An integrated approach of signature hole vibration monitoring and modeling for quarry vibration control

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ABSTRACT: In an urban production quarry, blasting close to a city boundary requires management of the vibration peak particle velocity of vector sum (PVS). Blasting is required to come within 30 meters of the boundary. An optimal technical solution was obtained through an integrated approach of signature hole vibration monitoring and modeling. A series of signature holes were fired and full vibration waveforms from these holes were recorded with several seismographs at distances ranging from 20 to 100 meters from the signature holes. Following the signature hole vibration monitoring, several production blasts were monitored with an array of seismographs. A vibration model using multiple seed waveforms for a point of interest was applied to the case assisting in the selection of blast design parameters. The selected blast designs were implemented and are proving to be effective in managing the vibration below the limit while maintaining high productivity. The capability of the model in terms of the PVS of particle velocity and frequency predictions is demonstrated in the paper. With the signature hole data as the input to the model, the model prediction agrees well with field measurements of PVS of particle velocity and amplitude spectrum from production blasts.

1 INTRODUCTION

In an urban production quarry, blasting close to a city boundary is a common situation. In such a case the quarry is often required to manage vibration peak particle velocity (PVS of particle velocity) and frequency to meet the vibration limits established by city regulators. On the other hand, the quarry needs to maximize productivity in order to maintain its profitability. Consequently, it is necessary for the quarry to apply the best technologies available to manage PVS of particle velocity and frequency for each blast. Today, accurate delay timing can be achieved easily with electronic detonators. In addition, GPS surveying provides a much more accurate location of blast holes and blast monitors than was possible a short time ago. Furthermore, with explosive delivery systems the charge weight in each hole can be recorded accurately. Improved accuracies of measurements, delay timing and explosive loading enables operations to manage blast vibration more reliably using advanced techniques of measurement, analysis and modeling of blast vibration.

This paper reports a case study at a quarry in North America and demonstrates the integral techniques of blast monitoring, analysis and modeling, developed in recent years by Orica. The relationship between PVS of particle velocity and the scaled distance from signature hole blasts provided an upper limit of the charge weight per delay for a given vibration limit. The relation between PVS of particle velocity and the scaled distance from a production blast can yield an un-optimized charge weight per delay. In combination with field data analysis and an advanced blast vibration model, charge weight per delay and the delay timing of a production blast is optimized for a vibration limit in terms of PVS of particle velocity and frequency of the vibration for maximum productivity. The results of the study were successfully implemented in the quarry.

2 CURRENT BLASTING PRACTICE AND VIBRATION LIMIT TO MEET

The blasts at the quarry normally consist of two rows and a total of 30 to 40 blast holes. The blasts employ a single deck in each blast hole with an average charge weight of 300 kg per hole. The blast hole diameter is 114 mm. The bench height is 24 m on average. The blast pattern is 4 m in burden and 5 m in spacing. The rock type is a hard limestone. Pyrotechnics delays are used down the blast hole.
The blast holes were delayed 25 ms between blast holes in the same row and 217 ms between the rows. Figure 1 shows a plan view of the blast with the delay timing marked at each blast hole. As shown, the time interval between some of the blast holes in the first and second row is only 8 ms (217 ms for the 1st hole in the second row and 225 ms for the 10th hole in the first row). Three vibration monitors at various distances behind the production blast are also shown in the figure (to scale).

The city regulators established 85 mm/s as the blast vibration limit at the city boundary. Before the recommendations were implemented from the present case study, the blasts were conducted 180 m away from the city boundary and the blast vibration was below the vibration limit. However, the blast vibration reached 650 mm/s at 30 m from the last row. Since the quarry was planning to mine the rock at 30 m from the city boundary, the blast vibration had to be managed when the blasts progressed towards the city boundary.

In order to best manage the blast vibration while achieving maximum productivity, a project of blast vibration monitoring, analysis, and modeling was conducted at the site. This included blast vibration monitoring of both signature holes and production blasts. The collected data and the blast vibration modeling using the multiple seed waveform vibration model (MSW), developed in recent years within Orica (Yang & Scovira 2007, Yang et al. 2008), provided optimized blast design options to control the blast vibration for blasting progressively towards the city boundary up to 30 m to the boundary.

