

Understanding Blast Vibration and Airblast, their Causes, and their Damage Potential

Author: Wesley L. Bender

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It must be understood by all concerned that blasting is not an exact science and that safe blasting incorporates experience as well as the study and proper application of the fundamentals involved. If the reader is not adequately experienced in the type of blast-related operation that he intends to undertake, he is advised to obtain assistance from a qualified, experienced person before commencing the work and under no circumstances should he attempt to design blasts or conduct blasting operations based solely upon use of the information contained herein.

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1. Introduction to Blast Vibration and Airblast

When a blast is detonated, only a portion of the total energy is consumed in fracturing and shifting the rock. The remaining energy is dissipated in two forms:

- (a) as vibration, in the form of seismic waves traveling very rapidly within the ground and along the ground surface and,
- (b) as airblast, in the form of compression waves traveling through the air.

Blast Vibration.

Immediately surrounding the detonating hole is a crater zone (or inelastic zone), within which the rock has been fractured and displaced by the shockwave and by the pressure of the hot gasses generated in the explosion process. Outside this crater zone, the shockwave continues to travel, spawning a family of seismic waves. These waves radiating outward are categorized as body waves traveling through the ground and surface waves traveling on the surface of the ground.

The body waves consist of P (or primary) waves and S (or secondary) waves. P waves are compression waves that radiate outward from the source at velocities ranging from several thousand to twenty thousand feet per second, depending upon the sonic velocity of the material through which they pass. Over long distances, P waves average 5 kilometers (approximately 16,000 ft) per second. In addition to traveling faster, the P waves are of a higher frequency and dissipate more rapidly than the other wave types. S waves are shear waves (motion perpendicular to P waves). Their frequency is lower than P waves, they do not dissipate as rapidly, and they travel at approximately 60 percent of the velocity of the P waves.

Higher frequencies dissipate more rapidly than lower frequencies because energy is lost with each cycle (or reversal of direction). Higher frequencies cycle more often and consequently lose energy more rapidly.

Surface waves are formed as the body waves reach the surface. Of the various surface waves, the dominant one is the Rayleigh wave, characterized by motion that is in the form of a retrograde ellipse. (A vertical rolling loop moving away from the source, with the direction of motion at the top of the loop being back toward the source.) Surface waves travel at approximately 90 percent of the velocity of S waves and are of a lower frequency. Surface waves do not diminish as rapidly as the body waves. In all instances, however, the intensities of body waves and surface waves dissipate with distance.

It is this difference in the velocity of the various wave types that enables a seismologist to determine the distance from a recording station to the epicenter of an earthquake by comparing the arrival time of the different wave types. For vibration that is recorded on blasting seismographs in fairly close proximity to a blast however, the waves have not had time to sufficiently separate, and individual wave types are not easily identified.

As seismic waves travel outward from the blast, they excite the particles of rock and soil through which they pass and cause them to oscillate. Spherical spreading, energy loss and imperfect coupling of the particles, among other factors, cause these seismic waves to dissipate with distance. When we record blast vibration, it is the motion of these particles at a given point that is measured.

Blast vibration is described using the following terms:

Displacement - the distance the particles move, usually only a few ten-thousandths to a few thousandths of an inch.

Particle Velocity - how fast the particles move. Since the velocity is continually changing, the maximum, or **Peak Particle Velocity (PPV)**, is the important value. This rate is expressed in inches per second or millimeters per second.

Acceleration - the rate at which the particle velocity is changing, measured in feet/second/second, millimeters/second/second or in G's.

Frequency - The number of oscillations per second that a particle makes when under the influence of seismic waves, measured in Hertz (cycles per second).

(The mathematical relationships of the above four terms as they apply to sinusoidal waveforms are contained in Appendix C of this document.)

Propagation Velocity - The speed at which a seismic wave travels away from the blast, measured in feet/second or meters/second. (As indicated in the previous discussion and above, note that propagation velocity is several orders of magnitude greater than particle velocity.)

It is possible to record blast vibration as particle velocity, displacement or acceleration, depending upon the type of sensor being used. It has become standard practice for blasting, however, to use particle velocity as the best descriptor of vibration as it pertains to damage potential to residential structures. Most modern blasting seismographs use velocity sensors.

When blast vibration is recorded with a seismograph, the actual velocity of the particle motion, regardless of its direction, is recorded using a geophone block containing three mutually perpendicular velocity sensors. When properly oriented to the blast, these record in longitudinal (to and from the blast), in transverse (side to side) and in vertical axes. Each of these axes is recorded by a channel on the seismograph. Since the velocities are recorded against an accurate time base, additional information such as frequency, displacement, acceleration and true vector sum can also be derived. This is accomplished internally by modern blasting seismographs.

In close proximity to the blast, body waves dominate. As the distance from the blast increases, the body waves dissipate faster than the surface waves. As the surface waves become the dominant motion, the dominant vibration frequencies will be lower.

Some published blast vibration standards allow higher particle velocities at higher frequencies (which normally occur closer to the blast). This factor alone may allow the blaster to stay within the specified frequency-dependent limits as his blasts approach a protected structure. In other words, with no change in blast parameters or site geology, both the intensity and the frequency of the vibration would be expected to increase as the distance to the blast becomes smaller.

When the distance between the recording point and the blast becomes large enough, there is little the blaster can do to alter the frequency of the vibration. The greater the distance from the blast, waves that have traveled different paths arrive at different times and overlap. At much greater distances, the entire blast begins to take on the characteristics of a single point charge of relatively long duration. Individually detonating charges cannot easily be identified on a seismograph record unless the recording is accomplished quite close to the blast.

Airblast or Air Overpressures from Blasting.

As in the case of ground vibration waves, air overpressure waves radiate outward from a blast, diminishing with distance. Air, acting as a fluid, can only transmit compression waves.

There are various sources of airblast, some of which the Bureau of Mines identified in their report, RI 8485, *Structure Response and Damage Produced by Airblast from Surface Mining*, in 1980 and by Wiss and Linehan earlier. While these reports may seem a bit outdated, the air overpressure sources contained therein are still valid. Among them are:

Air Pressure Pulse (APP) - direct rock displacement at the face or mounding at the collar (the result is a low frequency air overpressure wave)

Rock Pressure Pulse (RPP) - vibrating ground at the measuring point (the result is low frequency air overpressure and is usually inconsequential)

Gas Release Pulse (GRP) - gas escaping through fractured rock (the result is medium to high frequency airblast)

Stemming Release Pulse (SRP) - gas escaping through blown-out stemming (the result is medium to high frequency airblast)

Unconfined surface charges, including detonating cord on the surface (the result is high frequency airblast)

Those waves from sources resulting in higher frequencies could be properly termed "airblast". The term "air overpressure" is probably more suitable for the lower frequency waves, however it has become conventional to refer to all airborne blast pressures as airblast.

Airblast or air overpressures from blasting are measured in either decibels or psi or, in the case of SI (metric) units, in Pascals.

When comparing airblast with conventional noise sources, one must bear in mind that airblast is an impulse of very short duration and is not repeated continuously. For this reason, airblast limits are usually established that are well above the limits set for continuous noise sources and also above those limits usually imposed on firing ranges and the like that are sources of repeated impulses. Because of its very short duration, airblast makes a negligible contribution to recorded average daily noise levels.

That part of the air overpressure wave that is in the audible range (above 16 Hz or so) can be startling in an otherwise quiet surrounding. The energy level, however, is usually very small and will not normally contribute to actual damage. The lower frequency portion of the pressure wave, rather than being heard, is felt as concussion. This concussion tends to excite structures and cause windows and doors to rattle. Damage from this concussion at elevated levels is possible, but the major adverse contribution is to human response. If a nearby blast causes windows to rattle, the average person cannot tell whether it was airblast or vibration that caused it, although he will generally assume the latter.

2. The Effect of Blast Vibration on Materials and Structures

In order to provide some idea of what various PPV intensities represent, their effect on various structures and materials is contained in the following listing. These have been documented by researchers and organizations as referenced. Because of the many variables that could be encountered in the field, this listing should not be used to establish limits or be considered as the absolute point where the effect will always occur. To do so would also require consideration of frequencies. PPV units are inches per second.

PPV	Application	Effect	Reference
600	Explosive inside concrete	Mass blowout of concrete	j
375	Explosive inside concrete	Radial cracks develop in concrete	j
200	Explosive inside concrete	Spalling of loose/weathered concrete skin	j
> 100	Rock	Complete breakup of rock masses	a
100	Explosive inside concrete	Spalling of fresh grout	j
100	Explosive near concrete	No damage	l
50 - 150	Explosive near buried pipe	No damage	n
25 - 100	Rock	Tensile and some radial cracking	a
40	Mechanical equipment	Shafts misaligned	d
25	Explosive near buried pipe	No damage	o
25	Rock	Damage can occur in some rock masses	c
10 - 25	Rock	Minor tensile slabbing	a
24	Rock	Rock fracturing	b
15	Cased drill holes	Horizontal offset	d
> 12	Rock	Rockfalls in underground tunnels	b
12	Rock	Rockfalls in unlined tunnels	g
< 10	Rock	No fracturing of intact rock	a
9.1	Residential structure	Serious cracking	b
8.0	Concrete blocks	Cracking in blocks	d
8.0	Plaster	Major cracking	h
7.6	Plaster	50% probability of major damage	g
7.0 - 8.0	Cased water wells	No adverse effect on well	m
> 7.0	Residential structure	Major damage possible	e
4.0 - 7.0	Residential structure	Minor damage possible	e
6.3	Residential structure	Plaster and masonry walls crack	b
5.44	Water wells	No change in well performance	k
5.4	Plaster	50% probability of minor damage	g
4.5	Plaster	Minor cracking	h
4.3	Residential structure	Fine cracks in plaster	b
> 4.0	Residential structure	Probable damage	f
2.0 - 4.0	Residential structure	Plaster cracking (cosmetic)	e
2.8 - 3.3	Plaster	Threshold of damage (from close-in blasts)	g
3.0	Plaster	Threshold of cosmetic cracking	h
1.2 - 3.0	Residential structure	Equals stress from daily environmental changes	i
2.8	Residential structure	No damage	b
2.0	Residential structure	Plaster can start to crack	d
2.0	Plaster	Safe level of vibration	g
< 2.0	Residential structure	No damage	e
< 2.0	Residential structure	No damage	f
0.9	Residential structure	Equivalent to nail driving	i
0.5	Mercury switch	Trips switch	d
0.5	Residential structure	Equivalent to door slam	i
0.1 - 0.5	Residential structure	Equates to normal daily family activity	i
0.3	Residential structure	Equivalent to jumping on the floor	i
0.03	Residential structure	Equivalent to walking on the floor	i

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3. Probable Results of Impulsive Airblast

The relationship of decibels to pressure and the probable result of various airblast intensities are presented in the following chart. The equivalent wind gust velocities are also given for several intensities.

<u>Airblast Intensity</u> <u>dB</u>	<u>psi</u>	<u>Probable Result</u>	<u>Average</u> <u>Human Response</u>
180	2.900	Structural damage	Ear drum rupture possible
175	1.631		
170	0.917	Many windows break	Intolerable
165	0.516		
160	0.290		
155	0.163	(equal to a 96 mph wind gust)	
150	0.092	Poorly mounted windows can break	
145	0.052		
140	0.029	(equal to a 40 mph wind gust)	Distinctly unpleasant
134	0.0145	OSMRE and USBM limit	
130	0.0092	(equal to a 23 mph wind gust)	
125	0.0052		
120	0.0029		Mildly unpleasant
115	0.0016		
110	0.00092	(equal to a 7.2 mph wind gust)	
105	0.00052		
100	0.00029		
95	0.00016		
90	0.000092		Strongly perceptible
85	0.000052		
80	0.000029		
75	0.000016		
70	0.0000092		Distinctly perceptible
65	0.0000052		
60	0.0000029		Perceptible

In the foregoing chart it should be noted that Average Human Response is just that. One can find individuals who would tolerate considerably higher intensities of airblast without complaint, while others may claim to be distressed at much lower intensities.

