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BLASTING & THE ENVIRONMENT
Ground Vibrations
(Revised Feb. 2009)

by

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1. INTRODUCTION

In the United States of America there is a law which states that the maximum peak particle velocity shall not exceed 25 mm per second at the location of any public building. Peak particle velocities shall be recorded in three perpendicular directions. When a limit is put on the degree of ground vibrations such as this it allows the quarry or open pit manager three options, if blasting close to a built up area.

- Keep the quantity of explosive detonated per delay to a suitable level to keep within the limit of peak particle velocity set.
- Monitor blasts by use of a ground vibration recorder to keep vibration within the specified level. A method recommended where there are a larger number of public complaints.
- A survey of the site measuring ground vibrations at various measured distances. The results are plotted on a log-log graph. The best fitting straight line is drawn through them. From this graph the maximum peak particle velocity is read off together with the corresponding charge mass over distance.

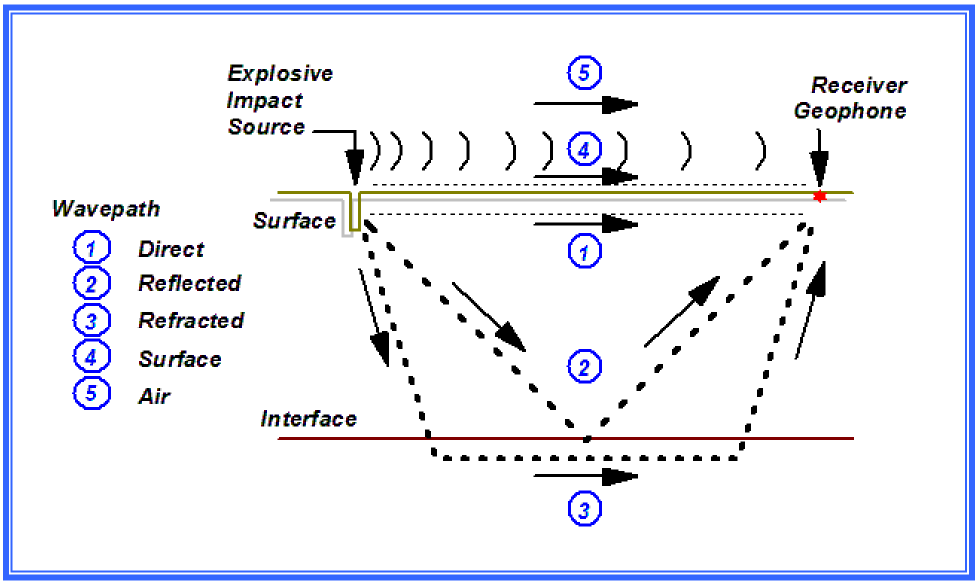

Figure 1: Illustration of Seismic & Air Waves produced from an Explosive Impact (Chiappetta RF 1981)

The degree of ground vibration felt is dependent on several aspects of the blast and the surrounding rock mass. The length of delays and the direction of progression of delays have a significant effect on ground vibration levels. The different way in which waves can arrive at a point is illustrated in **Figure 1**. Other factors are the burden and spacing, type and weight of explosive, confinement and overburden. Factors that have no measurable effect on vibration levels are charge length, total charge mass, angle of the borehole or its diameter, general surface topography or wind.

2. CHARACTERISTICS OF GROUND VIBRATIONS

2.1 Generation

When an explosive is detonated under confinement in a borehole, its energy is consumed in exerting very high pressures and temperatures in a very short time period causing the surrounding rock to melt, flow, crush and fracture.

At some distance from the shot point these inelastic processes cease and elastic effects begin to occur. These disturbances spread rapidly away from the shot point as a seismic event travelling at the speed of sound in rock. Thus, because of the radial propagation of seismic waves the event will only be completely defined by three mutually independent vector recordings taken along three mutually perpendicular axes.

2.2 Wave Forms

Seismic records identify several types of wave form which fall basically into two categories:

Body waves - which travel through the rock mass

Surface waves - which travel along the surface layers

When studying the effects and magnitude of blasting operations, it is unnecessary to distinguish between the various wave forms since it is the amount which a structure moves at a given frequency that is the governing factor.

2.3 Transmission

Close to a blast the wave motions are a jumbled mass of both elastic and inelastic wave forms with fairly high frequencies that is greater than 25 Hz. At about 30 meters from the exploding shot the waves begin to attain their true elastic nature and propagate radically outwards at about the normal frequency of the rock mass 10 - 50 Hz.

2.4 Vibration Terminology

Sinusoidal particle vibrating motion is assumed and the basic terminology is usually defined as follows:

Simple Harmonic Notion - A spring object combination, oscillating back and forth indefinitely with one degree of freedom (**Figure 2**).

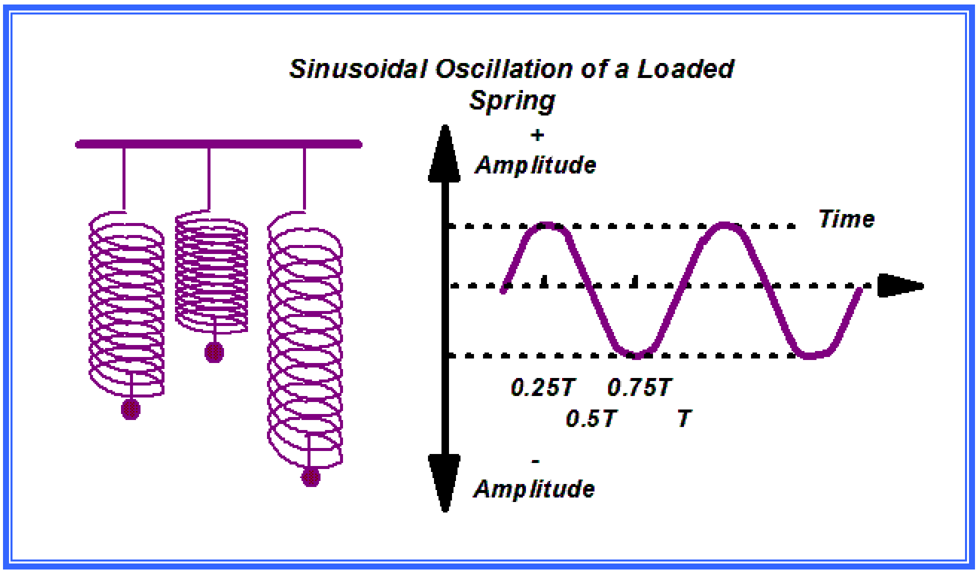

Figure 2: Sinusoidal Oscillation of a loaded Spring

Cycle - One complete oscillation of repeated events.

