Influence of Rock Mass Properties on Blast-Induced Rock Movement

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Abstract

In most metalliferrous open pit mines with heterogeneous orebodies, blast-induced rock movement is a crucial outcome that has unfavorable impact on ore and waste segregation in the post-blast muck pile, resulting in either ore loss (the ore is misclassified as waste and sent to the waste rock dump) and/or ore dilution (waste is misclassified as ore and sent to the processing plant). While many studies have been carried out to assess the influence of blast design parameters on blast-induced rock movement, the influence of rock mass characteristics in these studies have been overlooked.

This work presents the results of blast-induced rock movements recorded in more than 500 blast locations at Detour Lake Gold (DLG) mine in Canada. Using statistical analysis, the influence of variation of rock mass properties (i.e. rock type, intact rock strength, and intensity of rock structures) on the blast-induced rock movements were investigated. The analysis shows that the intact rock strength has significant impact on the blast-induced rock movement, whereas no relationship can be seen between the fracture frequency of rock mass and the magnitude of blast-induced rock movement. It also establishes a methodology for systematic analysis of these inter-related issues at an operating mine.

Keywords: blast design, rock mass properties, dilution, blast-induced rock movement

Introduction

Grade control is one of the most crucial challenges in open pit metal mining operations with heterogeneous ore bodies. Geostatistical techniques are commonly used to delineate boundaries of ore and waste in the form of block models based on exploration drilling data (LaRosa & Thornton, 2011). These initial ore/waste and high-grade/low-grade boundaries might then be rectified by operational grade control procedure such as assay analysis of blast holes' powder or reverse-circulation (RC) drilling (Isaaks et al., 2013). The identified ore and waste boundaries are moved after bench blasting and they are no longer accurate to be used as dig lines. This movement of rock caused by blasting has unfavorable effects on the segregation of ore and waste, resulting in misclassification of ore as waste (ore loss) or waste as ore (ore dilution). Both ore loss and ore dilution have significant economic impacts on an open pit mine operation.

Different techniques have been developed for direct measurement of blast-induced rock movement in open pit mines with varying success. These techniques are essentially based on rock movement measurements of few discrete locations within a blast. The techniques are categorized into two types based on the devices used for the measurement. Visual markers (such as sand bag, colored chain, and colored pipe) and remote detection monitors are two main types of devices used for this purpose, (Taylor & Firth 2003; Engmann et al. 2013). Generally, the measuring devices are placed at surveyed locations within the pre-blast rock mass and their new locations are found following the blast. The vector between the pre-blast and post-blast locations of each device can be used to calculate the magnitude and direction of the blast-induced movement of a particular point. The major disadvantage of using visual marker is that the measuring devices can be lost and thus the results of blast-induced rock movement will not be available until the rock material is loaded. Unlike visual markers, the remote detection technique uses traceable sensors that emit an electronic signal. The system consists of directional transmitter buried in separate holes within a blast location prior to blasting which are then located after the blast using an electronic scanner. The data are processed to define the blast-induced movement vectors of particular points, (Rogers et al., 2012).

Since 1980s, several methods have been developed for prediction of post-blast rock movement to define the boundaries of ore and waste after blast. These methods are categorized into empirical, numerical, and hybrid approaches (Thornton et al., 2005). Empirical methods that have been developed based on experimental field measurements, are generally taking into account blasting parameters, blast boundaries, and certain rock parameters to predict blast-induced rock movement (Domingo et al., 2015; Leite et al., 2014). Inability to capture and predict the blast-induced rock movement in different geological and rock mass conditions is the major deficiency of the empirical methods. Most of the numerical methods that have been developed for bench blast modeling are still unable to accurately predict blast-induced rock displacement, (Onederra et al. 2012; Torodoir et al., 2009; Firth & Taylor, 2001). The hybrid techniques combine both empirical and numerical models for estimation of blast-induced rock movement (Hunt & Thornton, 2014). Comparison of the results of these models with the rock movement monitoring results shows errors in the scale of few meters. Moreover, most of the conducted studies focused on the effect of blast design and blast sequencing on the magnitude and direction of blast movement. Limited efforts have been undertaken to investigate the effect of spatial variation of rock mass geomechanical properties on the blast-induced rock movement.

