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## **BLAST VIBRATION COURSE**

### **MEASUREMENT - ASSESSMENT - CONTROL**

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**MEASUREMENT - ASSESSMENT - CONTROL**

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## CHAPTER 2 – BASIC THEORY AND ATTENUATION FORMULA

### 2.1 GROUND VIBRATION

#### 2.1.1 The Nature of Blast Related Ground Vibration

When an explosive charge is detonated in a blasthole, the rock immediately surrounding the charge is fractured, split apart and may be displaced if the correct conditions exist. At a certain distance from the blasthole, the explosive energy released decreases to a level, which causes no further shattering or displacement, and continues to travel through the rock as an elastic ground vibration.

The ground vibration radiates out from the hole with decreasing intensity and reduces to below levels of perception with distance. Ground vibration, at sufficiently high levels, will damage buildings but can be alarming to people inside buildings at levels well below structural damage levels.

The energy travels in the form of waves, which may be illustrated by dropping a stone in a still pool of water. Near where the stone drops, waves are formed which spread concentrically out from the centre. The waves have a high amplitude at the drop point, but this decreases as the waves spread outwards, as illustrated in **Figure 2.1**.

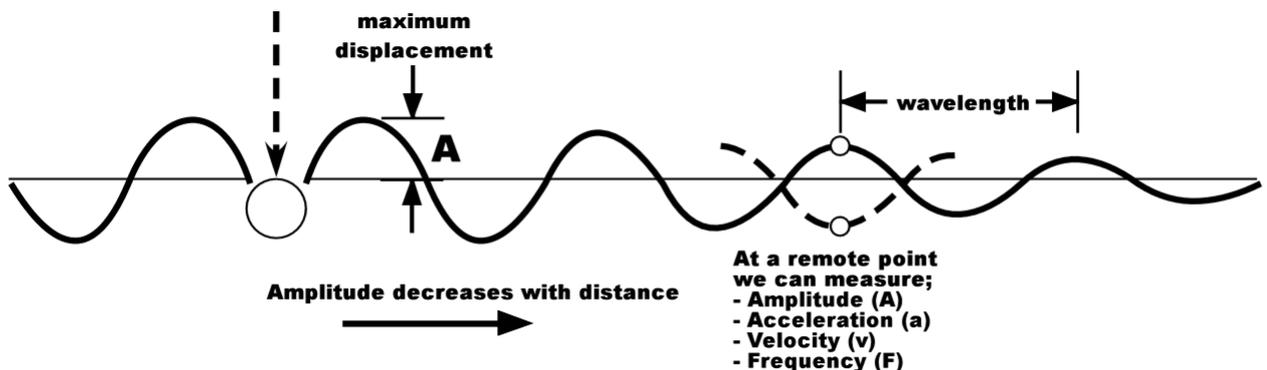


Figure 2.1 – Wave terminology

In uniform rock conditions, the ground vibration waves will spread out and reduce equally in all directions, similar to the pond illustration. Blasts rarely consist of only one charge and rock is an imperfect medium for the transmission of vibration. The blast vibration consists of the different waves from many holes with propagation controlled by the physical and structural properties of the ground through which it travels.

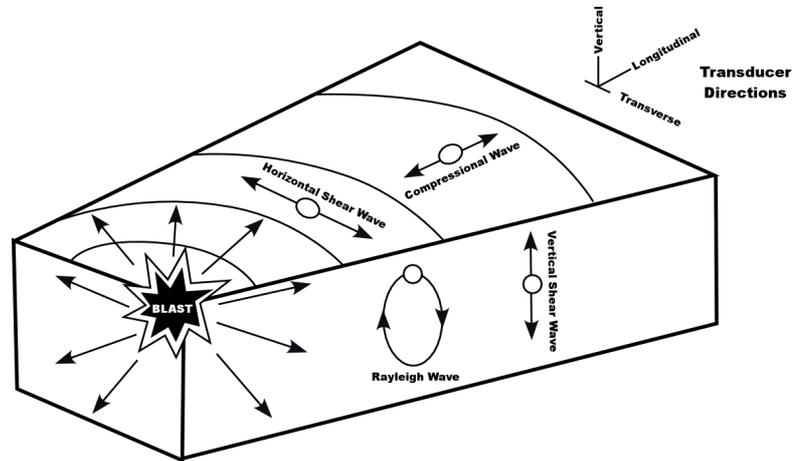
##### 2.1.1.1 Wave Types

Rather than being the simple wave type in the pond illustration, the ground vibrations are complicated seismic events consisting of three different kinds of waves, namely:

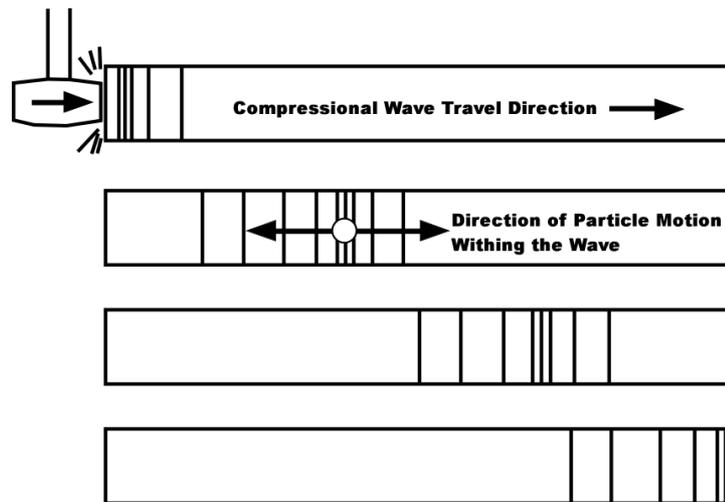
- Compressional (or P) waves.
- Shear (or S or secondary) waves.
- Rayleigh (or R) waves.

The Compressional or P wave is the fastest travelling wave through the ground. The simplest illustration of the motion of the particles within the P wave is to consider a long steel rod struck on the end. The particles of the rod move to and fro as the compressive pulse travels along the rod, ie. the particles in the wave move in the same direction as the propagation of the wave.

The P wave moves radially from the blasthole in all directions at velocities characteristic of the material being travelled through. The wave motion of P waves is illustrated in **Figures 2.2** and **2.3**.



**Figure 2.2 – Particle motion associated with the different wave types**



**Figure 2.3 – Compressional (P) wave particle motion**

The Shear or S wave travels at approximately 50-60% of the velocity of the P wave. The motion of the particles within the wave can be illustrated by shaking a rope at one end. The wave travels along the rope, but the particles within the wave move at right angles to the direction of motion of the wave. The wave motion of S waves is illustrated in **Figures 2.2** and **2.4**. The P and S waves are sometimes referred to as body waves because they travel through the body of the rock in three dimensions.

The Rayleigh or R wave is a surface wave, which fades rapidly with depth and propagates more slowly than the other two waves. The particles within the wave move elliptically in a vertical plane in the same direction as the direction of propagation. At the surface the motion is retrograde to the movement of the wave. The wave motion of the R waves is illustrated in **Figure 2.2**.

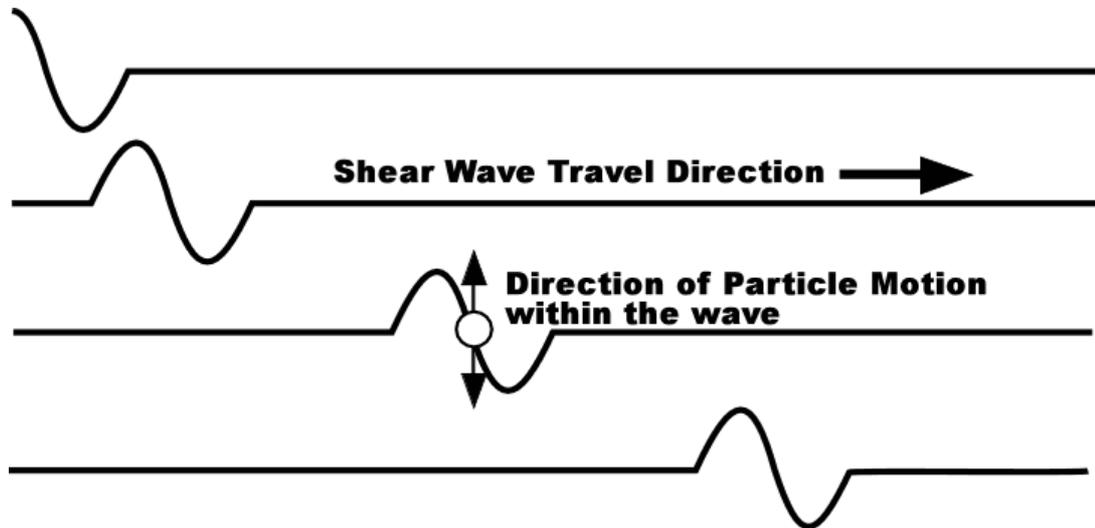


Figure 2.4 – Shear (S) wave particle motion

The essential features of the ground vibration arriving at a remote point can be illustrated in Figure 2.5.

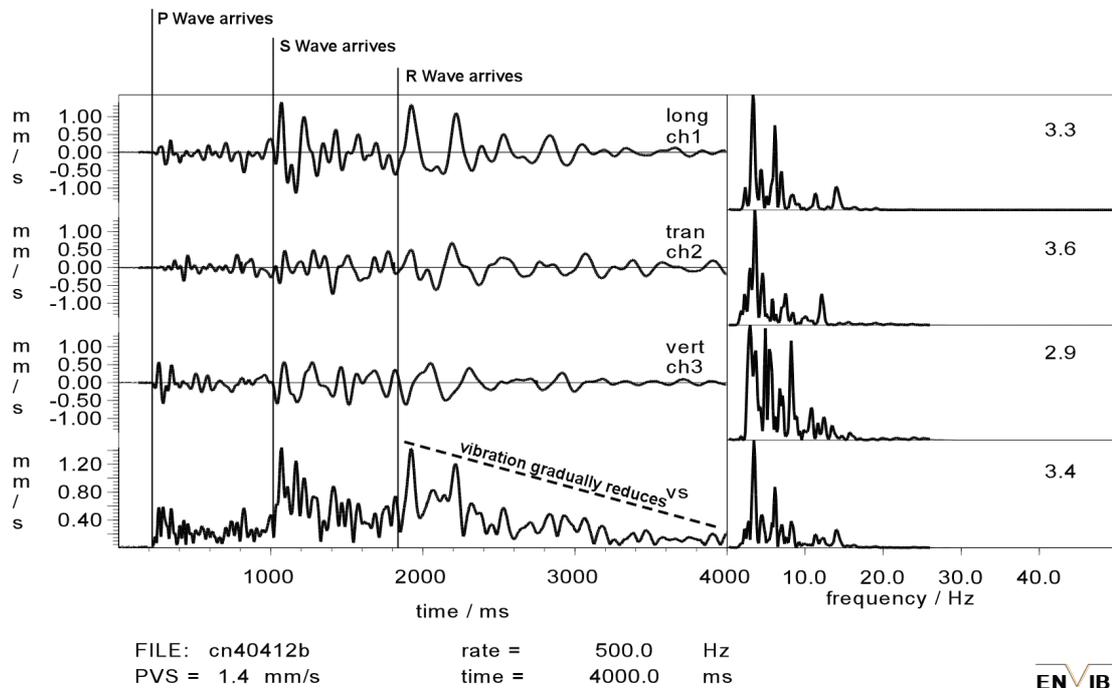
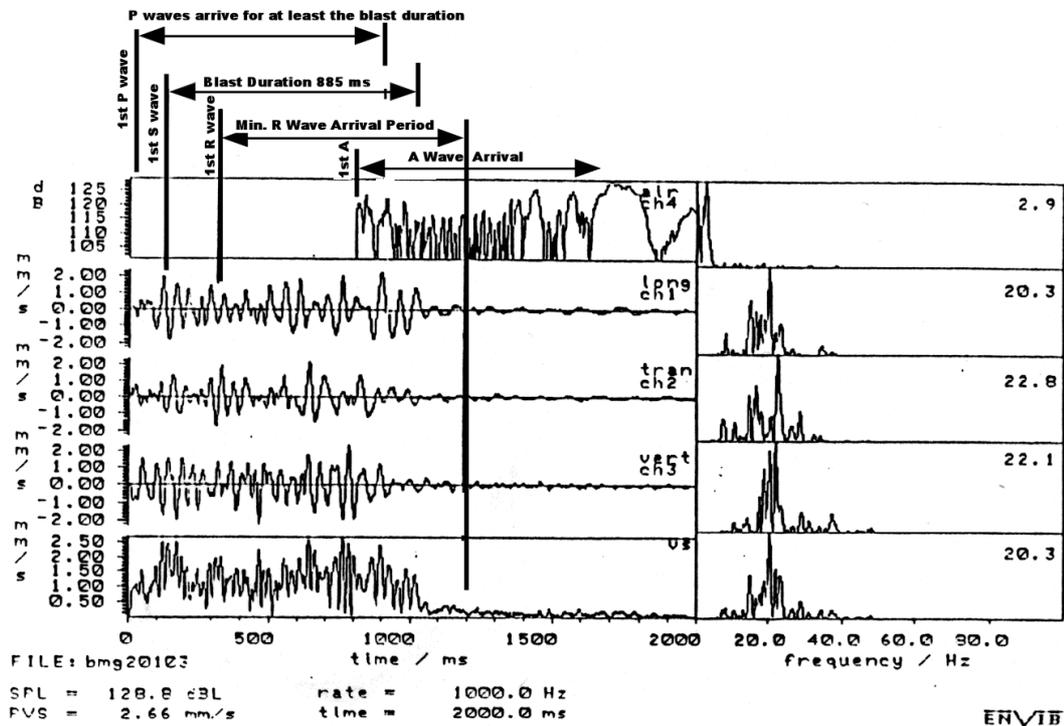


Figure 2.5 – Wavetrace from a single hole blasting shown P, S and R wave arrivals

This represents the wavetrace at a point approximately 1800 metres from a single hole blast of 1000 kg of explosives fired in the overburden of a Hunter Valley coal mine. The P wave arrives first followed by the various reflected and refracted vibrations associated with the P wave. This vibration gradually reduces until approximately 800 ms later, when the S wave arrives with its associated reflected and refracted waves. Approximately 900 ms later, the R wave arrives with its associated reflections and refractions. The vibration gradually decreases and returns to zero sometime after the 4 second time window.

For a multiple hole blast, the vibration arriving at a remote point is more complex. Each hole is fired at a different time and from a different location, which may introduce a directional variation to the vibration (see Section 7.4).

It is worthwhile noting at this stage that the development of the Shear and Rayleigh waves in **Figure 2.5** was observed in sites where strong horizontal structures were present, ie. coal overburden and also basalt with horizontal clay layering. At most other locations, the Shear and Rayleigh waves were unable to be separated by examination of the wavetraces because of small distances and unpronounced Rayleigh waves. A typical wavetrace to demonstrate this is shown in **Figure 2.6**.



**Figure 2.6 – Wavetrace from a multi hole blast showing P wave arrival and inclusive S and R wave arrival**

This shows the wavetrace for a Rhyodacite Quarry where 108 holes in 2 rows were fired with an average charge mass of 127 kg per hole. The monitoring station was at a distance of 335 metres. The blast duration (time between the detonation of the first and last hole in the pattern) of 885 ms is indicated, together with the anticipated arrival period of the P, S and R waves.

The vibrations, due to reflections and refractions of the waves, so much in evidence in the first example, are also not evident at sites with no horizontal structures.

Rhyodacite is an acid volcanic flow rock that at this quarry has been tilted and is well jointed and faulted and is without strong horizontal structures.

### 2.1.2 Prediction of Ground Vibration Levels

A number of researchers have investigated the problem of ground vibration prediction and have proposed various formulae. While not an extensive catalogue, the following formulae demonstrates the different approaches used:

- **Langefors Formula(Langefors and Kihlstrom, 1973)**

$$v = k \sqrt{\frac{Q}{D^{1.5}}}$$

where:            v     =   peak vibration (mm/s)  
                       K     =   rock transmission factor  
                       Q     =   instantaneous charge mass (kg)  
                       D     =   distance (m)

This formula was based on early research by Langefors and Kihlstrom into blasting in hard Swedish granite. The rock transmission factor allows for varying rock types and confinement conditions, eg. for hard granite K = 400.

• **Scaled Distance Formulae**

1. Square root scaled distance (United States Bureau of Mines (USBM), 1980; ICI, 1990; Australian Standard (AS) 2187.2, 1993):

$$v = k \left( \frac{D}{\sqrt{Q}} \right)^e$$

2. Cube root scaled distance (Ambraseys/Hendron, 1968; Hendron/Oriand, 1972):

$$v = k \left( \frac{D}{\sqrt[3]{Q}} \right)^e$$

where:            v     =   peak vibration (mm/s)  
                       Q     =   instantaneous charge mass (kg)  
                       D     =   distance (m)  
                       k     =   site constant  
                       e     =   site exponent  
                        $\frac{D}{\sqrt{Q}}$    =   scaled distance (square root)  
                        $\frac{D}{\sqrt[3]{Q}}$    =   scaled distance (cube root)

These formulae developed from research in America mainly from coal overburden blasting and some controversy exists as to which is more appropriate as good results have been obtained with both.

The square root scaled distance is most commonly used and is based on the observation that the charge is distributed in a long cylinder (the blasthole), therefore the diameter of the hole is proportional to the square root of the charge weight. However, it can be argued that as the hole length shortens in relation to the diameter, the charge mass approaches a spherical shape, in which case the diameter is proportional to the cube root of the charge weight.

In energy decay terms, the decay may depend on what waveform the energy is dissipated in. It was noted earlier that at some sites (such as coal mines) the surface waves predominate. At other sites, the energy is dissipated mainly through body waves. It may well be that at different sites with different explosive configurations and types of vibration waves generated that charge mass may be a more complex function than either square or cube root and the general equation:

$$v = k \left( \frac{D}{Q^n} \right)^{-1.6}$$



The site constant can then be modified to allow for site confinement conditions. It may be reflected in formula, such as quoted in AS2187.2-1993, Appendix J.

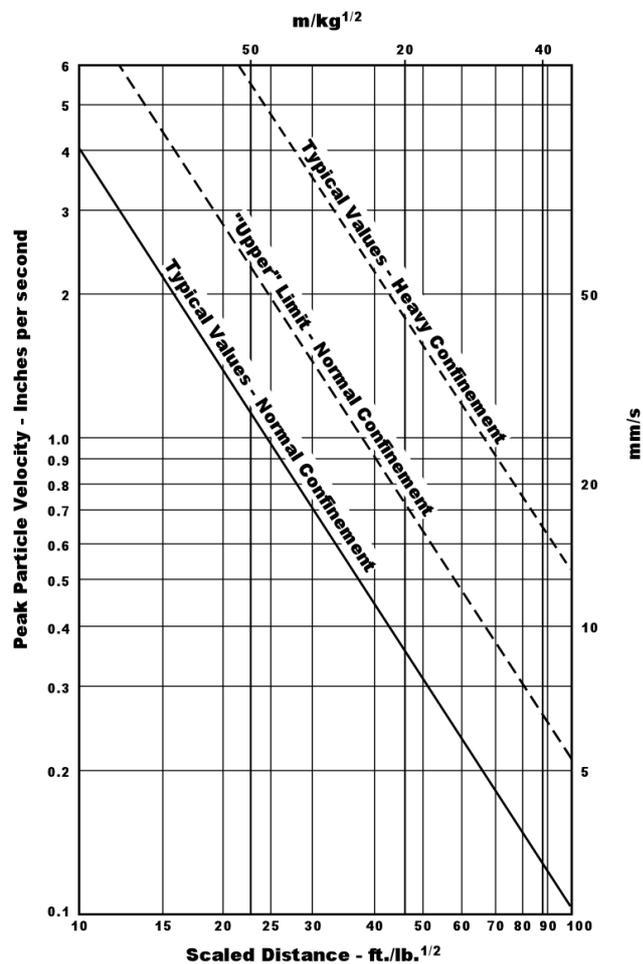
Firing to a free face, in hard or highly structured rock in:

- Mines or quarries: k = 500
- For a free face in average conditions: k = 1140
- For heavily confined blasting, near field: k = 5000

Another form is to consider the scaled distance (SD) ie.  $\frac{D}{\sqrt{Q}}$

eg. a scaled distance of 50 will protect against vibrations greater than 51 mm/s. A scaled distance of 60 will protect against vibrations greater than 25 mm/s, etc.

This can also be produced in chart form with allowances for increased confinement, as shown in **Figure 2.9**. It must be appreciated that there is considerable variation of ground vibration radially from a blast because of variation of ground conditions and other causes.



**Figure 2.9 – Scaled distance chart with increasing degrees of confinement**

The classical scaled distance formulae are based on the statistical analysis of a spread of data as shown in **Figure 2.10**. Even with predictions based on 95% of the data, readings up to 6 times the predicted value may be obtained. In a conservative assessment, the peak values should be used, unless the mechanism causing the directional increase can be identified and allowed for.

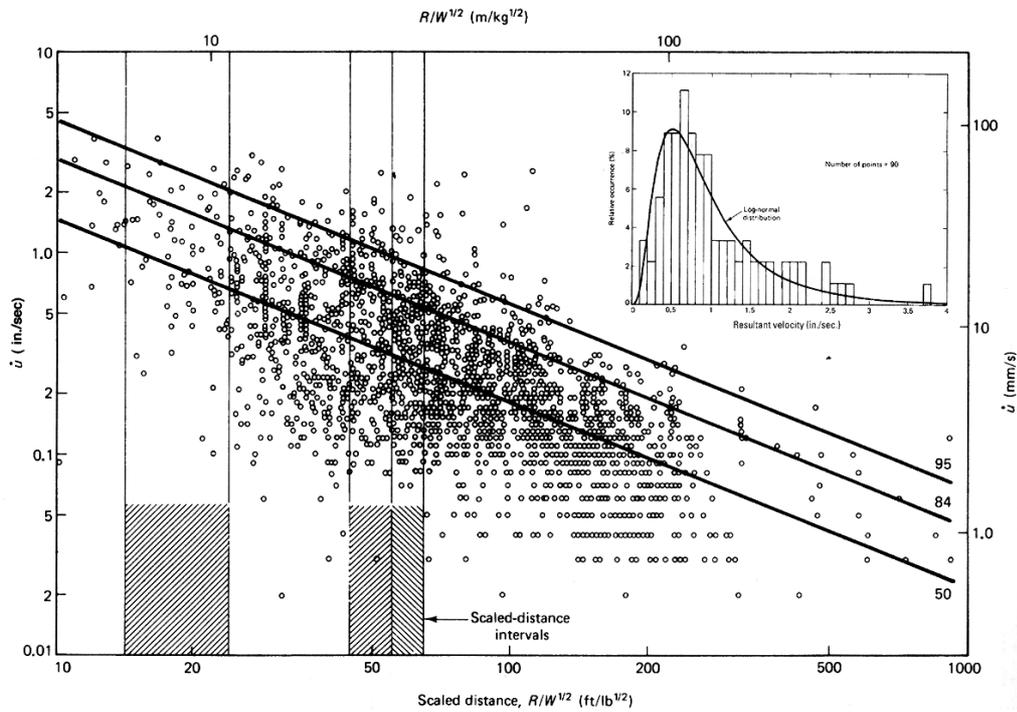


Figure 2.10 – Typical data spread, peak particle velocity versus scaled distance

At sites where the rock has a strong 'grain', such as steeply dipping bedding, vibration levels along the bedding may be 10 times the levels across the bedding or in deeply weathered ground. The results of a blast in such conditions are shown in Figure 2.11(a). An increase in vibration levels of eight times was consistently recorded at a station on a fault, typical spread of values for a blast is shown in Figure 2.11(b).

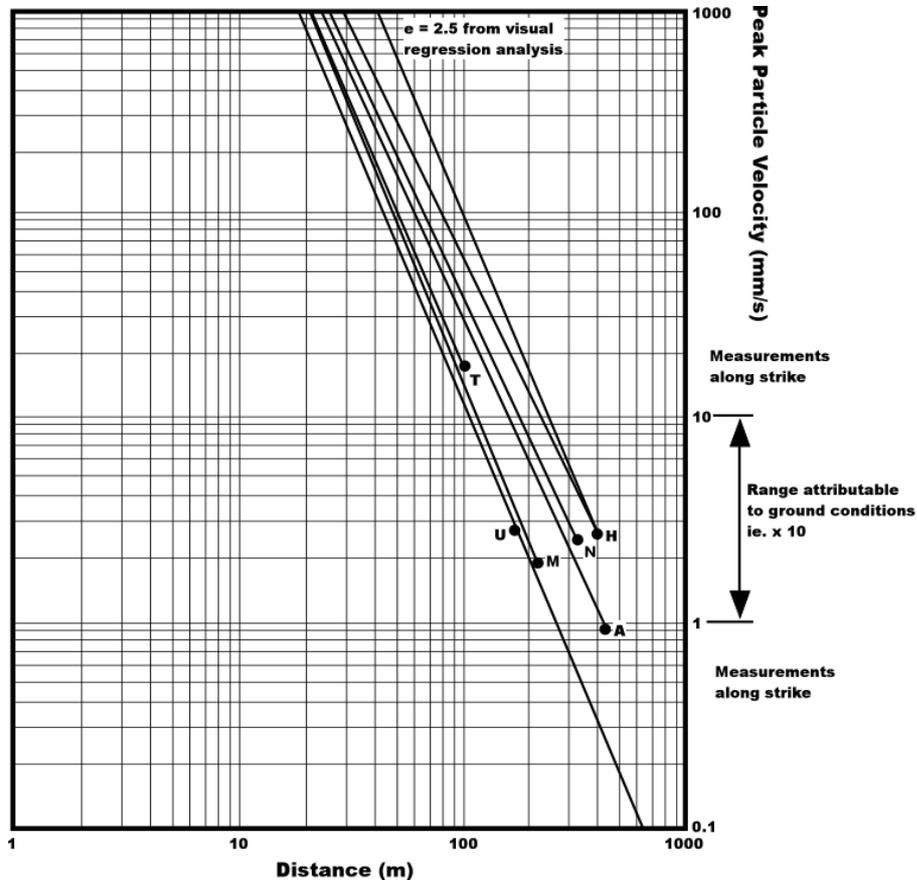


Figure 2.11(a) – Ground vibration versus distance for a site with variable ground conditions

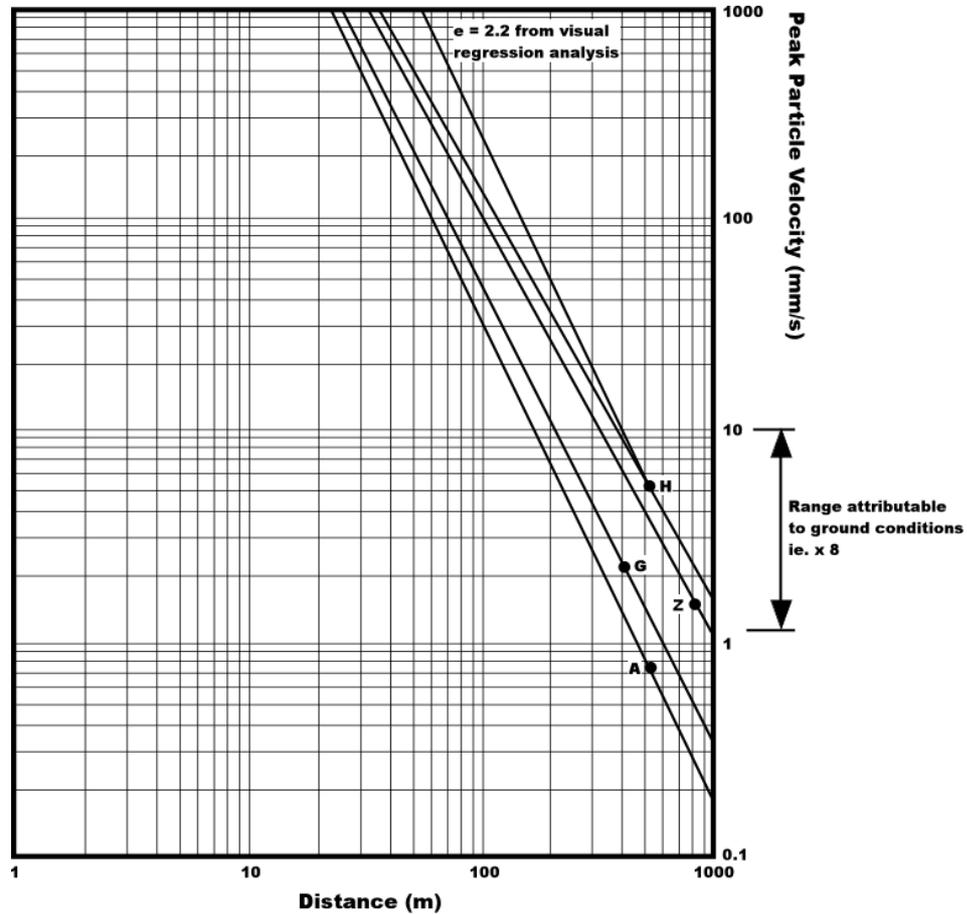


Figure 2.11(b) – Ground vibration versus distance for a site with an identified fault

The detailed analysis of many blasts from many different locations and rock types by Terrock Consulting Engineers has disclosed that the site exponent of 1.5-1.8 is appropriate for sub-horizontal coal mine overburden and basalt flows with horizontal clay floors.

Other rock types have quite different site exponents, which considerably alters the site constant in the predictive formula based on scaled distance. Typical values of site exponents for different rock types are:

- Rhyodacite/Rhyolite: 2.2 – 2.5
- Granite: 2.1 – 2.4
- Limestone: 2.1
- Ordovician sediments: 2.8
- Coal mine overburden: 1.5 – 1.8
- Basalt (clay floor): 1.5 – 1.6
- Basalt (massive): 1.9 – 3.0

The significance of high site exponent is that the ground vibration drops off more rapidly and lower vibration levels result at distance. This is demonstrated in Figure 2.12, which shows distance/PPV envelopes for a number of sites with different charge masses.

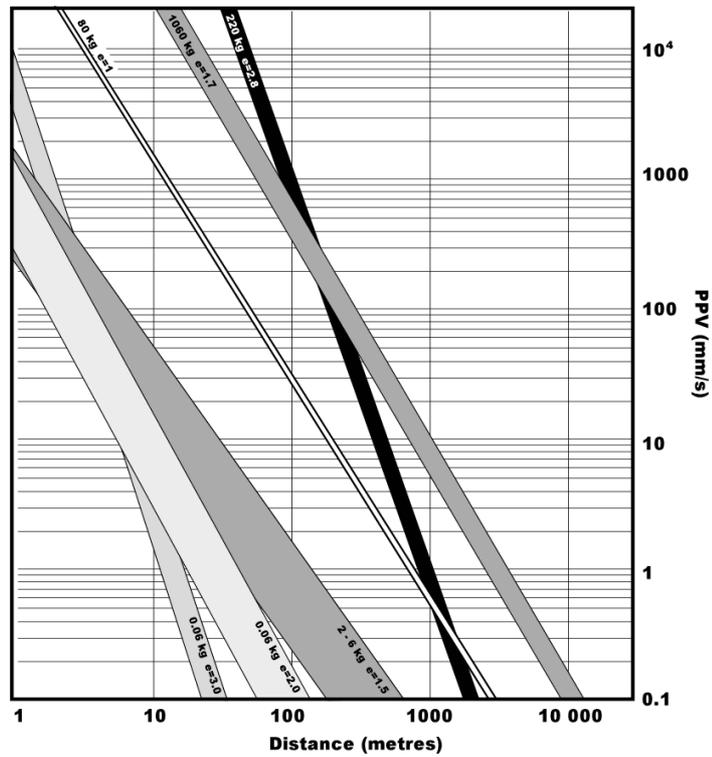


Figure 2.12 – Combined PPV/distance envelopes for a number of sites

## 2.2 AIR VIBRATION

### 2.2.1 The Nature of Blast Related Air Vibration

Air vibration (or airblast) results from the pressure or shock waves, which radiate in air from a detonating charge. When a pressure wave passes a given position, the pressure of the air rises very rapidly, it then falls more slowly to a pressure below the atmosphere value before retaining to atmospheric pressure after a series of oscillations. A typical Pascal air vibration wavetrace for a single hole is shown in **Figure 2.13**. With a multi-hole blast, the waves from the individual holes interact with each other to produce complicated traces.

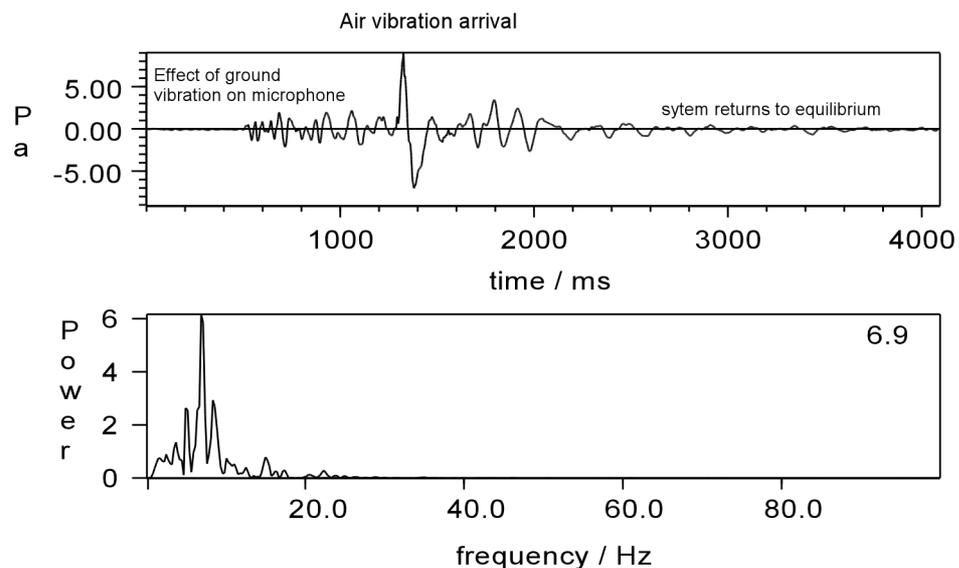


Figure 2.13 – Air vibration (Pascal) wavetrace for a single hole firing

The maximum pressure is known as the peak air over pressure or peak air vibration. The air vibration is within a range of frequencies from 0.1 Hz and 200 Hz. The air vibration above 20 Hz is audible and experienced as 'noise', while that portion below 20 Hz is inaudible. The higher frequencies are damped quickly and it is the low inaudible vibration that travels large distances and gradually reduces to below background levels. The low frequency vibrations are usually noticed by induced high frequency vibrations in structures, such as rattling windows, doors, crockery, etc.