Amplitude - The maximum displacement from the position of rest. Measured in millimeters.

Particle Velocity - The rate of change of displacement and the speed of excitation of a particle in the ground brought about by vibrating motion. It is not the propagation velocity of wave form in the rock mass. Particle velocity is measured in mm/sec.

Particle Acceleration - The rate of change of particle velocity acceleration is expressed in mm/sec^2 or in terms of gravity.

Frequency - The number of times the vibratory motion cycle is repeated in unit time. A cycle is one complete sequence of repeated events. Frequency is expressed in Hertz.

Wave Length - The length of a complete cycle expressed in meters.

Duration - This is the total time lapse of the seismic vibration and, under certain conditions of relatively long duration, may make the effects of the seismic event noticeable even at low amplitude and frequency.

2.5 Traces

Generally coal mine blasts are characterized by blasthole diameters of up to 350 mm with relatively thick overburden. Quarry blasts have much smaller diameter blastholes of up to 150 mm, with smaller charge masses. Duration of blasts range from 0.5 seconds to about 3.0 seconds. Construction blasting is characterized by small diameter holes of up to 75 mm and corresponding small charge masses. The distance to structures is also very much less, being as little as 1.0 m in some cases. In construction blasting the higher frequencies of ground vibration often predominate due to the short distances to structures of concern. **Figure 3** shows typical three component ground vibration recording for coal, open cast quarry and construction blasts.

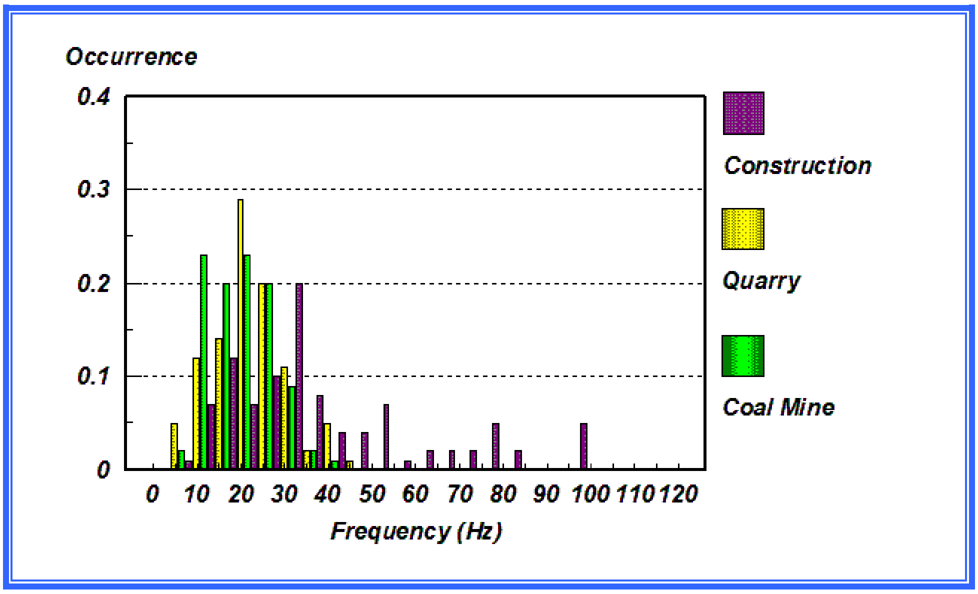

Figure 3: Predominant Frequency Histogram for Coal, Quarry & Construction Blasting.

Figure 4 shows frequency histograms, combining the triaxial readings for each of the examples in Figure 3. Frequency values below 2 Hz occurred for blasts that were measured at a long distance and in ground with a thick overburden. Additional research is required to quantify this low frequency energy and to determine its effects.

