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Rock fragmentation measurements in sublevel caving: field tests at LKAB's Malmberget mine

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Abstract

Ground vibrations from blasting are one of the main challenges faced by mines located near populated areas. To confront this challenge, Luossavaara-Kiirunavaara Aktiebolag's Malmberget underground iron ore mine in Sweden tested a change in blast design. Specifically, it tested production holes with smaller diameter to decrease the explosive detonated per delay and thereby lower the ground vibrations. However, smaller holes normally increase hole deviation and may also influence the chargeability of the holes, both of which have a negative effect on fragmentation. Therefore, a detailed evaluation was required before a final decision could be made. To evaluate the fragmentation, field tests were carried out in two drifts of an orebody in the mine. Cameras were mounted in both drifts to record the fragmentation in every loaded bucket. The recording was configured to start by a motion detection parameter; consequently, every movement underneath the cameras was captured. The recording process continued for over a year and resulted in more than 15,000 videos. To analyse such an enormous data for fragmentation, an internally developed quick rating system (QRS) was used to evaluate a total of 7,258 loaded buckets. Blasted rock in the load–haul–dump buckets was classified as fine, medium, coarse, or oversize based on the median fragment size (X_{50}). This paper explains the experimental setup of the test and the analysis procedures. The test results showed that smaller diameter boreholes tend to reduce the median fragment size slightly, and therefore favour the reduction of borehole diameter to deal with the ground vibration problem. The influence of borehole deviation and chargeability was not specifically investigated in this test and need further research to better understand subsequent fragmentation variations.

Keywords: *borehole diameter, rock fragmentation, sublevel caving, quick rating system*

1 Introduction

Sublevel caving involves massive underground blasting using long boreholes. This sort of blasting can result in high levels of ground vibrations, causing higher risks of seismic events and rock bursts in mines (Eremenko et al. 2009; Vallejos & McKinnon 2011; Zhang 2016). Ground vibrations are also a problem when blasting is done near populated areas, causing significant disturbance. They are therefore strictly regulated. To lower the level of ground vibrations and the risk of rock bursts, the amount of explosives detonated per delay can be reduced (Roy et al. 2014; Singh & Verma 2010; Zhang & Wimmer 2018). This can be achieved either by drilling smaller or shorter holes or by dividing long boreholes into two parts (Zhang & Wimmer 2018). However, both techniques have certain drawbacks. The division of a single blast (DSB) into two parts is still in the experimental stage (Zhang 2012; Zhang & Naarttijärvi 2005; Zhang & Wimmer 2018) Although there have been some promising results for narrow orebodies, the technique falls short of expectations for larger orebodies and needs further research (Zhang & Wimmer 2018). Meanwhile, drilling and development costs increase when smaller or shorter boreholes are drilled, as more holes and levels are required to maintain production targets (Zhang & Wimmer 2018). Another factor to consider is the borehole deviation. A reduction of borehole diameter will reduce the drill string diameter, thus decreasing the buckling strength of the drill strings and increasing the borehole deviation when long boreholes are drilled (Ghosh et al. 2017). Borehole deviation can have a negative impact on fragmentation, as less deviation is desired to maintain good fragmentation when blasting (Luossavaara-Kiirunavaara Aktiebolag (LKAB) 2013). To maintain the specific charge of the blast, additional holes need to be drilled in each ring when using smaller diameter boreholes resulting in better distribution of the explosives in the rock mass and promoting even fragmentation. The nature of fragmentation is important because of its effect on the gravity flow of the blasted material in sublevel caving (Wimmer et al. 2015), as well as the downstream processes (Badroddin et al. 2013).

Given all these considerations, a detailed evaluation is required to analyse the total effect of reducing borehole diameter on both fragmentation and costs. This paper describes the methodology to collect extensive dataset for fragmentation analysis at LKAB's Malmberget mine as well as the analysis of the impact on fragmentation when borehole diameters are reduced.

2 Methodology

This study included an extensive literature review of fragmentation measurement techniques, data collection and fragmentation analysis for boreholes with different diameters in LKAB's Malmberget mine, and significance testing to determine the statistical significance of the results.

