VibraMap and Site Attenuation Study
for
Cobleskill Stone Products, Inc.
Howe Cave Quarry
Cobleskill, New York

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Introduction

A vibration study was conducted by Vibra-Tech Engineers, Inc. at Cobleskill Stone Products's Howe Cave Quarry located in Cobleskill, New York. The vibrations produced by the detonation of one production blast and one single hole blast were monitored on February 28, 2006. This study was authorized by Mr. John Holmes of Cobleskill Stone Products, Inc.

The purpose of the study was to determine the effects vibrations from blasting in the west face area of the quarry will have on the Howe Caverns and on structures of concern in the community surrounding the quarry.

Vibra-Tech conducted a VibraMap study in order to characterize the vibration response resulting from the geologic conditions that exist between the Howe Cave Quarry's west face and the structures of concern in the community and to evaluate how these structures might respond to that vibration. The appropriate production blast firing times were determined to minimize the effects of blasting on the occupants of the structures. While conducting the VibraMap study, a site attenuation study was performed in order to define the equation of decay for the site. This equation can be utilized to determine proper charge weights for a given distance in order to maintain a given particle velocity at the Howe Caverns.

Field Procedure

One production blast and one single hole, or signature blast, were detonated on February 28, 2006. The maximum pounds per delay of the production blast was 426 lbs and the signature blast contained 935 lbs per delay.

Thirty-five GeoSonics SSU Microseis, one GeoSonics SSU 2000DK, four GeoSonics SSU 3000LCP+, one GeoSonics SSU 3000LC, and one Vibra-Tech Everlert III digital seismographs were utilized during this study. Thirty-four of the seismometers were deployed in a linear array starting approximately 258 feet east of the signature shot and running northwest toward Howe Caverns. Six seismometers were deployed at structures in the community surrounding the quarry. In addition, a Vibra-Tech Everlert III eight-channel digital seismograph and a GeoSonics SSU 3000LC digital seismograph was set up in the caverns to record the vibrations produced during the detonation of the two blasts. Two sets of three uniaxial geophones for the Everlert III were installed at two locations in the caverns. The first set of geophones (sensors 1, 2 and 3) was installed 143 feet east of the fans and the second set of geophones (sensors 5, 6 and 7) was 75 feet east of the fans. The both sets of geophones were 68 feet apart. For both sets of geophones, the vertical sensors were mounted to the ceiling, the horizontal sensors were mounted to the south and north wall of the cavern. The sensors were mounted to the cavern with metal plates and glue. The SSU 3000LC seismograph was placed inside the caverns 172 feet west of the fans at the end of the commercial tour area. The geophone was glued to a rock ledge approximately 6 feet from the floor on the south wall of the cavern.

Instrumentation

The GeoSonics SSU MicroSeis seismographs employed during this study are four channel recorders which directly measure particle velocity in three mutually perpendicular planes of motion. The fourth channel monitors air concussion effects. The GeoSonics SSU MicroSeis seismograph has a dynamic range up to 5.0 in/sec. The instruments were programmed to record vibration levels that exceeded a threshold level of 0.05 in/sec and 0.01 in/sec for seismograph with x4 amplification in the array toward the cavern. The record length was set at 5.0 seconds. The GeoSonics 2000 DK have a dynamic range up to 10 in/sec. The sampling rate is up to 1024 samples/second/channel. The instrument was programmed to record vibration levels that exceeded a threshold level of 0.05 in/sec and the record length was set to 5.0 seconds. The GeoSonics SSU 3000LCP+ and SSU 3000LC have a dynamic range up to 5.12 in/sec and the sampling rate is up to 1000 samples/second/channel. The instrument was programmed to record vibration levels that exceeded a threshold level of 0.05 in/sec and the record length was set to 5.0 seconds. The entire system is calibrated internally prior to each recording in addition to a yearly shake table calibration.

