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# Evaluation of parameters effecting blast induced vibrations

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**EVALUATION OF PARAMETERS EFFECTING BLAST INDUCED  
VIBRATIONS**

A thesis submitted in fulfilment of the requirements  
for the award of the degree

**DOCTOR OF PHILOSOPHY**

from

**THE UNIVERSITY OF WOLLONGONG**

by

**LESLIE W. ARMSTRONG  
B.E. (Chem), M.E. (Mining)**

**Faculty of Engineering  
Division of Mining Engineering  
2001**

## **DECLARATION**

I, Leslie W. Armstrong, declare that this thesis, submitted in fulfilment to the requirements for the award of Doctor of Philosophy, in the Faculty of Engineering, Division of Mining Engineering, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. This document has not been submitted for qualifications at any other academic institution.

During the Ph.D study period (July 1995 to December 2000), the author of this thesis was involved in a number of projects. The research work of this thesis including some of the results are published, acknowledged and implemented in the mining industry by ORICA Explosives and their customers. Following are the publications.

### **EXTERNAL PUBLICATIONS**

Blair D.P. and Armstrong L.W., "The spectral control of ground vibrations using electronic delay detonators.", FRAGBLAST – International Journal of Blasting and Fragmentation, 3 (1999) : 303-334

Armstrong L.W. and Sen G.C., "The measurement of blast induced vibrations in soil.", 1999, Proceedings Explo '99 Conference, 7-11 November, Kalgoorlie, WA, pp 99-104

Brent G.F. and Armstrong L.W., 1998, "Large diameter presplitting improved through two novel techniques.", Proc. 24<sup>th</sup> Annual Conf. Explosives and Blasting Technique, 8-11 Feb., New Orleans, Louisiana, USA

### **INTERNAL PUBLICATIONS**

Blair D.P. and Armstrong L.W., "The Use of Ground Vibration for the Assessment of Explosive Performance.", ICI Explo. Tech. Centre, Kurri Kurri, Feb 1996, No: 57359

Blair D.P. and Armstrong L.W., "Environmental monitoring and modelling for Ebenezer Mine.", ICI Explosives Tech. Centre, Kurri Kurri, January 1998, No: 57775

Armstrong L.W., Blair D.P. and Nagarajan M., "Control blasting near electricity power poles.", Orica Explosives Tech. Centre, Kurri Kurri, March 1998, No: 57777

Armstrong L.W. and Brodbeck A., "Monte carlo vibration prediction modelling at the proposed Basalt Hill quarry, NSW.", Orica Explosives Tech. Centre, Kurri Kurri, Dec 1998, No: 57923

Blair D.P. and Armstrong L.W., "Measurement and simulation of blast for the control of vibrations to the pit wall in KCGM's Fimiston operations.", Orica Explosives - Technical Centre, Kurri Kurri, July 1999, Cat B, No: 58102

Rowe J., Blair D.P., Molloy K., and Armstrong L.W., "Bayswater Coal Mine trial evaluating development product BB509 (EP/Polystyrene at 03 g/cc).", Orica Explosives Technical Centre, Kurri Kurri, September 1999, Cat B, No: 58108

Armstrong L.W., Law T.M. and Brodbeck A., "Vibration monitoring and blasting close to residential buildings. Cleary Bros bulky goods store Shellharbour, NSW.", Orica Explosives - Technical Centre, Kurri Kurri, October 1999, Cat B, No: 58118

Armstrong L.W., "Vibration attenuation site law for Bloomfield Colliery, NSW.", Orica Explosives - Technical Centre, Kurri Kurri, February 2000, Cat B, No: 58154

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Leslie W. Armstrong  
1 February 2001

## **DEDICATION**

I dedicate this thesis to my son Murray whose tragic death occurred during the course of this study. Murray's encouragement and discussions helped me through some difficult times and provided me with the inspiration to complete this study. Thanks Murray.

## ACKNOWLEDGEMENTS

The author wishes to thank his supervisors Professor Gour Sen and Professor Raghu Singh for their guidance, assistance, suggestions and critical comments.

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The support of my work colleagues at Orica Explosives and permission by Orica Explosives to publish this work is most gratefully appreciated. The author also sincerely appreciates the help of ORICA Explosives previous personnel.

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This study could not have been completed without the support and understanding of my wife, Elfriede and the encouragement of my son Warren. Warren's pursuit of his own studies against all obstacles inspired me to complete my studies.

## **ABSTRACT**

The following research focuses on the effect of measuring blast induced vibrations and the effect of the monitoring equipment and procedure on the outcomes.

Mining and quarrying operations today are faced with ever increasing restrictions on their operations especially in the environmental field. Development applications for new operations have to contend with environmental issues such as dust, air pollutants, blast induced vibration and noise levels that at times restrict production outputs. Vibration monitoring has become an integral part of the mine/quarry operations and it is essential that the operators have confidence in the equipment that is used to measure these environmentally sensitive parameters.

These issues were addressed in this thesis in both a laboratory investigation and a more practically oriented set of field trials. A standard technique used for measuring blast induced vibration levels was investigated and the error associated with the procedure was detailed. This standard technique was then compared to other commonly used mounting techniques. Some of these techniques have been accepted by the industry for many years basically because they are easy to carry out and do not require much time to set up. The errors encountered during this comparative trial were attributed to the poor bonding of the soil to the mounting device.

This study was focused on the practicality aspect of vibration monitoring. The procedure recommended was found to have small random errors which were attributed to the complex nature of the vibration wave travelling through the ground. The laboratory investigation highlighted areas where care should be taken when bonding the mounting block to a soil type environment. Field trials were conducted in both surface and underground mining operations and a large range of vibration levels were used as the vibration sources for these trials. An understanding of the vibration waveform and the importance of examining this waveform was discussed. The on screen display of all vibration monitoring equipment can give a misleading result as only the peak levels are displayed on the screen. What caused this peak level was examined.



A special purpose laboratory vibration rig was designed and constructed to test some of the soil properties and their effect on the vibration wave transmission through the soil. The standard monitoring technique was used in the laboratory study to test properties such as moisture content of the soil, compaction of the soil in close proximity to the mounting block, type and size distribution of the soil. All of these soil properties had an effect on the vibration transmission through the soil and this effect was quantified. The fields trial phase of this study was mainly carried out at a local open cut coal mine. This coal mine site proved ideal as the frequency of the blasting operation allowed for a large number of trials to be carried out in a small period of time. Also the operations had variable explosive charge weights per delay and the distance from the blast to the monitoring location was regularly varied. In the field trial phase of this study the variability of the standard technique was investigated and the error level that could be expected was quantified. A comparison between typical mounting techniques and the standard technique quantified errors that could occur with these other methods. The density of the mounting block was also investigated with no significant change being measured for a large range of mount densities used.

The investigation led to many conclusions and recommendations as follows:

1. The coupling or bonding of the soil to the monitoring equipment was found to be the most important factor.
2. A vibration monitoring procedure and equipment was recommended for soil monitoring applications.
3. The variation in the recommended procedure was measured and measurements within 10% of each other were shown to be similar because of the nature of the vibration wave travelling through the ground.
4. Variations in industry accepted mounting procedures were shown to be quite significant with the recommended procedure having a sound scientific background.
5. Modern day electronics have made important advances in the equipment used to monitor blast induced vibrations and careful selection is recommended.
6. Analysis of the blast induced vibration waveform was shown to be critical as erroneous results can occur if instrument read outs are only used.
7. Vibration monitoring and subsequent modelling and prediction can play a useful role in establishing greenfield site vibration data.

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## NOMENCLATURE

<b>A-D converter</b>	device to change analogue signal to digital signal
<b>Accelerometer</b>	device which measures force in acceleration units
<b>Accuracy</b>	true value of a measurement
<b>Acoustic impedance</b>	vibration wave resistance to travel through rock mass
<b>Activation energy</b>	energy required to start a chemical reaction
<b>Al<sub>2</sub>O<sub>3</sub></b>	alumina concentration of the soil sample
<b>Analogue</b>	continuous voltage signal from primary sensor
<b>Attenuation</b>	signal decrease with some parameter
<b>Blasthole</b>	hole drilled in rock mass to accommodate explosive
<b>Blasting</b>	breakage of material by use of explosives
<b>Bulk density</b>	density of large volume of material
<b>CaO</b>	calcium oxide concentration of the soil sample
<b>Compaction</b>	bringing together by force the individual soil particles
<b>Compliance</b>	within the limits of some requirement
<b>Coupling</b>	contact between items (eg. soil and mounting bock)
<b>CoV</b>	coefficient of variation (mean/standard deviation)
<b>Data logger</b>	device to collect and store transducer signals
<b>Detonation</b>	supersonic speed chemical reaction
<b>Digital</b>	signal in the form of 1s and 0s
<b>Elastic medium</b>	one that returns to original state when force removed
<b>Excavation</b>	removal of fragmented material to expose the mineral
<b>Explosive</b>	materials whose chemical reaction cause detonation
<b>FeO</b>	iron oxide concentration of the soil sample (Table 1, page 94)
<b>Fragmentation</b>	large rocks broken into small pieces
<b>Frequency</b>	oscillatory motion in cycles per second
<b>Gangue</b>	waste material
<b>Geometric spreading</b>	waveform flux density change with distance
<b>Geophone</b>	device which measures movement in velocity units
<b>Green field</b>	a new mine or quarry area
<b>Induced vibration</b>	vibration resulting from the detonation of explosives
<b>Instrument hammer</b>	device to strike outside of container to induce vibrations

<b>Interstices</b>	voids between particles in a container
<b>Line of best fit</b>	equation that minimises squared differences
<b>Love wave</b>	surface wave obtained in stratified ground
<b>Longitudinal</b>	see Radial
<b>MgO</b>	magnesium oxide concentration of the soil sample
<b>MIC</b>	Maximum Instantaneous Charge weight detonated
<b>Millisecond</b>	1/1000 <sup>th</sup> part of a second
<b>Mine/Quarry</b>	operation to remove the valuable commodity from the ground
<b>Mineral</b>	the valuable component of the ore
<b>Moisture content</b>	the amount of free water on a mass basis in a soil sample
<b>Mounting block</b>	a solid device to support primary sensor
<b>Nyquist frequency</b>	sampling frequency required to minimise errors
<b>Ore</b>	Excavated material containing the valuable mineral
<b>Overburden</b>	surface material covering the ore or coal
<b>Particle density</b>	density of individual grains
<b>Peaks</b>	largest positive value of a waveform
<b>PPV</b>	peak particle velocity of vibrating medium
<b>Precision</b>	accuracy of a process
<b>Primary waves</b>	longitudinal shock wave, first arrival at monitoring point
<b><i>p</i>-waves</b>	see primary waves
<b>Primary sensor</b>	device to measure ground vibration
<b>Predom frequency</b>	frequency at which half the energy occurs
<b>Pyrotechnic</b>	chemical compound used in delay detonators for timing
<b>Q factor</b>	inelasticity or coefficient of internal resistance of rock
<b>Radial</b>	waveform in the plane of the source and point
<b>Rayleigh wave</b>	surface wave obtained in stratified ground
<b>Resolution</b>	digital steps in data acquisition
<b>Resonance freq.</b>	natural vibration frequency of a structure
<b>Scaled distance</b>	ratio of distance to square root of charge weight
<b>Shear wave</b>	wave motion perpendicular to <i>p</i> -wave
<b>Shock wave</b>	supersonic wave set up by detonation of explosives
<b>Site law</b>	vibration attenuation law for a particular location
<b>Site law parameters</b>	site specific constants to define the site law
<b>Size distribution</b>	the mass percentage of different sized particles

<b>SiO<sub>2</sub></b>	silicon dioxide concentration of the soil sample
<b>Soil</b>	a mass of particles all less than 8 mm in size
<b>Standard deviation</b>	spread of measured data about a mean value
<b>s-wave</b>	see shear wave
<b>Transducer</b>	device to convert a physical event to an electrical signal
<b>Transverse</b>	waveform in the plane normal to the source and point
<b>Trough</b>	largest negative value of a waveform
<b>Urban sprawl</b>	residential encroachment on existing mining operations
<b>Waveform</b>	collection of data points from a primary sensor under vibration
<b>Velocity</b>	distance traversed with respect to time
<b>Vertical</b>	waveform in the vertical plane
<b>VPPV</b>	vector peak particle velocity

**NOTATIONS**

$\lambda$	Lamé's parameter (page 30)
$\nu$	Poisson's ratio (page 35)
$\rho$	medium density (page 30)
$\sigma$	stress (page 31)
$\epsilon$	strain (page 30)
$\Delta H_f^0$	standard enthalpy of formation at 298.15 K (page 23)
$\Delta H_r$	heat of reaction (page 19)
$\dot{A}$	particle velocity (page 31)
A	amplitude (page 39)
$a_n$	Fourier coefficient (page 41)
$b_n$	Fourier coefficient (page 41)
a	site attenuation law factor (page 179)
b	site attenuation law exponent (page 179)
$c_v$	specific heat (page 23)
C	propagation velocity (page 31)
D	relationship between the mount radius and the depth of burial (page 35)
E	specific internal energy (page 23)
E	error obtained with measuring X (page 106)
G	modulus of rigidity (page 30)
G	Young's modulus (page 37)
G	mass factor (page 35)
$k$ ,	reaction rate constant (page 18)
$p$	pressure (page 23)
Q	heat of reaction (page 23)
Q	coefficient of internal friction (page 37)
R	weight percent retained on screen size X (page 98)
RAD	mount radius (page 35)
t	time (page 29)
T	temperature (page 23)
$u$	velocity (page 23)
$u_R$	radial vibration component (page 68)

$u_T$	transverse vibration component (page 68)
$u_V$	vertical vibration component (page 68)
$V_p$	sonic velocity or $p$ -wave velocity (page 25)
$X$	displacement (page 29)
$X_c$	characteristic screen size (page 98)
$Z$	acoustic impedance (page 25)



## CHAPTER 1

### INTRODUCTION

#### **1.1 Forward.**

Mine and quarry operations are an integral part of our life style today. Everything that is done during the course of the day is touched even in some small way by the products of the mining industry. The whole purpose of the mine/quarry operation is to reduce the rock to a size that can be handled by excavation equipment and moved to expose the valuable mineral or ore below the surface of the ground. It is the mineral or ore that is processed and fabricated into useful objects that is used in our daily lives.

The majority of mine/quarry operations do not have the luxury of free digging material and have to provide a means to fragment the ground before excavation can occur. The most cost effective means of fragmenting the ground is by the use of explosives, which provide large amounts of energy, released on an extremely small time scale. This energy release causes shock waves to travel through the ground, which have an effect on everything in its path. At close proximity to the explosive source these shock waves cause untold damage to the surrounding rock material which is measured by the fragmentation of the rock material. At distances much further away from the explosive source the shock wave causes the ground to vibrate and at the free surface the vibration and the level it attains causes many concerns from neighbours living close to the mine/quarry operation. The concerns of the local neighbours are real, although some are motivated by commercial gain, and any responsible mine/quarry operator will take appropriate steps to minimise the local community fears and control the blasting operations to minimise the blast induced vibrations.

Before the mine/quarry operator can take any steps to control the blasting operation they must be able to measure the vibration level at the appropriate location. The monitoring equipment must record the vibration wave as it passes the location and it is imperative that it is only the blast induced vibration that is measured. If the vibration monitoring

procedure adopted is not correctly designed then the recorded waveform could possibly be due to faulty equipment or the poor coupling of the primary sensor to the ground.

Vibration measurement standards have been in place for many years but not a lot of attention was placed on the mounting procedure or coupling of the primary sensor to the soil. These standards detail equipment that should be used but the advances in electronics over recent years has allowed more accuracy in the vibration monitoring equipment to collect real data from blast induced vibrations. These so called standard methods leave a lot to be desired as far as the bonding or coupling of the primary sensor to the soil is concerned. It is this bond that will make the difference between measuring the real blast induced vibrations level or some fictitious level caused by the mounting procedure or monitoring equipment.

## **1.2 Reasons for Research.**

A lot of measuring procedures have evolved after many years of modification and the vibration monitoring procedure is no exception. In the past, equipment manufacturers have guided the standards and shaped the way vibration monitoring was carried out. This is not necessarily the best situation as commercialisation and science are not usually good bedfellows.

The idea for this research stemmed from years of vibration monitoring of blasting operations in mine/quarries and the lack of direction from the standards etc. as to the best practice to use. What are the effects of the properties of the soil, which is causing the bond to the primary sensor, and how do variations in these properties effect the outcome of the measurements? This question needs to be answered so that it is only the blast induced vibration that is being recorded. The results of the vibration monitoring exercise can be crucial to the viability of the mine/quarry and also if the measurement is carried out in a scientific manner then the concerns of the local residents about the absolute value of the vibration level will be minimal. Knowledge of the soil properties in contact with the primary sensor and how the vibration intensity is transmitted through the soil is important in understanding what the real effects of the blast induced vibrations are doing to structures. If, for example, poorly functioning equipment records vibration levels which are not the true levels (whether it be high or low) then



dramatic consequences can result. If the vibration monitoring procedure records results that are higher than the real values then reducing these levels could cause the closure of the mine/quarry. This causes stress on the local community (unemployment, lower levels of expenditure by employed residents etc.). But if the recorded levels are lower than the real values then damage to residents property will eventually occur which again could cause the mine/quarry to close.

Knowledge of the parameters of the monitoring procedure are essential in understanding the results of the monitoring exercise and to ensure the true value of the blast induced vibration level is recorded. After all events are measured today so that some form of control can be placed on these events and predictions to future scenarios many benefit the operations. The mine/quarry need a reliable measurement of the blast induced vibration for their operation to run at the most optimum condition. The local community need a reliable measurement device/procedure to ensure that the mine/quarry are maintaining their environmental limits within the allowed levels according to the mine/quarry development application.

The main need for this research is a complete understanding of the measurement technique so that the end user can be assured that what is being recorded is the blast induced vibrations from the mine/quarry operation. The parameters of the monitoring procedure and the mounting block and the maintenance of these parameters within strict limits will ensure that the blast induced vibration measured is a factual result and not some fictitious output from a poorly designed monitoring procedure.

### **1.3 Aim of Thesis.**

The main purpose of this study program was to report on an investigation into the validity of a vibration monitoring procedure developed over a number of years. The aspects of the design of the monitoring equipment have been detailed in literature in the past but the application and comparison of the standard mounting procedure have not been quantified before.

There has been a lot of work reported in the literature regarding vibration monitoring and the results of trials on this structure and trials in this and other mines etc. But, there

has not been any work reported on the effect on the mounting procedure of parameters of the soil that can cause coupling concerns. It will be shown that the coupling between the soil and the mounting block in the mainly procedure is the most important part of the monitoring procedure. If this coupling is not correct then the whole purpose for the monitoring exercise will be jeopardised and the results could be in error. The parameters of the soil or the condition of the soil will be examined and their effect on the bond between the mounting block and the soil investigated. These parameters will include the moisture content of the soil and how the behaviour of the grains of the soil can be affected by the inclusion of moisture around each individual grain.