This paper presents the results of blast-induced rock movement measured in more than 500 blast locations at Detour Lake open pit mine in Canada between 2013 and 2016. The study aims to investigate the influence of rock mass characteristics on the results of blast-induced rock movement.

(a) (b)

Figure 1: (a) Location of Detour Lake mine (b) Perspective view of the pit

Data collection from Detour Lake open pit mine

Detour Lake open pit mine is located in northeastern Ontario, Canada, about 300 km from Timmins. The gold mineralization occurs in different mafic/ultramafic rock units within sub-vertical mineralized envelopes in the form of discrete fault-fill or shear hosted, extensional quartz vein networks. The mineral deposits are highly heterogeneous and an economic cut-off grade, calculated for the mine operation, is used to determine the final destination of the broken material. Figure 1 shows the location of the mine and a perspective view of the pit.

The mine design is based on benches of 12 m height and the mining operation includes drilling and blasting, and shovel-truck system for loading and hauling. As the ore dilution is very important for the mine operation, blast-induced rock movements have been measured in the mine site, in certain production blasts, where the blast locations consist of high-grade/low-grade/waste material. In this paper about 500 production blast data between 2013 and 2016 for which rock movement records were available, are used. For each of these blast locations, blast design parameters as well as geological and geotechnical data were collected. Geological data for each blast location was acquired using the detailed lithological block model developed for the Detour Lake ore deposit. Geotechnical information for each blast location were mainly collected using eight geotechnical boreholes, drilled and logged within the pit area. The geotechnical logging information (e.g. Rock Quality Designation (RQD) and intact rock strength; measured by point load test) along the boreholes were composited into fixed 12 m vertical intervals (equal to the bench height). Geotechnical attributes were assigned to each blast location based on the nearest composited point.

Drilling and blasting information for each blast location includes: the dimension of drilling pattern (burden, spacing, sub-drill, and hole diameter) and blasting specifications (explosive type, powder factor, stemming length, delays, initiation type, and type of confinement). The bulk loaded explosive is 100% emulsion (Fortis Extra-70). All the blast-holes are initiated from the bottom using a Pentolite booster, which is initiated by a non-electric detonator (Exel handidet-SL). The typical pattern, for more than 85% of the blasts, is V-type which is detonated by a typical sequential system includes 42 ms delay within a row and 100 ms delay between rows. Table 1 presents the drilling and blasting information typically used at Detour Lake mine. The blasting parameters are almost unchanged for all the investigated blast locations.

Table 1. General blasting practice at Detour Lake mine

Burden	Spacing	Bench Height	Sub-Drill	Hole Diameter	Stemming	Explosive	Powder Factor
6 m	7 m	12 m	1 m	216 mm	4.5 m	Fortis Extra	0.22 kg/t

Figure 2 presents a typical production blast location at Detour Lake mine which shows high-grade ore (HGO) zone and waste materials in the forms of not-acid generating (NAG) and potential acid generating (PAG) material. In these blast locations, Blast Movement Monitoring (BMM) technique was employed to measure magnitude and direction of blast-induced rock movement.