The Vibra-Tech Everlert III digital seismograph employed during this study is an 8-channel recorder that measures particle velocity on six channels and air concussion effects on two. The Everlert III has a dynamic range up to 10.0 in/sec. The sampling rate is up to 1024 samples/second/channel. The instrument was programmed to record vibration levels that exceeded a threshold level of 0.03 in/sec and the record length was set at 7.0 seconds. Six Geospace Model 20DX 8-Hz uniaxial geophones were utilized with this seismograph. Four of the geophones measured in the horizontal plane of motion (affixed to the cavern walls) and two measured in the vertical plane (affixed to the cavern ceiling). The entire system is calibrated internally prior to each recording in addition to a yearly shake table calibration.

The tri-axial geophone system utilized three 5-inch spikes to ensure proper coupling to the ground. In areas were rock was exposed at the surface or inside the cavern, the tri-axial geophone system was glued to the exposed rock.

VibraMap Technique

Theory of Technique

Research conducted by the USBM, foreign groups, and individual scientists has shown that low frequency vibrations have the most potential for causing structural response and therefore typically generate the most complaints. Field blasting seismology has shown that sites producing low frequency vibrations are commonly associated with thick soil overburdens or thick sequences of rock having low seismic velocity. In addition, ground vibrations may be multiply reflected by subsurface interfaces between geologic strata, including a shallow water table or fault planes. These reflections often result in low frequency vibrations. It is an intuitive fact that the geology of a site directly effects the characteristic of the seismic signal.

In October of 1983 Vibra-Tech Engineers, Inc. was awarded a mining research contract by the USBM to study the effects of geology on surface mine blasting. The research was completed in 1985 and is detailed in a Mining Research Contract Report entitled "Geologic Factors Affecting Vibration from Surface Mine Blasting". Research conducted during this study shows that the seismic signal from a single-hole blast recorded in the near field (< 100 feet) is an impulsive spike. But as the source signal moves away from the blast site, it is transformed by the geology along the travel path. A seismometer in the far field (> 300 feet) would measure how the geology has transformed the impulse spike. Figure 1 below shows how the geologic transformation function operates.

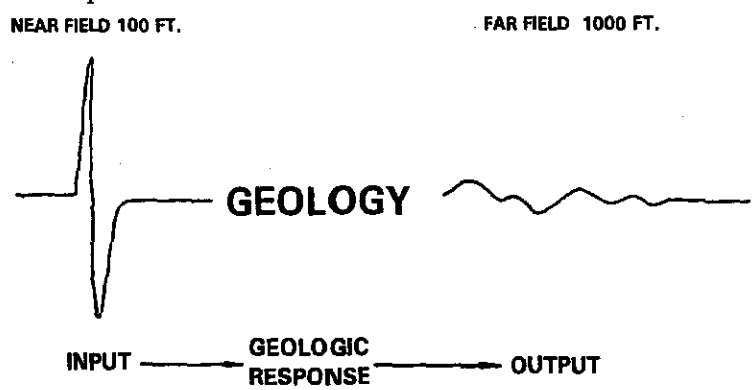

Figure 1. Geologic Transformation of Impulse Spike

The study further showed that two identical single hole blasts would produce reproducible time histories and frequency spectra for a specific seismometer location. Since a single hole waveform is a reproducible event, it is reasonable that the seismic signature from a multi-hole production blast can be predicted by summing a series of single hole waveforms that have been time-lagged at intervals corresponding to delay times from the production blast. Figure 2 on the following page shows how a synthetic seismogram for an 8-hole production blast can be created using this technique.

