Field Applications and Quantification of Electronic Detonator Technology

By

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Abstract

Recent studies and limited tests indicate favorable results utilizing high accuracy electronic detonator technology over conventional non-electric pyrotechnic systems. This study discusses the application of this technology using the Daveytronic programmable system in an on-going production basis. The study quantifies the performance as it relates to fragmentation, excavation, vibration and productivity in an eastern U.S. aggregate mining operation.

In order to insure accurate data, tight field controls were adhered to during the drilling and blasting process as they related to blast design, bench preparation, pattern layout, drilling and blasthole loading. Following the blast the excavation and crushing procedures were studied to quantify any down stream advantages due to improvements in fragmentation.

This study will help provide the industry with information as to the advantages of high accuracy electronic blasting systems over conventional pyrotechnic systems and show the results of an operation utilizing electronic detonator technology through their production season.

Executive Summary

The purpose of this study was to quantify the field performance and mining productivity enhancements of the Daveytronic digital electronic detonator developed by the Davey Bickford Company. The field data gathered was evaluated to determine the relationship between high accuracy detonators and overall blast performance as typified by improved muckpile fragmentation, increased excavator productivity levels, crushing cost savings and minimized vibration impacts. The field tests were designed to provide data within the following parameters.

- Fragmentation
- Excavation Productivity
- Crushing Costs
- Ground Vibration

This data was obtained through the detonation and monitoring of a designed series of production blasts throughout the 1999 production season at the Martin Limestone Company's, Weaverland Quarry. The production blasts were geometrically identical and located in the north and south walls of Level 4 at the Weaverland Quarry.

The blasts were divided into two sub-categories:

1. Three baseline blasts using conventional non-electric detonators.
2. Six high accuracy detonator blasts using the Daveytronic detonators.

The quality of the test site and a high level of field controls were two primary factors that were maintained in order to provide accurate and meaningful results.

The gathering and quantification of data was obtained through the use of digital seismograph recordings, vibration modeling and prediction software, proprietary rock fragmentation analysis software, post blast excavation study, a crusher throughput study and a primary crusher power consumption study.

The comprehensive study of the data within the above parameters provided vital information characterizing the benefits of using the Daveytronic detonator and its relationship to overall blast performance. A partial listing of these benefits would include:

- Optimized use of explosive energy within the blast
- Precise control of hole detonation and burden dimensions
- Improved rock fragmentation and size uniformity
- Excavation and crushing productivity increases
- Increased primary crusher throughput
- Reduced crushing and excavation costs
- Improved public acceptance to blasting

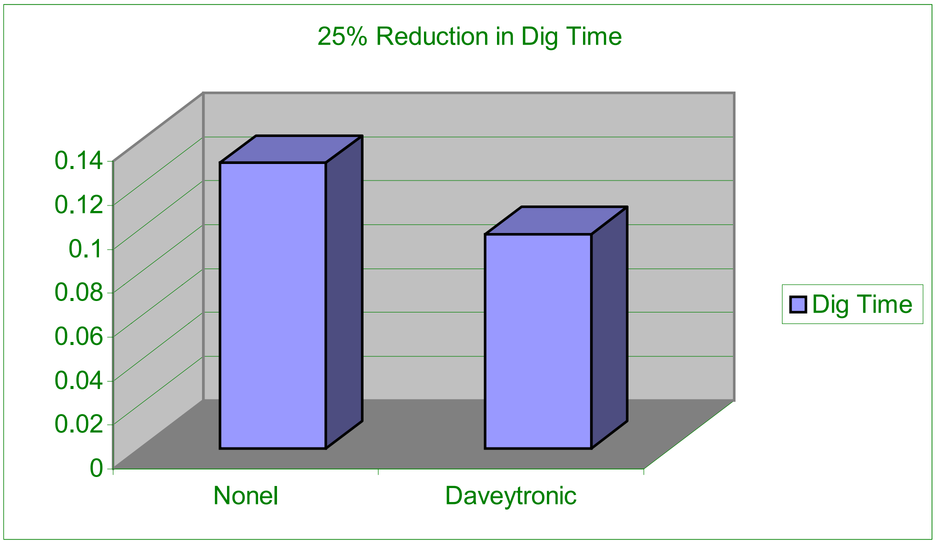
The analysis of the fragmentation data yielded results indicating that the post blast muckpiles from the test blasts utilizing the Daveytronic detonators were composed of a higher degree of fragmented rock with a more uniform size distribution.