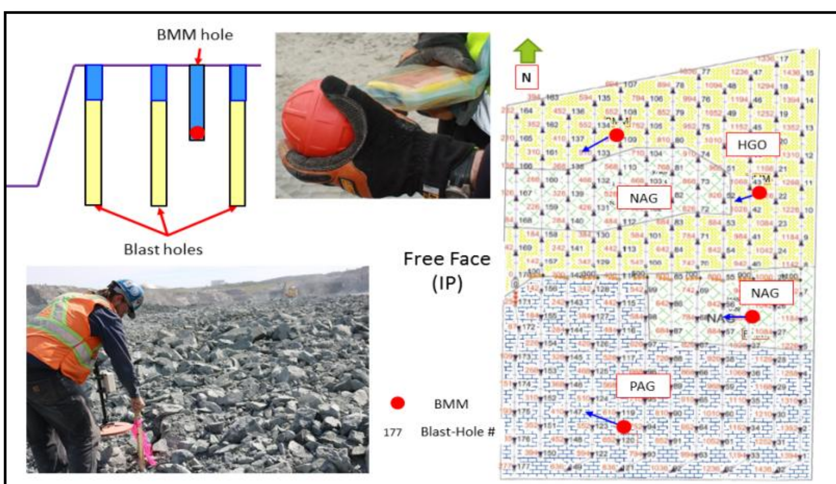


Figure 2. Schematic positions of BMMs for a particular blast location at Detour Lake Mine

All of these BMMs were buried in the body of blasts rather than in front or back of the blast. The collected data encompasses of 1530 records of pre-blast and post-blast locations of BMMs at more than 500 blast locations. The magnitude of horizontal movement, which represents the planer shift of ore and waste boundaries, was calculated for each BMM.

Statistical data analysis

The BMM records were captured from 11 different benches at the mine site. The value of horizontal movement varied between 0.09 m to 14.39 m with an average of 4.31 m and the standard deviation of 1.76 m. Figure 3 shows the histogram of the recorded data which shows a mode value of 4 m.

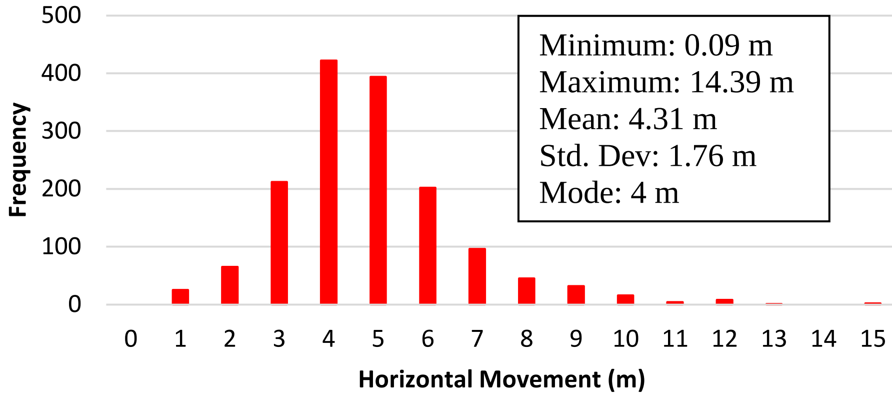
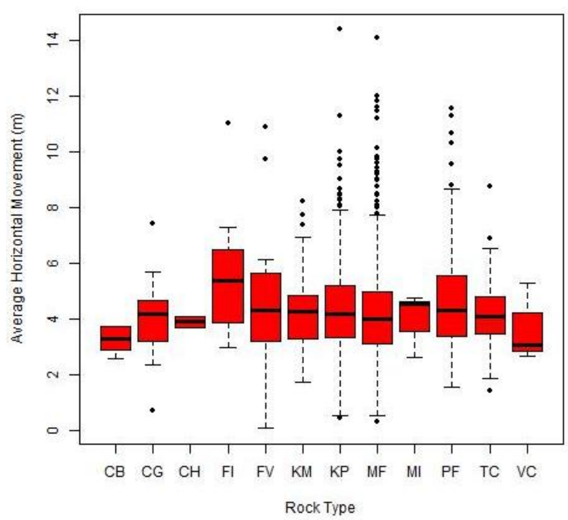


Figure 3. Hitogram of horizontal blast-induced rock movement

Blast-induced rock movement in various lithological units

Overall 12 different rock units have been encountered at Detour Lake mine which the dominant units are Mafic Flow (MF), Pillow Flow (PF), and their Potassically altered forms (KM and KP). Using the information on lithological rock units and blast-induced rock movement data for different blast locations, an Analysis of Variance (ANOVA) was carried out to determine whether there are any statistically significant differences between the mean blast-induced rock movements among different lithological units.