2.1 Fragmentation measurement techniques

Rock fragmentation is a measure of the fragment size distribution of the post-blast broken rock material (Cho & Kaneko 2004). It is a function of blast design, rock strength, and natural discontinuities and can be considered a key parameter to measure the blast performance. Assessment of rock fragmentation has always been of keen interest to mining engineers seeking to optimise blasting operations (Kemeny et al. 1993), as fragmentation influences the production rates and the machines' performance (Thurley 2013). It also plays a significant role in controlling and minimising the overall production cost, including loading, transporting, and crushing costs (Siddiqui et al. 2009). The impact of rock fragmentation on downstream processes has been widely studied for a long time (Seccatore 2019), with researchers seeking to optimise rock fragmentation and thus maximise overall mineral extraction (Onederra et al. 2015). A reliable method to predict and evaluate rock fragmentation is extremely important for blast optimisation (Roy et al. 2016; Babaeian et al. 2019).

Rock fragmentation is generally assessed by either a direct method, such as sieving analysis, or an indirect method, such as observational, empirical, or image-based methods (Babaeian et al. 2019; Beyglou et al. 2017; Johansson & Ouchterlony 2011; Roy et al. 2016; Sanchidrián et al. 2014; Elahi & Hosseini 2017; Wimmer et al. 2012). Sieving analysis comprises a tedious process of taking rock samples from muck piles, passing them through a stack of progressively smaller mesh screens with square openings, and weighing and classifying the rock fragments into different classes based on the mesh size through which they do not pass (Thurley 2013). In the observational method, a person counts and classifies the rock fragmentation manually (Babaeian et al. 2019). Empirical methods incorporate various functions, such as Swebrec and Rosin-Rammler, developed as a result of different experiments designed to predict the fragment size distribution of the blasted rock (Sanchidrián et al. 2014).

Although there are several techniques to assess rock fragmentation, certain practical limitations hinder the continuous monitoring of fragmentation in an underground environment (Campbell & Thurley 2017). For example, sieving analysis is considered the most accurate method to determine rock fragmentation (Siddiqui et al. 2009), but it is impractical for a routine fragmentation assessment because of slow feedback, high time consumption, high cost, and the interuptive nature of the process. In addition, it is not possible to sieve a full-scale blasted muck pile in the mine because of operational limitations (Bamford et al. 2017; Campbell & Thurley 2017; Roy et al. 2016; Thurley 2013). Visual methods (e.g. image analysis) are the most common techniques for rock classification (Chatterjee et al. 2010).

Measuring fragmentation by image analysis is a relatively fast and cost-efficient method with less interruption in the mining process than traditional sieving (Campbell & Thurley 2017). Most of the earlier research on image-based rock fragmentation analysis was carried out using 2D imaging systems (Onederra et al. 2015). Recent studies focus more on 3D images and 3D laser scanning systems to avoid the limitations of the 2D systems (Thurley 2013; Onederra et al. 2015; Campbell & Thurley 2017; Chmelina et al. 2020). However, image-based methods do not provide any information about material not visible in the images. Despite of limitations, 2D-based methods are still the most widely used for fragmentation assessment because of their fast and simple applicability (Jang et al. 2020). Analysis is usually accomplished by utilising some commercially available software like SPLIT, WipFrag, GoldSize, FragScan, TUCIPS, CIAS, PowerSieve, IPACS, KTH, WIEP, Fragalyst, etc. (Babaeian et al. 2019; Elahi & Hosseini 2017; Roy et al. 2016; Siddiqui et al. 2009).

In a sublevel caving operation, photographing loaded buckets of load–haul–dump (LHD) machines to determine fragmentation is a competitive technique in size distribution studies (Danielsson et al. 2017). However, analysis of a single image using, for example, SPLIT-Desktop®, can take 2–3 hours depending on the quality of the image (Petropoulos 2015). Therefore, it becomes very time consuming and even impractical to analyse an extensive dataset collected from continuous monitoring of LHD buckets using commercial software. Instead, a quick rating system (QRS) reported by Petropoulos (2015), Wimmer et al. (2015), Danielsson et al. (2017, 2019), and Manzoor et al. (2022a, 2022b) can be used to assess median fragment size, X_{50}, of the material inside the LHD buckets. QRS is a simple method in which actual images of the fragmented rock are compared to reference images to assess fragmentation (Wimmer et al. 2015). It is similar to the Compaphoto method (Cunningham 1996) but customised to evaluate rock fragmentation in LHD buckets (Wimmer et al. 2015). It allows a faster estimation of fragmentation based on reference images (Wimmer et al. 2015). As an observational method, QRS is significantly influenced by the observer's experience and biases, leading to a risk of low accuracy (Babaeian et al. 2019). However, Wimmer et al. (2015) found QRS classification, if carried out carefully, provided similar results when the results were compared with SPLIT-Desktop® and also with a limited data of sieving analysis. Therefore, this field test opted to photograph the LHD buckets and perform fragmentation analysis using QRS, thus acquiring an extensive dataset for results and conclusions.