Nonel Blasts	Mean Size (in)	8 inch minus % passing	Roslin - Rammler Uniformity Coefficient
AVG	**12.58**	**55.9**	**2.99**
Daveytronic Blasts	Mean Size (in)	8 inch minus % passing	Roslin - Rammler Uniformity Coefficient
AVG	**8.56**	**76.7**	**3.38**
Daveytronic Detonator	% difference in avg. Mean size	Increase in % passing	% increase in Uniformity
Total	**32% smaller**	**37%**	**13%**
North Wall	**34% smaller**	**41%**	**14%**
South Wall	**31% smaller**	**34%**	**12%**

The analysis of the crusher operator's daily productivity reports and primary crusher throughput data documented very little increase in the tons per hour through the primary crusher network. A slight increase in crusher productivity was measured for the North Wall blasts. However, the South Wall production levels were slightly below the baseline average. The re-direction of the blasts in the South Wall away from the newly developed sump pump station resulted in a less fragmented muckpile that reduced production. Presently, the south wall initiation point has been re-established to the eastern side of the bench and the overall blast performance has dramatically improved as it relates to fragmentation. Further analysis revealed that the secondary crushing and belt system could not facilitate any increase in stone throughput. Therefore the crusher operator manually limited the primary crusher productivity rate to better manage the total system. However, the kilowatt-hour per ton cost analysis of the electric power consumption of the primary crusher documented a 6-10% decrease in the power consumption per ton of rock associated with the increased rock fragmentation data.

Blast Number	**Primary Crusher tons / hr**		**Primary Crusher kWhr/ton**	**% Savings per ton**
24-G, pyrotechnic	657			
26-I, pyrotechnic	644			
27-J, pyrotechnic	673			
Avg. pyrotechnic	**658**		**0.163**	
Daveytronic Blasts				
34-Q, North	666		0.151	
35, South	689		0.139	
36-R, North	678		0.142	
41-W, South	599		0.162	
42-V, North	641		0.149	
45-Y, South	600		0.159	
Average N. Wall	**662**		**0.147**	**10%**
Average S. Wall	**630**		**0.153**	**6%**

The time study analysis of the post blast muckpile excavation indicated a 25% reduction in dig time that is directly proportional to the improved fragmentation data.



The findings during this study at the Martin Limestone quarry have provided dramatic evidence quantifying the benefits of using of high accuracy detonators in terms of improved blast performance as typified by:

- A 32% decrease in the mean size of rock in the post blast muckpile from 12.5 to 8.5 inches.
- A 37% increase in 8.0 inch and minus percent passing from 56% to 77%.
- A 25% reduction in the dig time to excavate the muckpile.
- A 6-10% savings in the primary crushing operational costs.

The blast induced ground vibrations exhibited consistent waveforms with no evidence of transient pulses yielding higher particle velocity levels. This is a direct result of the consistent controlled hole-to-hole burdens accurate hole timing provides. Transient vibration peaks usually indicate improper timing that results in charge detonation prior to the creation of a new free face from the previous adjacent hole detonation. This results in a highly confined charge incapable of overcoming the increased burden and the energy is then dissipated into the ground in the form of excessive vibration energy.

A signature hole blast and a frequency modification study was also conducted on a south wall production blast. This study resulted in significant decrease in the peak particle velocity and shifting of vibration energy into the frequency band above 30 hertz. The following sections of this study will in detail discuss the project scope, field procedures for the collection of data and the resulting data analysis and its interpretation.

Introduction

The last 20 years have shown dramatic progress in the advancement of blasting technologies, and the quality and performance of products. The introduction of the high accuracy detonator is reinforcing proper timing as a fundamental element of efficient blast design. The controlled sequence of hole detonation is one of the more critical parameters having a direct effect on overall blast performance in many ways.

