Destructive Wave Interference in Underground Blasting Utilizing Precise Timing.

AUTHORS

Braden Lusk, Dr. Paul Worsey – University of Missouri-Rolla
Kurt Oakes – Orica USA
Jerry Chambers – ETI/ Explosives Energies, Inc.
Scott Crabtree, Tony Brasier – Springfield Underground
Randy Wheeler – White Industrial Seismology

ABSTRACT

Destructive wave interference has been studied in theory for many years. In application however, limited information can be found. Recently, circumstances have enabled a multidisciplinary team to utilize electronic detonators and seismograph analysis to create destructive wave interference in an underground production blasting application. Springfield Underground, located in Springfield, MO, in conjunction with Orica, ETI, White Industrial Seismology, and the University of Missouri – Rolla has shown the ability to use destructive wave interference in underground blasting to reduce ground vibrations directly above.

Springfield Underground is approaching an area in their underground workings where ground vibrations from blasting experienced on the surface are of particular interest. With only eighty feet of cover, Springfield Underground must tunnel directly beneath the Springfield Municipal Water Supply Tanks. Limits for ground vibrations, regardless of frequency, have been set at 2.0 inches per second by consultants retained by Springfield Underground. The current blasting practices at Springfield Underground consist of a traditional V-Cut pattern with conventional pyrotechnic timing in a room of 50 feet wide and 32 feet tall.

In order to reduce ground vibrations to an acceptable level, Orica’s i-kon-System of programmable electronic detonators were used in the same pattern and seismic analysis provided an appropriate resonant frequency for the ground between the blasts and the surface. Using this information, the team was able to design a timing sequence that drastically reduced ground vibrations to an acceptable level even at eighty feet to the surface. Through the use of seismic technology and software, as well as precise accurate timing with electronic detonators, Springfield Underground can now proceed with the development of these reserves.

The paper discusses the process by which the reduction in vibration was achieved in practice, as well as a technical explanation of the effects of destructive wave interference and sacrificial holes.
INTRODUCTION

The application of destructive wave interference to reduce localized blast vibrations has been discussed in theory for many years. The theory involves creating a timing pattern such that blast waves peak on intervals that are half of the resonant frequency of the ground at the monitoring location. Once the frequencies and timing are determined, the premise is that peak particle velocity can be reduced by creating destructive interference between each delay in the blast. Only one problem wave remains if destructive interference can reduce vibrations within the shot. The problem wave is that from the first hole in the blast. Since there is no other wave to interfere with the amplitude of the initial wave, it continues unhindered to the area of interest. To combat this initial peak, a sacrificial or satellite hole of reduced intensity can be detonated first in the shot to interfere with the larger vibration emitted from the first production hole in the blast. The sacrificial hole also serves to provide additional relief for the initial production hole. Until recently, the ability to test the theory has been hindered by the lack of precision in commercial detonators. With the continued improvement and development of programmable high accuracy, high precision electronic detonators, the application of destructive wave interference is not only possible, but may be advantageous or even necessary for many operations.

One such case involves an underground limestone operation in Springfield, Missouri. The active workings of Springfield Underground have been approaching a Springfield Municipal Water Supply structure only eighty feet above the working horizon. Engineers utilized by Springfield Underground set a maximum peak particle velocity (ppv) at the tanks of 2.0 inches per second regardless of frequency. Previous measurements have shown that at this distance and orientation to the surface, traditional V-Cut rounds utilized by Springfield Underground produce ppvs on average above 3.0 inches per second. With the presented task of reducing vibrations in a localized area, members of a diverse team from many different companies began exploring the use of destructive wave interference. To produce a blast with the required timing accuracy and precision, Orica’s i-kon System of electronic detonators were used. After initial seismograph readings were analyzed, a resonant frequency was established and work began developing a timing sequence that would provide acceptable ground vibrations. Although not every blast produced vibrations under 2.0 inches per second at eighty feet, the average peak particle velocity of the shots utilizing destructive wave interference was 1.98 inches per second. Furthermore, development of an improved timing sequence is ongoing and several ideas remain to be evaluated.