The formula for converting pressure in psi to decibels is -

$$dB = 20 \log (\text{psi} / 2.9 \times 10^{-9})$$

or conversely,

$$\text{psi} = 2.9 \times 10^{-9} \times \text{anti-log} (dB / 20)$$

The formula for equating wind gusts to pressure is from PPG Industries' architectural design criteria for their windows and is expressed as -

$$\text{psi} = 1.78 \times 10^{-5} \times V^2$$

where V is the wind speed in miles per hour.

4. Human Response to Blast Vibration and Airblast

Human response is not something that the explosive user can readily control, although one might be able to affect it in a positive way if it can be understood and properly addressed. The main contribution of typical human response to blast effects is that it increases the perception that some damage was either possible or likely to have occurred from the blasting.

Most humans are quite sensitive to motion and sound. They can perceive levels of each that are well below (by a factor of 100 to 1000 or more) those levels that could cause damage to the average structure. As sensitive as they may be, however, humans are notoriously bad in their estimation of the intensity levels of vibration and airblast. Even trained individuals, in the absence of instrumentation, have been known to make poor estimates of intensity levels.

Among the factors that have an impact on human response are:

- (a) health of the individual.
- (b) orientation of the individual – i.e. in a standing position, more responsive to vertical motion; lying down, more sensitive to motion from side to side.
- (c) location of the individual – indoors, more receptive to structure noises; outdoors, blast effects are not as noticeable and may be masked by ambient noise and vibration.
- (d) activity of the individual – persons at rest are more sensitive than those actively engaged in some physical activity.
- (e) whether the individual is pre-warned or not (the startle factor) – persons expecting a blast will usually not consider the effects to be as severe as those who are not warned.
- (f) quality and type of construction (for those indoors) – structural noises and rattling of windows and doors.
- (g) ambient noise or vibration levels – blast effects are not perceived to be as severe when other ambient noise and vibration are present.

Obviously, there is a wide range of human response to blasting and blast effects. On one end of the spectrum is the individual who recognizes some benefit from the blasting operation. He or she will usually be a friend or ally and can actually assist in public relations with other more "average" neighbors.

At the other end of the spectrum is the individual who, for whatever reason, did not want the blasting operation there in the first place. It is not likely that anything you do, short of going away, will satisfy him. You can't ignore him, though.

Between these two extremes will be the individuals from whom you can benefit the most with a good informational or public relations program.

Attempts have been made by many to quantify Human Response in technical terms. In most cases, researchers have found that, while you can gather data on how humans respond to sonic booms, ground vibration, earthquakes, etc., the subject tends to be an elusive target. This is because there are many factors, physiological, technical and political, that can skew the results. While this may appear to make it seem futile to address human response, this is not the case.

The easiest case is the friend of the operation. Make sure that he understands that you appreciate his feelings toward your operation and that you also appreciate any efforts he may make on your behalf. While it isn't likely that he would change his opinion, you shouldn't ignore him. Stay in touch with him.

The most difficult, the fellow who didn't want you and your blasting in his neighborhood in the first place, is going to require a completely different approach. Don't ignore him either. It will only make him try harder to get you out of his life. Treat him with respect and treat him fairly, but be firm. If you didn't cause the damage that he may be claiming, there is no reason for you to pay for fixing it. When he calls and complains, don't immediately deny his claim. While you may feel certain that you didn't damage him, you cannot reach a conclusion until a proper investigation is done. Your best defense will be to use all the tools at your disposal. Pre- and post-blast surveys should be considered. Recording of blast vibration and airblast with blasting seismographs will help you disprove any false claims of damage.

While you might be inclined, as a good will gesture, to pay for minor damage claimed, be aware that if you knuckle under and pay for something that you did not cause, you will probably find that he has additional items to fix. You also run the risk of him boasting to others how he got you to take care of his problem. This could initiate a flood of complaints. Again, your best bet is to be fair, but be firm.

Before going further, with regard to the preceding comments, some (but not all) insurance companies will have a tendency to look at the cost of settling a claim versus the cost of fighting it. They will usually conclude that it is cheaper to settle than fight. Unfortunately, in addition to a total lack of fairness in the matter (and the loss experience that you or your company will receive because of it) this can establish a precedent for others who may then also claim damage.

Get a good investigative consultant or consulting group, pay promptly for only the damage that you cause (or was likely caused by you) and, above all, let your insurance company know how you feel in the matter.

Getting back to human response, what can you do to properly address those individuals who are average in their response? First, try to find out what their concerns really are. Most people haven't been around blasting and may be more fearful of it because of the unknown or because of what they see in movies or on television. When they see earthquake damage on TV, they don't understand the differences between the ground motion that caused it and the ground motion from blasting. It is understandable that they might be concerned. You (or your blast effects consultant) should explain beforehand what they will feel, see and hear when you conduct your blasting operation. Educate them. Pre-blast surveys provide an excellent opportunity to meet and talk with these people. Take advantage of that opportunity.

While some may argue against warning neighbors when a blast is going to take place, the lack of a proper warning severely increases the startle effect. In my experience, when I have been standing with neighbors and have counted down to a properly designed blast, the usual comment has been, "Is that all there is to it?" On the other hand, when a blast is detonated with no warning, most people perceive it to be worse than it really is.

Most individuals appreciate the attention that you show them when you monitor vibration and airblast at or near their residence. Granted, there are some who will refuse to allow equipment to be set up on their property, but they are usually in the minority. In some instances, just knowing that the blast effects were recorded by instruments will preclude someone from claiming damage.

Structural response has an impact on human response when the structure amplifies or otherwise adversely affects the noise and/or motion that the human may hear or feel indoors when you blast. Low frequency concussion that may only sound like a muffled thump outdoors, will probably rattle windows and other objects indoors when it reaches the side of a structure.

In the author's experience, many complaints blamed on blast vibration should have actually been attributed to airblast. Without instrumentation, the average homeowner has no way of telling the difference. When someone a half mile away complains that you shook their house and you calculate a peak particle velocity well below the average threshold of human perception, don't tell them they're crazy. They know what they experienced. Investigate their complaint. It's possible that your blast generated a low frequency airblast pulse in their direction.

If the blast under consideration is going to be a one time affair, consider establishing a safe viewing location for the neighboring residents. Not only will they appreciate the attention and the chance to witness the blast, they will not be in their houses to possibly hear the windows or other objects rattle. (Make sure the viewing location is truly safe, though. Your efforts at PR will suffer greatly if they are frightened or have to duck flying objects.)

Above all, be a good neighbor. Design blasts to keep adverse effects to a minimum. Cultivate good relationships with your neighbors. Remember, some day you might need to modify your operating permit for a mining operation or, in the case of construction, need to blast in an area where permitting has been difficult in the past. A few friends and neighbors who speak highly of your blasting may come in handy. In the meantime, keep good blasting records, monitor your blasts and keep a good log of complaints as they are received and the disposition of the investigation of those complaints.

Most persons, when invited to witness a well-designed blast, are usually disappointed and tend to feel that the effects are minimal. Some have gone so far as to accuse the blasting company of purposely setting off a much smaller blast than normal, when the opposite situation has actually occurred.

For further study on the subject of human response, see Oriard (1999 and 2002) or USBM RI8485 as referenced in Appendix D.

5. Blast Scaling

To facilitate comparing or estimating the effects from blasts of varying charge weights and varying distances, some scaling method is required. The conventional scaling method in use is referred to as **Scaled Distance (D_s)**, a number (without units) that provides a means of scaling a ratio of distance and charge weight.

Square Root Scaled Distance is derived by dividing the true ground path distance between the detonating charge and the object of interest by the square root of the charge weight. This is used for scaling blasts involving linear charges (the length is more than four times the diameter) and would apply to most conventional blasts.

$$\text{Square Root } (D_s) = \text{Distance} / \text{Weight}^{1/2}$$

Cube Root Scaled Distance is similarly derived except that it uses the cube root of the charge weight. Cube Root scaling is used for those instances where the item of interest involves airblast or air overpressures, underwater blast pressures and for those infrequent instances where ground vibration is generated by a spherical charge (the length of the charge is less than four times the diameter).

$$\text{Cube Root } (D_s) = \text{Distance} / \text{Weight}^{1/3}$$

When scaling blasts, the proper charge weight for the calculations would be the total quantity of explosive that is detonated in a given instant. Instant (for this purpose) has been further defined as being that amount of explosive detonating within any 8 millisecond time period.

With proper care, D_s can be used to predict blast vibration. When utilized in conjunction with blast vibration monitoring, it facilitates the design of blasts to conform to vibration limits. Shorter distances and higher explosive weights result in a lower D_s and would yield more vibration. Conversely, greater distances and smaller explosive weights result in a higher D_s number and less intense vibration.

In order to accommodate a large range of Scaled Distances and PPVs, the data is usually plotted on graphs that are logarithmic in both horizontal and vertical axes.

The correct D_s is the lowest number calculated for various configurations within the blast and will more closely relate to the highest intensity of vibration. Technically speaking, there are as many D_s numbers as there are holes detonating. If all the holes are loaded nearly identically and are detonated on individual delays, the closest hole will naturally yield the lowest number.

If the blast has varying charge weights (the shot may be deeper in some areas), the lowest D_s may be calculated for a hole that is actually farther away, toward the center of the blast, or even on the far side of it from the object of concern.

With regards to distance measurements, bear in mind that blast-induced ground vibration (for our purposes) can travel only through the ground. It can't jump across an open space. The shortest path through the ground between the detonating hole and the object of interest should be the distance used. If the distance is a couple of hundred feet, measure it with a tape. Out to five hundred feet or so, use a wheel or pace it off (if you can do so accurately). For distances of five hundred feet or more, a GPS would prove valuable. Whatever method is used, remember to adjust for any change in terrain. Strive for maximum accuracy.

Similarly, the correct distance for air overpressure purposes would be the shortest distance through air between the detonating charge and the item of concern.

Precautions to observe when scaling blasts.

Possible problems with Scaling (square root or cube root) may be encountered in certain situations. If more than one hole is detonated simultaneously, in most instances they will not all cooperate fully in increasing vibration. An example might be a long row of charges detonating simultaneously, with the point of interest located adjacent to the row. Obviously, the nearest hole and those close to it would cooperate. Holes at a much greater distance would not. Oriard (2002) found that only the holes that were included in a length along the row equal to twice the distance from the row to the point of interest contributed appreciably to the vibration intensity. For example, say you are recording 20 feet to the side of such a row. Only the nearest hole and those located within about 20 feet to either side of that hole would contribute. Counting additional holes would yield a lower D_s number, but without an appreciable increase in vibration intensity.

A similar situation could occur if one were to try to record near a hole with an extremely long charge length. While these situations do not occur often in normal blasting schemes, they are brought to your attention so that you might recognize them when they are encountered.