A lot of field studies have looked at attenuation laws for blasting induced vibrations in particular areas of a mine. This site specific law is then used in other areas of the mine with sometimes quite alarming results. On a macro scale, as in these field trials, the geology and structure of one area of the mine and of another area of the mine can be quite different. As such the vibration transmission characteristics of the vibration wave through the ground is a fundamental property of the mineral structure of the ground. It will be shown that this variation in transmission rates or attenuation of the vibration level also occurs on a micro scale. It is the soil around the mounting block that has to transmit the energy in the vibration wave to the mounting block and then to the primary sensor. The type of soil will be investigated and there will be shown a difference relating to the type of soil the vibration wave is travelling through.

Soils as defined in this study are a conglomeration of small discrete particles and many thousands can be found in a small handful of the soil. It will be shown that the particle size distribution as defined by the Rosin–Rammler equation doesn't have a major influence on the transmission of the vibration wave through the soil. However, when the size distributions are taken to the extremes then the coupling will be compromised.

The most important parameter of the soil and one that can be influenced by the operator is undoubtedly the compaction of the soil around the mounting block. The compaction effect on the bond between the soil and the mounting block and hence the primary sensor will be examined. It is this bond that determines the exchange of energy from the vibrating wave to the primary sensor and the effect of the compaction regime will be discussed.

The equipment used in vibration monitoring has been developed to a high degree of sophistication today. Some of the properties of the equipment will be discussed together with their effect on the “result” of the vibration monitoring exercise. The properties of this equipment, which can have a bearing on the recorded vibration level, will be examined.

Many mounting procedures have been proposed in the past and a lot of equipment manufacturers have their favourite ways of mounting the primary sensor to the ground. It will be shown that there are large variations in the vibration level for the same source that can be recorded by some of these mounting procedures. The vibration source used in this section of the study was a typical blast from an open cut coal mine and the levels of vibration recorded will have large ranges. The standard procedure will be examined and its suitability for monitoring vibration levels even at high frequency investigated. Some of the procedures are quick and easy to install but what price is paid for “the easy way out” syndrome.

As with any measuring technique there will be errors and these errors must be evaluated if the procedure can be relied upon. The standard mounting technique does have inherent errors and the level of these errors will be investigated and discussed in detail. These errors can play a major role in the precision or accuracy of the result from the monitoring procedure and if they are not quantified then the variation in the results from different trials can not be truly classified as resulting from the changes made from trial to trial. These errors will be investigated and ways of minimising and maintaining them at low levels will be discussed.

The parameters of the procedure itself were then investigated and in particular the effect of the mounting block on the vibration level measured at a particular location. The effect of the mounting procedure on the vibration energy passing through the mounting location (the mounting block and the ground) will be investigated. A modification to the standard mounting procedure will be investigated to show the density effect of the mounting block on the recorded blast induced vibration waveform.

The basic aims of this thesis are to examine the vibration monitoring procedure and show that the “correct” level of blast induced vibration can be measured if guidelines are followed. With all mine/quarry operations today environmental concerns can cause restriction to some operations particularly if the vibration levels are not measured correctly.



## CHAPTER 2

### LITERATURE REVIEW AND THEORETICAL DISCUSSION

#### **2.1 Literature Review**

In all aspects of daily living contact with some object that was initially a lump of ore or mineral in the ground is made. This ore or mineral is not usually found on the surface in large enough quantities, so mining of the ore or mineral is required. Mining is a hard, dusty and environmental unfriendly occupation and some of the unit operations in the entire mining process produce outcomes that are not exactly accepted by everyone. These outcomes are controllable and one of the first issues is to measure the outcomes and their effect on the environment.

In the majority of mine/quarry operations the ore or rock material that has an economic value is covered by a top layer of gangue or waste material which could be up to 50 metres thick. This overburden material must be broken up or fragmented into small pieces that can be lifted and placed into excavation equipment for removal to a sterile area. The fragmentation of this overburden material is usually carried out using explosives and this is where the environmental outputs from the mining process become an issue. The use of explosive is cost effective in fragmenting the overburden material but one of the main issues is the production of blast induced vibrations.

Environmental issues have become more apparent over the past decade because the mine/quarry operation in the past was usually many kilometres from any local residents and the number of affected residents was small compared to today. In today's mining climate local residents live on mine/quarry boundaries and can feel every time a blast is detonated. All mine/quarry operations today carry out responsible practices and one of the important and integral aspects of blasting is the monitoring process used to measure the blast induced vibrations at the mine boundary. The responsible mine/quarry operator will control the blasting operations so that the blast induced vibration levels are within the allowable limits set by local councils in development applications.

With any form of control there must be some form of measurement and it is imperative that the measurement system is designed to record the primary event that has to be controlled by the process. In the case of blasting the measurement system is the vibration monitoring equipment and the primary event being measured is the blast induced vibrations at a location on the ground at the edge of the mine property. Standards Associations throughout the world have detailed procedures to be adopted to measure primary events for many situations but sometimes, through lack of input by the relevant industry, these standards are difficult to interpret and do not address all of the issues at hand.

In Australia the relevant standard used in vibration monitoring is the Australian Standard AS2187 – 1993. This standard details the use of explosives in the mine/quarry industry and blast induced vibration monitoring is mentioned in Section 10.2, which refers to Appendix J. In Appendix J, Ground Vibration and Airblast (Informative) the limits of blast induced vibration (from an explosive detonation at the mine/quarry) at a neighbouring house is detailed. These limits are as follows:

- 10 mm/s for residential or commercial premises at their boundary
- 25 mm/s for industrial premises at their boundary.

There is very little said about the way in which the device used to measure the blast induced vibration (the primary sensor) is actually bonded or coupled to the vibrating ground or structure except to say “the transducer should be effectively and securely coupled to the ground”. But if it is the blast induced vibrations that is to be measured then surely the primary sensor must be correctly attached to the ground before it can measure any effect of the blast induced vibrations on the ground. This is the most important parameter to be examined in this study.

As the urban sprawl encroaches on existing mine/quarry operations there is more than ever a need for a standard to measure the blast induced vibrations from these operations. The standards are becoming stricter in their advice as these standards are being upheld in courts of law these days. Brochu and Eltschlager (1999) discussed the seismograph standard put forward by the International Society of Explosive Engineers. This standard details the equipment physical characteristics that should be considered. Mention is made of the sensor density which should be matched to the density of the soil as near as

practically possible. The location of the sensor to buildings is discussed and sandbagging and spiking the sensor to the ground is recommended.

Standards have to be dynamic documents and are basically designed as guide lines for a particular action to be taken. In the case of vibration monitoring standards these guide line are being much more defined. For example, underwater blasting is a specialised field and the existing standard in one American state was investigated as to its validity in today's environmental climate. Miller et. al. (1999) discussed standards for blasting underwater including the "bubble pulse" from an underwater explosion where "the bubble pulse generates low frequency vibrations that have the most potential for damaging structures". The use of scaled distance alone is not recommended for vibration compliance and control, as a frequency component should also be included. Their work showed that the vibrations from underwater blasting are best predicted using a variable frequency versus peak particle velocity standard. Air blast was also investigated and was concluded that depth of charge was the controlling factor in this case. So it can be seen that as the conditions change as we progress as a society, so too must our standards that we rely upon for direction when disputes arise. A understanding of what affects the monitoring procedure is discussed in this paper. Guidelines for the proper installation of monitoring equipment are detailed if the actual blast induced vibrations are to be measured accurately.

Some analytical work has been carried out on the various mounting or coupling methods used to bond the primary sensor to the ground or structure of interest. However, not a lot of definitive work has been reported on the faithfulness of a particular bond in measuring the "true" blast induced vibration level at a particular location. There are many "different" bonding techniques and some can not be used in some situations, but it can be limited to a couple of techniques that cover all situations and will measure the blast induced vibrations and not some artefact of the mounting procedure. A paper by Grogan (1998) detailed some of the geophone attachment methodologies. In this paper the manufacturers methodologies are discussed as well as the US Bureau of Mines standard. These methodologies rely on the user having some forward knowledge of the vibration level that will be experienced at the location, which is the case when vibration must be maintained within certain limits. Some methods of bonding are accepted for one type of structure but would be totally impractical in other



circumstances. Soil mounting is recommended by completely burying the geophone to a depth of 15 cm or more but no allowance for the geophone cable is mentioned. Short spikes and sandbagging are acceptable when low vertical accelerations are expected. However details are not given on any study to compare the different bonding methodologies but acceptance of these methodologies to faithfully record the blast induced vibrations at a particular location is understood.

As with any measuring system some thought has to go into the procedure if the outcome of the measurement techniques are to have any validity. The vibration monitoring procedure incorporates both physical and electronic aspects and both must be accurate if the result is to be believed. The monitoring equipment in use today has been developed to a high degree of sophistication and relatively small pieces of equipment are able to store massive amounts of event data. The main constraint these days is the power capacity of this equipment as it is often the mine/quarry operations that have problems initiating the blast at the specified time due to production difficulties. The physical side of the procedure is the one aspect that the operator can play a very important part. If the equipment is not coupled to the event being measured in the correct manner then it must be asked what is really being measured. A paper by Blair (1995a) discusses the science behind the development of the standard mounting method used in this study. A mount to support the primary sensor should be constructed as a cube or right cylinder with an aspect ratio of one. As there are competing influences of radiation and scattering there is an optimum design for the mount. The radius of the mount was shown to be related to the soil shear wave velocity and an upper frequency that can be successfully recorded. Secondly a mass factor of the mount, related to the mass, density and geometry of the mount, was considered. The ground coupling was shown to be negligible if these two parameters were maintained within certain practical limits.

Once a method is decided upon, the equipment is designed and the procedure determined it must be tested in the field. It is difficult to test the vibration procedure in the field, as it is impossible to know what exactly the vibration level at any location would be. Same weight explosive sources detonated at the same distance from a vibration monitor will inevitably record different vibration levels due to the structure and geology of the ground through which the vibration wave is travelling. The question will always be asked as to the effectiveness of the coupling to the ground in these

monitoring exercises. But with the confidence of a sound scientific background engineered into the vibration mounting procedure little doubt can remain as to the faithfulness of the recordings obtained. Some fieldwork carried out by Blair (1995b) discussed the different mounting methods and some structures that are affected by blast vibrations. The spike method of mounting was shown to over-estimate the vibration level by 46% and therefore, this method should be used with caution when monitoring vibration levels for compliance situations. Structures such as bridges, grain silos and pit walls all vibrate when subject to explosive loadings. These structures can withstand some level of vibration but when the frequency is at the resonance frequency this can cause some catastrophic results. Moving this blast induced vibration frequency to a higher level was shown to be possible with high accuracy delay detonation of blast holes in a pattern of blastholes.

Vibration monitoring is not only used when the vibrations are blast induced. Seismic monitoring relies on the same principals in that it is the ground movement or vibration that is being measured but this time it is a natural occurrence that has caused the vibrations. For seismic engineers and scientists to obtain an understanding of how the ground is moving as a function of time and to make future predictions based on these measurements they must be able to have confidence in the vibration monitoring. Mounting of the primary sensor to the ground is also an important step in recording the ground movement whether it is natural or induced by small explosive charges. Work by Khrono (1983) discusses the ground coupling of both vertical and horizontal geophones. The data was found to fit a geophone response with a single coupling resonant frequency and damping factor. For frequencies above the coupling resonant frequency the coupling can be disturbed and the amplitude and the phase can be altered. Burying the geophone was found to minimise errors that can be experienced in the field. It was recommended to replace spiked geophones by burying the geophone in the soil.

One thing that is often overlooked in the placement of the primary sensor is the effect of any local structure on the waveform recorded. The whole purpose of the monitoring procedure is to measure the blast induced vibration waves as they pass the monitoring location. However if some structure is attached to the primary sensor then this structure can back react on to the primary sensor and some change in the waveform will be recorded. This effect is shown quite clearly in a paper by Crouse et. al. (1984) who

discusses the results of trials at an accelerograph station into the effects of the physical structure itself on the recording taken at this station. The structure consisted of a concrete pad with a wooden shed attached to shelter the accelerograph. The real parts of the complex foundation impedance functions were similar to theoretical impedance functions. The imaginary parts, a measure of the foundation dampening, were found to be close to the theoretical prediction for a surface foundation. Amplification of the earthquake waves was shown in specific directions and their conclusion was that more careful attention should be paid to the construction of earthquake monitoring stations.

Seismic events even though they can be catastrophic are more or less accepted as part of life living on this planet. The crust surrounding the inner core of the planet is continually moving which results in earthquakes, which we have all experienced or seen the results of. But blasting operations are in a different category and the vibrations that result from the detonation of explosives is not accepted by the community at large because of many factors. Neighbours living close to mine/quarry operations frequently complain about the blasting operations and the damage that these operations can cause. However, sometimes the damage is perceived as being caused by the blasting operations when it was really caused by some other process, sometimes a natural process. A paper by Siskind (1998) gives a very good outline on the procedure that should be adopted when complaints are received from blasting operations. Since a lot of complaints are more of a perceptive issue it is important to gather information on a scientific basis with input for the complainant to satisfy both parties to the vibration issues. His paper details some 31 areas where information can be gathered to form an "impact Assessment for Blasting Operations". If procedures similar to this are followed when and if the blasting operators are taken to court then some back ground information will always be helpful in supporting the blasting operator's case.

Years ago when blasting operations were being noticed by regulatory bodies due to complaints from residents it was the peak level that was the deciding factor in the damage of structures. A lot of research has gone into structural damage and blast induced vibrations and now a days the standards incorporate some of this research in the "limits" that are applied to these blasting operations. Responsible mine/quarry operators can control both the peak levels and also the frequency content of the operations so sensitive regions can be avoided. As blasting operations consist of

individual blastholes being detonated at separate time intervals it is possible to have these detonations at a frequency that will be conducive to the nearby structures. Some good work published by Siskind (1986) who looked into frequency analysis and response spectra from blast induced vibration at a high complaint area of blast near a coal mine. His work has shown the “FFT determinations are satisfactory if they are assigned to appropriate specific peaks or distinct parts of a vibration record”. However, vibration waveforms exhibit multi-peaked frequency traces and the allocation of one frequency to this multi-peaked trace can lead to misunderstanding of what is really happening as the ground is affected by the blast induced vibration. He goes on to say the accuracy does nothing for the actual damage potential as there is always some spread in the data used to define the limit set out in the standard. He then discusses blast vibration duration and response spectra analysis and says that it has been suggested that a “steady state” occurs which can be related to damage which is in the order of 5 cycles, so eliminating the effect of duration of a blast on structural damage.

Even though the mine/quarry operators can control the blasting operations at the blast site, the blast induced vibration waves travel through the ground and these waves are modified in various ways during the time these waves are effective in the ground. This is similar to vibration attenuation site laws that are used to predict the vibration level in that it is site specific. Vibration wave attenuation and dispersion are parameters that should be considered when designing blast operating conditions in sensitive areas. Then understanding of the attenuation and dispersion of the vibration wave can help to control these vibrations. This was shown in some work by Blair (1996) on the transmission of vibration waves through solids and the attenuation characteristics of the rock material. Small laboratory samples used to determine *p*-wave and *s*-wave values do have problems if the grain size is similar to the core size. A large sample approximately 0.7 metres cube was used with good agreement between theory and measured values being recorded. The models used were based on intrinsic and scattering loss mechanisms for seismic waves in rocks. The transmitted waveforms showed evidence of elastic scattering and this scattering decreased with increasing mean grain diameter from these blocks. He states that the scattering loss is scale-independent and the treatment is applicable to scattering at lower frequencies.

However, it is not only the blast induced vibrations that can cause damage. Mining operations use many different types of equipment and each one reacts on the ground to produce some form of vibration. Although this mining equipment does not introduce a lot of energy compared to blasting in the ground these vibrations are never the less important and must be known to differentiate between blasting induced vibrations. A paper by Sen et. al. (1996) looked at the vibrations generated by blasting and construction equipment. Their paper discussed the cube root scaled distance law compared to the square root scaled distance law and found that their data was more consistent with the cube root law. Their results also showed that blasting induced vibrations had similar “natural frequencies and vibration characteristics” to construction equipment (pile driver and rock breaker).

As with any measurement scheme one of the main outcomes is a means of predicting future events from the input parameters. Traditionally a decay power law is used to relate the vibration level to a scaled distance and a set of site specific parameters are determined from past blasts. This type of approach has been used at existing mine/quarry operations and also at new or greenfield sites where single blast holes are detonated to obtain the site parameters. A paper by Toomik and Tomberg (1998) looked at underground blasting and its effect on surface vibration levels in competent rock areas. Their work was looking at oil shale deposits where fracture to release the oil and not cause excessive damage was an important criteria and the deposits were only 3 metres below ground level and some 30 metres thick. From their work they determined charge weight laws that would be applicable for different depths of coverage. They then say that the structure between the explosive source and the monitoring point will play a role in modifying the predictive formula used to determine the peak particle velocity.

The decay power law has been used extensively in the past and some work has been carried out to look at relationships that can better describe the vibration level. Some workers have looked at various deviations of the basic decay law and one of the popular deviations is a cube root or square root of charge weight. However a paper by Ghosh and Daemen (1991) discuss the vibration attenuation predictive equations in use today. They say that log-log plots of vibration data can hide some of the underlying physics of wave attenuation. Their improved predictor separates the geometric effect (decay with

distance) and the influence of material behaviour (inelastic attenuation producing nonlinear curve in log-log scale). Their data fits the predictors very well and extrapolation can be used to predict levels that are very close to those measured. They do say that blasting is not a controlled science as single hole blasting can produce different vibration levels and multiple hole delay blasting produces wave interference that can cause vibration levels to be different.

These predictive relationships are useful in determining the charge weight that can be detonated while still maintaining a certain vibration level. However, it must be remembered that the predicted level is a best estimate and the actual level can be higher or lower than the predicted level. If it is essential that the vibration level does not exceed a certain level then for more confidence a 95% confidence range should be determined based on this decay site law. Work carried out by Ester and Vrkjan (1999) discuss the blasting issues which high-density residential building can cause. The residential houses were as close as 14 metres from the blasting operations and a pit some 210 metres by 70 metres and up to 28 metres deep was blasted. A total of 15 monitoring locations were set up and an attenuation law was established from test blasting to maintain a “ground oscillation velocity” of 2.0 cm/s. An explosive with the highest velocity of detonation was used as it gave the lowest ground oscillation velocity. Frequent blasting 2 to 10 times a day lead to a lot of complaints so the ground oscillation velocity was reduced to 1.0 cm/s, which minimised the number of complaints and allowed the project to continue even though costs were increased.