CB	Carbonated Breccia
CG	Chloritic Greenstone
CH	Chert Marker
FI	Felsic Intrusive
FV	Feldspar Volcanics
KM	Potassically Mafic Flow
KP	Potassically Pillow Flow
MF	Mafic Flow
MI	Mafic Intrusive
PF	Pillow Flow
TC	Talk Chlorite
VC	Volcaniclastics

Figure 4. Blast-induced movement based on different rock types

Figure 4 shows the box-plot of the recorded horizontal rock movement for different lithological units. The ANOVA analysis indicates that the null hypothesis which the mean blast-induced rock movement is the same for all lithological units is rejected. This implies that rock type can influence the blast-induced rock movement.

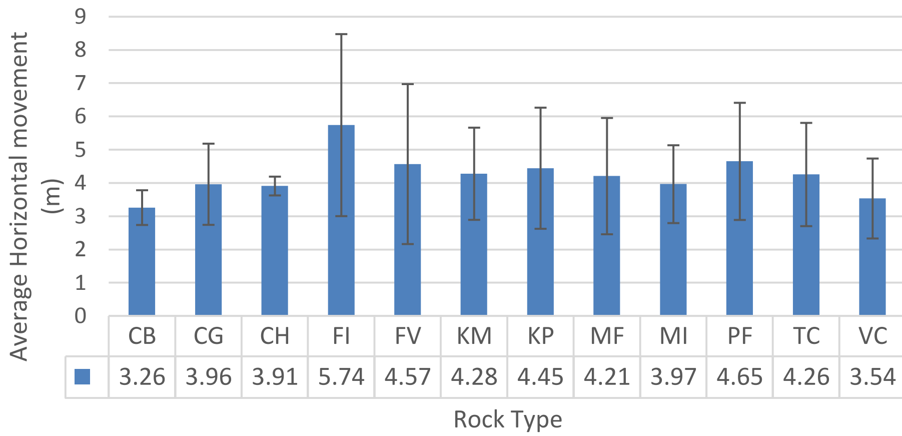


Figure 5. Average horizontal movements of different rock types

Figure 5 depicts the mean and standard deviation of recorded horizontal rock movement for various rock types. Maximum horizontal rock movement values have been recorded for FI (Felsic Intrusive) rock; whereas, CB (Carbonated Breccia) shows the least rock movement values.

Effect of rock mass geotechnical parameters on blast-induced rock movement

The geotechnical parameters assigned to each blast location includes RQD and intact rock strength (measured as point load index (IS_{50})). Table 2 presents statistics of these geotechnical parameters.

Table 2. Summary of geotechnical parameters for different blast locations at Detour Lake mine

	RQD (%)	IS_{50} (MPa)
Minimum	49.0	4.0
Maximum	100	14.7
Average	94.0	9.6
Standard deviation	7.1	2.2

The average RQD of 94% indicates that the rock mass in majority of the blast locations is less fractured. Also, the high average IS_{50} value indicates that the intact rock strength in most of the blasting locations is strong/very strong. Overall, blasts were mostly performed in strong to extremely strong rocks with the fair to excellent condition of RQD, (Deere & Deere, 1988; Ulusay, 2014).