PROCESS DESCRIPTION

The project team involved members from Springfield Underground, Orica, ETI, White Industrial Seismology, and UMR. The scope of the project was to reduce ground vibrations from typical underground production blasts to an acceptable level at a distance of eighty feet directly above the underground blast. The target was 2.0 inches per second. A series of thirteen electronic detonator blasts and five traditional non-electric blasts were monitored during this project. Each shot was monitored with an array of three seismographs on the surface. However, for the purpose of this paper, the data has been limited to the recordings made directly above the headings. The additional data does not add relevant information. Along the same line, only
the vertical seismic wave traces are presented. The vertical wave was always where the peak vibration occurred, and therefore horizontal sensor orientations are only of secondary importance.

Initially, timing for the electronic detonators utilized the same blast timing as traditional non-electric detonators used at Springfield Underground. The electronic detonators were programmed to replicate the theoretical timing produced by these pyrotechnic detonators, which can be seen in Figure 1.

![Figure 1 - Screen shot from ShotPlus-i showing the standard pyrotechnic delay pattern used at Springfield Underground. The timing was also replicated using Orica i-kon electronic detonators for the initial characterization of vibration.](image)

The first task at hand in reducing the vibrations to an acceptable level was to characterize the resonant frequency associated with the geology in the localized area above the blast. Traditionally, vibration characterization of resonant frequency has been obtained by observing seismograms from single production hole tests (signature holes) at the desired distance. This method is utilized for accuracy in measurement due to the relative inaccuracy of conventional pyrotechnic detonators used for production blasting. In this case, non-electric delay detonators have been used for many years in production shots without reason for this type of characterization.
A visual comparison of waveforms shows that resonant frequencies can be determined with electronic detonators without disrupting production requirements. Figures 2 and 3 are vertical vibration seismograms collected eighty feet directly above each blast. Figure 2 is the vertical seismogram for a typical V-Cut round using non-electric detonators at Springfield Underground. Figure 3 is the vertical seismogram for the same V-Cut design and timing using Orica’s i-kon System. It is simple to determine that waveforms and frequencies from individual hole detonations can be determined from the electronic detonator blast, but cannot be determined in the equivalent non-electric blast.

Figure 2 — Typical V-Cut production round at Springfield Underground. The figure shows the vertical seismogram for a non-electric detonator round. Notice clipping of waves. PPV = 3.00 ips.

Figure 3 — Equivalent V-Cut production round at Springfield Underground utilizing Orica i-kon detonators. PPV = 3.52 ips.
With the visual comparison of the two vertical seismograms, several items are noteworthy. First, the electronic detonator waveform is much cleaner than the equivalently timed non-electric seismogram. Also, with cleaner waveforms and a lack of interference, frequencies are visually higher in the electronic blast. Fourier Analysis of each seismogram supports this as seen in figures 4 and 5. The electronic detonator shot seismogram in Figure 3 also shows that the pyrotechnic delay timing is a particularly poor choice for this application. The waveform shows that peaks are building due to additive/constructive wave properties that occur when the delays are accidentally timed too close to the resonant frequency.

Closer analysis of the waveform shows that the electronic timed blast provides resonant frequencies entrained in the waves of the seismogram for the entire shot. The relatively large delays in the pattern allow for the wave of each individual hole to complete their cycle prior to any interference from subsequent holes firing. Thus at close ranges in the order of the eighty feet distance directly above the underground blast that these vibrations were collected, individual holes can be characterized quite effectively. It must be stated that in order to characterize frequencies with this method, close range monitoring is necessary. In the non-electric blast shown in Figure 2, delay inaccuracies in the detonators allow for waves to interfere due to timing conflicts. While this seemingly reduces particle velocities in the majority of the shot, it is worth noting that the initial wave on each blast creates a similar peak particle velocity for the entire shot. As in many cases the peak particle velocity comes from this initial hole or delay and dampens out in the body of the shot.

![Fourier Analysis](image)

Figure 4 – Fourier Analysis of Typical V-Cut production round at Springfield Underground. Notice a wide range of frequencies in the waveform.
Once initial characterization of the vibration was completed, a decision was made to attempt a combination of methods for reducing the vibrations to the 2.0 inches per second requirement. The 8 ms delay was selected as an optimum period because it satisfied the need to detonate holes very quickly within the “V”, while simultaneously providing good destructive interference. With close inspection of the seismograms, it can be seen that the optimum delay period could be from 8 ms to 12 ms depending on the particular wavelengths inspected. This corresponds to a resonant frequency of approximately 40 to 60 Hz. In addition to utilizing the optimum delay timing to create destructive wave interference in the body of the shot, a lightly loaded sacrificial hole was used on the first delay of the shot to interfere with the first production hole in the shot, but not create an initial troublesome full height peak particle velocity. Only by using high accuracy programmable detonators could this effort be possible. The timing for this fifth shot can be seen in Figure 6.
Figure 6 – Timing pattern selected to reduce vibrations on the fifth shot of the series. Key features of this pattern include the use of an eight millisecond delay between production holes for the majority of the shot and a sacrificial hole in the center of the V-Cut. The sacrificial hole was programmed to fire on the first delay of the blast, eight milliseconds prior to the first production hole.