As the distance increases from the explosive source both the vibration level and the frequency of the vibration wave are altered. The vibration level has been studied over the years and as stated above decay law attenuation is the usual way to predict the vibration level at distance. However the change of the frequency with distance has been known for years and the determination of frequency at distance is governed by fundamental properties of the ground the vibration wave is travelling through. Usually this frequency change is associated with attenuation – dispersion pairs that describe the changes that affect the vibration wave. This work discussed by White (1983) in his book gives a very good account of the effects of waves travelling through the ground. Although applied to seismic waves it is also applicable to blast induced vibration waves travelling through the ground. He discusses the loss mechanism and attenuation and

draws on a lot of work published by many authors. The loss mechanisms discussed include fluid in pores and the absorption of energy, a thermoelastic effect where the wave causes heating of solid particles and crystal imperfections which cause resistance to wave travel. He also discusses some attenuation-dispersion pairs for “lossy” solids (particulate materials) that are assumed to be causal.

Modelling work has been reported in the literature where the investigators have examined the effect of vibration waves on structures on the surface of the ground. Equations have been developed over the years to define how the structure reacts to earthquakes and appropriate action taken to minimise structural damage. Some of these equations have been included in a computer program that models the effect on the mount embedded in the ground. The work of Luco and Wong (1982) discuss earthquake response of symmetric elastic structures subject to SH-wave excitation and Rayleigh waves. Some suggestion of filtering of the incident wave by the foundation is given and also the rocking effect of Rayleigh wave excitation is discussed. Modelling of large buildings and concrete structures has shown that the nonvertical incident wave is significantly different to vertically incident waves. Equations are developed that are used in the modelling programs used in this study. Some work from Wolf and Somaini (1986) show their modelling work on an unbounded soil in a soil-structure interaction analysis in the time domain. Equations are developed that are used in the modelling program in this study of the mounting block used to support the primary sensor.

Other work by Warburton (1957) considers a circular solid resting on an elastic stratum subjected to a forced vibration loading. Good agreement was obtained between theory and measurements taken in the field. This work showed that when the vibrating force is applied to the solid resting on the surface the resonance frequency was dependent on the mass factor (relating mass, density and geometry of solid), the depth factor (relating depth of stratum and radius of solid) and Poisson’s ratio for the stratum.

The vibration waveform is a complex combination of at times many separate wavelets. These wavelets are the signature waves from each individual hole detonating and its affect on the ground. The analysis of a vibration waveform is a specialist function requiring years of training and some workers in the past have undertaken this task and reported their findings in the literature. A book written by Moore (1985) discusses the

analysis of vibration records and shows the complexity of the common vibration trace that is recorded from a blast. Techniques are shown that represent the vibration trace so that a better understanding of this vibration trace can be undertaken. Many of the mathematical techniques available for the analysis of the vibration trace are also discussed.

## **2.2 Theoretical Discussion**

### **2.2.1 Vibration wave generation**

One of the most annoying aspects of the mining industry is the environmental by-products of mining operations that are inevitably harmful to both our health and the structures we build. In all mining operations the local councils have put systems in place to determine conditions that the mining operations must obey if the operation is to remain as an on-going concern. Most local councils use existing standards (ie. Australian Standards, AS2187.2) as the guide and the limits for vibration levels have been discussed in the previous section.

The mining operation employs blasting practices to fragment the rock so that the valuable mineral or fuel can be exposed for removal to the market place. A relatively small diameter blasthole is drilled in the ground and explosives are loaded into the hole and covered with a stemming material (small crushed rock). The purpose of the blasthole is to contain the explosive reaction allowing it to work on the confining material and hence cause controlled damage of the surrounding rock material. A series of these blastholes are drilled in the area to be blasted and each hole is connected in an initiation sequence before being fired to fragment the ground in an orderly fashion.

#### **(a) The Explosive**

The explosive is a relatively stable mixture consisting of a compound containing oxygen which can be released during the reaction and a compound containing a fuel, both are required to propagate the chemical reaction. Both of these reactants can be commonly available compounds and the most prolific industrial explosive used in the



mining industry today is called ANFO that consists of Ammonium Nitrate (a common fertiliser) and Fuel Oil (diesel fuel used in motor vehicles for example). These reactants, when mixed in the optimum proportions, form the explosive that is relatively stable, as, even when mixed, it is safe to transport through out the country to the mine site. It is not until the reactants are forced together and the chemical bonds are shattered that the explosive detonates. In all responsible mine/quarry operations this detonation process occurs in a controlled manner.

### (b) Chemical reactions during detonation

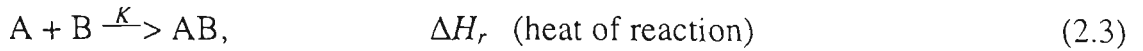
Chemical reactions are not usually spontaneous and even if they are spontaneous the reaction conditions must be such that initial energy conditions are high enough to force the reaction to begin. Once the reaction starts, in some cases, the energy released by the reactants being transformed into products can sustain the chemical reaction. From elementary chemical principles a rate expression can be derived for a particular reaction and a rate expression can be defined in terms of a temperature dependent term and a composition dependent term.

$$\begin{aligned} r_i &= f_1(\text{temperature}) \times f_2(\text{composition}) \\ &= k \times f_2(\text{composition}) \end{aligned} \quad (2.1)$$

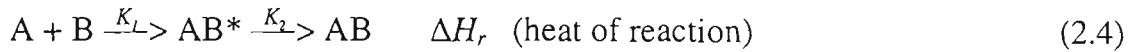
The reaction rate constant,  $k$ , can be represented by Arrhenius' law

$$k = k_0 e^{-E/RT} \quad (2.2)$$

where  $k_0$  is a frequency factor and  $E$  is the activation energy of the reaction. This expression gives a very good approximation to temperature dependence of the reaction. However in a typical industrial explosive reaction energy must be supplied to overcome the initial state of the reactants before the chemical reaction can continue. The formation of the products from the reactants more than likely goes through some transition state where unstable intermediates are formed which make the formation of the more stable products to a more energy stable state possible. For a typical chemical reaction the following representation can be made.



But for this reaction to occur the reactants must be changed in some way so that the more stable products can form, so



This simplified reaction mechanism applies for reactants and products that are in equilibrium but the same basic understanding can apply for the combination of the reactants in a detonation process. The reactants in this case are forced together by a series of smaller detonation processes until the input energy is large enough to overcome the energy level of the original reactants. A schematic representation of this process is shown in Figure 2.1.

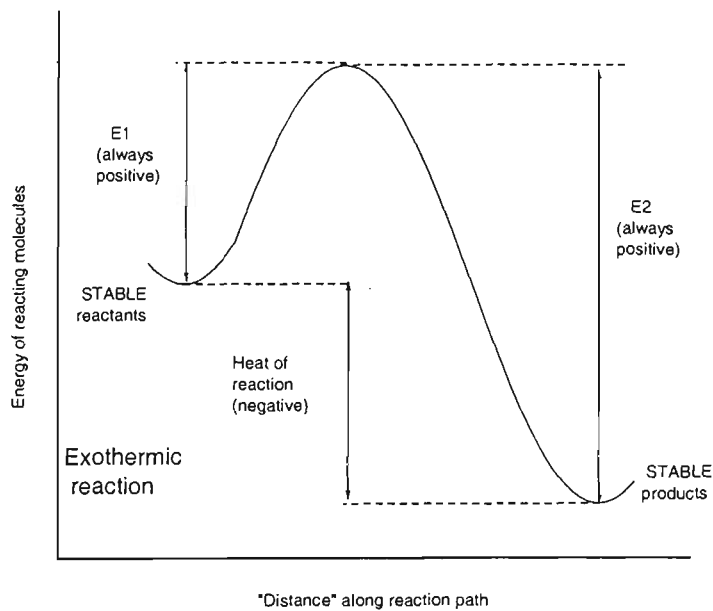
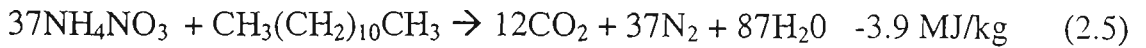


Figure 2.1 Schematic of energy level transformation of reactants to products

The chemical reaction consists of combining the oxidant and the fuel together with such a force that the existing “stable” chemical bonds are broken and new more stable compounds are formed. For example using the explosive mentioned above, ANFO, the following chemical reaction occurs.



With the breaking of the chemical bonds, by force, there is a release of energy (3.9 MJ/kg) as the new compounds formed are at a more stable and less energetic state than the initial reactants. The ammonium nitrate is a solid and the fuel oil is a liquid and as such both occupy a relatively small volume. Compared to the products of the reaction, carbon dioxide (CO<sub>2</sub>) and or nitrogen (N<sub>2</sub>) are both gases while water (H<sub>2</sub>O) is a liquid but at the reaction conditions would be a vapour. Each mole of a gaseous product occupies 22.5 litres of volume at standard temperature and pressure so at the reaction conditions these volumes would be much greater. It can be seen at the reaction conditions the gaseous products would be under extreme pressure and would be “searching” for any way to equilibrate this pressure and hence aid in the damage of the confining rock structure.

### (c) Detonation

Detonation can be defined as the forcing together of compounds that react to form more stable less energetic products. From the bond energies of the reactants and the products above the energy released when this reaction occurs can be calculated. When 1 kilogram of the explosive mixture is detonated approximately 3.9 MJ of energy are released and the products from the chemical reaction are at a lower energy level than the reactants are so are more stable. This amount of energy is not excessive, as far as chemical reactions are concerned, but it is the time scale that this energy is released over and the state of the products at the completion of the reaction that causes the destructive power of the explosion. The temperature of the reaction can be up to 4000K and the pressure from the formation of the gaseous products can be in excess of 10 GPa. So it can be seen that under the conditions of the reaction (elevated temperature and pressure) and the time scale for the reaction to occur that the conditions are right for the production of a shock wave which will travel throughout the confining material causing damage to the surrounding ground. These product gases (at the temperature and pressure) form a driving force which can be used to move the fragmented ground under controlled conditions.

The detonation process is a steady state process and when a cylindrical charge of explosives is considered the reaction is regarded as self-propagating. As the reaction progresses the axial compressive effect of the shock front changes the state of the explosive so that the exothermic reaction stabilises to the requisite velocity (the VoD of the explosive). In solid explosives (for example detonating cord and boosters) this compressional energy will be unevenly spread resulting in some areas of high temperature by friction and plastic deformation, which aid in the propagation of the reaction front. In mixed explosives (such as ANFO) the reaction does not have time to be completed in the part of the reaction zone that directly affects the reaction rate. The remaining unconsumed reactants liberate their energy in the after-combustion zone and contribute indirectly to the reaction rate consequently, these explosives have a lower VoD. However, in mining applications this energy is not lost but is contained by the confining ground and allowed to react on the ground to help in the fragmentation process.

The reaction zone has been measured by experiments and has a thickness of approximately 0.2mm (explosive dependent). The pressure can be up to 220 GPa while the temperature can be in the vicinity of 3000K and the density of the reactants in the reaction zone, will have increased by 30%. The reactants pass into the detonation path and experience a sudden rapid increase in pressure followed by a pressure decrease as the reaction progresses. The pressure at the rear of the reaction zone is maintained by the acceleration of the reaction products and at the rear of the flow where the transformation of chemical energy is slow the flow is no longer steady. The reaction zone accelerates away from this rear zone leaving a flatter pressure profile where the remainder of the reactants is consumed. The boundary between this steady state region and the un-steady state region is called the Chapman-Jouget plane. Ideal explosives complete their reaction within this plane and non-ideal or commercial explosive have un-reacted reactants that move into the zone behind the reaction front.

The detonation wave is a shock wave in a reacting explosive material. The chemical reaction occurs nearly instantaneously within a very short distance and the energy released helps to drive the process to completion for the length of the explosive column. A snap shot of the shock wave at an instant in time is shown in Figure 2.2.

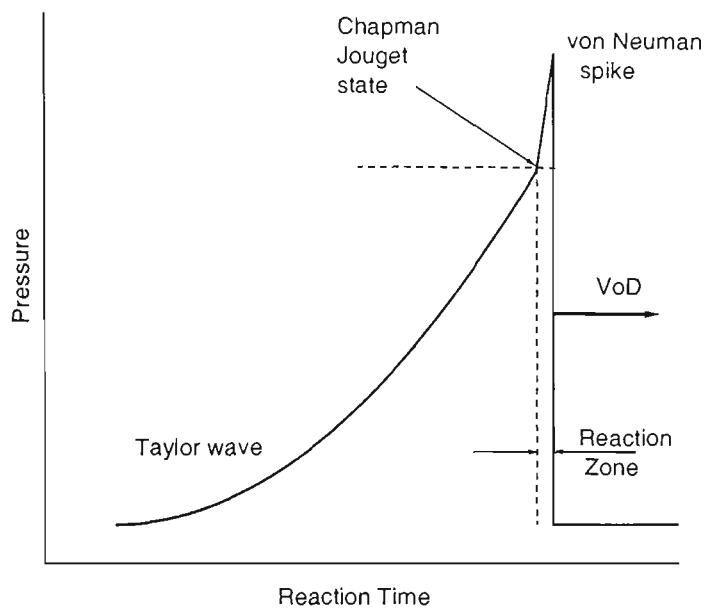


Figure 2.2 A detonation wave in a condensed explosive.

The pressure profile in the reacted zone is known as the Taylor wave and shows how the pressure decreases as the reaction front progresses. The spike at the reaction zone, called the von Neuman spike, initiates the reactants and is the point at which the reactants change to products. This all happens in the reaction zone bounded by the reaction front and the Chapman-Jouget plane at the rear. The state of the reaction zone (pressure, density, particle and shock velocity) is characteristic of a particular explosive at a given initial density. Behind the Chapman-Jouget plane the hot pressurised gases expand in a manner determined by the confining material.

#### (d) Detonation wave and shock wave

The detonation of the reactants forms a detonation wave, which travels the length of the explosive where the chemical decomposition is assumed to take place, thus producing a shock wave. The energy conservation equations have the same form for detonation waves as for shock waves and the chemical reaction changes the explosive reactants to reaction products. The conservation of energy must apply for both this detonation wave

and the shock wave. The chemical reaction can even change the total number of moles in the equation. However the initial internal energy of the reactants is only the same as the initial internal energy of the products when both the reactants and products are

polytropic gases (ideal gas with constant specific heat  $c_v$ ). The energy conservation equation for a detonation having a heat of reaction  $Q$  and velocity of detonation of  $D$  becomes

$$\text{Detonation : } p_1 u + \rho_0 D Q = \rho_0 D \left( c_v (T_1 - T_0) + \frac{u^2}{2} \right) \quad (2.6)$$

$$\text{Shock : } p_1 u = \rho_0 D \left( c_v (T_1 - T_0) + \frac{u^2}{2} \right) \quad (2.7)$$

Where  $p$  is pressure,  $u$  is velocity and  $T$  is temperature.

For a condensed explosive the specific internal energy  $E_1 - E_0$  is a function of temperature, pressure and specific volume. As the reactants and products are in a different form it is not possible to exactly express the internal energy for the detonation in a condensed material in a simple way. The difference is not large and as an approximation can be written as follows:

$$\text{Detonation : } E_1 - E_0 \approx Q + \frac{u^2}{2} \quad (2.8)$$

$$\text{Shock : } E_1 - E_0 \approx \frac{u^2}{2} \quad (2.9)$$

The heat of reaction is the heat evolved when the detonation products are formed and are at STP (temperature of 0° Celsius and 1 atmosphere pressure). Here  $Q$  is defined as

$$Q = - \left( \sum n_i (\Delta H_f^0)_i - \sum n_j (\Delta H_f^0)_j \right) \quad (2.10)$$

where the standard enthalpy of formation at 298.15 K is  $\Delta H_f^0$ .

The temperatures and pressures at the reaction conditions of some common explosives are shown for example in Table 2.1. As can be appreciated the shock wave set up as a result of these reaction conditions is quite drastic and this induces a wave like motion in the rock particles, which travels through out the rock mass.

Table 2.1 Comparison of reaction properties of some commercial explosives

Explosive	TNT	NG	ANFO
Density (g/cc)	1.64	1.59	0.90
Pressure (MPa)	206	247	74
VoD (m/s)	6950	7699	5531
Gas Volume(l/kg)	579	716	973
Q (MJ/kg)	5.36	6.25	3.91
Weight strength	1.20	1.40	1.00

After Persson et al. (1994)

The detonation of explosive materials occurs in a very short time scale. A property of the explosive used to quantify its performance is the velocity of detonation (VoD) or the speed of the chemical reaction. If a 10 metre column of explosive with a VoD of 5 km/s (typical of ANFO explosive material) were detonated it would take 2 milliseconds for the entire column to be consumed. This reaction rate and the resultant release of energy sets up a shock wave in the confining material. The shock wave that results from this chemical reaction causes massive destruction of the confining material close to the blasthole and is radiated in all direction from the blasthole throughout the confining medium. The rate of transmission of this shock wave is a fundamental property of this confining material.

#### (e) Properties of host material

In reality the confining material is not completely homogenous and as such there are many discontinuities that the shock wave encounters on its path through the confining material. At each of these discontinuities and the internal resistance to movement of the rock mass some energy is lost and the magnitude of the shock wave decreases with distance from the explosive source. At each of these boundaries the energy is partitioned between transmission over the boundary and reflection by the boundary. The amount of this partitioning is dependent on the acoustic impedance of the confining material that is related to the density and the sonic velocity of the material by the following:

$$Z = \rho * V_p \quad (2.11)$$

where  $Z$  is the acoustic impedance,  $\rho$  is the density of the medium and  $V_p$  is the sonic velocity or  $p$ -wave velocity of the medium.

#### **(f) Generation of waves during detonation**

The shock wave generated during the detonation of the explosive close to the blasthole causes extensive damage to the confining material. The pressure of the product gases begins to cause movement of the rock mass resulting in the equilibration of the gas pressure with time as the path to the atmosphere is established due to the rock mass cracking. However, during this process the shock wave is travelling through the ground with ever decreasing magnitude as the distance from the explosive source increases. The speed or sonic velocity of the wave through the ground is relatively constant and is a fundamental property of the ground through which the shock wave is travelling. This velocity can range from 1 km/s for sandstone material to 6 km/s in competent solid rock structures such as granites and basalts. Of course this value can be altered by the inclusion of discontinuities and changes in the geology of the local rock mass.

#### **(g) The stress wave**

The stress wave travelling through the ground causes a compression wave to be formed in the plane of the explosive source and an observation point and shear wave to be formed in the plane normal to the direction of travel of the stress wave. Depending on the structure of the ground other types of surface waves can also be formed such as Rayleigh and Love waves. The waves generated by an explosive source can be categorised in three components and to describe these waves, measurements of three orthogonal motion components must be made. One is the longitudinal or radial component where a sensor is aligned in the plane between the explosive source and the monitoring location. The second is the transverse component, where the sensor is aligned in the horizontal plane at right angles to the longitudinal plane. While the third is the vertical component, where the sensor is aligned in the vertical plane through the monitoring location and the explosive source.