1. Firstly, the vibration characteristics can be accurately related to the charge weight and distance. Such a relationship is site specific and can be used to model blast vibrations from a production blast at the same site. In contrast, it is not easy to correlate a peak in a vibration trace from a production blast to a particular charge. This is because the vibration trace recorded from a production blast could be superimposed from several blast holes depending on delay timing among the blast holes.
2. Secondly, the vibration waveforms measured at various distances from the single hole blast can be used as seed waveforms to model blast vibrations from a production blast.
3. From the recorded waveforms, the ground resonant frequency and the range of vibration frequencies that the ground supports can be estimated.
4. In addition, the signature hole blasts can also be used to estimate the ground sonic velocity that is required for blast vibration modeling and is also useful for estimating the mechanical properties of in-situ rock.

The signature hole vibration data was collected from blasts of eleven single holes at the site. Four blasts were fired with 2–3 signature holes in each blast. The delay between two signature holes was 1500 ms to separate the waveforms for independent processing. A total of sixty vibration waveforms were recorded from signature hole blasts. Five to six tri-axial accelerometers were used as vibration sensors at various distances in each blast. Each signature hole blast had vertical and horizontal free faces that had similar conditions compared to a blast hole in the production blast (with a surface burden of 5 m in average).

3.1 Ground sonic velocity

An apparatus was built in-house to record both the detonation time of a signature hole and its vibration at a monitoring location on the same time base. The accelerometers were plastic bonded to the rock surface after the topsoil was stripped. The distance between the charge and the vibration sensor was measured with GPS surveying. Figure 2 shows a signal of detonation time along with blast vibration recorded on a monitor. In order to display the arrival time of the p-wave (not the surface wave) of the vibration signal, the recorded vibration signals were expanded on the vertical axis in Figure 2 and the “clipping” of the signal in Figure 2 is not from the original signal. The distances from the initiation point of the charge to the sensor for the sonic velocity measurement vary from 24 m to 50 m and the effects of rock joints and discontinuities on the sonic velocity were included in the measurement.

3 SIGNATURE BLAST HOLE VIBRATION MONITORING

Single blast hole vibration data is useful in several aspects.
A total of eight measurements were made and an average ground sonic velocity was obtained as 2328 m/s. The field sonic velocity of the rock mass is normally lower than that measured from a laboratory rock specimen.

3.2 Resonant frequency and frequency range that ground support

From dynamic mechanics theory, a system with a single degree of freedom has one resonant frequency (Timoshenko 1937). A blast overburden or a site is a continuous deformable body and has in principle infinite degrees of freedom. Consequently, the overburden of a blast has an infinite number of resonant frequencies. Practically speaking only the range (bands) of the resonant frequencies can be estimated. For a given ground condition, the range of the resonant frequencies may vary insignificantly for a relatively small change of the distance. A range of the resonant frequency may be used for this application.

The ground resonant frequency can be estimated using a single blast hole detonation as input to the ground and measuring the dominant frequency of the ground response or the frequency corresponding to the peak amplitude in the spectrum. In this case, the input to the ground from the detonation of a single blast hole is approximated as a delta function in the time domain or as a function in the frequency domain of constant amplitude, as shown in Figure 3. The dominant frequency from the response of a structure to a delta function input is the resonant frequency of the structure. The dominant frequency of signature hole vibration can be considered to be the resonant frequency of the ground.

The dominant frequency for a set of triaxial vibration waveforms can be obtained from summation of Fast Fourier Transforms (FFT) of the tri-axial components of the particle velocity waveforms. In this way the relative contribution from each component is automatically taken into account. The dominant frequency is defined as the frequency at which the amplitude is the maximum over the whole frequency range ($\omega_r$ in Figure 3).