There are two systems of measurement of blast related air vibration. Air vibration in purely pressure terms is measured in Pascals (Pa) or its derivative (kilo Pascals). Because the difference in air pressure levels between sound pressure levels that are barely noticeable and those that will damage buildings is very large, a decibel scale, which is logarithmic, is commonly used for sound related pressure. They are related by the formula:

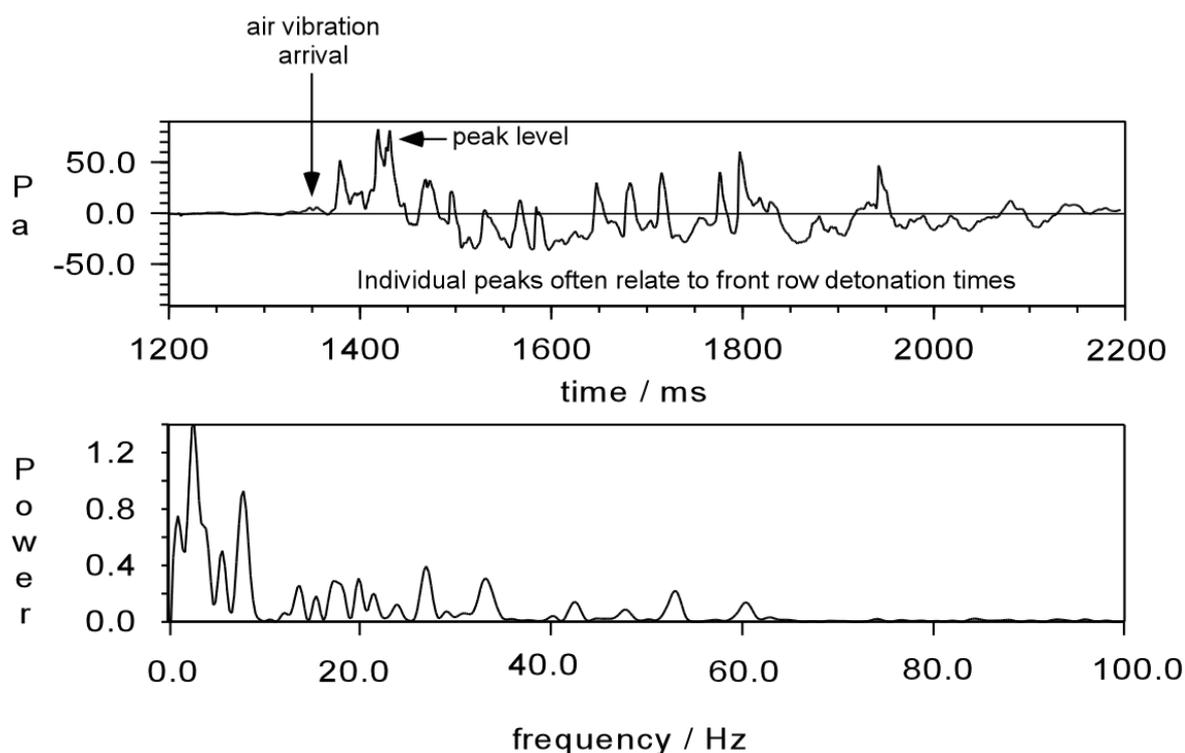
$$DB = 20 \log \frac{P}{P_0}$$

Where P is the measured pressure and P<sub>0</sub> is the reference pressure of .00002 Pa.

Air vibration measurement is further complicated by the use of a decibel A (dBA) scale for audible community noise level measurement and the use of decibel (Linear Peak or dBL Peak) for measurement of impact from blasting noise. If a precision sound level meter was set to measure air vibration from a blast recorded 115 dBL (Peak), an identical meter set to measure community noise would record approximately 90 dBA.

On the decibel scale, an increase of 6 decibels (dBL) represents a doubling of sound pressure levels.

A comparison of a decibel and Pascal wavetrace forms of the same multi-hole blast are shown in **Figures 2.14(a)** and **2.14(b)**. Note that decibels are always positive.



**Figure 2.14(a) – Pascal wavetrace for a multi row firing**

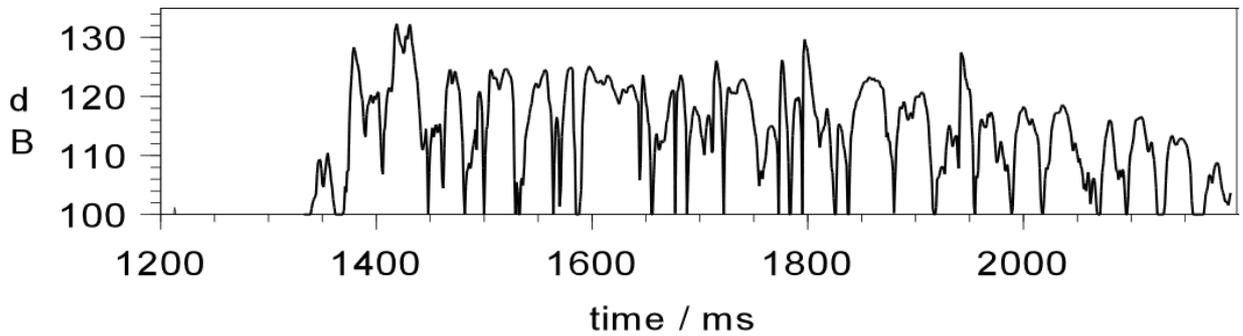


Figure 2.14(b) – Decibel wavetrace for the same multi row firing

## 2.2.2 Prediction of Air Vibration Levels

The basic air vibration attenuation formula is:

$$P = A \left( \frac{D}{\sqrt[3]{W}} \right)^a$$

where:

P	=	peak pressure (kPa)
A	=	site constant
a	=	site exponent
D	=	distance from blast (m)
W	=	charge mass per delay (kg)

From the ICI 'Handbook of Blasting Tables', airblast overpressure for unconfined surface charges may be estimated using:

$$P = 185 \left( \frac{D}{\sqrt[3]{W}} \right)^{-1.2}$$

An analysis of measurements taken by Terrock Pty Ltd of air vibration resulting from 7 kg shells exploding at a military firing range give the results :

$$P = 14700 \left( \frac{D}{\sqrt[3]{W}} \right)^{-1.82}$$

When analysed using a 'forced' exponent of 1.2, the results were:

$$P = 182.5 \left( \frac{D}{\sqrt[3]{W}} \right)^{-1.2}$$

Details of these analyses are attached as **Figures 2.15(a)** and **2.15(b)**. The above formula for unconfined charges can be used with confidence.

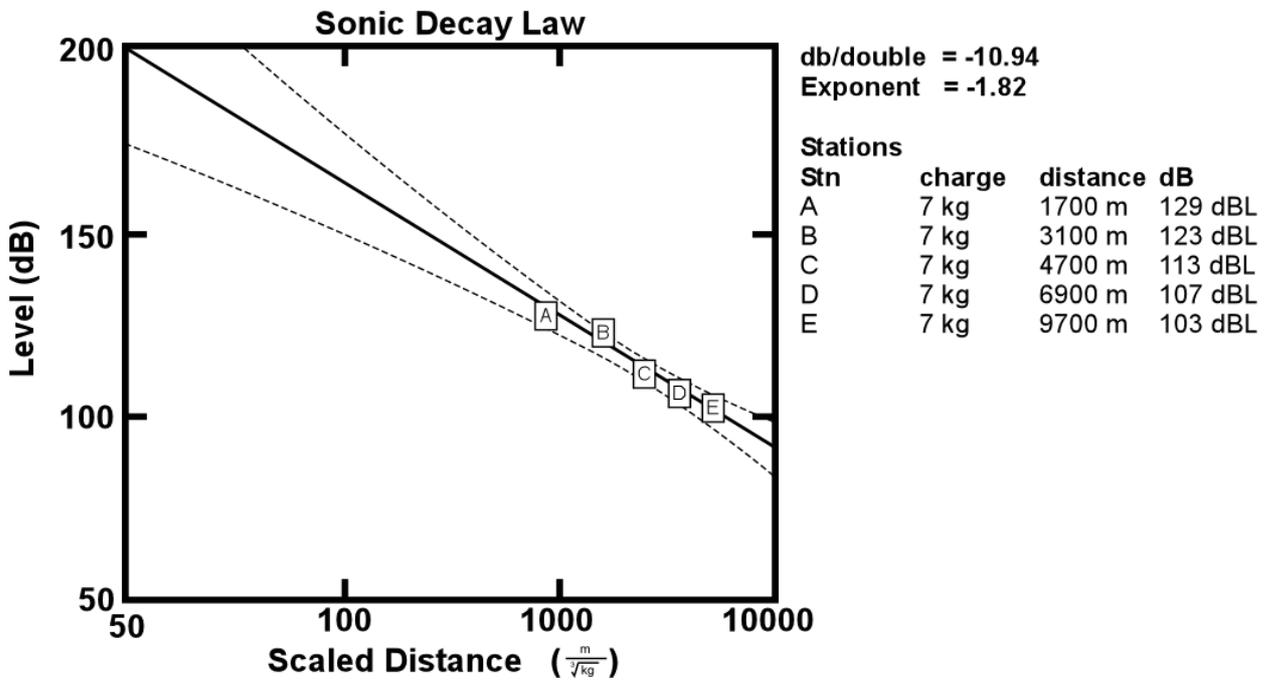


Figure 2.15(a) – Firing range – sonic decay of airblast due to 7 kg shells

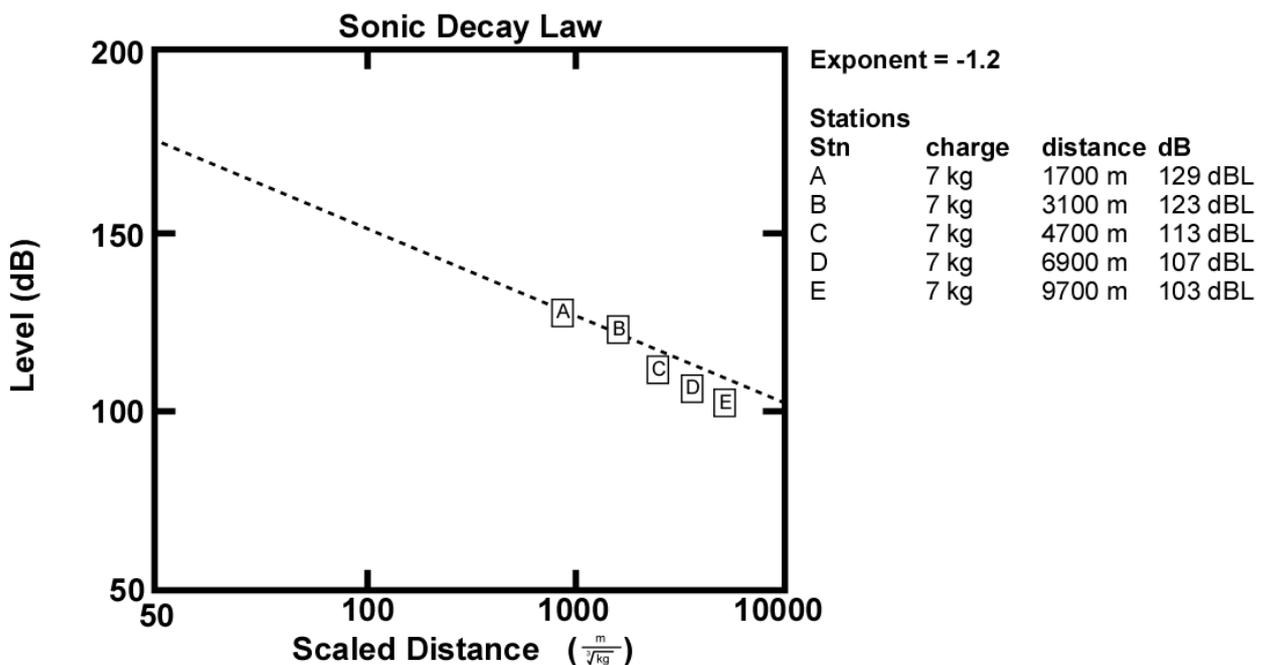


Figure 2.15(b) – Firing range – sonic decay determination for unconfined charges

From the ICI 'Handbook of Blasting Tables', airblast overpressure for fully confined blasthole charges may be estimated using:

$$P = 3.3 \left( \frac{D}{\sqrt[3]{W}} \right)^{-1.2}$$

Measurement of air vibration levels resulting from quarry blasting using confined blasthole charges has given airblast levels greater than those estimated from the above formula. For example an analysis of air vibration from quarry blasting in a Victorian quarry gave the results:

$$P = 54.8 \left( \frac{D}{\sqrt[3]{W}} \right)^{-1.49}$$

which, when using a forced exponent of -1.2 gave the results:

$$P = 12.7 \left( \frac{D}{\sqrt[3]{W}} \right)^{-1.2}$$

Details of these analyses are shown in **Figures 2.16(a)** and **2.16(b)**.

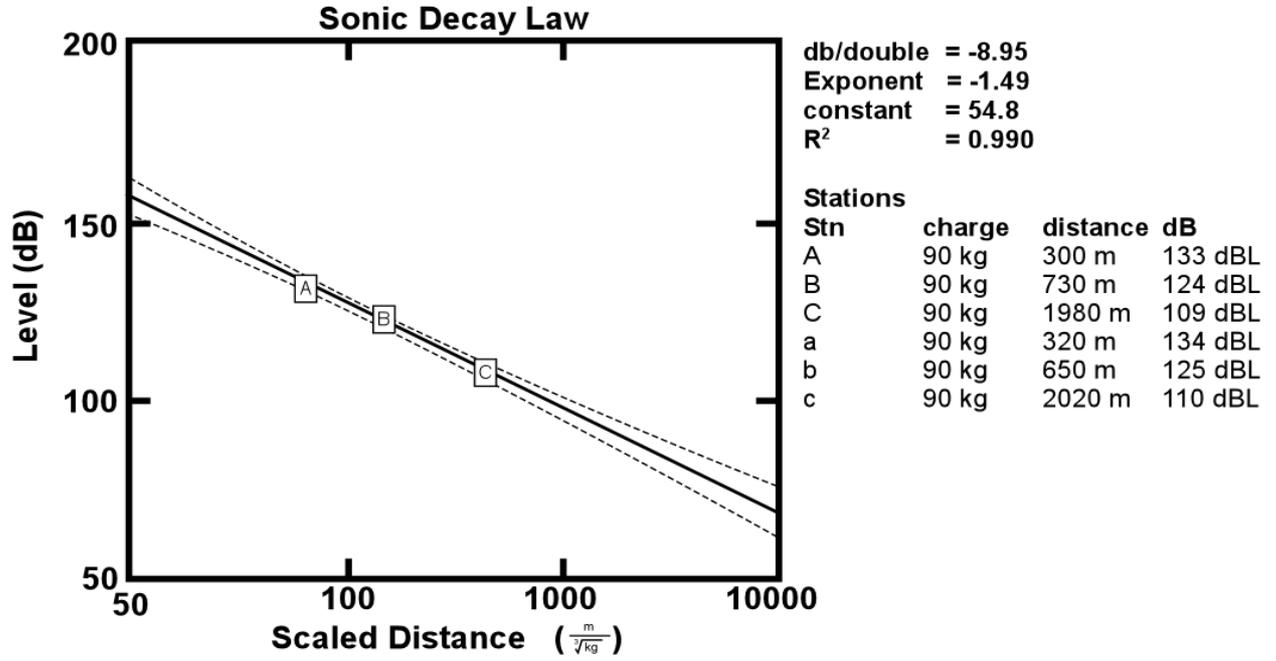


Figure 2.16(a) – Sonic decay of airblast due to confined charges in basalt quarry

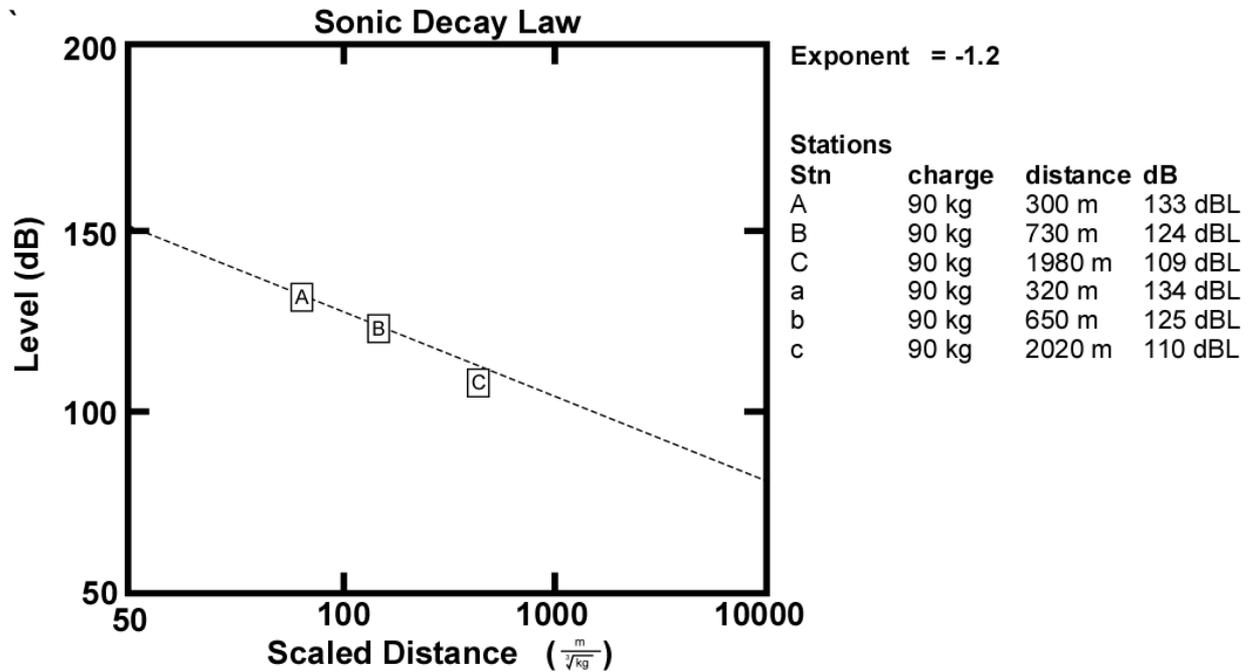
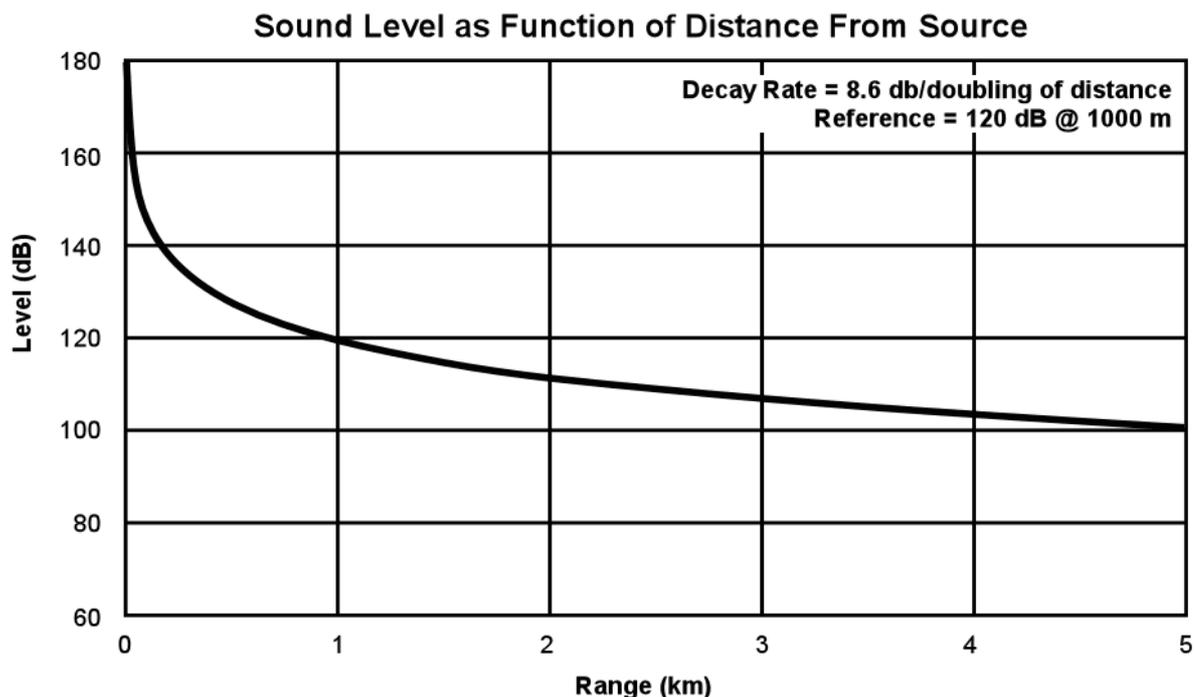


Figure 2.16(b) – Sonic decay of airblast due to confined charges in basalt quarry; exponent = -1.2

From our experience, the range of coefficients for quarry blasting and a 1.2 exponent is 5.9 to 34 (34 being for a badly underburdened blast).

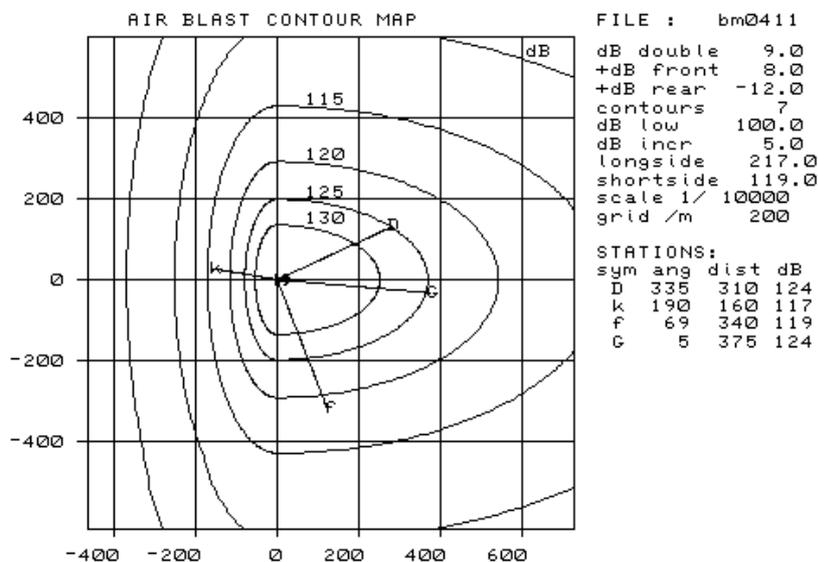
Investigations by Terrock have shown the drop-off rate in decibel terms to be between 7 and 10 dBL with doubling of distance, with 8.6 dBL being common and corresponds to a -1.43 exponent. This drop-off rate is demonstrated in **Figure 2.17**.



**Figure 2.17** – Sound level as a function of distance from source, 8.6 dBL decay with doubling of distance

From the above formula, air vibration levels are a function of distance only and, if predicted air vibration levels were graphed, circular contours would result. This approach is valid for above surface, surface or buried charges in a crater situation. When buried charges are fired to a vertical free face, a directionality is introduced to the contours. For mining and quarrying situations, the air vibration levels are 3-12 dBL higher in front of a free face than at the same distance to the side or behind the free face. This is the basis of our elliptical contour model.

This has been extensively tested using multi-station monitoring. A typical elliptical airblast contour for a blast is shown in **Figure 2.18**.



ENVIB

**Figure 2.18** – Elliptical airblast contours demonstrating the directionality when firing to a free face

This approach has proven valid provided there is no wavefront reinforcement, meteorological reinforcement or shielding, which will modify the contours. We are currently testing an empirical formula for predicting the distance that the 120 dBL (D<sub>120</sub>) contour occurs in front of the face.

### 2.3 WATER BORNE VIBRATION

Shock waves radiate from underwater blasting operations in a similar manner to the pressure waves in air. The shock waves have the potential to damage adjacent structures such as lock gates, but also to injure or kill people in the water. From the ICI 'Handbook of Blasting Tables', the underwater concussive effect may be estimated using the following formula:

$$P = A \left( \frac{R}{\sqrt[3]{W}} \right)^{-1.13}$$

where:

P	=	peak pressure (kPa)
W	=	charge mass per delay (kg)
R	=	distance from charge (m)
A	=	54.6 x 10 <sup>3</sup>

When the underwater charge is confined in a blasthole underwater - P (confined) = 0.4 P.

The following figures may be used as a guide:

<b>Physiological Effects of Blasting Underwater</b>	
<b>Peak Pressure (kPa)</b>	<b>Report Injury</b>
3500	Absolutely lethal to humans.
1400	Lung injuries etc.
280	50% chance of being lethal to small animals.
40	Completely safe to humans and animals.

## CHAPTER 3 – MEASUREMENT EQUIPMENT

### 3.1 MEASUREMENT EQUIPMENT GENERAL DESCRIPTION

#### 3.1.1 Ground Vibration Measurement

Referring back to the rock in the pond illustration, a float on the surface of the water would bob up and down in the same place as the waves pass (as illustrated in **Figure 2.1**).

Measurements can be taken of the motion of the float. The displacement (A), velocity (v), acceleration (a) and frequency (f) of the bobbing can all be measured and used to describe the effect of the wave on the float. The four measurable parameters are inter-related as follows:

$$v = 2 \pi f A \qquad a = 2 \pi f v \qquad a = 4 \pi^2 f^2 A$$

Similarly, the ground vibration can be measured at a remote point and displacement, particle velocity, particle acceleration and frequency can be measured. Experience has shown that Peak Particle Velocity correlates with damage more closely than peak displacement or peak acceleration. Consequently instruments that measure peak particle velocity are used in assessing ground vibration. These instruments are commonly known as blasting seismographs. It is common for blasting seismographs to contain circuitry and a microphone to permit air vibration signals to be analysed.

The passage of blasting vibrations forces the ground particles to move in a complex elliptical manner in three dimensions. To fully define the motion it is necessary to measure the three mutually perpendicular components, ie. longitudinal (radial) (x), transverse (y), and vertical (z). The particle velocity at a point is the vector sum of the three components at the same instant of time.

ie. particle velocity:  $v = \sqrt{v_x^2 + v_y^2 + v_z^2}$

The peak value, known as the Peak Vector Sum (PVS) or Peak Particle Velocity (PPV), is the highest value of the vector sums.

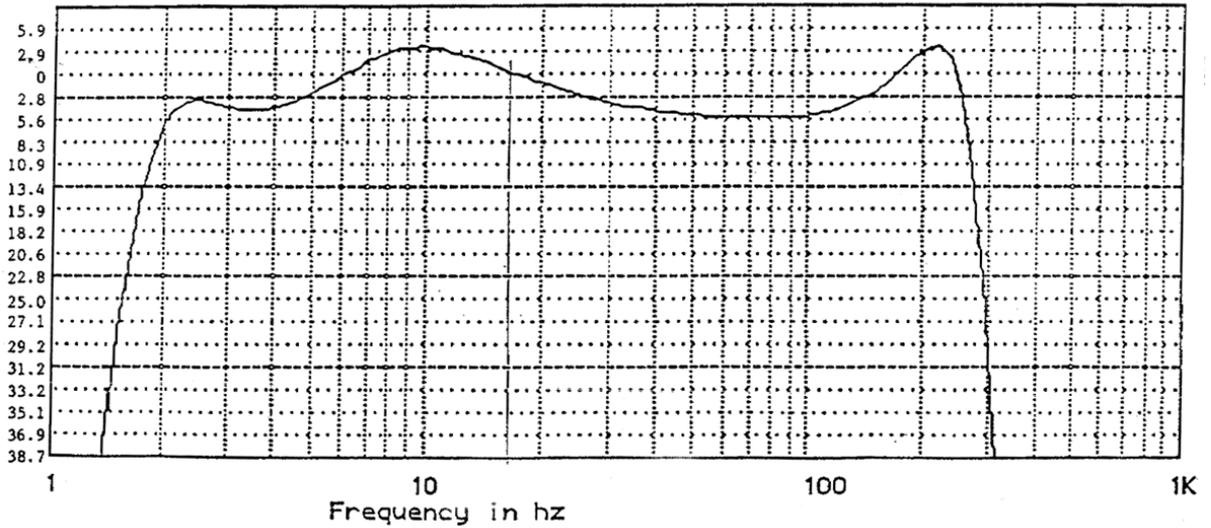
The Peak Particle Velocity is the velocity of motion of a particle on or in the ground induced by the passing of the blast vibration waves and is not the velocity of the waves through the ground.

The peak values of the individual components rarely occur at the same instant. This makes manual calculation of the PPV from wave trace examination time-consuming. Most blasting seismographs have the facility to calculate the vector sums electronically and present a PPV statement in some form.

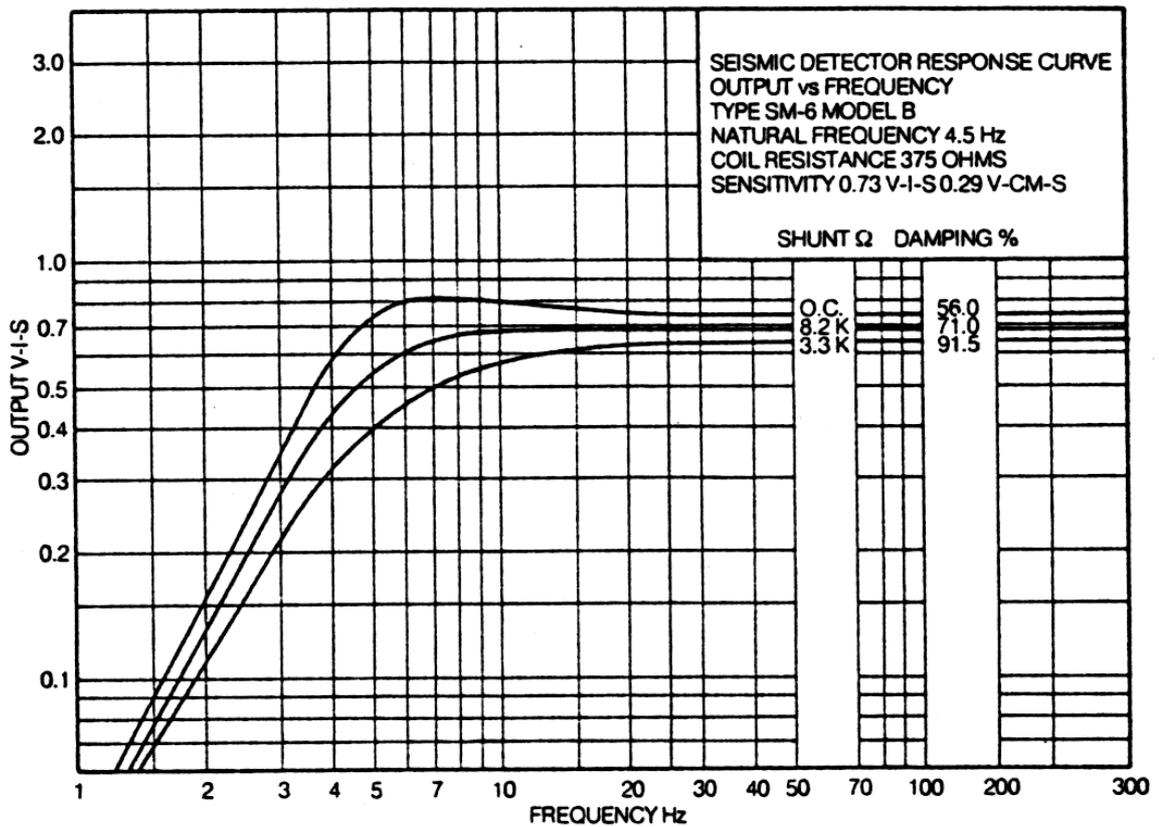
Blasting seismographs consist of a transducer (generally a geophone, although an accelerometer may be used) connected to a processor to collect and analyse the signals and in many cases store them. Some form of printer to produce hard copy of the results is common. The triaxial geophone contains three mutually perpendicular transducers, each consisting of a spring-loaded moving mass system located within a moving coil. The system moves in a magnetic field created by a permanent magnet. When the ground vibration causes the coil to move within the magnetic field an electric current signal is induced with a magnitude proportional to the velocity of the coil. The signals are conducted to the processor by cable.

It is important that blast vibration measurements be made with transducers that have a frequency response covering the range of frequencies to be measured. The frequency response curves for two brands of geophones that comply with the general requirements of AS2187-1993 are shown in **Figures 3.1** and **3.2**.

**GEOPHONE FILTER RESPONSE PLOT**



**Figure 3.1**



**Figure 3.2: Use Frequency Response Curve for 8.2 K $\Omega$  Shunt Resistance**

It can be seen that substantial corrections are required for frequencies below 10 Hz. Also different transducers have different outputs so any transducer interchange should be conducted with caution.

Because of limited data storage facilities and exposure to vibrations other than from blasting, it is common to have the seismograph triggered by the blast and the signal stored. Most seismographs have the facility to vary the trigger mode, trigger level, pre-trigger recording time and recording time.

Common trigger modes are:

- Ground vibration trigger.
- Air vibration trigger.
- Either ground or air vibration trigger.
- Manual trigger.
- Streaming to disk (Continuous recording)
- Firing Pulse Trigger.

It is necessary to choose an appropriate trigger method and trigger levels for a particular application. The setting should be low enough to be triggered by the blast, but not so low as to be triggered by background vibration such as traffic or machinery.

Ground vibration is the usual trigger mode except where long distances are involved. Air vibration can only be reliably used on still days because wind gusts often give higher vibrations than those from the blast. Also, if air vibration is used as a trigger, increased pre-trigger time must be available to record the ground vibration signal at distance, ie. at 1 km, the ground vibration arrives approximately 3 seconds earlier than the air vibration.

At large distances, because the vibration levels are low, the blast vibration can often only be captured using a manual trigger (in co-operation with the shotfirer), firing pulse trigger or else a streaming to disk mode to continuously record and store data for a long period to ensure the blast event has been covered.

### **3.1.2 Air Vibration Measurement**

Air vibration is measured with a microphone with suitable frequency and dynamic response. A pressure wave passing the microphone causes a diaphragm to respond and generates an electrical signal. The electrical signal is converted into a pressure signal (Pa or dBL) by a processor. On peak reading instruments the maximum needle deflection or LED readout is held to permit a reading to be made.