### **(h) The body waves**

The waves can be further categorised into body waves and surface waves. Body waves can be further divided into compressive (compression or tension waves) and are sound like waves which are usually denoted as *p*-waves. The *p*-waves are usually the first to arrive at a monitoring point and are compressive waves. Individual ground particles are forced to oscillate about an equilibrium point and transmit the energy to a neighbouring particle to continue the motion of the wave through the ground. This type of motion is shown in Figure 2.3(a) and it can be seen that as the particle motion is in the direction of travel of this wave the maximum transmission rate would be experienced in this wave type. The second type of body wave is the distortional or shear wave, which are usually denoted as *s*-waves. The *s*-waves have a slower propagation rate than the *p*-waves, as the particle motion is in a direction normal to the propagation direction as shown in Figure 2.3(b). Again the particle motion occurs about an equilibrium point and the energy is passed from one particle to the next but there exists opportunity for energy losses due to the motions being orthogonal to each other.

### **(i) The surface waves**

The vibration waves generated by the detonation of the explosives also sets up surface waves that can at times be quite large. These waves usually occur at large distances from the source and travel at slower speeds than the body waves. With this difference in propagation rates it is often found that the waves separate at distant monitoring locations and sometimes these surface waves can have higher amplitudes than the body waves at this distant location. The surface waves also rely on the propagation of particle to particle transfer of the energy for the continuation of the wave through the ground. The particle motion of this type of surface wave is shown in Figure 2.3(c).

However it is not a straightforward path between the explosive source and the monitoring location as there can be many ray directions and the local geology and structure will play a big role in the levels of vibration experienced at any location. It must also be emphasised that if there are many waves arriving at the monitoring location from the one explosive source then it is imperative that it is only those waves that are a result of the explosive detonation at the mounting location are recorded.

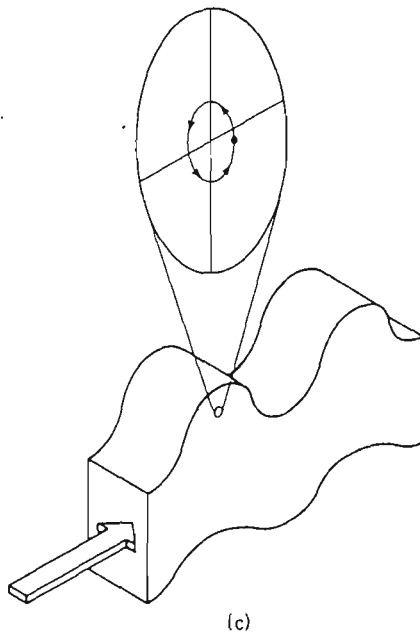
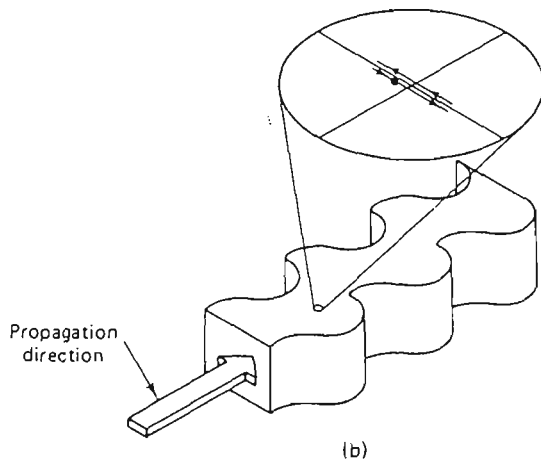
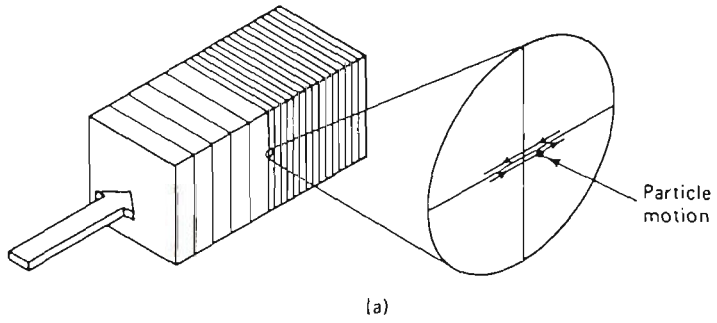


Figure 2.3 Vibration wave propagation (after Dowding, 1993)

### 2.2.2 Analytical representation of a wave.

The representation of vibration wave motion in an analytical sense can be viewed upon in classical physical terms. Jaeger and Cook (1976), Bollinger (1971), Kolsky (1963) and Bullen (1954) all give a detailed analysis of a wave, and the different surface wave types, as the vibrating disturbance travels through the ground.

An impulse disturbance sets up a vibration wave, which is transmitted in all directions through out the medium. This disturbance is in the form of an impulse load and as such sets up a shock wave in the medium. If the disturbance is an explosive source and the distance from the source is in the order of hundreds of metres from the explosive source the following occurs.

The destructive compressional force falls within the elastic region of the medium i.e. below the elastic limit of the material a short distance from the disturbance. The force of the shock wave causes local displacement of the material, which in turn, due to the elastic nature of the medium, forms an oscillatory motion of the local particles. The energy is transferred from particle to particle in a wave like motion. At this stage there is no bulk movement as the energy of the shock wave is within the elastic range of the medium. The shock wave propagates through the medium as a wave and as such has a wave propagation velocity and each particle exhibits particle motion i.e. an oscillatory velocity or particle velocity.

The force of the system is stress dependent on time and is related to the material response to the disturbance controlled by the elastic properties of the material. The energy in the vibration wave travels as kinetic energy (particle to particle motion) and potential energy (particle displacement in the wave motion). The energy flux decreases as distance from the source increases as some function of (distance)<sup>-2</sup> but energy loss occurs as the wave propagates through the medium due to friction and absorption within the medium which attenuate the wave amplitude.

The wave motion as it travels through the medium can be compared to simple harmonic motion or a spring-mass system. The wave motion can be:

- 1) Transient, typically a blast wave attenuating with time and distance from the initial impulse disturbance.
- 2) Periodic or resonance where the structure can be set to vibrate at a natural frequency due to the frequency of the initial disturbance.
- 3) Random or noise where prediction can only be achieved on a probabilistic basis.

Assume the impulse disturbance is some function of distance and time

$$f(x,t) = f(x - vt) \quad (2.12)$$

where  $x$  is displacement,  $t$  is time for this displacement to act over and  $v$  is the velocity.

As  $x$  increases some small quantity  $dx$  in some time  $dt$  then

$$f(x + \Delta x, t + \Delta t) = f((x + dx - v(t + dt))) \quad (2.13)$$

This is also a definition of velocity.

If we represent a vibrating wave in simple harmonic terms, then

$$f(x - vt) = A \sin[k(x - vt)] \quad (2.14)$$

where  $A$  is the amplitude of the wave and  $k$  is a factor to ensure the dimensions are satisfied. The period of a wave is defined as the time between points on the wave at the same amplitude

$$T = (t_2 - t_1) \quad (2.15)$$

And for a sinusoidal wave

$$T = 2\pi / kv \quad (2.16)$$

The wavelength,  $\lambda$  (also known as the wave number) is the distance travelled by the wave in one complete cycle of the wave

$$\lambda = Tv = 2\pi/k \quad (2.17)$$

The angular frequency  $kv = 2\pi f = \omega$

where  $f$  is the wave frequency.

Substituting  $k$  and  $\omega$

$$\begin{aligned} f(x - vt) &= A \sin(kx - \omega t) \\ &= A \sin 2\pi (x/\lambda - t/T) \end{aligned} \quad (2.18)$$

if a phase angle is added to the equation of motion ie. a second wave appears at some time after the arrival of the first wave then this second sinusoidal wave can be represented by

$$f(x - vt) = A \sin [k(x - vt) + \phi] \quad (2.19)$$

where  $\phi$  is the angular spacing between the first and second waves.

However pure sinusoidal motion does not occur on a macro scale in nature and losses due to distance and inherent rock structure absorption occur. Blast induced vibration waves are transient pulses and as such its time scale is limited and the amplitude attenuates with both time and distance for the source of the disturbance.

The amplitude  $A$  of the pulse is a function of the initial amplitude  $A_0$  then

$$A = A_0 \sin[2\pi(x-vt)]/L \quad (2.20)$$

where  $L$  is the distance travelled

Now the particle velocity,  $\partial A/\partial t$ , can be determined from this equation. The particle velocity is a partial differential of this function with respect to time

$$\partial A/\partial t = -(2\pi v A_0/L)\cos[2\pi(x-vt)/L] \quad (2.21)$$

Because there is motion there is strain so the strain is a partial differential with respect to distance

$$\partial A/\partial x = (2\pi A_0/L)\cos[2\pi(x-vt)/L] \quad (2.22)$$

Now the energy in the wave has a kinetic energy component and a potential energy component.

The kinetic energy is

$$(\frac{1}{2})\rho(\partial A/\partial t)^2 dx = (2\pi^2 v^2 A_0^2 \rho/L^2)\cos^2[2\pi(x-vt)/L]dx \quad (2.23)$$

where  $\rho$  is the medium density.

Now strain,  $\epsilon$ , depends on whether the wave is a longitudinal wave (compression or  $p$ -wave) or a transverse wave ( $s$ -wave).

The strain energy for a  $p$ -wave is

$$(\frac{1}{2})(\lambda+2G)\rho(\partial A/\partial x)^2 dx = (2\pi^2 A_0^2 (\lambda+2G)/L^2)\cos^2[2\pi(x-vt)/L]dx \quad (2.24)$$

where  $G$  is the modulus of rigidity of the medium and  $\lambda$  is Lamé's parameter relating stress and strain in perpendicular directions. While the strain energy for a  $s$ -wave is

$$(\frac{1}{2})(G)(\partial A/\partial x)^2 dx = (2\pi^2 A_0^2 (G)/L^2)\cos^2[2\pi(x-vt)/L]dx \quad (2.25)$$

The velocity of propagation of a wave acting on a body of constant density and constant internal forces for a  $p$ -wave is given by

$$C_p = [(\lambda + 2G)/\rho]^{1/2} \quad (2.26)$$

And for a  $s$ -wave is given by

$$C_s = [G/\rho]^{1/2} \quad (2.27)$$

When these propagation velocities are considered it can be shown that the energy in the wave is divided equally between kinetic energy and potential energy thus the particle velocity and strain can be related by the following relationship

$$\partial A / \partial t = -C \partial A / \partial x \quad (2.28)$$

$$\epsilon = -\dot{A} / C \quad (2.29)$$

where  $\epsilon$  is strain,  $\dot{A}$  is the particle velocity and  $C$  is propagation velocity.

The relationship of stress to strain allows the stress to be calculated for a body wave using

$$\sigma = -\dot{A} \epsilon / C_s \quad (2.30)$$

where  $\sigma$  is the traditional representation for stress

One important relationship that comes out of all this is the linear relationship between stress at any point and the wave propagation velocity. This ratio is known as acoustic impedance, which by analogy is sometimes referred to as the mechanical counterpart of Ohm's law.

$$\text{Acoustic Impedance} = -\rho v \quad (2.31)$$

The amount of energy, in unit time, delivered through a unit area perpendicular to the direction of travel is known as the energy flux. This energy flux is found by integrating along the wave.

$$\begin{aligned} P &= \int_{x-c}^x [4\pi^2 C^2 \rho A_0^2 / L^2] \cos^2 [2\pi(x-Ct)/L] dx \\ &= 2\pi^2 \rho C^3 A_0^2 / L^2 \end{aligned} \quad (2.32)$$

For a spherical wave the total flux  $P$  in unit time through an envelope of large radius  $r$  is

$$P = (8\pi^3 \rho C^3 A_0^2 r^2) / L^2 \quad (2.33)$$

Where  $A_0$  is the displacement amplitude at  $r$

$$\dot{A}_0 = 2\pi A_0 C / L \quad (2.34)$$

$$\epsilon_0 = 2\pi A_0 / L \quad (2.35)$$

as no energy is lost in a perfectly elastic medium then  $P$  is constant so the amplitude of the peak particle velocity, the strain and hence the stress must decrease inversely with the distance  $r$  from the source.

The discussion above applies to body waves and as such there is no "free" surface to allow movement of the top layers of soil. The body waves and the corresponding treatment must be adjusted for this free surface and in the case of most common

“surfaces” there is a layering or stratified geological pattern upon which all structures rest. The work of Rayleigh and Love have lent their names to surface waves (Bullen, 1954), which occur under certain conditions. Generally speaking, when a solid is bounded by distinctive layers then surface waves, Rayleigh and Love waves, may occur.

Rayleigh waves and Love waves have a velocity of propagation usually smaller than body waves and their effect decrease with depth ie. they only exist a certain distance from the free surface.

Rayleigh Waves usually spread out in two directions and travel more slowly with distance than elastic body waves. Seismic records have shown there are generally three types of waves. The first wave to arrive is the longitudinal (*p*-wave) vibration being a dilatation wave which are those waves travelling at the highest propagation velocity. The second wave to arrive is the transverse (*s*-wave) waves, which are distortion waves. The third group waves are the surface waves which usually have an large amplitude compared to first and second groups in both vertical and horizontal components. The vertical component of these Rayleigh waves is usually the predominant component as far as amplitude is concerned. Rayleigh waves are plane polarised and their particle motion is usually in a reverse direction and is elliptical in motion perpendicular to the free surface. The amplitude decreases exponentially with increasing distance beneath the surface and in a solid the velocity of propagation is not dispersed and propagates with a velocity proportional to the *s*-wave velocity of the medium.

$$C_R = \gamma C_S \quad (2.36)$$

where  $\gamma = 0.9533$  when Poisson's ratio  $\nu = 0.5$

and  $\gamma = 0.9194$  when Poisson's ratio  $\nu = 0.25$

The direction of vibration of Rayleigh waves is usually parallel to direction of propagation but Rayleigh waves vibrating horizontal to the wavefront have been found.

Love waves are generally encountered when the confining medium is usually stratified. When the density and elastic properties of the layers are markedly different to those properties of the body of the medium then these surface waves can be generated. Love waves can, under the right conditions, occur between layers of material with different elastic properties. Love waves generally occur if the velocity of propagation of the disturbance is greater in the lower layers of the medium. Particle motion of the Love

wave is parallel to the free surface and perpendicular to the direction of propagation. Love waves propagate with a velocity lying between the velocities of propagation of waves of distortion in the surface and lower layer. The Love wave propagation velocity is greater than the wave propagation velocity in the surface layer and less than the wave propagation velocity in the lower (or body) layers.

### 2.2.3 Wave effect at a boundary

When a vibration wave acts at a boundary, four new waves may be generated. A dilatation wave or  $p$ -wave and a distortion wave or  $s$ -wave are refracted into Med2 (see Figure 2.4) away from the wave source. Also two similar waves (a  $p$ -wave and a  $s$ -wave) are reflected back into the medium of the incident wave (Med1). If the assumption that the normal tangential displacement and stresses across the interface are equal holds then no differential movement of the mediums occur.

$$\sum u_1 = \sum u_2 \quad (2.37)$$

$$\sum v_1 = \sum v_2 ; \sum w_1 = \sum w_2 \quad (2.38)$$

$$\sum(\sigma_x)_1 = \sum(\sigma_x)_2 \quad (2.39)$$

$$\sum(\lambda\Delta + 2G \partial u/\partial x)_1 = \sum(\lambda\Delta + 2G \partial u/\partial x)_2 \quad (2.40)$$

$$\sum(\tau_{xy})_1 = \sum(\tau_{xy})_2 ; \sum(\tau_{xz})_1 = \sum(\tau_{xz})_2 \quad (2.41)$$

For the boundary conditions to be satisfied then Huygen's principle can be applied. Huygen's principle states that points on a wavefront can be considered point sources for secondary wavelet formation. The new wave surface will be formed at the tangency of the secondary wavelets. Thus for incident dilatation waves then

$$\sin a_i/C_{P1} = \sin a_1/C_{P1} = \sin \beta_1/C_{S1} = \sin a_2/C_{P2} = \sin \beta_2/C_{S2} \quad (2.42)$$

And for incident distortion wave then

$$\sin \beta_i/C_{S1} = \sin a_1/C_{P1} = \sin \beta_1/C_{S1} = \sin a_2/C_{P2} = \sin \beta_2/C_{S2} \quad (2.43)$$

Where  $a$  and  $\beta$  are the angles between the normal to the interface and the incident, reflected and refracted waves of dilatation and distortion respectively

$$A_1 = A_i(\rho_2 C_{P2} - \rho_1 C_{P1})/(\rho_2 C_{P2} + \rho_1 C_{P1}) \quad (2.44)$$

$$A_2 = 2A_i \rho_1 C_{P1}/(\rho_2 C_{P2} + \rho_1 C_{P1}) \quad (2.45)$$

Where  $A_i$  is the amplitude of the incident wave,  $A_1$  is the amplitude of the reflected wave and  $A_2$  is the amplitude of the refracted.



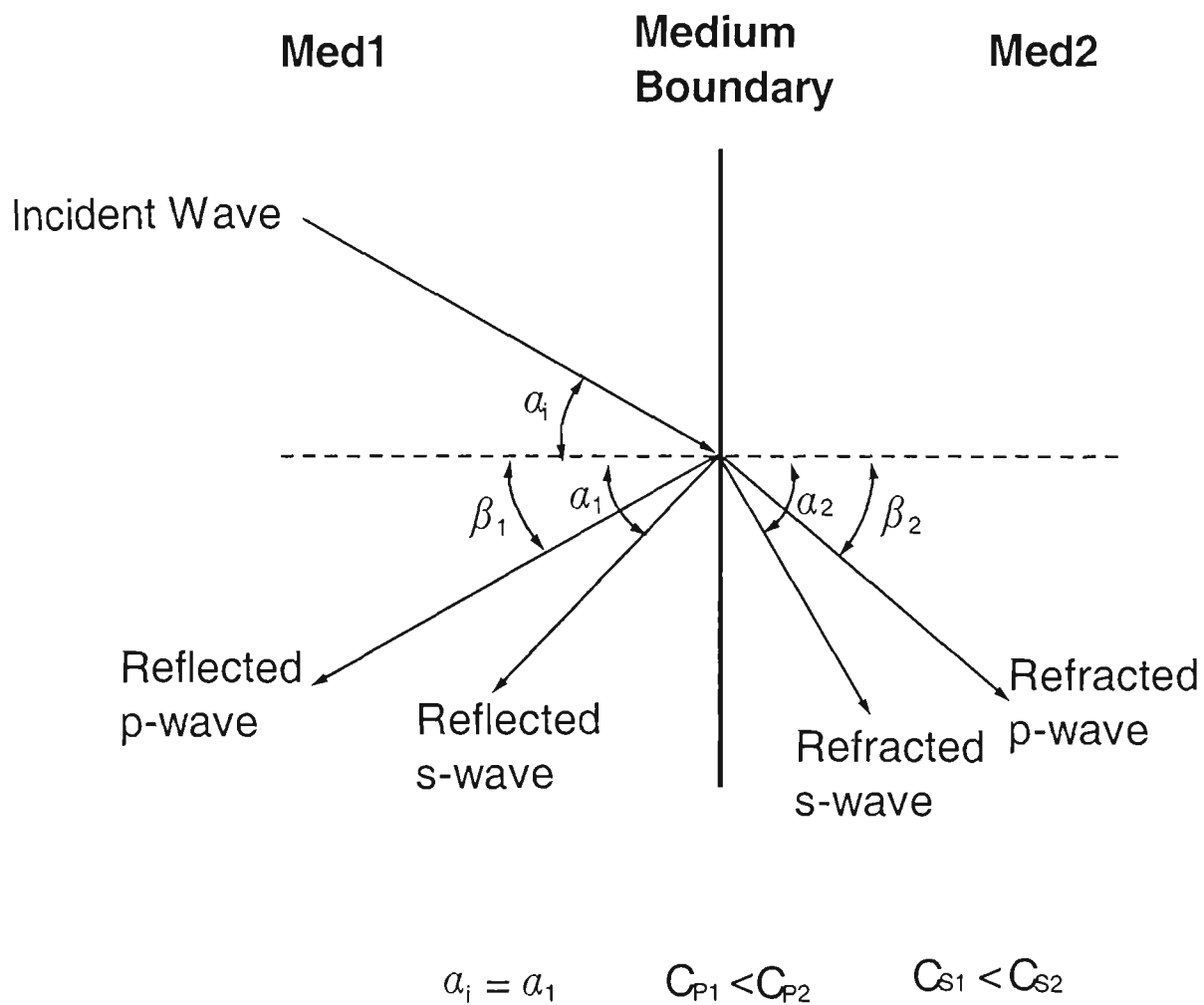


Figure 2.4 Analytical representation of a wave at a boundary.