A drastic improvement in ppv can be seen in the vertical seismogram (Figure 7) from the shot fired using the timing from Figure 6 programmed into electronic detonators. Hole loadings were not changed, yet ppv is nearly halved. The reason for lower ppv values is destructive wave interference. Noticeable clipping can be seen in nearly all of the wave forms in the seismogram in Figure 7. This clipping occurs due to waves interfering on intervals that are approximately half of the resonant frequency of the ground. This is not perfect due to the gaps in timing and not using the optimum timing delay interval throughout the shot. While the peak particle velocity is lowered, frequency ranges are also lowered compared to the shot characterized by Figure 3 due to the increase in wavelength caused by the interference. Fourier analysis of the seismogram in Figure 7 shows that the decreased frequencies are still not in the problematic range below 10 Hz (Figure 8).
Eight more blasts were monitored using similar timing and design as shown in Figure 6. Only minor changes were made to the blast design. Table 1 shows both electronic and non-electric shots in the series with their corresponding peak particle velocities. i-kon test 5 begins the combination sacrificial hole and interference timing. At this point, you can see a significant change in the ppv and frequency content.

After fully instituting the sacrificial hole and interference timing, the peak vibration levels ranged from 1.48 to 2.40 inches per second, with an average vibration value of 1.98 inches per second. This is a significant decrease over the vibrations from the pyrotechnic blasts which have averaged over 3.0 inches per second at 80 ft.

Although a significant reduction in ground vibration was achieved through the use of high accuracy programmable electronic detonators, seismograph and software technology, and application of destructive wave interference, further reductions could be achieved. While the sacrificial hole on the first delay of the blast is capable of reducing initial peaks with clipping, another peak occurs in the body of the blast that can not be reduced with a sacrificial hole. These peaks are produced when a gap in the eight millisecond delay timing occurs. There is concern with programming an 8 ms delay between every hole in the shot. Traditionally, V-cut
rounds have been designed to allow for the initial V to relieve and move prior to firing additional production holes. This extended delay period allows for wave interference to cease and thus require an initial peak before resuming ppv reducing interference between holes. It is believed that proper selection of hole sequencing could allow for a constant delay between every hole in the blast and not cause the round to “lock up”. This method has not been tested as of yet, but plans are in place to test the theory in the near future.

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Table 1 – Series shots with corresponding ppv.

**CONCLUSIONS**

This project has provided an opportunity to attempt the use of destructive wave interference in practice. The data shows that for localized vibration reduction, destructive wave interference is a valid method. A substantial reduction in ground vibration was realized through the use of highly accurate programmable electronic detonators and optimum delay timing near half of the resonant frequency of the ground. Also, the use of a sacrificial hole was key in reducing the initial peak from the first delay of the blasts. While not every blast was able to produce ppvs less than 2.0 inches per second, the average of 1.98 inches per second was nearly a 40% reduction over traditional pyrotechnic blasts. Further decreases are expected in future attempts.

Future test blasts will utilize the optimum delay timing throughout the shot, and potentially two to three sacrificial holes at the beginning of the blast. The first and second sacrificial hole will be loaded to one third and two thirds of a production hole respectively. These holes will aid in reducing initial ppvs in the blast.

A key element in the success of this research was the use of electronic detonators. The accuracy and precision required in the timing of the shot does not lend itself to any other type of initiation system. The Orica i-kon System of programmable electronic detonators performed very well and provided the accuracy needed for the project.
The future for electronic detonators underground may lie in the application of destructive wave interference. Utilizing electronics for underground aggregate production blasting is economically difficult due to cost; however, when vibration concerns result in the potential loss of reserves or abandonment of a civil project, electronic detonators may be necessary for reducing vibrations to acceptable levels, and could prove beneficial for reducing scaling, increasing pull depth, and improving fragmentation.
REFERENCES