2.2 Site description

The field tests were performed at LKAB's Malmberget mine, the second largest underground iron ore mine in the world (Shekhar et al. 2019). It is located in Gällivare municipality in northern Sweden. It consists of 20 orebodies spreading over an area of 2.5 by 5 km (Lund 2013) of which 13 are currently being mined (Shekhar 2020). The orebodies are scattered throughout the mine and have a width of 20–100 m (Ghosh et al. 2017). The mine uses both the transverse and the longitudinal sublevel caving (SLC) methods (Shekhar et al. 2017), depending on the width of the orebody (Manzoor et al. 2022a). The major iron ore mined at the site is magnetite, with some quantities of haematite in some orebodies (Lund 2013). In 2019, the mine produced 16 million tons of ore (Manzoor et al. 2022b). The mine operates with several main haulage levels located at 600, 1,000, and 1,250 m (Manzoor et al. 2022b). The ore is drilled in a fan-shaped pattern (Figure 1), and each ring normally consists of eight boreholes. However, the number of holes per ring can be as high as 10 depending on the location of the ring (Manzoor et al. 2022b). The holes can reach a maximum spacing of 4.2 m in the upper part of the rings (Shekhar et al. 2017). They have normally a diameter of 115 mm, with length ranging from 20 to 50 m (Manzoor et al. 2022b). In the test trying to reduce ground vibrations, the diameter of the boreholes was reduced to 102 mm in some parts of the mine.

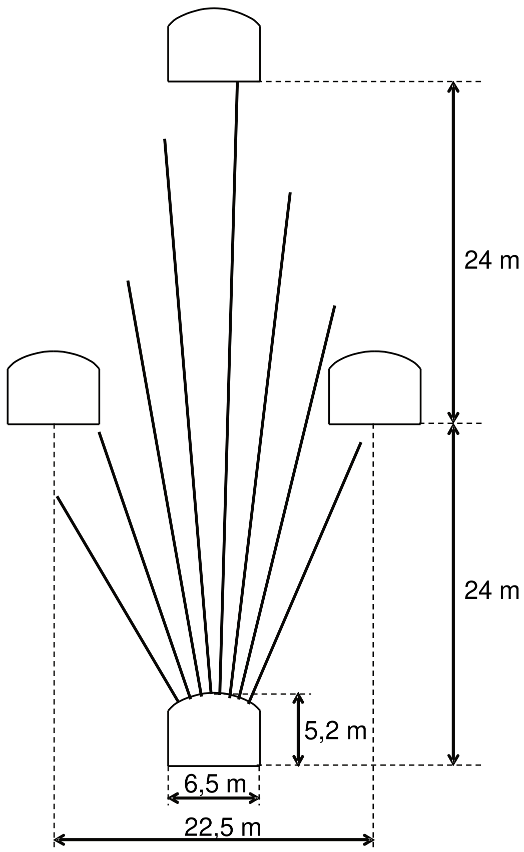

Figure 1 Schematic layout of a drilled ring (Manzoor et al. 2022b)

After blasting, the broken ore is loaded from drawpoints and hauled to the orepasses using LHD machines. The mine uses LHD machines with an average bucket capacity of 21 tons. The orepasses transfer the blasted material from production levels to haulage levels; from here, the material is transported to the crusher station using trucks. After the primary crushing underground, the material is hoisted to the surface processing plant (Manzoor et al. 2022b).

2.3 Significance testing

Significance testing is used to support or reject claims based on sample data (Anderson et al. 2016). It starts with a null hypothesis which represents the claim to be used as a basis for argument. The null hypothesis can then, based on the outcome of the tests of significance, either be rejected in favour of an alternate hypothesis or not rejected. For significance testing, this study used the following null and alternate hypotheses.

- Null hypothesis: There is no significant difference in fragmentation for 115 and 102 mm borehole diameters.
- Alternate hypothesis: There is a significant difference in fragmentation for 115 and 102 mm borehole diameters.

Hypothesis testing can be directional or non-directional depending upon the claim in the hypothesis. Directional hypothesis testing looks for an 'increase' or 'decrease' in the parameter and is carried out using one-tailed tests. Non-directional testing looks for a 'change' (could be an increase or decrease) in the parameter and is carried out using two-tailed tests (Anderson et al. 2016). This study used two-tailed tests for hypothesis testing as it analysed the change in fragmentation due to reduction in borehole diameter. To assess the hypotheses, the study used a significance level of 5% and calculated p-values using two sample t-tests. The p-value represents the measure of probability that any given result occurs just by chance (Akoglu 2018). The t-tests were used to compare the means of the two groups. These tests help in hypothesis testing to determine if an explanatory variable (in this study, the borehole diameter) has an effect on the response variable (in this study, the fragmentation) or whether the two are statistically different (Moore 2007). If the p-value for a given test was less than 0.05 (significance level of 5%), the null hypothesis was rejected in favour of alternate hypothesis, as there was less than 5% probability that the null hypothesis was true. Otherwise, the evidence suggested that the null hypothesis could not be rejected.