### 2.2.4 Computer Modelling

Modelling work was carried out on mounts of the same geometry by varying the density of the mount material. Wolf and Somaini (1986) and Luco and Wong (1982) investigated building foundations being acted upon by vibrating waves and gave some insight into the effect that the vibration waves have on the primary sensor mount. The stiffness characteristics of the mount were determined (from Wolf and Somaini, 1986) from a polynomial of degree 4 as shown below. The soil properties and the mount parameters were used as inputs to the program and the amplitude outputs were based on the vibration wave frequency.

Parameters of the mounting block design had to be taken into account as Luco and Wong (1982) showed that the structure (the mounting block) could have an influence on the vibration wave. The structure or mounting block must have both horizontal stiffness and vertical stiffness. This would make the mount rigid under vibration loading and the mounting block would move as the ground moves under the vibration loading. In the case of vibration mounting blocks a rocking stiffness would not apply as the block doesn't protrude above the surface of the ground.

$$\text{Horizontal Stiffness} = 8 * G * \text{RAD} * (1 + D)/(2-\nu) \quad (2.46)$$

$$\text{Rocking Stiffness} = 8 * G * \text{RAD}^3 * T_2 / (3 * (1-\nu)) \quad (2.47)$$

$$\text{Vertical Stiffness} = 4 * G * \text{RAD} (1 + 0.54D)/(1-\nu) \quad (2.48)$$

Where G is the mass factor and RAD is the mount radius and D is relationship between the mount radius and the depth of burial and  $\nu$  is Poisson's ratio and  $T_2 = 1 + 2.5 * D^3$

The horizontal velocity of the surface wave was shown (Luco and Wong, 1982) to depend on frequency and an equation was used to determine the amount of vertical, horizontal and rocking motion of the structure (primary sensor mount). A torsional response was shown to be produced by a SH wave incident on the structure which could be neglected in this case, as the primary sensor mount was cylindrical and torsional motion would be very small. Reduced high frequency component was also shown to occur due to scattering of the foundation, which is pertinent in this case. A rocking response due to Rayleigh waves was shown to effect the high points of the structure on a building which could be neglected in this case, as the primary sensor mount was at the free surface level.

$$\text{Vertical} = 1 \quad (2.49)$$

$$\text{Horizontal} = 1 + 0.199A_0 - 2.659A_0^2 + 1.456A_0^3 - 0.229A_0^4 \quad (2.50)$$

$$\text{Rocking} = -0.0131A_0 + 0.789A_0^2 - 0.526A_0^3 + 0.082A_0^4 \quad (2.51)$$

where  $A_0$  is a dimensionless frequency term.

The above equations are used to determine the change in amplitude as a function of some dimensionless frequency. The mounting block was shown to be linear in a range

up to approximately 500 Hz and even when the density was altered this linearity did not change to any significant degree. So the parameters of the design of the mounting block were such that this design should reliably transmit vibration waveforms as faithfully as possible to the primary sensor attached to the mounting block.

### 2.2.5 Frequency decrease and attenuation

White (1983) states that many workers look at attenuation/dispersion pairs which can be used to discuss frequency decreasing. If  $a_p$  is attenuation and  $c_p$  is phase velocity (or frequency) then there is a relationship. There is an assumption of linear behaviour for small strain even when attenuation is quite evident for linear lossy solid as shown by seismic records. Lossy solids (a solid where stress is proportional to strain on a micro scale, as in this instant) must be causal ( a function that is zero before some reference time ie. no output response before the initiation of the source).

If a plane compressional wave acts in the X-direction then distance and time can be related by:

$$u_x(x,t) = 1/(2\pi) \int_{-\infty}^{\infty} U_x(0,\omega) e^{-a_p x} e^{-i\omega x/c_p} e^{i\omega t} d\omega \quad (2.52)$$

where  $a_p$  and  $c_p$  both functions of  $\omega$  which is the angular frequency.

For this material to obey these assumptions, causality must apply. For this to happen ( $\omega/c_p$ ) must be the Hilbert transform of  $a_p$  plus a first order term. The Hilbert transform is the convolution of a function with a distribution, which represents a modified waveform, which can be used in analytical determinations.

$$\omega / c_p(\omega) = \omega / c + [a_p(\omega)]_{\pi/2} \quad (2.53)$$

here  $c$  is a phase velocity at some frequency ie.  $f(\infty)$

However, Kjartansson (1979) states that a power law fit to attenuation is possible. This fit assumes there is proportionality between stress and strain in the frequency domain such that:

$$P_{xx} = M_0 (i\omega / \omega_0)^{2\lambda} E_{xx} \quad (2.54)$$

$$= M_0 |\omega/\omega_0|^{2\lambda} e^{i\pi\lambda \text{sgn}\omega} E_{xx} \quad (2.55)$$

where  $\pi\lambda$  is phase angle between stress ( $P_{xx}$ ) and strain ( $E_{xx}$ ) and  $M_0$  is a complex propagation constant.

Another loss parameter is the Q factor. The Q factor is the sharpness of the resonance wave, or more broadly coefficient of internal friction, caused by a disturbance source. When a disturbance source causes a wave to vibrate at a frequency  $f_1$  and an increase in the disturbance source frequency of  $\Delta f$  causes the vibration wave amplitude to increase by a factor of  $1/\sqrt{2}$  then:

$$Q = f_1/2\Delta f \quad (2.56)$$

The study of wave attenuation through the ground first started with the study of waves through a rod or plate. Axial stress along the rod and perpendicular to the rod were determined and relationships for the wave in the rod determined. When these relationships are expressed in terms of Lamé's coefficients ( $\lambda$  and G) Young's modulus can be derived. Using Young's modulus a description of the body waves can be derived from which Q can now be shown to be independent of frequency .

$$Q^{-1} = \tan \pi\lambda \quad (2.57)$$

Thus the attenuation/dispersion pair can be expressed as:

$$\alpha_P(\omega) = [|\omega_0| \tan(\pi\lambda/2)]/c_0 |\omega/\omega_0|^{1-\lambda} \quad (2.58)$$

$$c_P(\omega) = c_0 |\omega/\omega_0|^\lambda \quad (2.59)$$

These relationships show there is a connection between attenuation and frequency (phase velocity).

### 2.2.6 Wave effect through soil.

Now at a monitoring location as the vibration wave approaches many events begin to happen. The equipment to measure this vibration wave must be placed so that it does not interfere or change the wave. But by placing equipment in the soil to measure the vibration wave at a location the soil has been disturbed which could have an effect on the level of the vibration wave at the location. That is why it is important to realise that whatever equipment is used to measure the vibration wave it must have minimal impact on the vibration wave itself. But it is not sufficient to place the sensor on the ground or

soil without providing any coupling of the soil to the sensor as there will be differential movement between the sensor and the soil.

The shock wave set up by the detonation of the explosives can be felt for distances up to 3 to 4 kilometres away from the explosive source. As stated above it is not usually the body waves that have the predominant effect but more the surface waves and the amplitude of these surface waves will depend on the structure of the ground that the wave travels through. It is a well known fact that the high frequency waves attenuate much faster than the lower frequency waves (Atlas Powder Company, 1987) due to the inelasticity of the rock mass or the ground. The rock mass comprises many particles and the vibration wave has to travel through this conglomerate mass of material on the way losing energy. This loss of energy occurs at each and every boundary that is encountered by the vibration wave. Loose sandy soil for example will tend to move instead of transferring the energy to neighbouring particles for continuation of the vibration wave. Fragmented ground is another "barrier" for the transmission of the vibration wave. Of course the level of attenuation is dependent on the physical aspects of the barrier compared to the physical characteristics of the vibration wave. The high frequency waves are generally associated with short wavelength of the wave and as such, narrow discontinuities can have a major attenuation effect on this type of wave. These higher frequency waves are also attenuated due to the inelasticity of the rock mass. This inelasticity occurs especially at the surface where weathering conditions have cause the ground to consist of many individual particles hence hindering the transmission of the vibration wave energy from particle to particle. On the other hand long wavelength waves, of which the surface waves fall into this category, will cross over narrow discontinuities and not be affected as much. A measure of this inelasticity of the rock is termed the coefficient of internal friction or Q factor. Normal underground rock structures have higher Q values than fractured or loosely compacted soils. A comparison of some materials is shown in Table 2.2 and as can be seen generally the higher the Q value the less attenuating will be the vibration wave through that material. For example basalt, granite and marble all have high Q values and have better transmission rates of the vibration wave than would the caprock such as sandstone and shale. Of course this is a generalisation and some deviation from this statement is always found.

Table 2.2 Coefficient of internal friction (Q) values for selected materials.

Material	Frequency (Hz)	Q	p-Wave velocity
	(Hz)		(km/s)
Basalt	3500	561	5-6
Granite	2000	311	5-6
Marble	3500	547	6
Caprock	5000	47.0	2-3
Limestone	2800	71.4	3
Sandstone	2500	69.1	1-2
Shale	50	17.2	1-2

The attenuation of the vibration wave is a combination of both the geometric spreading of the wavefront and the rock inelasticity. This is the attenuation–dispersion pair that White (1983) discusses in his book and has often been equated by the following expression.

$$A = \frac{A_0 e^{-ar}}{r} \quad (2.60)$$

where A is the amplitude at distance r from a source, A<sub>0</sub> is the initial amplitude and a is a coefficient of inelastic attenuation in an infinite medium.

The coefficient of inelastic attenuation is further related to Q but this theoretical approach should be used with caution as the relationship is based on single homogenous material, which is rarely found in the real world. Furthermore, Q should also be used with caution as its dependence on temperature, strain etc. is difficult to establish.

Although the explosive source and the monitoring location are in a straight line, which is the shortest distance between both, sometimes the vibration wave can take a quite different path to reach the monitoring point. The material between the two points could be normal weathered material having propagation velocities of approximately 1000 m/s but below the explosive source there could be a highly transmissive layer allowing velocities in the region of 5000 m/s. This subterranean layer will transmit the vibration wave at a much higher rate than the surface layers resulting in a much more complicated wave structure being received at the monitoring point. These ray paths must be

considered in any monitoring exercise as exclusions of these possibilities could lead to misleading assumptions from the data recorded.

However, even if the vibration wave arrives at the monitoring point by a direct route or some indirect path the whole purpose of the equipment set up at the monitoring point is to measure the vibration wave at the monitoring point. The vibration wave should not change just because monitoring equipment is placed at a particular location if so the equipment or procedure is not measuring the blast induced vibrations at the point but some artefact of the monitoring procedure.

So it can be seen how important the placement of the monitoring equipment can be to capture the true blast induced vibration wave from the explosive detonation. The vibration wave is a combination of wavelets from individual blasthole detonations and during its passage through the ground to the monitoring point it is modified in a way dependent on the type and structure of the ground. The vibration monitoring equipment must be able to record faithfully the ground vibrations at the location. For instance if the vibration wave frequency is in the order of 1000 Hz, which can occur for single hole detonations close to the blasthole in competent ground then by the Nyquist theory (Moore, 1985) the minimum sampling rate should be the maximum frequency present divided by two. This sampling rate is needed to adequately sample the vibration waveform but higher sampling rates would be required to effectively sample the vibration waveform and obtain enough points on the waveform.

The signal obtained at a monitoring point is a trace of the output from the primary sensor as a function of time. In other words at discrete intervals of time the primary sensor voltage is sampled and stored in memory. This process is continued until the sample duration has been reached. But this sampling rate does not take any account of the frequency of the vibration wave and as the frequency can vary during the blast, the frequency would have to be known before hand to set the sampling rate to sample the waveform adequately. To obtain the best sampling interval the properties of the vibration waveform must be understood. The frequency of a time series, which is a vibration trace or a collection of points in the time domain, can be calculated by determining a Fourier series that represents this time domain waveform. The time

domain trace consists of an infinite superposition of sine and cosine waves of different amplitudes and frequencies. The time domain waveform,  $X(t)$ , is represented by :

$$X(t) = \sum_{n=0}^{\infty} \left( a_n \cos \frac{2\pi n t}{T} + b_n \sin \frac{2\pi n t}{T} \right) \quad (2.61)$$

where  $a_n$  and  $b_n$  are the Fourier cosine and sine coefficients,  $n$  is the number of sample points and  $T$  is the sample duration. But these coefficients are related to a frequency,  $f = n/T$ , where  $T$  is the time over which the samples were taken of the time series record  $X(t)$  as given below:

$$a_n = \frac{2}{T} \int_0^T x(t) \cos \frac{2\pi n t}{T} dt \quad (2.62)$$

$$b_n = \frac{2}{T} \int_0^T x(t) \sin \frac{2\pi n t}{T} dt \quad (2.63)$$

So we now have a mathematical representation of the time series event which makes it much easier to extract properties of this time series event. This leads to the power spectrum representation of the time series event, which shows how the energy in the fluctuations is distributed with frequency of these fluctuations, and depends on the Fourier components derived from the time series trace. As power is the rate at which energy is transmitted, the power spectrum magnitude is proportional to the square of the amplitude of the Fourier components of the trace at the frequency of interest. Thus the power spectrum can be an indicator of how energy, or power, is distributed with frequency content of the time series trace.

The maximum frequency in the power spectrum is termed the Nyquist frequency and is defined as the number of samples taken divided by twice the sample duration. Frequencies above this range can be represented by integral values of the Nyquist frequency and are superimposed within the lower frequency bands. This superimposition on the lower frequency band of the power spectrum is termed aliasing and basically means the sample interval time was too large for the waveform frequencies in the time domain. This effect can be minimised by filtering the signal before sampling by using a low pass filter to eliminate frequencies greater than the Nyquist before the recording begins.

But the vibration wave is a cumulation of all frequencies emitted from the explosive detonation and if the maximum frequency can be determined and sampling at a rate to



adequately sample this frequency then all lower frequencies will also be adequately sampled. Inefficient sampling of the vibration wave as far as frequency is concerned can lead to inaccurate recordings of the vibration level at the monitoring location. The primary sensor itself must be capable of responding to the maximum frequency of the vibration wave and sensors used today in blast vibration monitoring equipment have resonance frequencies in the 20 kHz to 30 kHz range which is well above the frequencies expected from blast induced vibrations. These primary sensor also have a linearity over a range of frequencies which means that the voltage level output from the sensor is linearly dependent on the magnitude of the physical event within this frequency range. This linearity makes the calibration of the equipment relatively easy and stable.

The signal recorded by the monitoring equipment is usually in the form of an electrical analogue signal. Electrical analogue signals are used to detect the primary event as the voltage signal is easy to vary in relation to the magnitude of the primary event. However these analogue signals which are usually plus-minus a certain level are more difficult to handle and store once they have been acquired from the sensor. This voltage level now has to be converted to a digital signal that represents the analogue voltage levels originating from the primary sensor. The analogue signal is digitised where the maximum voltage level of the sensor is divided into discrete levels and represented by a number depending on the resolution of the analogue-to-digital converter used. The analogue-to-digital converters are available in a number of resolutions and their voltage 'bins' are represented as shown in Table 2.3.

So it can be seen that by increasing the bit resolution of the analogue-to-digital converter the recorded digital voltage will approach the analogue level with very little error. The digital signal from the analogue-to-digital converter is much easier to store and calculations can even be made in real time in some application, which can be displayed on a screen as soon as the event is recorded.

Table 2.3 Resolution of analogue-to-digital converters.

Resolution	Bit range	No. of bins	Volts/bin ( $\pm 5V$ max)
8-bit	$2^8$	256	0.01953
12-bit	$2^{12}$	4096	0.00122
16-bit	$2^{16}$	65,536	0.00008

The equipment parameters discussed here play a major role in the accuracy of the signal recorded from the primary sensor. For the recorded signal to be truly faithful in representing the output from the primary sensor these parameters must be incorporated in any equipment that is used to measure the blast induced vibrations. The sole purpose of the vibration monitoring equipment is to faithfully measure the vibration level, that is used as an indicator of the performance of the blasting operations.

With the equipment selection made, the most important part of the procedure and one that requires a little attention from the operator is the coupling of the primary sensor to the vibrating ground. The vibration wave travelling through the ground causes the ground particles to move and all particles in the ground move in unison which also causes any structures attached to the ground to move. When the ground vibrates the primary sensors must also move in unison with the ground and to accomplish this, the primary sensors must be coupled or bonded to the soil as effectively as possible.

The mounting procedure used to couple the primary sensor to the soil produces a boundary that the vibration wave must overcome to vibrate the mounting block as the soil vibrates. At this boundary a number of processes are encountered. Firstly, there is the scattering effect of the vibration wave at the boundaries. This scattering effect causes some reduction in the energy of the wave that is transmitted as it encounters another boundary. Secondly, there is a radiation effect due to the back reaction of any structure on the soil and the extra vibration energy this can produce. These effects and others need to be understood if effective vibration monitoring is to be carried out. To this effect the work of Blair (1989, 1991, 1995a and 1995b) is used as the basis for the standard procedure which has been employed through out this study.

### 2.3 Mounting block analysis.

Before a measurement of any event takes place a procedure must be established that will accurately measure the event of interest. The procedure must take into account any errors that may be introduced by the measurement technique. It is not good practice to measure the length of a cricket pitch, for example, with a 30cm ruler when fewer errors would be obtained if a 30m tape were used. The same applies to vibration measurement. The best equipment available today is of little use if the primary sensor is not coupled to the primary event (ie. the moving soil) effectively. The properties of the mount could have a bearing on the vibration level recorded by the primary sensor. This current research forms the backbone of the standard procedure used in this work to measure blast-induced vibrations in soil.