Blasters should also be aware that just because two blasts have the same calculated D_s , the potential effects may not be the same. A large blast at a great distance and a small blast much closer might have the same D_s , but the characteristics of the blast-generated vibration would not be the same. The distant blast would have lower frequencies and lower acceleration levels while the closer blast characteristics would be just the opposite. It is for this reason that one of the OSMRE alternative blasting level criteria allows a D_s that varies with distance.

6. Predicting Blast Vibration

Various methods of predicting blast vibration have been used by researchers through the years, but the most commonly used prediction curves were developed by Lewis L. Oriard, a noted seismologist from Huntington Beach, California (now retired). His curves are based upon data gathered from a large number of blasts in various geological settings. Most other researchers have come to similar conclusions with their estimations usually falling somewhere within Oriard's parameters.

The graph that follows contains curves representing Oriard's upper and lower bounds for typical down-hole blasting and also a higher approximation for those instances where there is very high confinement, such as in pre-splitting. It is important to understand that, due to the many variables involved in blast design and site-specific geology, it is possible that data points can fall above or below the bounds for typical data shown on the graph. Oriard's basic formula for predicting blast vibration is:

$$PPV = H \times (D_s)^{-1.6} \times K_1, K_2, K_3, \text{ etc.}$$

where **PPV** is the Peak Particle Velocity (in inches per second) of a particular axis,

H is a factor that varies as follows:

Lower bound for conventional blasting =	24.2
Upper bound for conventional blasting =	242
Typical bound for increased response (pre-splitting, etc.) =	605

D_s is the Square Root Scaled Distance (as defined earlier),

The attenuation slope of **-1.6** is typical. It can be steeper for body waves recorded close to the blast or can be flatter at extended distances where surface waves would dominate. In your estimations for a given location it is best to use an attenuation slope of **-1.6** until enough data is gathered to facilitate calculating a site-specific attenuation slope.

K₁, K₂, K₃, etc. are factors as described below:

- The resulting peak particle velocity will decrease with -
- decreasing confinement of the explosive energy,
 - decreasing elastic moduli,
 - increasing spatial distribution of the energy source,
 - increasing time of energy release or timing scatter,
 - decreasing coupling of the energy source,
 - and other similar factors.

(PPV would obviously increase when the effect of these factors is reversed.)

Of the factors involved, charge weight and distance, followed closely by confinement of the explosive energy, will have the most impact on vibration. Confinement of the energy is increased as the burden and spacing increase, the depth of burial of the charge increases, strength of rock improves, quality of stemming improves, etc.

Spatial distribution of the energy source would occur when two holes detonating simultaneously are separated by some finite distance. The combined weight of explosive in such holes will not generate as much vibration as one hole containing a similar total charge weight. The effect will vary depending upon the distance between the holes. The greater the distance, the less they will cooperate.

In using the Oriard prediction curves it is important to understand that the particle velocities used are those from individual channels and not the vector sum.

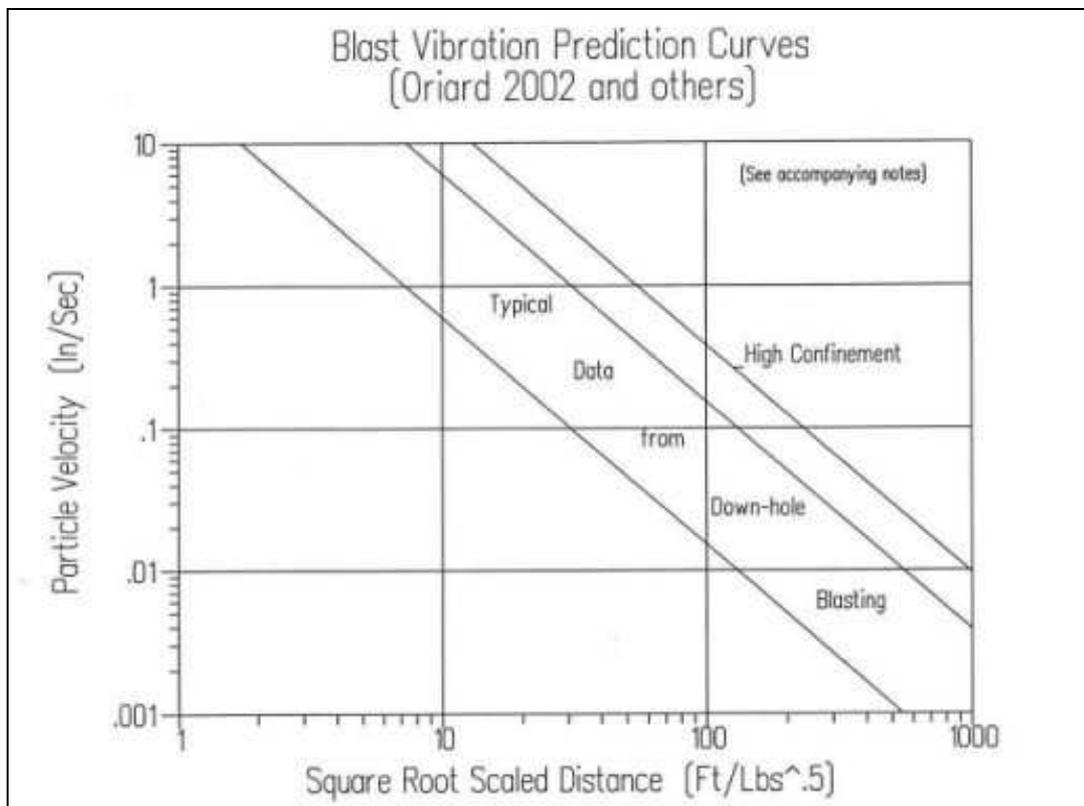
True vector sum is derived by summing the squares of the particle velocities of all three channels (at the same instant in time) and extracting the square root of that sum. Although this would indeed yield the absolute highest particle velocity for the event, current convention does not use vector sum. When our current vibration standards and prediction curves were developed, digital seismographs had not been developed and analog equipment was still in use. Vector sums could only be derived by hand digitizing the data, hence single channel data were used. Modern digital seismographs have the ability to calculate and display vector sum. The true vector sum could be as much as 73% higher than the highest individual channel although, in practice, it is usually only 15 to 20% higher. This difference should be taken into consideration if a vector sum vibration limit were to be proposed, with the limit increased accordingly.

Persons experienced in blast vibration prediction will use the range given in the curves (or formulas) as a basis and adjust them for any blast-specific variables that they can identify and quantify through experience. Data from previous blasts at the site should be plotted on log-log paper (usually obtainable from university or community college bookstores) or plotted on a computer using a good graphing program. Success in predicting blast vibration largely depends upon the experience of the predictor and the accuracy of the input data. In addition to making sure the charge weights are correct, the correct number of holes per delay should be verified and, if more than one hole or deck is detonating simultaneously, the spatial separation of those holes or decks should be noted.

In developing prediction curves for blasts, it is extremely helpful to gather data from a wide range of Scaled Distances. If all of the data is from a narrow band of D_s , it will be difficult to establish a regression factor.

When predicting blast vibration (or airblast, for that matter) it is always preferable to predict within a range rather than predicting a single number. It is also important to base your estimate on as many data points as possible.

If you are attempting to predict vibration for the first blast at a site, you will have to rely upon your experience at predicting and on as many of the blast and geological parameters as you can quantify.



7. Predicting Airblast or Air Over-Pressures

In a manner similar to vibration, air overpressures from blasting can be predicted, however Cube Root Scaling is used rather than square root.

The curves that follow are based upon data gathered from blasts in many varied locations and from research done by various individuals and organizations. Again, due to variables, many of which are difficult to quantify, data points for a given event may fall above or below the bounds shown on the graph. Results are approximate at best because wind velocity and direction can fluctuate widely in a very short span of time.

The prediction curves use a basic formula for estimating air overpressures:

$$\text{Peak Air Overpressure (in PSI)} = K (D_s)^{-1.2}$$

where D_s is the Cube Root Scaled Distance (as previously defined).

The curves representing the normal upper and lower bounds for confined charges and for the average for unconfined charges use combined **K** factors (intercepts at a D_s of 1) as follows:

Lower bound for normal blasting	0.78
Upper bound for normal blasting	2.5
Average for unconfined charges	82

The attenuation slope of **-1.2** is typical for static conditions and represents a reduction of approximately 7.2 dB for each doubling of distance. Some researchers have used attenuation slopes as flat as -1.0 or -1.1; however, the difference in pressures from using those slopes does not become a major factor until a considerable distance has been reached. If the airblast is caused by detonating high velocity explosives in mid-air, the actual slope may approach -1.3 or -1.4. This steeper slope would be the result of the higher frequencies decaying more rapidly than the lower frequencies that result from conventional blasts.

In addition to charge weight and distance (which impact the Cube Root Scaled Distance), the following factors affect the intensity of air overpressures or airblast:

Depth of burial of the charge

Terrain features, trees and foliage or other screening

Blast face orientation (facing toward the recording point increases the intensity recorded)

Velocity of blast progression (either across the face or along the surface)

Explosive composition (This can affect the elapsed time of energy release. Compared to other factors, this is minor and can normally be disregarded for most conventional in-ground explosive products)

Atmospheric conditions such as:

Changes in Barometric Pressure - minimal effect that can normally be disregarded.

Humidity - normal daily fluctuations may be disregarded; however, the difference between a very dry day and a rainy one can be noticeable.

Temperature gradients -

Normal (cooler with increasing altitude) - sound is refracted upwards and the blast may not be noticeable at a distance.

Inversion (warmer with increasing altitude) - sound is refracted downwards and the blast may suddenly become noticeable at a distance.

Note: A temperature inversion has little effect in the immediate area of the blast and usually only affects airblast intensities beyond a radius equal to the height of the inversion layer. Rather than focusing airblast and causing damage, a temperature inversion usually results in the blast suddenly becoming audible at a greater distance.

Wind direction and velocity - These have a major impact on air overpressure intensity. Downwind from the blast, the intensities will not dissipate as rapidly as they would upwind from the blast. Also, because wind velocities typically increase as you move upward from the ground surface, the wave front is being bent downward. This can add from several to 20 or so decibels to the intensity.