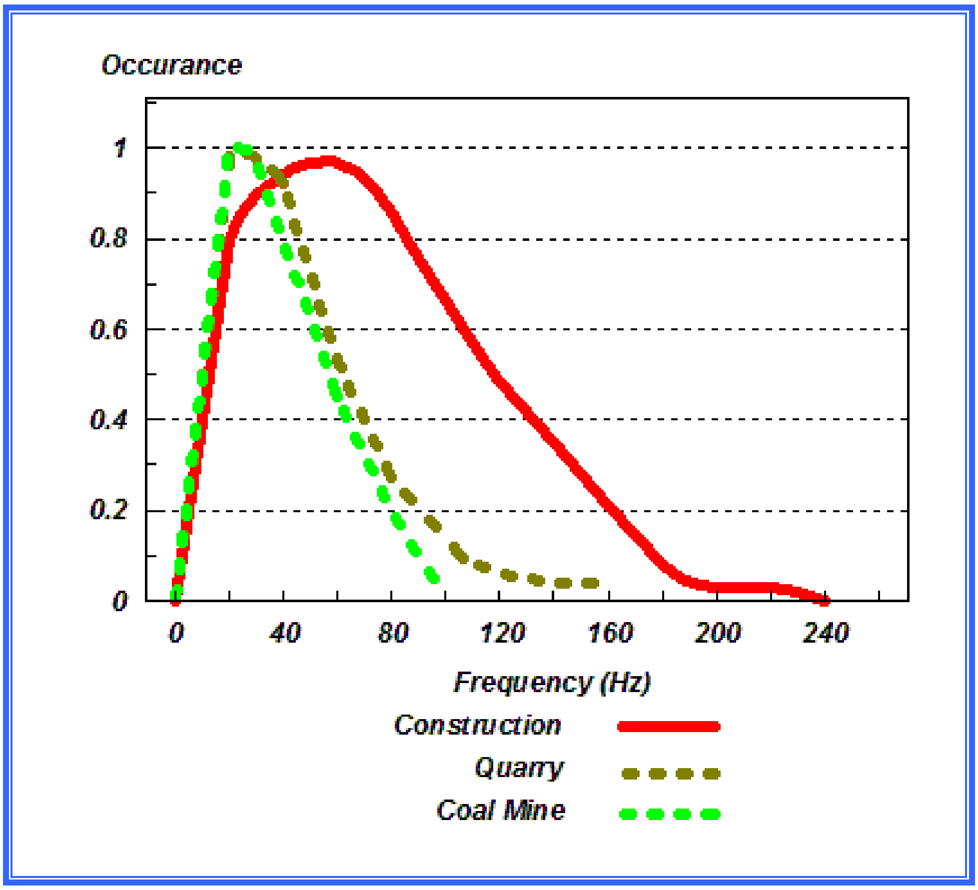

Figure 4: Minus 20 dbl ranges Graph of Coal, Quarry & Construction Blasting

2.6 Concept of Scaled Distance

Scaling is the designation of relationships correlating ground motion levels at various distances from blasts. A scaling factor based on a dimensionless parameter for distance is used. The scaled distance is derived from effects of geometrical dispersion on the outboard ground motion wave from an explosion. Since the energy in the ground shock is distributed over successively greater volume of rock, the peak ground level decreases.

The ground motion wave front resulting from a column charge takes the form of an expanding cylinder. **Figure 5** shows the outbound ground motion cylinder around a section of a column charge. The column of this compression cylinder varies as the square of its radius. Thus, the peak level of ground motion at any given point is inversely proportional to the square of the distance from the blast point.

The empirical formula relating peak particle velocity to scaled distance has been developed from results obtained in the field.

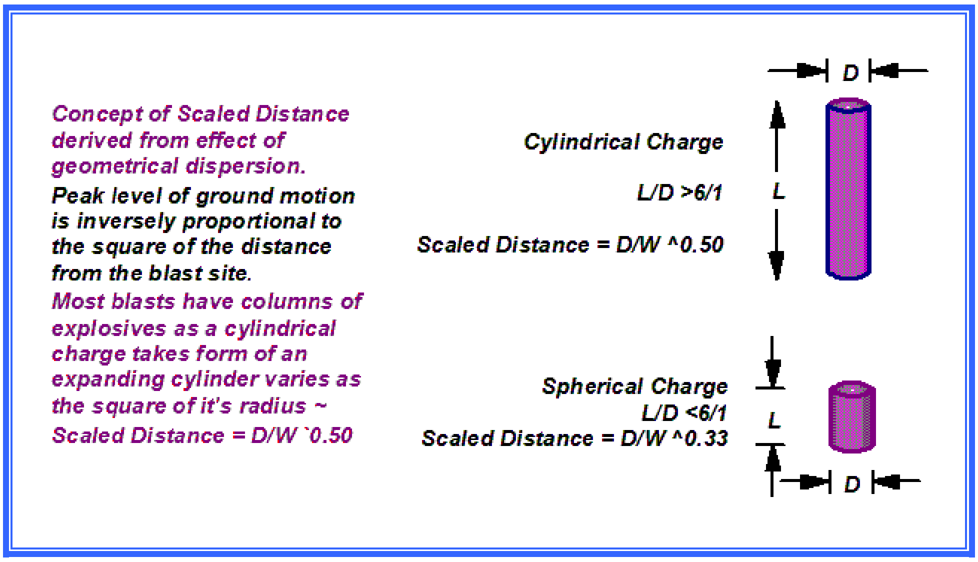

Figure 5: Ground Motion due to Geometrical Spreading

3. PEAK PARTICLE VELOCITY

3.1 Prediction

Vibration levels increase as the charge mass per delay increases and the distance from the blast decreases, see **Figure 6**. The United States Bureau of Mines has determined an empirical propagation equation relating particle velocity to charge mass and distance.

$$V = K\left(D/\sqrt{E}\right)^{-x} \qquad - (1)$$

where V = particle velocity in millimeters per second

D = distance from blast in meters

E = maximum charge per delay in kilograms

K & x are constants relating to the particular site.