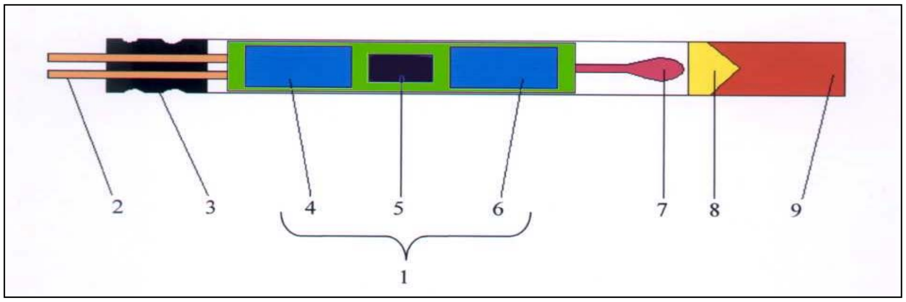
The measure of the potential effectiveness that the available explosives energy has to both break and displace the rockmass is directly proportional to the effective burden that energy must overcome. This relationship is a crucial element in basic blast design. Any variation in hole detonation timing results in that hole being fired prior to or after its nominal firing time. The hole-to-hole detonation could still remain properly sequenced, or holes could potentially detonate totally out of sequence. This will result in burden to energy relationships that can have adverse impacts on the performance of a blast. The results of these impacts have been witnessed in the past as:

- poor rock fragmentation.
- large amounts of oversize.
- high ground vibration levels.
- high air blast levels.
- flyrock incidents.
- increased need for secondary blasting.
- increased excavation and crushing costs.

Research has shown that the standard pyrotechnic delay elements that are currently being utilized throughout the world do not provide the accuracy's necessary to consistently and measurably mitigate impacts. Within the last 10 years several groups have produced and studied the high accuracy detonator. These studies have concluded that accurate hole detonation would provide the explosives using industry with the potential to effectively minimize these adverse timing related impacts. Even though this past research has quantified the positive results that high accuracy detonators would provide the end user, until the development of the "Daveytronic" detonator, manufacturers have not successfully

The Daveytronic

DAVEYTRONIC® Cross Section of detonator.



1. Circuit board IED assembly.
2. Duplex detonator wire.
3. Crimped plug.
4. Logic capacitor.
5. ASIC processor.
6. Firing capacitor.
7. Fuse head.
8. Primary charge.
9. Base charge.

undertaken the development of a high accuracy programmable digital electronic detonator on a full scale basis.

The testing procedures conducted at the Martin Limestone Quarry were designed to provide data to quantify the detonator's performance within the following parameters:

- Detonator accuracy
- Rock fragmentation
- Excavator productivity
- Crushing costs
- Ground vibration control and predictability

The scope of the testing program is as follows:

A series of test blasts would be detonated throughout an extended period of time during the production season at the quarry site. These blasts would be located in level 4 of the quarry. The maintenance of a high level of field controls during drilling, blasting and data collection processes to insure integrity of data was extremely important throughout the testing procedures.

The test blasts would be symmetrical to one another in terms of their geometry and loading parameters. They would, however, differ in the method and type of detonation system used. The first three blasts in the North Wall would be identically configured and fired using conventional non-electric system that has been utilized at this quarry for more than 10 years. The data from these blasts would serve to provide baseline information used for performance analysis comparisons.

The successive blasts detonated during the production season would be fired using the Daveytronic detonator. The programmable times input into these detonators would represent the nominal firing times of the non-electric designs. The overall blast performances would then be monitored, compared and quantified using the following instrumentation and techniques.

Digital ground motion seismographs were periodically placed at locations adjacent to the blast site to monitor and record the blast induced ground vibrations produced by the test blasting operations.

A south wall single hole test blast was detonated to establish the ground vibration signature of the site. This signature wave was then be used to implement a vibration modification software technique capable of predicting synthetic waveforms for production blast vibration prediction.

Following each blast, prior to any excavation, the muckpile dimensions were documented and the image of each muckpile was photographed and video taped for a optical fragmentation analysis. During the post blast excavation process video taping was also compiled of the muckpile interior to also be used in the fragmentation analysis study.

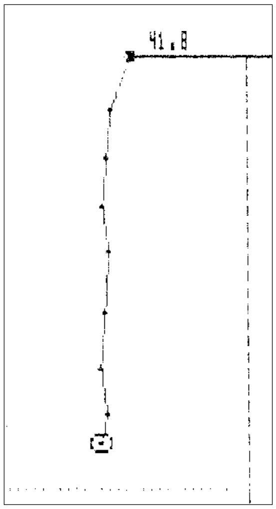
Throughout the study and field testing procedures many precautions were taken to insure the data collected would be truly representative of the actual performance of each individual blast. These field controls will be further discussed in the following section of this document.