As discussed earlier, a vibration wave travelling through the ground is a combination of complex waves, which cause the ground to react in different ways in different planes. The ground itself adds to the complexity of the waveform measured at any point. Typically a *p*-wave (or primary wave) is the first arrival at the mounting point as this *p*-wave travels at the greatest speed through the ground. The *p*-wave has a positive onset on arrival, which is detected by the primary sensor. The *p*-wave is the movement of the ground particles (elastic material) in the plane of the mounting point and the explosive source. These particles move backwards and forwards between the explosive source and the mounting point. This is predominantly measured by one component of the primary sensor pointing towards the explosive source and called the radial or longitudinal component.

A *S*-wave (or secondary wave) is the wave caused by the vibrating of the ground particles in the horizontal plane, which is orthogonal to the plane containing the *p*-wave. The *s*-wave is sometimes called a shear wave as the particles slide from side to side in relation to a line between the explosive source and the monitoring point. The speed of the *s*-wave is somewhat slower than the *p*-wave and it is predominantly detected in the component known as the transverse component (in the horizontal plane). *S*-wave onset can be either positive or negative and is heavily dependent on the structure of the ground between the explosive source and the mounting point.

Other waves that occur at the mounting point due to blast vibrations are known as surface waves. This is the movement of the “free” surface against the lower density atmosphere, such waves are usually known by names such as Rayleigh waves, and Love waves (Bullen, 1954). These are usually the waves that are felt at the surface and is detected by the component in the vertical Plane (ie. the plane vertical to the line between the explosive source and the monitoring point). A typical vibration wave showing the three components is depicted in Figure 2.5.

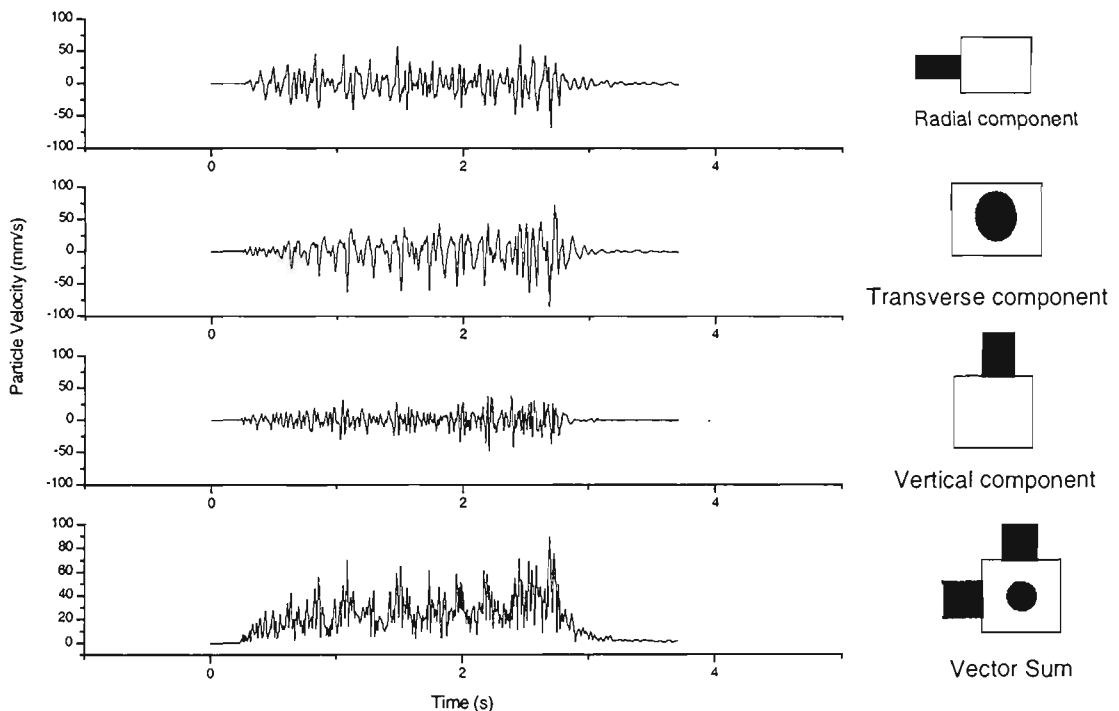


Figure 2.5 Component waveform structure and the vector sum waveform.

The effect of these complex 3-dimensional waves at a monitoring point was simulated in the laboratory. A shaker table of known input characteristics was used to simulate the incident vibration wave and the mount and primary sensor were coupled to the soil in a box. The box was secured to the shaker table. Because the characteristics of the shaker table were known accurately the inputs for the experiments were known. The geometry and structure of the mounting material (soil) were varied and the response of these changes monitored and compared to the input data. In this way a response function could be determined. This response function should be unity if the output data replicates the input data, or the larger the variation from unity the greater will be the

error of the mounting scenarios. For example, a typical resonance function for the radial component function of the test mount is shown in Figure 2.6. In this figure it can be seen that the amplitude decreases as the depth of burial increases from 0.008m to 0.15m. This factor has a major influence on the response of the mount to the input vibration energy. This effect would cause errors in the vibration level measured and could be one of the reasons that one of the mounting scenarios tested in this study would be prone to errors (ie. deeply embedded spike method with the primary sensor some distance above the ground level).

Vibration monitoring is an integral part of mining operations today. To ensure that the blast-induced vibrations only are being monitored, coupling the primary sensor to the soil is an important part of the monitoring procedure. In this work the primary sensor is mounted on a block of concrete, brass etc. placed in a soil container and the soil tamped around the block. This set-up is placed on a shaker table, which has controlled, measurable input parameters, and the primary sensor measures the vibration induced by the shaker table.

The response function (dynamic compliance) of the mounting block is a function of the effectiveness of the transmission of the vibration energy applied to the test set up. The properties of the soil coupled to the block were varied with the compaction of the soil being one of the main soil properties considered. The results shown in Figure 2.7, for the radial component, indicate that the amplitude of the transmitted vibration wave increases as the compaction increases from moderate compaction to high compaction. The compaction methods varied from a pneumatic ramming device for high compaction to a small weight for manually tamping the soil for moderate compaction. As Figure 2.7 shows, it is important to get the coupling correct if the vibration levels transmitted through the soil are to be faithfully measured at any point in the soil. Thus, if for example, as in the spike case, the primary sensor is forced into the soil without any compaction, localised compaction occurs around the spike. But due to the shape of the spike the only force holding the primary sensor in place is the weight force of the primary sensor itself. The slightest differential movement in the vertical direction can cause the entire length of the spike to be decoupled and an unfaithful record of the vibration level of the event will be obtained.

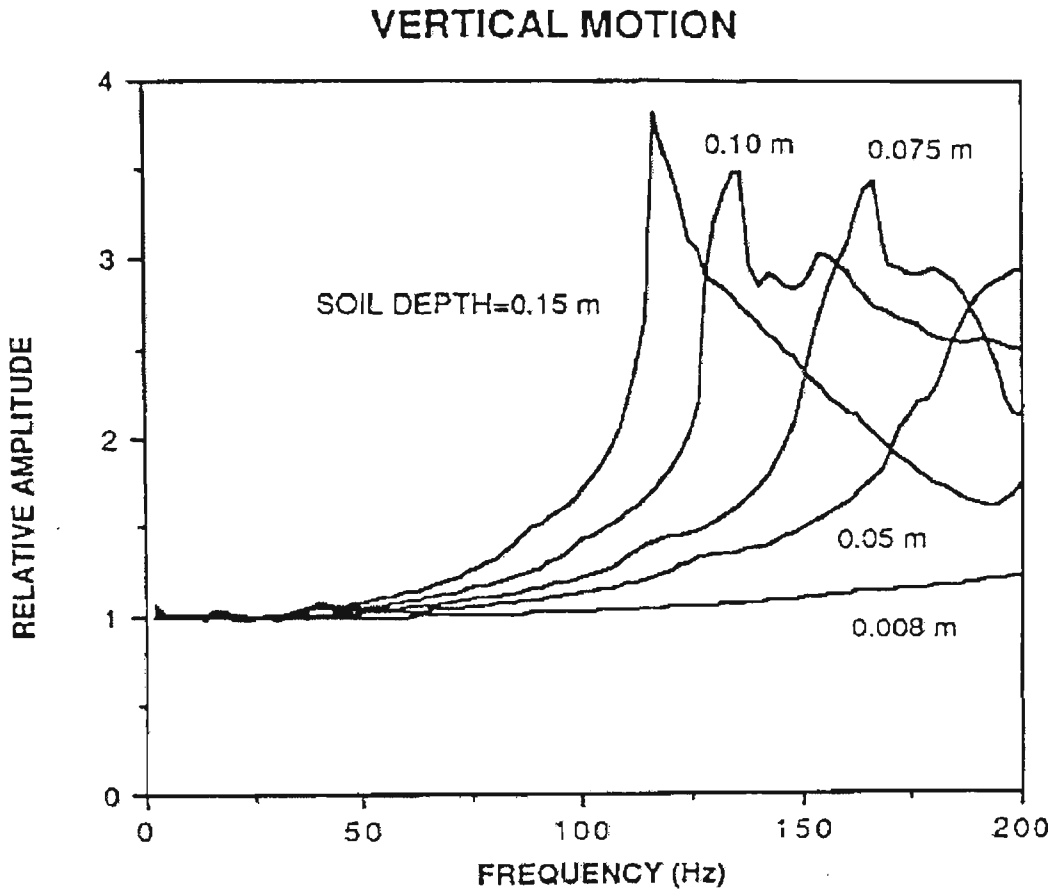


Figure 2.6 Burial depth effect on vibration frequency (after Blair, 1989)

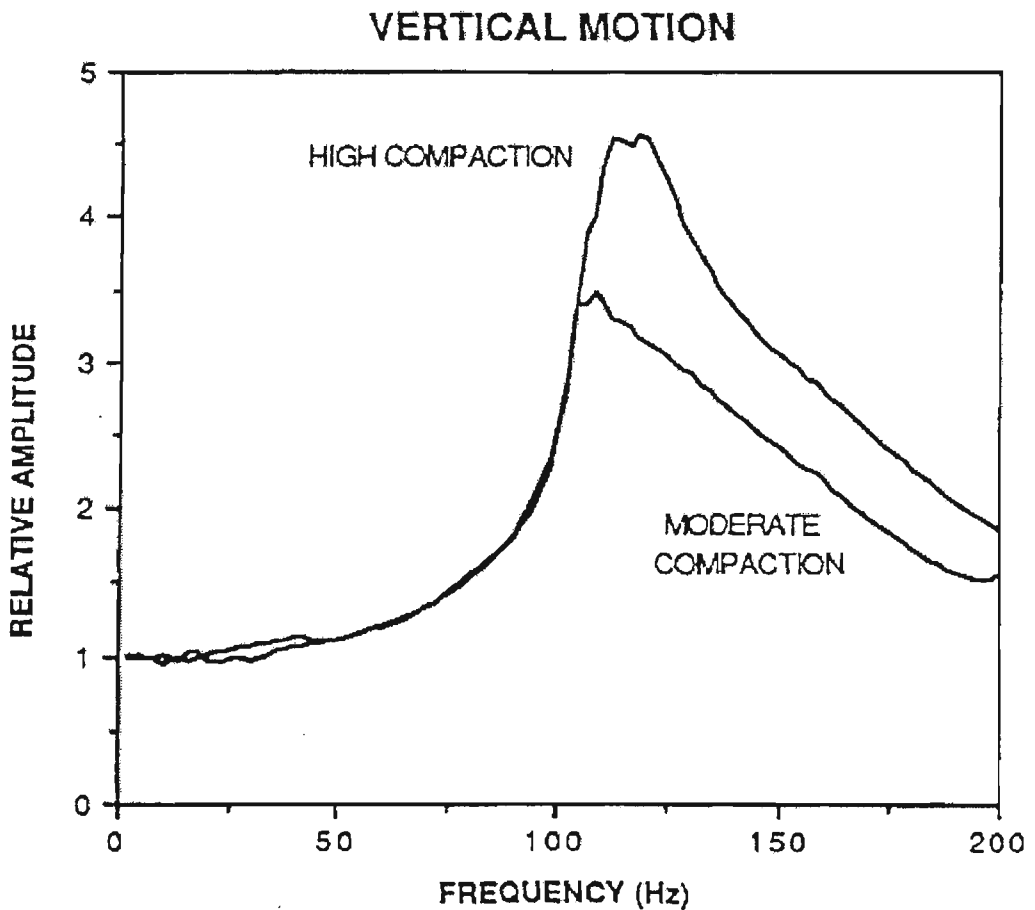


Figure 2.7 Compaction effect on vibration frequency (after Blair 1989)

The depth of burial of the primary sensor was then investigated and the results are shown in Figure 2.8. The amplitude of the vibration wave detected at the primary sensor is shown as a function of frequency of vibration. As the depth of burial increased from 0.0m to 0.18m the amplitude decreased indicating an increase in the coupling of the primary sensor. If the primary sensor is placed on the surface and hence only the base of the plate bolted to the primary sensor is in contact with the soil, very high amplitudes are recorded. This is due to the primary sensor “bouncing” on the soil and a large differential movement between the soil and the primary sensor being reported. This “bouncing” effect is reduced as the depth of burial is increased and the amplitude of the vibration wave recorded approaches that input by the shaker table.

When these results were compared to a simple fundamental mode, the theoretical results for the same experimental conditions gave reasonable agreement. These results are shown in Figure 2.9. However, it was noted that there was some scatter due to variations in compaction but “the canister clearly records the soil motion faithfully for frequencies to 100 Hz or so”.

This work described above was based on a primary sensor being embedded in soil in a box placed on a shaker table and the vibration measured in the vertical direction. When the vibration direction was changed to the horizontal plane similar results were obtained as far as depth of burial was concerned. However, when the primary sensor was placed on the surface and vibrated in the horizontal direction “slippage” of the primary sensor across the surface was noted.

It was also shown in this work that finite volumes of soil in the box influence the lowest measured frequency of vibrations. This procedure was then carried out in the field where the present standard procedure was developed. Blair (1995b) investigated the influence of the soil properties on the vibration levels and concluded that if the soil density and shear wave velocity are known then the dimensions of an embedded mount can be determined to obtain an acceptable response over the frequency range of interest.

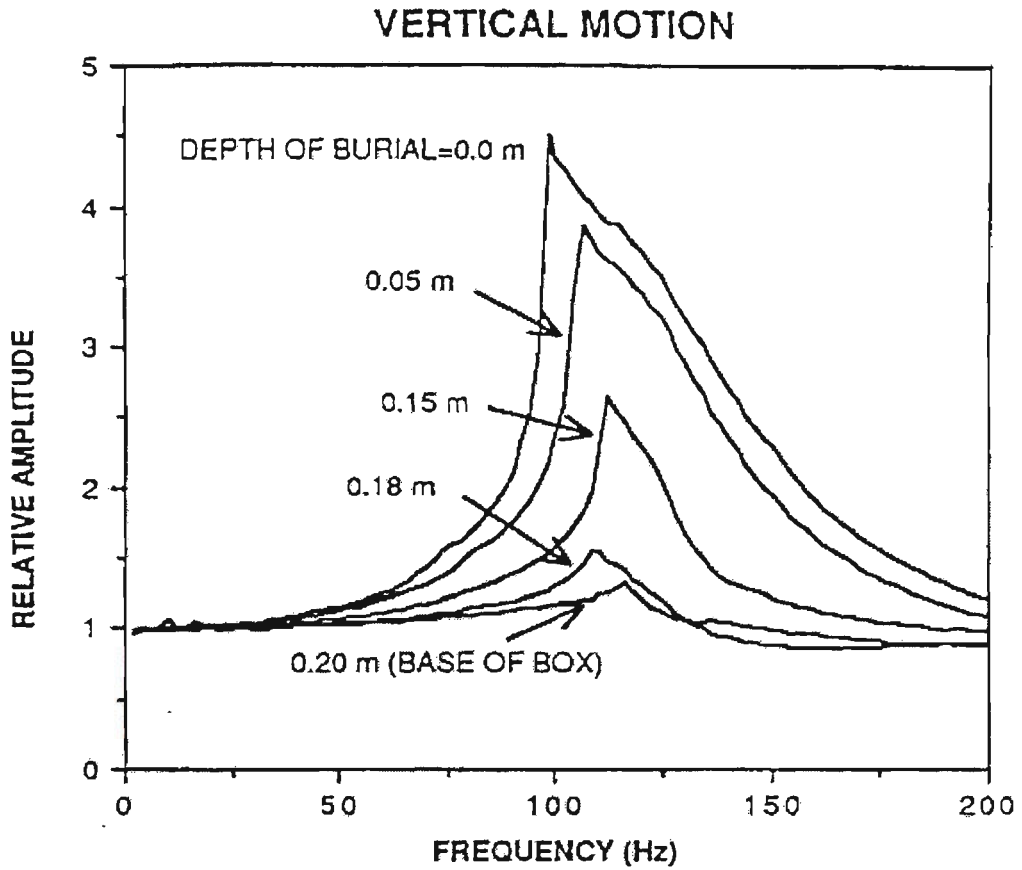


Figure 2.8 Shaker table burial of depth as a function of frequency (after Blair 1989)

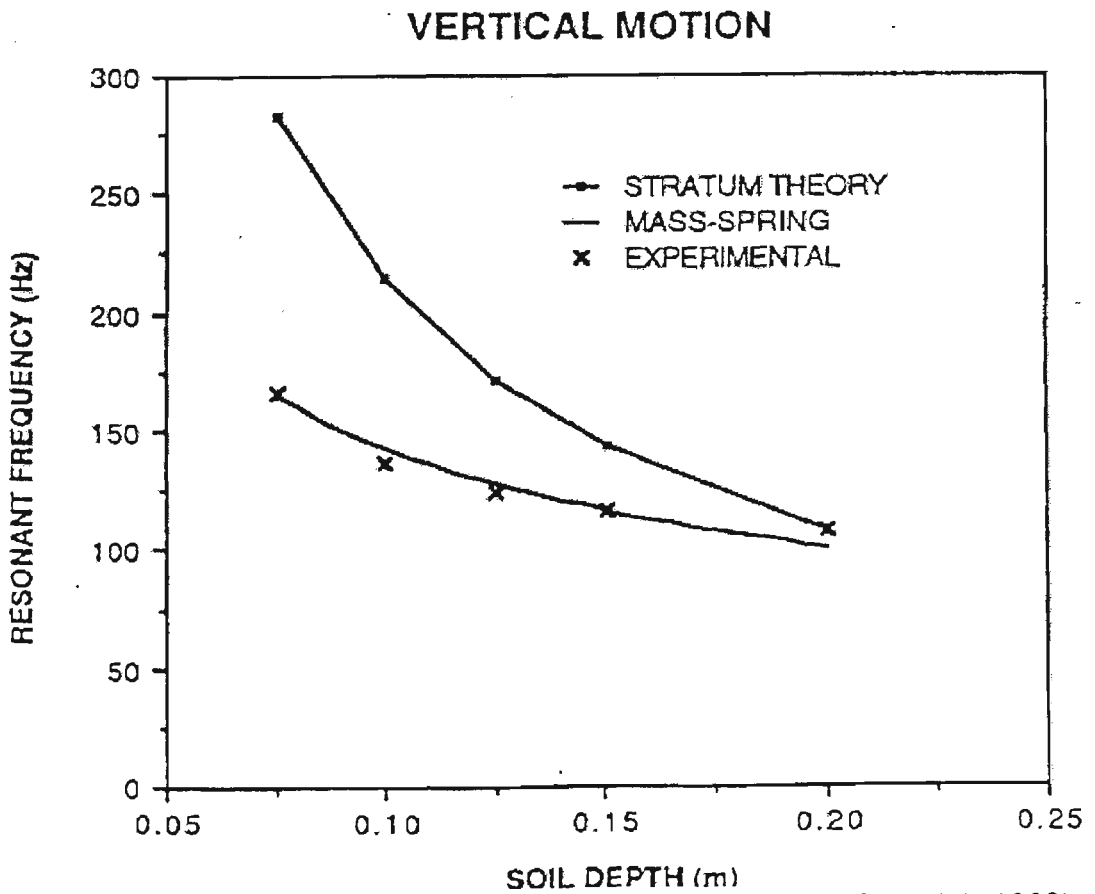


Figure 2.9 Theory and experimental data correlation (after Blair 1989)



It was shown that under a vibration load (ie. blast induced vibrations) the depth of burial of the mount influenced the response measured by the primary sensor quite remarkably. A summary of these findings is shown in Figure 2.11. As shown a near linear response with frequency is obtained when the depth of burial is equal to the length of the mount supporting the primary sensor. A reasonable agreement when the field results when compared with theoretical results was found as shown in Figure 2.10. It was concluded from this work that “the total response of a surface or embedded structure to seismic waves consists of the radiation response and the scattering response”. The radiation response was the back reaction of the mount on the soil as the mount itself is vibrated and was measured in the investigation. The scattering response was the reflection of energy incident upon a structure (mount) and is usually encountered in earthquake studies on buildings. It was stated that “the scattering influence has been totally ignored in obtaining the response of embedded mount for blast monitoring”.