Other dedicated blast monitoring instruments are capable of storing the signals to permit wave traces to be made. Other sources of pressure (noise) that can effect air vibration instruments are wind gusts, traffic, and background noise.

### **3.1.3 Water Borne Vibration Equipment**

Water borne vibration is measured with a hydrophone. Hydrophones respond to pressure in a similar manner to the microphones in air and generate an electrical signal, which is converted to a pressure signal (Pa) by a processor. Some peak reading precision sound monitoring equipment can be used to measure water borne vibration by the fitting of a hydrophone.

## **3.2 EQUIPMENT AVAILABLE**

### **3.2.1 Basic Peak Reading Analogue Equipment**

Coyne Electronics PVM3 and PVM4 are examples of this type of instrument for measuring ground vibration. Any ground vibration sends a signal to the processor, which is then translated to a vector sum statement on a LED screen.

The Bruel and Kjaer 2231 and 2218 (with low frequency modification), and 2209 Precision Sound Level Meters are examples of peak reading instruments when set to Linear Peak (Hold). The peak reading is read from a needle and scale. They may also be used for single channel hydrophone and accelerometer measurements. The Bruel and Kjaer 2231 has a digital display.

### **3.2.2 Wave Form Recording**

It is often desirable to have wave traces of the vibration as a tool to analyse the performance of the blast (also to confirm that a peak reading was actually a blast and not some other event). Commonly used equipment may be analogue or digital recording.

Analogue recording - the signals from the peak reading instruments mentioned above may be sent to a data recorder with suitable frequency response, or to an ultraviolet chart recorder such as a Visilight. The signals from the data recorder cassette may then be processed by such means as the ENVIB Software System, to produce full wavetraces including a Vector Sum Trace and full Fast Fourier Transform frequency analysis.

Digital recording - the vibration signals from the geophone and microphone are stored directly on the hard disc of a portable computer for subsequent analysis. This system requires a signal pre-conditioning module, ie. SPM8 or CJ4, the computer to be fitted with an A/D board, and appropriate software.

### **3.2.3 Dedicated Self Triggering Vibration Monitors**

A number of manufacturers have developed different models of blasting seismograph with different failings and features and modified to reflect advancing technology. Instruments in common use in Australia are:

- Micro-Innovations - PVM A6/Sinco ETNA 8.
- Blastronics -  $\mu$  MX.
- InstanTEL - Blastmate DS 677, MiniMate and MiniMate Plus.
- Datamaster - Dynamaster Blast Monitoring System.
- Terrock - Vibpak/CJ4/ENVIB Vibration Monitoring System.

The PVMA 6/ETNA 8 can be upgraded by installation of a Data Card system to record and store the wave data for full ENVIB analysis. The recent trend has been the miniaturisation of the data collection side and development of 'clever bricks', such as Blastronics  $\mu$  MX and InstanTEL MiniMate Plus. These act as peak reading machines by themselves, but when connected to computer, permit full waveforms and analysis to be made of the stored signals.

### **3.2.4 Remote Triggered Remote Access Systems**

To overcome the particular problems of monitoring open cut coal blasts, ie. requirement to monitor air vibration levels at large distances with low or unreliable ground vibration levels as a trigger, often during wind events, these systems were developed. The Dynamaster system is typical.

They consist of an early warning trigger unit, remote monitors (remote slave units) and a actual computer unit, all linked by radio communication. One or several early warning units are located close to the blast and are triggered by the first ground vibration exceeding the trigger level. The EWU transmits a radio signal, which switches the remote units to record mode. The Remote Units record the air and ground vibration signals for a pre-configured time and store the data. At a convenient time, the stored signals are downloaded remotely from the central control unit and hard copy wave traces produced.

When operated correctly they reliably record blast vibration signals in normally difficult monitoring situations and reduce the time spent in collecting data.

Blastronics and Instantel also have developed remote operation capability of their units by mobile telephone communication.

## CHAPTER 4 – PRACTICAL OPERATION OF MEASUREMENT EQUIPMENT

### 4.1 SELECTION OF EQUIPMENT

The equipment used for measuring blast vibration should comply with specifications approved by the regulatory authorities. This authority would generally approve equipment with specifications conforming to AS2187-1993, which states:

#### ***"Ground Vibration***

*J4.2.1 Measuring equipment. The measuring equipment should be capable of providing a direct reading of the maximum instantaneous peak particle velocity, which is the vector sum of the three orthogonal ground vibration components detected by the geophone.*

*Ground vibration should be measured with tri-axial transducers, and the measurement equipment should have a maximum absolute error of 15% over a frequency range of 5 Hz (lower cut-off frequency) to 250 Hz. The dynamic range of the equipment should be sufficient for the vibration levels to be measured.*

*The instrument should have these three components:*

- a) tri-axial transducer;*
- b) processor; and*
- c) recorder.*

*They should be interconnected with cables.*

*The recorder should give a printed recording of the date, the time, and the resultant peak particle velocity as measured by the transducer. The tri-axial transducer housing should have indicators, which show the orientation of the individual transducer components.*

#### ***Air Vibration***

*J4.3.1 Measuring Equipment. The measuring equipment should be capable of measuring in decibels (dB) on a linear scale and the peak value.*

*Airblast should be measured with equipment that has a maximum absolute error of  $\pm 15\%$  over a frequency range of 2 Hz (lower cut-off frequency) to 200 Hz. The dynamic range of the equipment should be sufficient for the vibration levels to be measured.*

*A recording device is desirable but, if it is not provided, the measuring instrument should have a 'hold' facility to allow the peak reading to be read easily. A 'hold' facility should be accompanied by an easy reset device in the event that a false trigger occurs."*

Other considerations when selecting equipment should be:

- **Measuring Period**

The equipment should have sufficient recording time to capture the full blasting event at the distance measured. The larger the distance, the longer measuring period is required because of the different propagation velocities of the vibration waves, eg. **Figure 4.1** shows a general time/distance relationship for ground (P, S and R waves) and air vibration, based on typical wave velocities for Hunter Valley coal mines.

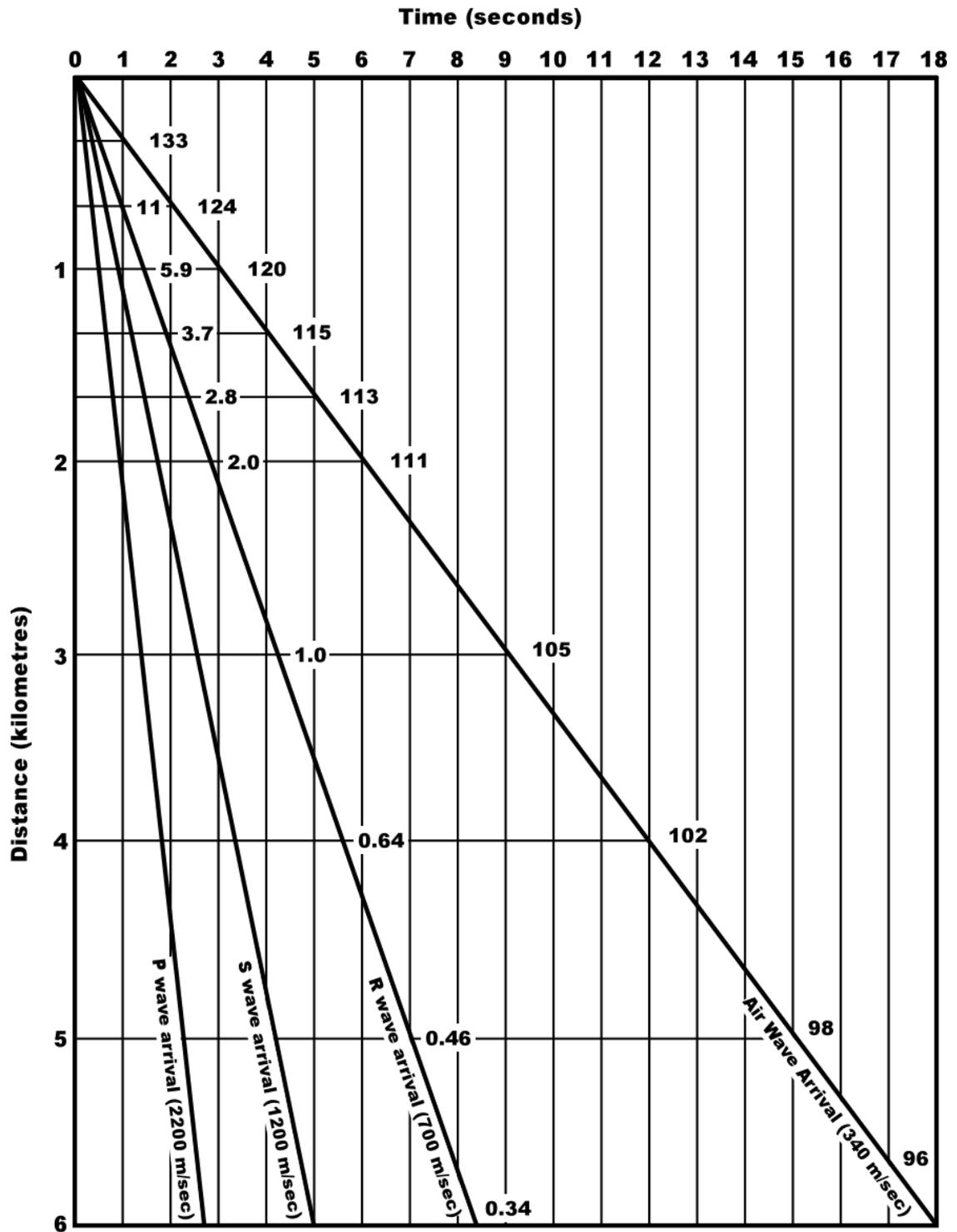


Figure 4.1

Figure 4.2 shows a signal trace obtained from overburden blasting at a Hunter Valley open-pit coal mine showing in excess of 11 seconds between the arrival of the P and airwaves. The minimum measuring period must be the difference in arrival times between the P wave and air vibration, plus the blasting event time.

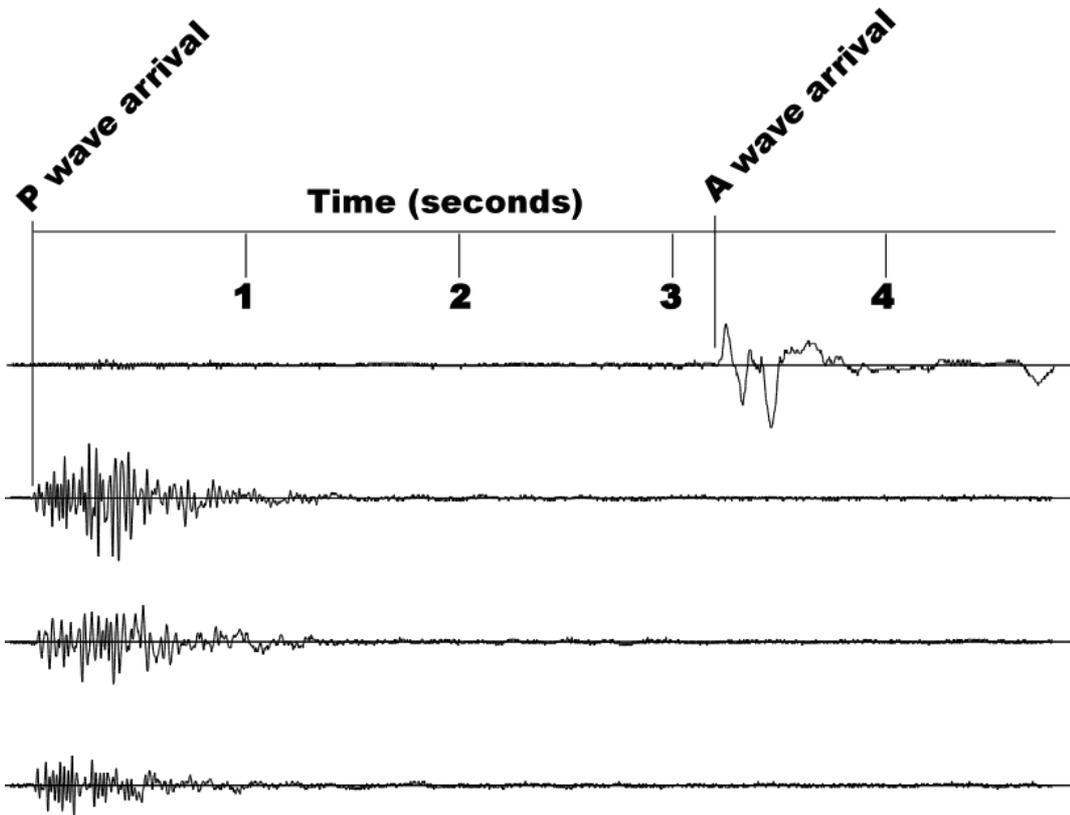


Figure 4.2

Other factors to be considered in the selection of equipment are:

- **Wavetrace Production**

For detailed blast analysis it is desirable to have a wave trace of the blasting event. The instrument should have the facility to readily produce a wavetrace in useable form.

- Storage of recorded data.
- Ease of operation.
- Weather proofing/dust proofing.
- Robustness.
- Maintenance and support facilities.
- Sufficient dynamic range (see **Figure 4.3**).
- Adequate frequency response (see **Figures 3.1 and 3.2**).

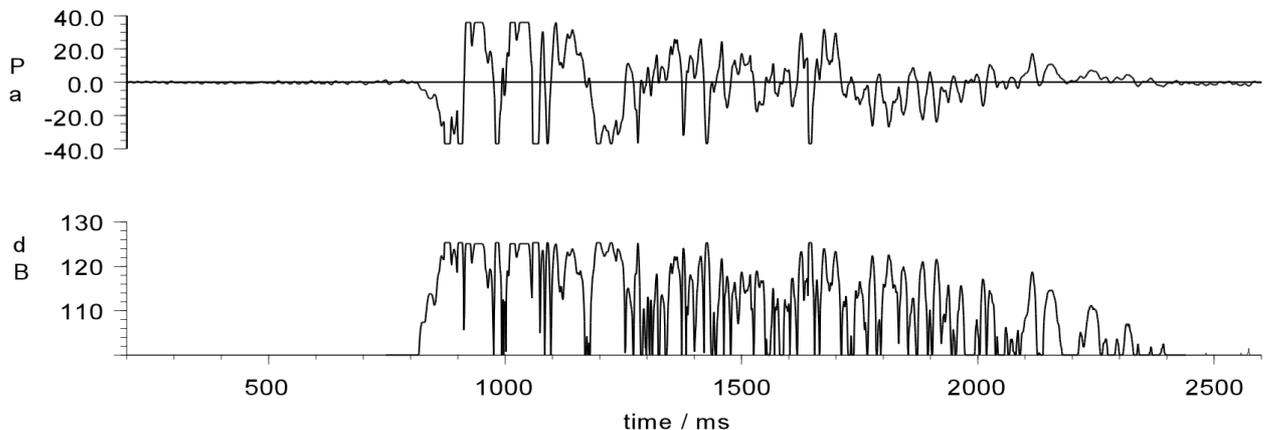


Figure 4.3 – Inadequate dynamic range

## 4.2 INSTALLATION

### 4.2.1 Ground Vibration

One of the most important aspects of ground vibration monitoring is the mounting of the transducers (geophone, accelerometer, etc). The geophone should be mounted to faithfully respond to the motion of the wave passing through the ground, not to the response of the monitoring structure to the vibration. The degree of securing required is a function of the amplitude of the motion as well as the frequency.

AS2187.2-1993, Appendix J, states:

*"When particle accelerations are less than 0.3 g it may not be necessary to hold the transducer to the measurement surface. If particle accelerations are greater than 1.0 g, bolts or cement are needed."*

From  $V = 2 \frac{a}{\pi} f$ , particle accelerations of 0.3 g corresponds to 5.8 mm/s @ 80 Hz and 11.6 mm/s @ 40 Hz, etc. 1.0 g corresponds to 19.4 mm/s @ 80 Hz and 38.9 mm/s @ 40 Hz.

From our experience, it is not good practice to sit the geophone on the ground. For low anticipated levels the geophone should at the least be sandbagged, sunk into the ground and tamped or spiked to the ground with plate and spikes.

As the vibration level increases, the geophone must be plastibonded to hard surfaces, such as concrete or rock, or buried and securely tamped below the surface of soils, etc. to accurately measure the vibration.

Because of inaccuracies of prediction of vibration levels, it is prudent to opt for secure mounting regardless of anticipated levels.

Insecure mounting may result in a higher vibration level reading because the transducer responds to the motion when it is unduly shaken. Similarly, high readings will result if the geophone is securely mounted to an insecure object, such as a loose brick or rock 'floater' in soft soil.

The geophone should be oriented in the direction of the blast. For permanent monitoring stations, a 200 mm concrete block sunk into the soil and firmly tamped will provide a suitable mounting. The geophone may be bolted or plastibonded to the block.

### 4.2.2 Air Vibration

The microphone should be mounted at least one metre above the ground level and preferably at least 3 metres away from the walls of buildings and fences. This is to prevent possible reflection of vibration from the surfaces increasing the vibration levels. The microphone should be fitted with a wind shield and oriented to be most uniformly sensitive to the vibration.

A summary of microphone mounting considerations is shown in **Figure 4.4**.

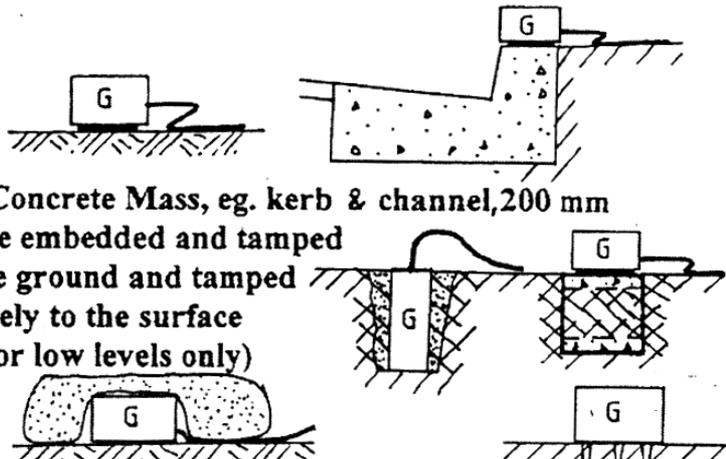
## 1. GEOPHONE ATTACHMENT

Insecure Geophone mounting results in higher vibration levels.  
Geophones should be oriented in the direction of the blast.

### Recommended

Plastibonded to :

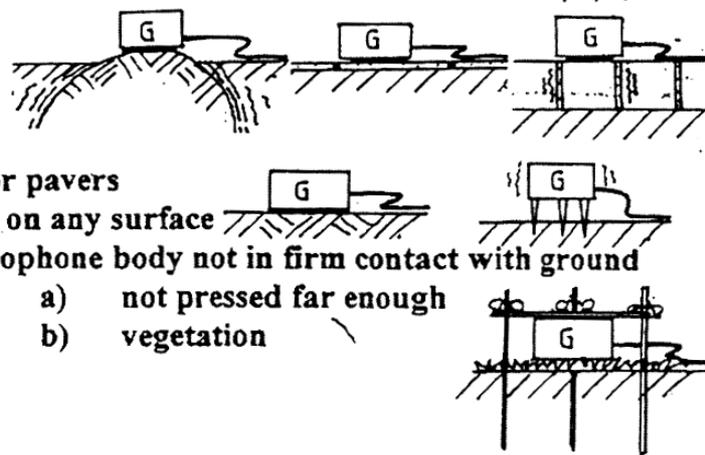
- Solid Rock
- Substantial Concrete Mass, eg. kerb & channel, 200 mm concrete cube embedded and tamped
- Sunk into the ground and tamped
- Spiked securely to the surface
- Sand bags (for low levels only)



### Not Recommended

Plastibonded to :

- Loose Rock
- Thin concrete
- Loose bricks or pavers
- Sitting loosely on any surface
- Spiked, but geophone body not in firm contact with ground because of
  - a) not pressed far enough
  - b) vegetation



## 2. MICROPHONE

Microphone should be :

- at least 1 m above ground surface
- 3 m away from buildings, fences, etc.
- fitted with a windshield
- oriented to be most uniformly sensitive to vibration.
- Secured to prevent being blown over.

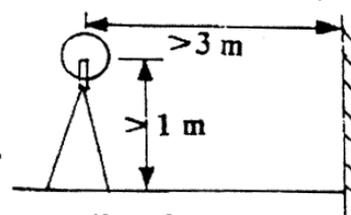


Figure 4.4

## 4.3 CALIBRATION AND FIELD CHECKS

The vibration measuring equipment should be calibrated on a regular basis - every one or two years. This can be achieved by:

- Sending instruments to a suitably equipped and recognised testing laboratory.
- Field calibration alongside a calibrated instrument.
- Using a calibrated tone calibrator for microphone.
- Using a calibrated vibrating table for geophone.

Permitted accuracy from AS2187-1993 is:

- Ground vibration maximum absolute error of 15% over a frequency range of 5 Hz to 250 Hz.
- Air vibration maximum absolute error of  $\pm 15\%$  over a frequency range of 2 Hz to 200 Hz.

Field calibration has the advantages that measurements are made at the actual vibration frequencies of a blast and the frequency spectrum of both instruments can be compared. Checks can also be made on the efficiency of coupling the geophones.

## **CHAPTER 5 – BLAST AND LOCATION DETAILS**

It is essential in any blast vibration analysis to have good records of blast details and an accurate representation of the blasting site and surrounding area. The extent of the surrounding area will vary for the scale of blasting operations. For large scale open-pit blasting, 5 km or more may be required. For quarry blasting, 1-2 km would normally be sufficient.

### **5.1 SITE AND LOCATION PLANS, AERIAL PHOTOGRAPHS**

The types of site representations that may be available include:

#### **5.1.1 Aerial Photographs**

May be custom flown by the mine/quarry for annual face, stockpile checks, etc. Will be recent but may not extend into adjacent areas.

Another source is the regular (5-8 years) State Government aerial photographs obtainable from State mapping authorities. May not show current faces, but can be obtained for surrounding areas. Nominal photographic scales are 1:15,000 and 1:25,000. Enlargements to any scale or to cover specific areas can usually be obtained when ordering.

#### **5.1.2 Orthophoto Maps**

Available from the State Government map shops. Show photographic details, with contours overlain on various scales, but 1:10,000 is common. May not show current working faces.

#### **5.1.3 Mine/Quarry Bench Plans, etc**

These are usually updated periodically and may provide accurate face locations. Usually do not extend to surrounding area.

#### **5.1.4 Government Topographic Maps**

Available in scales of 1:25,000, 1:50,000, 1:100,000, 1:250,000. The scale 1:25,000 is the most useful for quarry scale operations.

#### **5.1.5 Sewerage District Detail Maps**

Detailed plans exist over most sewerage districts and show streets, allotments, houses, etc on scales of 1:10,000, 1:5,000 and 1:2500. These are useful for close order analysis.

#### **5.1.6 Street Directories**

As a last resort the 1:20,000 street directory maps may be used for analysis in metropolitan areas.



A record sheet detailing blast component prices for a Blast Cost Report is included as **Figure 5.2**.

### BLAST COST REPORT

<b>Location:</b> METQ Metropolitan Quarry.					
<b>Date:</b> 14/09/94		<b>Weather:</b> Fine, cloudy, still.			
<b>Time:</b> 12:02		<b>Rock type:</b> Hard Rock		<b>Face height(m):</b> 13.5	
<hr/>					
<b>BLAST DESIGN</b>					
<b>BLASTHOLE:</b>	<b>Diameter (mm):</b> 89	<b>PATTERN:</b>	<b>Burden (m):</b> 3.8		
	<b>Length (m):</b> 14.7		<b>Spacing(m):</b> 3.8		
	<b>Angle (deg):</b> 10.0		<b>Rows :</b> 3		
	<b>Subgrade (m):</b> 1.0		<b>Holes :</b> 60		
	<b>Water Depth(m):</b> 2.0				
<hr/>					
<b>Density(t/cu.m):</b> 2.70	<b>Volume Broken(cu.m):</b> 11696	<b>(tonnes):</b> 31580			
<hr/>					
<b>BLAST COST DETAILS</b>					
<hr/>					
<b>Drilling :</b>	<b>metres</b>	<b>\$/m</b>	<b>Cost \$</b>		
	882.0	5.00	4410.00		
<b>Loading :</b>	<b>manhours</b>	<b>\$/manhr</b>	<b>Cost \$</b>		
	10.0	20.00	200.00		
<hr/>					
<b>Explosives :</b>	<b>weight</b>	<b>\$/kg</b>	<b>Cost \$</b>		
ICI Handibulk Wet (GMB)	4450.0	1.25	5562.50		
Powergel Magnum II 55mm	208.6	5.28	1101.41		
Anzomex "P" Primers	23.6	15.12	356.83		
Anzomex "K" Primers	0.7	26.27	18.39		
<b>Initiation Devices :</b>	<b>Units</b>	<b>\$/unit</b>	<b>Cost \$</b>		
Exel Primadet DLD No 7	60	7.60	456.00		
Exel Primadet DLD No 8	5	3.50	17.50		
Exel Connectadet 17ms	4	4.80	19.20		
Exel Connectadet 25ms	15	4.80	72.00		
Exel Connectadet 42ms	21	4.80	100.80		
Exel Connectadet 65ms	19	4.80	91.20		
Electric	1	1.85	1.85		
<hr/>					
<b>Powder Factor(kg/cu.m):</b> 0.40(kg/t):	0.15				
<hr/>					
<b>TOTAL DRILLING AND BLASTING COSTS</b>					
	<b>\$/m</b>	<b>\$/hole</b>	<b>\$/cu.m</b>	<b>\$/tonne</b>	<b>TOTAL</b>
<b>Explosives</b>	8.84	129.96	0.67	0.25	7797.68
<b>Drilling</b>	5.00	73.50	0.38	0.14	4410.00
<b>Loading</b>	0.23	3.33	0.02	0.01	200.00
<b>TOTAL COSTS</b>	<b>14.07</b>	<b>206.79</b>	<b>1.06</b>	<b>0.39</b>	<b>12407.68</b>

Figure 5.2 – Blast Cost Report

Data bases for the storage of blasting records on computer are available. The advantages of data bases are the ready retrieval of data for comparison and analytical purposes.

# CHAPTER 6 – ANALYSIS OF BLAST VIBRATION MEASUREMENTS

## 6.1 PEAK READING

Peak readings must be verified by either synchronised date/time print-out or supervision of the instrument at the blasting event, otherwise there is uncertainty of the cause of the peak reading.

Peak readings can be used in analysis of data to determine site law and to produce contour maps for both air and ground vibration.

## 6.2 WAVEFORM TRACES

Analysis of waveform traces, apart from the peak value may disclose such information as:

- All transducers were working (see **Figure 6.1**).
- The geophone was securely mounted (see **Figure 6.1**).

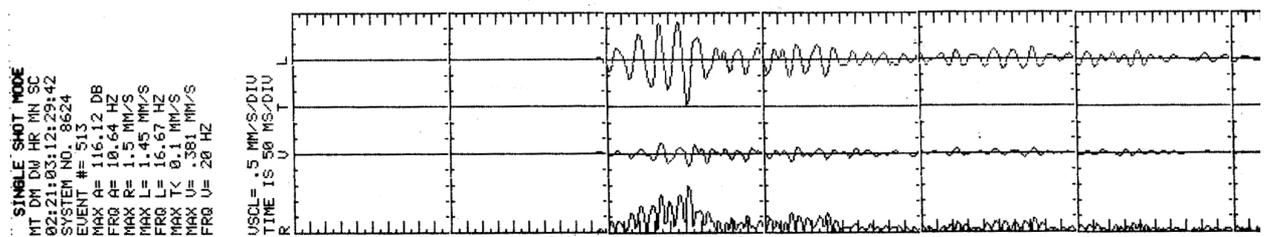


Figure 6.1 – Etna 8 wavetrace from a poorly coupled geophone with a faulty channel

- The vibration was an actual blast - vibrations sufficient to trigger an instrument, but not a blast are shown in Figures 6.2, 6.3, 6.4 and 6.5.

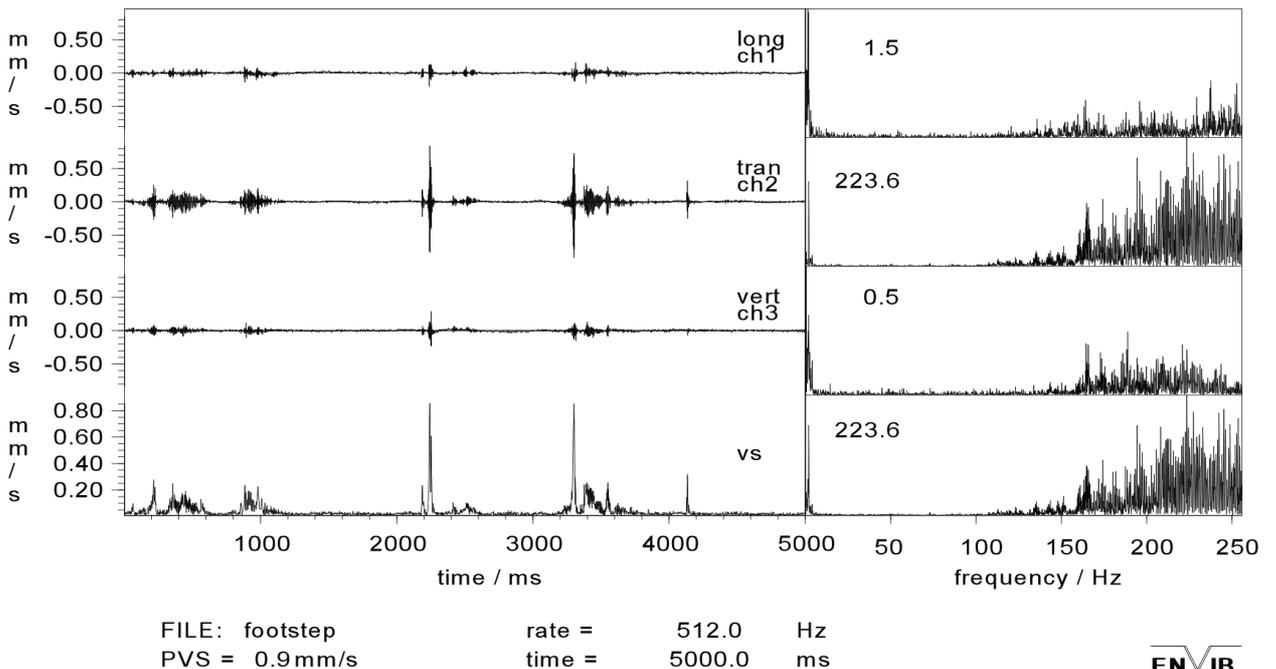
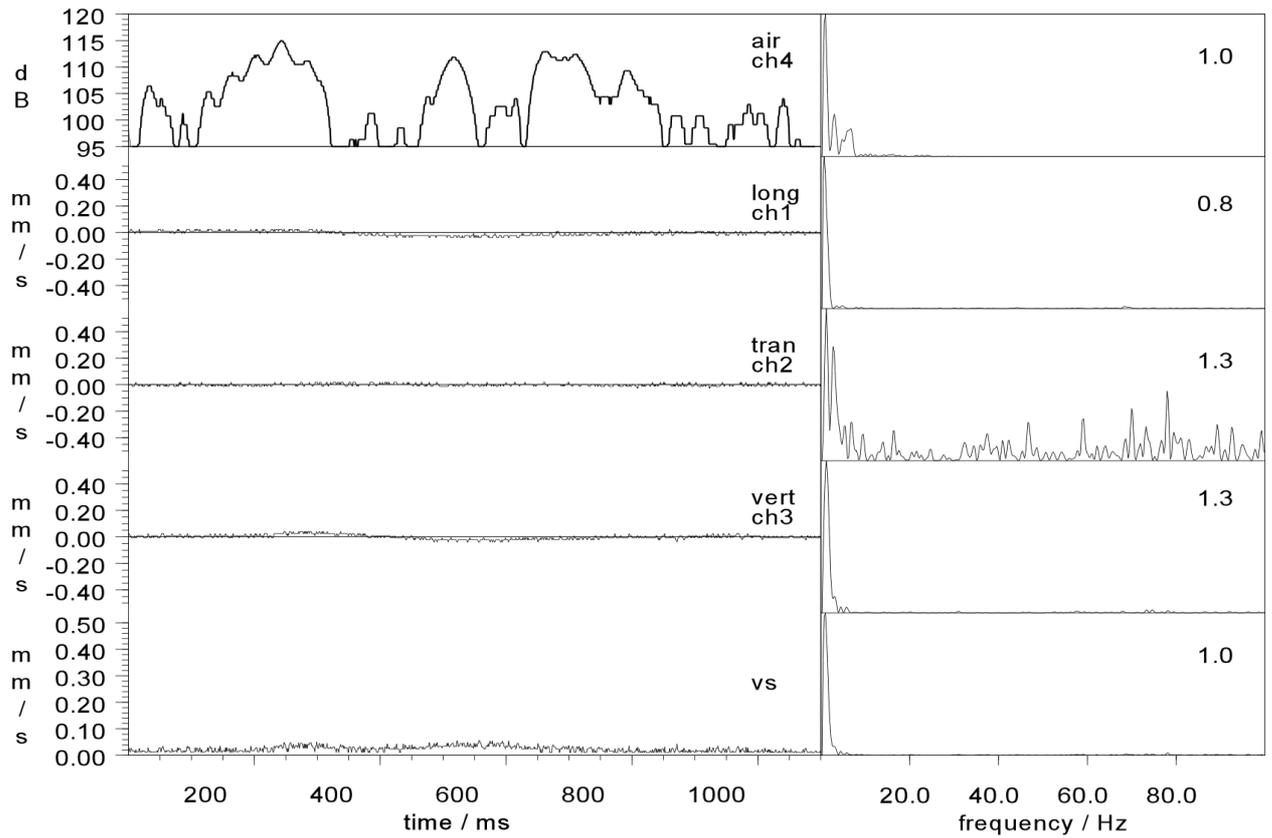