Field Controls

In order for the data gathered during this study to be accurate and meaningful towards the goal of quantifying the performance differences between the conventional non-electric detonators and the Daveytronic detonators, close attention was paid to maintain a high level of field controls. These field controls were monitored and applied as they related to:

- Bench preparation
- Pattern layout
- Blast hole drilling
- Blast hole loading procedures
- Post blast data collection

The test bench encountered at the Weaverland Quarry was the quarry floor from a previous lift of level 3 stone. It was a level and uniform bench with very competent surface. This bench provided the drill very favorable conditions for easy accurate leveling and positioning of the drill during the drilling operations. The drill pattern was laid out for each blast using set back markers from the previous blast. A two-dimensional laser-profiling device was used prior to the loading of every face row blast hole to insure the proper burden to explosive load ratio was maintained. The final walls from each of the blasts were all relatively vertical with very little back break.



The implemented blast design during these test blasts utilized a 6.25 inch blast hole drilled to a bench depth of 50-55 feet with 4 feet of sub-drilling. The two rows of holes were drilled on a 17 ‘ X 18 ‘ (front row) and a 16’ X 18’ (back row) square pattern. The pattern of each blast consisted of two, 12 hole rows of blast holes. In order to insure proper toe burden dimensions, set back markers were placed prior to the detonation of each blast event to insure the proper placement of the following blasts face row of holes.

The production blasts treated in this study were loaded using an EX-700, 40% emulsion blend and SLX-600 packaged explosives in the bottom of each hole with the upper portions of the holes loaded with ANFO. The bulk products were manufactured by the St. Lawrence Explosives Company and the packaged SLX was manufactured by the Slurry Explosives Corporation. Prior to the blast hole loading each of the holes were again measured to verify the correct depth and the presence of water. If water was encountered, the holes were pumped and sleeved prior to the introduction of explosives. The following table provides the average blast geometry and the loading parameters of the production blasts.

Bench Height	53-55’	Explosives Used	40% emul. / ANFO
Sub Drill	3-5’	Primers Used	2 lb., 1lb. ,75 lb.
Blast Hole Length	53-55’	Explosive Density	0.85 – 1.25 g/cc
Burden (front)	16’	Explosive Diameter	6.25”
Burden (back)	17’	Explosive Length	42’
Spacing	18’	Explosives Weight	475-550 lb. / hole
Stemming	12’	Loading Density	2.5 – 2.7 tons / lb.
Stemming Material	3/8” Crushed Stone	Energy Factor	160- 165 kCal / hole
Rock Density	2.37 g/cc	Volume of Rock	1330 tons / hole

Each of the holes in the nonel and Daveytronic blast’s were double primed to conform with Pennsylvania State blasting regulations. The explosive column rise was carefully monitored at each blast hole to insure the proper explosive column height and the designed amount of stemming material.

The post blast data collection was conducted by Mr. Brian Wingfield of the Hall Explosives Company. The methods used to gather video data of the excavation procedures and the optical rock fragmentation images were systematically repeated for all post blast data collection periods. The power meters installed on the primary and secondary crusher systems provided real time data that was recorded daily by the crusher operator.

Fragmentation

The estimation and quantification of the size distribution of rock fragments is an extremely important operation in the mining and quarrying industry. Adequate fragmentation can be defined differently depending upon the type of operation that is using the material. The term “adequate fragmentation” typically refers to reducing the average size of the rock fragments, the elimination of oversize material, and maintaining the uniformity of the muckpile. No matter what type of operation, the primary stage of crushing is accomplished in the pit during the blast.

Minimizing the fragment sizes during the blasting operation with the use of chemical energy (explosive energy) can result in significant savings in the downstream costs of crushing that uses a much more expensive form of mechanical energy. Improved blast induced crushing will also realize cost saving through the lowered excavator and crusher maintenance costs.

This study quantifies the fragmentation performance increase realized in the pit using the chemical energy (explosives) more efficiently through the use high accuracy detonators. The precisely controlled release of explosive energy in a sequence of blast holes at firing times designed to provide the optimum Δt between hole yields maximum fragmentation. Poor fragmentation with a high percentage of oversize and non-uniform muckpiles are in part a result of energy losses encountered during out of sequence or improperly timed blasts.