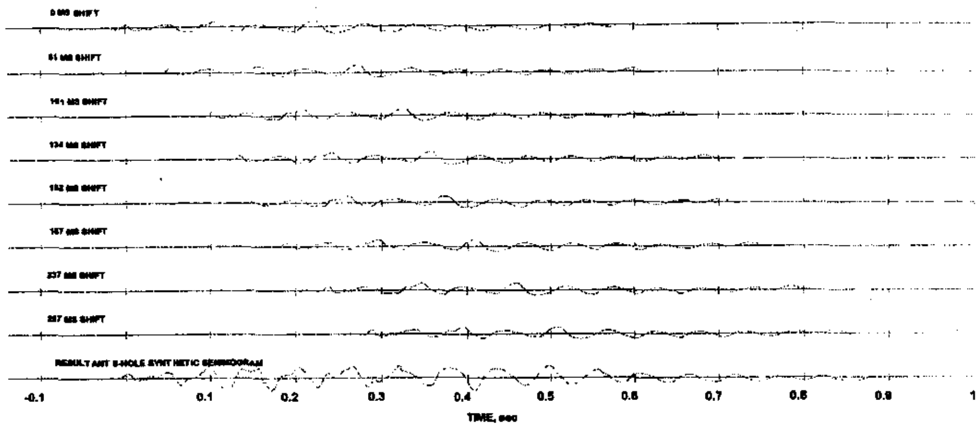

Figure 2. Creation of Synthetic Seismogram from Time Lagged Single-Hole Waveforms

The predicted waveforms were compared to measured waveforms. The comparisons showed that the character (frequency content & duration) of the waveforms was similar.

Since manipulation of blast delay times proved to be successful, it is possible to choose optimal blast delay times that produce minimal adverse vibrations. An optimum delay time would be one that creates destructive (out-of-phase) interference between the seismic signals from adjacent blast holes. A signal processing technique known as autocorrelation determines the correlation of a time lagged version of the original signal with the signal itself. The autocorrelation function can be used to calculate a lag (delay) time when adjacent single holes would be out-of-phase (minimum correlation) or in-phase (maximum correlation). The Figure 3 below illustrates this concept.

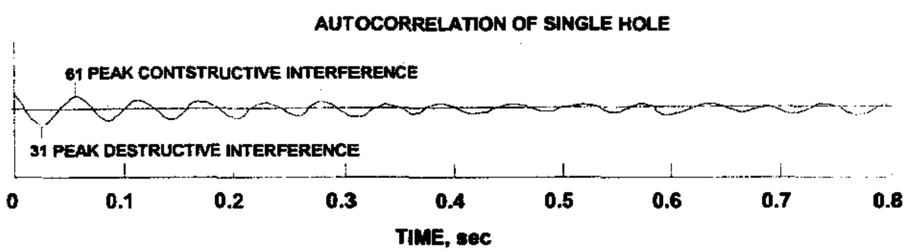

Figure 3. Autocorrelation Function Used to Calculate Lag Time

It can be seen from the figure above that a 61 ms delay interval between holes in a production blast would produce in-phase or constructive vibrations. Conversely, 31 ms delay between holes would create out-of-phase or destructive interference.

The VibraMap technique is a powerful, site specific method developed by Vibra-Tech to show the effect of various delay intervals on the predicted frequency spectra for a production blast. The technique convolutes a single hole frequency spectrum with the delay-time frequency spectrum. The result of this convolution is a Fourier spectrum of a synthetic waveform created by a constant delay interval. The Fourier spectrum for the waveform is plotted horizontally across the page. The delay interval is then incremented by 4 ms, a new synthetic waveform is created, and the Fourier spectrum of this new waveform is plotted horizontally across the page on the next line down. This process is repeated for an entire range of delay intervals. The horizontal axis of these plots represents vibration frequency, the vertical axis is delay interval, and the relative intensity of the color is proportional to the amplitude of the spectrum with the warmer colors (red - yellow) corresponding to maximum Fourier amplitudes, and cooler colors (blue - white) corresponding to minimum Fourier amplitudes. A representative suite of VibraMap plots for the signature blasts is included in Appendix A of this report.

This procedure is repeated in trial and error computer simulation of the ground vibration characteristics at each of the seismometer locations of concern for each desired blast configuration. Blast timing patterns which enhance the ground's low natural frequency vibration can produce geologic resonance. This resonance can increase ground peak particle velocity, vibration duration, and predicted structural response. Proper selection of delay intervals in the production blasting can minimize the energy at or near these natural frequencies of the ground, reducing ground vibration duration, peak particle velocity, and structural response. The final VibraMap recommendations represent the singular result of optimizing the vibration effects for all locations simultaneously.