Wiss (1978) suggested that one may attempt a rough approximation of the effect of wind direction and velocity by modifying the attenuation rate of -1.2 by adding to it the result of:

$$\text{Additive} = 0.0265 V \cos A$$

where **V** is the wind velocity in mph,

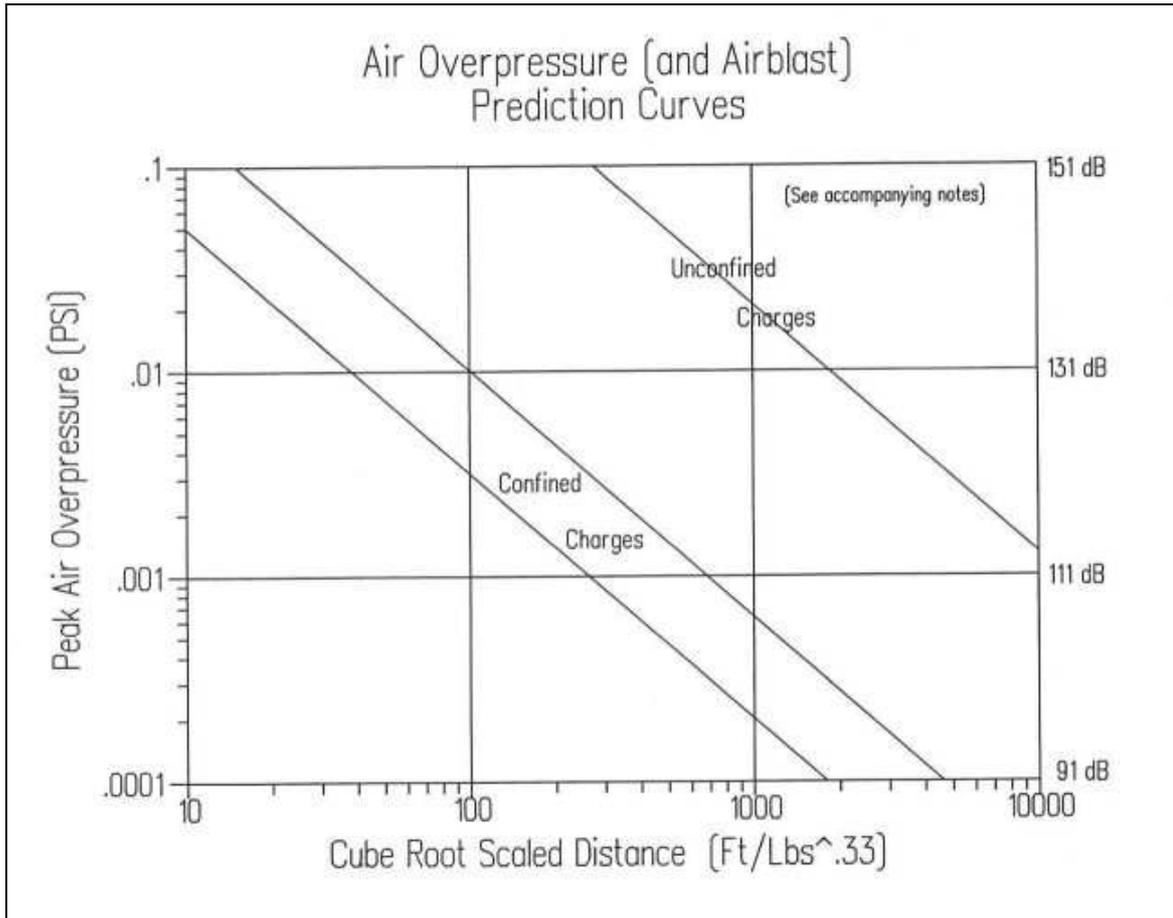
and **A** is the angle (in degrees) between the wind direction and a line from the blast to the recording point.

(Wind blowing from the blast directly toward the recording point would be 0 degrees, resulting in an attenuation rate lower than -1.2. Conversely, a wind blowing directly away from the recording point would be 180 degrees, resulting in an attenuation rate that is higher than -1.2.)

(CAUTION: The above modification of the attenuation rate was derived from data gathered from blasts during wind conditions up to a maximum of approximately 30 mph. At wind velocities in excess of this, the formula can result in a slope that is flat or inverted. Such a slope would result in predicted blast air overpressures that would remain constant or increase with distance, a situation which is not physically possible.)

In addition to the cautions concerning charge weights and delays mentioned in the previous comments on predicting vibration, it is important that the shortest distance through the air be used as the distance for predicting airblast. Depending upon the terrain, this may not always be a straight line.

The estimation of air overpressures is considerably more difficult than estimating vibration due to weather variables that can change from moment to moment. For this reason, it is usually advisable to allow for a greater margin of error when estimating air overpressures and airblast. Gathering data for specific sites and carefully noting weather conditions at blast times can assist in building accurate prediction curves for specific operations or specific sites.



8. Blast Vibration Regulatory Limits

U. S. Bureau of Mines -

In 1974, the Bureau of Mines began a study to gather and update available blast vibration data. Work was included in the area of structural and human response to vibration. This resulted in the publishing in 1980 of Bureau of Mines Report of Investigations 8507, *Structure Response and Damage Produced by Ground Vibration From Surface Mine Blasting*. Some of the conclusions contained in the report are as follows:

1. Peak Particle Velocity is the most practical descriptor of vibration as it applies to the damage potential for residential structures.
2. The potential for damage to residential structures is greater with low frequency blast vibration (below 40 Hz) than with high frequency blast vibration (40 Hz and above).
3. The type of residential construction is a factor in the vibration level required to cause damage.
4. Alternative blasting level criteria were proposed that utilized limits over a wide range of frequencies and included consideration of some limits on displacement. A graph containing the RI 8507 alternative criteria is included at the end of this discussion.

Office of Surface Mining and Reclamation Enforcement (OSMRE) -

In 1983, the OSMRE established regulations controlling vibration at all surface coal mining operations. Three optional methods of limiting vibration are allowed:

1. The first option limits Peak Particle Velocity based upon the distance to the nearest protected structure. Each blast must be monitored by a seismograph. Velocities must be kept at or below the following levels at said structures:

Distances up to 300 feet	1.25 inches/second
Distances of 301 to 5000 feet	1.00 inches/second
Distances beyond 5000 feet75 inches/second

2. The second option does not require monitoring, but requires the operator to design his blasts utilizing Scaled Distances (D_s). The calculated Scaled Distances must not fall below the following values:

Distances up to 300 feet	50
Distances of 301 to 5000 feet	55
Distances beyond 5000 feet	65

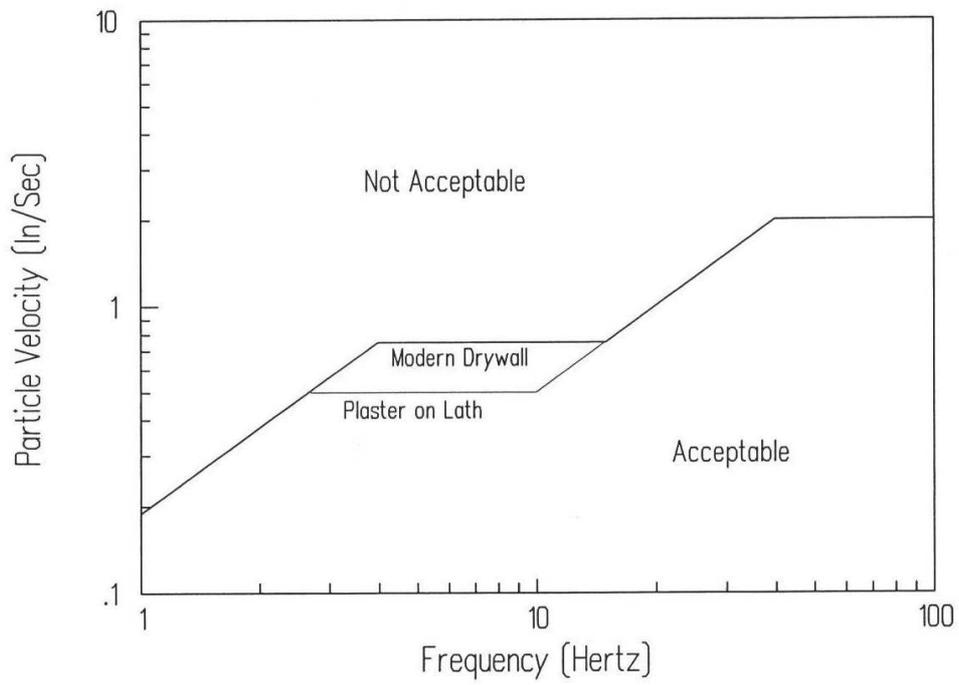
3. The third option requires an operator to monitor his blasts with a seismograph and allows the use of Particle Velocity limits that vary with frequency, similar to the Alternative Blasting Level Criteria proposed in RI 8507 by the Bureau of Mines. The OSMRE option differs from RI 8507 in two areas: (1) it does not differentiate between drywall and plaster-on-lath construction, allowing 0.75 inches per second for either case, and (2) it allows a Particle Velocity of 2.0 inches per second to be acceptable down to a frequency of 30 Hz rather than 40 Hz. A chart depicting this option is included on the following pages.

An analysis of the three OSMRE alternatives indicates that the second option, while not requiring recording, is quite conservative. This option could be feasible in remote locations where distances to structures were large. The third option will usually provide the operator with more flexibility, particularly for close-in blasts where frequencies would be higher.

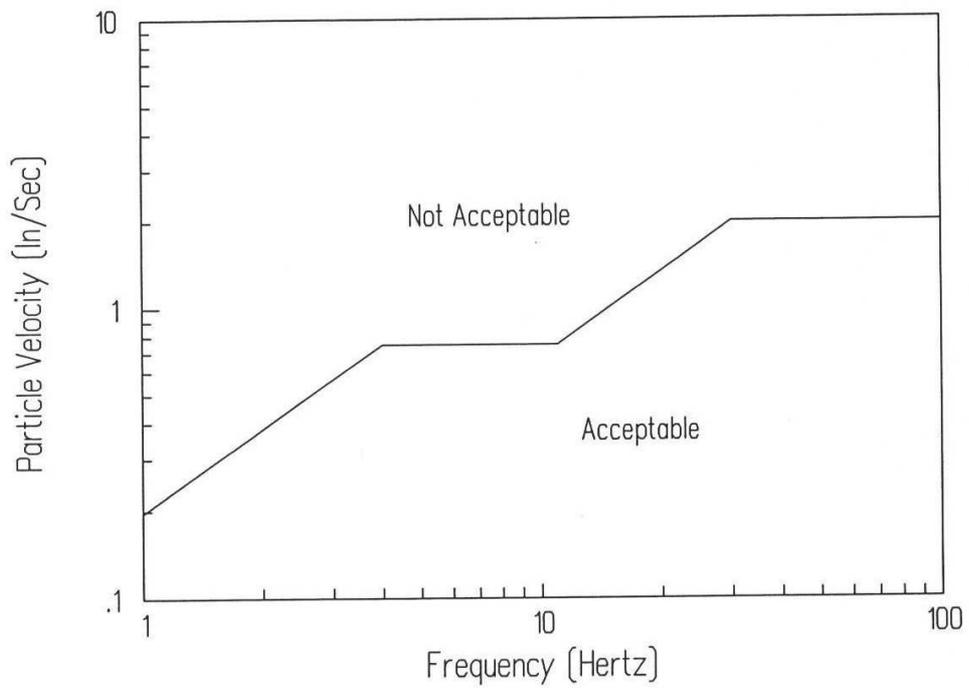
Other blast vibration limits have been proposed for specific instances and applications. It is not unusual to find PPV limits approaching 0.5 inches per second for fragile or historic structures. These situations should be evaluated and limits applied on a case by case basis.

It is also not unusual to find instances where the limit for a residential structure is incorrectly applied to massive concrete structures, buried pipelines and other vibration resistant structures. In many of these, a far better approach would be to use a ground control specification rather than vibration limit. The damage potential more likely would come from back-break or rock-block movement than from blast-generated vibration.

RI8507 Alternative Blasting Level Criteria



OSMRE Alternative Blasting Level Criteria 30 CFR Part 816.67(d)(4)



9. Airblast Regulatory Limits

Bureau of Mines Report of Investigations 8485 (1980), "Structure Response and Damage Produced by Airblast From Surface Mining" generally recommends a maximum safe overpressure of 0.014 psi (134 dB) for airblast recorded at residential structures.

The OSMRE addressed airblast limits in their regulations of 1983. However, they also took into consideration the characteristics of the recording systems and established the following limits:

Recording device with a lower frequency response limit of 0.1 Hz 134 dB *

Recording device with a lower frequency response limit of 2.0 Hz 133 dB

Recording device with a lower frequency response limit of 6.0 Hz 129 dB

Recording device C weighted, slow response 105 dB *

* These can be used only with prior approval of OSMRE.