Ideally, detonation from a spherical (point) charge gives a better approximation of the delta function than a long cylindrical charge. However, there is often a need to use signature hole vibration traces to model blast vibration from a production blast. The charge configuration of the signature hole blast is selected to be typical of the loading for the production blast. Therefore, the estimate from the dominant frequency of a signature hole blast vibration provides an approximation of the ground resonant frequency.

From limited signature hole blasts at the site, it was estimated that the resonant frequency was within the range of 8–32 Hz for the distance from 20 m to 70 m (where the signature blast was monitored). Figure 4 shows that there is no substantial vibration amplitude beyond approximately 120 Hz.
In other words, the ground cannot support vibrations with a frequency greater than 120 Hz.

3.3 Signature hole vibration PVS of particle velocity vs. scaled distance

Figure 5 shows the signature blast PVS of particle velocity of the vector sum of velocity waveforms against the charge weight scaled distance. The correlation coefficient of the best-fit is 0.93, indicating a strong correlation between the PVS of particle velocity and the scaled distance. The curves for the upper bounds of 84% (one standard deviation above the best-fit) and 97% (two standard deviations above) are also displayed in the figure. The regression equations are shown in the figure. The equations can be used to determine charge weight per delay and input to the blast vibration model.

4 PRODUCTION BLAST MONITORING

A total of six production blasts were monitored using the layout shown in Figure 1. The blasts were loaded with single deck charges and initiated with non-electric detonators. Figure 6 shows the production blast PVS of velocity waveforms against the minimum charge weight scaled distance. The concept of the minimum scaled distance is described in Yang et al. (2008). The correlation coefficient of the best-fit is 0.84, indicating a strong correlation between the PVS of particle velocity and the minimum scaled distance. The curves for one and two standard deviation upper bounds are also displayed in the figure. The corresponding equations are displayed in the figure and they can be used to estimate charge weight per delay for vibration control.

5 DETERMINATION OF CHARGE WEIGHT PER DELAY

From the relationship for signature hole PVS of particle velocity and the scaled distance in Figure 5, the allowed charge weight per delay for a given vibration limit can be obtained under a selected probability. The vibration in Figure 5 was from a single-hole blast and there is no blast vibration superposition from other blast holes. Therefore, the vibration from a signature hole blast could be lower than that from a production blast with the same charge weight per delay. Therefore, the allowed charge weight from the signature hole vibration indicates an upper limit of charge weight per delay in designing a production blast under a vibration limit. On the other hand, the relation for the production blasts in Figure 6 can lead to overly conservative estimate for the charge weight per delay since the production blasts from which the data were collected were initiated with pyrotechnics detonators and the vibration could be substantially overlapped from blast holes. Table 1 lists the charge weight estimate for a vibration limit of 85 mm/s. As seen from the table, the production blast vibration data in Figure 6 provides much more conservative charge weight estimate for the vibration limit than the signature hole vibration data.

The estimated charge weight per delay in Table 1 cannot provide any information about different delays. In order to obtain a well-tuned charge weight per delay and delay timing of a production blast, blast vibration modeling was conducted using the MSW Blast Vibration Model (Yang & Scovira 2007, Yang et al. 2008). The PVS of particle velocity and the frequency of the vibration were managed within the vibration limit for maximum productivity.
6 MULTIPLE SEED WAVEFORM VIBRATION MODEL AND MODELING

6.1 Model concept

At present, most existing vibration models are designed for far-field vibration prediction (Wheeler 2006, Hinzen 1988). In far-field vibration the variation in distances from different blast holes to a monitor are insignificant as shown in Figure 7a. Typically these models do not account for waveform changes from different blast holes. Consequently, all of these models use only one set of the same seed wave to represent each blast hole in a blast for modeling vibration at a given point of interest.

However, for near-field blast vibration the differences of distances between blast holes and a monitor are significant, compared to the distance from the center of the blast to a monitor, as shown in Figure 7b. The case of the present study is a typical example of the near field blast vibration since the length of the blast was 120 m and the city boundary is only 30 m from a blast. In this case, the vibration from a hole closer to a vibration monitor contributes a vibration of significantly higher amplitude and shorter duration than one from a blast hole farther from the monitor (Figure 7b). The increase of the waveform duration (waveform broadening) could be attributed to two mechanisms: frequency attenuation and asynchronous propagation of different wave types over the travel distance (Yang & Scovira 2008).