The data was processed by the WipFrag photo image analysis system. The images were gathered using a Sony TRV-900 digital video recorder, transferred to disc and loaded into the image processor for delineation and size distribution analysis. The digital images were gathered during the excavation procedures at locations throughout the resulting muckpiles to insure the merged findings would be representative of the true level of blast induced fragmentation.

The majority of the images were obtained from inside the muckpile that were filmed during the post blast excavation of the rock. At intervals of approximately every 5 meters into the muckpile the excavator would pull back and permit the digital image recording of the exposed rock to be analyzed. This procedure was followed after each of the production test blasts, throughout the excavation of the muckpiles.

During the analysis of the images, the data files were saved in the system and used to create a merged analysis report. This report is very representative of the size distribution and uniformity of each of the resulting muckpiles during the testing procedures. The analysis of the merged fragmentation data yields results showing that the post blast muckpiles of the test blasts utilizing the Daveytronic detonators were composed of a higher degree of fragmented rock with a more uniform size distribution.

Nonel Blasts	Mean Size (in)	8 inch minus % passing	Roslin - Rammler Uniformity Coefficient
TB-1 , N	13.07	50.7	2.62
TB-2 , N	10.08	69.9	3.32
TB-3 , N	14.58	47.1	3.04
AVG	**12.58**	**55.9**	**2.99**
Daveytronic Blasts	Mean Size (in)	8 inch minus % passing	Roslin - Rammler Uniformity Coefficient
TB-34Q, N	8.6	76.7	3.50
TB-35, S	6.55	89	3.33
TB-36R, N	9.35	73	3.24
TB-41, S	11.43	56.7	3.19
TB-42, N	6.83	87.1	3.45
TB-45Y, S	8.03	79.5	3.54
AVG	**8.56**	**76.7**	**3.38**

Daveytronic Detonator	% difference in avg. Mean size	Increase in % passing	% increase in Uniformity
Total	**32% smaller**	**37%**	**13%**
North Wall	**34% smaller**	**41%**	**14%**
South Wall	**31% smaller**	**34%**	**12%**

According to the test data, the Daveytronic detonator blasts have demonstrated noteworthy increases in performance as it relates to rock fragmentation. The merged analysis of the Daveytronic blasts resulted in a 32% reduction in the average mean size of rock and a 37% increase in the 8 inch and minus screen size passing to nearly 77% passing. These numbers can be directly related to reductions in crushing costs and equipment maintenance costs. The 13% increase in the “Uniformity Coefficient” indicates that the fines and oversize content of the muckpiles have also been reduced.

The data also indicated slight differences in the fragmentation performance of the individual North and South production walls of the quarry. These differences correlate directly with the differences in the crusher and productivity data for these blast locations discussed in the “Productivity” section of this paper.

This fragmentation data is very typical of the fragmentation performance increases the Daveytronic system has demonstrated in all previous trials. It is the opinion of Daveyfire, that the overall fragmentation performance at this site could be further maximized through a refinement in the basic blast design parameters. The blast designs resulting in the above data were all identical using the original pyrotechnic blast design.

The review of the video recordings of the blasts verified that much of the oversized rock in the muckpiles originated from the cap rock above the level to which the explosives could be safely or efficiently loaded to maintain proper confinement levels.

Productivity

When comparing the overall performance of separate blasts as they relate to fragmentation, primary parameters to consider are the post blast excavation productivity, crusher throughput, and crushing costs. It is in these areas that the performance of differing blast designs will be accessed regarding their cost effectiveness. This discussion will primarily focus on the productivity differences in muckpile excavation, primary crusher throughput and primary crusher operating costs following the blasts at the Weaverland Quarry.

Blast Number	Primary Crusher tons / hr		Primary Crusher kWhr/ton	% Savings per ton
24-G, pyrotechnic	657			
26-I, pyrotechnic	644			
27-J, pyrotechnic	673			
Avg. pyrotechnic	**658**		**0.163**	
Daveytronic Blasts				
34-Q, North	666		0.151	
35, South	689		0.139	
36-R, North	678		0.142	
41-W, South	599		0.162	
42-V, North	641		0.149	
45-Y, South	600		0.159	
Average N. Wall	**662**		**0.147**	**10%**
Average S. Wall	**630**		**0.153**	**6%**

In the process of muckpile excavation the most important factors to consider are the "diggability" of the rock. This is the quantification of the actual time and energy spent digging the blasted material. An indicator of any increased level of fragmentation should be realized in faster digging rates of the excavator and reduced time to totally deliver the shot rock to the primary crushing system.