Generally, the above USBM and OSMRE limits on blast vibration and on airblast are quite conservative as they would apply to the potential for actual damage. It would appear that they were developed more for reducing human annoyance than to prevent damage to residential structures. Residential structures and humans are rather sensitive "seismographs", although they tend to not be calibrated well. Buildings respond to minor vibration and to air overpressures by rattling windows and making other sounds. When the occupants hear these, the overall effects tend to be amplified. For this reason, it is important that blasters and blast designers strive to minimize the adverse effects of blasting as much as possible.

Important: The fact that blast vibration and airblast are kept below accepted standards does not guarantee that claims for damage will not be made (although the occurrence of actual blast-induced damage would be extremely unlikely).

10. Blast Recording

Definitions:

Seismograph - an instrument that writes a permanent continuous record of motion. A seismograph's physical constants are known accurately enough that it can be calibrated. The motion is recorded against a time base, allowing for the calculation of acceleration, displacement, velocity and frequency.

Transducer (or **sensor**) - an individual device that converts motion or pressure to voltage or capacitance.

Geophone or **Geophone block** - a housing that contains three motion transducers mounted in mutually-perpendicular axes; longitudinal, transverse and vertical.

Longitudinal axis - horizontal and oriented to record radial motion emanating from the source. The direction of the arrow on the geophone block. Motion to and from the source.

Transverse axis - horizontal, but oriented 90 degrees from the longitudinal axis. Motion from side to side.

Vertical axis - vertical, oriented 90 degrees from other two axes. Motion up and down.

Seismographs could be constructed with sensors to record in terms of particle velocity, particle displacement or particle acceleration. It is conventional in blasting, however, to record velocity. Modern units are also capable of recording the output of other types of sensors such as strain gauges, pressure transducers, etc.

We monitor the effects of blasting (1) to defend against claims of damage, (2) to comply with job specifications or regulatory or permit limits, (3) for in-house use such as slope stability or protection of owned facilities, (4) gauge the effectiveness of our blast designs, and (5) for research purposes.

A blasting seismograph is a four-channel, self-triggering recording device. It can usually process the data and print results in the field or store events for later download to a computer, or both. It is a sophisticated instrument, but it can't differentiate between a blast and other sources of motion, such as that from nearby operating equipment, heavy feet or a car door slam, etc. Most seismographs can also be accidentally triggered by a nearby source of RF (radio) energy.

Blasting seismographs are usually programmable for:

Operating mode - single shot, continuous (several shots), manual trigger, or histogram (strip chart).

Trigger source – ground vibration or airblast, or both.

Trigger level - The intensity level that will cause the seismograph to start recording.

In order to make sure the event is recorded, use the lowest trigger level consistent with avoiding false triggers. Trigger on airblast alone only if absolutely necessary. (Bear in mind that pressure waves travel much slower in air than vibration does through the ground. Depending upon the distance from the blast and the size of the pre-blast data buffer in the instrument, the ground vibration may have already passed through the recording point before the instrument would be triggered by airblast.)

Recording duration - How long the seismograph will record after it has been triggered.

Set the recording duration sufficiently long to record the entire event, including airblast. A good rule of thumb is to use the total blast initiation system time and then add one second for every 1000 feet (or portion of 1000 ft) of distance from the blast.

Geophone location.

The geophone should be located on the ground near the base of the structure to be protected. Optionally, it can be located at an interim site closer to the blast in the case of great distance and/or small charge weights. If at all possible, record on original ground rather than fill.

Do not record blast vibration:

On structures (unless that is the only possible location or is mandated).

Over hollow spaces or areas of subsidence.

Immediately adjacent to posts, poles or any other object that could oscillate and contribute to the motion in that specific location.

On grass, leaves, mulch, planter mix, loose soil or near trees and their roots.

Be specific in your documentation as to the monitoring location. Relate it to some permanent landmark. Be accurate. Don't estimate distances, measure them.

Geophone orientation should be level and with the longitudinal sensor (usually indicated by an arrow on the geophone case) pointing toward the blast.

If for some reason you are required to record on or in a structure, align the longitudinal sensor parallel with one wall, preferably pointing closest to the direction of the blast. In these instances, it is advisable to also place a second seismograph outside the structure and align its geophone so that its sensors are parallel to the ones inside. (Bear in mind that, in this instance, you are recording the structure's response to ground motion rather than the ground motion itself.)

Geophone Anchoring.

Proper coupling to the ground surface is very important. A geophone block that slips, bounces or rocks will result in readings that contain artificially high velocities and artificially low frequencies.

Possible anchoring methods (listed from best to worst):

bolting

epoxy

burying

spiking

wax

double-sided tape (carpet tape)

holding in place (not advisable unless you are an experienced operator)

merely resting on the surface

The use of sand bags or shot bags is questionable unless protection from flyrock is required. If used, make sure that the sand bag is firmly in contact with the ground surrounding the geophone block. A sand bag may raise the center of gravity of the geophone block and will not stop rocking or sliding above approximately 1/3 of a G.

The anchoring method required is determined by the amount of acceleration that is anticipated. See the attached graph for Seismograph Geophone Anchoring Recommendations.

Accelerations do not have to be very high to cause a geophone block to slip or rock. It can be shown that a combination of 1/3 G of vertical acceleration, when combined with 1/3 G of horizontal acceleration, can cause a poorly-anchored geophone to slip.

Recording airblast.

When recording blast vibration, always include the recording of airblast. Structures may respond to airblast that you cannot readily hear and can result in creaking, rattling or other internal noises. Many blast vibration complaints are actually the result of airblast-induced structure motion rather than ground vibration.

Orient the microphone at least 3 feet above the ground and away from walls, internal corners or other reflective surfaces. Although most microphones are omni-directional in the frequency range of most airblast, point them toward the blast. This will avoid the problem of someone thinking you are "cheating".

Record linear, peak air overpressure levels (either in dB, psi or in Pascals). Do not use A or C weighting as is common in conventional noise recording. A or C weighting will not properly record the low frequency air overpressures that are the cause of most structure response complaints.

A graph showing the attenuation curves for various sound-weighting schemes follows. The weighting curves shown are intended to duplicate the hearing capability of the human ear at various intensities. (A is for low Sound Pressure Levels, B is for medium SPLs and C is for high SPLs.) The horizontal line at 0 dB represents the linear, un-weighted sound level. If human annoyance was the concern with airblast, these weighting curves might apply. Our main concern, however, is structural response and sound weighting is not appropriate in this instance.

Care of the seismograph.

The leading problems experienced by seismograph users are usually caused by:

1. Dirt in the printer/plotter. Don't leave the instrument (and especially the printer compartment) open in the field. When stowing the geophone, microphone and microphone stand, wipe off the dirt and mud before putting them in the accessory compartment. Vacuum out the unit occasionally.
2. Failure to keep the batteries charged. A fully-charged instrument should monitor for one or two weeks or longer before the battery becomes too low to power the instrument. Follow the manufacturer's instructions on charging the battery. The better units utilize a voltage regulator that will not allow the battery to overcharge, even if it is left on the charger for extended periods of time. If the battery will not hold an adequate charge, the unit probably needs servicing.

It is important that the time and date on the instrument's clock be reasonably accurate. This ties the record to a specific event. This is especially important if you are using the instrument in a continuous monitoring mode and are leaving it set out to record a series of events.

Seismograph Calibration.

When monitoring for legal protection purposes, have the instrument calibrated annually, but absolutely no less often than 18 months. Some agencies mandate a factory calibration within the preceding 12 months or, in some instances, more often. Between calibrations, the instrument's self-check is usually sufficient to verify that the sensors are functioning properly and that the geophone is sufficiently level to provide an accurate reading.

Failure to record.

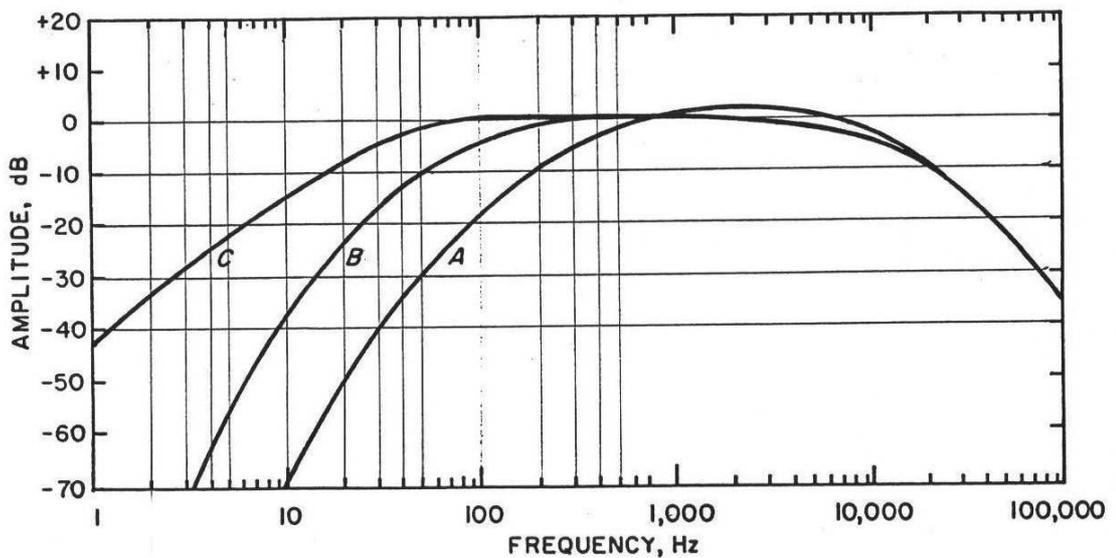
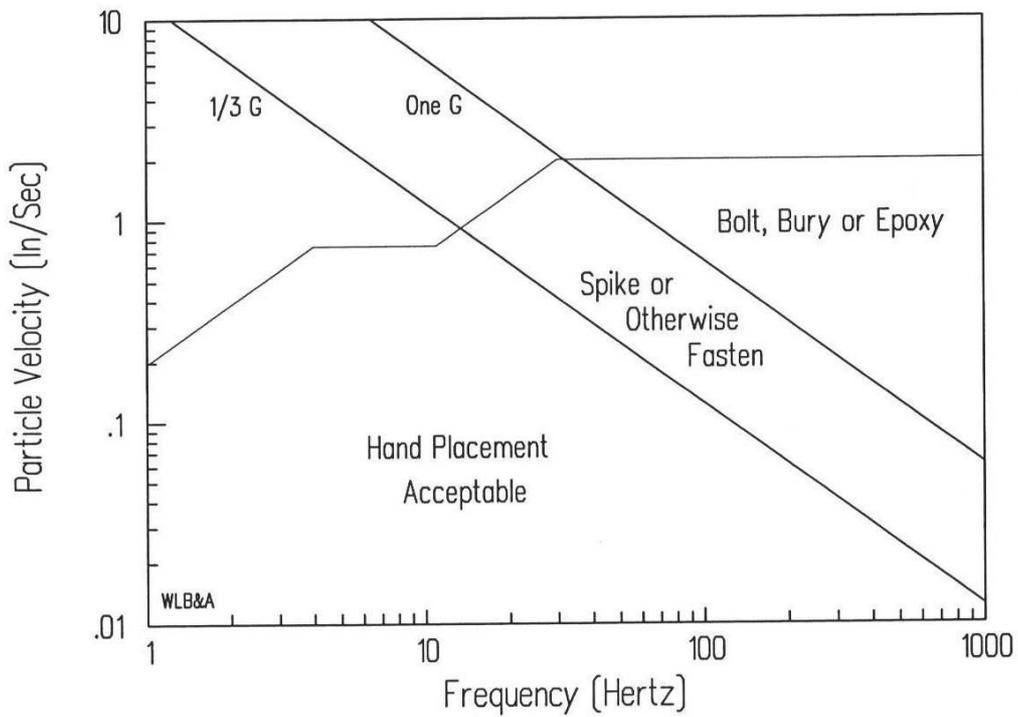
If for any reason the seismograph fails to trigger and record a blast, the seismograph operator should fill out a form (similar to the one that follows) to certify that a proper attempt was made. The document should be filed with the blast report. If at all possible, determine the reason for the failure and take corrective action. If the distance was too great and/or the vibration intensity too low to trigger the instrument, either lower the trigger level or move the instrument closer to the blast for future attempts. It is far better to extrapolate a known result than to have to estimate the blast vibration intensity.