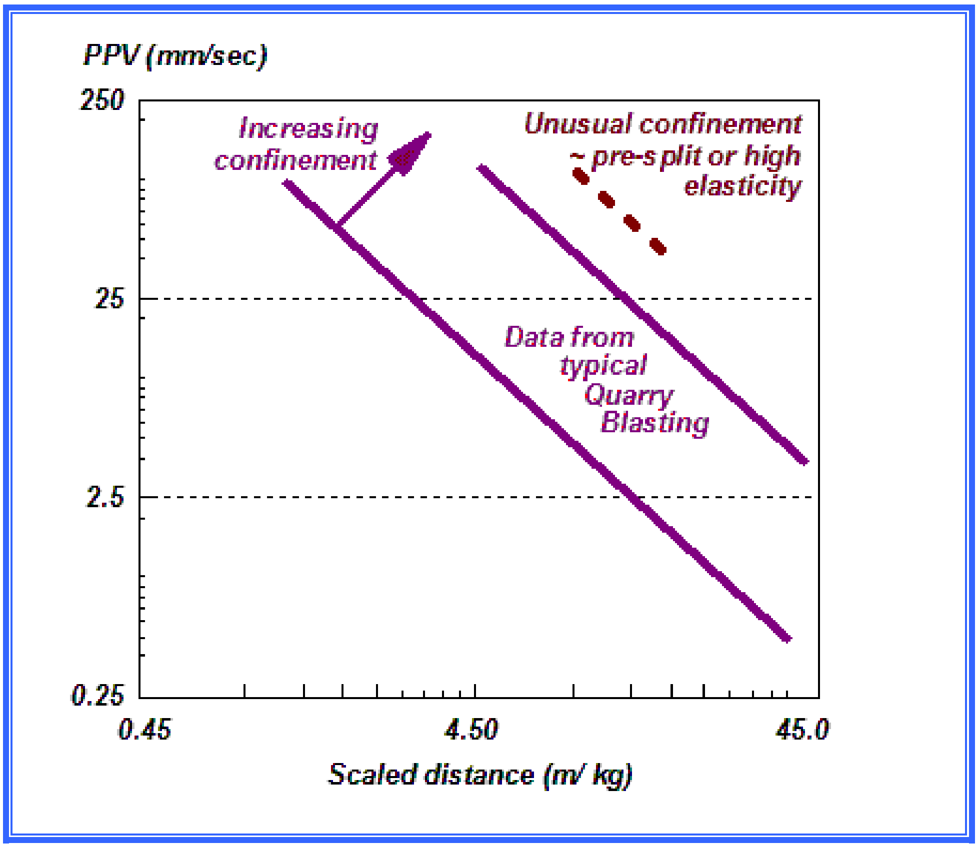

Figure 6: Peak Particle Velocity versus Distance

An instrumental investigation would enable accurate measurements for K and x to be determined. Where this is not possible an analysis of all data of all test sites by the United States Bureau of Mines has indicated that provided the value of

$$D/\sqrt{E} > 31 \qquad - (2)$$

Where $D/\sqrt{E}$ is called the Scale Distance

then the blasting operations are, from the vibration aspect, safe anywhere in any conditions. However, this may prove restrictive in practice and a survey may be required. **Figure 7** shows the maximum safe vibration levels for various types of buildings.

At closer distances than thirty (30) meters the interference of different wave types may produce rather larger amplitudes than predicted. However at these short distances, except in construction blasting, other factors have to be taken into account particularly that of fly rock. The provision of adequate precautions to prevent damage by such causes will automatically take care of any potential vibration problems. For a more precise assessment vibrograph readings would be necessary.

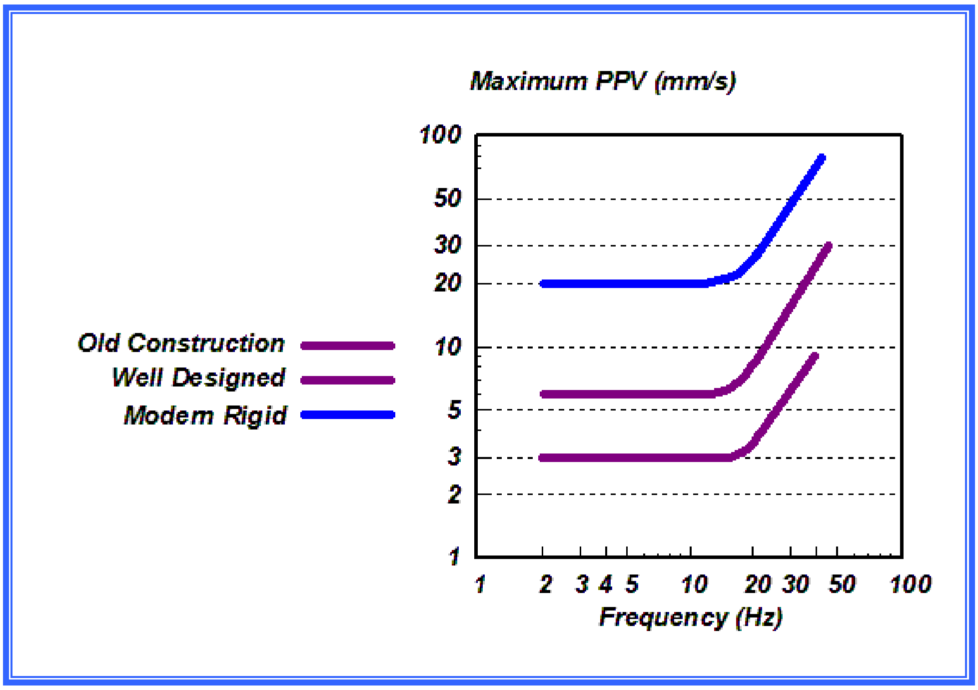

Figure 7: Maximum Vibration Levels for Buildings

3.2 Factors Affecting Generation

Actual ground vibrations generated will depend on:

- Rock mass characteristics
- Explosive power
- Confinement
- Distance
- Timing and direction of propagation
- Subdrill

3.2.1 Rock Mass Characteristics

If an instrument were located in the same bed of rock as the blast, frequencies would be fairly high, up to 50 Hz for igneous rock and down to 10 Hz for shales and mudstones. With an instrument installed upon a thick layer of overlying clay then the dominant frequency would tend to be from the surface waves. Depending upon the moisture content of the surface layer the frequency could be as low as 3 Hz.

The presences of faults, dip of strata, schistocity, affect vibration transmission. Fault planes may act as a wave guide causing a local reinforcement of vibration effects. Sandstone has a higher frequency and transmission properties than shale and mudstone. Vibration levels across pre-split planes are not reduced but behave as in a solid rock mass. This is due to the radial nature of the waves and the fact that a presplit plane is, usually, in contact with the mass.

3.2.2 Explosive Power

Different explosives develop different amounts of shock and heave energy, dependent on the borehole pressure they reach during detonation. Vibration levels tend to be higher for explosive with higher borehole pressure. In blasts for which more than one delay is employed the weight of explosive can be considered to be the maximum quantity detonated per delay. This provided that the delay interval is sufficiently large for constructive interference between the various delays, with consequent reinforcement of the vibration, not to occur.

Vibration levels tend to vary with the relative weight strength of the explosive. The majority of empirical vibration data has been gained in surface blasting where the most popular explosive until recently has been ANFO. With the advent of powerful watergels and emulsions allowance must be made for their extra power. It is not sufficient simply to take the mass of the explosive.

$$W_{eff} = \frac{W \times RWS\ Explosive}{RWS\ ANFO = 100} \qquad - (3)$$

where W_{eff} = effective charge weight per delay

W = charge weight per delay

3.2.3 Confinement

The greater the distance of a blasthole from a free face the longer it takes the explosive to break the rock and vent the explosive gases. The longer this breakage process the greater will be the proportion of energy which is forced into the surrounding rock mass as a potentially disturbing force.