The excavation process at the Weaverland Quarry usually is accomplished through the use of three Caterpillar 773D 60 ton rock trucks and a Caterpillar 992 front end loader with a 13 yard rock bucket. During the shifts while the primary crusher is operating, records were kept regarding the source of the stone and the total tonnage of stone these trucks move to the primary during each shift. In order to obtain accurate and representative data, the excavation of each of the post blast muckpiles was closely monitored. The analysis of this information primarily focused on the shifts that demonstrated high availability of equipment and zero equipment failures or crusher shutdowns. These same operating hours that reflected un-interrupted typical throughput efficiencies during the excavation of each muckpile were used to determine the overall power consumption that the primary required to crush and convey the stone.

According to the operators' records, the summary of the data is as follows: The average primary crusher throughput of stone during the excavation of the baseline test blasts was 658 tons per hour. This is a relatively high number compared to the previous monthly average throughput rates of the primary. The records reveal that the throughput rates of the Daveytronic test blasts in the North and South Walls were 662 tons and 630 tons per hour respectively.

The electrical department of the quarry provided power consumption meters that were installed on the drive and belt motors of the primary and secondary crushing systems that were used to quantify the blast performance in terms of crushing cost savings.

The average kilowatt-hour per ton of stone power consumption to process the baseline test blasts was 0.163 kWhr / ton. The kWhr / ton consumption rates for the Daveytronic tests in the North and South Walls was 0.147 and 0.153 kWhr's / ton respectively. This data revealed a 6-10% percent savings in overall primary crushing costs through the use of high accuracy digital detonators.

Ground Vibration

Blast induced ground vibration is an impact from the use of explosives that has historically been an extremely difficult problem to effectively solve. There are many variables and site constants involved in the equation that when combined, result in the formation of a complex vibration waveform generated by the confined detonation of an explosive charge. The application of proper field controls during all steps of the drilling and blasting operation will help to minimize the adverse impacts of ground vibrations, providing a well designed blast plan has been engineered. This design would consider the proper hole diameter and pattern that would reflect the efficient utilization and distribution the explosives energy loaded into the blast hole. It would also provide for the appropriate amount of time between adjacent holes in a blast to provide the explosive the optimum level of energy confinement.

The parameters having the greatest effect on the composition of the ground vibration waveform are:

- Geology between the blast site and the monitoring location
- Accurate timing between blast holes in a detonation sequence

Throughout this study the ground vibrations generated by the production blasts were recorded at the Hoover residence east of the quarry site. The following tables summarize the seismic analysis in terms of the peak particle velocity and frequency content of the recorded vibrations.

Pyrotechnic Detonators

Blast 24G	Radial		Vertical		Transverse	
Seismograph Location / ft.	PPV (in/sec)	Freq. (Hz)	PPV (in/sec)	Freq. (Hz)	PPV (in/sec)	Freq. (Hz)
Hoover / 975’	0.16	24	0.15	38	0.22	24

Blast 26I	Radial		Vertical		Transverse	
Seismograph Location / ft.	PPV (in/sec)	Freq. (Hz)	PPV (in/sec)	Freq. (Hz)	PPV (in/sec)	Freq. (Hz)
Hoover / 1050’	0.13	19	0.13	31	0.2	23

Blast 27J	Radial		Vertical		Transverse	
Seismograph Location / ft.	PPV (in/sec)	Freq. (Hz)	PPV (in/sec)	Freq. (Hz)	PPV (in/sec)	Freq. (Hz)
Hoover / 1150’	0.23	22	0.18	55	0.28	29

Daveytronic Detonators

Blast 34Q,N	Radial		Vertical		Transverse	
Seismograph Location / ft.	PPV (in/sec)	Freq. (Hz)	PPV (in/sec)	Freq. (Hz)	PPV (in/sec)	Freq. (Hz)
Hoover / 1579’	0.22	22	0.10	63	0.22	25