The MSW model uses multiple sets of seed waveforms (Figure 8) and transfer functions to model the vibration waveform change from different blast holes to a given point of interest. In addition, the screening effect of the broken ground from earlier firing holes within the same blast in the path of vibration is also modeled using a screening function described previously (Yang & Scovira 2008). Consequently, the MSW model is suitable for both near and far field blast vibration predictions.

To model the vibration at a point of interest from a production blast, a signature wave (three tri-axial components) is selected for a blasthole according to the nearest-smaller distance of the signature wave ($d_{s,k}$) compared to the distance ($d_{hl}$) from the blasthole to the monitor in the production blast (as shown in Figures 8 and 9). The change in
The waveform change over the distance difference $\delta d = d_{lsd} - d_{sd}$ is modeled with the Kjartansson transfer function—a constant $Q$ model (Kjartansson 1979).

The Kjartansson transfer function was successfully used for modeling both amplitude and frequency attenuations of seismic waves at lower strains typical to the far-field regime (Kjartansson 1979, Blair 1987, Kavetsky et al. 1990). It assumes that the rock exhibits linear visco-elastic behavior. However, in the near-field, particularly in highly non-linear soft ground, the Kjartansson transfer function is not suitable for modeling amplitude attenuation. On the other hand, it may still be a useful choice for modeling frequency attenuation for near-field blast vibration since it is one of the simplest models for the frequency attenuation and the latter is the major phenomenon for the waveform change over a small distance ($\delta d$). Consequently, in the MSW model, the Kjartansson transfer function is not used for amplitude attenuation. The vibration amplitude is determined from the non-linear charge weight scaling law established from the signature hole vibration. However the frequency attenuation, that produces a modified wave shape is adopted from the Kjartansson transfer function.

It is worth mentioning that the MSW model prediction is not sensitive to the rock quality factor $Q$. This is because the wave transformation by the transfer function is minimal if seed waves recorded at distances of small increments (e.g., 15 m) are comparable to the distances from the blast holes of the blast to the points of interest.

By employing multiple seed waveforms, $p$, $s$, and surface waves from charges at different distances can be included in the model. Waveform changes in amplitude, frequency, and duration due to the mixture of wave types and frequency attenuation with distance are automatically taken into account by the multiple seed waveforms. In addition, some geological effects on different seed waveforms can also be input to the model.

Table 2 displays the multiple seed waveforms used in the modeling along with the distances where the seed waves were recorded. The time window of the display for each waveform is 200 ms except that the seed wave recorded at 79 m is displayed with a time window of 300 ms since its duration is longer than 200 ms. As can be seen, the seed waveforms change with distance. It is important to use seed waveforms measured at a distance representative of the distance between a blast hole and a monitor location. For example, when modeling the contributions from a blast hole to a monitor point at a distance of 23 m, the seed waveforms measured at 21 m are used (the distance from Table 2 next lower than the actual distance). The waveform change over the remaining unmatched distance (2 m) is modeled using the transfer function.

### 6.2 Model prediction vs. measurements

Signature hole waveforms in Table 2, the ground sonic velocity of 2328 m/s, and signature hole PVS of particle velocity attenuation of the best-fit in Figure 5 were used as input to the MSW vibration model. Since there is no measurement for the seismic rock quality factor $Q$, a value of 50 for $Q$ was selected for a moderate hard rock.

With a number of seed waves recorded at distance increments comparable to the distances from...
the blast holes to the points of interest, the MSW model prediction is not sensitive to the rock quality factor Q since the wave transformation by the transfer function is minimal.