3 Fragmentation analysis using QRS

Before performing fragmentation analysis using QRS, the study first recorded the material hauled by the LHD machines. Every loaded bucket of the LHD machines at the two production drifts was photographed for continuous monitoring of the rock fragmentation. For that purpose, HD surveillance cameras were used.

3.1 Test setup

Input data for this research were collected from production level of 1,052 m, in one of the bigger orebodies in the mine. To record the whole loading operation, two cameras were installed in the roof of two production drifts, o4930 and o4960. The drift o4930 was drilled with 102 mm diameter while the drift o4960 was drilled with 115 mm diameter boreholes. A schematic layout of the experimental setup for data collection is shown in Figure 2.

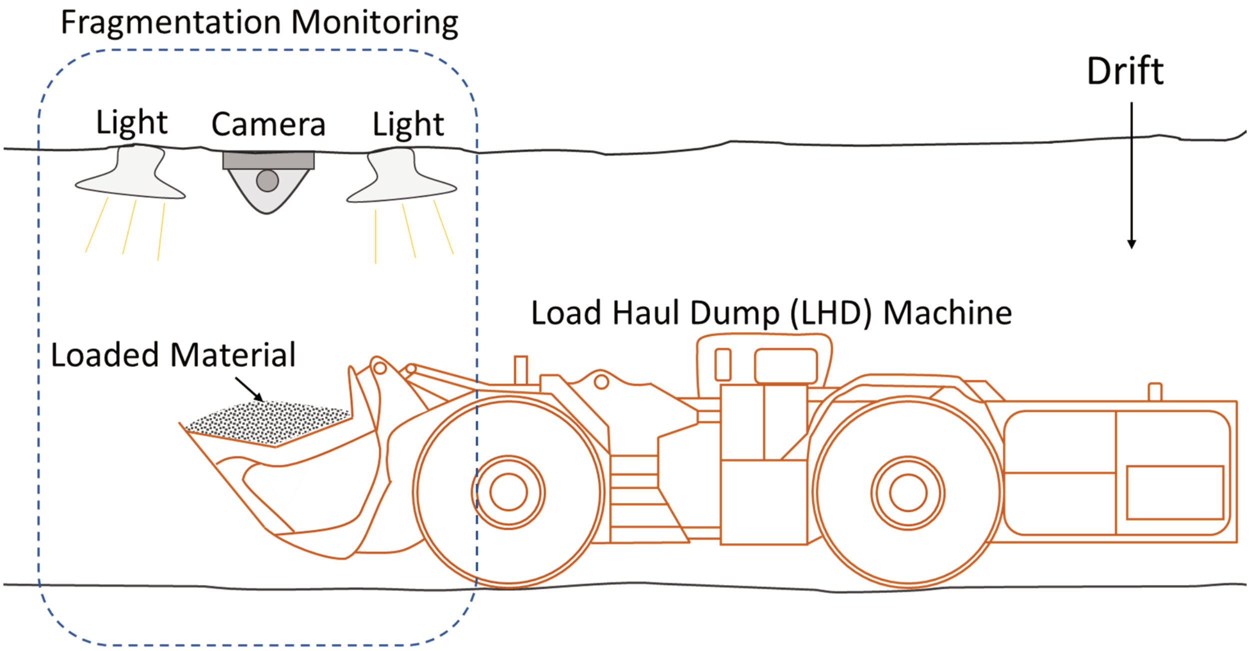

Figure 2 Schematic layout of fragmentation monitoring in the mine

As the dark environment of the mine does not support recording high quality videos, cameras were assisted with proper lighting. A schematic layout of the arrangement of the cameras and lights in the roof of the drifts is given in Figure 3.