Seismograph limitations.

Aliasing - A digital sampling phenomenon that occurs when the highest frequency of the vibration exceeds half the sampling rate of the instrument. This phenomenon will usually show up as a high frequency wave (that is usually correct) superimposed over a low frequency wave (that is incorrect). An anti-aliasing filter can prevent this from occurring in properly designed seismographs. Most modern blasting seismographs record at a minimum sampling rate of 1024 samples per second per channel. At the universally accepted four to one ratio, this provides a satisfactory frequency response for field use of up to 256 Hertz. It should be noted that, for research work, it is customary and preferable to use a ten to one (or higher) ratio.

If the instrument has an anti-aliasing filter and you are recording in very close proximity to the blast, the higher frequencies may be filtered out.

Seismograph Geophone Anchoring Recommendations (compared to OSMRE Alternative PPV criteria)



Standard sound measurement weighting scales.

SEISMOGRAPH OPERATOR'S REPORT

(To be filled out following a blast where blast vibration levels do not exceed the trigger level of the monitoring equipment)

Client _____

Project _____

Date _____ Time of Blast _____ Blast Number _____

Seismograph Make & Model _____ Serial Number _____

Trigger Source _____ Trigger Level _____

Range Selected _____ Record Duration _____

Sensor Test Results (at set-up) _____ (after blast) _____

Geophone Location _____

Witnesses (if any) _____

Additional Comments _____

I certify that the above listed monitoring equipment was properly set in place for the blast indicated and that the trigger level was set at the value specified above.

Signature of seismograph operator:

(printed name)

(company)

11. Designing Blasts to Minimize Vibration

Before proceeding, it is very important to understand (and all successful blasters do) that most of the parameters involved in blast design are interrelated or interactive. By this we mean that making a change in one parameter will have an impact on the others and could necessitate additional changes.

With the understanding that efforts at correcting one problem could possibly lead to others, let's look at what we can do with blast design to reduce vibration. Blast vibration is affected by the following list of variables. These are in turn modified by blast design parameters as indicated.

Variables over which the blaster has no control -

1. Distance - The farther from the blast, the less vibration, however you have to blast the rock where you find it.
2. Site geology - As the distance between the blast and the recording point increases, geology plays a somewhat larger role in the vibration frequency and how quickly the vibration dissipates. While this variable may be technically interesting to some, its impact is minor due to the normal rapid dissipation of blast vibration with distance.

Variables over which the blaster does have control -

1. Quantity of explosive per delay - This is one of the major factors in controlling blast vibration. Blast design parameters that affect this would be hole diameter, number of decks, initiation scheme, etc. Generally, reducing the quantity of explosive per delay will reduce the vibration generated, but the powder factor must remain high enough to adequately fracture the material. (See number 3 following.) Most blasters avoid decking if at all possible because it is labor intensive. Decking not only provides some reduction in blast vibration but, in certain instances, can yield better fragmentation.
2. Confinement of the explosive energy - Another major variable in blast vibration. Confinement is affected by burden and spacing, the quantity (and quality) of stemming, drilling accuracy, amount of sub-drilling and primer location, all as they relate to the quantity of explosive. Highly confined blasts (such as pre-splitting) generate higher vibration levels per unit weight of explosive. Mud-capping of boulders generates less vibration per unit weight of explosive (but much higher airblast). If a certain amount of throw or heave is acceptable, or if means are employed to prevent excessive throw, reducing burdens will lower vibration levels appreciably. However, one must be careful of increased airblast.

Bottom initiation will generally result in slightly more vibration than top initiation; however, the need to adequately break or pull the bottom usually outweighs any vibration benefit that might be gained from shooting from the top down.

3. Powder factor - Affected by almost all of the blast design parameters. The key here is to use as close to the optimum amount of explosive as possible and to distribute it through the material to be blasted in such a way as to adequately fracture and shift the mass. Too low a powder factor will not adequately fragment the material and a large portion of the available energy will be lost as seismic energy resulting in higher blast vibration. Too high a powder factor can result in flyrock along with higher airblast and vibration.
4. Explosive/borehole coupling - Although this has some minor effect on vibration, reducing coupling is seldom tried. Pre-splitting uses decoupled charges, but still results in high vibration levels because the increased confinement (the burden is far greater than normal) has a greater impact on vibration than the decoupling. Because of the difficulty in implementing it, reducing vibration by decoupling explosive charges is normally not utilized.

5. Spatial distribution of the energy source - This is a phenomenon that is a possible means of reducing vibration and can also increase the frequency of the vibration. Two examples of this are: (1) Two holes containing 100 lbs each and detonated simultaneously will generate less vibration than one hole containing 200 lbs. To take good advantage of this concept, the holes or decks detonating simultaneously should be separated by some reasonable distance, say half the width or half the length of the blast, whichever is greater. The more distance, the better. Adjacent, or nearly adjacent, holes or decks detonating simultaneously will benefit minimally from this effect. (2) A second example would be a long column of explosive generating less vibration than a spherical charge of the same weight because it is imparting vibration to a greater area. There have also been instances where a quarry or open pit mine might detonate two distinctly separate blasts simultaneously, with neither contributing appreciably to the vibration of the other.

6. Timing of energy release - Most regulatory agencies specify a minimum of 9 milliseconds (ms) between detonating charges, considering all explosives detonating within any given 8 ms time period to have detonated in the same instant. This is done solely for determining explosive weight for Scaled Distance calculations. In actual practice, delays of 5 ms to 9 ms can minimize vibration in very close-in blasting situations (say 10 to 25 feet). As distance increases, 9 ms will yield less vibration than shorter delay periods, but will not yield the minimum possible. The optimum time delay will depend on site-specific variables, but will tend to be in the range of 17 to 50 ms, with the higher delay being applicable only in larger blasts.

In the matter of selecting delay timing, some organizations have advocated a process that records the results from detonating a "signature" hole, and then using a computer program to superimpose identical waveforms over one another at differing time intervals in an attempt to find some optimum delay time that appears to offer the least amount of vibration. While this seems theoretically possible (and is easily accomplished mathematically), the method has met with only limited success. The biggest drawback is that it does not consider blast geometry, direction of initiation propagation and other blast parameters, factors which play an important part. It also assumes that the geology is consistent in all directions, a situation which may not exist.

There is a simpler method of the foregoing process that has met with some success where it is desirable to limit vibration in just one direction. The vibration resulting from a single signature hole (with burden, size and loading parameters being identical to a production hole) is recorded at several locations along a line in the direction of interest. A frequency spectrum analysis or Fast Fourier Transform (FFT) is then accomplished on the recorded data. A search is made to find one or more frequencies at which the ground in that direction does not readily transmit energy. This frequency is then converted to a delay time between detonating charges. If a realistic time can be found, a production blast is designed and detonated to test the timing. Basically what is done is to find a frequency that the ground doesn't readily transmit and then to try to pulse it at that frequency.

In considering either of the above two methods, it is very important to understand that: (1) The geology needs to be reasonably consistent between the blast and the structure or in the direction of interest, and (2) the method used to reduce blast-generated vibration in one direction may very well increase it in another.

7. Blast orientation. The maximum vibration will tend to be in a direction opposite to that in which the material is being heaved or thrown. By changing the direction of throw, you may also change the direction of maximum vibration, but usually only in a minor way. Again, be aware that, while you may be reducing the vibration in one direction, you may very well increase it in another. In most open pit mining operations, the geology will allow the rock to pull better in one direction than in others and the orientation of faces may have to be largely determined by geology, property boundaries and/or mining methods.

For conventional blasting, remember that the most efficient blasts will also have the lowest vibration levels.

12. Designing Blasts to Minimizing Airblast

From the causes of airblast listed earlier, we can readily see what steps need to be taken to reduce or prevent airblast. Exposed explosives charges and surface detonating cord trunk lines should never be used in urban situations.

We will assume here that you are using proper blast designs with normal burden, spacing and powder factors. If this isn't the case and you are experiencing excessive airblast, you may need to revisit your basic blast designs and compare them with well established standard criteria.

The main cause of high frequency airblast tends to be holes blowing out, either by ejecting the stemming or by venting through mud seams. Check your stemming quality and quantity. It's conventional to use drill cuttings for stemming holes because it is convenient. Cuttings, however, are not the most efficient stemming material. Pea gravel or any round stone is the worst. (Remember, shot in a shotgun load is round.....) Any fine material that turns into a slurry when loaded in a water-filled hole will also blow out quite readily. The best stemming material is angular crushed stone. Research has shown that the best size would be approximately $1/17^{\text{th}}$ of the borehole diameter. If you can readily obtain something close to this and use the correct quantity per hole, you should be able to confine the energy rather than letting it vent to atmosphere. It will take some experimenting, but the correct stemming height should be close to 80% to 100% of the burden dimension. You may find that this can be reduced if you are using the correct stemming material. The amount required is indirectly proportional to the quality. If the correct size of stemming is in short supply, at least pour a couple of feet of it directly on the explosive column and fill the remainder of the hole with drill cuttings.

To prevent holes from venting to the atmosphere in other ways, you should have your driller log the holes, watching for mud seams. When there is an obvious weak zone or cavity in a hole, it would be advisable to stem through it and resume loading (with another primer) once you are past the seam or weak zone.

Videotaping your blasts will greatly assist in troubleshooting sources of airblast from either of the above two causes.

Low frequency airblast can be caused when the velocity of initiation along a free face approaches or is above the speed of sound. This can also occur in a row of holes on the surface of the blast. The speed of sound in air at sea level is a little over 1100 feet per second. 1 millisecond of delay per foot of spacing results in blast progression of 1000 feet per second and 2 milliseconds per foot would be half of that, or 500 feet per second. It has been found that reducing the velocity of blast progression along the face to half the speed of sound or slower reduces this cause of airblast considerably. It is important to remember, however, that the delay timing should not be increased to the point of causing misfires through cut-offs in initiation systems or explosive columns. You must design for a buffer zone of several or more rows of holes between a hole that is detonating and detonators in holes where the initiation signal has not been received. If this is not done, misfires are often the result. Many successful blasters prefer to use delay timing between holes in a row of 2 ms to 5 ms per foot of burden. Many also prefer to use delay timing from row to row that is double, or nearly double, the delay timing in a row. Following these initiation design procedures will usually bring the blast progression below half the speed of sound and should prevent excessive low frequency airblast from this source.

Important: In your search for the reduction of airblast, do not compromise safety by causing misfires. In the above adjustments to blast progression, it may become necessary to increase your down-hole delay time so that a sufficient buffer zone exists.