If a blast ratio is increased from the optimum in any given operation by some 20 % the ground vibration level can, according to Andrews, be increased by a factor of two or three because of the corresponding decrease in blasting efficiency. Use of a weaker explosive, perhaps to try and reduce costs, has the same effect as opening the drilling pattern.

An example of a factor affecting the blasting efficiency outside the operators control is where a flexibly wrapped, slumpable explosive is loaded into wet holes. The average loading density will vary according to the depth of water in the hole. It follows that parts of the rock will be under blasted if, in the planning of the blast, the hole were assumed to be dry. If the reverse is assumed and the holes are dry then over blasting occurs. Under blasting will result in higher ground vibrations and over blasting in air blast and noise.

Very approximate values can be put to the constant "K" used in equation 1.

- Chevron pattern = 0,75
- Square pattern = 1.00
- Single row = 0,75
- 2 to 3 rows = 1,00
- 4 to 5 rows = 1,50
- Over 5 rows or choked = 2,00
- Pre-split = 4,00

These values are approximate and should be used as guide lines only to forecast the possible result of a blast.

A pre-split can cause considerable damage if it possesses an infinite burden and a large number of holes are fired simultaneously. However the charge is usually decoupled and this reduces the energy released into the surrounding rock mass.

3.2.4 Distance

This is of great importance in considering vibration generation and, as a general rule, increasing distance is accompanied by a reduction in intensity of the vibrations. The frequency tends to decrease as the distance increases as shown in **Table 1**.

3.2.5 Timing and Direction of Propagation

A further effect that timing has on the peak particle velocity is related to the direction of initiation. When the blast progresses towards a structure the effective delay interval is reduced, thus increasing the chances of adverse interference of vibration energy, see **Figure 8**, between adjacent holes. When the delays progress away from the structure, adverse interferences are is less likely. Structures perpendicular to the progression of delays receive intermediate level vibrations. **Figure 9** shows this effect.

Table 1
Average Vibration Frequencies in Blasting

Type of Blasting	Typical		
	Hole Diameter	Distance to	Frequency
	mm	m	Hz
Civil,trenching etc	30-50	5.0-50	30 to 60
Quarrying	89-125	100-500	20 to 40
Coal, Overburden Stripping	150-+	500-2'000	1 to 2

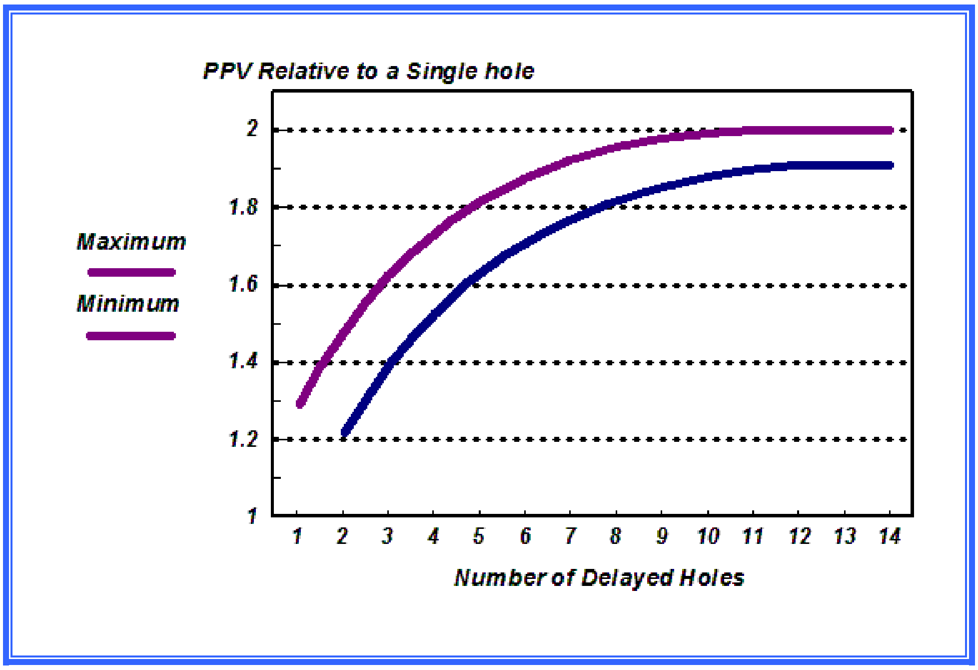

Figure 8: Effect of Successive Delays on PPV

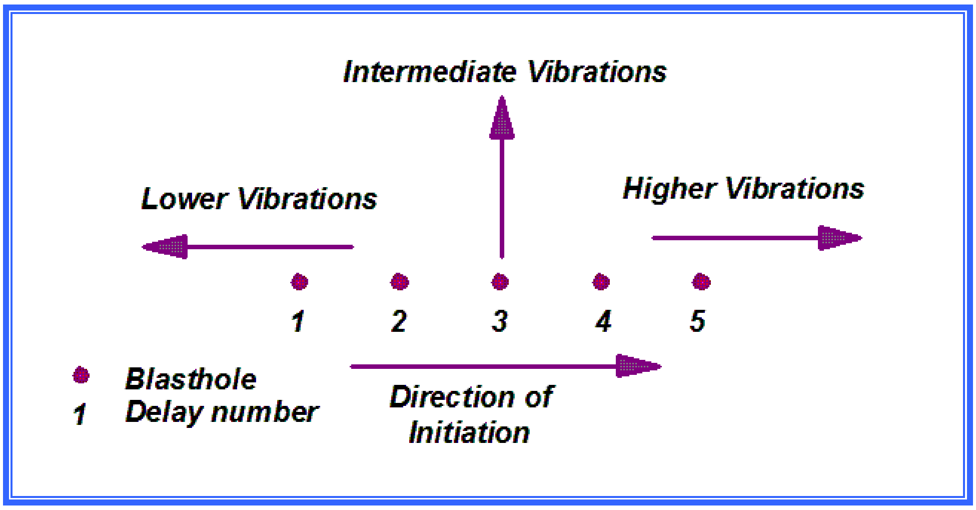

Figure 9: Effect of Delay Sequence on Particle Velocity

3.2.6 Subdrill

When the length of subdrill exceeds about one third of the burden, or 8 - 12 borehole diameters, each additional increment provides less and less energy for fragmentation and displacement of rock and more energy for ground vibration.