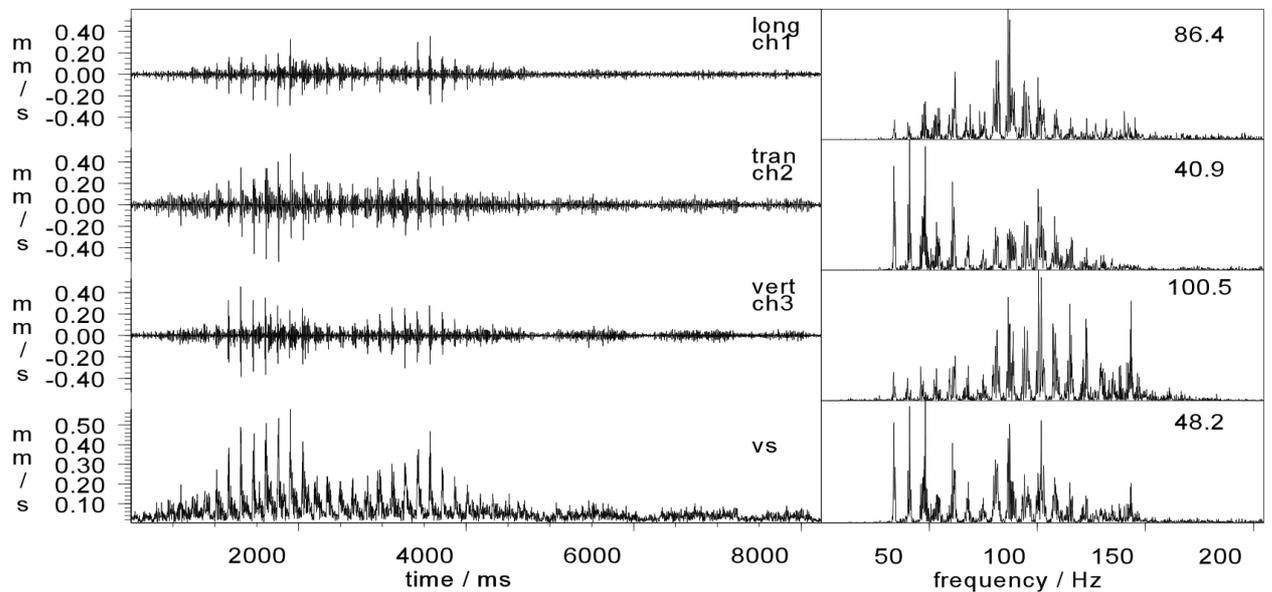
Figure 6.2 – Wavetrace of a false trigger caused by pedestrian activity



FILE: wind4  
PVS = 0.1 mm/s                      rate = 1024.0 Hz  
SPL = 115.0 dBL                    time = 1100.0 ms



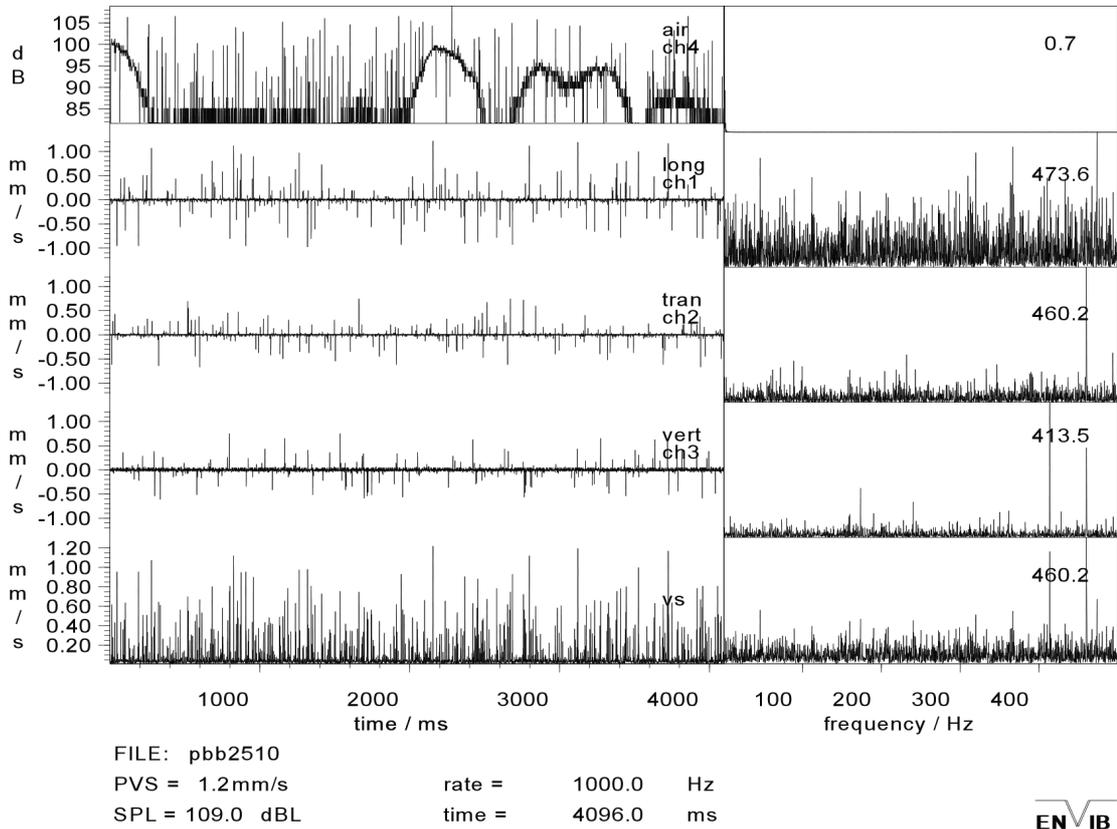
Figure 6.3 – Wavetrace of a false trigger caused by a wind gust



FILE: jr07b02                      rate = 409.6 Hz  
PVS = 0.6 mm/s                    time = 8237.3 ms

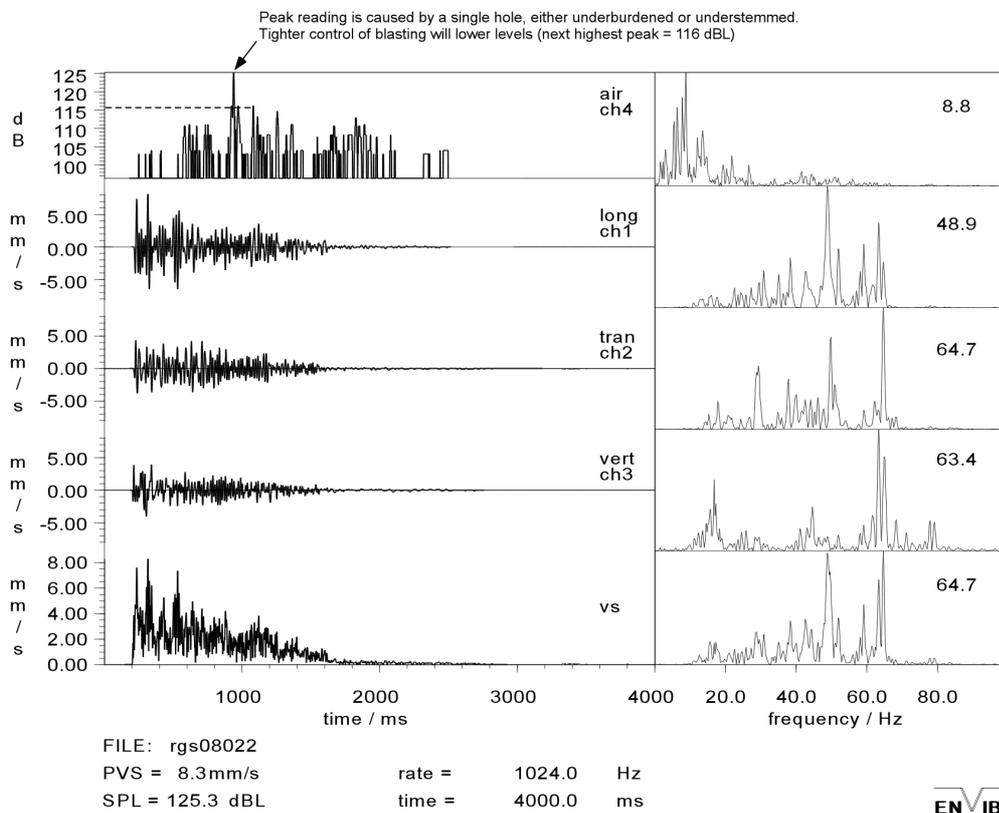


Figure 6.4 – Wavetrace of a false trigger caused by a passing train



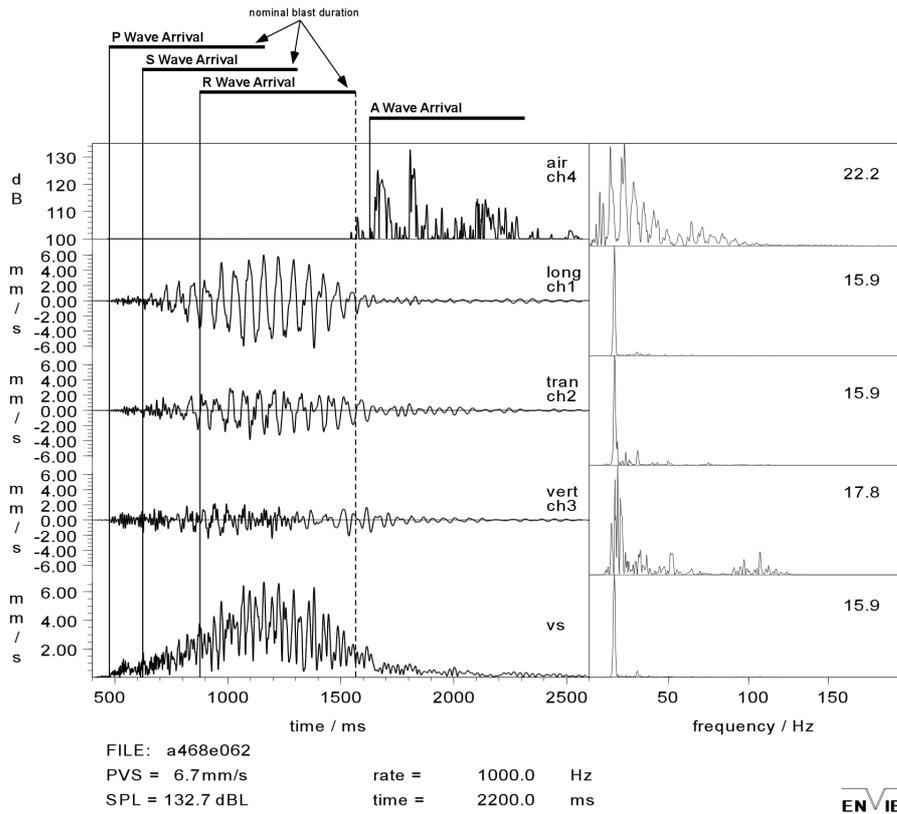
**Figure 6.5 – Wavetrace of a false trigger caused by an unknown electrical interference**

- Where in the blast did the peak value occur (both ground and air vibration)? This often can be related to a specific hole or section of the blast where high values resulted from a control process that could be improved (see **Figure 6.6**).



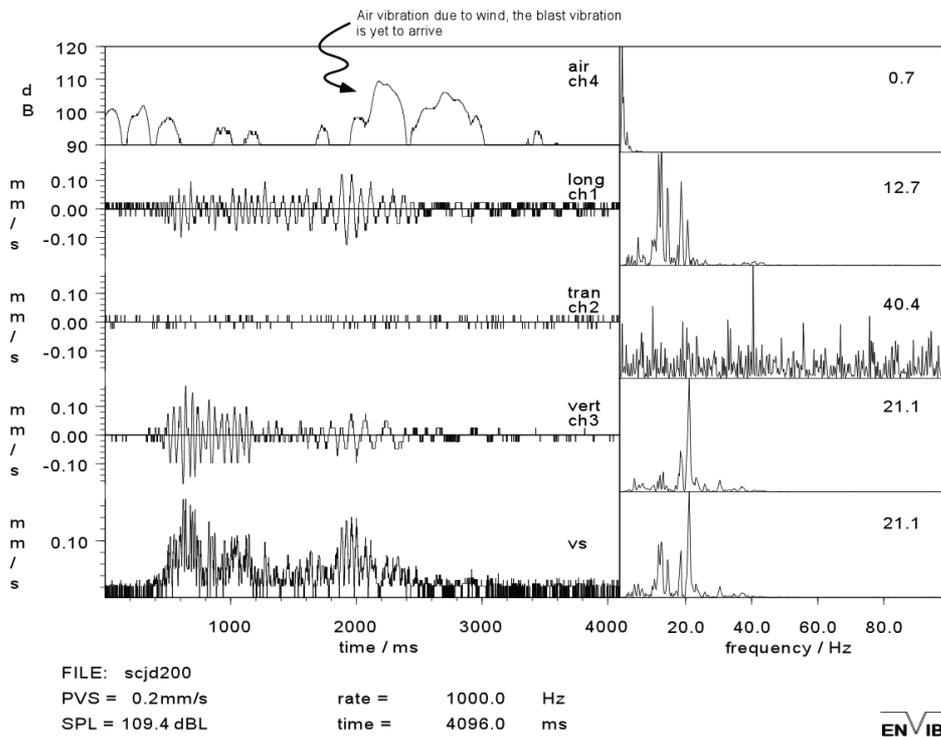
**Figure 6.6 – Wavetrace with peak air vibration from one blasthole**

- Separation of wave types.
- Rampant Rayleigh waves (see **Figure 6.7**).



**Figure 6.7 – Wavetrace showing 'rampant' Rayleigh waves**

- The air vibration had arrived, ie. the air vibration reading is not just background or the wind (see **Figure 6.8**).



**Figure 6.8 – Wavetrace with insufficient time window to capture the air vibration**

- P, S, R and a wave analysis compares the arrival times of the Compressional, Shear, air and Rayleigh waves.

Such information may be useful when investigating the causes of high vibration levels.

Wave traces are produced in the following forms:

- **Ground Vibration**

Traces the three perpendicular components versus time and a vector sum statement. More useful is the individual channel traces plus the vector sum plotted against time.

- **Air Vibration**

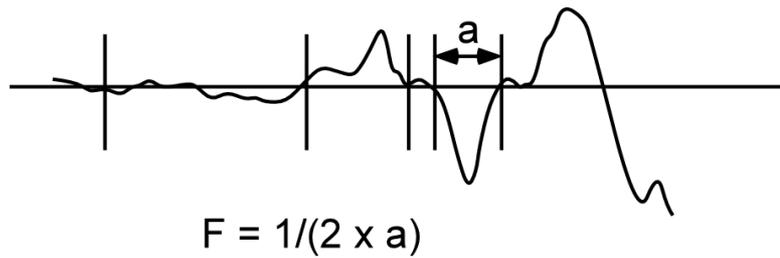
Traces either Pa or dBL versus time.

- **Vibration in Water**

Traces kPa versus time.

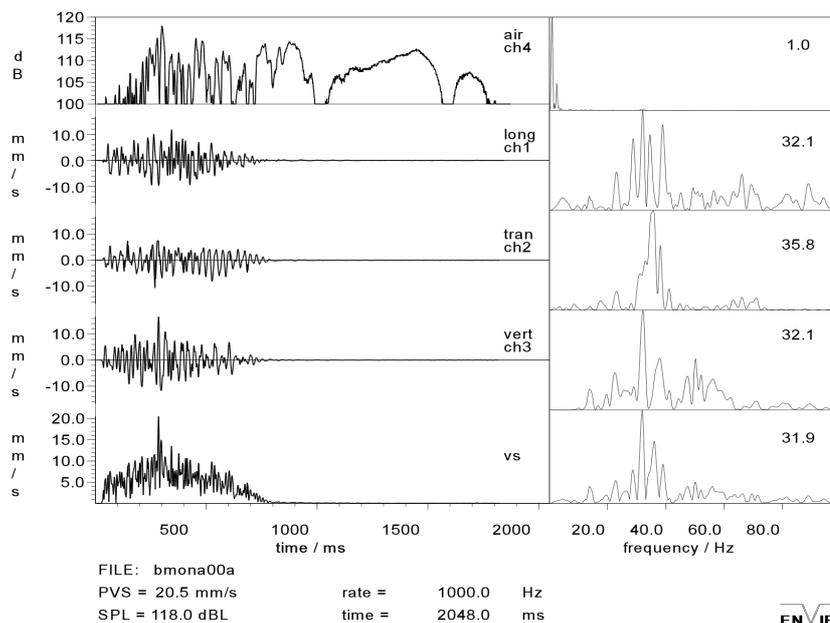
### 6.3 FREQUENCY ANALYSIS

- Simple approximation using the zero crossing method at the occurrence of peak particle velocity and the peak airblast:



- Fast Fourier Transformers (FFT).

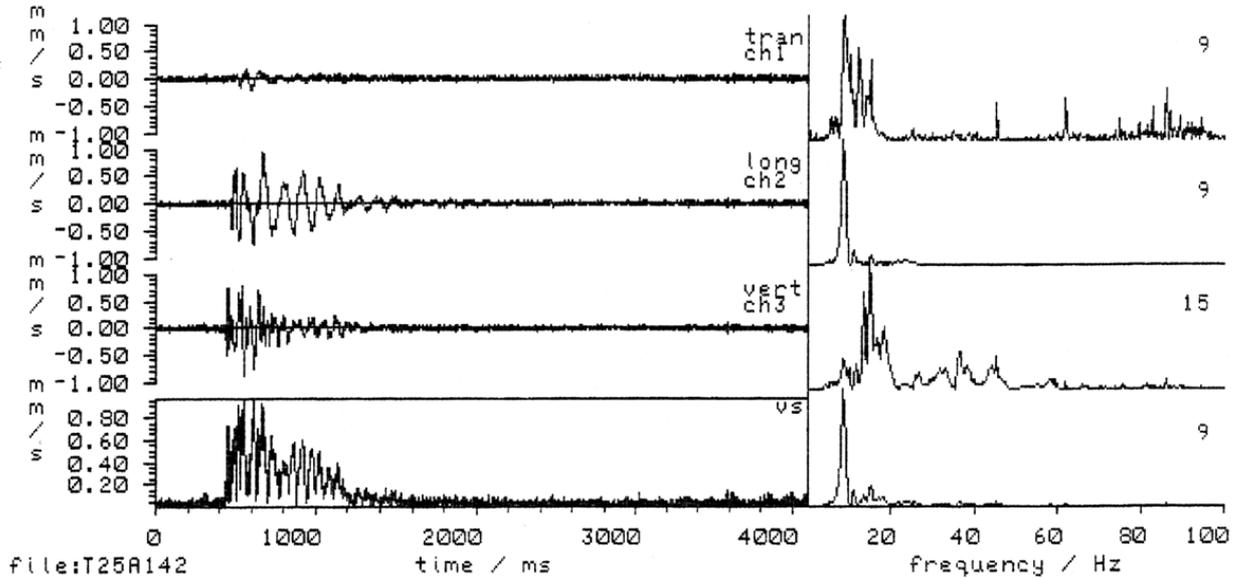
Shows full frequency spectrum for the vibration. A typical example is shown in **Figure 6.9**.



**Figure 6.9 – Vibration wavetrace with frequency spectrum**

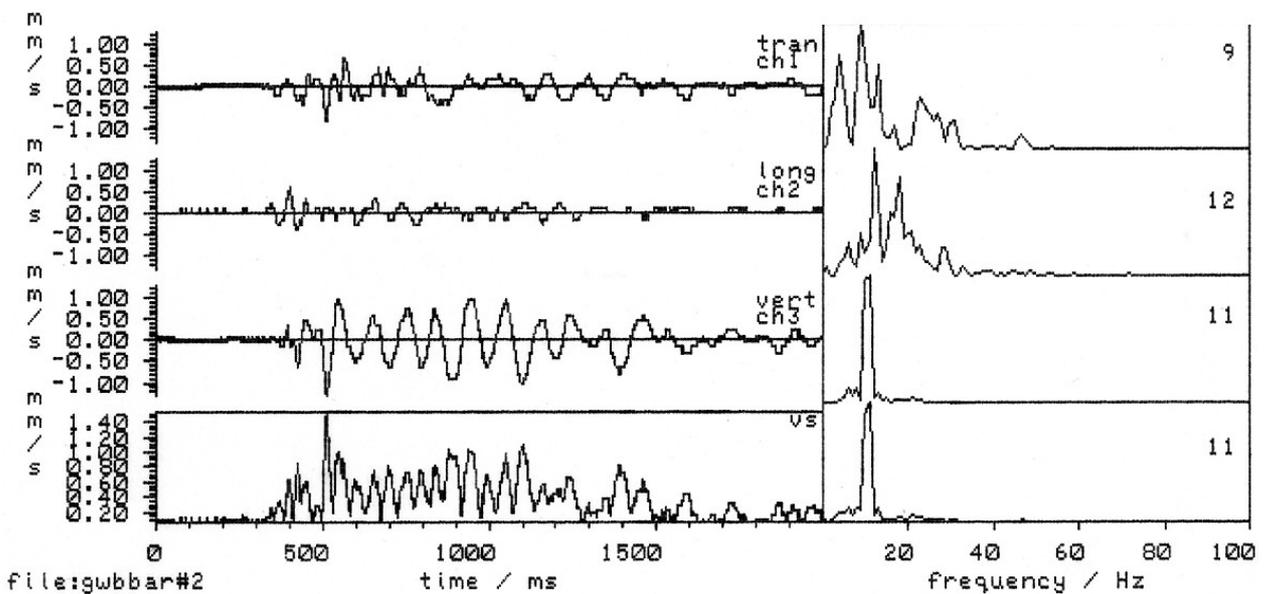
## 6.4 TRANSFER FUNCTIONS

For structural response investigations, compares the input signal from the ground with the response signal from the structure and gives a plot of the amplification of the common frequencies. The following example was a test blast near an historic Bow Truss bridge. The vibration trace taken on the ground near the abutment and the vibration trace taken in mid-span to show the structural response are shown in **Figures 6.10(a)** and **6.10(b)**.



PVS = 0.97 mm/s ENVIB  
 G.W.B. Barwon River Crossing. Test Blast 2, Ground Stn. 31-10-90(1514)

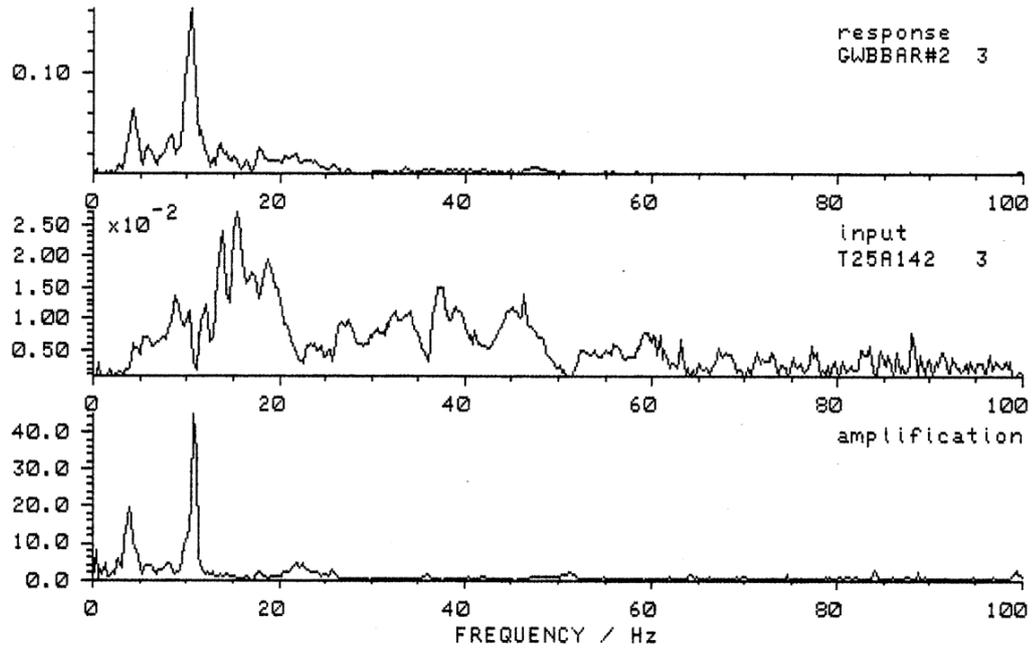
Figure 6.10(a)



PVS = 1.53 mm/s ENVIB  
 G.W.B. Barwon River Crossing. Test Blast 2, Mid-Span. 31-10-90(1514)

Figure 6.10(b)

The frequency spectrum of the vertical channels of the ground (input) and bridge (response) are shown in **Figure 6.11**, together with the amplification factors of the common frequencies.



Response of Bridge Structure to Ground Vibration Input. —

Figure 6.11

## 6.5 CONVERSIONS OF ACCELERATION, VELOCITY AND DISPLACEMENT USING THE INTER-RELATIONSHIPS

$$v = 2 \pi f A$$

$$a = 2 \pi f v$$

Measurements may be taken with geophones or accelerometers and velocity, acceleration and displacement traces produced from either signal.

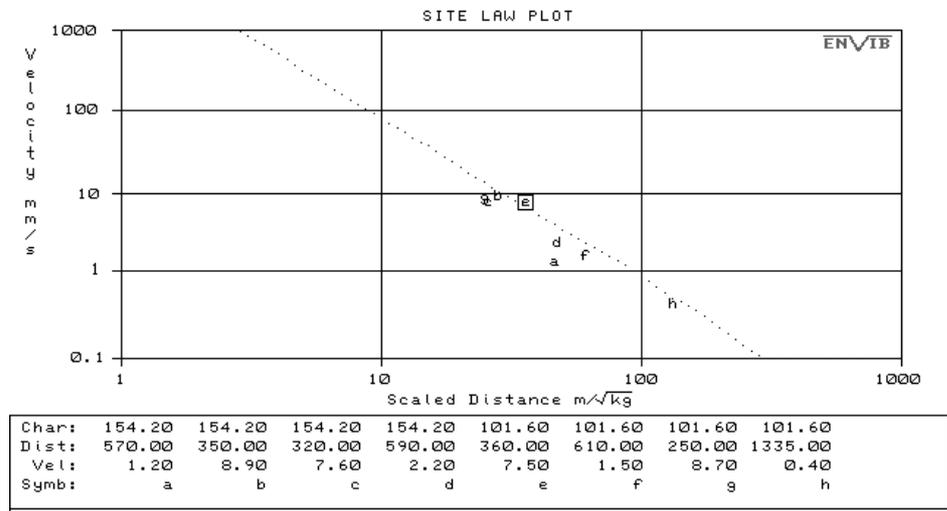
## CHAPTER 7 – ASSESSMENT AND PREDICTIONS

A number of techniques have been developed using vibration readings, together with the distance and orientation of the monitoring point relative to the blast for further analysis to gain an understanding of the mechanisms causing vibration. The understanding can then be used for control and prediction purposes.

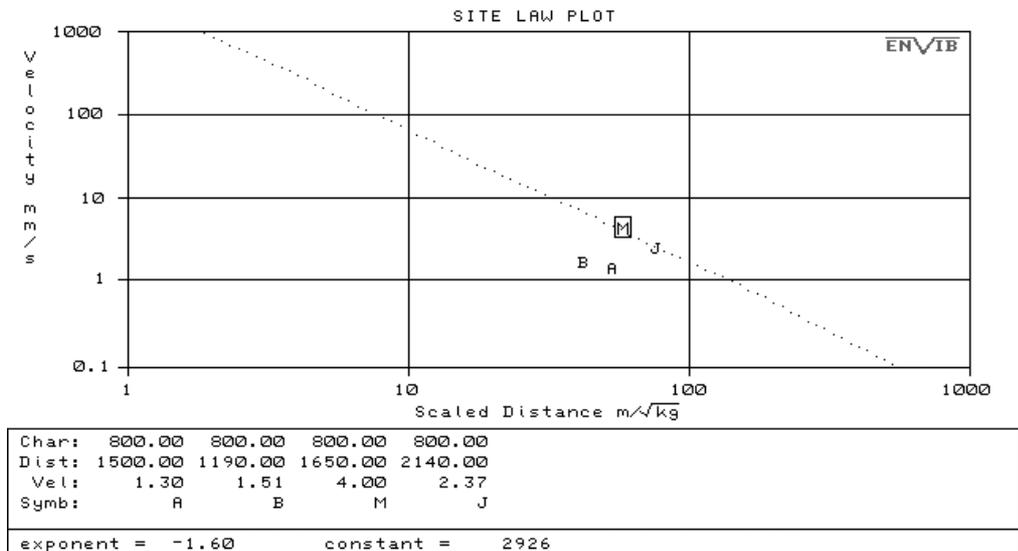
### 7.1 GROUND VIBRATION

#### 7.1.1 Site Law Determination

The charge mass, distance and PPV for each of the measuring points are plotted for a number of blasts and the Site Law is determined. A typical example is shown in **Figures 7.1(a)** and **7.1(b)**. This is particularly applicable if the points are along a radial line from the blast. Least useful are a number of points at similar distances around a blast. The Site Law is preferably determined from a number of blasts, monitored with several instruments at different distances.



**Figure 7.1(a) – Site Law determination – granite quarry**



**7.1(b) – Site Law determination – coal overburden**

## 7.1.2 Estimation Graph

Once the Site Law is determined, the results can be used to predict the vibration levels for any charge mass/distance combination by the production of an estimation graph (Figures 7.2(a) and 7.2(b)).

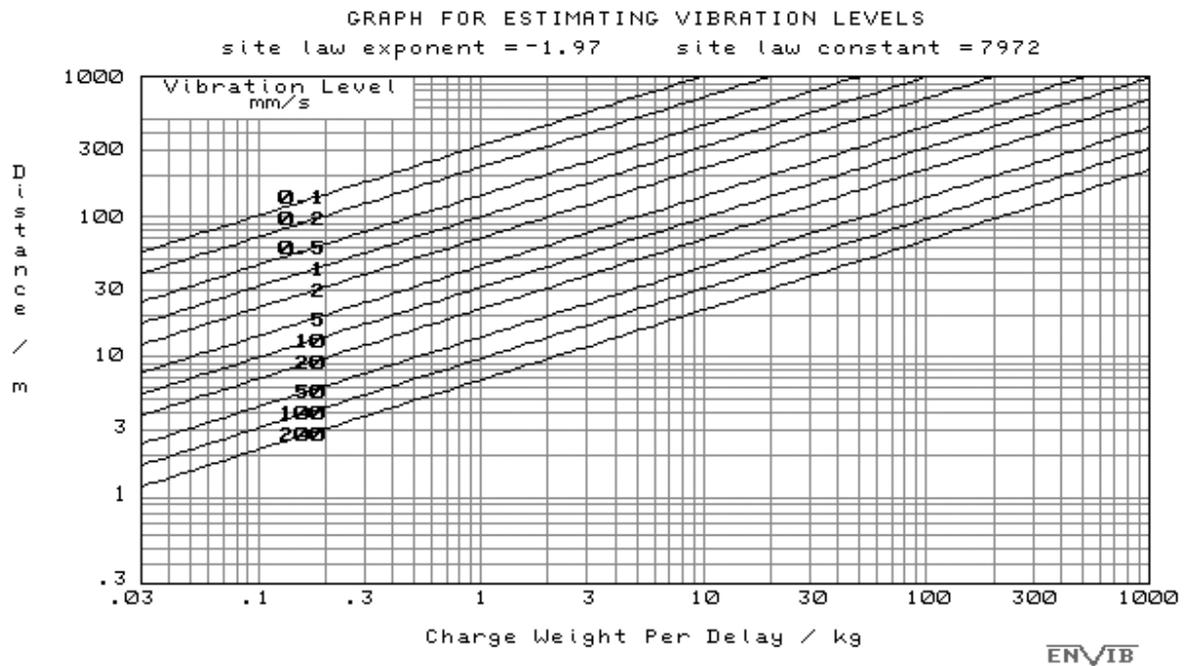


Figure 7.2(a) – Vibration estimation graphs – granite quarry

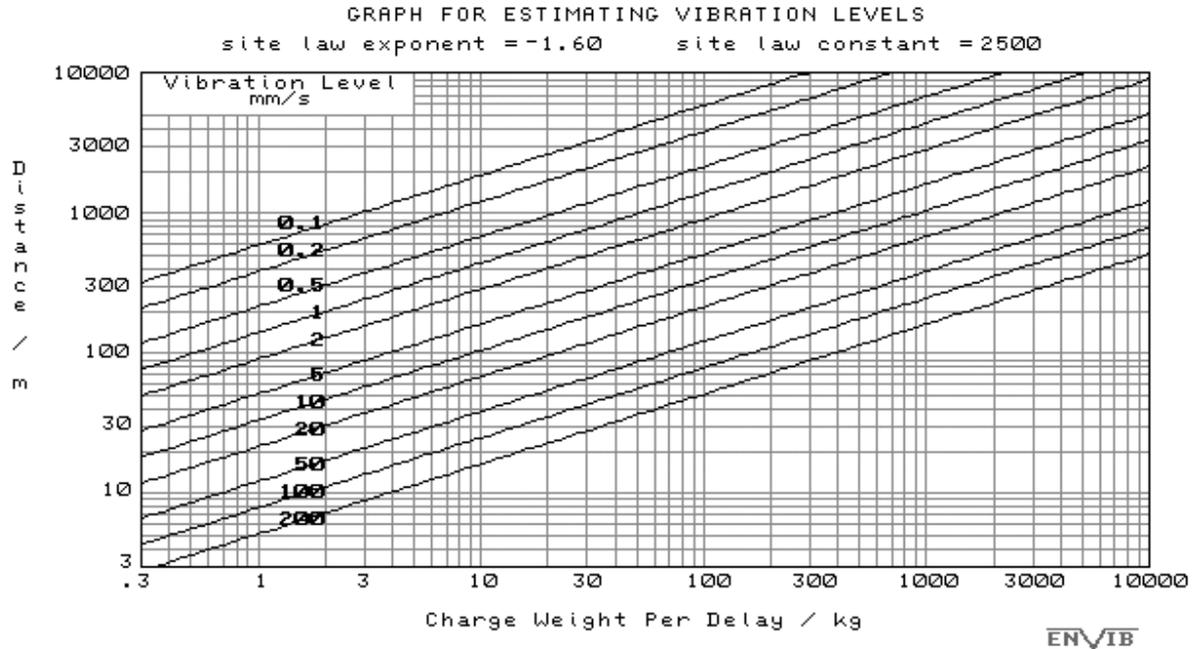


Figure 7.2(b) – Vibration estimation graph – coal overburden

## 7.1.3 Estimation Table

If the estimation graph is too difficult to follow, the same Site Law data may be presented as an estimation table (Figures 7.3(a) and 7.3(b)).