From these field trials, the laboratory trials and theoretical studies, an in-house standard method was adopted for coupling the primary sensor to soil for vibration monitoring. Soil is defined as fine particulate material. However, wherever possible bedrock should be used where the primary sensor is securely glued onto the bedrock for monitoring vibration levels. The soil embedment method has a sound scientific background and in effect is traceable back to scientific principles. It is the coupling of the soil to the mounting device (or the primary sensor) that is the main issue, as the primary sensor (accelerometer or geophone) can be securely bolted to the mounting device. What has been shown by this work is that if it takes very little effort to couple the primary sensor to the soil then it will take very little effort to uncouple the bond, which could happen during the monitoring of a blast. It is worth the extra effort to make sure the bond (or coupling) between the vibrating soil and the primary sensor is effective for the entire duration of the blast.

This procedure has been adopted as the best practice and one that has sound scientific principles behind it. The geometry of the mount has been fixed and the material to be used should have an acoustic impedance (or stiffness) greater than that of the soil. This ensures that there will be no differential movement between the primary sensor and the mount (ie. the system moves as one). The physical size of the mount has been shown to have an influence on the vibration levels measured as far as the frequency is concerned.

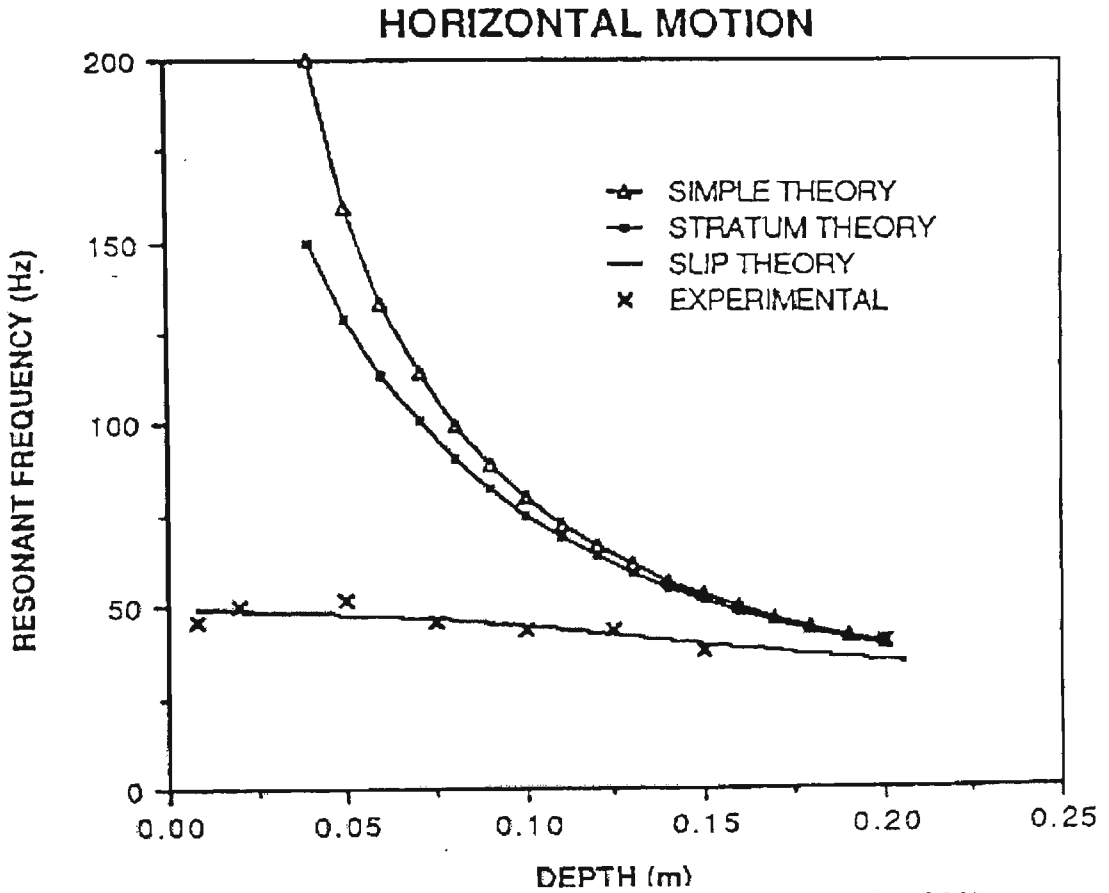


Figure 2.10 Theory and experimental data (after Blair 1989)

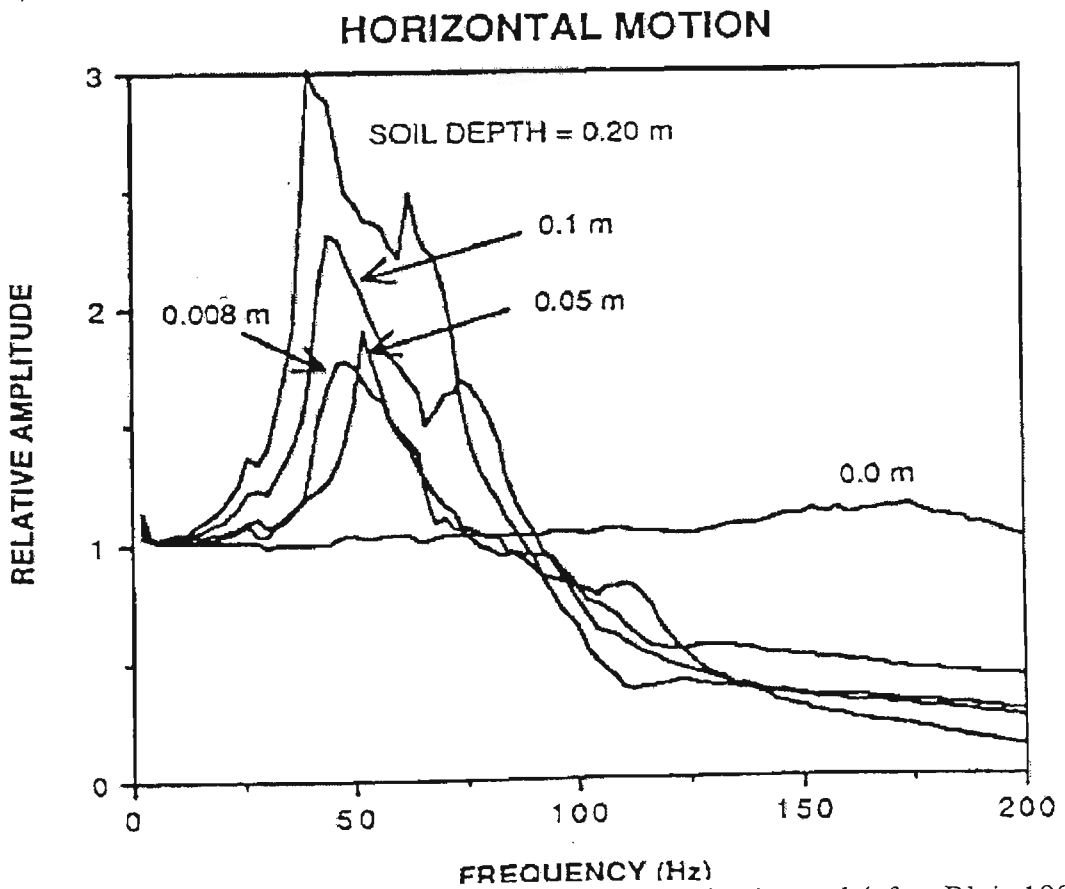


Figure 2.11 Depth of burial effect on frequency – horizontal (after Blair 1989)

All mounts will have a maximum frequency at which they can faithfully transmit the incident vibration wave to the primary sensor. If high frequencies are expected (close to blast holes, competent rock structure etc.) then bonding to original bedrock should be used as the “mounting block”.

The physical dimension of the mounting blocks has been found to be important. Typically a length to diameter ratio of 1 (for a cylinder) and a length of side ratio of 1 also (for a cube) are used. This geometry minimises any problems associated with the centre of gravity being greater than the base length divided by 2 which could lead to the mount becoming unstable and inducing spurious erroneous vibrations into the mount system.

The main area of concern for the mine/quarry operators is the coupling of the soil to the mount. The procedure or best practice recommended is to dig a hole just larger than the mount and as deep as the mount and place the mount in the hole. Slowly backfill the gap between the mount and the ground with the original soil while tamping the soil to compact it and thereby bonding the soil to the mount. Continue until the gap is full and the top of the back filled soil is at the original soil level. Normally extra soil will be required to fill the annulus but this is required to effectively bond the soil to the mounting block. The standard mounting procedure used in this study is shown schematically in Figure 2.12.

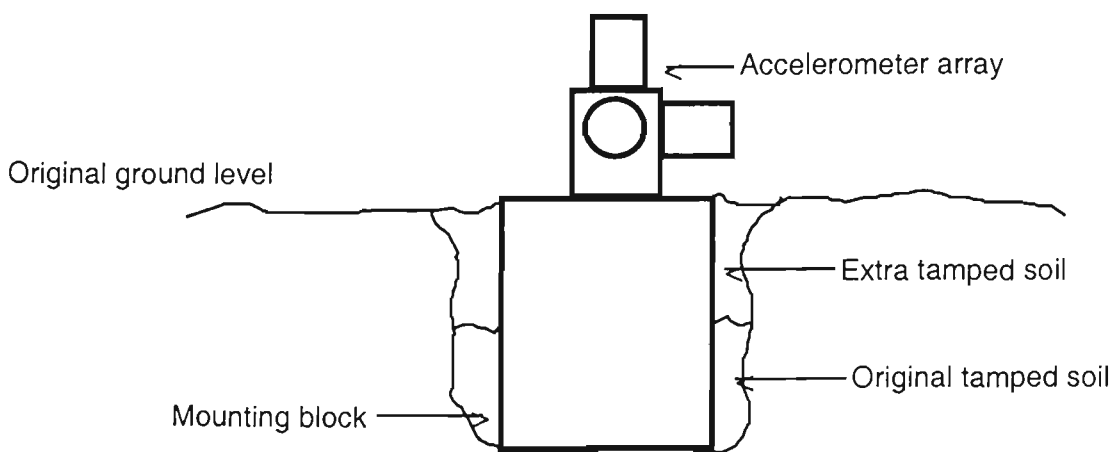


Figure 2.12 Schematic diagram of in-house standard soil mounting scenario.

## 2.4 Discussion

From the literature reviewed and in particular the relevant standards, there did not appear to be any detailed description of the recommended mounting procedure that should be used to couple the vibration monitoring equipment on to the vibrating soil. The standards, although only recommendations, differ quite markedly from the mounting procedures adopted by equipment manufacturers who appear to take the easy way out without taking into account the consequences of poor ground coupling on the blast induced vibrations measured.

A lot of good work was done by Blair (1989, 1991, 1995a, 1995b, 1996) where he investigated the properties of the coupling of the soil to the mounting block. His work showed that the depth of burial was important and an embedded mounting block was recommended for measuring blast induced vibrations in soil. Some comparative studies were undertaken in the field using detonators as the source of the blast induced vibrations.

No work had been carried out to compare the “accepted” mounting practice one against another and the variation that could be expected in this type of measurement technique. This was the basis of the work carried out in this study. Basically four different mounting procedures (embedded mounts, sandbagged mounts, one spike mount and three spike mount) were trialed using a typical blast pattern as the vibration source. The standard technique used was also tested for its variability and a statistical approach will be adopted to measure the degree of variation that would be typically measured.

## 2.5 Chapter Conclusions

- Literature review showed that little work had been conducted on mount coupling.
- Stress waves set up from a chemical reaction when explosives detonated.
- Body waves and surface waves travel throughout the medium.
- Analytical representation of wave at boundaries.
- Mounting block analysis of Blair showed embedment increases coupling.



## CHAPTER 3.

### VIBRATION MONITORING PROCEDURE and EQUIPMENT.

#### **3.1 Introduction.**

This chapter details parameters and properties of the primary sensor mounting procedures in use today and the equipment used to measure blast induced ground vibrations.

It is essential that a thorough understanding of the equipment and its capabilities be appreciated if truly meaningful results are to be obtained. This is more so today as many legal battles are being fought around blast induced ground vibrations causing building damage especially in residential areas that are approaching existing mines/quarries. The imposition of tight environmental limits is also causing mine/quarry operators to be more responsible in their total quarry operations.

Section 3.2 shows the typical primary sensor mounting methods that are recommended in standards and in equipment manufacturer documents. Section 3.3 discusses the equipment used to capture the output from the primary sensor and a block diagram of the pertinent parts of the monitoring equipment essential to monitoring blast induced ground vibrations is shown. Section 3.4 shows the requirements of the correct sample record time needed. Although the blast has an initiation sequence that lasts for 1.6 seconds (for example) the ground is still shaking for approximately 1 second after the blast. Section 3.5 discusses the sample interval time and shows that if this parameter is not correct much lower values than those experienced at the monitoring location will be recorded. Section 3.6 shows the accuracy that can be obtained when the correct electronic components are used in the data capture circuit in the data logger. A discussion on 8-bit, 12-bit and 16-bit resolution will show the differences that can be achieved.

### 3.2 Existing procedures.

Blast induced vibration monitoring is carried out as a normal procedure of any responsible mining or quarrying operation. Since the urban sprawl has caught up with these operations, in particular quarrying, the need for monitoring at the operation's boundary has become an integral part of blasting procedures. It is becoming more apparent to the mine management that the need for an accurate and more importantly, a reliable vibration monitoring system is an important part of the operation.

Environmental agencies are increasingly imposing stricter limits on mining and quarrying operations, and the vibration part of these limits is also included in these strict limits. As these limits become tighter, more emphasis is placed on the mine/quarry management to enforce them and so understanding the monitoring and its implications is necessary.

The most important section of vibration monitoring procedure is undoubtedly the coupling of the primary sensor (the accelerometer or geophone) to the soil or ground that is being shaken by the blasting operation. If the environmental agency vibration limits are set at 5 mm/s at the mine/quarry boundary then the shotfirer, responsible for the blasting, needs to know what the true vibration level for a blast is. The vibration level that is measured must be a true representation of the level being experienced at the mine/quarry boundary and not some artefact of the measuring equipment (Armstrong and Brodbeck, 1998).

Vibration monitoring equipment suppliers all have their particular way of bonding the accelerometer or geophone to the ground and it is usually the way that requires the least amount of effort. But, and this cannot be stated too often (Armstrong, 1999), if the primary sensor is not coupled to the ground effectively, then there will be a differential movement between the ground and the primary sensor. If there is a differential movement then the operator of the vibration monitoring equipment should ask himself "What is really being measured, ground vibration or sensor movement, or something else?"

There are standards published to guide mine/quarry operators in the storage and use of explosives and attached at the rear of these standards in an appendix is usually a page or two on air blast and vibration from blasting. It has only been over the past five years or so, coinciding with the urban sprawl approaching existing mine/quarry operations, that a more concise standard has been published specifically related to blast induced by-products such as air blast and ground vibration.

However, in these standards little detail has been given as to how the vibration at a particular place in the ground (the mine boundary etc.) is to be measured (Armstrong, 1999). Simple statements such as sandbagging, spiking in the soil are sometimes used to satisfy the need to couple the primary sensor to the ground. A recent paper by Grogan (1998) attempted to list a series of mounting procedures that have been accepted in so-called standards as the means of coupling the primary sensor to the ground. Some of these methods include double sided tape to stick the primary sensor to the vibrating surface, which can be used if the vibration levels of less than 0.2 g are to be expected. But surely if it is known that the level will be less than 0.2 g and this is less than the limit allowed then there is no need to go to the trouble of carrying out the expensive process of monitoring the vibration level in the first place.

In the standards there does not appear to be a simple standard method by which the primary sensor can be effectively coupled to the soil to accurately measure the blast induced vibration level. These so-called “accepted methods” have not been compared to show the merits of each method. For too long now mine/quarry operators have been left to their own devices to monitor their blast induced vibration by methods that, in some cases, leave a lot to be desired.

When monitoring vibration levels, it is true, that soil is probably the most difficult material to measure the vibration level in. Because of its particulate nature, coupling the primary sensor to the soil per se is not easy. Then the questions rise- which particle of soil is used? And how is the primary sensor secured to the particle? Soil is defined as a collection of many thousands of particles in a one-centimetre cube volume. The particle sizes range from sub millimetre to 10 millimetre particles. So it can be imagined coupling a primary sensor to this material is no easy matter and should not be dismissed with a flippant attitude of “just place it on the ground and it will be OK!”



Some of the commonly accepted methods of coupling the primary sensor to the soil that are recommended in various standards today are discussed below.