The ultimate goal of a vibration control program is to avoid ground vibrations that closely match the natural frequency of nearby structures. By avoiding constructive interference at the resonant frequency of each particular location, vibration amplitude and duration may be reduced. In this way, the VibraMap addresses all three contributors to structural response: ground vibration frequency, amplitude, and duration.

Discussion of VibraMap Analysis

One single hole charge was detonated in the Howe Cave Quarry on February 28, 2006. Since the VibraMap calculations are dependent on the source-receiver path, the placement of the single hole charge is an important parameter. The placement of the single hole charge was determined by Vibra-Tech and North American Quarry & Construction Services so as to optimize the coverage for current and future mining operations. Vibra-Tech has performed the VibraMap calculations for the signature blast at the request of Cobleskill Stone Products, Inc.. The data will be stored by Vibra-Tech for use in VibraMap calculations of other blast designs in the future if desired.

Recommendations

In making the VibraMap calculations, we have assumed the bench height will remain approximately 87 feet with a borehole diameter equal to 6.5 inches. Holes will be deck loaded with two columns of explosives separated by a 5-foot inert deck. These designs assume that nonelectric initiators will be used to detonate the explosives, based upon information provided by Cobleskill Stone Products and North American Quarry & Construction Services. The recommended delay times are given according to the closest commercially available delay times offered by the explosive manufacture. Because VibraMap employs destructive interference between individual blast hole vibrations, better results may often be achieved by the addition of an additional row. The VibraMap calculations are intended to reduce not only structural response but also geological response. As such, the duration of the ground vibrations will not necessarily increase when the duration of the blast increases.

For the single hole signature blast detonated in the Howe Cave Quarry, the VibraMap analysis indicates that the following delay intervals would significantly reduce the high Fourier amplitudes at the low frequencies. VibraMap analysis was based on two rows of seven holes with two decks per hole. Blasting delay times in order of preference are: 17 ms deck time x 34 ms hole time x 84 ms or 93 ms row time, 9 ms deck time x 25 ms hole time x 67ms row time, and 25 ms deck time x 34 ms hole time x 84 ms row time. The production blast detonated along with the single hole signature blast had 127 ms between the first and second rows and 93 ms between the second and third rows. As indicated above, the VibraMap analysis recommends the 93 ms row time as one of the two best times. The 127 ms row time should be avoided since it produces higher levels of low frequency energy. The recommendations discussed above satisfy the objectives of the VibraMap:

1. Minimize the Fourier amplitudes in the 3 to 12 Hz frequency range, the natural frequency of many types of structures.

2. Minimize the Fourier amplitudes near the natural frequency of the recording location thereby reducing both peak particle velocity and vibration duration.

3. Adherence to recognized safe production blasting practices.

The results of the VibraMap calculations for the single hole shot detonated at the Howe Cave Quarry are summarized in Table 1 in Appendix B of this report. Sample design layouts for the table are also included in Appendix B. Because the VibraMap calculations are site specific, the recommended firing times for a production blast would be determined by the single hole shot located most closely to the production blast. Using these recommended firing times in production blasts at locations other than the production shot bench area in the Howe Caverns Quarry may produce poor results and is not recommended by Vibra-Tech.

As blasting progresses away from the test areas, seismograph recordings of the ground vibration must be analyzed to verify the effectiveness of the VibraMap recommendations. Should the effectiveness of the VibraMap delays be compromised by moving too far from the original test locations, new signature blasts may be required. Similarly, if new benches or faces are opened, the vibration signatures at the locations around the quarry may change. Only by firing and recording a new signature blast in the new material may this effect be evaluated.

The VibraMap recommended firing times may lose their effectiveness if the blasthole pattern deviates from that used in the VibraMap calculations. Thorough planning prior to drilling blast patterns is required to fully utilize the vibration control provided by the VibraMap service.

Assumptions and Definitions

The following are the assumptions and definitions that the VibraMap technique uses. We are clarifying them here so that there is no misunderstanding about the application of the method.

