Integral system of monitoring and modeling for blast optimization

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ABSTRACT: Most mines seek fine fragmentation for down-stream operations to maximize mineral abstraction with minimized energy cost, e.g., mine-to-mill blast optimizations. On the other hand, maintaining stable highwalls and undisturbed nearby community is highly desirable. To obtain fine fragmentation, it is often required to design blasts with favorable energy concentration through explosive loading or blasthole delay timing. Blast designs have potential to increase blast vibration in general. To achieve the optimization, an integral system for accurate monitoring and reliable modeling of full blast design parameters for rock fragmentation and blast vibration is required. Current technology in the literature falls short for each of the needs. This paper presents an integral system, which includes the accelerometer-based blast vibration monitoring system, the multiple seed waveform blast vibration model, and the multiple blasthole fragmentation model. The three components together complete a close loop of the needs for blast optimization.

Keywords: Near-Field Blast Vibration Monitoring, Near Field Blast Vibration Modelling, Full Blast Design Parameter Fragmentation Modelling.

1 INTRODUCTION

Blasting is one of a mine's major operations. It is the most economical means to break the rock and excavate ore body. When using a blast to fragment rock, damage to highwalls or nearby underground structures must be minimized. Consequently, a blast design improvement always requires examining both the rock fragmentation and the blast vibration.

A proper site characterization is of critical importance, which includes obtaining the effect of the site geology on blasting results. However, currently in literature, most blast monitoring systems being used are based on geophones. For example, a typical geophone has an amplitude limit of 254 mm/s with a frequency range of 3-250 Hz. If it is placed too close to blastholes, the measurement would be saturated at 254 mm/s in amplitude, yielding misleading information. For underground blast monitoring, both its amplitude and frequency limits are not suitable.

Prediction models of blast vibration are all single-seed models, i.e., using the same seed waveform to represent the contribution from each blasthole. Such models may be useful for far-field vibration.

However, they are not suitable for near-field blast vibration such as at highwalls from a trim blast. Today for rock fragmentation modeling, simulation of the millisecond interactions among explosive charges in a blast is most required simulations for blast optimization. However, only ‘single blasthole’ models are available that cannot simulate explosive charge interactions.

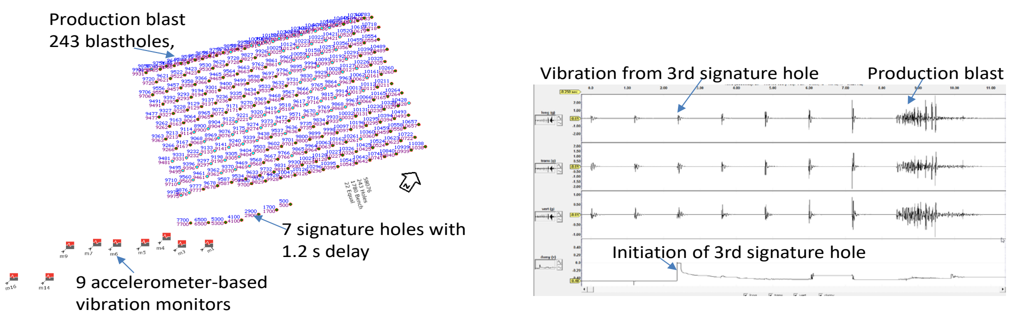
This paper presents an integral system for monitoring and modeling blast vibration and rock fragmentation. The case applications demonstrate that each component of the system plays an irreplaceable role for successful blast optimization.

2 NEAR FIELD BLAST MONITORING

When the effect of the blast vibration from a trim blast on a highwall is concerned, the vibration monitoring should best be conducted on the highwall rather than at a further location. When the vibration is recorded at a further distance, the vibration signals contain more information from the geology in the path rather than the response of the highwall. For explosive performance investigation recording blast vibration in the vicinity of blastholes is also necessary.

Near-field signature hole blast vibration testing is the easiest to carry out and the only one that is used today in the field for characterizing site geology for blasting. Near-field nonlinear rock response to blast loading may be captured in the data collection. Furthermore, the geometric scale of the signature hole testing matches what is required for blasting.

Fig. 1a shows a typical setup of a near-field signature hole blast vibration monitoring. In this example, seven signature blastholes were initiated with long delays (1200 ms) to separate the firing events. At 1300ms after the initiation of the last signature blasthole, the production blast was initiated. Nine vibration monitors were deployed to record the blast vibration. The blast vibration and the rock fragmentation from the production blast are used to calibrate the MSW blast vibration and the MBF models for the site. The MSW and MBF share the same input from the signature hole blast vibration information at the site and all the blast design parameters of the blast to be simulated. Each of the nine monitors recorded a set of blast vibration from signature blastholes and production blast (Fig. 1b).