Figure 10 shows the predicted versus the measured PVS of particle velocity. For the scaled distance ranging from 1.2 to 3.6, the difference of the regression lines between the model prediction and the measurement is less than 20% (Figure 4). The small discrepancy between the model prediction and the measurement could be due to the limited number of data points (18) obtained. At a scaled distance of less than 1.2 the model over predicts the vibration. This could also be due to the limitation of the linear superposition of the model. At such a small value of the scaled distance (close to or less than 1), the non-linear model (MSW NL) may provide better predictions (Yang & Scovira 2008). After the test of the model in Figure 10, confidence in using the model to assist the design of blasts was established at the site.

6.3 Modeling charge weight per delay at distance 30 m and 55 m to city boundary for given delay interval

As described above, the city imposed a vibration limit of 85 mm/s at the city boundary. From the signature hole vibration analysis, the potential maximum charge weight per delay was listed in Table 1. If a suitable inter-charge delay is selected in such a way that the overlap of blast vibrations from different blast holes is minimized, the maximum charge weight per delay from the signature blast may be implemented in the blast. The longer the delay, the smaller the vibration overlap. However, an excessively long delay between charges could have adverse effects on blasts. For example, rock motion caused from an earlier firing deck could
30 m and 55 m behind the last row. Delay times of first decks in each hole are displayed in the blast patterns. The delay between decks is 25 ms and only one delay interval exists in a blast, in contrast to the blast in Figure 1 where two intervals exist, 8 ms and 25 ms. Five monitor locations are assumed with predicted PVS of particle velocity marked beside each monitor.

The recommended blast designs have been implemented at the site. The blast vibration has been managed in accordance with the vibration limit since the new blast designs were implemented.

6.4 Frequency shifting of vibration from the new design

Shifting vibration frequency has been an issue of long debate in the blast vibration community (Blair & Armstrong 1999). With the time scatter of pyrotechnic detonators, it was hard to test if shifting frequency was possible at a site. Consequently, with the pyrotechnic detonators, the blast vibration control is mainly concentrated to the amplitude control (e.g. PVS of particle velocity). Very few documented case studies on vibration frequency shifting were reported from literature. Today with accurate timing of electronic detonators, shifting frequency becomes feasible (Wheeler 2005, Yang et al. 2009).
Although the vibration model can predict vibration waveforms from a production blast, it is not easy to quantitatively compare predicted and measured vibration waveforms. Instead, comparing the amplitude spectrums in frequency domain is more revealing. Figure 13 shows a typical amplitude frequency spectrum with the previous timing design shown in Figure 1. The dominant frequency of the vibration is around 20 Hz with energy peaks in the range of 15–30 Hz.

Figure 14 shows that the dominant frequency of the blast vibration from the new design is concentrated at 40 Hz with a single delay interval of 25 ms between decks. The predicted and measured frequencies agree well, as shown in the figure. As discussed in the previous section (also Figure 4), the resonant frequency of the ground is estimated to be within 8 to 32 Hz. Therefore 40 Hz is out of the range of the resonant frequency and is preferable for reducing the ground resonance (vibration). However, since the ground could support even higher frequencies (as discussed previously), frequency of the vibration may be further optimized in a future study.

7 CONCLUSIONS

The integral techniques of blast monitoring, analysis and modeling, developed during recent years by Orica have been applied successfully in quarry blasts. Signature blast hole vibration monitoring provided important information on several aspects for blast vibration management at the site.

The relationship between PVS of particle velocity and the scaled distance from the signature hole vibration provided an upper limit of the charge weight per delay for a given vibration limit. The blast monitoring of production blasts bench marked the practice before introducing the improved design from the present study and provided testing of the blast modeling at the site.

With the vibration modeling using the MSW model, charge weight per delay of production blasts is optimized for maximum productivity while controlling the blast vibration under the vibration limit in terms of PVS of particle velocity. The selected delay timing yielded favorable frequency shifting for the vibration.

The MSW model has several advantages over most existing models in terms of modeling waveform change over distances, p-, s-, and surface waves in vibration propagation, more in-situ geological effects, and broken ground screening. It can model the blast vibration PVS of particle velocity and frequency reliably. With this advanced tool, further improvement of the blast design at the site may be conducted in a future study.

REFERENCES