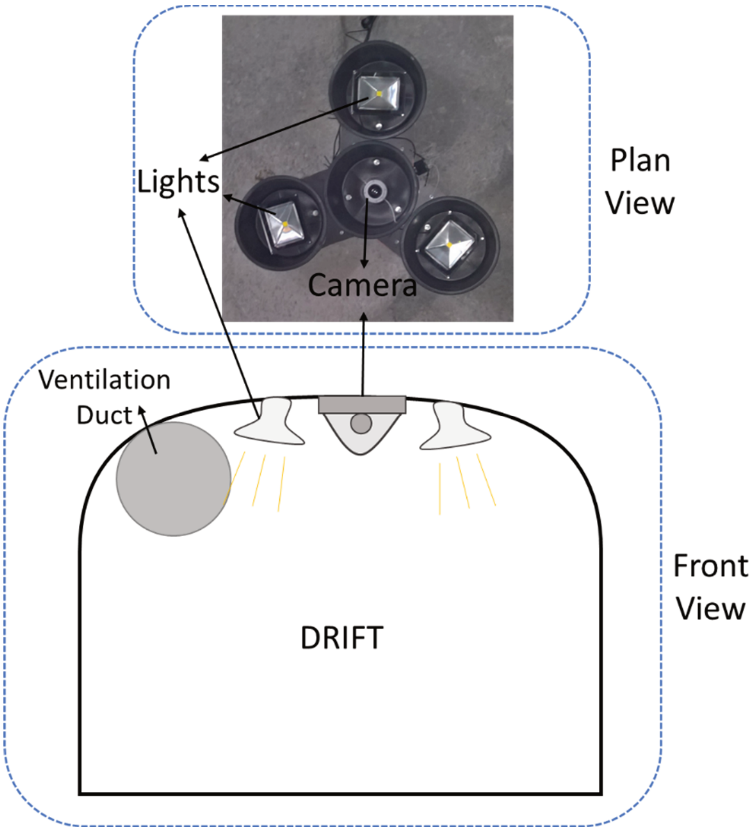

Figure 3 Camera and lights arrangement (plan and front view)

The cameras were configured to start recording by motion detection parameters. The specifications of the cameras used for data collection are given in Table 1. Besides other specifications, the cameras have different shutter speeds. Higher shutter speed is better when capturing frames of moving objects at higher speed. However, both cameras were effective in producing required data considering the speed of the studied LHD machines.

Table 1 Camera specifications used for data collection

Parameter	Camera 1	Camera 2
Model	Axis M3025-VE	Axis Q3515-LV
Video type	H.264	H.264
Video resolution	1,920 × 1,080	1,920 × 1,080
Frames per second	30	30

As the cameras were triggered by motion detection, any sort of movement under the cameras caused a video to be recorded. These movements were mostly caused by the LHD machines going into the drift to load the material and going out of the drift to dump the material into the orepass. However, other vehicles, such as staff cars, water sprinklers (machines sprinkling water in the drift for dust suppression), etc., as well as oscillating ventilation duct due to blasting, also resulted in video recordings. Short videos of 20–30 seconds, depending upon the duration of movement under the cameras, were recorded whenever LHD machines passed underneath the cameras. Dust tends to reduce video quality, but it did not affect the recording process in this study. However, the headlights of the LHD machines sometimes caused distortion of the frame pixels. Therefore, significant efforts were made to align the cameras and mount the lights in a way to minimise the undesired light effects. The recording lasted over a year starting from November 2017 to December 2018, which resulted in more than 15,000 videos.

The mine uses a wireless online loader information system (WOLIS) for weighing and recording every loaded bucket from the drawpoints. The system keeps a record of the date, time, ring being loaded, weight and grade of every bucket. The loading data from WOLIS was also collected to match the bucket information with the recorded videos using the date and time. In that way, the origin of every loaded bucket could be identified and matched with the correct video.

3.2 Data processing

The recorded data was transferred to a network associated storage (NAS) and was downloaded to a PC during regular visits to the mine. After collection, the data were processed before fragmentation analysis. A MATLAB® code was used to extract the maximum possible number of frames from the videos. Depending on the length of the video, 500–1,200 frames were produced. Since motion detection cameras were used to record the videos, they contained a considerable amount of redundant and not representative images, including all video recordings caused by movements in the drift not related to the LHD machines. These were removed from the dataset. The videos recorded when the LHD machines were going towards the drawpoint with an empty bucket to load the material were excluded from the data as well.

Figure 4 shows some examples of frames extracted from the videos. Empty frames (e.g. Figure 4a) indicated that the LHD machine was approaching the filming area, and its headlights triggered the motion detection sensor. The ventilation duct hanging beside the cameras, as shown in Figure 3, was found to trigger the sensor because it oscillated during blasting. Some frames included vehicles other than LHDs (e.g. staff vehicles, service vehicles, etc., as shown in Figures 4b and 4h). Empty LHD buckets and other machine parts can also be seen in some frames (Figures 4e, 4f, and 4g).