VIBRATION LIMIT TABLE  
FOR PPV = 10.00 mm/s

---

SITE LAW CONSTANT = 7927.00  
SITE LAW EXPONENT = -1.97

---

DIST/m	CHARGE/kg
10	0.11
15	0.26
20	0.46
30	1.03
50	2.85
70	5.58
100	11.40
150	25.64
200	45.58
300	102.56
500	284.89
700	558.39
1000	1139.57
1500	2564.04
2000	4558.29
3000	10256.16
5000	28489.31
7000	55839.07

Figure 7.4(a) – Vibration limit table – granite quarry

VIBRATION LIMIT TABLE  
FOR PPV = 5.00 mm/s

---

SITE LAW CONSTANT = 2500.00  
SITE LAW EXPONENT = -1.60

---

DIST/m	CHARGE/kg
10	0.04
15	0.10
20	0.17
30	0.38
50	1.06
70	2.07
100	4.23
150	9.52
200	16.92
300	38.07
500	105.74
700	207.24
1000	422.95
1500	951.63
2000	1691.79
3000	3806.54
5000	10573.71
7000	20724.48

Figure 7.4(b) – Vibration limit table – coal overburden

### 7.1.5 Contour Maps

The vibration measurements taken may also be plotted as a contour map. This enables the vibration from the blast to be estimated anywhere. The contour map may be produced as a scaled transparent overlay to be placed on a map (see **Figures 7.5(a)** and **7.5(b)** for an example). The Site Law may also be shown in contour form for demonstration purposes (**Figures 7.6(a)** and **7.6(b)**).

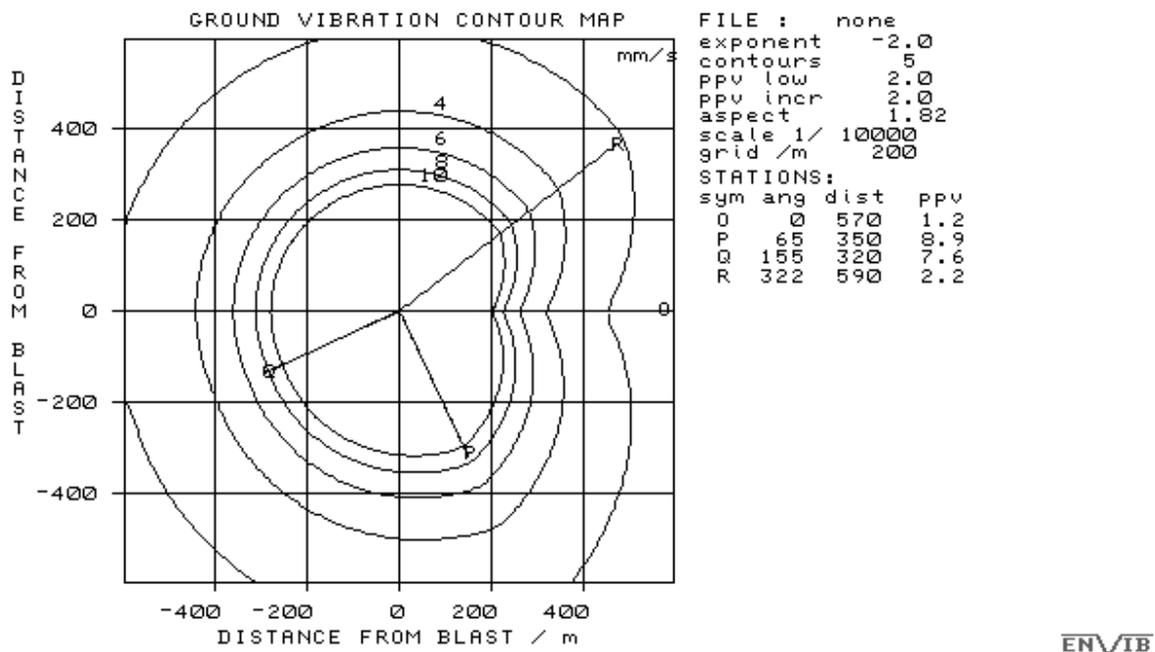
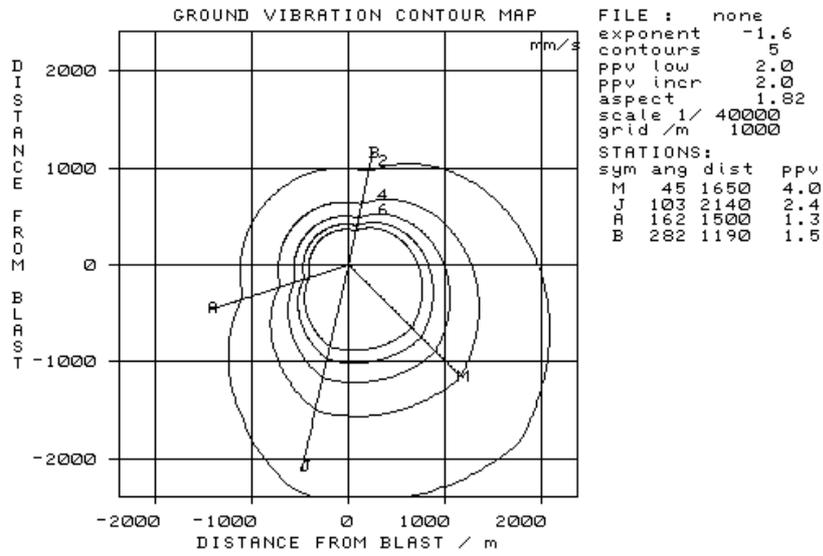
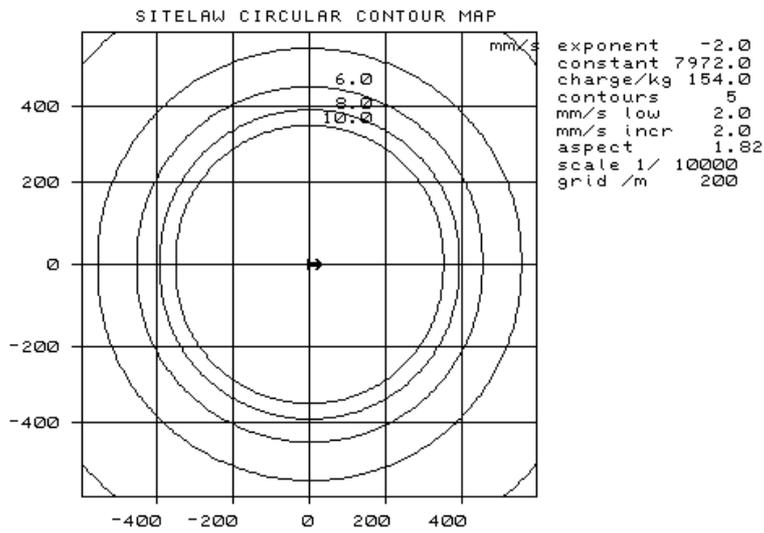


Figure 7.5(a) – Ground vibration contour map based on measurements from a granite quarry



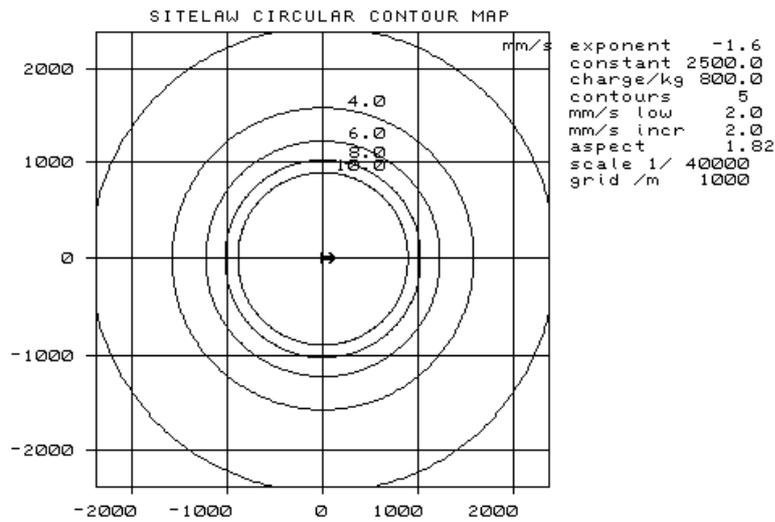
ENVIB

Figure 7.5(b) – Ground vibration contour map based on measurements from a coal overburden blast



ENVIB

Figure 7.6(a) – Ground vibration contour map based on granite quarry Site Law



ENVIB

Figure 7.6(b) – Ground vibration contour map based on coal overburden Site Law

## 7.2 AIR VIBRATION

### 7.2.1 Sonic Decay Analysis

The decay of air vibration may be determined in a similar manner to the Site Law. **Figures 7.7(a)** and **7.7(b)** show a typical set of data. Because air vibration is very directional, the measuring points should be in a line radiating from the blast. The 9 dBL drop-off rate with doubling of distance has been found to be to be useful on quite a number of occasions.

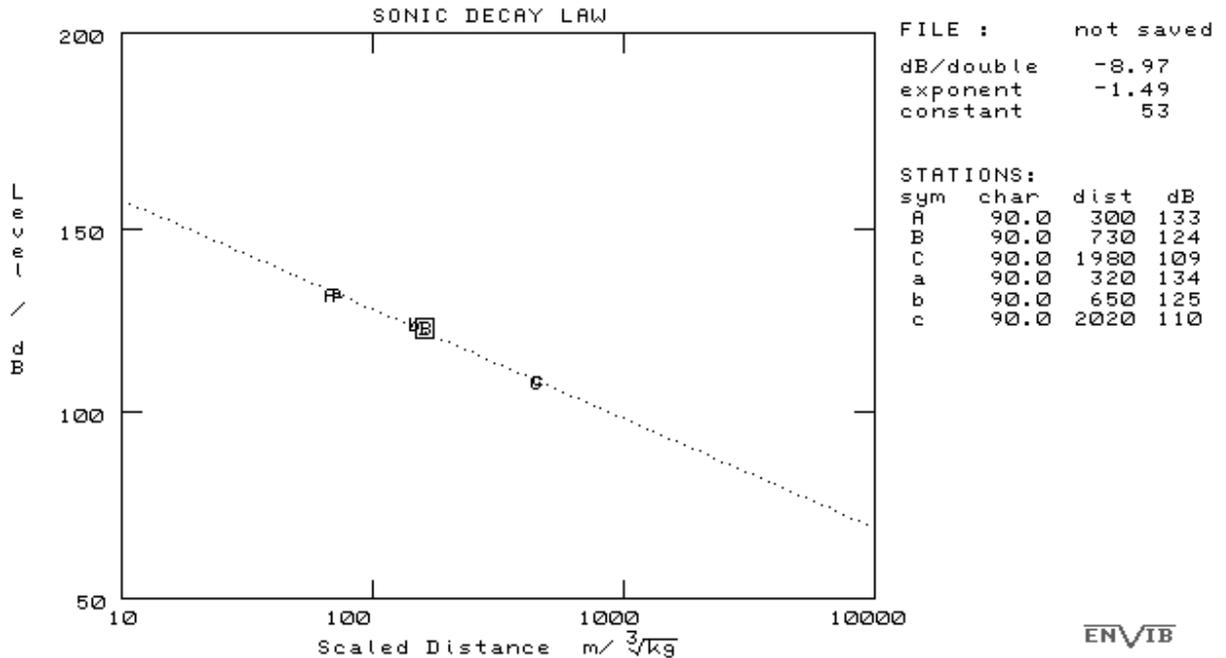


Figure 7.7(a) – Sonic decay law determination – granite quarry

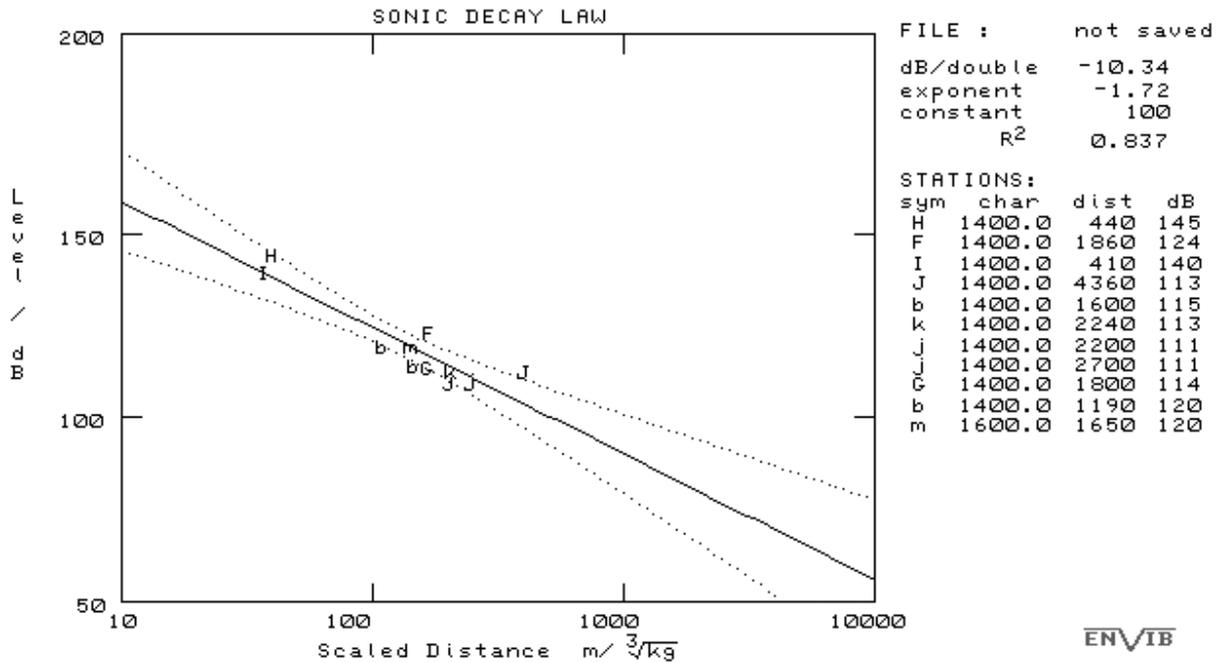


Figure 7.7(b) – Sonic decay law determination – coal overburden

## 7.2.2 Contour Maps

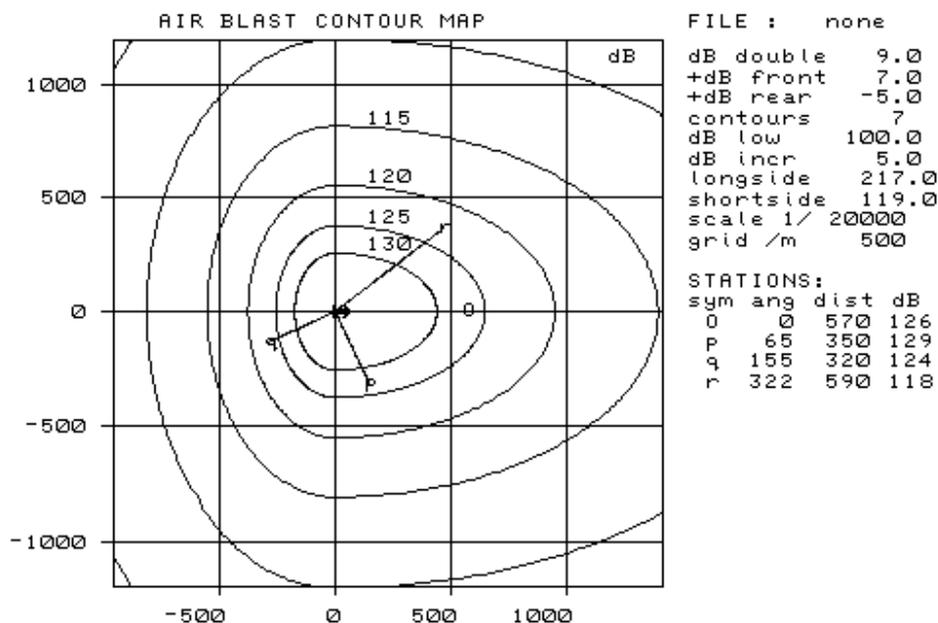
The air vibration readings may be used to produce an elliptical air vibration contour map. A typical example is shown in **Figures 7.8(a)** and **7.8(b)**. The shape of the ellipse is determined by:

- 9.0 decibel drop-off rate with distance doubling.
- Lengthening in front by the energy escaping from the front of the blast. An increase of 6 dBL to 12 dBL in front of the blast is the usual range.
- Shielding in front or behind squashes the ellipse.

The contour maps can be used to estimate the vibration level at any point around the blast.

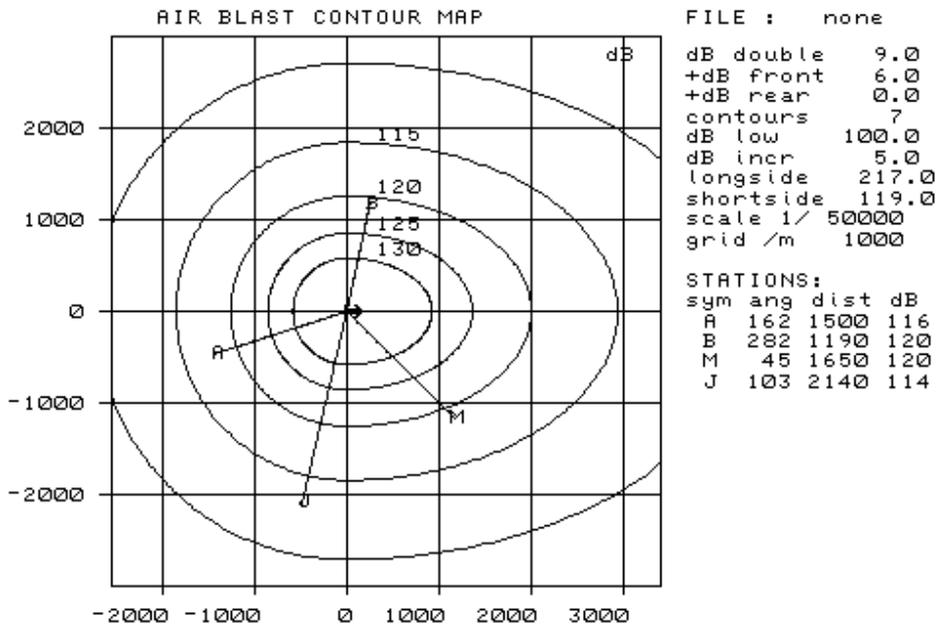
They also show the importance of face orientation in influencing the resultant level of airblast.

The airblast contour assessment techniques enables mines/quarry staff to improve their control of airblast problems and make improved use of face orientation to selectively control airblast in the surrounding area. Consideration of face orientation during mine planning and extraction sequencing may also be used to advantage.



ENVIB

Figure 7.8(a) – Air vibration contour map – granite quarry



ENVIB

Figure 7.8(b) – Air vibration contour map – coal overburden

### 7.3 EFFECTS OF ATMOSPHERIC CONDITIONS

When a blast is fired, the air vibration travels as a wavefront outwards from the blast at the speed of sound, equally in all directions as shown in **Figure 7.9**. The speed of the wavefront is then effected by wind (speed and direction) and by atmospheric temperature. The effect of wind and air temperature can be demonstrated if the wavefront is considered as a series of sound 'rays' radiating out from the blast, and perpendicular to the wavefront.

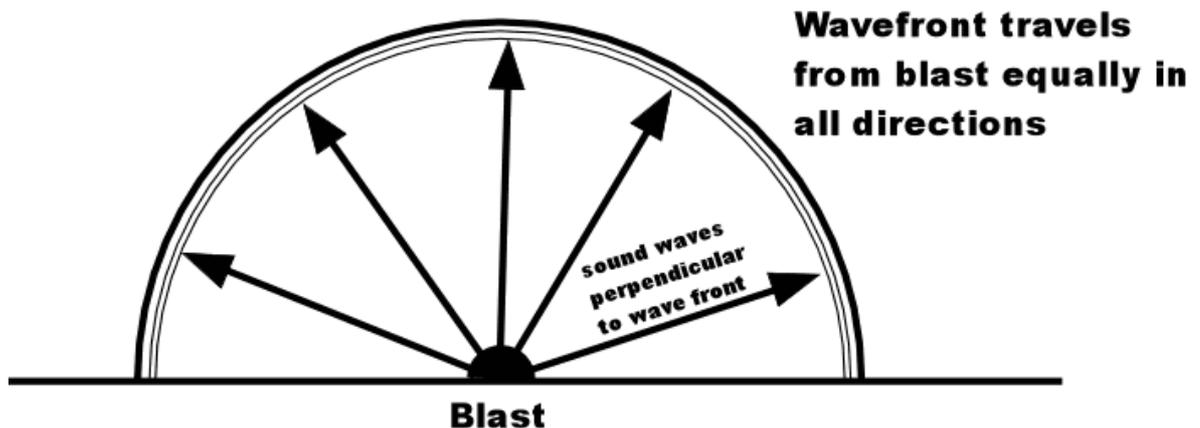


Figure 7.9 – Wavefront and sound rays from a blast with constant air temperature

A reinforcement situation occurs when the sound rays are deflected by wind or air temperature variation and are concentrated at the surface. This results in a higher air vibration level than that resulting from normal drop-off rate.

The effect of wind on the speed of sound is a directional increase downwind and corresponding decrease upwind. The effect of wind speed increasing with altitude on the sound rays is shown in **Figure 7.10**.

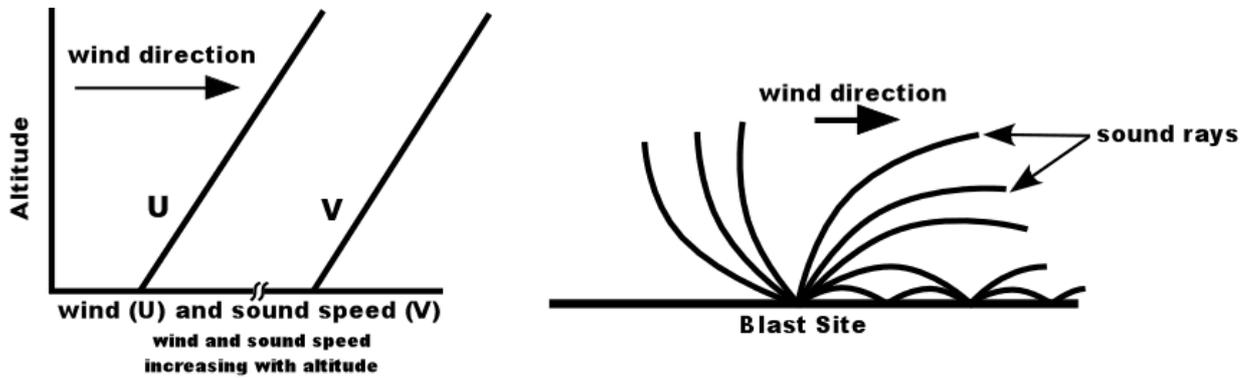


Figure 7.10 – Effect of wind (with speed increasing with altitude) on sound rays

Wind contributes to the magnitude and gives direction to the reinforcement in temperature inversion situations and can be a source of the reinforcement in a 'wind shear' situation where, at some altitude, there is a dramatic rise in wind speed and a direction change.

If there is no wind and the air temperature drops with increasing altitude, the sound rays curve upward as shown in **Figure 7.11**. This is the 'normal' atmosphere situation, with the temperature dropping at approximately 1 degree C per 100 metres and the speed of sound dropping accordingly. Normally, there is no reinforcement because there can be no concentration of rays at the surface.

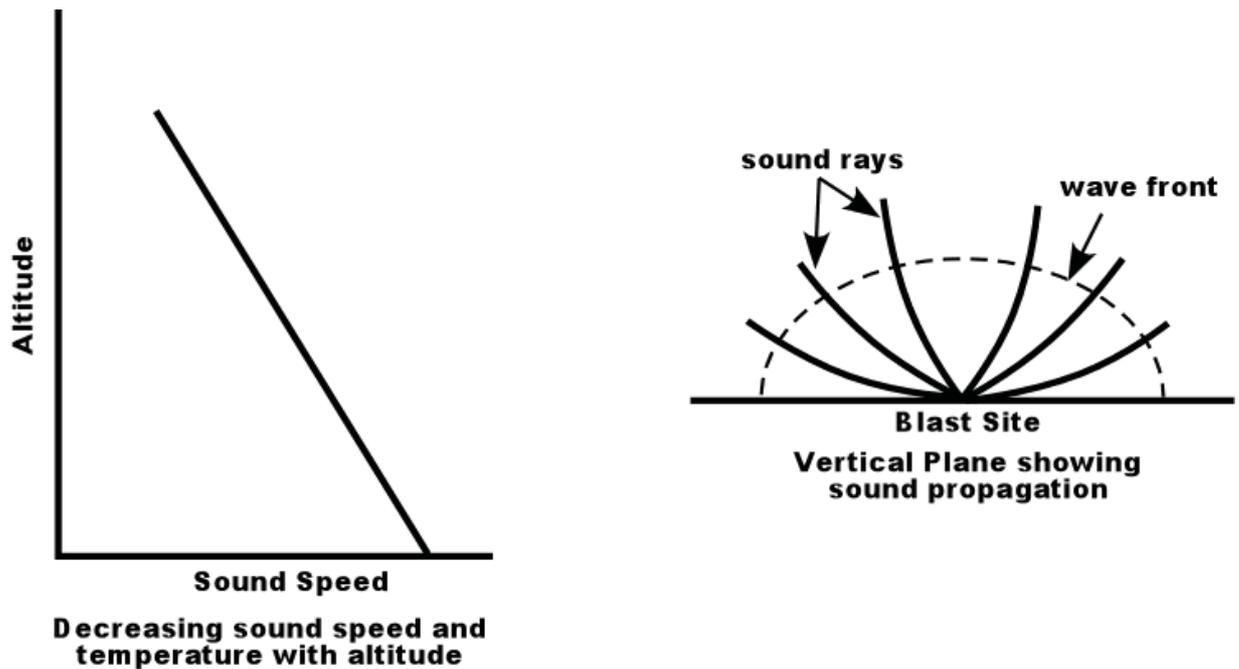


Figure 7.11 – Effect of temperature decreasing with altitude on sound rays

If there is no wind and the air temperature rises with increasing altitude, the sound rays curve downwards, as shown in **Figure 7.12**. In this situation, there is no reinforcement because the sound rays are not concentrated at the surface.

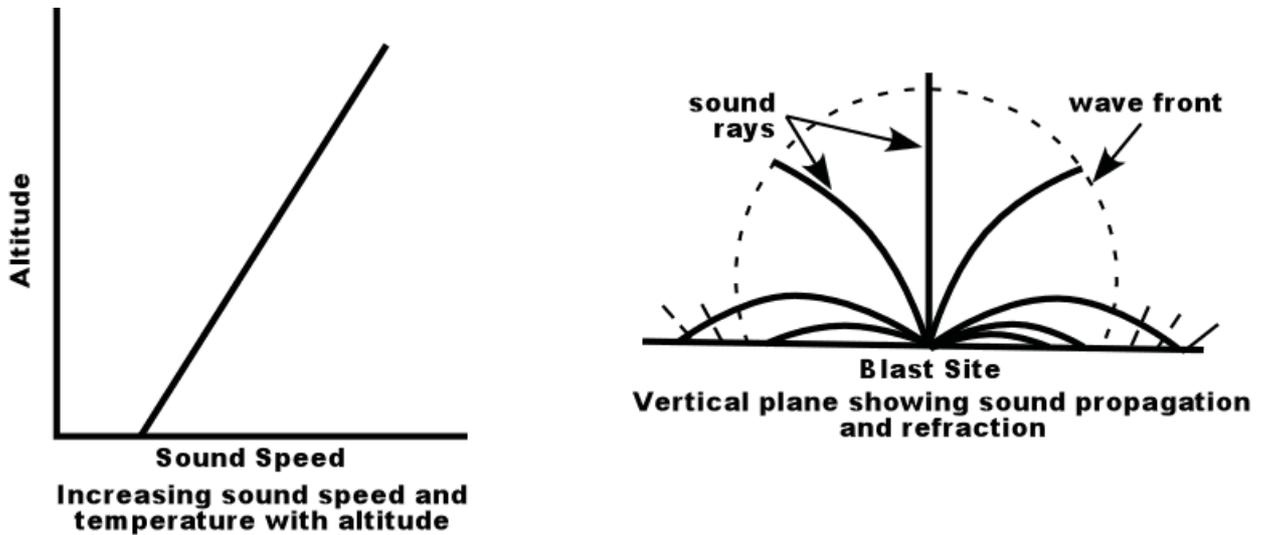


Figure 7.12 – Effect of temperature increasing with altitude on sound rays

The effect of a temperature 'inversion', or layer of warm air overlying cold air, is to bend the rays downward with increasing velocity. If the conditions are right, a reinforcement can occur at the surface by the concentrating of the sound rays. A typical example is shown in **Figure 7.13**.

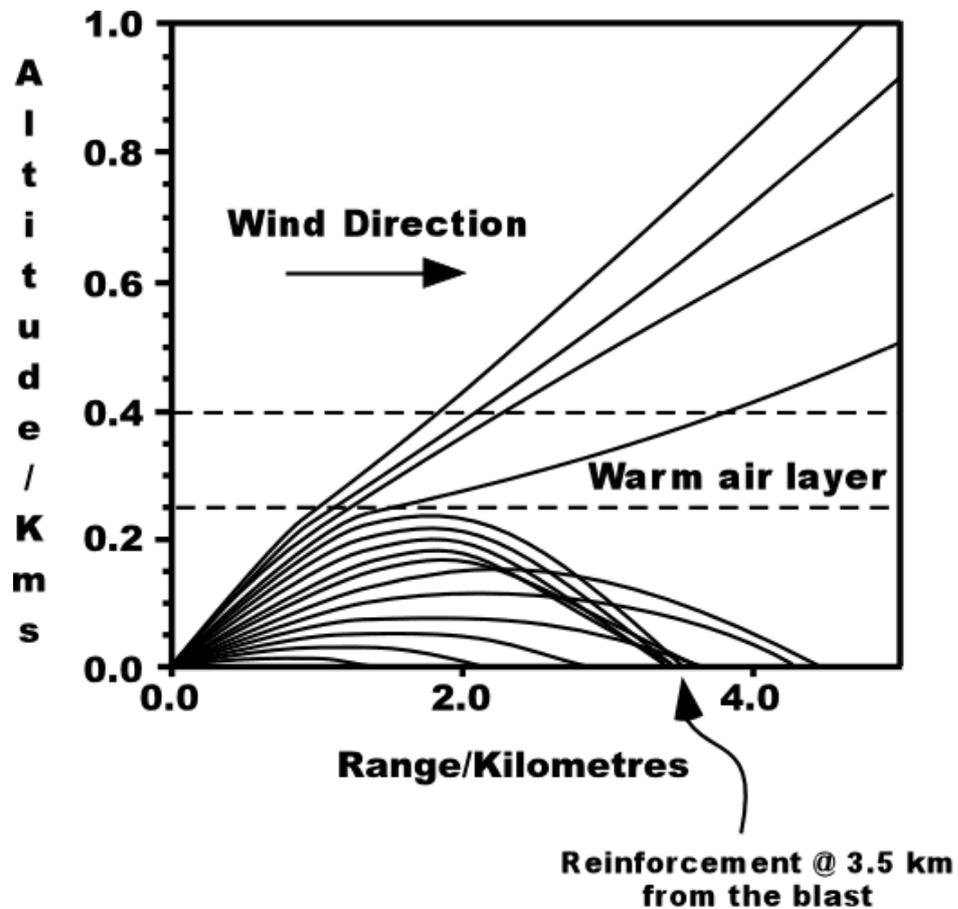
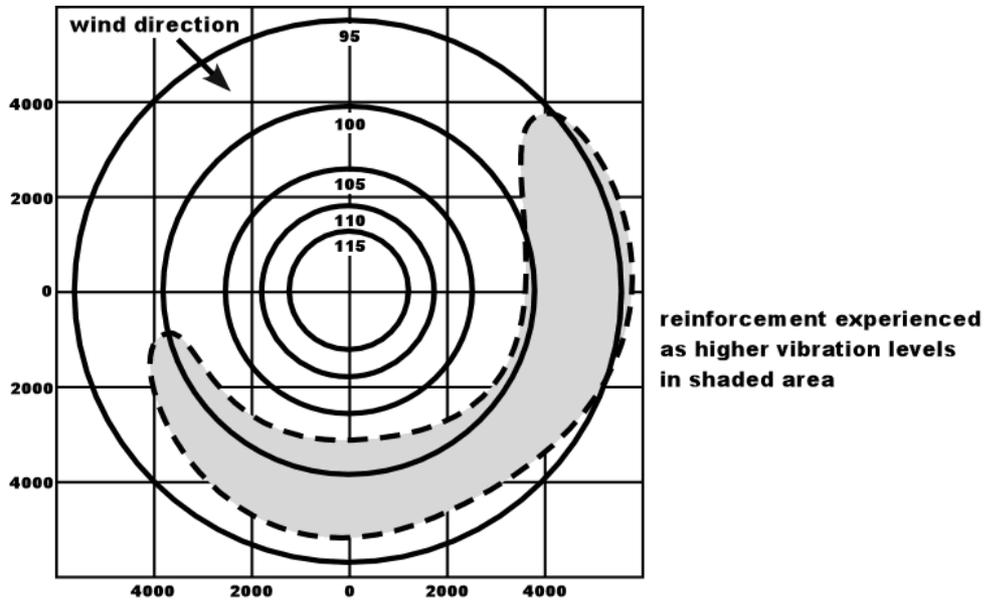


Figure 7.13 – Combined effect of wind and temperature inversion on sound rays causing surface reinforcement

The combined effect of an inversion and wind is to concentrate the surface reinforcement downwind from the blast. The plan demonstrating this reinforcement is shown in **Figure 7.14**. The shaded area indicates a strong reinforcement.



7.14 – Plan showing the directional effect of wind on meteorological reinforcement

Meteorological reinforcement usually occurs at distances greater than 2 km from the blast, and can result in complaints from people experiencing a higher level of vibration than they are used to receiving, but below any statutory limits. Without detailed meteorological data close to the blast site, it is impossible to predict if reinforcement will occur on a particular day. A computer program has been developed by Terrock Consulting Engineers, which is useful for explaining why reinforcement may have occurred, but the absence of detailed local data limits its application for prediction purposes.

The frequency of occurrence of temperature inversions is not known but, in our experience, only a small number of inversion-related complaints have been investigated and the increase in vibration level resulting from reinforcement can be up to 20 dBL, but is usually less.