1a) Blast Monitoring Setup 1b) Recorded blast vibration at a monitor

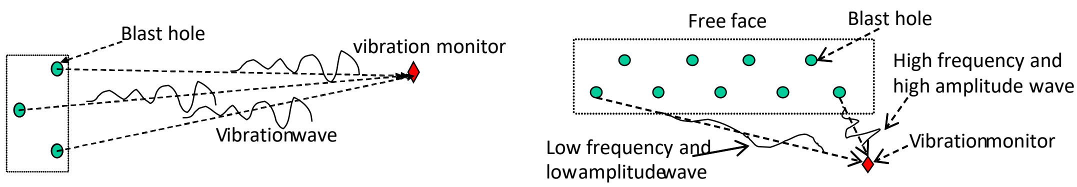
Figure 1. Typical setup and a record of a near-field signature hole blast vibration monitoring.

Signature blasthole vibration data is useful in several aspects. Firstly, site specific vibration characteristics (e.g., peak particle velocity - PPV) can be accurately related to the charge weight and distance. Such a relationship can be used as model input for blast modelling. Secondly, the vibration waveforms measured at various distances can be used as seed waveforms to model blast vibrations from a production blast. The ground resonant frequency and the range of vibration frequencies that the ground supports can be estimated for managing vibration frequencies at highwalls. The ground sonic velocity can also be estimated for blast modeling and rock property assessment.

Monitoring equipment was assembled with commercially available components – triaxial accelerometers, charge amplifiers and high frequency data recorders, which can record a wide band of frequencies (0.5 – 20 kHz) and amplitudes (0-10,000 mm/s). The monitoring system is suitable for near-field (e.g., 7m), far-field (e.g., 1000m), open pit, and underground blast vibration monitoring.

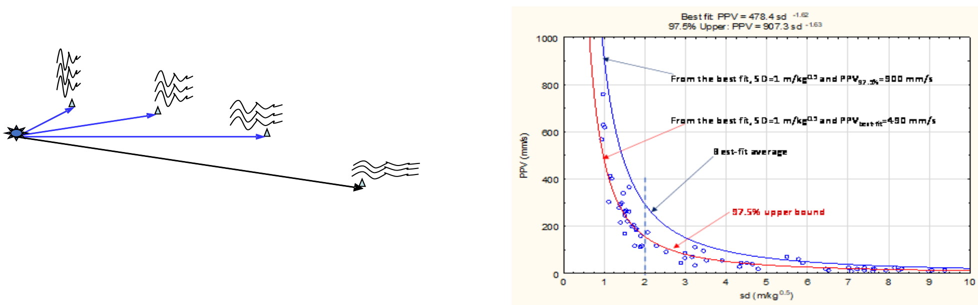
3 MSW BLAST VIBRATION MODEL

Far-field blast vibrations may be defined as situations where the distance difference from blast holes to a monitor is insignificant compared to the distance involved from the center of the blast to a monitor, as shown in Fig. 2. A typical example is the vibration near a house from a quarry blast 800 m away. In this case, the geometry of the blast pattern is insignificant relative to the distance involved. The waveforms contributed from different blastholes to the point of interest are similar. On the other hand, near-field blast vibration may be defined as where the distance differences from the blast holes to a monitor is significant as compared to the distance from the center of the blast to a monitor, as shown in Fig. 2b. A typical example of a near-field blast vibration is the vibration at the crest of a new highwall from a cast blast. In this case, the vibration from a hole closer to the monitor contributes a vibration waveform with significantly higher amplitude and more high frequency components than from a blast hole farther to the monitor.



a) far field blast vibration b) near field blast vibration

Figure 2. A typical far- and near-field blast vibration.



The dots are measured blast vibration and red and blue lines are from regression

Figure 3. MSW model uses multiple seed waveforms collected at different distances at the same site.

Since the waveform from a blasthole changes with distance due to its frequency attenuation and different p-, s-, and surface wave propagation speed (Gladwin & Stacey, 1974), the MSW model uses multiple sets of seed waveforms collected at different distances from signature blastholes (Fig. 3a) to model vibration contributions to points of interest from different explosive charges of a blast. By employing multiple seed waveforms, p-, s-, and surface waves from explosive charges at different distances can be included in the model. Since each seed waveform is encoded with the effects of geology and distance along the path, using multiple seeds allows for the input of additional site geological information into the model. As a result, the MSW model can provide more reliable predictions compared to a 'single seed' model. Fig. 3b is the signature hole blast PPV vs. the charge weight scaled distance (SD=$\frac{d}{\sqrt{w}}, d - distance, w - charge\ weight$) that is used for modelling the vibration amplitude from a charge to a point of interest.