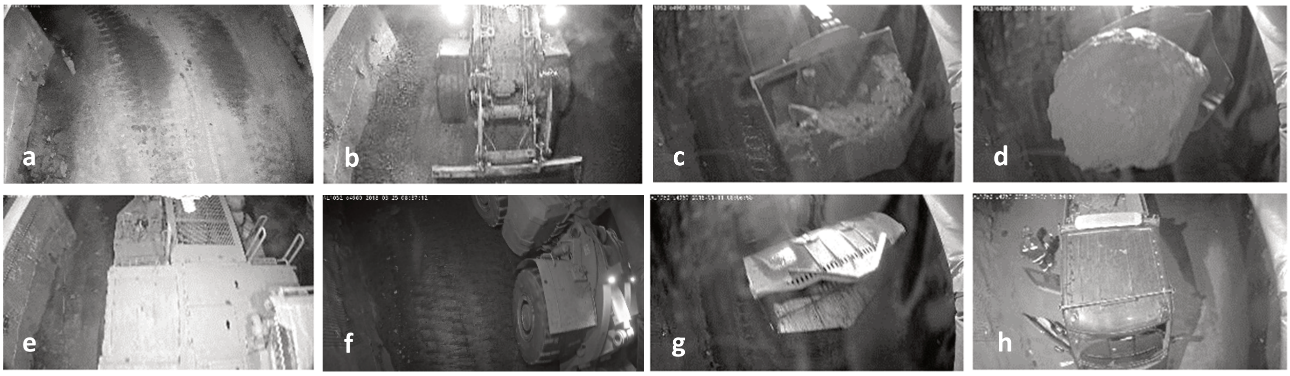

Figure 4 Different types of frames extracted from the recorded videos

The extracted frames were stored in separate folders based on the recording date and time of the videos. All folders were then manually explored to review the relevant frames (similar to Figures 4c and 4d) for fragmentation analysis.

3.3 QRS classification

In this study, based on the median fragment size, the loaded material inside 7,258 buckets was classified into four categories: fine, medium, coarse, and oversize. The fine category contained the rock material with median particle size, $X_{50} < 50$ mm. This means that at least 50% of the material in the image has a size less than 50 mm. The medium category comprised material with $X_{50} = 50$–400 mm. The coarse category contained fragmentation with $X_{50} = 400$–1,000 mm, and the oversize category referred to $X_{50} > 1,000$ mm. This classification has previously been used by Manzoor et al. (2022b). Images showing different fragmentation categories are provided in Figure 5.

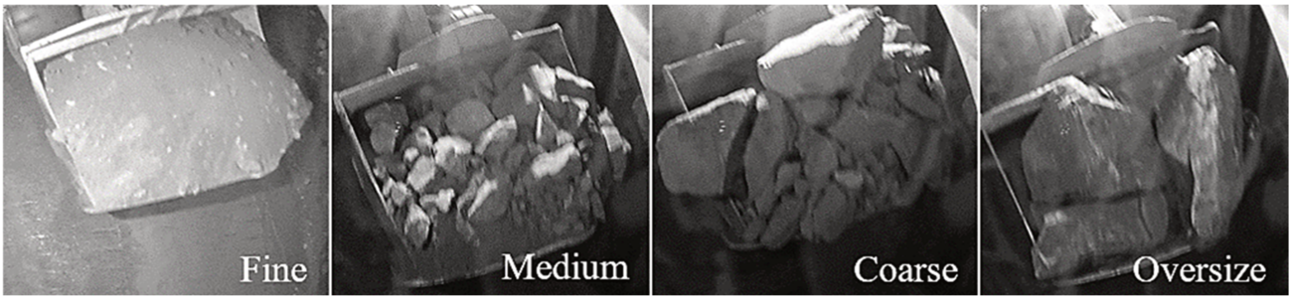

Figure 5 Frames showing different fragmentation categories based on X_{50} from the recorded videos (Manzoor et al. 2022b)

In addition to the four fragmentation categories, the study calculated the percentage of boulders as well. The buckets containing boulders were counted and divided by the total number of buckets loaded from the ring. In Malmberget mine, a boulder is any rock fragment bigger than 1 × 1 × 1 m (Gustafson et al. 2016). In this study, the boulders (B) were divided into two types, B1 and B2. B1 type referred to the smaller boulders with one dimension bigger than 1 m and the other dimension less than 1 m, as shown in Figure 6a. B2 types were bigger boulders with both visible dimensions bigger than 1 m, as shown in Figure 6b.