4. FREQUENCY

Specifying the maximum ground particle velocity alone does not usually take into account two very significant parameters, namely the predominant frequencies of the ground motion and the structure in question.

The main conclusions drawn from a study by Medearis were:

- Residential structures, such as houses, have a natural frequency in the range 5 - 30 Hertz. This is illustrated in **Figure 10.**
- **I**n general, frequencies show no tendency to vary with age or location.
- There is no correlation with plan area of structure.
- Damping has no tendency to vary with age or location.
- Neither peak ground velocity nor peak ground acceleration are optimum predictors of damage.
- Peak velocity may be predicted with greater confidence than the structural response.

Sisken et al in 1980 published results of a comprehensive study of ground vibrations and come to the conclusions that:

- The amplitude frequencies and duration of ground vibrations change as they propagate because of:
  - Interactions of various geological media and structural interfaces,
  - spreading of wave train due to dispersion,
  - Absorption - this is greater for higher frequencies.
- Thick soil overburden and large distance create long-duration low frequency wave trains. This increases the response and damage potential of nearby structures.
- Coal mine blasts are characterized by trailing large amplitude, low frequency wave because of larger overburden layer.

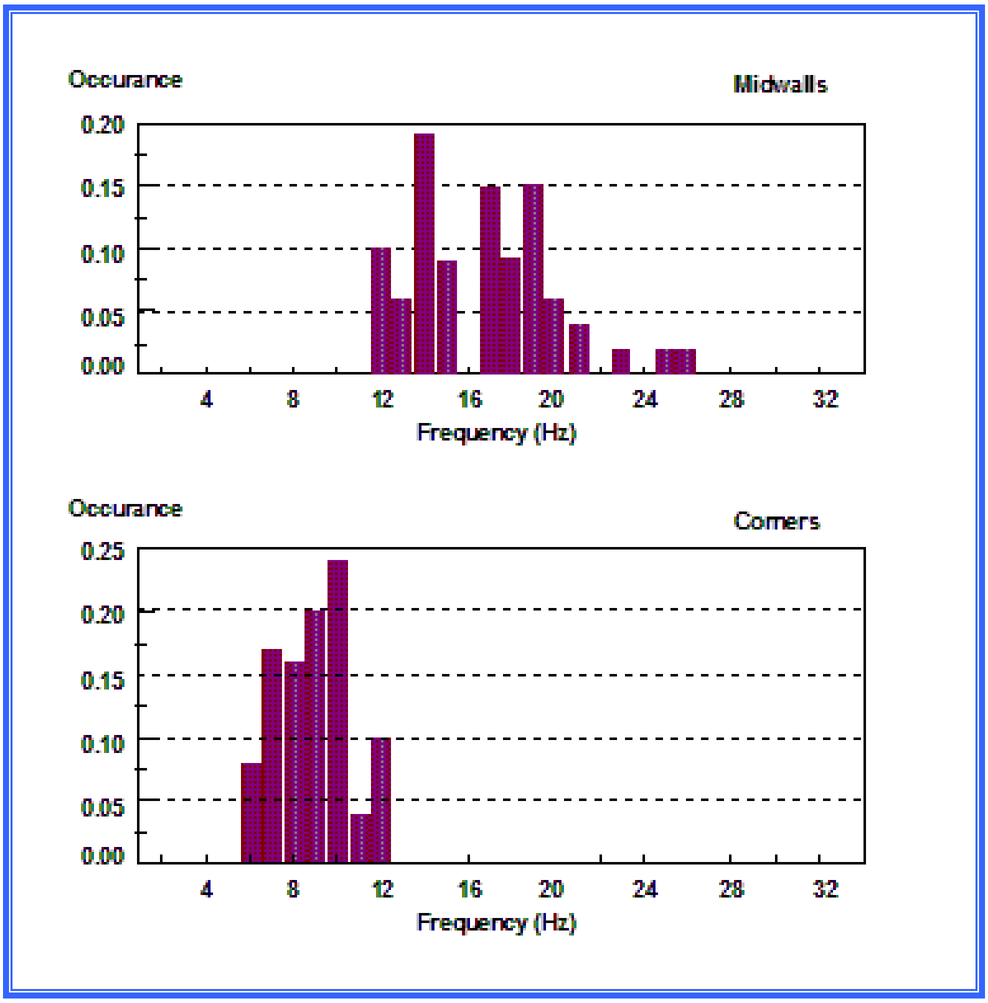

Figure 10: Predominant Frequency Histogram of Midwall & Corner Motion in Residential Housing

- Normally ground motion above 45 Hertz in frequency causes little damage to structures.
- Corner motion amplification factors for all of the structures studied were as high as 4 and for the mid walls were as high as 8 times that of the ground vibrations measured.

From these studies the United States Bureau of Mines concludes that damage potentials for low frequencies, that are less than 40 Hertz, are considerably higher than for high frequency. The chance of damage from a blast generating a PPV below 12 mm per sec is not only small but decreases more rapidly than the mean prediction for the entire range of vibration levels. An alternative recommended blasting level criterion using both the measured structure amplification and damage summary are shown in **Figure 11**.