- The method assumes that delays remain constant during the shot. At present we cannot determine the optimum delays for shots with variable delay times, such as may be achieved with some of the more recent initiation systems.

- The calculations assume the same number of columns in each hole and the same number of holes in each row. Small changes in the basic pattern will make little difference; however, an extremely irregular shot may generate different vibration than that produced by the designs recommended in this report. Large blasts (many holes) are more tolerant of small deviations in blast pattern; smaller blasts require care and planning to adhere to the VibraMap recommendations and optimize results.

- Multiples of a particular delay interval are not equivalent to that delay interval. For example, if we recommend 25 ms between holes in a row, 50 ms initiators *should not be used* in their place. Multiples of a recommended delay interval are often much worse than the suggested interval.

- The calculations assume equal charge weight per delay. Small differences (10 to 15 percent) will have little effect on the results. However, if substantial differences are made between column charges, that information will be needed for the calculations.

- We recommend that the most accurate initiation system available which is consistent with other blasting requirements should be used. Standard accuracy delay detonators can have ranges of firing times of approximately ±7 percent compared with high accuracy detonators which have a range of ±2 percent. This means that a 500 ms standard delay detonator could fire anywhere between 465 to 535 ms, whereas a high accuracy delay detonator could fire anywhere between 490 to 510 ms. Predictable vibrations are only achieved through more accurate firing times. Thus, an increase in the accuracy of the firing times yields an increase in profitability of the VibraMap technique.

Disclaimers

- The recommendations regarding blast delays are based upon a superposition of vibration waves generated by individual charge detonations and filtered through the geologic medium. The recommended delays do not account for changes in burden, spacing, depth, powder factor, etc., that may be necessary to accommodate these delay intervals. Failure to properly adjust these other variables may totally negate the advantage of using the recommended charge delays.

- The blast design which incorporates these recommendations remains the responsibility of the blasting contractor. All aspects of the blast design, including burden, spacing, geometry, and delays, as well as consideration for geological variations, are the responsibility of the blaster-in-charge and explosives contractor. In the event that the blasting contractor has any reservations regarding the incorporation these delays in his blasting plan, Vibra-Tech disavows the recommendation of these delays and advises using the blaster's professional judgment.

- Although we have recommended delays which we feel are consistent with good production practice, we will neither take credit for improvements, nor accept blame for decreases in productivity.

- Due to the hundreds of variables for which only the blaster has control, Vibra-Tech cannot, and will not, assume responsibility for the results of the blasting. Vibra-Tech has recommended charge delays for use by the blaster only if these recommendations fit within the parameters he sees necessary for proper and safe blasting.

Regression Analysis

In any investigation of ground vibration, it is necessary to determine the distance propagation equation of the rate of attenuation of the vibration. This dissipation of energy with distance varies from site to site and can only be determined by recording vibration as several distances from the source at the site. This study consisted of one linear array where vibration attenuation data was collected. This array consisted of 34 seismometers deployed approximately 258 feet east of the signature shot and running northwest toward Howe Caverns.

Data collected from the detonation of the production blast and the signature blast was utilized for the site attenuation study. Seismographs in the array recorded the resulting vibrations. The signature and production blast were located on the west face of the quarry. The amount of explosives detonated for Signature Blast 1 was 935 pounds per delay. The amount of explosives for Production Blast 1 was 426 pounds per delay.

Discussion of Regression Analysis

Since the risk of blast-induced vibration damage is a concern for Howe Caverns, vibration data was collected during the detonation of the signature and production blasts. This phase of the investigation determined the rate of attenuation of peak particle velocity resulting from the detonations. When a blast is monitored in a method that collects vibration data versus distance and charge weight, it is possible to analyze the data in such a way that it becomes an indicator of the vibration effects for future blasts and not merely a record of past events. Once the rate of attenuation is defined, the determination of possible zones of concern based on proximity to the cavern can be predicted.