If production requirements allow, it could also prove beneficial to schedule your blasts to take advantage of times when winds are blowing in a favorable direction or to take advantage of calmer wind conditions.

13. Blast documentation

It is extremely important to have adequate documentation of your blasts. This is more than just properly accounting for the explosives that you consume in your blasting operations. You must have a document that completely describes the blast. This can be in any format that you find convenient, but it must be accurate and it must be complete.

A good test to determine the adequacy of your blast documentation is to see if you (or better yet, another blaster) could reproduce the blast, in detail, solely from the data on the blast report. Any additional information that you have to provide from memory in order to reproduce the blast is information that should have been included on the original report.

Why is it critical to be able to reproduce a blast and to do so accurately? Assume for the moment that someone has filed a damage claim against you for a blast on a specific day. Most people (including judges and juries) who do not have first hand experience with blasting and blast effects, will tend to believe that blasting can cause all manner of structural damage and defects. Unless you, with or without your experts, can prepare a defense that proves that the damage could not have been caused by the blast in question, it is quite likely that you will be held responsible for the damage claimed.

To disprove a damage claim, one of the facts that must be established is the maximum amount and nature of blast-generated ground vibration that would have been experienced at the site of the damage claimed. Hopefully, you recorded the vibration with a blasting seismograph. If not, people knowledgeable in blast vibration can make acceptable estimates and testify as to the highest level of vibration experienced, but they need good blast records on which to base their calculations. They will be primarily interested in the specific location of the blast, the highest charge weight per delay and the time separation between delays. They should also have information on the orientation and geometry of the blast, the specific timing pattern utilized, type(s) of explosive used, burden, spacing, hole count, hole diameter and depth(s), stemming height, etc. These will help in estimating the amount of confinement of the blast.

If you monitored the blast for vibration and air over-pressure (airblast), all the better. Bear in mind that the specific location of the seismograph must also be noted. Try to relate the location of the seismograph to relatively permanent landmarks so that the location can be reconstructed a year or two later. Even when you monitor a blast, good blast documentation is important. The seismograph tape is only half the picture. You also need to know what caused the amount of vibration or air over-pressure that was recorded.

A couple of additional comments regarding blast documentation are in order:

(1) Blast records filled out in the field and in the blaster's own handwriting, signed by the blaster, are far better in court than a computer-generated printout (that might have been put together some time after the blast in question).

(2) Be accurate. Don't list a charge weight of 15 lbs and a distance of 500 feet if the real charge weight was 16.5 lbs and the distance was actually 475 feet. For the highest charge weight per delay, don't just divide the total explosives weight by the number of delays and then list the result. Put down the actual largest charge weight per delay that was loaded in the shot. Finding an inaccuracy on a blast report will probably lead an opposing attorney or the plaintiff's expert to argue that the rest of your records cannot be trusted.

Every blaster has his own favorite blast report format. A sample blast report form is included on the next page. Regardless of the format you use for the details, always include a diagram of the blast.

BLAST REPORT

BLAST IDENTIFICATION AND DATA:

Client _____ Project _____
Date _____ Time _____ Shot # _____ Location _____
Weather _____ Temp _____ Wind _____
Type of material blasted _____
Number of holes _____ Diameter _____ Depth _____
Burden _____ Spacing _____ Subdrilling _____ Stemming _____

EXPLOSIVES:

INITIATION SYSTEM:

Type	Quantity	
_____	_____	EB Caps _____
_____	_____	Machine _____
_____	_____	Circuits _____
_____	_____	Interval _____
_____	_____	Non-electric _____
_____	_____	Delays _____
Total weight	_____	Average weight per hole _____
Total cubic yards	_____	Powder factor _____

Per 8ms delay: Maximum holes _____ Maximum explosives _____

(Diagram blast on reverse side)

INSTRUMENTATION:

Seismograph _____ Operator _____
Location _____
Scaled distance _____ Report number _____
Critical structure distance _____ Direction _____

CERTIFICATION:

Blaster's name _____ License _____ State _____
Blaster's signature _____

14. Exploding Myths

Through the years there have been a number of strange theories, processes and phenomena that have come to the attention of blasting consultants, forensic specialists, geophysicists and others involved in addressing blast effects. Some of these were proposed by well-intentioned, but otherwise inexperienced persons, while others appear to have been dreamed up by individuals (some of whom were highly educated) in an attempt to explain some otherwise impossible situation. It might prove enlightening to look at a few of them.

Myth 1. Concrete can be readily damaged by blast vibration.

Most concrete slabs, walks, etc. will develop cracks over time for any number of reasons, but external vibration is not one of them. Explosive charges in or under concrete may cause damage to it, but this would have been the result of rock-block movement, cratering, or by heaving the concrete upward. If it was possible to crack concrete with vibration, concrete demolition work would be much easier and far less expensive. Among the normal causes of concrete damage are inadequate soil compaction, tree roots, normal curing shrinkage, heavy traffic, etc.

Myth 2. A pre-split crack can be used to control vibration.

Blasters, and even some fairly knowledgeable consultants, have fallen into this trap. While an abrupt canyon wall may attenuate surface waves, a pre-split crack will not make an appreciable difference in vibration attenuation except in very close proximity to the charge. A pre-split plane has a finite length and depth and vibration will go around it. The crack is not sufficiently open, having numerous contact points that will transmit vibration. As early as 1965, the Bureau of Mines (RI 6695) investigated this as a possible means of reducing ground vibration. In 1975, the Explosive Excavation Research Lab of the U. S. Army Engineer Waterways Experiment Station in Livermore California conducted its own study (Tech Report E-75-2). Both agencies determined that a pre-split fracture plane was ineffective as a buffer for vibration. In some instances, more vibration will result from a pre-split blast than from conventional production blasts with normal burdens.

Myth 3. Damage can be expected to occur automatically if blast vibration standards are exceeded.

Blast vibration standards in current use are quite conservative. As previously mentioned, it would almost appear that some of them were formulated for human response factors rather than to prevent damage. There are numerous instances where the limits spelled out in these standards have been exceeded, sometimes by double, without causing any damage.

The blaster should be cautioned however that, in refuting a claim of damage, it is not sufficient to use as his sole defense the argument that his blast vibration and airblast were within specified limits. That may form part of his defense, but it is much more important to base it upon some other type of irrefutable evidence.

Myth 4. Blast vibration can travel underground along some geologic layer or discontinuity and then suddenly come to the surface at some distant point and damage a structure.

This theory is usually proposed when an "expert" is trying to explain why he feels a complainant's residence was damaged while other structures much nearer the blast were not adversely affected. We can mostly thank texts that describe seismic refraction theory for handing us this problem. Even though there are an infinite number of rays in waves that emanate from a detonating charge, to simplify refraction theory, the diagrams normally only show a single ray traveling from the charge down to a layer, thence along the layer, and finally coming back up to the recording device on the surface. This ray represents the ray with the earliest arrival, not the largest motion. Depending upon the distance from the blast, the largest motion would probably have been a surface wave. No structure or portion of the ground between the detonation and the complainant's residence escaped also being affected by passing seismic waves. If damage did indeed occur to the subject residence, there should also be evidence of damage at others closer to the blast.

Myth 5. Airblast was reflected off of a cloud layer / inversion layer (pick one) and focused on the complainant's residence causing damage.

As previously mentioned in the discussion of temperature inversions, the effect only occurs at an extended distance from the blast. The airblast from normal blasts at that distance has diminished to a point well below that capable of causing damage. If windows weren't also broken between the complainant's home and the blast, this damage from reflection theory falls short.

Myth 6. Vibration energy was trapped in a waveguide, causing it to travel much farther from the blast, eventually causing damage when it surfaced.

While one may occasionally find conditions in nature similar to a waveguide, they are fairly rare. The most common of these might occur when a layer of alluvium overlays solid rock. In this situation, vibration waves in or on the alluvium might not diminish as rapidly as they might have if the condition did not exist, but they will still be diminishing rapidly with distance. The vibration closer to the blast would have been of a higher intensity and if there was damage at the distant location, it would have also been accompanied by damage closer to the blast.

In addressing and refuting some of the foregoing myths, a useful tool as suggested by Oriard (1999 and 2002) is called the **Scale of Effects**. Scale of Effects comes out of earthquake technology where it has been used for years to identify zones of similar damage around the epicenter of an earthquake. Within a given zone, damage levels will be relatively similar and can be assigned to a specific intensity level on the Modified Mercalli scale. Higher numbers, closer to the epicenter, indicate the higher levels of damage. As the distance from the epicenter becomes greater, the decreasing levels of damage result in zones that are assigned lower numbers. In all cases, the numbers are assigned based upon ranges of actual documented damage or effects. For a further discussion of the Modified Mercalli scale or earthquakes in general, the reader is referred to a good earthquake text, to Richter's book or to one of Oriard's books listed in Appendix D.

To use the Scale of Effects for evaluating blast vibration damage, one must consider the following question: *"If the damage claimed was indeed caused by the blast, what other effects would have had to have occurred at the same time?"* Often the damage claimed would have required extremely high levels of vibration, yet other far more sensitive objects nearby were not harmed.

A classic example of this occurred in Southern California some years ago. The owner of a \$7 million home claimed damage from blasting that took place approximately a half mile away. The damage claimed included cracks in the concrete garage floor, swimming pool, pool deck, chimney and plaster, a broken PVC water line, cracks in a paved tennis court, and displacement of opposing bathroom walls that showed separation of almost a half inch near the ceiling. In the owner's words (who happened to be an attorney), this was a "classic example of blast vibration damage". Where the Scale of Effects came into play was the fact that there were several statues delicately balanced on pedestals in the main hall of the residence. These statues would have surely been toppled and broken had the damage claimed been from blast vibration, but they were not. A second application of Scale of Effects was in the bathroom. If vibration from blasting had caused the walls to be permanently displaced outward at the top, why did it not also crack the mortar in the joints in the flagstone shower at one end of the bathroom?

It was fairly obvious that there had been some major shrinkage issues in the bathroom materials and the area in the garage that was cracked was located on poorly compacted fill. Although some of the damage claimed bordered on the ridiculous and was easily refuted, the Scale of Effects helped immensely in defending the contractor in this case.

Myth 7. Vibration from a blast acted as a triggering force when it was added to existing strain in a structure (i.e. the straw that broke the camel's back).

Strains that occur in structures start as soon as the structure is under construction and continue throughout its life. These are caused by many sources, among which are the shrinkage of building materials as they cure, expansive soils, changes in weather, temperature variations between day and night or different seasons, etc. Most of these far exceed the strain from blast vibration. The slight elevation of strain level during a blast would still fall well short of peak strains that the structure has experienced numerous times prior and would thus not be capable of being a trigger source.

If one were to monitor and document the various cracks in structures over an extended period, one would find that they would open and close on a continuing basis, depending upon the strain being generated by normal environmental sources. If you were to detonate a blast nearby during one of the phases when the cracks were relatively closed, the argument could be made that the blast vibration assisted in the healing of the cracks. Of course, this would be ludicrous, but that is exactly the same logic being used by persons who claim that blast vibration acted as a trigger source and caused the crack in the first place.

Lew Oriard (1999) also refutes this theory quite effectively. He states that, "*Because of the action of powerful environmental forces, all houses undergo large cyclic strains on a continuing basis. That simple fact alone dictates that a triggering force would have to be quite large. Otherwise the crack would already exist.*"

Myth 8. Damage from structural fatigue will result from repeated exposure to vibration from blasts.

