULDER COUNT TEST-TRIAL

During the two-month period that the boulder count method was tested, the results show that it can be viable to use the same images used in QRS for boulder identification. However, since the calibration of the method for boulder counting is yet to be done, no clear conclusions were made regarding the total number of boulders during the test period. A refining and calibration of the method will be carried out as a future step of this research.

The results of the trial are presented as the percentage of trucks carrying boulders out of the total number of trucks for each fragmentation class. In Figure 10, the boulder distribution for both months can be seen. For month 1, a total of 1699 trucks were analysed, while for month 2, the number of trucks was 3394. As previously mentioned, a boulder was here defined as any fragment bigger than 1.3 metres in any direction.

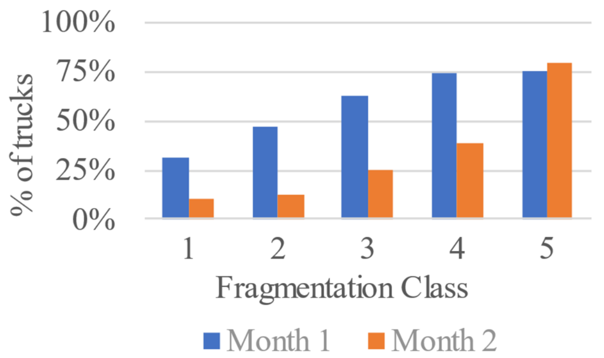

Figure 10 Percentage of trucks by fragmentation class with boulders.

During the trial, the percentages of trucks carrying boulders were high, indicating a possible number of boulders present during the trial period. The trucks could contain more than one boulder each. In total, during month 2, the percentage of trucks carrying boulders were lower than month 1. However, the trend is similar with more boulders present in the coarser classes.

It is important to notice that the origin of boulders is uncertain and that boulders can be found mixed in all fragmentation classes. With the limited information on what area in the mine the material is coming from, it is not possible to know if the presence of boulders is a direct result of the dilution from the caved zone or blasting issues. Therefore, the difference in percentage for both months could be explained by analysing the production levels from which the material comes from. Identifying issues with the blasting and drilling operations as well as differences in the geology of the production levels and the number of boulders present in the cave is vital to understand the formation of boulders.

It must also be mentioned that if the size limits for the boulders were changed i.e. from 1.3 m to 1 m, the percentages would increase heavily. The opposite would occur if the size limit were to be increased to i.e. 1.5 m. Therefore, the calibration of the method for boulder counting is necessary for an accurate boulder representation.

4 RESULTS AND DISCUSSION

4.1 Fragmentation Distribution

In general, for a mining operation to work effectively, the size of the material coming from the production levels should not be too big or too small. Both the very fine and the very coarse material create problems during loading, through e.g. increased cycle time and a possible increase in operational costs. In addition, boulders require secondary breakage and causes increased wear and tear on the equipment.

In Figure 11, the monthly fragmentation distribution of all classified data in percentage of the total number of trucks can be seen. The distribution shows that the mucked material in Konsuln, for the most part, has an operational size that won’t delay or halt the operation. The fragmentation mostly fluctuates between Class 2 and Class 4. Class 3 is more prominent, possibly indicating normal operation, as this fragmentation class does not have the issues related to finer or coarser material.

From the figure it can be seen that for six of the months of the study, Class 2 and Class 3 were observed more frequently. These two sizes are usually the most optimal for the mining operation, particularly material from Class 3 that is not considered too big nor too small. Class 1 (very fine) is not very common, which is positive since this type of fragmentation size carries issues that can potentially increase the loading time as the muck pile becomes more difficult to penetrate (Danielsson et al.,2018).

Class 5 (very coarse) is also not as frequent, which could indicate that issues associated with the handling of bigger fragments might not represent a large problem. However, it must be emphasized that Class 5 alongside the rest of the fragmentation classes, usually contain boulders. Therefore, it would be valuable to be able to estimate the number of boulders in a reliable and effective way as a complement to the general fragmentation estimation.