When statistical analysis techniques are applied to the vibration data pairs (Peak Particle Velocity vs. Scaled Distance) a site-specific velocity attenuation formula can be developed. (Scaled distance, as referred to in this study, equals the distance from the explosive charge to the recording location, in feet, divided by the square root of the charge weight, in pounds.) This technique, know as a least squares regression analysis, will yield a velocity attenuation formula that takes on the form:

$$V = H\left(D_s\right)^{\beta} \qquad \text{Equation 1}$$

Where D_s is Scaled Distance
H is y-intercept ($D_s = 1$)
β is slope

The variable H and β are constants that are particular to a site. Linear regression analysis will determine the specific value of these variables based on the input data pairs of Peak Particle Velocity and Scaled Distance. Generally, H can vary from 20 to 1,000 for ground vibration data. The slope β should always be negative and typically varies from –1.1 to –2.4.

The Office of Surface Mining Reclamation and Enforcement (OSMRE) recognizes this analysis tool as an acceptable method of demonstrating blast vibration regulatory compliance.

Results of Regression Analysis

In order to determine a site-specific attenuation relationship, the collected peak particle velocities are plotted with their corresponding scaled distance on a log-log plot. The data collected for the cavern array was combined and analyzed. This resulted in a total of 66 valid data points. A minimum of thirty data pairs is recommended by the OSMRE to complete a confident regression analysis. Figure 1 in Appendix C is a graphical depiction of the predicted ground surface particle motion for the cavern array.

The relationship between peak particle velocity and scaled distance can be obtained by determining the "best fitting" line to the plotted data. The mean (best fit) curve of the plotted data represents the best approximation of the amplitude of the vibrations from a blast at a given scaled distance. Statistically, one half of all vibrations recorded at a given scaled distance should exceed the mean amplitude, the other half should be less than the mean. The regression analysis of the peak particle velocity vs. distance data for the combined arrays plotted in Figure 1 calculated a best fit equation of

$$PPV(in/\sec) = 90.81 \times D_s^{-1.639} \qquad \text{Equation 2}$$

Where D_s is Scaled Distance

The coefficient of determination (goodness of fit) for the combined ground vibration data set was 0.87. The OSMRE defines a minimum acceptable value of 0.70. The standard deviation for the combined ground vibration data sets was 0.39. The standard deviation should be less than 0.50 according to OSMRE.

The collection of scaled distance vs. particle velocity data for the determination of attenuation relationships will result in a good deal of scatter about the mean line. This scatter can result because of changes in geologic conditions, geophone coupling, or different wave types at the peak. Because of this scatter it is often prudent to determine lines of increasing confidence. Lines of increasing confidence are computed by adding multiples of the standard error of the estimate adjusted for the number of data pairs. The confidence lines for 95 percent and 99 percent are also shown on Figure 1.

Statistically, there exists a 95 percent probability that the peak particle velocity generated from a blast at a given scaled distance will not exceed the 95 percent confidence line intercept at that scaled distance. In other words, the 95 percent confidence value is that particle velocity that will not be exceeded 95 out of 100 blasts at that scaled distance. A similar relationship exists regarding the 99 percent confidence line.

The equation of the 95 percent confidence line calculated for the peak particle velocity vs. scaled distance data plotted in Figure 1 was as follows:

$$PPV(in/\sec) = 221.12 \times D_s^{-1.639} \qquad \text{Equation 3}$$

Where D_s is Scaled Distance

The equation of the 99 percent confidence line calculated for the peak particle velocity vs. scaled distance data plotted in Figure 1 was as follows:

$$PPV(in/\sec) = 312.66 \times D_s^{-1.639} \qquad \text{Equation 4}$$

Where D_s is Scaled Distance

Using Equation 3 from above, a peak particle velocity limit of 1.0 in/sec can be substituted into the equation in order to determine the appropriate charge weight for a particular distance. The results of these substitutions are listed in the table below.