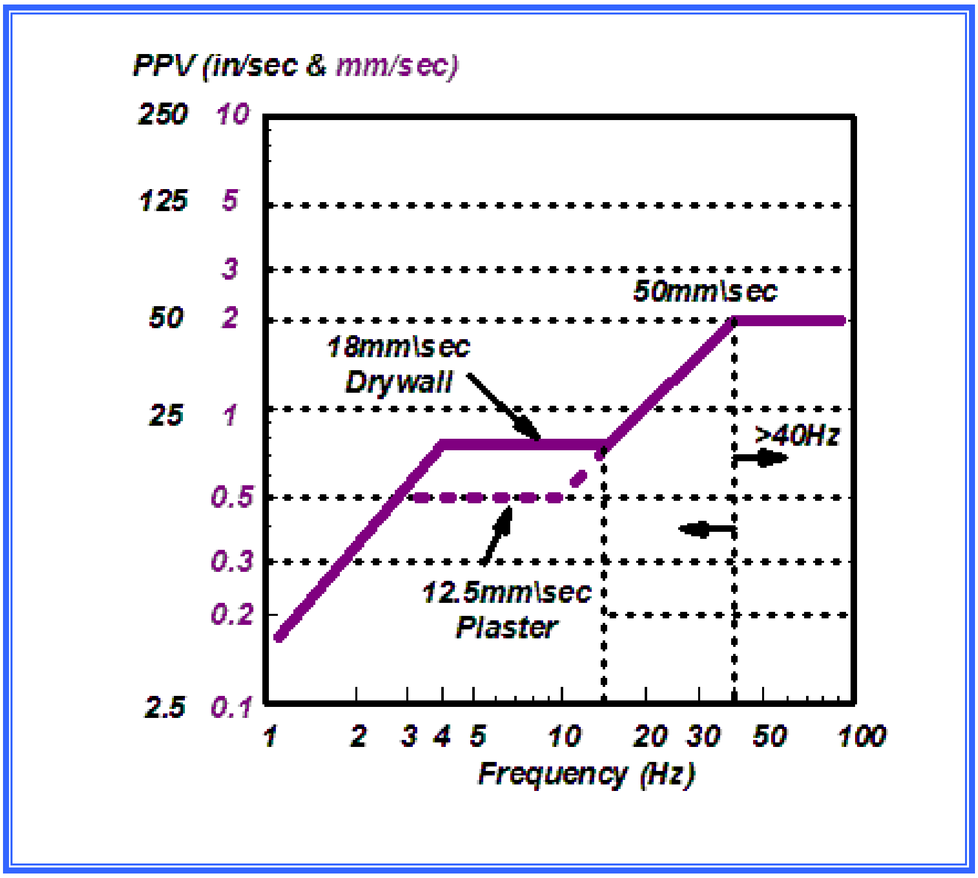

Figure 11: Safe Levels of Blasting Vibration for Houses.
Using a Combination of Velocity & Displacement.
(Reference USBM)

5. DAMAGE RESPONSE CRITERIA

5.1 Criteria for Rock Masses (Bauer & Calder) Table 2

Table 2, below, sets out the PPV required breaking rock. It can be seen that these levels are very high when compared to the levels to prevent damage to structures. When related to structural damage a peak particle velocity of less than 25 mm per second is considered between a safe zone and a possible damage zone. In many case examined damage has not been observed where the PPV is below 50 mm per second.

Several factors concerning this damage criterion are worth emphasizing.

- It is the maximum peak particle velocity of any one of the three mutually perpendicular components of ground vibration.
- It applies to residential structures in a reasonable state of repair and soundness.
- It is for vibration levels in the ground near the concerned structure and not for vibrations measured at some point within the building.
- It is frequency dependent as per Figure 9.

Table 2
Effect of PPV on Rock Mass

PPV	Effect on Rock Mass
up to 250	No fracturing of intact rock
250 to 625	Minor tensile slabbing will occur
625 to 2'500	Strong tensile and some radial cracking
over 2'500	Complete breakup of the rock mass

5.2 Human Response

Complaints are often received of excessive vibrations based on a person's subjective assessment of what they feel are severe. The susceptibility of human beings to vibrations depends upon frequency as well as particle velocity, as shown in **Figure 12**.

In general terms, the lower the frequency the more perceptible the vibration becomes. It also depends upon the age of the person, their occupation and their position at the time of feeling the vibration. When standing people are most sensitive to vertical vibrations and when lying down sensitivity is greatest for horizontal vibrations. The human body has its own natural frequency depending on the attitude as can be seen in **Table 3.**

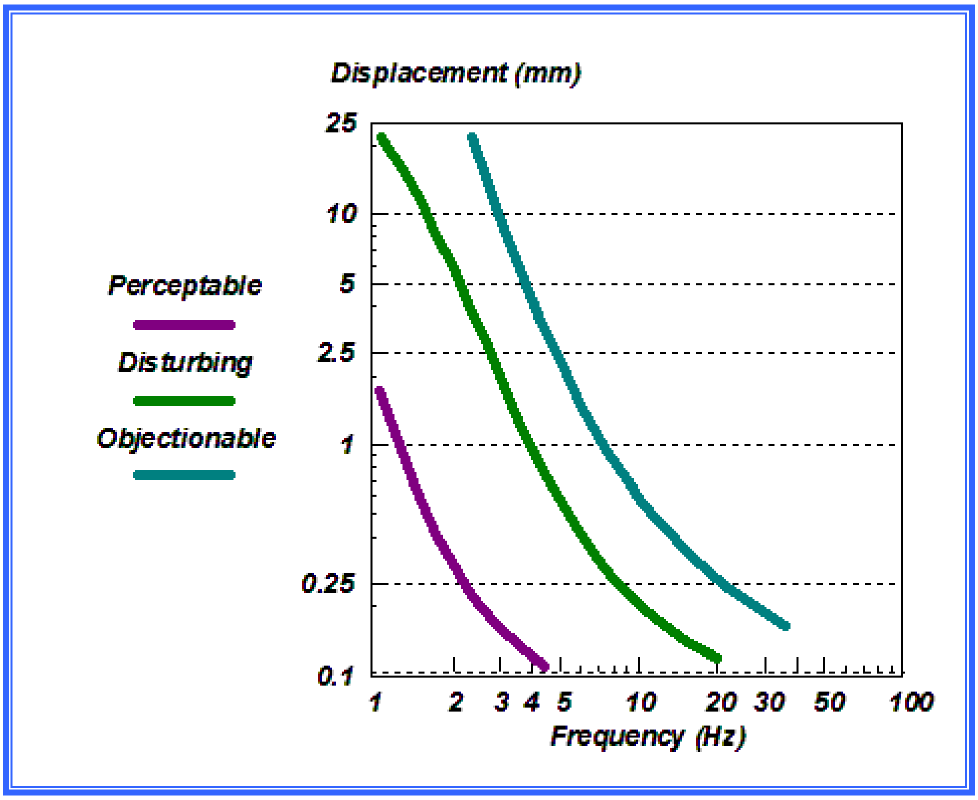

Figure 12: Human Response.