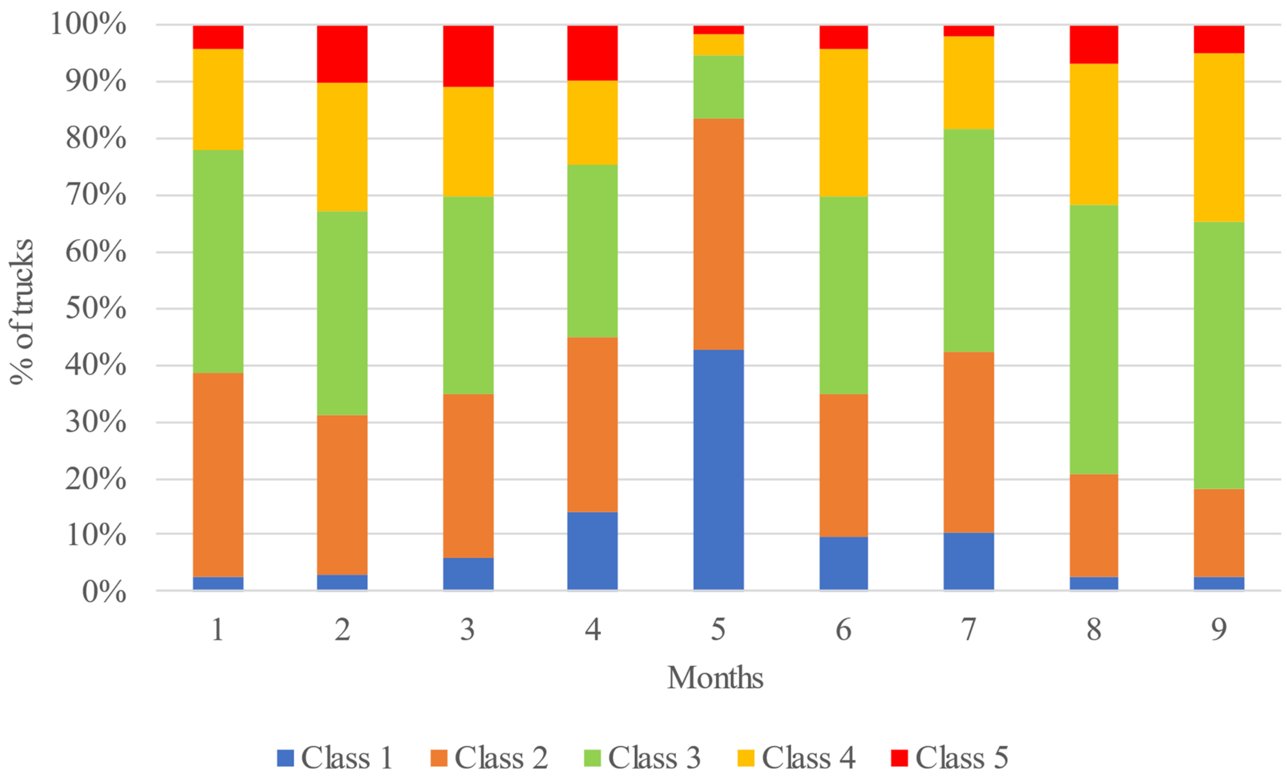

Figure 11 Fragmentation distribution per month (2023).

Although the fragmentation distribution is mostly relatively good, in month 5 the finer fragmentation classes (Class 1 and Class 2) were more frequent than the rest of the period, see Figure 12. This behaviour significantly deviates from both the previous and following months, but no clear explanation to this could be found.