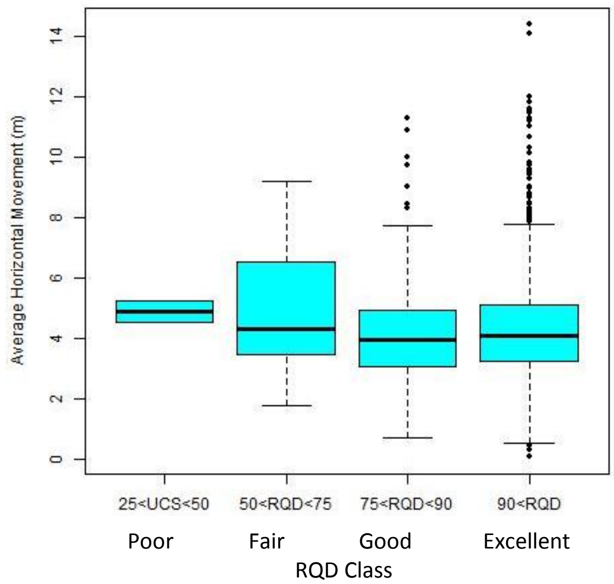


Figure 6. Box-plot of blast-induced rock movement for different RQD classes

In order to investigate the influence of rock mass fracturing on blast-induced rock movement, the blast locations at Detour Lake mine were classified into five different RQD classes (ranging from very-poor to excellent). No blast location fell under the category of very-poor RQD condition. Figure 6 shows the box-plot of the recorded horizontal blast-induced rock movements for different RQD classes. Figure 7 presents the average and standard deviation of horizontal rock movement in each rock mass class. The results show that the mean horizontal rock movement varies slightly between 4.18 m to 5.03 m and no trend can be observed.

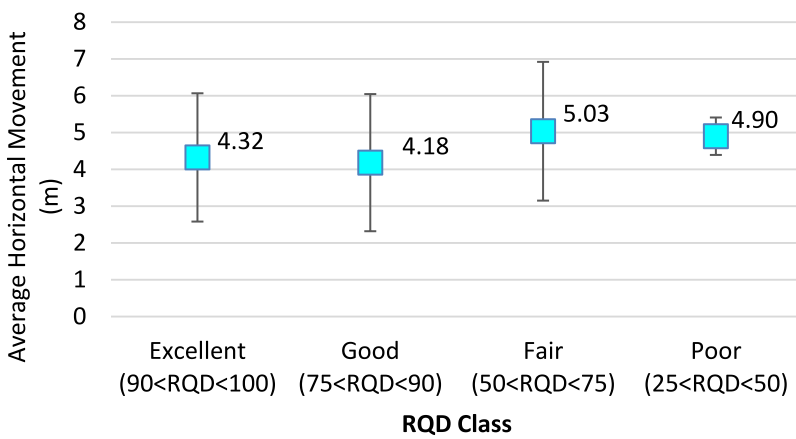


Figure 7. Average horizontal movement of different RQD classes

The results of ANOVA analysis suggest that the null hypothesis of equality of average horizontal rock movement in different RQD classes is valid. This implies that the degree of rock mass fracturing in situ does not have substantial influence on the blast-induced rock movement at this site.

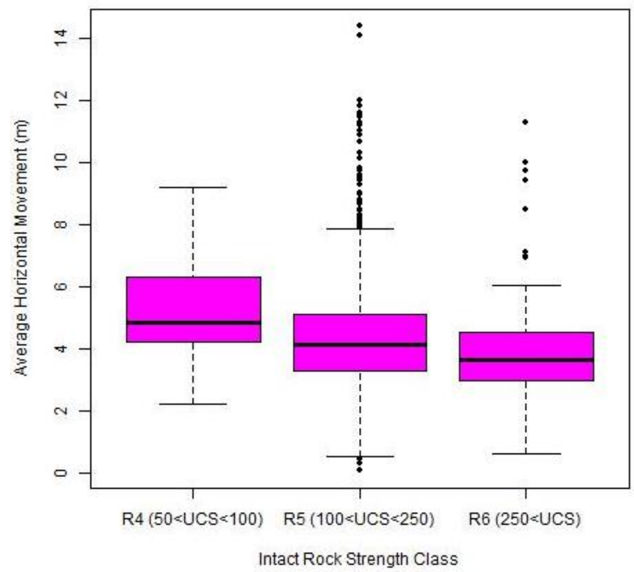


Figure 8. Blast-induced movement based on different intact rock strength classes

In this study, the point load strength index (IS_{50}) was used as the intact rock strength parameter for different blast locations. Many correlations have been proposed between the uniaxial compressive strength (UCS) and point-load strength index (IS_{50}), (D'Andrea et al., 1964; Broch & Franklin 1972; Bieniawski 1975; Chau & Wog 1996; Del Porto & Hurlimann 2009). In current work, we used the conversion factor, K equal to 24 to obtain uniaxial compressive strength, (Broch & Franklin 1972). The blast locations were classified into three different groups based on the compressive strength of their intact rock, including: R4 (50 (MPa) <UCS< 100 (MPa)), R5 (100 (MPa) <UCS< 250 (MPa)), and R6 (250 (MPa) < UCS). Figure 8 presents the box-plot of horizontal blast-induced rock movement for different intact rock strength classes.