In the MSW model, it is assumed that at a given scaled distance, PPV is a random variable belonging to a normal distribution $PPV \sim N(PPV_{best-fit}, \sigma)$. Both the best-fit (average) and the 97.5% upper bound prediction from the regression of signature hole blast vibration are used to model the geological random effects causing the variation of PPV. The 97.5% of the upper bound prediction is for predicting where a new measurement could occur with 97.5% probability. For a given scaled distance, the standard deviation σ is obtained as:

$$\sigma = \frac{PPV_{97.5\%} - PPV_{best-fit}}{1.96} \tag{1}$$

For each explosive charge, a random $PPV_i = PPV_{best-fit} + \sigma\gamma_i$ is obtained, $\gamma_i \sim N(0,1)$. Ground sonic velocity c_i and initiation time t_i are also modeled as random variables of normal distribution (Yang & Lownds 2011).

For far-field vibration modeling, if several seed waveforms exist for the point of interest, multiple seeds can be randomly selected for blastholes to represent the site geology more reasonably. In addition, the MSW model considers effects of screening and confinement reduction of broken ground from earlier firing charges that are nearby the present firing charge or in the path of the vibration. The effects on both amplitude and waveform are modeled. The screen algorithm also simulates the effects of the location and initiation time of an earlier firing charge in the path area of the vibration (Yang & Kay 2011).

The MSW model is suitable for highwall vibration control as well as far field vibrations. The MSW model has been applied at many mines and construction sites (open pit and underground) in the globe (Kim et al. 2014, Yang et al. 2023), with all the cases yielding reliable predictions.

4 MBF MODEL

A real production blast often has variable burden and spacing for each blasthole, the location of which is defined routinely by GPS surveying. In a production blast, each blasthole may contain multiple decks (charges) with different initiation times and locations. Additionally, different explosives may be used within a blast. Free faces often have irregular geometries. All these variables significantly contribute to rock fragmentations. The model has been further developed for underground blasting, such as tunneling, and stope blasts with complex geometries defined according to the envelope of blastholes. In addition, if drill monitoring data is available, the effect of high-resolution of rock property within a blast can also be modelled on rock fragmentation. The MBF model has been used worldwide by mining companies and civil construction sites. It is a significant advance from 'single-blasthole' models, e.g., Kuz-Ram that have been widely used in the blasting industry over last 30 years (Cunningham 2005).

PPV relates to 3D dynamic strain (Yang 2016) and it can be a control parameter for rock fragmentation in the MBF model. Based on the work by Seaman et al (1976) and assuming a constant rock breaking time (Δt) at a site, the average fragment size can be established (Yang, et al. 2023):

$$\bar{x} = \frac{x_0}{N_0 \, exp\left(\frac{PPV - PPV_0}{\eta}\right)} \tag{2}$$

where, $\frac{x_0}{N_0}$= the effective size of the initial fragment (m), x_0 is the average size of the in-situ blocks defined by jointing, and N_0 is the average number of effective fractures within a block and is expected to increase with the intensity of the shock wave. PPV_0 may be related to the critical strain for rock breakage $PPV_0 = c\varepsilon_c$, where c is the sonic velocity of the rock. ε_c may be estimated by $\varepsilon_c = \frac{UCS}{E}$. UCS is the dynamic uniaxial compressive strength. For simplicity, the MBF model uses the Rosin Rammler ($R(x) = 1 - e^{-\left(\frac{x}{\bar{x}}\right)^n}$) function to describe the size distribution of the rock fragments at a point. *R(x)* is the cumulative volumetric fraction for fragment sizes smaller than x. In the present modeling, $\delta = \frac{x_0}{N_0}$, η and n are hard to measure, which are calibration parameters since the blast design parameters are all explicitly input to the MBF model.

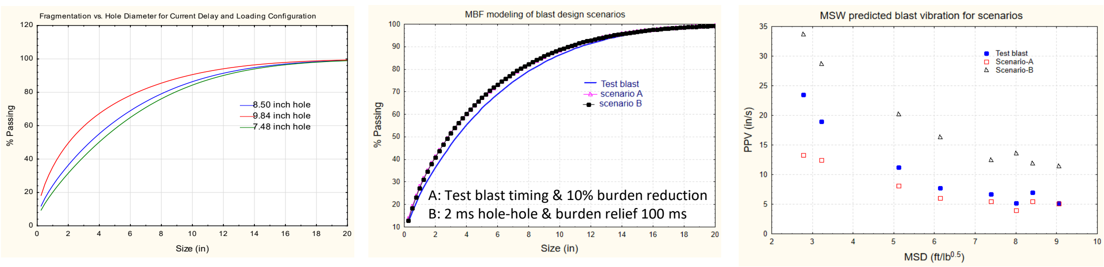
PPV calculation at a point in rock uses key concepts are the complete PPV charge weight scaling law (e.g., Fig. 3b) established from near-field blast vibration monitoring and extrapolated to the wall of blastholes (Yang 2018). Each charge is computationally divided into spherical charge elements (the length equals to the diameter) that has an initiation time. The dominant charge element at a calculation point is identified that has the minimum scaled distance. The time of the blast wave arrival at the calculation point from the dominant charge element is defined as the fragmentation time at the point. Contribution from a charge element is determined according to its scaled distance and the time difference of its blast wave arrival time from the fragmentation time at the point. The contributions from all charge elements are non-linearly integrated with the charge weight scaling (Yang, 2018). From the integrated charge weight, the distance from the dominant charge element to the calculation point, and the parameters of the complete charge weight scaling law established for the site, the PPV and the average fragmentation size from Equation (2) are calculated. The size distributions from all calculation grid points can be integrated to obtain the fragmentation size for the whole blast or for a selected zone of the blast.