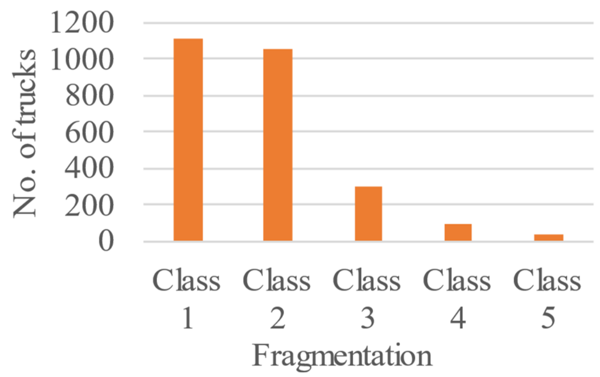

Figure 22 Fragmentation distribution for month 5 (2023).

Figures 13 and 14 show the fragmentation class of the material for month 6 and month 7. During these months, the distribution between the main classes was much more equal, suggesting that the drilling, charging and blasting operations were carried out well and the characteristics of the material were satisfactory. Similar fragmentation was observed throughout the rest of the months, where most of the trucks had material from Class 2 and 3. Although overall, the distribution was similar, during month 8 and month 9, there was an increase in Class 4 (coarse fragmentation) material while Class 2 was less common than in the other months. The reason behind this occurrence is not clear as of now. Some reasons behind this could be the variation in the quality of the material, or differences in the drilling, charging, and blasting processes. As mentioned previously, due to Class 3 being the most prominent fragmentation class observed, issues with the handling of the mucked material after it has been moved from the draw point might not affect production as much. Nonetheless, more information on months 5 and 9 would help for a better understanding of the reason for this behaviour. However, a good fragmentation distribution would minimize the problems down the production chain.

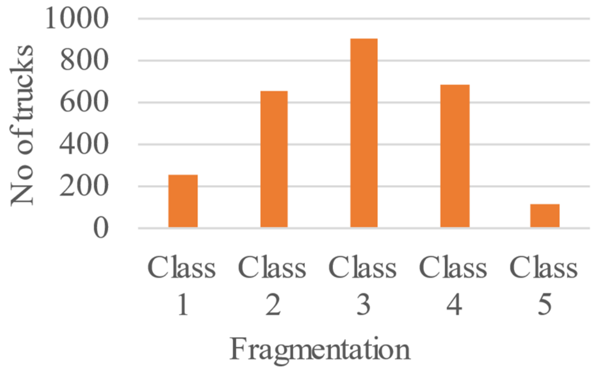

Figure 33 Fragmentation distribution for month 6 (2023).

Figure 44 Fragmentation distribution for month 7 (2023).

5 CONCLUSIONS

This study presented an overview of fragmentation measurements using QRS for large scale evaluation of the mined material from an SLC mine. Fragmentation classification using QRS allows for a big volume of data to be processed, being time efficient and yielding a broader picture of the state of the mined material. The following conclusions are drawn based on the results of the study:

- Class 1 (very fine fragmentation, X_{50} = 5mm), was not frequently observed during most of the analysis. However, during one particular month most of the material was from this class. Having a very fine material carries its own issues, as the material compacts and may requiring more time for digging and loading operations.
- The results of the fragmentation classification showed a good overall fragmentation distribution. For most of the studied months, Class 3 (medium fragmentation, X_{50} = 225mm) and Class 2 (fine fragmentation, X_{50} = 16mm) were more prominent.
- Fragmentation Class 5 (very coarse fragmentation, X_{50} = 781mm), was less common than Class 4 (coarse fragmentation, X_{50} = 362mm).
- The method for counting boulders using the images from QRS looks promising, but calibration of the method is required to get confidence in the results. Success in this step could open the possibility for implementation on a larger scale.
- During the two-month period in which the method for boulder counting was tested, there was a significant number of boulders estimated. Specifically, during the first month, Class 4 and 5 had more than 70% of the trucks with boulders on them.
- A method to measure the fragmentation and the number of boulders in an effective and reliable way would help in the process of improvement of the mining operation.

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