Distance	Max Pounds per Delay
300	124
350	169
400	220
450	279
500	344
550	417
600	496
650	582
700	675

Discussion of Cavern Vibration Data

Proposed blasting in the Howe Cave Quarry will come in close proximity to the Howe Caverns. The closest proximity the blasting will come to Howe Caverns will be 300 to 350 feet. Since there is a concern for blast induced vibration damage to the caverns, vibration sensors were attached to the interior of the cavern walls. During this phase of the investigation simultaneous measurements of the cavern walls were taken to determine how the cross-section of the cavern is deflected during the blast vibration event. Figures 1 and 2 in Appendix D show the vibration time histories recorded from the sensors on opposite walls of the caverns. The traces from opposing walls are overlaid in order to see the relative displacement of the cavern. These measurements indicate that the relative displacement of the cavern is minute indicating a minimum amount of stress is applied to the cavern walls by blast vibration. In contrast, if these figures showed that the opposing time histories were out-of-phase with each other, this would indicate that the cavern walls experience a very large relative displacement and hence a high level of stress during a blast event.

In addition, the rate of decay of vibration from the surface array to the caverns was also determined. The table below summarizes the peak particle velocities observed by the seismograph located on the surface at the shaft pipes above the fan gate and the sensors attached to the cavern walls.

Blast Type	Surface Inst. S/N 4459 (in/sec)	Channel	Subsurface Cavern Set 1 (in/sec)	Channel	Subsurface Cavern Set 2 (in/sec)	Channel
Production	0.1325	L	0.0262	H_N	0.02	H_N
			0.0306	H_S	0.02	H_S
	0.0918	V	0.0581	V	0.06	V
Signature	0.3059	L	0.172	H_N	0.165	H_N
			0.204	H_S	0.120	H_S
	0.2141	V	0.192	V	0.150	V

L = Longitudinal, V = Vertical
The longitudinal component of the surface instrument is oriented in the same direction as H_N and H_S sensors in the cave.

Based on the results of the table there is a slight reduction in particle velocity from the surface to the cavern. This should ensure an additional factor of safety for the cavern. This relationship may change as blasting progresses closer to the caverns because of the geometry between the explosive charge and the caverns.

The seismograph (S/N 3406) that was placed inside the caverns 172 feet west of the fans at the end of the commercial tour area recorded a maximum peak particle velocity of 0.055 in/sec for the production blast and 0.26 in/sec for the signature blast. This seismograph located at the end of the commercial tour area was approximately 1,540 feet from the production blast and approximately 1,040 feet from the signature blast.

Research on Vibration Damage to Underground Structures

When studying the effects of vibrations from blasting on underground structures, such as mines tunnels, or caverns, we must understand that vibration amplitudes and frequencies are affected by distance, depth below the surface, geologic composition, and structure. At distances beyond the immediate blast zone, approximately 50 to 250 feet, the strongest vibration waves are surface waves. One characteristic of surface waves is their rapid decrease of amplitude with distance. In the case of surface mine blasting, vibrations rapidly decrease with depth as well as horizontal distance. As a result, vibrations at large depths will generally be dominated by the relatively low amplitude body waves.

Although, not studied as extensively as vibration damage to residential structures, the U.S. Bureau of mines and other researchers have studied the effects of the vibration generation from blasting in underground works and the possible damage to underground structures from nearby large surface blasts. These studies have mainly been in response to safety concerns and the potential for damage due to blasting vibrations in mines and tunnels. Primary damage concerns include tunnel collapse and subsidence and damage to rock mass. Damage to rock mass would include spalling, crack extension, and block sliding

Siskind in Vibrations from Blasting cites nine studies of vibration effects on underground mine works and tunnels.Most of the studies involve nearby large scale surface mine blasting, but a few deal with blasting in adjacent underground works. The following is a short review of the studies cited by Siskind, as well as two additional studies.