Blast 35,S	Radial		Vertical		Transverse	
Seismograph Location / ft.	PPV (in/sec)	Freq. (Hz)	PPV (in/sec)	Freq. (Hz)	PPV (in/sec)	Freq. (Hz)
Hoover / 1210’	0.35	28	0.18	33	0.35	23

Blast 41W,S	Radial		Vertical		Transverse	
Seismograph Location / ft.	PPV (in/sec)	Freq. (Hz)	PPV (in/sec)	Freq. (Hz)	PPV (in/sec)	Freq. (Hz)
Zimmerman / 1372’	0.35	20	0.24	26	0.56	13
Hoover / 1145’	0.24	28	0.23	22	0.25	24

Blast 42V,N	Radial		Vertical		Transverse	
Seismograph Location / ft.	PPV (in/sec)	Freq. (Hz)	PPV (in/sec)	Freq. (Hz)	PPV (in/sec)	Freq. (Hz)
Hoover / 1478’	0.32	18	0.23	25	0.14	35

Blast 45Y,S	Radial		Vertical		Transverse	
Seismograph Location / ft.	PPV (in/sec)	Freq. (Hz)	PPV (in/sec)	Freq. (Hz)	PPV (in/sec)	Freq. (Hz)
Zimmerman / 1372’	0.18	33	0.22	32	0.11	34

A review of the ground vibration information indicates more consistency in the characteristics of the vibration waveforms generated by the north and south wall production blasts. The waveform amplitudes are generally constant during the blast event and do not exhibit transient spikes that typically occur whenever “scatter” in detonator timing yields over-confined explosive charges through improperly sequenced hole detonations. The reduction of these “transients” in blast induced seismic events will effectively increase the reliability and accuracy of regression analysis studies using high accuracy detonators.

On 10/19/99 a second seismograph was set up 1372 feet to the south of blast 41W at the Zimmerman residence. The location of the Zimmerman property is situated directly behind the south wall blasting area. The particle velocities and frequency information recorded indicated that there may be a tendency at this location to produce excessive low frequency high PPV vibrations. Vibration signals of this type are “undesirable” and usually associated with heightened human intolerance to blasting and increased structural response to blast vibrations.

Research developed by the USBM (United States Bureau of Mines), universities, and others over the last 15 years in the blasting industry has concluded that a residential structure’s level of response to a blast induced ground vibration is dependent on both the peak particle velocity and the frequency of the waveform. The frequency is the number of oscillations that the ground particles vibrate per second as a blast vibration wave passes by the structure’s location.

Above ground structures will resonate much like a tuning fork whenever they are excited by a vibration containing adequate energy matching the fundamental frequency of the structure. This value of this frequency is mainly dependent upon the mass, height and stiffness of the structure. The maximum response of a house to blast induced ground vibration occurs whenever the frequency of the ground vibration matches the natural resonant frequency of the house. Likewise, if there is little or no energy at the resonant frequency of the structure, the structural response to the vibration will be negligible.

Further studies have also shown that there are direct relationships between the firing times of blast holes in a detonation sequence and the frequency composition of the ground vibration recorded at a particular structure in question. These studies have also concurred that a total blast sequence is simply defined as a series of single hole detonations that are separated by a given amount of time (Δt). It is the relationship between this Δt and the geology of the site that has the most effect on the amplitude and frequency composition of the ground vibration wave. The geology is generally a constant in the equation but it will change as the blasting operations move throughout the mine or quarry.

This relationship between timing and geology has led to the development of several sophisticated computer programs to predict and modify blast induced ground vibrations. These programs process a single hole blast ground vibration signature at a given production blast location, and through thousands of mathematical iterations predict the synthetic waveform, its amplitude and frequency composition for any given Δt between adjacent holes in a row and Δt between consecutive rows in a blast.

The introduction of a high accuracy electronic detonator into the commercial explosives market is having many positive effects in the area of predicting and controlling blast induced ground vibrations. The success rate of these programs to provide repeatable results using pyrotechnic detonators has been very poor. Typically, the optimum or recommended Δt between charges is a value of delay time that can not be achieved through commercial pyrotechnic detonator systems. Even when the suggested times are achievable through combinations of available surface and in hole detonators, the inherent scatter in pyrotechnic based systems will cause the blast sequence to fire at actual times other than the designed nominal firing times. These variances from the nominal firing times can potentially result in actually magnifying the impact rather than mitigating it. The programmable digital detonators have overcome this limitation and provide the application of virtually any Δt between charge detonations in a blast.