5 CASE EXAMPLES

The case study was conducted at a gold mine in Canada (Yang & Patterson 2017). The rock at the mine is a hard competent granite. The blasthole depth is 13.6 m in average and diameter is 216 mm. The stemming is 4.6 m. The explosive is a booster sensitive emulsion. Burden and spacing are 6.1 m and 6.5 m respectively. The mine was looking to improve shovel productivity in ore by reducing fragmentation size as much as possible, with a rough target of reducing the number of shovel buckets to fill the truck by 25% (3 loads versus 4). Various scenarios were modeled and compared. It may not necessarily be that the exact designs from the modeling are adopted in the blast. However, it is important that the modeling can provide insight for blast engineers on how to achieve their optimization goals.

A test blast was conducted with a combination of a signature hole blast and a production blast (e.g., Fig. 1). The purpose of the test blast was to acquire site characterization parameters of near field blast vibration through signature hole blast monitoring, which are input to both MSW and MBF models. The MBF model generates rock fragmentation which was compared with the measured rock fragmentation from the same blast to calibrate the model for the site. The MSW model is also calibrated against the measured blast vibration from the production blast.

Several scenarios were modeled to understand the sensitivity of design parameters on fragmentation results. The mine can drill three different blastholes with diameters 190 mm, 216 mm, 250 mm. Fig. 4a shows the fragmentation for three diameters if all other blast parameters are kept the same as the test production blast. The blasthole diameter of the test blast is 216 mm. Changing the blasthole diameter from 216 mm to 250 mm could result large increase in fines for example, the percentage of passing at 100 mm can increase by 12%. When the blasthole diameter decreases from 216 mm to 190 mm, the percentage passing at 100 mm can decrease by 5 %. Such modeling demonstrates the sensitivity of changing the blasthole diameter on the rock fragmentation.



a) Fragmentation from three blasthole diameters b) FBM modeling two scenarios and test production blast c) MSW blast vibration prediction for the scenario blasts

Figure 4. Scenarios of fragmentation and PPV compared with the test production blast.

Fig. 4b shows two modeling scenarios compared with the fragmentation of the test production blast. The scenario-A uses the same delay timing and loading as the test blast, but 10% reduction of the burden from the test blast. The scenario-B has the same blast pattern and loading and reduces hole-to-hole delay from 42 ms to 2 ms keeping the row-to-row delay 100 ms as the test blast. Scenario-A requires more drilling and explosive loading. The scenario-B does not add extra cost, and yields the same fragmentation improvement as the scenario-A. Both cases produce 5% more passing at the size range from 102 to 152 mm. Following the modeling, scenario-B was implemented at the mine with success. Fig. 4c shows the blast vibration predicted by the MSW for the scenario blasts. The scenario-A yields lower blast vibration compared with the original test blast since reduced burden would reduce the confinement to the blastholes, which results in lower vibrations. Scenario-B reduces the inter blasthole timing from 42 ms to 2 ms, which causes more overlapping of blast vibration from different blast holes and increases the peak particle velocity of the vibration. The trends of the MSW modeling in Fig. 4c are expected.

6 CONCLUSIONS

The accelerometer-based blast vibration monitoring system enables blast vibration monitoring in the vicinity of blastholes as well as in the far-field. Near-field blast vibration monitoring evaluates blasting impact to highwalls and collecting site-specific input to MBF and MSW. The MBF model simulates all blast design parameters explicitly. With the signature hole blast vibration and fragmentation measurement for a test blast, the MBF model can be established for a mine site. The model can then be used to explore benefits from new blast design scenarios. The MSW blast vibration model uses multiple seed waveforms as inputs that are suitable for near-field blast vibration predictions and input more site geological information than models using a single seed waveform.

The paper demonstrates the parallel use of MSW and MBF at a mine site for blast optimization. While the rock fragmentation is improved, the blast vibration is under the check. Vice versa, controlling blast vibration not only needs MSW model, but it also requires MBF modeling to ensure rock fragmentation is not over compromised. The system of monitoring and modelling is applicable to open pit, tunnelling, and underground stope blasting.

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