The results of ANOVA analysis suggest that the average value of horizontal rock movement varies as the intact rock strength changes. The results indicate that the strength of intact rock has substantial contribution to the magnitude of blast-induced rock movement. Figure 9 shows the average and standard deviation values of horizontal rock movement in each intact rock strength class. It can be seen that the average horizontal rock movement decreases as the strength of intact rock increases.

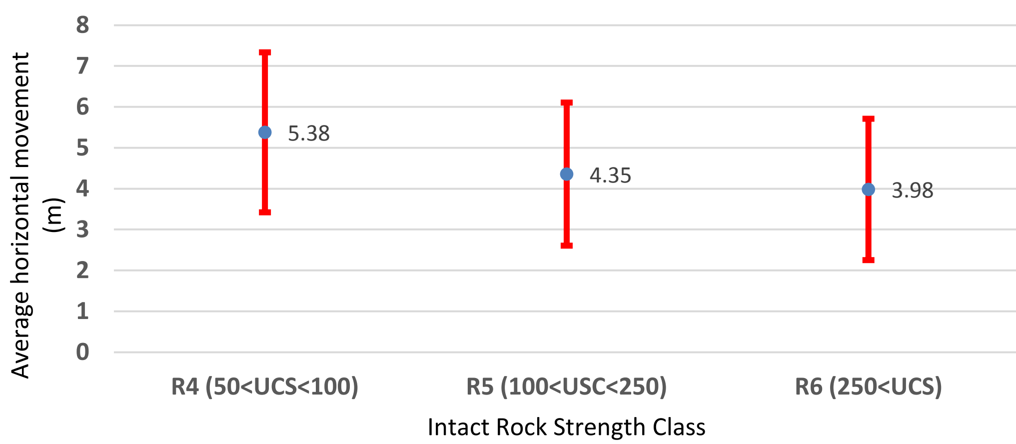


Figure 9. Average horizontal rock movement of different intact rock strength classes

Discussion

To justify the statistical analysis observed in section 3, it is considered that the energy of a blast consists of four components (Sanchidrian et al. 2007).

$$E_E = E_F + E_S + E_K + E_{NM} \qquad \textbf{Equation 1}$$

Where, E_E is the total explosive energy, E_F the fragmentation energy, E_S the seismic energy, E_K the kinetic energy, and E_{NM} the energy forms not measured such as air blast and heat. However, the above equation essentially describes the concept of explosives energy partitioning in fragmentation and movement of rock. The actual breakdown for each of these components even for a single hole blast is not known, as that will depend not only on the relevant properties of the target rock but also on the energy release characteristics of the explosive employed. This is further complicated by the fact that the partitioning of the explosive energy between shock and gas expansion phase also depends on the borehole conditions (i.e. diameter, confinement, etc) as well as on the method of initiation of the explosive column (Mohanty, 2009; 2012). In addition, in a normal multi-hole blasting operation, the usual scatter in firing times of each hole has also to be taken into account. Thus, even if the blast design is kept fixed, as was in this case, the proportioning of the explosive energy among these various phenomena can only be considered qualitative.

This hypothesis was assessed by studying the blast-induced rock fragmentation of the blast locations investigated in this study. For this purpose, the information on loading time and truck quantity (volume of broken rock loaded in each truck- fill factor) for all truck cycles, which were deployed for mucking out of each blast location, were investigated. This information was used as indirect key performance indicators (KPIs) of rock fragmentation quality in each blast location. Similar trucks and shovels were always used for mucking the investigated blast locations. The high loading time and low truck quantity indicates poorer rock fragmentation. Each blast location has been mucked out by more than thousands of loading and hauling cycles. Therefore, the averages of these two KPIs were calculated for each blast location. Finally, the blast locations were divided into different classes based on the intact rock strength classes (R4, R5, and R6). Figure 10 presents the average of these KPIs for different intact rock strength classes. It can be seen that by increasing the strength of intact rock the loading time increases while the truck quantity decreases. This implies that fragmentation of muck-pile in weaker intact rocks (R4 class) is relatively smaller than the stronger intact rock (R6 class). This can consequently justify higher blast-induced rock movement in weaker intact rocks observed in Figure 9. It is recognized that the reported numbers in Figure 10 for different intact rock classes differ only by a small percentage; however, the reported mean values are based on significantly high statistical population.