Table 3
Sensitivity of the Human Body

Position	Typical Frequency Hz
Standing	5 to 12
Prone	3 to 4
Sitting	4 to 6

The major whole body resonances are in the infrasonic band 1 - 10 Hertz, especially at 4 - 5 Hertz and resonance at these frequencies lowers the threshold to perception and discomfort.

In the United States results of empirical observations on human response to blasting vibrations produced the following relationship, shown in **Table 4**, between response and ground velocity.

Many blast complaints result from the human response triggering extensive property inspection which in turn finds damage produced by other means.

Table 4
Human Response

Response	Particle Velocity mm/sec
Perceptible	2 to 5
Noticeable	5 to 9.5
Unpleasent	9.5 to 20
Disturbing	20 to 32.5
Objectionable	32,5 to 50

5.3 <u>Structural Damage</u>

In all work where structural damage is caused by ground vibrations the great problem is to gain regular access to property and to make detailed "pre" and "post" shot observations. It is very difficult to accumulate sufficient reliable data linking a hair line crack in plaster with one or more blasting events. Minor damage may be linked to a blasting event or it may be due to poor construction, subsidence of foundations or even to heavy traffic on a nearby road.

Most current damage criteria are based solely on PPV. Medearis has shown that PPV is not a good indicator by itself of threshold damage and it is better to use Pseudo Spectral Relative Velocity (PSRV).

The Pseudo Spectral Relative Velocity is the velocity response calculated for the "model" when excited by a transient. It takes into account the frequency content of the transient, and its length together with the natural frequency and the damping effect of the structure. The PSRV is a parameter from earthquake engineering. It is possible as an approximation to "model" a structure as a simple equivalent harmonic oscillator, a combination of mass, spring and damping element.

In single and two storey structures the United States Bureau of Mines suggests that "racking stress", particularly at corners, is the major problem and that the vibration in the corners is assumed to indicate cracking potential, because it corresponds to whole structure response. In strong earthquakes failure by base shear may occur - whereas the base shear stress in a blast is very low. The value for maximum bending stress is also low. In addition there is the racking stress at corners; rectangular load bearing walls are sheared into parallelograms. Midwall and floor or ceiling oscillations may also be encountered. These oscillations are the cause of rattling window panes and pictures tilting.

The strength of the structure depends upon the strength of the materials used and the quality of workmanship. Most buildings have very good safety factors. In construction blasting, blasts are set off close to support pillars made of reinforced concrete. Strength of office footing vs. concrete age is based on the standard strength age chart. **Table 5** below shows the relation between PPV and concrete age.

Table 5
Allowable PPV in Concrete

Age of Concrete	PPV mm/sec
0 to 2 hours	0.00
4 hours	1.80
8 hours	3.30
18 hours	8.10
24 hours	10.20
30 hours	15.20
36 hours	15.20
42 hours	17.30
2 days	20.40
3 days	30.50
4 days	37.00
5 days	45.70
6 days	50.00
7 days	51.00
2 weeks	81.30
3 weeks	96.50
4 weeks	101.50

6. PRIMER LOCATION AND COLLAR STEMMING

In a study done by Messes Brinkman, Smith and Togieddin it was found that collar primed blastholes generated larger PPV's than those bottom primed. Of the three vibrational components the largest differential in PPV occurred in the compressional motions. The vertical component has the least different vibration component between top and bottom priming. The largest PPV's obtained were invariably those in the vertical component.

The study showed that an increase in the amount of stemming resulted in higher PPV's. Selection of a suitable collar stemming amount depended upon the position of the primer, the charge diameter and charge weight if ground vibration levels were to be minimized.

Effects from collar priming would be expected to be greater than bottom primed blastholes, because the rock at the collar would be affected almost immediately. As a consequence, vibratory actions and the fracturing of ground at collars would commence at the primer and then proceed downward. This would occur even as explosive in the lower part of the hole was detonating. If the velocity ratio Ve/VP is not close to one (1) it is because the travel rate for the compressional waves in the rock leads that of the reaction front in the explosive. As each successive pulse is generated it continually re-enforces those that have gone before. With collar priming this means that the rock around the collar is repeatedly pre-stressed and weakened in its resistance to the explosive energy being generated. This intensifies the surface ground motions. To reduce this effect more stemming should be placed in the collar. A condition is eventually reached whereby the vibrations generated by collar priming with long stemming equal that generated by toe initiation.

7. MINIMIZING COMPLAINTS

In the foregoing sections of this paper the basic causes of ground vibrations have been discussed together with factors affecting their amplitude. In addition there are various ways in which they can be reduced or their apparent effects minimized:

- The amount of explosive detonated per delay should be minimized and the delay should be of long enough duration not to enhance the shock wave.
- Select a burden that is not excessive. Do not try to minimize powder factor in the belief that it will reduce ground vibrations.
- In the use of chevron patterns, minimize the number of holes with a zero delay.
- Use an initiation sequence which maximizes progressive relief for blastholes, i.e. sufficient delay interval.
- Use minimum sub-drilling compatible with good blasting results.
- Develop favorable blast geometry relative to those buildings where damage potential exists.
- Keep the blast face parallel to the predominant set of joint lines.

- Perhaps the most important, complaints can be reduced by keeping people concerned informed of the blasting taking place and the precautions taken to prevent excessive ground vibrations occurring.

REFERENCES

Dick and Siskind - Keeping your blast under control

Anon - AECI Explosives Today Series 2 No. 27
The effect, measurement and control of ground vibrations.

Ball M. - Vibrations from Blasting Problems and Solutions.
December 1976.

Watts R. - Some comments on the possibility of damage to pipelines due to ground vibrations from blasting. Pipelines Industries Guild Journal No. 42.

Page C. (Dr) - Controlled blasting Techniques.

Anon - Explosives Technical Handbook - Atlas Powder Company

Gamble & Jow & Simpson - Effects of Blasting Vibrations on uncured concrete foundations.

Brinkman, Smith, Togieddin - The effects of primer location and collar stemming lengths on surface ground motion at close-in scale distances.