The consensus of various segments of the engineering community holds that, for permanent deformation to occur from fatigue, strain must regularly exceed at least half of the yield strength of the structure or material. While strains generated from blasts could possibly exceed half the yield strength of a material or structure, it would take very large charges detonated in extremely close proximity to do so. Damage would far more likely be caused by block movement rather than vibration. Other types of damage would become apparent before fatigue could occur.

The Bureau of Mines in RI 8896 (1984) also addressed this issue. They constructed a house in the path of an advancing large open pit coal mine. Due to mine operational constraints, the blasting tests were discontinued when the high wall reached a distance of 300 feet from the house. At that point, because they had not been able to obtain structural damage from the blast vibration, they resorted to the installation of mechanical shakers in the structure in an attempt to cause cosmetic damage through accelerated fatigue tests. The shakers were set up to put vibration through the structure equivalent to approximately 0.5 inches per second of PPV. The frequency was set to fall within the resonant range of portions of the structure (5.90 to 9.35 Hertz).

The shaking of the structure finally managed to generate a tape joint crack and a crack in joint compound over a nailhead (basically cosmetic damage) after 56,000 cycles. This would have been the equivalent of 28 years of shaking, twice a day, from blast-induced vibration at a PPV ranging from 0.3 to 0.5 inches/second.

Appendix A - Blasting Complaint Report

Complaint received: Date: _____ Time: _____

Complainant's name: _____

Address: _____ Phone: _____

Specific complaint: _____

Date and specific time of occurrence (as reported by Complainant):

Date: _____ Time: _____

Complaint received by: _____

=====

Results of Investigation: _____

Investigated by: _____

=====

Disposition of Complaint: _____

(use additional pages as necessary)

Appendix B - Metric Conversions

The following information is provided to facilitate the conversion of blast calculations between imperial (US) and SI (metric) units -

Official Definitions (according to U.S. and Canadian law):

$$1 \text{ inch (in.)} = 25.4 \text{ millimeters (mm)}$$

$$1 \text{ pound (lb.)} = 453.59237 \text{ grams (g)}$$

Useful Conversion Factors:

Distance:	feet (ft)	x	.3048	=	meters (m)
	meters	x	3.2808	=	feet

Weight:	pounds (lbs)	x	.454	=	kilograms (kg)
	kilograms	x	2.2026	=	pounds

Peak Particle Velocity:	in/sec	x	25.4	=	mm/sec
	mm/sec	x	.3937	=	in/sec

Volume:	cu. yards (yd ³)	x	1.308	=	cu. meters (m ³)
	cu. meters	x	.7645	=	cu. yards

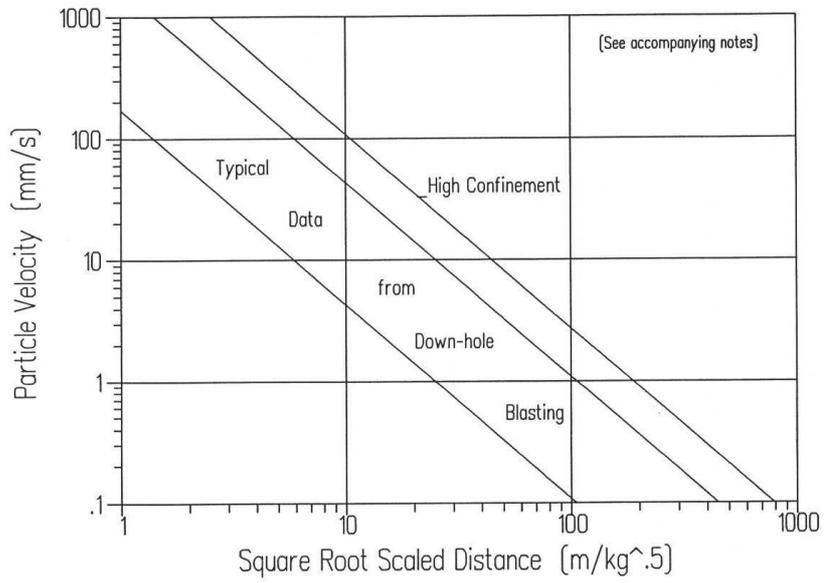
Powder Factor:	lbs/yd ³	x	.93	=	kg/m ³
	kg/m ³	x	1.6863	=	lbs/yd ³

Square Root Scaled Distance:	ft/lbs ^{1/2}	x	.45236	=	m/kg ^{1/2}
	m/kg ^{1/2}	x	2.2106	=	ft/lbs ^{1/2}

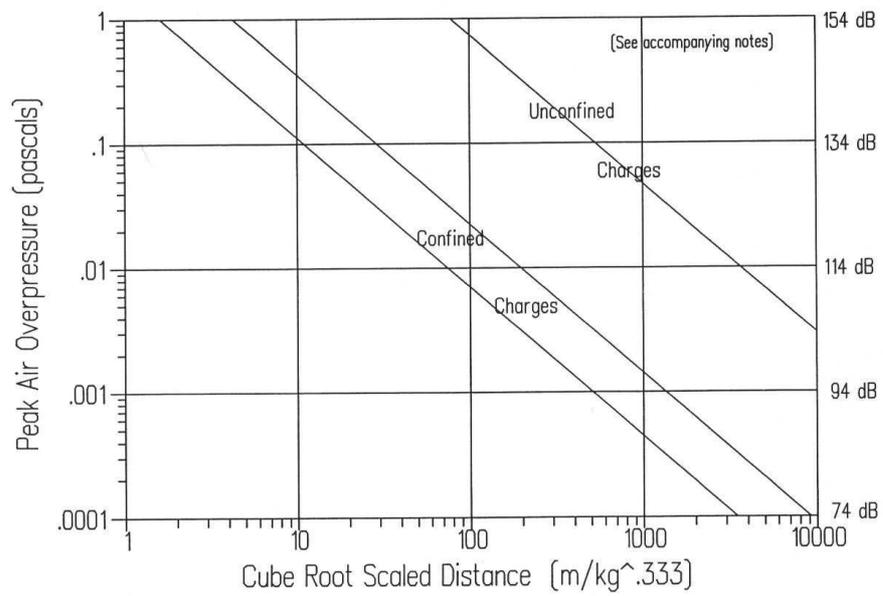
Cube Root Scaled Distance:	ft/lbs ^{1/3}	x	.3965	=	m/kg ^{1/3}
	m/kg ^{1/3}	x	2.5221	=	ft/lbs ^{1/3}

Pressure:	psi	x	.145	=	Pascals
	Pascals	x	6.895	=	psi

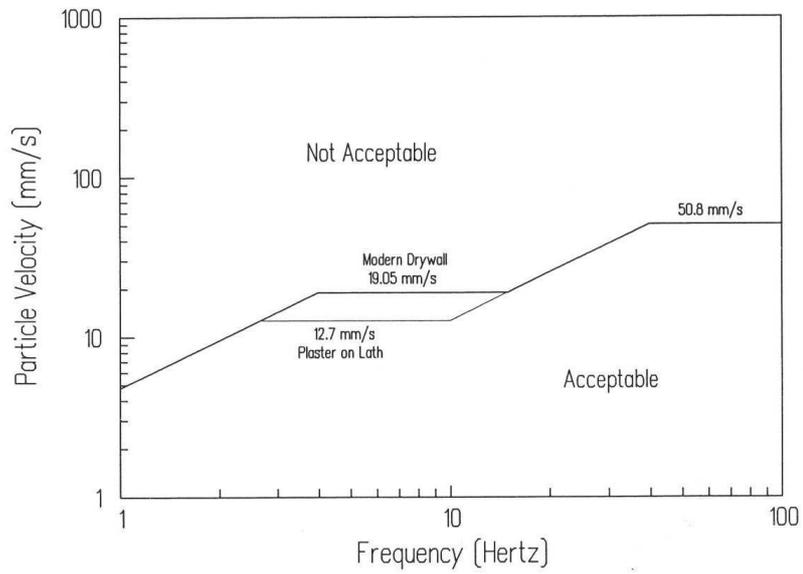
Blast Vibration Prediction Curves - Metric (Oriard 2002 and others)



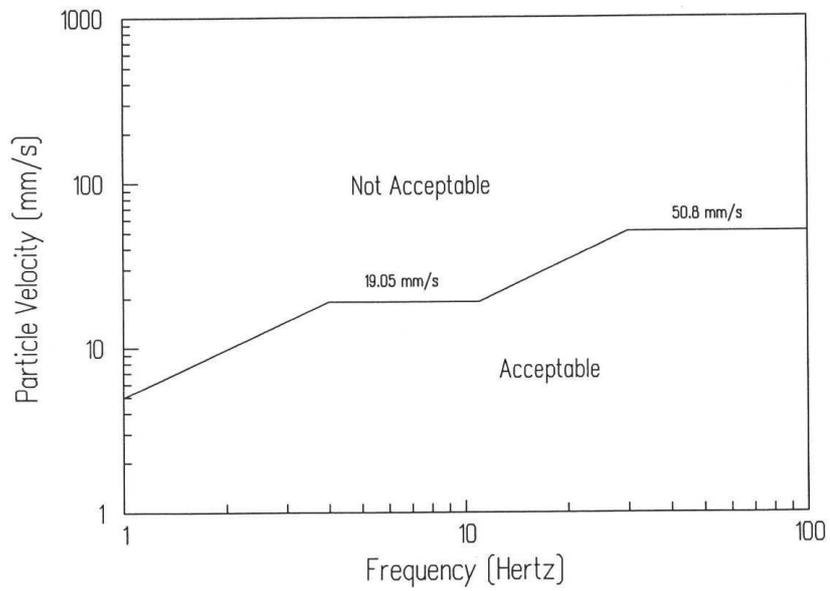
Air Overpressure (and Airblast) Prediction (metric version)



RI8507 Alternative Blasting Level Criteria
(Metric Version)



OSMRE Alt. Blasting Level Criteria - metric
30 CFR Part 816.67(d)(4)



Appendix C - Calculations for Sinusoidal Waveforms

The following equations express the relationships between Velocity, Displacement, Frequency and Acceleration for sinusoidal waveforms.

$$V = 2 \pi f D \quad \text{or} \quad V = 386.1 \text{ Gs} / (2 \pi f)$$

$$D = V / (2 \pi f)$$

$$A = 2 \pi f V$$

or

$$A_g = (2 \pi f V) / 386.1$$

$$f = V / (2 \pi D) \quad \text{or} \quad f = A / (2 \pi V)$$

Where:

V is velocity in inches/second

D is peak displacement in inches

A is acceleration in inches/second²

A_g is acceleration in Gs

f is frequency in Hertz (cycles per second)

π is 3.14159....

Appendix D - References and Additional Reading

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Stagg, M. S., and Engler, A. J. (1980), "Measurement of Blast-Induced Ground Vibrations and Seismograph Calibration," Bureau of Mines Report of Investigations, RI 8506.

Tart, R.G., Oriard, L.L., and Plump, J.H., (1980), Blast Damage Criteria for Massive Concrete Structure. ASCE National Meeting, Specialty Session on Minimizing Detrimental Construction Vibrations, Portland, OR, ASCE Preprint 80-175 April 1980.

Wiss, J. F. and Linehan, P. W., (1978), Control of Vibration and Blast Noise from Surface Coal Mining. Bureau of Mines Open File Report 103-79. National Technical Information Service.

Note A - These publications are exceptionally good in their treatment of the subject matter.

Note B - This publication will prove to be of great value to those persons or organizations who investigate claims of blast vibration or airblast damage.