## 7.4 WAVEFRONT REINFORCEMENT

When a single blasthole is fired, a vibration wavefront is created which spreads uniformly in all directions at the propagation speed (eg. approx. 340 m/s for sound waves). At any period after the blast, the wavefront will be at a radius from the hole, which is proportional to the time. This is illustrated in **Figure 7.15**.

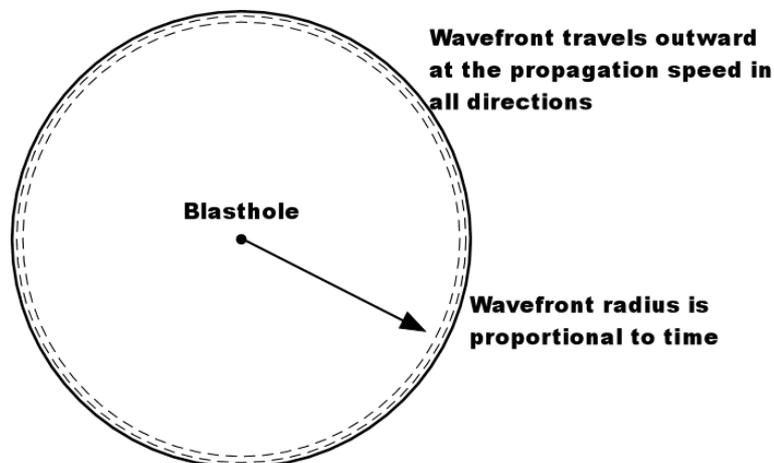
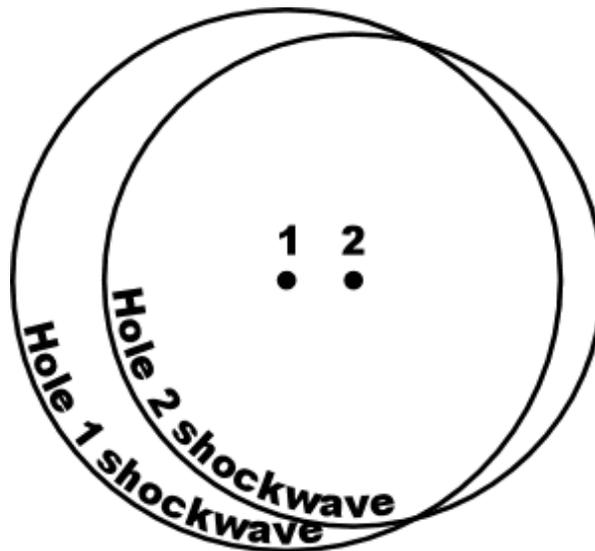


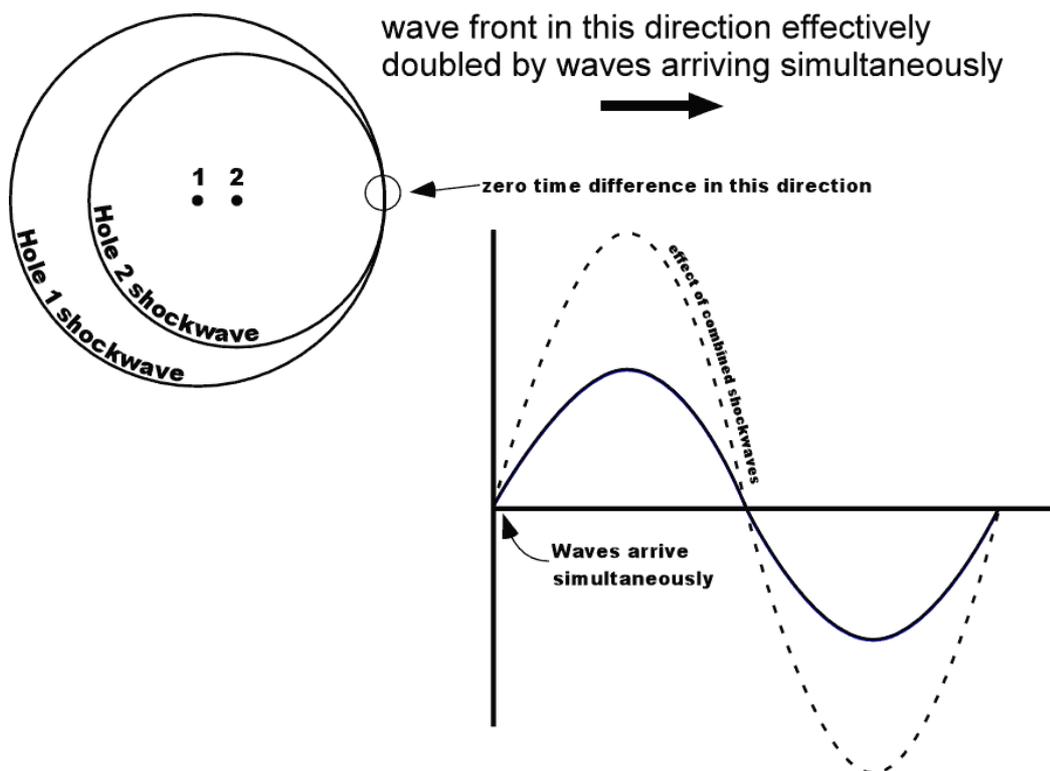
Figure 7.15 – Wavefront radiating from a blasthole

When two holes are fired with a time delay between them the wavefronts will be of different radius because of the time delay and different centres because they are physically separated. This is shown in **Figure 7.16**.



**Figure 7.16 – Wavefronts from two holes with a time delay between initiation**

Under certain circumstances, when the distance between holes and the time delay period coincides with the travel time of the wavefront between holes, the wavefronts will coincide in one direction. This is shown in **Figure 7.17**.



**Figure 7.17 – Reinforcing wavefronts from two holes with a time delay between initiation**

This is the simplest case of wavefront reinforcement, where the two waves reinforce each other and lead to an increase in vibration experienced in the direction of initiation.

### 7.4.1 Simple Air Vibration Reinforcement

An example of the simple reinforcement described above is provided by the analysis of air vibration resulting from a blast pattern with 9 metre spacing, 8 metre burden, 25 ms spacing delay and 100 ms burden delay. In the example shown below, 4 rows of 4 holes have been designed to initiate in delayed sequence with a 25 ms interval between each blasthole. When the shot is fired, strong airblast reinforcement occurs in one direction, as shown in the following wavefront diagram (Figure 7.18).

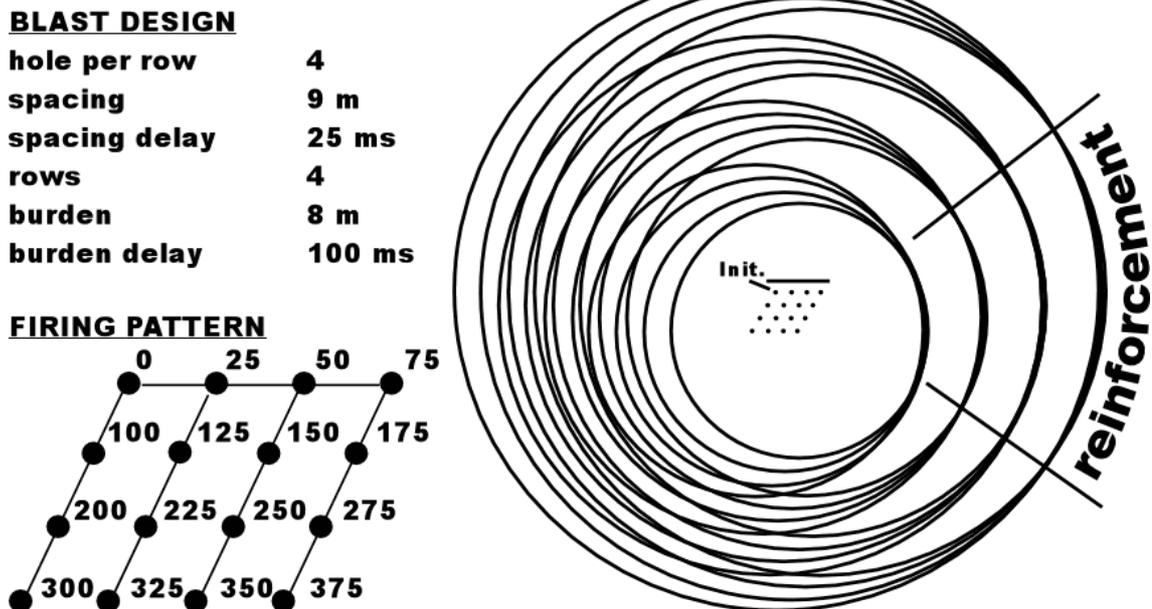


Figure 7.18 – Wavefront diagram from a blast with strong directional reinforcement

Air vibration levels in the area of strong directional wavefront reinforcement were increased by up to 20 dB. The wavefront reinforcement shown in Figure 7.18 was avoided by changing the spacing delay from 25 ms to 42 ms, as shown in Figure 7.19.

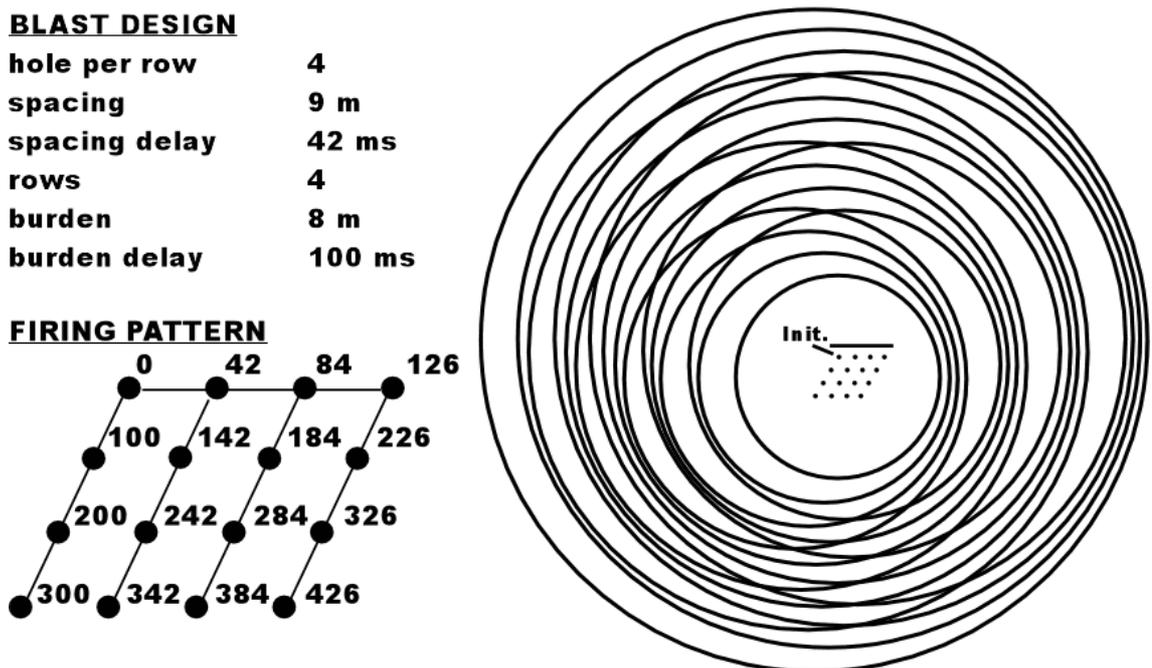


Figure 7.19 – Wavefront diagram for a blast without strong directional reinforcement

## 7.4.2 More Complex Reinforcement

When the 9 metre spacing x 8 metre burden blast pattern, described above, with a 100 ms burden delay has the spacing delay changed to 17 ms, reinforcement occurs in two directions at an angle of approximately 45° from the direction of initiation, as shown in **Figure 7.20**, and also in the opposite direction.

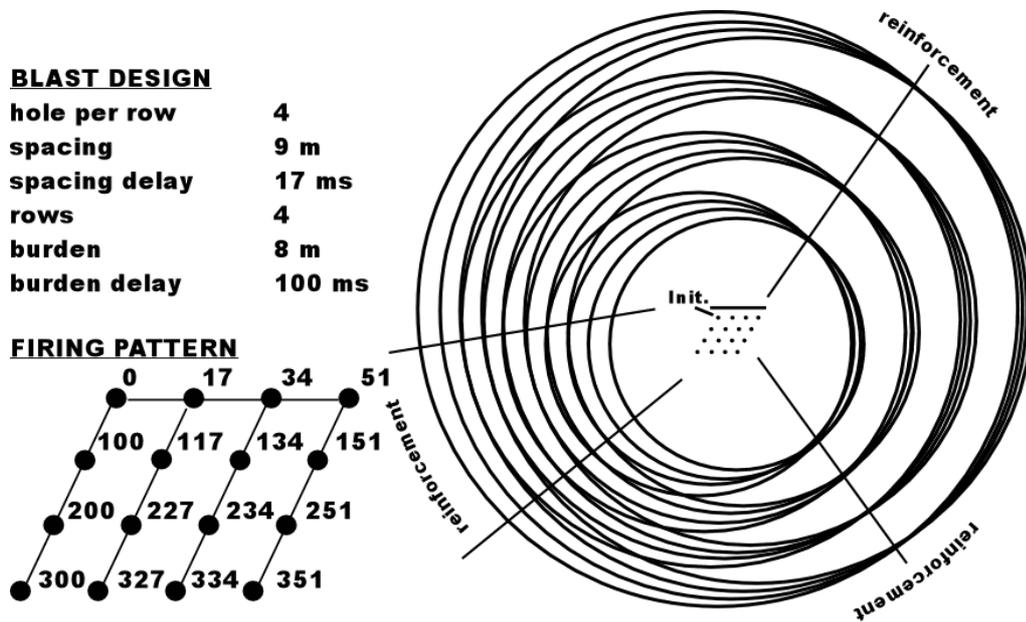


Figure 7.20 – More complex reinforcement

Air vibration levels in the two directions of wavefront reinforcement, at 45° from the direction of initiation, have shown increases in the range 5 dBL to 20 dBL, depending on the number of blastholes involved.

## 7.4.3 Pre-splitting

An example of wavefront reinforcement, for both air and ground vibration, is given by the following example of a pre-split blast. Wavefronts combine in a direction at right angles from the pre-split line to increase vibration levels, compared with that resulting in the direction of the pre-split line.

The wavefront diagram for the airblast is shown in **Figure 7.21**. The ground vibration wavefront diagram is similar in appearance.

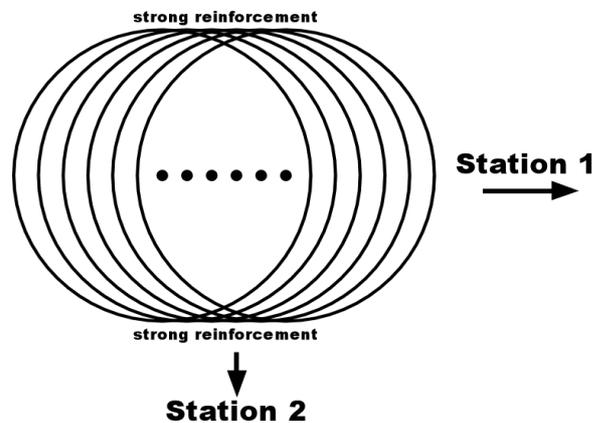


Figure 7.21 – Wavefront diagram for a pre-split

The measurements obtained during a pre-split blast at an open pit coal mine are shown in **Table 7.1**. The pre-split consisted of 35 holes, 311 mm diameter, 5.0 metre spacing, 200 kg per hole fired ‘instantaneously’ with 5 g/m detonating cord.

**Table 7.1 - Measurements obtained during a pre-split blast at an open pit coal mine**

	Distance	Air Vibration	Ground Vibration
Station 1	400 metres in line with pre-split holes	113.6 dBL	27.0 mm/s
Station 2	670 metres perpendicular to pre-split holes	121.6 dBL	35.7 mm/s
Adjusting the reading from Station 2 to 400 metres equivalent distance, using site exponents, gives the following adjusted measurements:			
Station 2	400 metres	128.0 dBL	83.0 mm/s
Difference:		1.4 dBL	56.0 mm/s
Directional magnification:		x 5.2	x 3.1

In this case, because of wavefront reinforcement, the air vibration has been magnified in the order of 5 times (14 dBL increase) and the ground vibration in the order of 3 times (56 mm/s increase).

#### 7.4.4 Ground Vibration Reinforcement

Wavefront reinforcement of ground vibration depends on the rock structure as well as the drilling and delay pattern. Shear wave reinforcement has been observed in sub-horizontal sediments overlaying coal seams when a blasthole spacing of 11 metres was combined with a small spacing delay of 9 ms.

Site conditions for Rayleigh (surface) wavefront reinforcement identified to date are horizontal basalt flows overlaying clay seams, and sub-horizontal sediments overlaying coal seams.

An example of Rayleigh wavefront reinforcement was identified at a metropolitan basalt quarry, where blasting operations were being carried out within 70 metres of houses. Blast vibration complaints were being received on a regular basis from residents located as far as 1 km from the blast site and, hence, a thorough blast vibration investigation was carried out.

The ground vibration levels (Peak Particle Velocity) recorded appeared unrelated to charge mass and similar high levels were being recorded, even though the charge mass per delay was reduced from 30 kg to 10 kg and charges were decked.

Detailed examination of blast vibration wavetraces and wavefront diagrams showed a relationship between Rayleigh wavefront reinforcement and the magnitude of resultant vibration waves, as illustrated below.

#### 7.4.5 Directional Wavefront Reinforcement

One drilling and delay pattern associated with complaints used a 2.2 metre spacing, 2.2 metre burden, 25 ms spacing delay, and 42 ms burden delay. The Rayleigh wavefront diagram for this pattern (**Figures 7.22**) shows a strong directional reinforcement that increases ground vibration levels at a certain direction. When the 25 ms spacing delay was changed to 17 ms, the wavefront diagram (**Figure 7.23**) showed that strong reinforcement resulted in a different direction.

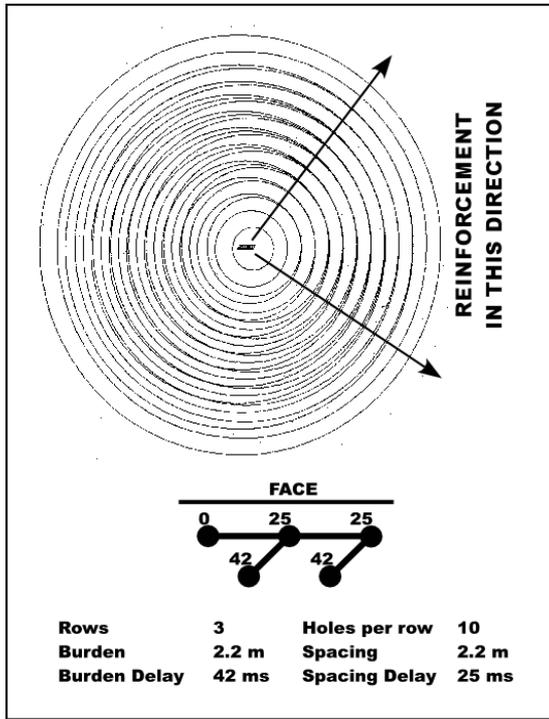


Figure 7.22 – Wavefront diagram with strong directional Rayleigh wave reinforcement

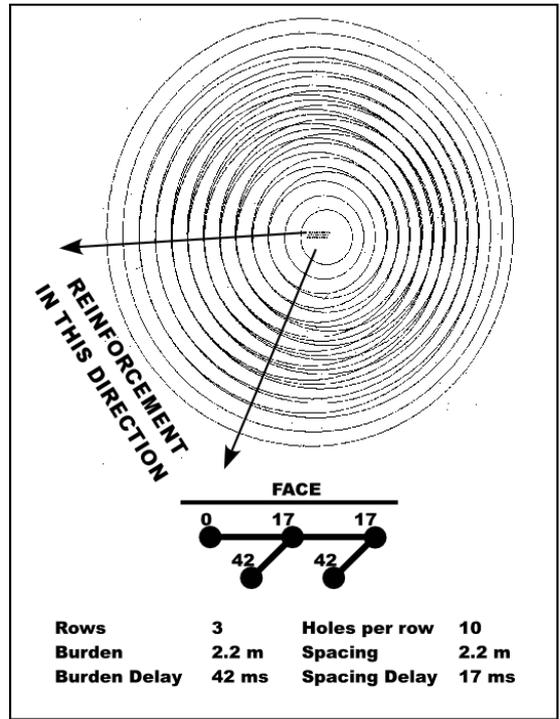


Figure 7.23 – Wavefront diagram with strong directional Rayleigh wave reinforcement (2)

An example of vibration waves resulting at a distance of 60m/s from the blast in a direction of strong reinforcement is shown in **Figure 7.24**. Relevant details for this blast were - 2.2 metre spacing, 2.2 metre burden, 25 ms spacing delay, and 42 ms burden delay.

Examination of the wavetraces from a monitoring station in the reinforcement direction showed a build-up of Rayleigh waves with the peak value occurring at a time that corresponded with Rayleigh wavefront reinforcement.

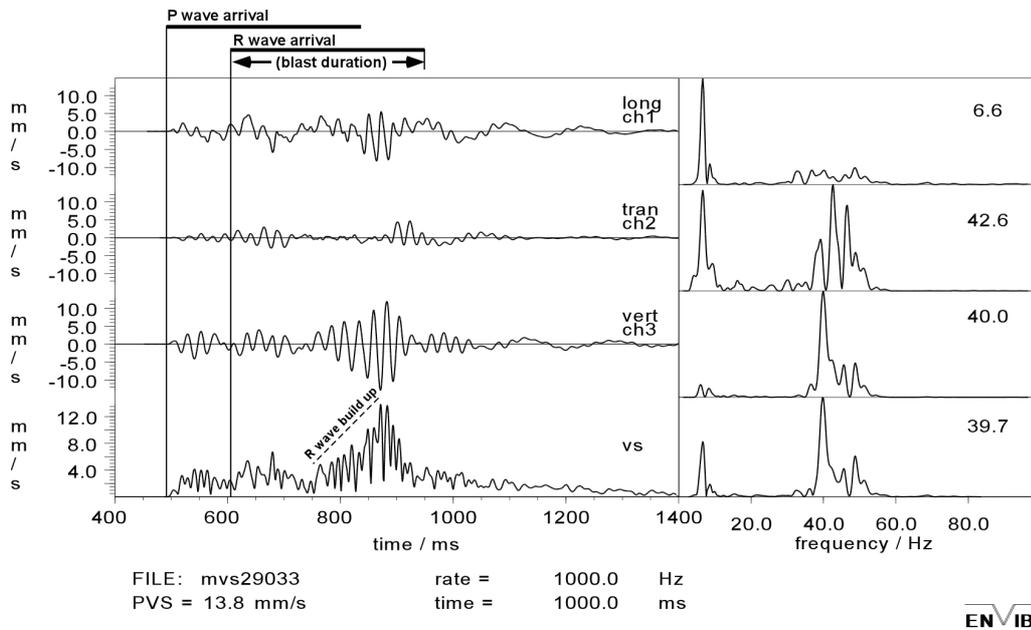


Figure 7.24 – Wavetrace for a monitoring station 60 metres from the blast site showing Rayleigh wave build-up

An increase in vibration of approximately 3 times the magnitude (that would have resulted without wavefront reinforcement) was observed to occur in this situation.

Control of vibration levels to the statutory limit of 10 mm/s could not be achieved in all directions by a simple substitution of 17, 25 and 42 ms delays. A pattern that was successful in preventing wavefront reinforcement and reducing ground vibration levels in all directions for a 2.2 metre x 2.2 metre pattern was to use spacing delays of 25 ms between two holes and then joining two 17 ms delays to give a 34 ms delay to the third hole. The 25 ms x 25 ms x 34 ms pattern was then repeated for the full front control row. The 42 ms burden delay was retained.

The detonation times for each hole, when using the non-reinforcing pattern, are shown in **Figure 7.25**.

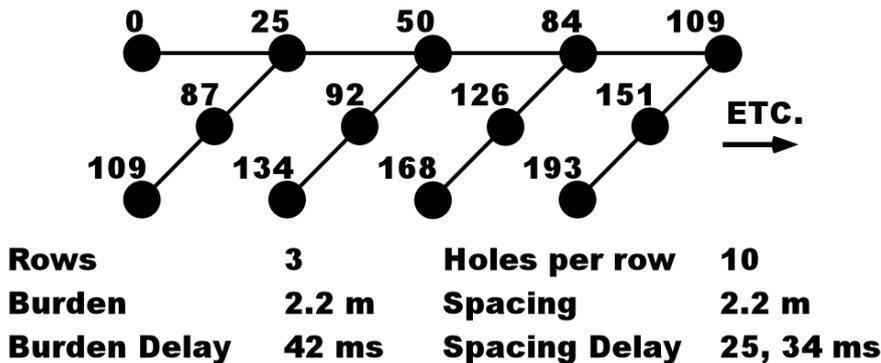


Figure 7.25 – Detonation times for non-reinforcing pattern

The Rayleigh wavefront diagram for this non-reinforcing pattern and the wavetrace for a station without Rayleigh wave reinforcement are shown in **Figures 7.26** and **7.27**, respectively.

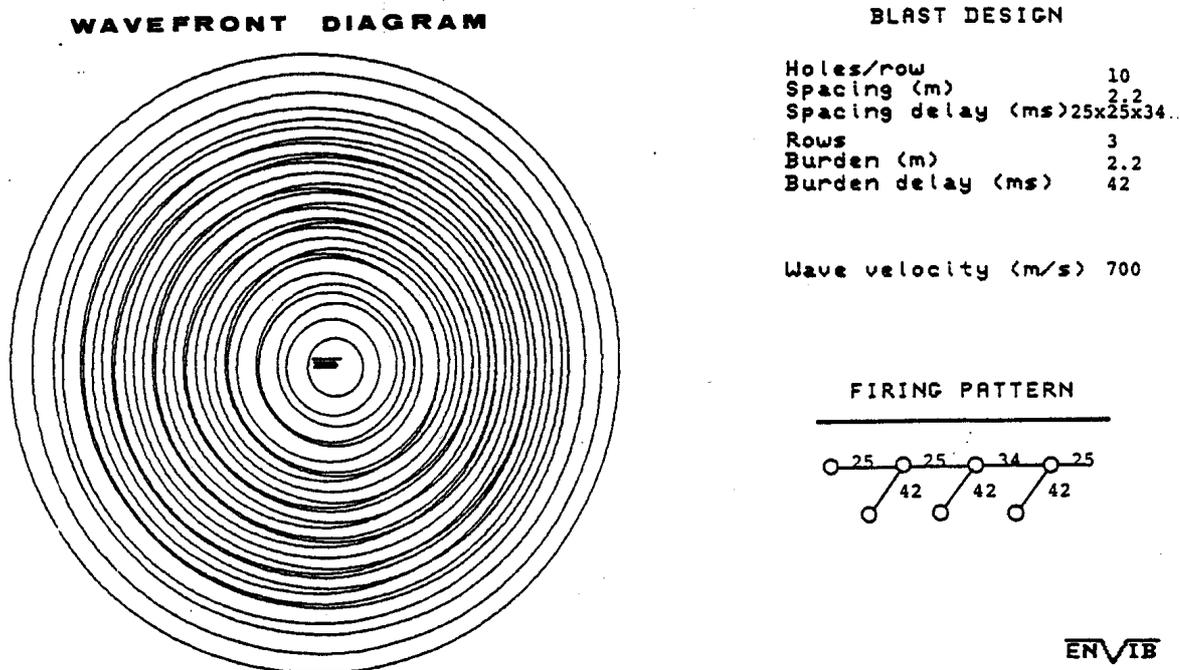


Figure 7.26 – Rayleigh wavefront diagram for a non-reinforcing pattern

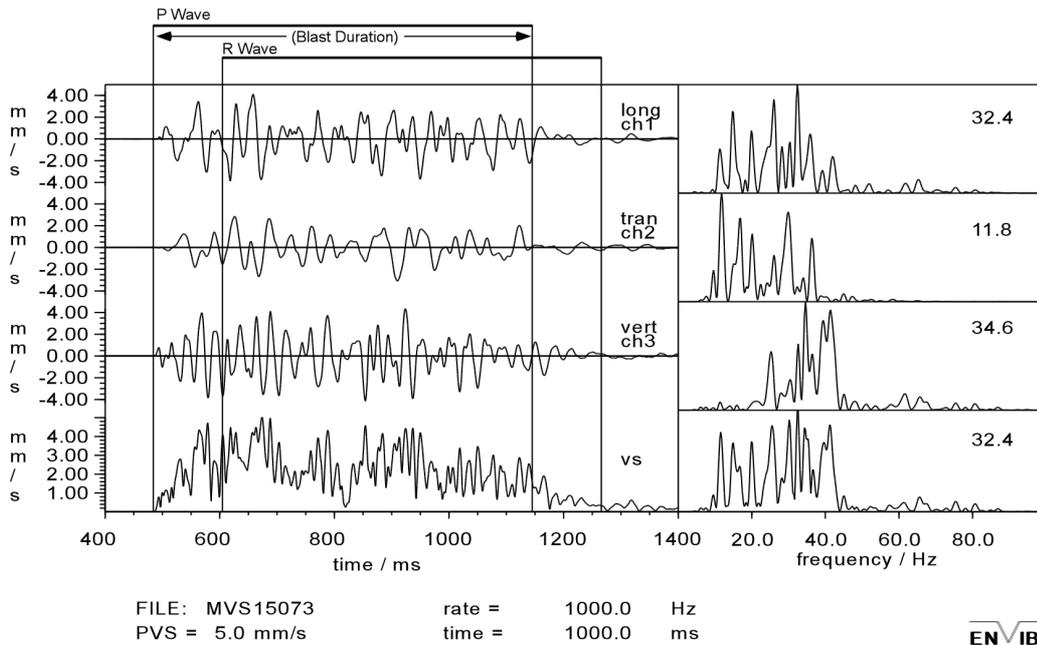


Figure 7.27 – Wavetrace for a monitoring station without Rayleigh wave reinforcement

The successful application of non-reinforcing patterns at the quarry has ensured that blast vibration levels stay below statutory limits, and has permitted an increase in drilling pattern and charge mass per delay, with a consequent reduction in blasting costs.

#### 7.4.6 Another Example of Rayleigh Wave Build-up

The wavetrace taken at a complainant's house, at a distance of 830 metres from the blast site, located in a strong reinforcement direction, is shown in Figure 7.28. The elapsed time of the delay sequence was approximately 200 ms.

The P and S waves have decayed to below background levels and only the R wave exists. The almost pure 7 Hz frequency is a sub-harmonic of the constant arrival times of the reinforced wavefronts.

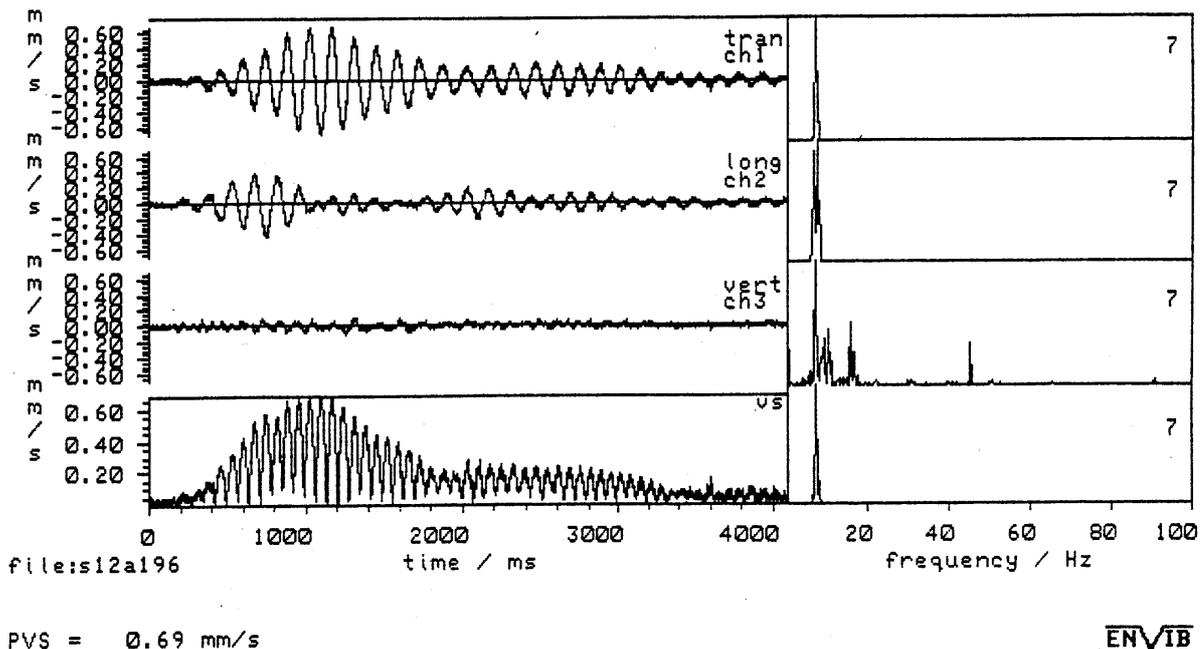


Figure 7.28 – Wavetrace for a monitoring station 830 metres from the blast site showing Rayleigh waves

## 7.4.7 Conclusion

Wavefront reinforcement from blastholes fired in a blasting pattern can combine in certain circumstances to give increased vibration levels in certain directions. The wavefront reinforcement model described identifies if wavefront reinforcement occurs and permits delay patterns to be designed, which will avoid or reduce wavefront reinforcement.

## 7.5 SEED WAVE ANALYSIS

Seed waveform analysis evolved in an attempt to quantify the effect of wavefront reinforcement, especially when the wavefronts are not exactly coincident. This analysis involves taking the waveform from a single blast hole and then combining them in a computer to correspond with the arrival times of the wavefront analysis.

## 7.6 AIR VIBRATION

The waveform of the pressure from a single blast hole, in a perfect atmosphere is an 'N' wave, as shown in **Figure 7.29**. Our experience is that the positive pulse in the peak pressure value, but the negative pulse lasts longer. In the real atmosphere, with wind etc, the n wave shape varies.