- *Thoenen and Windes (1942) in USBM Bulletin 442 measured mine and pillar vibrations from quarry blasting at three locations in an underground limestone mine to determine if the mine roof had a characteristic resonant (or natural frequency). They contended that specific resonance frequencies of large roof section or the roof as a whole would make the roof susceptible to damage from blasting vibration. Their tests found that the roof as a whole does not react dangerously to imposed vibration, such as might be caused by blasting, however, loose pieces of the roof may react to vibrations and fall.*
- *Engineering Research Associates, Inc. (1953) in a report for the U.S. Army Corps of Engineers conducted tests of roof stability under blast vibration loading in unlined tunnels in sandstone and granite. The tests found the sandstone was the weaker of the two materials. The limit of observed roof failure in the sandstone corresponded to a radial particle velocity of over 36 in/sec.*
- *Langefors and Kihlström (1973) proposed the following criteria for tunnels: PPVs of 12 in/sec (305 mm/s) result in the fall of rock in unlined tunnels, and PPVs of 24 in/sec (610 mm/s) result in the formation of new cracks.*
- *Sakuri and Kitamura (1977) studied the effects of blast vibrations in two unlined tunnels in granite and two concrete-lined tunnels. They concluded damage would occur at a peak particle velocity of 13.8 in/sec. Crack initiation was observed at 13.3 in/sec in concrete lining.*

- *Rupert and Clark (1977) studied blast vibration effects from a nearby surface mine in a nearby underground coal mine. They observed minor damage in the form of localized thin spall and possible collapse of previously-fractured coal ribs from vibrations above 2.0 in/sec.*
- *Jensen et al. (1979) studied underground vibrations from surface mine blasting at the Jenny Mine in Kentucky. The authors observed no roof failures at roof vibrations of 17.5 in/sec and only a few loose stones at 5 in/sec.*
- *Fourie and Green (1993) studied underground vibrations at a coal mine from surface mine blasting. The authors found negligible damage at 4.3 in/sec for one significant blast of 7,040 lb/delay at a horizontal distance of 96 feet. In all tests they found the integrity of the mine to be unaffected.*
- *Singh and Roy (1993) studied the effects of surface mine blasting at three locations, an underground coal mine, underground water dam and an underground mine roadway. At the underground mine they observed no changes at the highest measured PPV of 0.50 in/sec. The authors observed a PPV at 0.92 in/sec at the underground dams without damage occurring to the dams. At the underground mine roadway the authors observed a PPV of 1.89 in/sec in the roof and a PPV of 1.24 in/sec in the coal pillars. There was neither spalling in the roof or the pillars except for some small pieces of coal and dust thought to already be loose.*
- *Androeux et al. (1994) studied overbreak and crack extension from blasting. The authors found that the extension of existing cracks with the maximum extents of 15 feet, occurred at PPVs of 11.8 to 15.7 in/sec.*
- *Calder (1977) observed that no fracturing of intact rock will occur with a PPV of 10 in./sec (254 mm/s). However, PPVs of 10 to 25 in/sec (254 to 635 mm/s) result in minor tensile slabbing, and PPVs of 25 to 100 in/sec (635 to 2,540 mm/s) would cause strong tensile and some radial cracking. The break up of a rock mass will occur at a PPV of 100 in/sec (2,540 mm/s).*
- *Oriard (1982) proposed that most rock masses suffer some damage at a PPV above 25 in/sec (635 mm/s).*(Scoble et al., 1997)

The research conducted on the vibration risks in underground structures points to the general observation that major failure such as roof collapse and pillar failure would require vibrations greater than 12 in/sec. In some cases, loose pieces were dislodged at lower levels of 1.2 to 5 in/sec. Vibrations below 1.0 in/sec have been found to be totally harmless to underground workings.

Vibration Monitoring Recommendations for Howe Caverns

Based upon the research presented here and the vibration levels recorded in the caverns, as reported in the previous section, Vibra-Tech would recommend monitoring the roof and walls of the caverns near the area of the fan. Install a split transducer system in cavern to monitor vibration on the ceiling and walls of cavern. Vibration levels at the closest point of the cavern to the blasting should be predicted based on the recorded levels in the cavern and the ratio of the distances. If the measured or predicted peak particle velocity exceeds 1.5 in/sec, inspect the cavern for loose or fallen debris. Continue to update the regression plot with measured peak particle velocity from cave and accurate scaled distance as the blasting progresses toward cavern system.

Respectfully submitted,
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