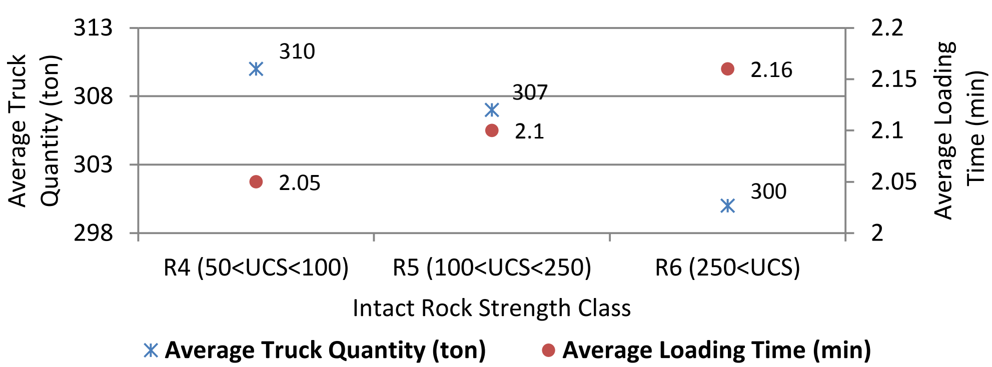


Figure 10. Average loading time and truck quantity for different intact rock strength classes

Conclusion

Blast-induced rock movement plays an important role in grade control in heterogeneous metalliferrous open pit mines. Uncontrolled blast-induced rock movement can have important economic impacts on a mine operation due to ore loss and ore dilution. This paper presents the results of blast-induced rock movements, measured in Detour Lake Gold mine. The results show that rock mass properties (particularly intact rock strength) can influence the magnitude of blast-induced rock movement, whereas, other rock mass properties (e.g. fracture frequency) might not have substantial contribution to the resulting rock movement. Higher blast-induced rock movements were recorded for rocks with lower mechanical strength. This can be attributed to the smaller size of rock fragments that are created by blasting shock waves in softer rocks. This observation was validated by investigating the diggability and truck filling data with different rock strength.

The results of this study can be used to develop guidelines to control blast-induced rock movement and consequently ore dilution in open pit mines. Understanding the spatial variation of intact rock properties, allows identification of different blasting domains across the pit. Accordingly, blast design parameters (e.g. powder factor, the extent of buffer zone left unmucked) can be adjusted for each blasting domain to minimize the blast-induced rock movement while obtaining the optimum fragmentation results. The information on spatial variation of intact rock strength can be acquired through a systematic collection of geotechnical data for different blast locations, prior to blasting. Such information can be sought directly through simple field rock strength tests (e.g. point load test, Schmidt hammer test) or indirectly via measurement of penetration rate of blastholes and establishment of a relationship between intact rock strength and penetration rate.

Additional work would be required to validate and improve prediction of blast-induced rock movement based on variation of intact rock strength. However, the findings in this study can be considered only relative in identifying the roles of some key rock parameters in controlling dilution and maintaining high productivity, as the corresponding blasting parameters for each blast were not monitored by the mine. These would include periodic but systematic measurement of actual in-hole velocity of detonation of the explosives in use, and more importantly, firing time accuracy of the delay rounds in each blast. Any deviation from the actual delay design can significantly affect rock movement, and therefore dilution. When coupled with actual measurement of these blasting parameters, the approach described provides a sound and quantitative tool for dilution control and improved productivity.

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