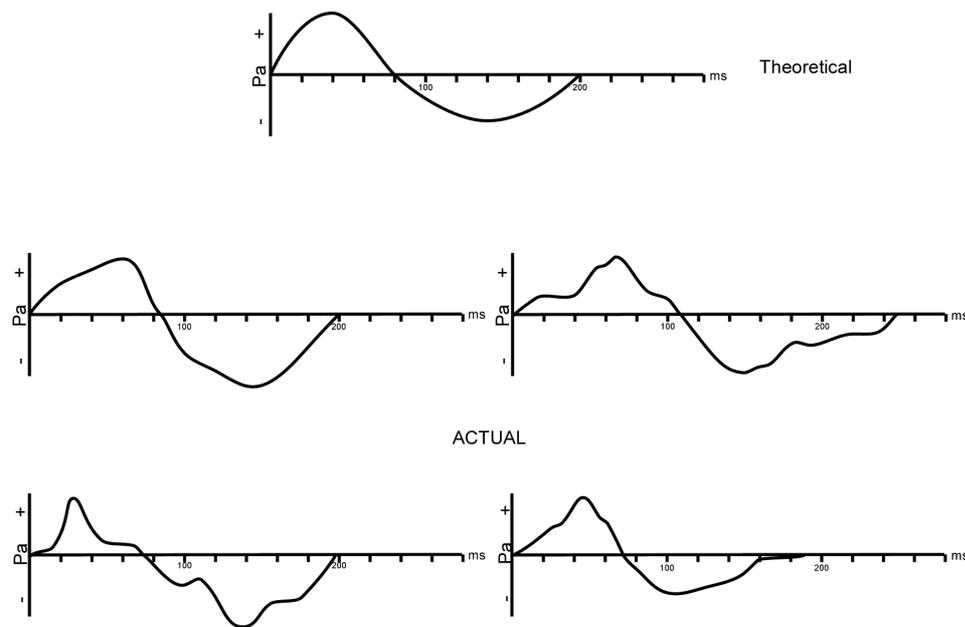


Figure 7.29 – The 'N' wave

There appears to be a relationship between the duration of the positive peak and the distance and charge mass. With distance, the amplitude of the peak reduces, but the duration increases. The 7 dBL to 9 dBL drop off with doubling of distance rule applies.

The analysis is conducted as follows:

- The air vibration wavefront analysis is conducted for the front row of a blast. The distance apart of the wave fronts in the direction of interest is either scaled or calculated and converted to milliseconds assuming a velocity of sound in air of 340 m/s. The air vibration from later rows does not contribute to the peak airblast, except if the stemming fails due to poor materials or insufficient length.

- An actual seed waveform is then taken from file or a synthetic air vibration seed wave (single hole) is created and then a number are combined at the time interval between. This is demonstrated in **Figures 7.30 to 7.32**.

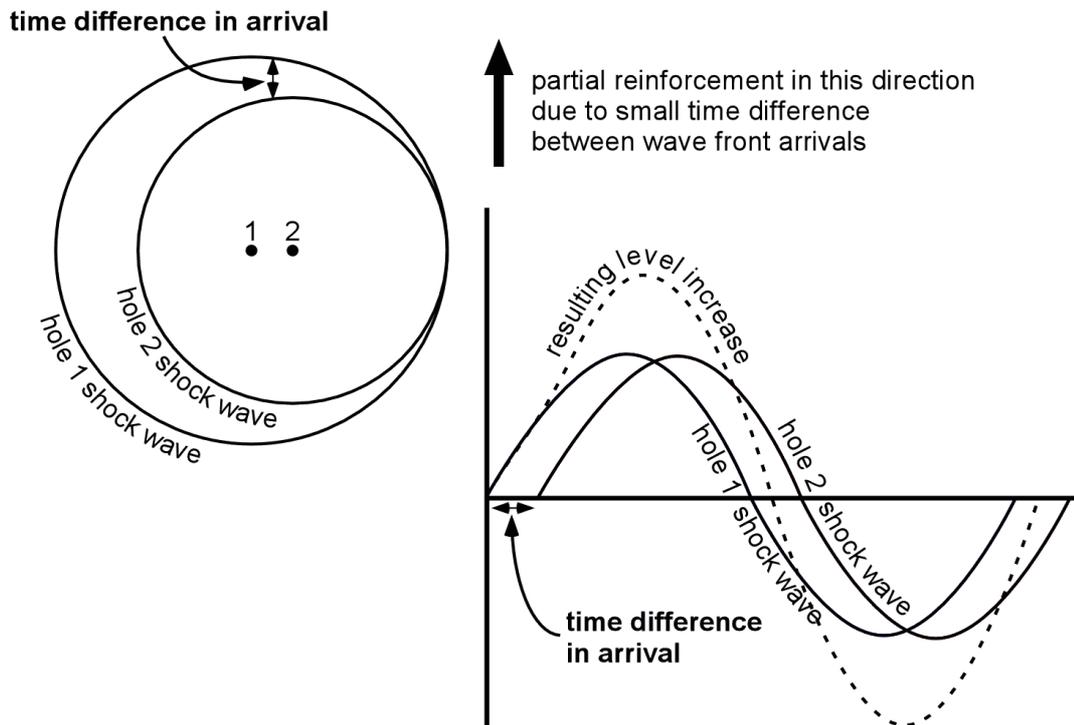


Figure 7.30

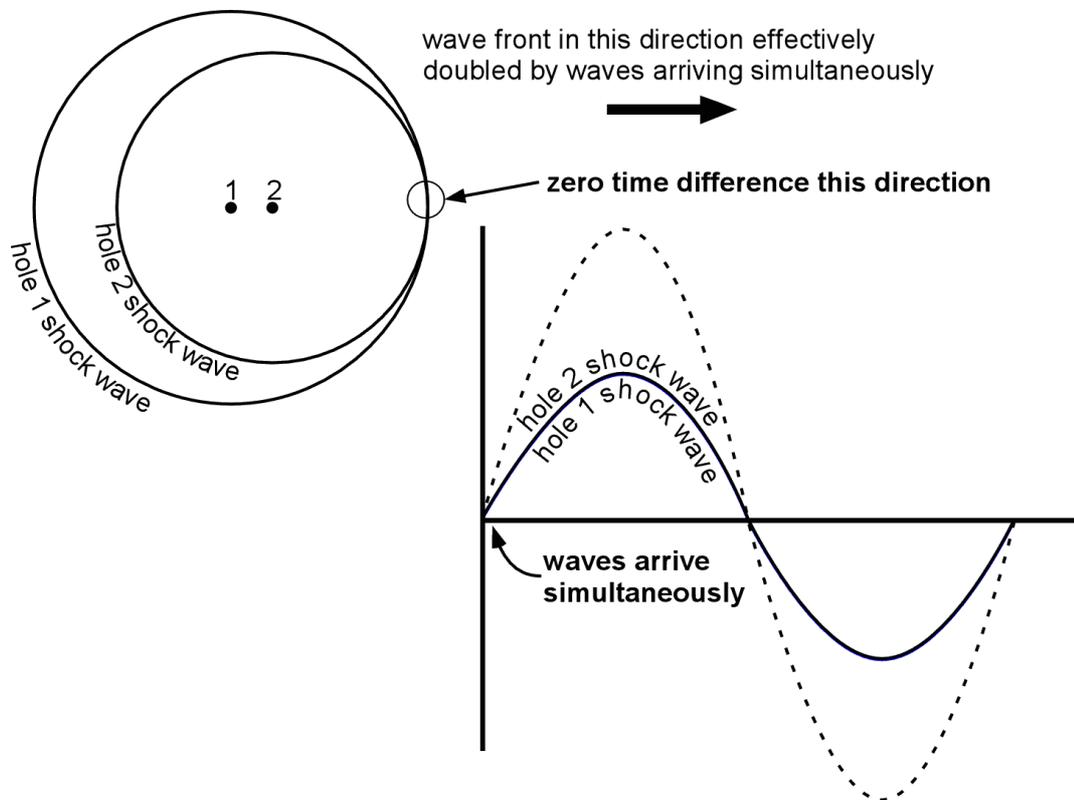


Figure 7.31

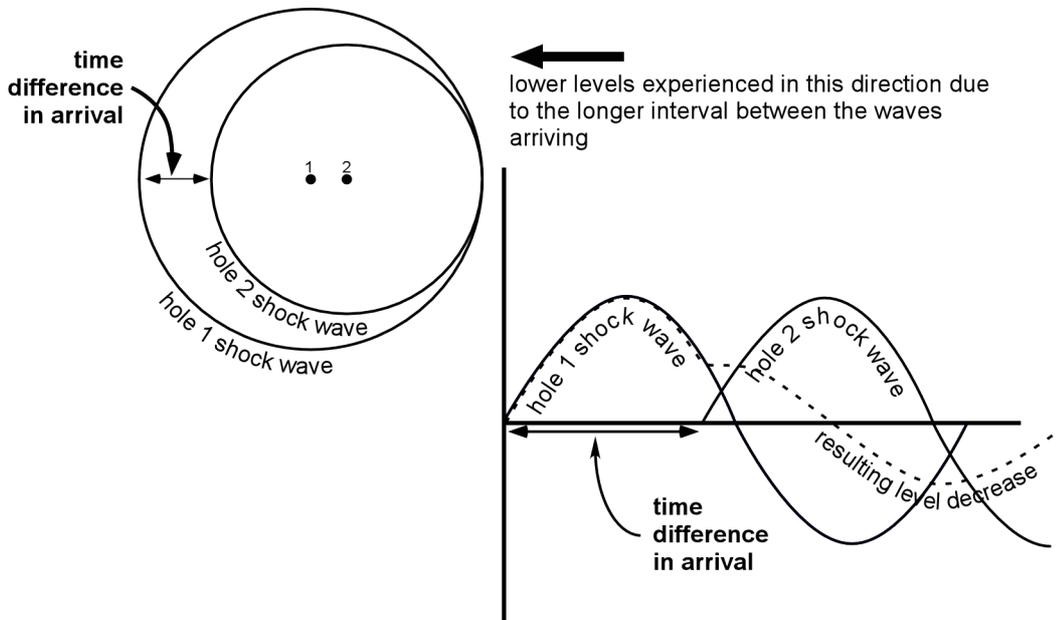


Figure 7.32

- The increase in Pa for the combined wave over the single wave is converted to a decibel increase. Calibration to date indicates that the actual increases are about half the increases indicated by the model.

## 7.7 TOPOGRAPHICAL SHIELDING

In hilly terrain or deep excavations, air vibration levels resulting in the surrounding area are reduced by secondary shielding and back-shielding.

Secondary shielding occurs to the front (and side) of blasts. The amount of secondary shielding depends on the effective barrier height and the incident angle between the blast and the monitoring station. The terms are illustrated in **Figure 7.33**.

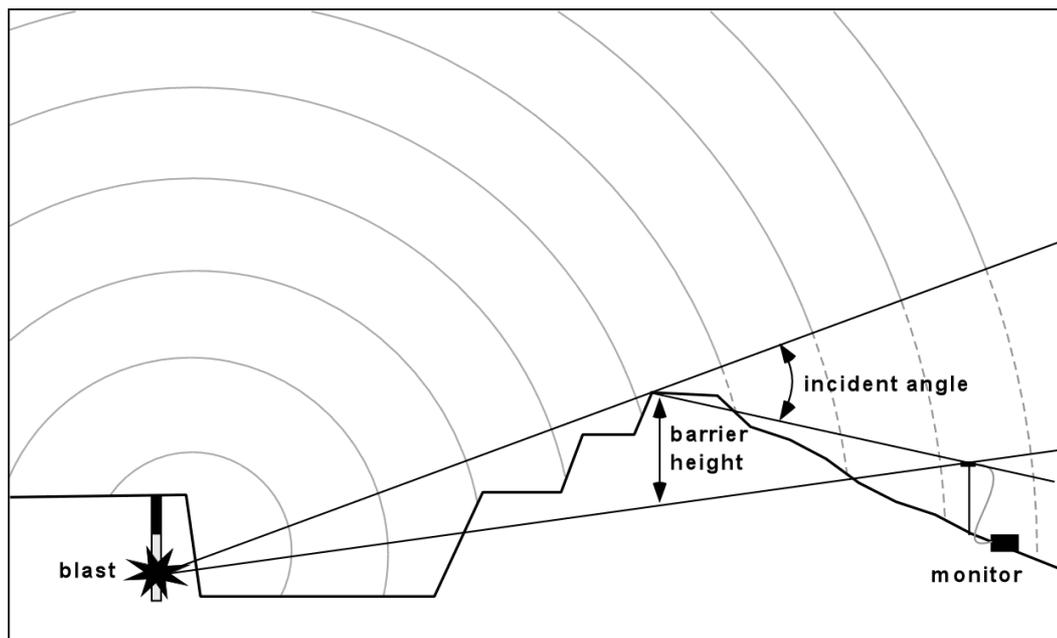


Figure 7.33 – Shielding terminology

The amount of secondary shielding can be estimated from **Figure 7.34**. Secondary shielding is not experienced in shallow deposits in flat terrain because the incident angles are low.



Figure 7.34 – Estimation graph for secondary shielding

The effect of secondary shielding on air vibration contours is shown in **Figure 7.35**.

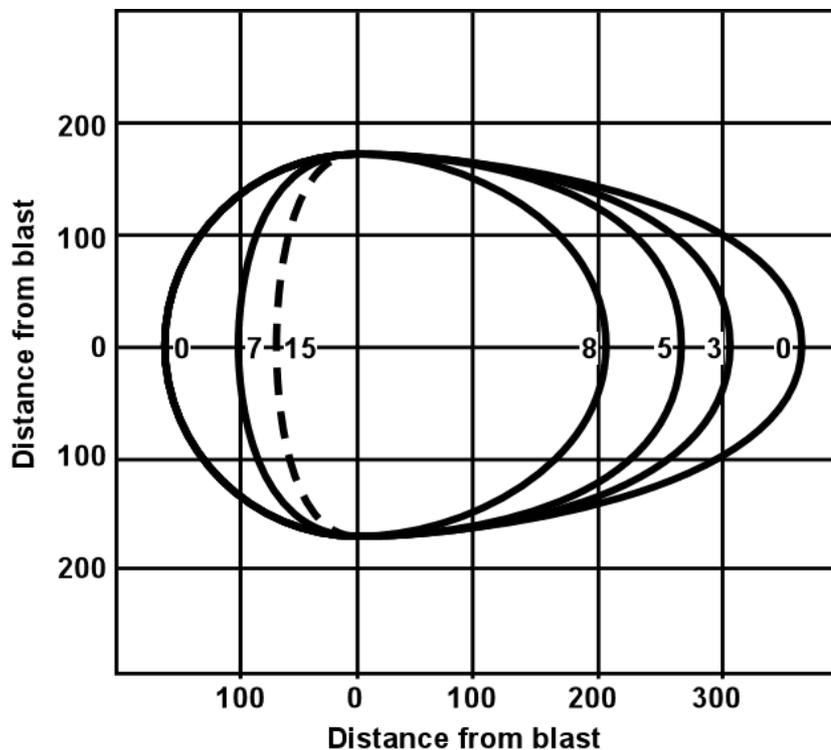


Figure 7.35 – The effect of shielding on elliptical contours

An additional shielding is experienced behind faces when firing to a free face and the stemming is adequate to prevent stemming ejection or cratering. In this case, the degree of back-shielding can be estimated from **Figure 7.35** to  $\pm 2$  dBL. The effect of back-shielding on air vibration contours is shown in **Figure 7.36**.

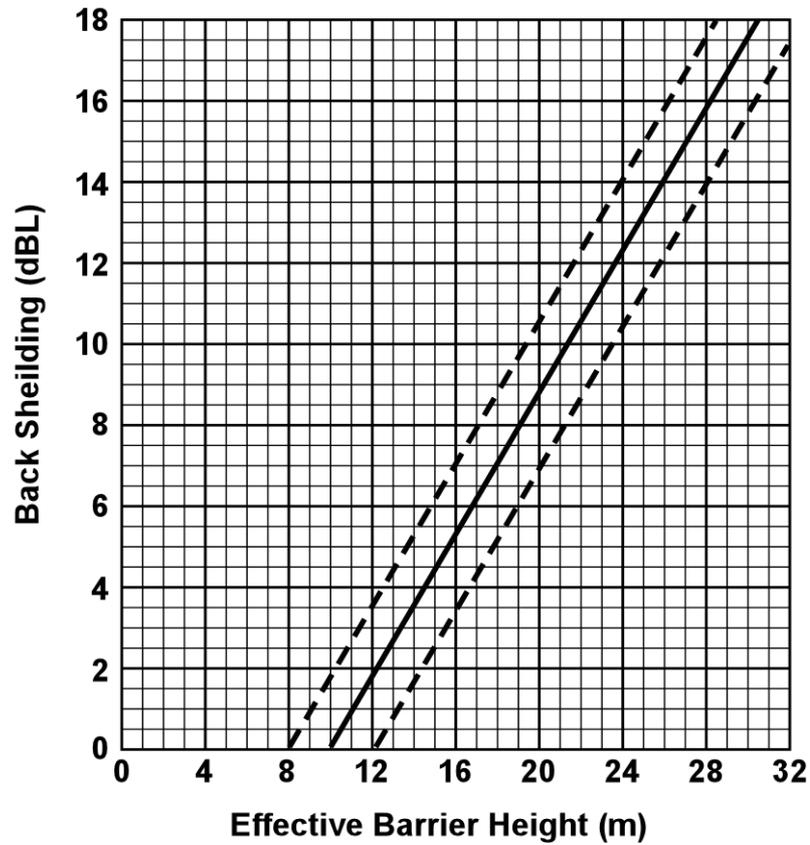


Figure 7.36 – Estimation graph for back-shielding

## **CHAPTER 8 - BLAST VIBRATION CONTROL**

Blast vibration can be controlled by an understanding of the causes of high vibration levels, careful attention to detail and the application of correct techniques. The following points are emphasised:

### **8.1 PERSONNEL**

The shotfiring crew can have a considerable influence on blast vibration levels. All persons responsible for blasting should be suitably qualified and experienced, be aware of the need for controlling blast vibrations and aware of the consequence of their actions. Poor control and sloppy work practices during loading can cause dramatic increases in vibration levels.

### **8.2 PERMISSIBLE VIBRATION LEVELS**

Be aware of permissible vibration levels for the particular operation. Develop blasting techniques that keep vibration below permissible levels.

### **8.3 ESTIMATION OF VIBRATION LEVELS**

Blast vibration levels can be estimated by appropriate scaled distance formulae (Site Law). Be aware that these are only estimates that can have considerable error because of different ground conditions between sites. Site Law for each site should be determined by monitoring blasts and predictions made from that determined. The Site Law should be upgraded and modified as additional measurements are taken.

### **8.4 BLASTHOLE ACCURACY**

The burden of blastholes can have a significant influence on vibration levels. Too much burden may increase ground vibration levels, too little burden in front row holes may result in flyrock and will increase air vibration levels. The object of marking out and drilling should be to have holes drilled with the correct burden (within an acceptable range, but not less than the design) at the correct inclination and orientation, to the correct depth with minimum deviation.

To mark out and drill the holes it is necessary to survey the face. This may be done with basic low-tech methods, such as tape and fishing pole, clinometer, etc. Laser theodolites are being used increasingly to provide an accurate profile for the design of blastholes, but this method does have limitations. The more irregular the face, the more effort is needed in surveying and design during marking out.

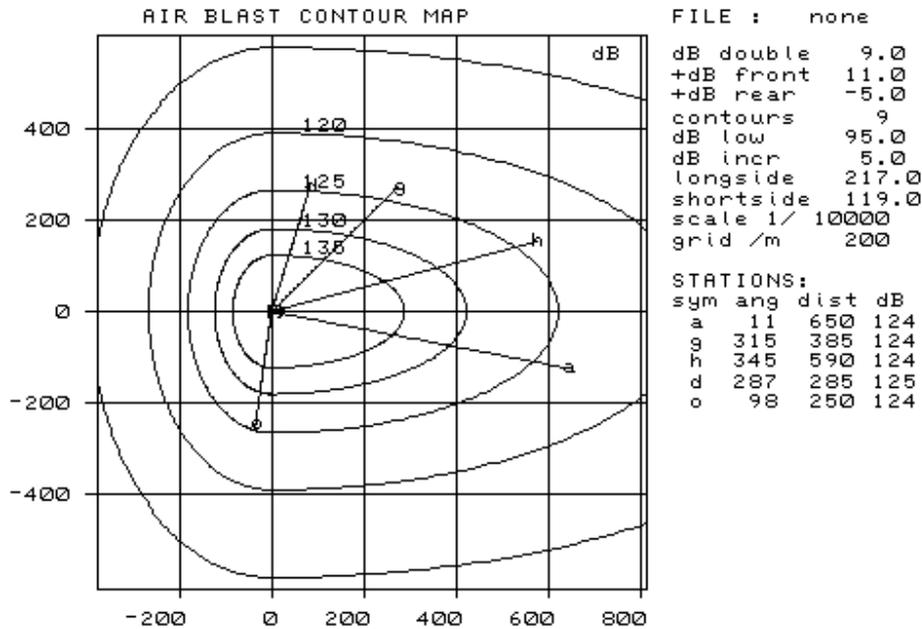
Deviation in the drillhole can be checked by lowering a torch lens up and down the hole on a string line (if dray). Boretracking (in conjunction with laser profiling) provides accurate profiles of the burden in front of each hole and is proving a useful tool in the control of air vibration.

The hole depths should be checked with a tape and recorded. If possible, collapsed or short holes should be re-drilled before charging commences.

## 8.5 EFFECT OF FRONT ROW BURDEN

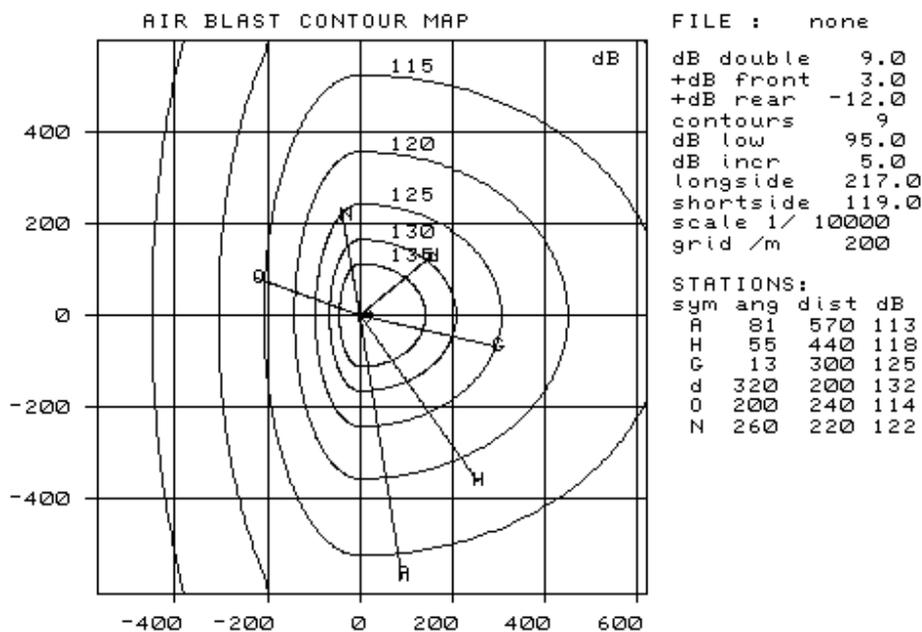
The effect of front row burden reduction is demonstrated in **Figures 8.1(a) and 81(b)**.

The blast contoured in **Figure 8.1(a)** had a minimum burden of 2.8 metres. The blast contoured in **Figure 8.1(b)** had a minimum burden of 3.6 metres. Both were 89 mm diameter holes. The 0.8 metre difference in burden equated to about 10 dBL increase in air vibration to the area in front of the blast.



ENVIB

Figure 8.1(a) – Air vibration contours showing the effect of 2.8 metre burden.



ENVIB

Figure 8.1(b) – Air vibration contours showing the effect of 3.6 metre burden reduction.

## **8.6 CHARGE MASS**

Charge mass is one of the variables in the scaled distance formula for prediction of ground vibration and airblast (as MIC or maximum instantaneous charge).

The designed charge mass should be based on the hole diameter, explosive density and column height. This is the amount that should be placed in each hole. Additional charge to 'top up' holes to designed column height should be added with caution to front row holes.

Reduction of charge mass can be shown to reduce vibration levels in the scaled distance formulae. Because it is the cube root (air) or square root (ground) of the charge mass in the formula, substantial charge mass reduction must be made to reduce vibration levels. Decking the charge is one technique to effect a charge mass reduction.

Other techniques may be more effective in vibration reduction and should be tried first, eg. more front row burden to reduce air vibration.

Substantial reductions in charge mass without decking, can usually only be achieved by totally altering the blast geometry, eg. using a smaller diameter blasthole that will reduce burden, spacing and stemming height. However, the smaller burden may actually increase air vibration levels.

In critical close order construction blasting, the small charge masses may have to be 'bulked' by the use of polystyrene beads to occupy a realistic volume in the hole.

## **8.7 CHARGING**

The charge mass in a blasthole influences the resulting ground and air vibration. It is essential that the appropriate charge mass is loaded into each hole. Check on the rising of the explosive column in the hole.

Be especially wary in ground with cavities. Do not bring the explosives column into the designed stemming zone. Be aware that gassed emulsion explosives expand after placement and need 20 minutes for full expansion. Check the depth of the top of the explosives column before adding stemming. Remove excess explosives with a 'snot sucker', or heap extra material on the hole collar. If cavities are found, it may be necessary to load the explosive inside a lay flat plastic liner to prevent 'bombs'.

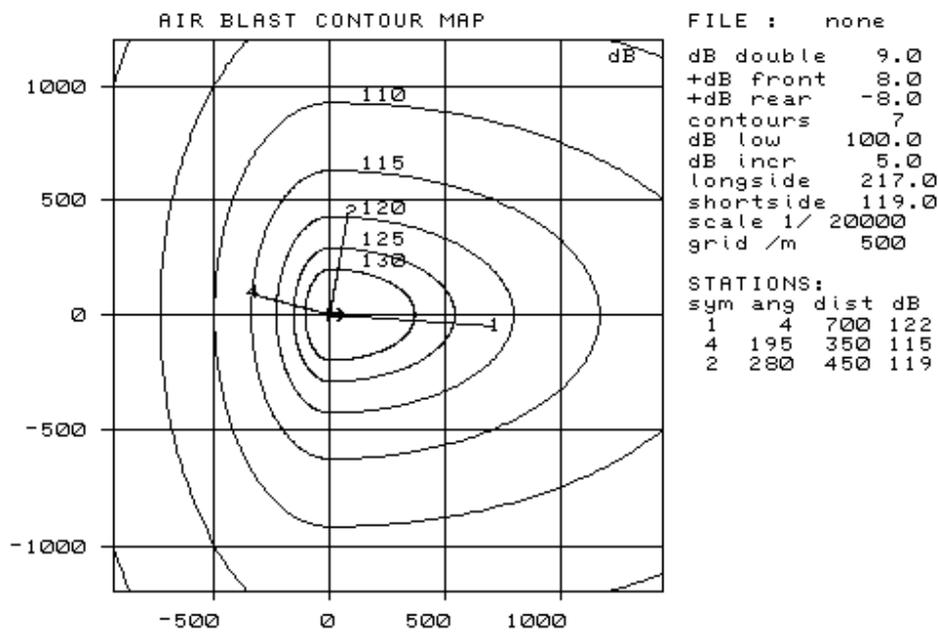
## **8.8 CONFINEMENT OF CHARGES**

Do not use unconfined charges or detonating cord in sensitive situations. Confining the charges decreases air vibration levels. In small scale construction, blasting it may be necessary to use blasting mats or back fill. To confine the charge to limit air vibration in larger scale blasts, one technique is to leave clay overburden intact over a rock excavation to form a level drilling base. This provides a safer working area and keeps hole depths more constant but also confines the charge.

## 8.9 STEMMING

Stemming is used to contain the gases of the explosion for sufficient time for the gases to fracture and move the rock. Stemming ejection can be a major source of air vibration. Stemming should be of angular crushed rock approximately one tenth the hole diameter (drill cuttings are not good stemming).

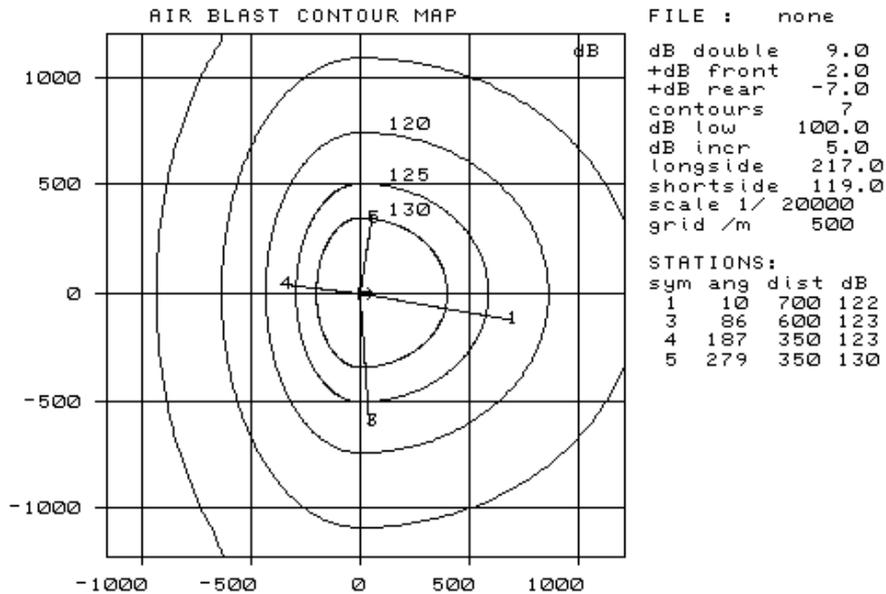
If stemming length is equal to or greater than the burden (and good quality stemming is used) stemming ejection will not occur. Stemming height may be reduced to approximately 0.8 times burden in second and successive rows with no increase in vibration levels. Stemming height may be reduced further but the blasts should be monitored as vibration levels may increase. The air vibration contours for three blasts with stemming reduction are shown in **Figures 8.2(a), (b) and (c)**. The reduction of stemming from 3.0 metres to 1.6 metres has added 5 dBL to the front of the blast and 12 dBL to the sides and rear of the blast.



ENVIB

Figure 8.2(a) – Air vibration contours showing the effect of stemming height reduction

<b>Hole diameter:</b>	102 mm
<b>Face height:</b>	15 metres
<b>Minimum burden:</b>	3.5 metres
<b>Minimum stemming height:</b>	3 metres
<b>Average charge:</b>	148 kg
$\frac{\text{Stemming height}}{\text{Burden}} = 0.86 \text{ metres}$	



ENVIB

Figure 8.2(b) – Air vibration contours showing the effect of stemming height reduction

<b>Minimum burden:</b>	3.5 metres
<b>Minimum stemming height:</b>	2 metres
<b>Minimum front row stemming height:</b>	3.5 metres
$\frac{\text{Stemming height}}{\text{Burden}} = 0.57 \text{ metres}$	

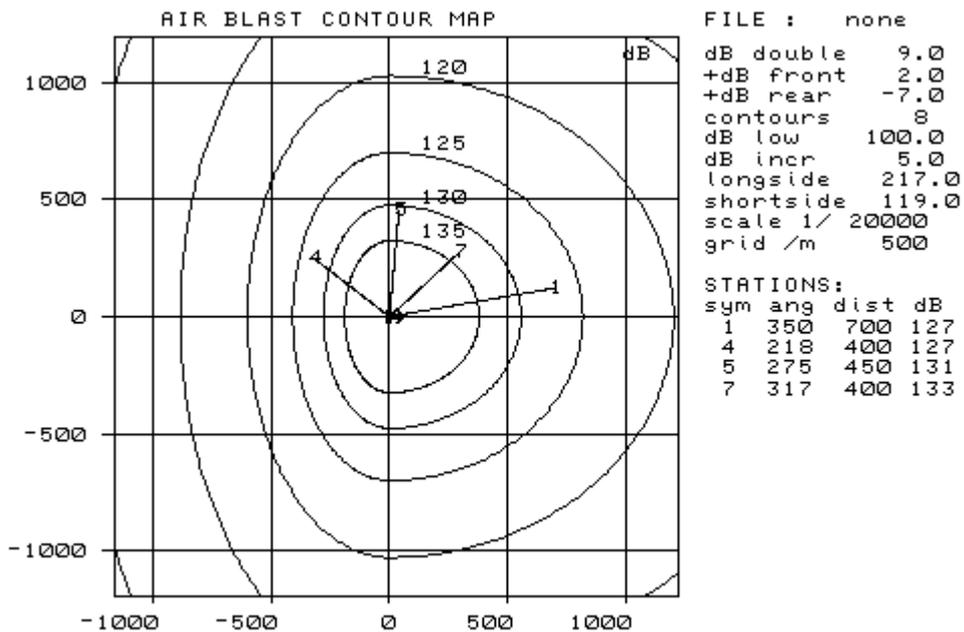


Figure 8.2(c) – Air vibration contours showing the effect of stemming height reduction

<b>Minimum burden:</b>	3.5 metres
<b>Minimum stemming height:</b>	1.6 metres
<b>Minimum front row stemming height:</b>	2 metres
$\frac{\text{Stemming height}}{\text{Burden}} = 0.46 \text{ metres}$	

## **8.10 DELAY PATTERN**

Using an inappropriate delay pattern can greatly increase vibration levels because of wavefront reinforcement. From our experience, ground vibration can be increased 3 to 5 times and air vibration increased by up to 10 dBL by reinforcement. To determine if a particular pattern reinforces, it is necessary to have a program, such as the Terrock Pattern Program.

## **8.11 FACE ORIENTATION**

The face orientation can influence air vibration levels by up to 10-12 dBL. Plan extraction sequence to face the blast away from houses or sensitive areas (where possible). Air vibration levels will be lower at the side or behind the blast than at the same distance in front of the blast.

## **8.12 TOPOGRAPHY**

Air vibration from a blast is influenced by the surrounding topography. The amount of shielding can be predicted by the graphs developed and produced elsewhere. Air vibration will be less for deeper benches of multi-bench operations because of shielding.

## **8.13 METEOROLOGICAL CONDITIONS**

Wind shear and temperature inversion layers can increase vibration levels and result in complaints, usually at distances further than 3 km from the blast site. Air vibration levels may be increased by 10 dBL or up to 10 dBL by the focusing or reinforcement of the air vibration waves.

Low cloud cover (without temperature inversion) and wind direction do not necessarily increase vibration levels. During the inversion season (late autumn to mid winter) try to conduct blasting operations in mid afternoon to correspond to the maximum height of the inversion.

## **8.14 KEEP GOOD BLASTING RECORDS (INCLUDING FIRING TIMES)**

This will aid blasting efficiency and prevent uncertainty in the event of a complaint. A location plan to accurately position the blast sites and measurement stations is essential for measurement of distances for comparative analysis. Simple plotting of routinely monitored vibration against distance, on the appropriate log scale will give a performance indicator.