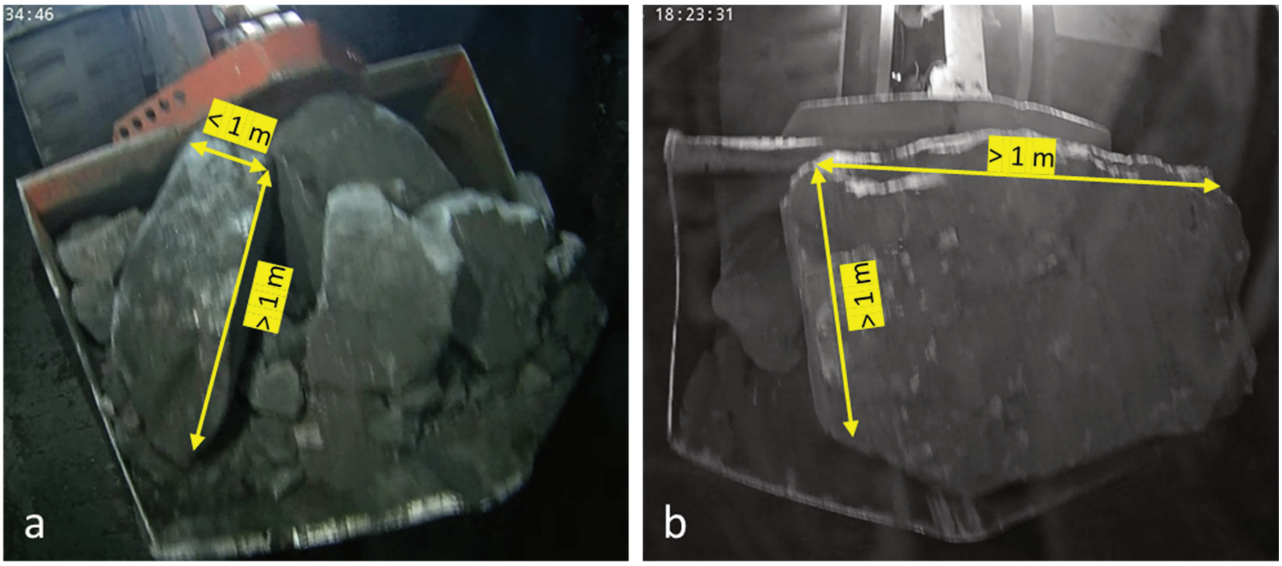

Figure 6 Defined dimensions of the two boulder types, examples taken from the recorded videos

4 Results

In the test, the fragmentation was analysed up to an extraction ratio of 100%. The extraction ratio represents the ratio of extracted tonnage and planned tonnage from any ring. After 100% extraction ratio, the origin of the material loaded from the drawpoint becomes highly uncertain as it could consist of caved waste material or material from the upper levels and not the material blasted in that particular ring. The size distribution of such material would therefore not be influenced by the differences in borehole diameter as it does not belong to the rings under study. Table 2 shows the group means, up to an extraction ratio of 100%, of different fragmentation categories for material originating from boreholes drilled with the two different borehole diameters.

Table 2 Group means of different categories for both diameters

Fragmentation category	Borehole diameter	
	102 mm	115 mm
Fine	49.57%	46.25%
Medium	40.12%	41.43%
Coarse	3.80%	5.74%
Oversize	6.52%	6.58%
B (B1+B2)	16.32%	16.42%
B1	4.78%	4.14%
B2	11.54%	12.27%

As the data in Table 2 show, there was a small difference in the percentage occurrence of different categories for different borehole diameters. The fine fragmentation increased from 46.25 to 49.57%, while the other categories decreased to some extent by decreasing the borehole diameter. The difference in group means given in Table 2 is visualised in Figure 7.