A single hole test blast was detonated in the south production wall on 11/1/99 and was recorded at the Zimmerman residence. The “Fourier Frequency Spectrum Analysis” of this blast indicated that there is a very dominant low frequency characteristic at this recording site. The analysis displayed that both horizontal components yield a 17 hertz dominant frequency. It is the horizontal components of the vibration wave that have the most effect on above ground structures in terms of structural response. Typical residential structures, by their design, are more susceptible to induced resonant mid-wall bending and corner shear racking by the horizontal components of a blast induced vibration. The vertical components have more effects on the ceiling and floor shear responses.

The application of the vibration modeling and prediction technique using this signature hole data indicated that the dominant frequency domain could potentially be increased to frequencies above 30 hertz, outside the typical upper resonant frequency limit of residential structures. The computer analysis determined that the application of 31 ms between holes and 85 ms between rows would produce the most favorable blast induced vibrations.

Using the above firing times, blast 45Y was detonated on 11/16/99 in the south wall of the quarry. The ground vibrations were recorded at the Zimmerman residence. The peak particle velocity of 0.22 inches per second was more than 40% less than the levels generated by the single hole detonation on 11/1/99. The FFT analysis of the predicted synthetic waveform was compared to the blast 45Y actual recorded waveform. The FFT of the actual vibration data is extremely similar to the FFT of the predicted synthetic vibration signal yielding dominant frequencies in excess of 30 hertz. This data demonstrates the potential to reliably predict and modify the frequency characteristics of ground vibrations through the use of computer modeling techniques and high accuracy detonators.

Conclusion

The Daveytronic digital programmable electronic detonator trials that were conducted at the Martin Limestone Company's Weaverland Quarry during the 1999 aggregate production season have resulted in the acquisition of promising data. The testing procedures were designed to compare the performance of the Daveytronic detonator with a commercially available non-electric pyrotechnic delay system in order to quantify the benefits a high accuracy detonator would provide the end user.

The areas of performance quantification that were of most importance during the initial phases of testing this product were as follows:

- The quantification of improved rock fragmentation.
- Improved excavator productivity.
- Increased crusher throughput.
- Reduced crushing costs.
- Vibration frequency modification.

The field testing procedures were conducted within the 1999 quarry production season. The baseline pyrotechnic blasts, the single hole blast and the Daveytronic production blasts were detonated in a very safe manner by the Hall Explosives Company and with total cooperation Martin Limestone Company. The technical assistance offered by Mr. Brian Wingfield of Hall Explosives throughout the study to implement the Daveytronic system and gather the field data were greatly appreciated.

The rigorous analysis of the large amounts of data accumulated during the field testing procedures indicates that the introduction of the Daveytronic detonator into the commercial explosives market will provide the explosives industry with a very beneficial and necessary tool. The test data quantified positive trends in the overall blast performance within the test parameters treated in this study. This is a technology that the blasting industry has anticipated and viewed as a major technological advancement and quantum leap in the science of blasting. The accuracy and flexibility of the programmable detonator is providing the explosives industry with options never before available to optimize the timing designs for maximum benefits in the areas of ground vibration control and maximized fragmentation. The industry’s whole approach to blast timing design can now be focused on pure productivity and blast performance, rather than be restricted by the limited interval selections and inaccuracies the conventional pyrotechnics timing systems offer.

This testing program has provided conclusive data demonstrating notable improvements in overall blast performance. The study documented a major increase in rock fragmentation and its effect on downstream costs and productivity. All increases in blast performance and productivity were achieved without any optimization in the blast design. The continued implementation and optimization of the Daveytronic detonator at the Martin Limestone Quarry is currently in process. The production requirements of the quarry and the limitations of the secondary crushing system will permit the blast pattern to be expanded to a dimension effectively reducing the powder factor by 20 – 30 % without any negative effect in stone production. These design refinements will also reduce Drill and Blast costs that will in turn lower the per ton aggregate production costs. The implementation of optimized blast and timing designs at the Weaverland Quarry during the year 2000 production season will provide further data to be added to this study.

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