## **8.15 VIDEO RECORDING**

The video recording of each blast can be an important tool in the assessment of blasting performance and analysis of results. The slow motion replaying of blasts can readily show events that can lead to high vibration levels such as:

- Stemming ejections.
- Underburdened faces, flyrock and gas ejection from the face.
- Overburdened faces - sections of the face not moving.
- Cratering, flyrock and gas ejection from the collar region.
- Toe problems - toe not moving.

## CHAPTER 9 - BLAST VIBRATION LIMITS

People can feel blast vibration well below damage levels and, in many cases, will regard blast vibration as intolerable well before damage is likely to occur. This factor has been considered by the Standards Association of Australia when setting blast vibration standards, and has been further considered by regulatory authorities when encouraging those responsible for blasting to maintain blast vibration levels below those specified in AS2187-1993, whenever possible.

### 9.1 REGULATORY ENVIRONMENTAL LIMITS

Some blasting operations are regulated by reference to the Australian Standard AS2187-1993. Other operations may be regulated by other limits such as licence conditions, or contract specifications, which may differ from the Australian Standard. For any job be aware of the vibration limits and conduct operations accordingly.

#### 9.1.1 Ground Vibration Limits

People can feel ground vibration levels of approximately 0.5 mm/s.

The SAA Explosives Code AS2187-1993 recommends a general level of 10 mm/s for ground vibration resulting from blasting at houses and 25 mm/s for other structures, as quoted below.

The peak particle velocity measured at the ground surface should not exceed the limits recommended in Table J1 and its related Notes.

**TABLE J1 - Recommended Maximum Peak Particle Velocity**

Type of Building or Structure	Peak Particle Velocity (Vp) mm/s
Houses and low-rise residential buildings; commercial buildings not included below	10
Commercial and industrial buildings or structures or reinforced concrete or steel construction	25

#### NOTES:

1. This Table does not cover high-rise buildings, buildings with long-span floors, specialist structures such as reservoirs, dams and hospitals, or buildings housing scientific equipment sensitive to vibration. These require special considerations, which may necessitate taking additional measurements on the structure itself, to detect any magnification of ground vibrations, which might occur within the structure. Particular attention should be given to the response of suspended floors.
2. In a specific instance, where substantiated by careful investigation, a value of peak particle velocity other than that recommended in the Table may be used.
3. The peak particle velocities in the Table have been selected taking into consideration both human discomfort and structural integrity together with the effect on sensitive equipment located within buildings.

Higher levels may be permitted for ground vibration with high frequencies such as that resulting from small scale construction blasting at close distances to houses.

Current practice by most Australian regulatory authorities is to specify a maximum PPV limit of 10 mm/s for ground vibration resulting from blasting at houses, with preferred levels for long-term operations being below 5 mm/s.

## 9.1.2 Air Vibration Limits

The SAA Explosives Code AS2187-1993 states:

*"Appropriate levels for airblast for local conditions may be required by the relevant authority. A limit of 120 dB for human discomfort is commonly used and 133 dB to avoid structural damage is generally appropriate".*

Air vibration from blasting is barely noticed below 100 dBL (Peak). Air vibration levels of 110 dBL (Peak) are readily acceptable by the community.

Current practice by most Australian regulatory authorities is to specify a limit of 120 dBL (Peak) (2 Hz) at the source of complaint for air vibration resulting from blasting in mines and quarries, with preferred levels being below 115 dBL (Peak)(2 Hz).

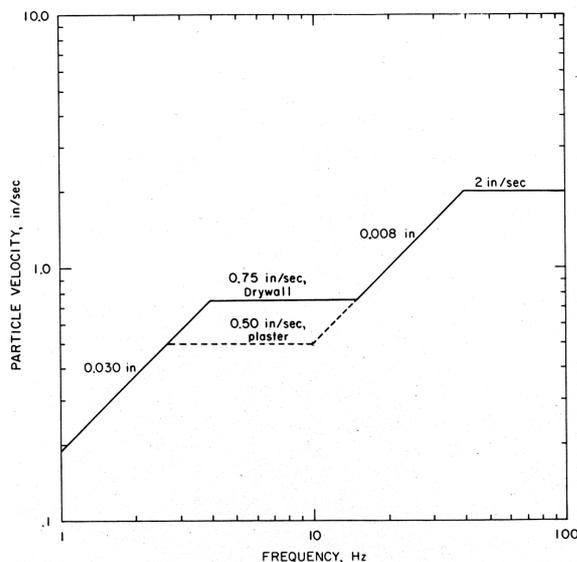
Higher levels may be acceptable for short-term construction blasting operations, provided that those responsible for blasting give effective warning to people in the area. It is currently accepted that damage will not occur to buildings if air vibration is kept below 133 dBL (Peak).

## 9.2 STRUCTURAL DAMAGE LIMITS

The Limits recommended in AS2187-1993 are based on human discomfort, structural integrity and the effect of sensitive equipment located within the buildings. Structural damage occurs at vibration levels in excess of these limits.

### 9.2.1 Ground Vibration

Note 2, which relates to Table J.1, was included to allow for the fact that where resultant vibration consists of frequencies outside the resonant frequency of a structure, higher peak particle velocities are permissible than those conservatively specified in Table J.1. In the absence of a specific frequency related damage level being specified in the Australian Standard, and after careful investigation, reference may be made to the authoritative United States Bureau of Mines Report of Investigations RI8507 (1980) Standard (USBM RI8507-1980) for guidance. An alternative frequency dependent blasting level criteria specified in USBM RI8507-1980 is presented in **Figure 9.1**.

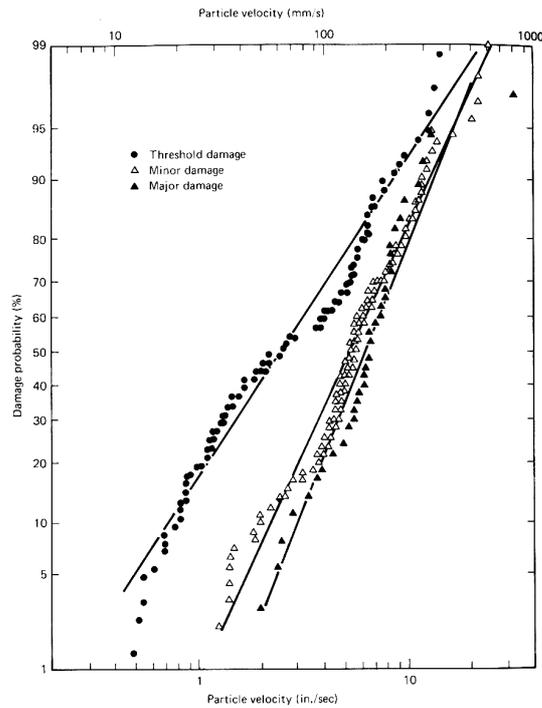


**Figure 9.1 – Frequency dependent vibration level criteria**

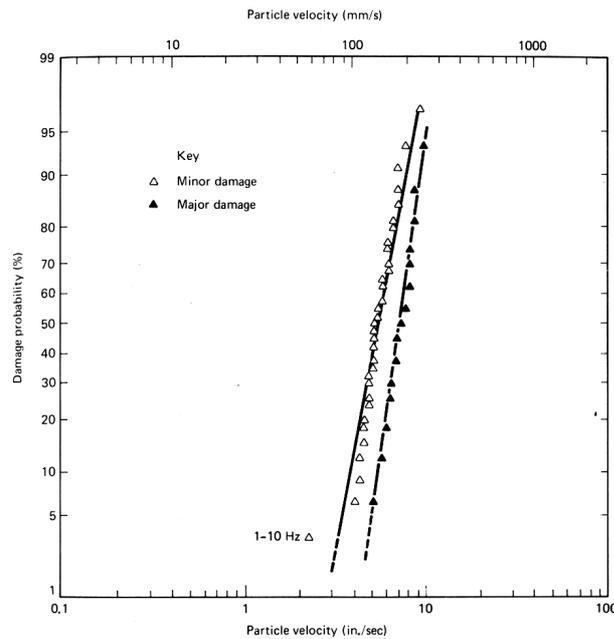
The essential feature of this criteria is that for construction blasting at close quarters where the predominant blast vibration frequency is above 40 Hz, then a limit of 2 in/s (51 mm/s) is appropriate.

Vibration levels exceeding the above limits does not automatically mean damage to structures. Structural response to vibration is a complex matter depending on frequencies present in the vibration, natural frequencies of the building, and construction of the building.

There is an increasing probability of damage with increasing ground vibration levels above the limits shown. For all frequencies, damage probability versus PPV is shown in **Figure 9.2**. For higher frequencies damage probability are shown in **Figure 9.3**.



**Figure 9.2 – Probability damage analysis for low frequency blasts and shaker tests, set 4 – USBM RI8507**



**Figure 9.3 – Probability damage analysis for high frequency blasts, set 6 – USBM RI8507**

Table 9.1 – Damage Classification for the Analyses in Figures 9.2 and 9.3

Uniform Classification	Description of Damage
Threshold:	Loosening of paint; small plaster crack at joints between construction elements; lengthening of old cracks.
Minor:	Loosening and falling of plaster; cracks in masonry around openings near partitions; hairline to 3 mm cracks (0 to 1/8 in); fall of loose mortar.
Major:	Cracks of several mm in walls; rupture of opening vaults; structural weakening; fall of masonry, eg. chimneys; load support ability effected.

### 9.2.2 Air Vibration

The structural damage air vibration limit of 133 dBL from J.3.3. of the Australian Standard is the lowest recorded level at which damage was observed from air vibration. Once again, there is an increasing probability of damage with increasing air vibration levels above this limit. This is demonstrated in the results from various studies summarised in USBM Report 8485. The summary of maximum safe overpressures is given in Table 9.2, and the glass breakage probability given in Figure 9.4.

Table 9.2 – Summary of maximum safe overpressures from all sources

Author	Overpressure source	Maximum safe Lb/in <sup>2</sup>	Overpressure dB	Sensitive element
Windes (82).....	Single unconfined charges.	0.100	151	Glass, poorly mounted.
Perkins (36).....	.....do.....	.100	151	Do.
Poulter (39).....	.....do.....	.032	141	Do.
Reed (43).....	Large surface blasts.	.017	136	<64-ft <sup>2</sup> window 1 chance in 10 <sup>3</sup> .
Reed (42).....	General.....	.029	140	Glass.
ANSI (1).....	Single unconfined charges.	.057	146	Do.
von Gierke (70).	Confined blasts	.047	144	<1 chance in 10 <sup>5</sup> 1,000 people impacted, glass.
Redpath (41)....	Blasts.....	.060	141	<1 chance in 10 <sup>4</sup> 3.5 ft window.
Sutherland (63).	Steady-state sources, fatigue.	>.041	>143	Wood frame and concrete walls.
Taylor (64).....	Small line charges.	<.029	<140	35,000 panes in 30 greenhouses 0.7% damaged.
Do.....	General.....	.014	134	Threshold.
Sutherland (63).	Sonic booms....	.045	144	Plaster.
Do.....	.....do.....	.053	145	Glass.
Wiggins (80)....	.....do.....	.015	134	Paint fleck fell.
Do.....	.....do.....	.035	142	Plaster, new.
Do.....	.....do.....	.056	146	Glass,
Kryter (19).....	.....do.....	.035	142	39-ft <sup>2</sup> window.
Clarkson (7)....	.....do.....	.076	148	Plaster.
Leigh (22).....	.....do.....	>.069	>148	Plaster.
Blume (3).....	.....do.....	.026	139	Glass.
This research...	Production blasting.	.014	134	Based on response and ground vibration.

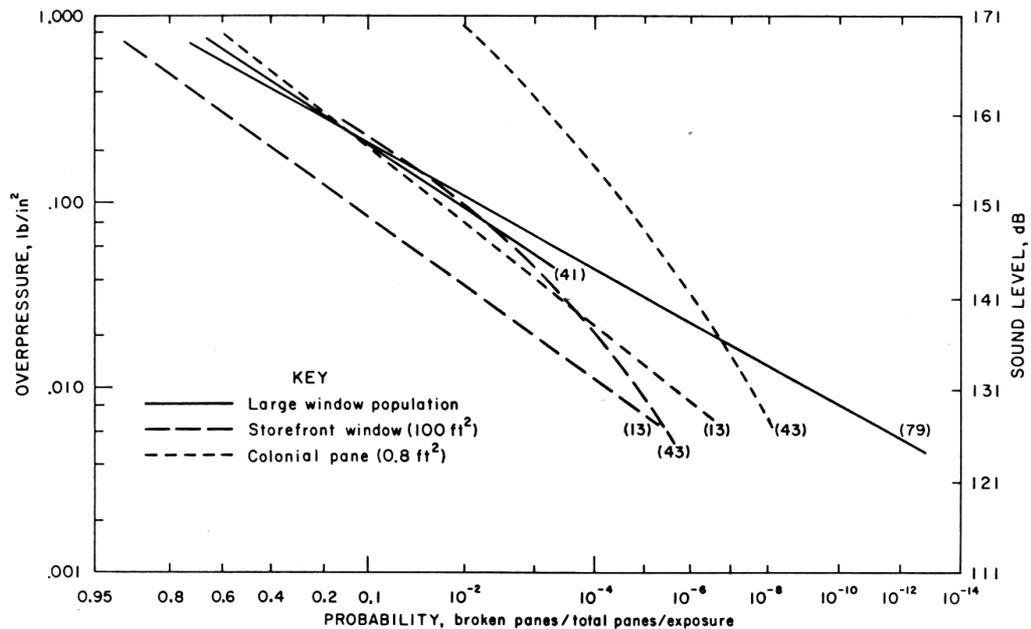


Figure 9.4 – Glass breakage probability from sonic booms and airblast

### 9.2.2.1 Airblast Damage Summary

Many studies have been made of glass and structural damage from impulsive noises including airblast and sonic booms. Despite the widely varied source characteristics, assumptions of damage probabilities, and experimental design, and also the differing interpretations among the studies, there is a consensus that damage becomes improbable below approximately 0.030 lb/in<sup>2</sup> (140 dB). The various safe airblast and sonic boom damage criteria summarised in **Table 9.1** are based on no greater damage risk than one chance in a thousand. The apparently greater damage risk from sonic boom is probably an artefact of the analyses, with large population sampled with few pre-boom damage inspection.

There is less than 1 in 1000 chance of damage to glass below 140 dBL. The minimum damage level for plaster (from sonic booms) is 144 dBL.

The damage limit analogy between air vibration from sonic booms and blasting appears to be relevant. High airblast is likely to crack windows before walls.

## 9.3 ASSESSMENT OF BLAST VIBRATION CLAIMS

People complain about blast vibration for a number of reasons. The reasons may be:

- High vibration levels.
- Concern that their property is being damaged even though the vibration levels felt are low.
- Individual or collective opposition to a mine or quarry.

Examples of comments received from complainants about blast vibration are :

- "The whole house shook".
- "The windows rattled".

- "The picture fell off the wall".
- "Ornaments fell off the shelf".
- "The roof tiles lifted".
- "I was shaken off the chair onto the floor".
- "I was dozing and the blast knocked me off my bed".
- "The cracks opened up before my eyes".

### **9.3.1 Handling of Complaints**

Records should be kept of all blasting operations (mandatory at mines and quarries), including accurate times of firing.

On receipt of a complaint, the complainant's name and address, nature of the complaint and date and time of the event should be recorded. Complaints should be investigated in person by the person in charge of blasting and a genuine attempt made to satisfy the complainant.

Swift action, a sympathetic ear, and good public relations may prevent an unpleasant situation developing. It may be necessary to explain blasting procedures, the nature of vibration, structural response, regulatory limits, etc, in layman's terms, as we have in our prepared notes – 'Blast Vibration, Measurement and Control'.

Monitoring of subsequent blasts and follow-up visits to gauge response may be part of the public relations. If vibration levels are below regulatory limits, reassurance may be all that is required. If levels are exceeding regulatory limits, the blasting procedures should be reviewed and vibration levels reduced to below the limits by using appropriate techniques.

In the event of repeated complaints or prolonged high vibration levels, professional or technical investigations may have to be conducted by an organisation such as ours.

### **9.3.2 Damage Assessment Procedures**

If damage is alleged:

1. Estimate vibration levels at the complaint source on the day of the complaint:
  - a) Actual measurements (monitor the next blast(s)) at the complainant's house. Seek subjective views as to whether it was similar to the blast complained of.
  - b) Estimation by extrapolation from routine measurements at other locations or from previous blast monitoring history. It will be necessary to have an accurate plan or air photo so the distance from the blast to the complaint source can be determined.
  - c) Estimation from basic scaled distance formula (least accurate).
  - d) Obtain meteorological data, where necessary, to check if inversion or wind shear conditions existed at the time of firing.
  - e) Obtain detailed blast report, including drilling and delay patterns, and time of firing. Check powder factor, burden and delay patterns for reinforcement.

2. Assessment of damage by inspection:

Inspect the site and record alleged damage using blast report sheets and photographs and if necessary record all existing cracks in the building. Note the building construction, age, provision for drainage, soil type and closeness of large trees. If possible, compare buildings with similar age and construction at different locations for a comparison. A thorough inspection is very time consuming, but may be justified if there is likely to be ongoing blasting, complaints or legal proceedings.

3. Compare determined vibration levels with the Comfort Criteria and Damage Limit Criteria.

4. Assessment of the cause of damage:

Form an opinion as to the likely cause of damage by answering the following questions:

- i) Were vibration levels above damage criteria?
- ii) Could the type of damage be blasting related?
- iii) Can the damage be explained by other mechanisms?
- iv) What is the most likely cause of damage?

5. Cracks in buildings and structures can be caused by a number of agencies including:

- Differential thermal expansion and contraction between the structural components.
- Structural overloading.
- Shrinkage and swelling of wood framing.
- Fatigue and ageing of wall cladding.
- Uneven foundation settlement.
- Seasonal expansion and contraction of reactive clay soil beneath foundations.
- Growth of clay bricks with age.
- Shrinkage of concrete, plaster, plaster products and mortar with age.
- Differential shrinking of concrete and mortar of different composition with age.
- Vibration (traffic, slamming doors, wind).
- The vibration levels at my house are high because of the particular run of reef that runs from the quarry to my house.

One interesting comment received from the owner of a house that had been subjected to 123.3 dBL and 28.2 mm/s from a construction blast was 'that was nothing, you should have been here when the nearby quarry was operating'.

There may be genuine reasons for complaint and genuine damage sustained. People begin to complain when vibration levels exceed 110 dBL and 2 mm/s (at low frequencies), with the level of complaints increasing when airblast levels reach the range 115 dBL to 120 dBL or exceed 5 mm/s.

Many blast vibration and alleged damage complaints have underlying reasons. The complainant may be under emotional stress from causes beyond their control, like unemployment or marriage breakdown. In one case investigated, the underlying cause was the quarry using a truck with a faulty silencer to cart rock past her house (in a rural area) with about a 15 minute cycle time.

The complainant may just need reassurance that the vibration they 'feel' is not causing structural damage. Advice that blast vibration is being monitored to ensure that it is below safe regulatory limits is also helpful.

On the political front, groups may be formed to campaign for a 'cause' such as the closing of a quarry or mine or have it relocated. These campaigns may be quite heated and attract considerable media attention.

Communication with the local community can sometimes be improved by the formation of a 'Community Committee' with representatives from local government, mines inspector, environmental officer, mine/quarry and community representatives, to provide a platform for the airing of grievances and the spreading of positive information.

In some cases, community concern can be reduced when advice is given of a definite date for the ceasing of operations at the mine or quarry and an after use reclamation proposal that may be of benefit to the community.

There may be individuals wanting to be bought out by the mine/quarry operators and use the complaint path to expedite negotiations. Other complainants seek cash compensation for 'damage' to their property, which they state was due to blasting.

It is prudent to be aware of hidden agendas when investigating a blast complaint because there may be more involved than the monitoring of blast vibration levels.

Common crack types found in particular circumstances and not blasting related are as follows:

- f) Plasterboard - look for cracks at the joins of sheets and at wall/cornice/ceiling joins caused by movement of the timber frame, age shrinkage of the filler products and seasonal temperature and moisture variation.
- g) Hard Plaster (render, etc) - look for hairline cracks around patches corresponding to 'hodfuls' and 'druminess' caused by age shrinking and loss of bond with laths, and bricks.
- h) Concrete (paths, floor slabs, bricks/blocks) - concrete shrinks with age as part of the normal chemical reaction (as much as 1 mm/m in the first year, but slower after that). Concrete also expands and contracts with temperature change. With slabs, paths, etc, look for cracks at approximately 2 metre centres and at changes of section.
- i) Check for the provision of expansion joints and shrinkage cracks - concrete brickwork (block work) also shrinks and cracks form if no provision is made. Cracks tend to be of constant width and may be near windows or other changes of section. The cracks may be vertical or stepped. Long unbroken walls should have expansion joints.
- j) Concrete Water Tanks - also crack and often leak. Cracks are formed because of shrinkage of the concrete. Cracks also form between different batches either because of slight variation in composition or the surface drying between pours.
- k) Clay Bricks - grow with age but the mortar shrinks. Hairline cracks frequently develop between the bricks and the mortar.

- l) Lintels - look for cracks at the end and mid-span of lintels over especially long openings (eg. garage doors). Thermal expansion and contraction of steel lintels and deflection may crack brickwork. Poured concrete lintels will shrink away from brickwork in stone, brick and concrete block houses.
  
- m) Uneven Foundation Settlement - especially common on reactive clay areas. Seasonal moisture variation causes expansion and contraction of the supporting soil. Indicated by cracks wider at the top than the bottom. Look for causes of variable soil moisture such as poor drainage, large trees nearby, garden beds against walls, verandas and paths along stable walls.

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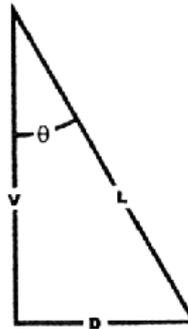
## **APPENDICES**

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**Inclined Blastholes**

V = Vertical Distance including vertical sub-grade (m)  
 D = Horizontal Distance (m)  
 L = Length of Blasthole (m)  
 $\theta$  = Inclination of vertical (degrees)



$\theta$	5°		10°		15°		20°		25°		30°		35°		40°		45°	
V	D	L	D	L	D	L	D	L	D	L	D	L	D	L	D	L	D	L
5	0.4	5.0	0.9	5.1	1.3	5.2	1.8	5.3	2.3	5.5	2.9	5.8	3.5	6.1	4.2	6.5	5.0	7.1
6	0.5	6.0	1.1	6.1	1.6	6.2	2.2	6.4	2.8	6.6	3.5	6.9	4.2	7.3	5.0	7.8	6.0	8.5
8	0.7	8.0	1.4	8.1	2.1	8.3	2.9	8.5	3.7	8.8	4.6	9.2	5.6	9.8	6.7	10.4	8.0	11.3
10	0.9	10.0	1.8	10.2	2.7	10.4	3.6	10.6	4.7	11.0	5.8	11.5	7.0	12.2	8.4	13.1	10.0	14.1
12	1.1	12.0	2.1	12.2	3.2	12.4	4.4	12.8	5.6	13.2	6.9	13.9	8.4	14.6	10.1	15.7	12.0	17.0
14	1.2	14.1	2.5	14.2	3.7	14.5	5.1	14.9	6.5	15.4	8.1	16.2	9.8	17.1	11.8	18.3	14.0	20.0
15	1.3	15.1	2.6	15.2	4.0	15.5	5.5	16.0	7.0	16.6	8.7	17.3	10.5	18.3	12.6	19.6	15.0	21.2
16	1.4	16.1	2.8	16.2	4.3	16.6	5.8	17.0	7.5	17.7	9.2	18.5	11.2	19.5	13.4	20.9	16.0	22.6
18	1.6	18.1	3.2	18.3	4.8	18.6	6.6	19.2	8.4	19.9	10.4	20.8	12.6	22.0	15.1	23.5	18.0	25.5
20	1.8	20.1	3.5	20.3	5.4	20.7	7.3	21.3	9.3	22.1	11.6	23.1	14.0	24.4	16.8	26.1	20.0	28.3
22	1.9	22.1	3.9	22.3	5.9	22.8	8.0	23.4	10.3	24.3	12.7	25.4	15.4	26.9	18.5	28.7	22.0	31.3
24	2.1	24.1	4.2	24.4	6.4	24.8	8.7	25.5	11.2	26.5	13.9	27.7	16.8	29.3	20.1	31.3	24.0	33.9
25	2.2	25.1	4.4	25.4	6.7	25.9	9.1	26.6	11.7	27.6	14.4	28.9	17.5	30.5	21.0	32.6	25.0	35.4

## APPENDIX 2 - INVESTIGATION OF BLAST VIBRATION MEASUREMENT RECORDS

### **A2.1 INTRODUCTION**

All blast vibration measurement equipment used to monitor both air vibration (airblast overpressure) and ground vibration resulting from blasting in open-pit coal mines in the Hunter Valley records peak levels of air vibration and ground vibration during the measurement period.

In some instances, the peak vibration level recorded does not correspond with the peak airblast overpressure or ground vibration level resulting from the blast.

These 'false' peak levels may be due to:

- Wind, or some other non-blasting source.
- Electrical interference.
- Incorrect settings on the measurement equipment.
- Inappropriate instrument coupling.

### **A2.2 PRELIMINARY INVESTIGATION**

The first step in the investigation is to validate the measurement.

This includes:

#### **A2.2.1 Comparing the Time and Date on the Blast Vibration Record with the Time and Date of the Blast**

Inaccuracies sometimes exist in the time and date on the blast vibration record, and the time and date recorded by the person responsible for the blast.

If discrepancies exist, the time and date settings on the measurement equipment should be checked, and any alternative information about the time and date of the blast should be checked.

#### **A2.2.2 Examining the Waveform Record for the Measurement**

This will generally provide evidence as to whether the peak level recorded corresponds with the peak level of a vibration wave trace that is consistent with the blasting event.

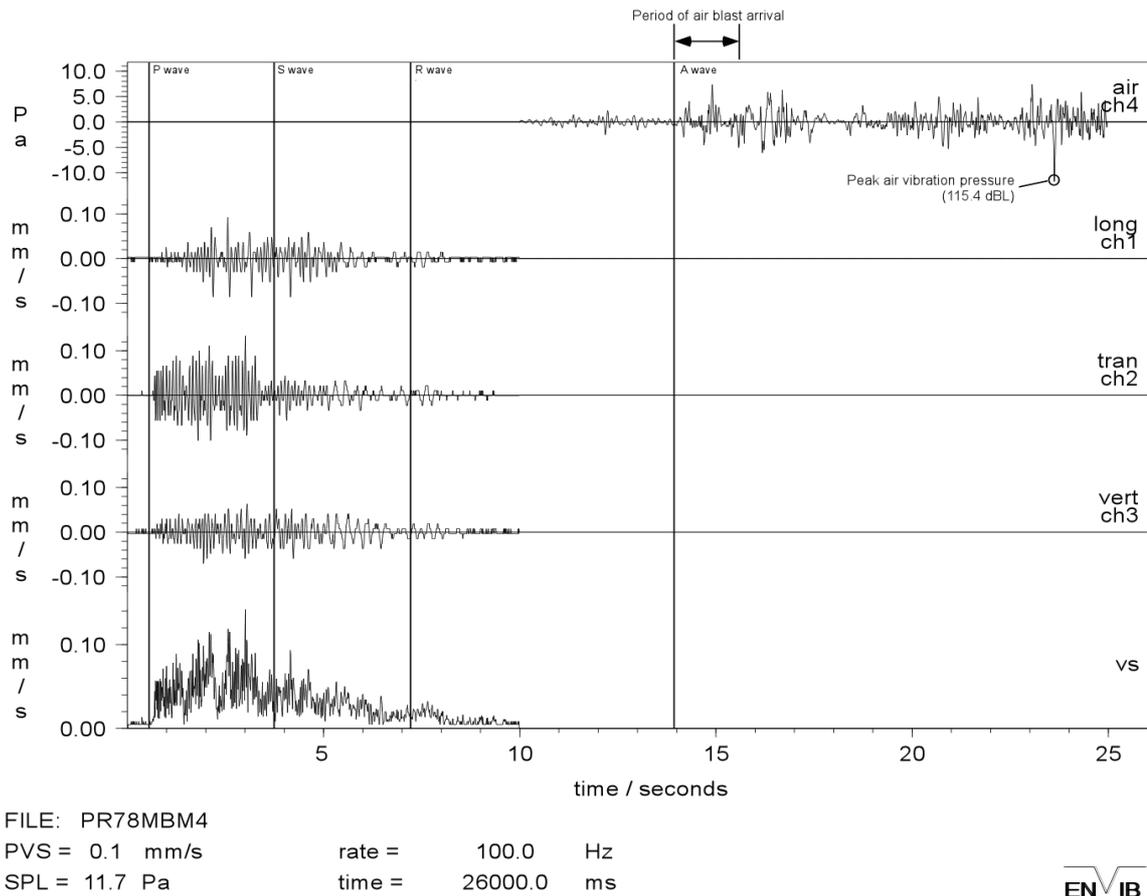
In some cases the magnitude of the air vibration and/or the ground vibration waveform will be below the resolution of the measurement equipment being used.

In windy conditions the air vibration trace may be strongly influenced by wind gusts, and the airblast overpressure waveform may not be apparent.

#### **A2.2.3 P, S, R, A Analysis of the Waveform Record**

When a blast is fired in Hunter Valley open-pit coal mines, ground vibration radiates from the blast site with propagation velocities of 2200 m/s for P (compressive) waves, 1200 m/s for S (shear) waves, and 750 m/s for R (Rayleigh) waves. Air vibration (airblast overpressure) waves follow the ground vibration at the speed of sound (approximately 340 m/s).

Details of the P, S, R, A analysis for the waveform recorded at a measurement station, which shows the relative arrival times of P, S, R, A (air vibration waves), is shown in **Figure A2.1**.



**Figure A2.1 - Details of P, S, R, A Analysis of the waveform record**

The peak air vibration level of 115.4 dBL (11.8 Pa) was recorded 8 seconds after the period of airblast arrival. The peak air vibration level during the period of airblast arrival was 110.9 dBL (7.0 Pa). It should be noted that this peak of 110.9 dBL was predominantly due to wind. Subsequently, more detailed analysis showed that the actual airblast overpressure level was 91 dBL, which is 10% of the 110.9 dBL air vibration level recorded during the period of airblast arrival.

In many cases, the P, S, R, A analysis of the waveform record does not permit the actual airblast overpressure level to be directly determined, but permits a statement to be made that the air vibration level at the time of airblast arrival was below a specified limit (in this case illustrated in **Figure A2.1** this limit was 115 dBL). In cases where this statement is sufficient to deal with the situation, no further investigation is necessary.

#### **A2.2.4 Information Required for Preliminary Investigation**

- Date and time of blast.
- Measurement record, which should include:
  - Date and time of measurement.
  - Peak vibration levels.
  - Waveform record (preferably showing the commencement of the ground vibration wave) plus any additional data (which varies with type of measurement equipment) necessary to permit a P, S, R, A analysis to be carried out.

For Dynamaster monitors, a DAT file is required together with a waveform print-out on which the AB Log Delay and the VL Log Delay plus are printed. For Blastronics  $\mu$  MX monitors, a QWF file is required together with a waveform print-out (or RTF file).

- Elapsed time of the delay sequence of the blast.
- Distance from blast to measurement station (or co-ordinates of blast site and measurement station(s)).

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## **A2.3 MORE DETAILED INVESTIGATION**

In cases where the preliminary investigation (which includes examination and P, S, R, A analysis of the waveform record) is insufficient to deal with the situation, further investigation will be required.

The methods used will vary with the actual case, but may include:

### **A2.3.1 Regression Analysis**

Regression analysis, in which blast vibration levels are plotted against scaled distance (which is determined by distance from blast and charge mass per delay, or M.I.C.) This will assist in identifying measurements that are influenced by factors other than distance and charge mass.

### **A2.3.2 Frequency Spectra Analysis**

Frequency Spectra Analysis of the waveform record.

### **A2.3.3 Estimation of Vibration Levels**

Estimation of the vibration levels resulting at the measurement station using blast specifications, site law parameters, and other assessment models.

### **A2.3.4 Wavefront Reinforcement Analysis**

Wavefront reinforcement analysis of the drilling and delay pattern to check for evidence of wavefront reinforcement and directions.

### **A2.3.5 Quantification of Wavefront Reinforcement**

Quantification of wavefront reinforcement using comparative data and seed waveform methodology.

### **A2.3.6 Meteorological Analysis**

Meteorological Analysis – using a model developed by the U.S. Ballistics Research Laboratories. This model requires meteorological data, which includes details of temperature, wind speed, and wind direction, at significant levels up to 600 metres above the ground.

## **A2.4 INFORMATION REQUIRED FOR MORE DETAILED INVESTIGATION**

### **A2.4.1 Information Supplied for Preliminary Investigation**

- Date and time of blast.
- Measurement record, which should include:

- Date and time of measurement.
- Peak vibration levels.
- Waveform record (preferably showing the commencement of the ground vibration wave) plus any additional data (which varies with type of measurement equipment) necessary to permit a P, S, R, A analysis to be carried out. For Dynamaster monitors, a DAT file is required together with a waveform print-out on which the AB Log Delay and the VL Log Delay plus are printed. For Blastronics  $\mu$  MX monitors, a QWF file is required together with a waveform print-out (or RTF file).
- Elapsed time of the delay sequence of the blast.
- Distance from blast to measurement station (or co-ordinates of blast site and measurement station(s)).

#### **A2.4.2 Other Measurement Records that are Available**

These will depend on the actual case, but will generally include all measurement records for the blast, even though these may not have high quality waveform records.

Relevant measurement records for other blasts.

#### **A2.4.3 Blasting Specifications**

- Blasthole diameter, depth, and inclination.
- Face height.
- Loading details, including charge mass, explosives type, and any decking details.
- Stemming height and type.
- Drilling pattern and delay pattern.
- Rock type and general ground characteristics.

#### **A2.4.4 Mine Location Plan or Scaled Photo-Plan**

Showing location of blast and measurement stations, and orientation of blast pattern.

#### **A2.4.5 Data from the Mine Meteorological Station**

This commonly includes details of temperature, wind speed, and wind direction at 10 minute averages for one hour before and after the blast.

Above ground data can be obtained from the New South Wales Bureau of Meteorology, Special Services Unit, or other authoritative source.