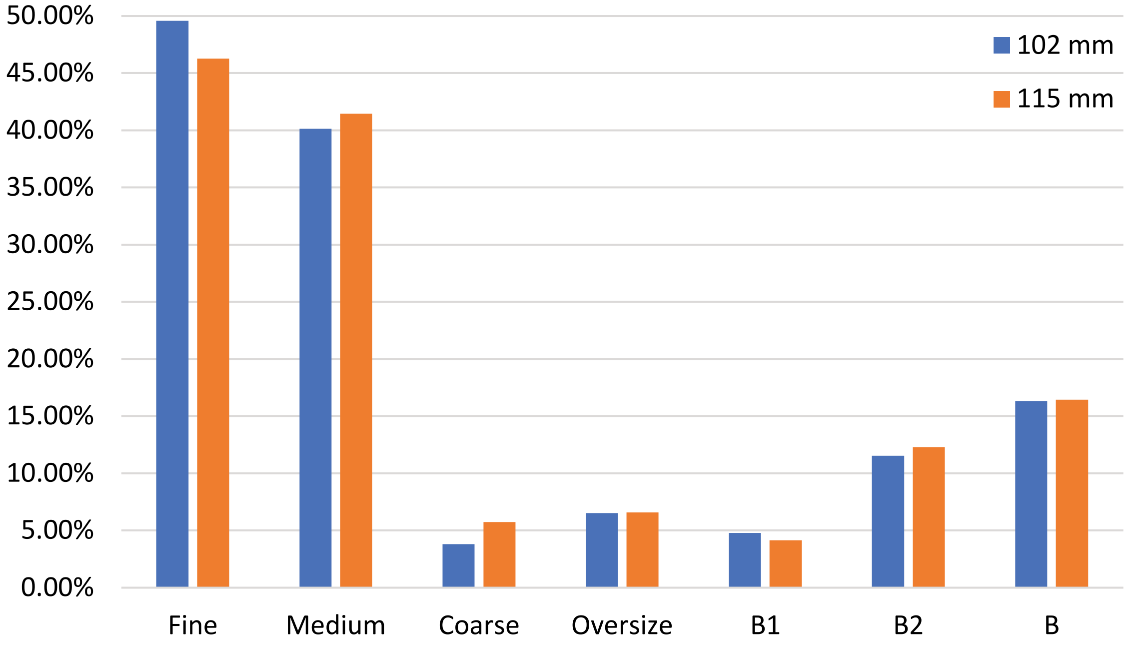

Figure 7 Bar plots showing the difference in group means for different fragmentation categories

As the figure shows, the reduction in borehole diameter reduced the fragment size to some extent. That is why the percentage of the occurrence of fine material increased, while the percentage of the occurrence of other categories decreased. For boulders, the overall percentage (B) was almost the same but the percentage of smaller boulders (B1) slightly increased, and the percentage of bigger boulders (B2) slightly dropped, showing a reduction in fragment size. The difference between the group means, however, appears to be limited.

To determine if the difference in mean values of X_{50} for different fragmentation categories based on different borehole diameters was statistically significant, the study performed two sample t-tests to support the findings with evidence. Table 3 shows the results of the t-tests for the null and alternate hypotheses given in Section 2.3.

Table 3 Results from t-test for two independent samples/two-tailed test

Fragmentation	Difference	t (observed)	|t| (critical)	Alpha	p-value
Fine	0.033	1.275	2.101	0.05	0.218
Medium	-0.013	-0.629	2.101	0.05	0.537
Coarse	-0.019	-1.911	2.101	0.05	0.072
Oversize	-0.001	-0.034	2.101	0.05	0.974
Boulders (B)	-0.001	-0.030	2.101	0.05	0.977
Boulders (B1)	0.006	0.656	2.101	0.05	0.520
Boulders (B2)	-0.007	-0.278	2.101	0.05	0.784

As the computed p-values shown in the table for all the variables are higher than the significance level of 5% (alpha = 0.05), the null hypothesis cannot be rejected for any of the variables. It means the risk of rejecting the null hypothesis is more than the significance level of 5%. Therefore, it is not rejected. The results show the reduction in borehole diameter from 115 to 102 mm slightly reduced the fragment size. However, the significance testing shows the difference in the percentage of the occurrence of any fragmentation category due to change in borehole diameter is statistically *not* significant.

5 Concluding remarks

The technique to continuously monitor fragmentation in LHD buckets (using video cameras with motion detection) and analyse the fragmented material using QRS was successfully used to analyse approximately 15,000 videos. QRS, being an observational method, can have the observer-bias. One way of removing such bias can be the use of machine learning algorithms which can also speed up the analysis for such a large dataset.

The over-arching question for the mine is whether it is possible to reduce vibrations by using smaller holes without having negative consequences for production, in this case, fragmentation. The results, even though statistically not significant, do not indicate a worsened fragmentation but instead show a slight improvement. Therefore, it may be concluded that the attempts to use smaller diameter borehole can continue.

The underlying factors that influence fragmentation, such as hole deviation, chargeability, borehole collapse, powder factor, etc., were not evaluated separately, but they likely contributed, both positively and negatively, to the total fragmentation found in this study. An individual analysis of those contributing parameters can shed more light on how rock fragmentation is defined.

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