### **3.2.1 Double sided tape bonding.**

This method naturally implies there is a solid surface to which the primary sensor is to be attached. This is not a recommended procedure as the solid surface is usually part of some structure. Even though the vibration is induced in the ground by the blasting operation, the structure might not be effectively coupled at the monitoring point to the vibrating ground. All structures vibrate in a complex and unpredictable way so monitoring on a particular structure is probably not the best location to measure the blast induced ground vibration.

The double-sided tape is usually a plastic film with adhesive material on each side. The surfaces to be “stuck together” must be clean and dry and free from dust before the adhesive tape is applied, see Figure 3.1. This method could have some merit if the vibration levels are extremely low.

If a high vibration level is experienced, and this often happens in a blast, then the non-rigid bond between the primary sensor and the structure could allow some differential movement between the structure and the primary sensor. The plastic film is flexible and allows movement, to a certain extent, between the two surfaces it is bonding together. This is also the case with the adhesive film and as there are two layers of adhesive film there is a high probability that differential movement can result. This method is not suitable for bonding to soil as soil is a particulate material and the adhesive film would stick to individual soil particles and not the bulk of the soil material. As the levels to be monitored are not usually known accurately, this method should be viewed with some reservation and will not be investigated in this work.

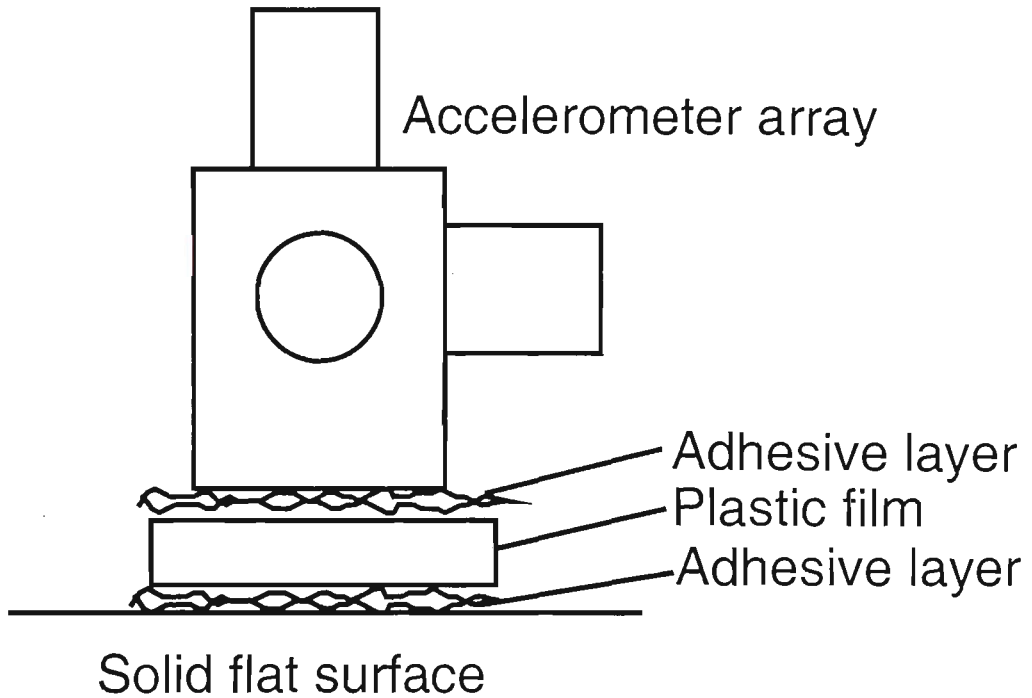


Figure 3.1 Double sided tape bonding.

### 3.2.2 Weight force bonding.

Most primary sensors, accelerometers or geophones, have a mass that is in the region of 0.5 kg to 1 kg. This mass will exert a force on the surface it is resting on and together with friction will provide a form of bond to this surface. This weight force is strictly limited to the mass of the unit. In a vibrating situation only small vibration levels would be required before differential movement between the primary sensor and the vibration ground would occur.

The coupling relies on an absolutely clean solid surface and the weight of the primary sensor and the friction resistance is the only force involved in ensuring a bond between the primary sensor and the monitoring point. The difficulties experienced with this method are a clean surface that would need the use of solvents followed by some drying time. Cleaning the surface by wiping with one's hand, clothing etc. will only introduce an oily film which in effect could help to reduce the bond between the primary sensor and the monitoring point. This method, shown in Figure 3.2, is also not recommended and will not be investigated in this work.

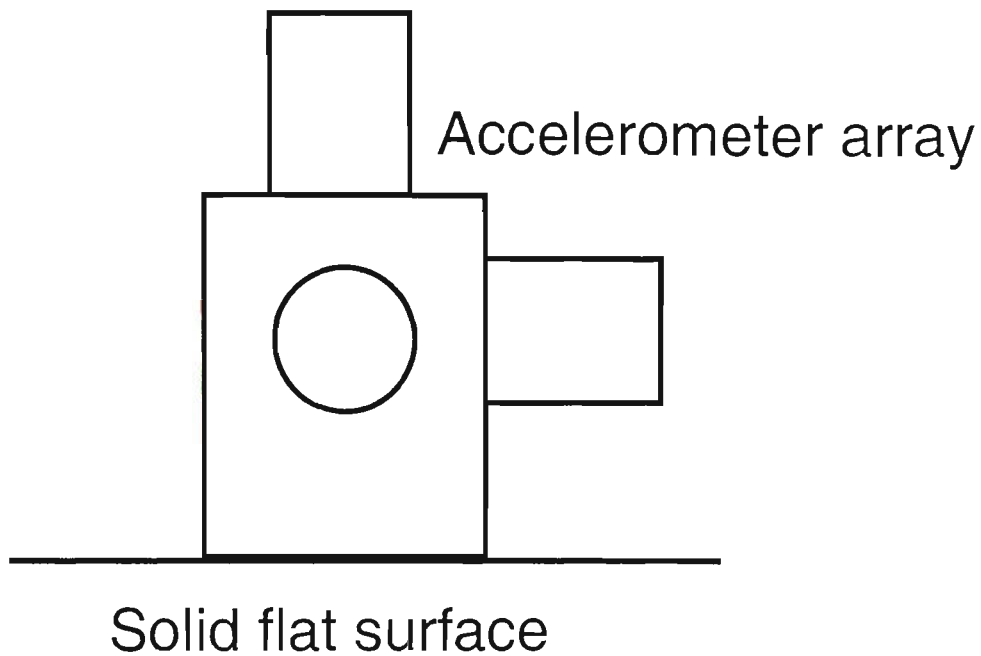


Figure 3.2 Weight force bonding.

### 3.2.3 Magnetic bonding device.

Magnet forces have been used in the past to secure small ferrous objects to a ferrous structure for the purpose of some form of measurement. A permanent magnet is placed between the two ferrous surfaces to be bonded together. This permanent magnet continually emits a magnet flux from its surface which causes a force field that attracts material that are known as “magnetic”. The magnetic flux or force field emitted by the permanent magnet causes a realignment of the atomic structure of the ferrous object, in this case the base of the primary sensor and the metal structure. The atomic structure, the electron field and the spin of the electron themselves, as a whole possesses a resultant magnetic field called a paramagnetic magnetic moment that causes the bond between the magnetic materials. Atoms such as iron, cobalt and nickel exhibit this property and only these materials can be used successfully for magnetically bonding two surfaces together.

This device uses a strongly magnetic disk, which is secured to the base of the primary sensor and then placed on any magnetic object to complete the coupling process, see Figure 3.3. Once again the monitoring point is on some structure which has its own in-built reaction to any vibration source so the level that is being measured is not necessarily the level that is induced in the ground by the blasting operations. Cleanliness is again an important aspect of this method as even a few small grains of

soil between the primary sensor and the magnetic structure can act like ball bearings and cause differential movement between the primary sensor and the structure. This method does have merits where vibrating machinery is concerned but for blast induced vibrations in soil it should definitely not be considered.

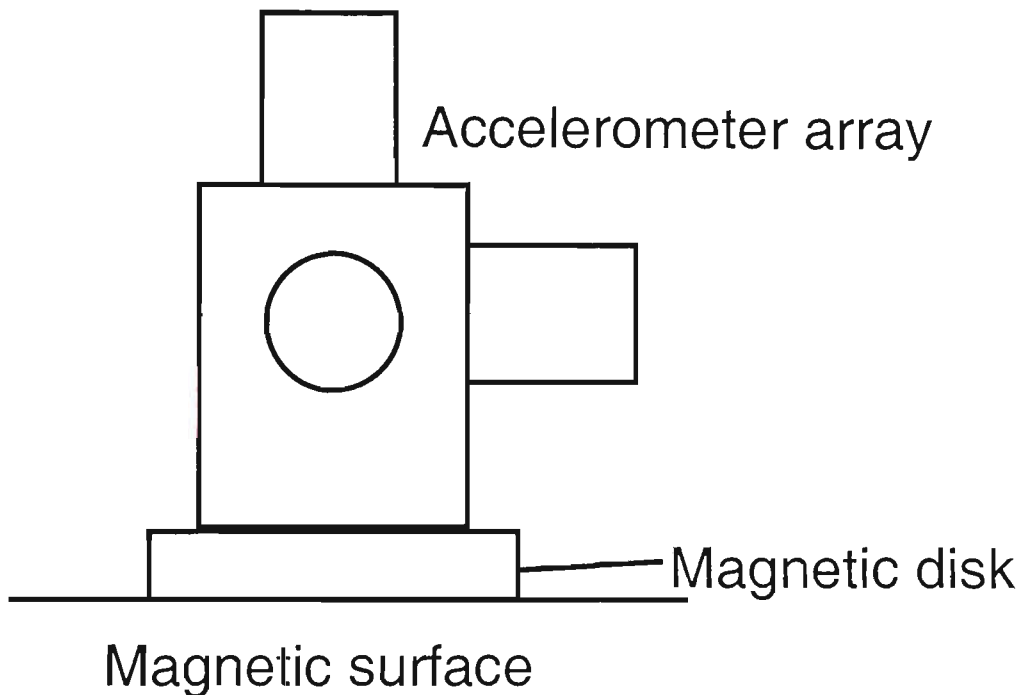


Figure 3.3 Magnetic force bonding

### 3.2.4 Sandbag bonding.

This is another weight force bonding method and essentially relies on the “increased” weight of the primary sensors to bond the primary sensor to the vibrating surface. The sandbag is filled with fine particulate material, which by its nature, is deformable, and can be easily formed to the shape of the primary sensor that is being bonded to the vibrating ground. The filled sandbag is large enough to cover the primary sensor. The fine particulate material in the sandbag can be easily moved.

This is a widely accepted method used to couple the primary sensor to the mounting point, as shown in Figure 3.4. In this method the condition of the mounting surfaces is not critical as it relies on the weight of the material in the sandbag to provide a downward force large enough to prevent the primary sensor from moving relative to the ground. However, the material in the sandbag can become mobile when the blast induced vibration acts at the mounting point. Therefore, the resulting waveform

recorded by the primary sensor does not represent the true vibration waveform at the monitoring point. Sand bagging the primary sensor to the monitoring point is a fairly widely used procedure and will be investigated in this study.

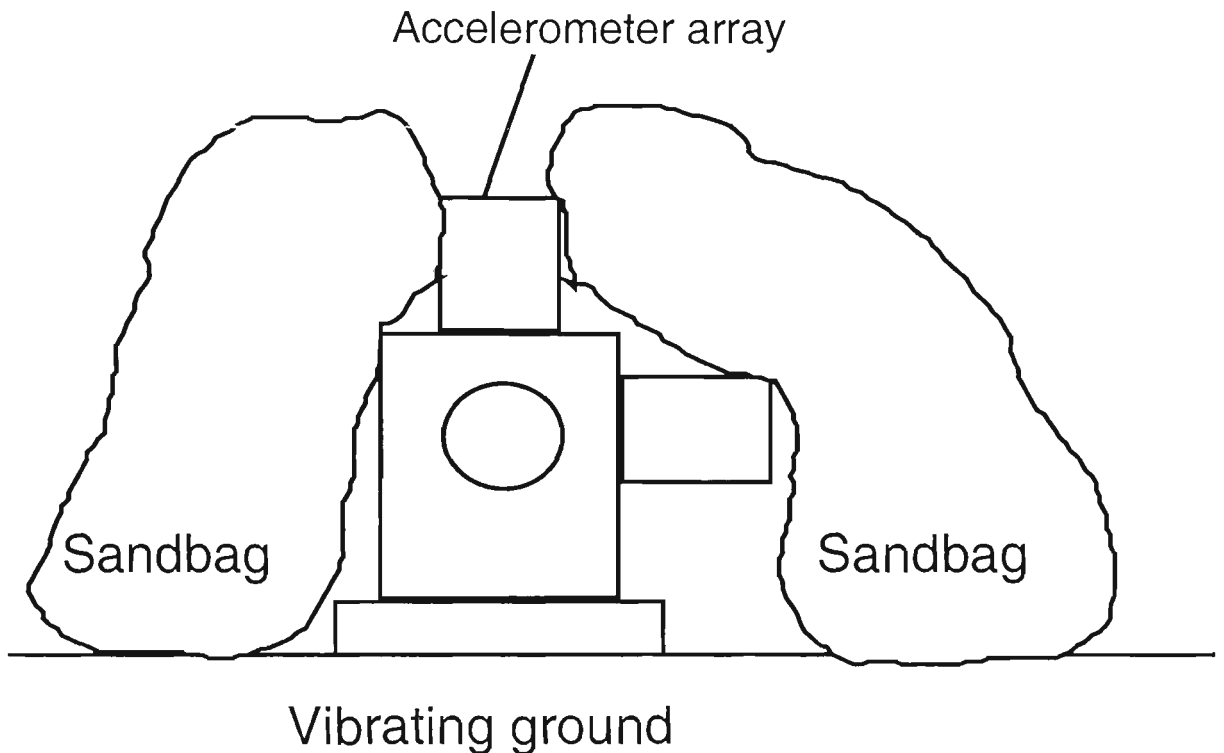


Figure 3.4 Sandbag bonding

### 3.2.5 Embedded bonding.

Blast vibration monitoring is usually carried out in the ground that consists of fine particulate material. This fine particulate material or soil is extremely difficult to bond to in a bulk sense as the top layers of the soil are not necessarily effectively coupled to the lower layers of the soil. This coupling does increase with depth as the degree of difficulty in digging a hole, for example, increases with the depth of the hole. This increased bonding within the soil layers with depth results from the natural weathering process. The normal heating and cooling due to night and day and the saturation of the ground with water by rain fall all help to compact the soil with the passage of time. The purpose of monitoring blast induced vibration is to understand how the blasting operations affect the ground and consequently any structure on the ground. The procedure used to measure these blast induced vibrations must be reliable, not difficult to accomplish and repeatable for similar blasting conditions at the same location. Thus it was viewed as imperative to establish a standard procedure.

This is the standard method that should be used when coupling the primary sensor to the ground in soil. The primary sensor and its associated cable is secured to a mounting block, which is then coupled to the soil by burying the block in the ground. A hole just larger than the block is excavated. The block is placed inside the hole and the soil placed in the gap between the block and the hole. The soil is then tamped to ensure a bond between the block, the tamped soil and the hole walls. This mounting scenario is the main theme of this work and will be discussed in detail. The density of the primary sensor has been thought to influence the transmission of the vibration signal, and in some standards the density of the primary sensor has been defined to be within certain limits. This method is schematically shown in Figure 3.5.

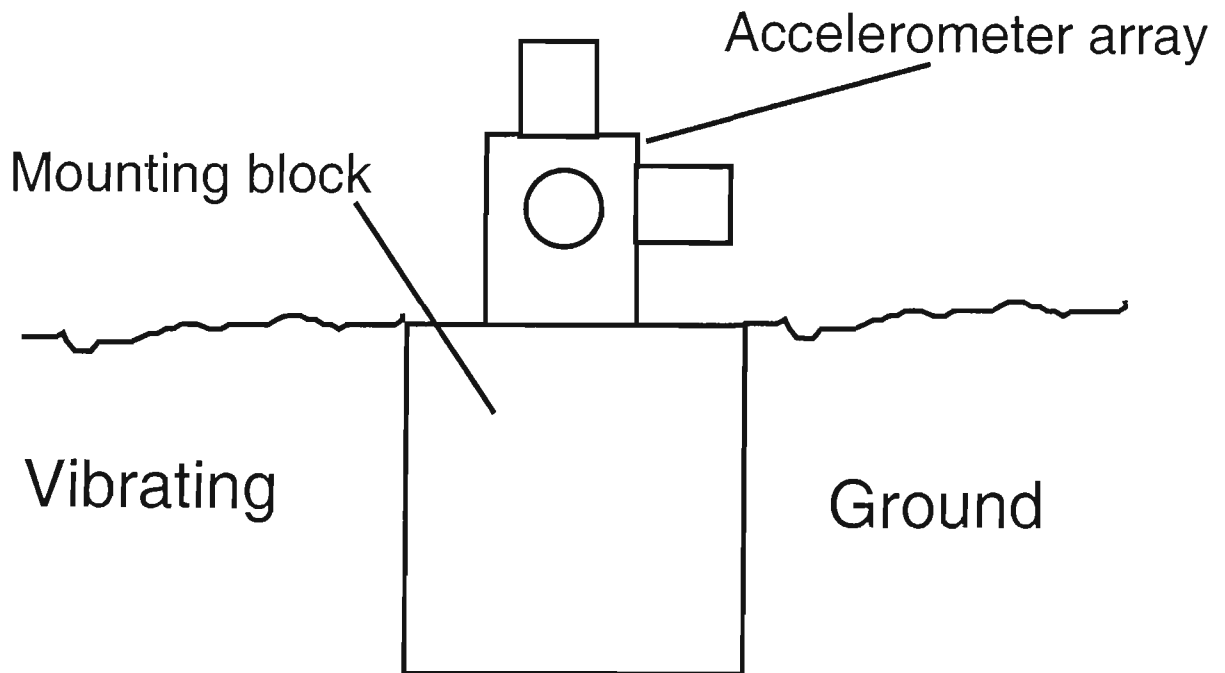


Figure 3.5 Embedded bonding

### 3.2.6 Spike mount bonding.

In some operations, the monitoring of blast induced vibrations and the laborious method used to set up the equipment required, was viewed as a little unnecessary. Even some equipment manufacturers have “specified” quick and simple means of mounting the primary sensor to the ground. But whatever the mounting method used it is the coupling between the soil, or the ground, which must be effective to eliminate any differential movement between the soil and the primary sensor.

This method of coupling the primary sensor to the soil has been popular and is supported by many equipment manufacturers. One spike or a series of spikes is secured to the base of the primary sensor and the primary sensor is then forced into the soil by placing the foot on top of the primary sensor until it is firm in the ground. The equipment manufacturers state that “it is quick and easy” to mount the primary sensor in this way but as will be shown in a later chapter, this method is fraught with errors. If it is that easy to mount the primary sensor to the soil then surely the coupling can also be that easily disrupted. This method is schematically shown in Figure 3.6.

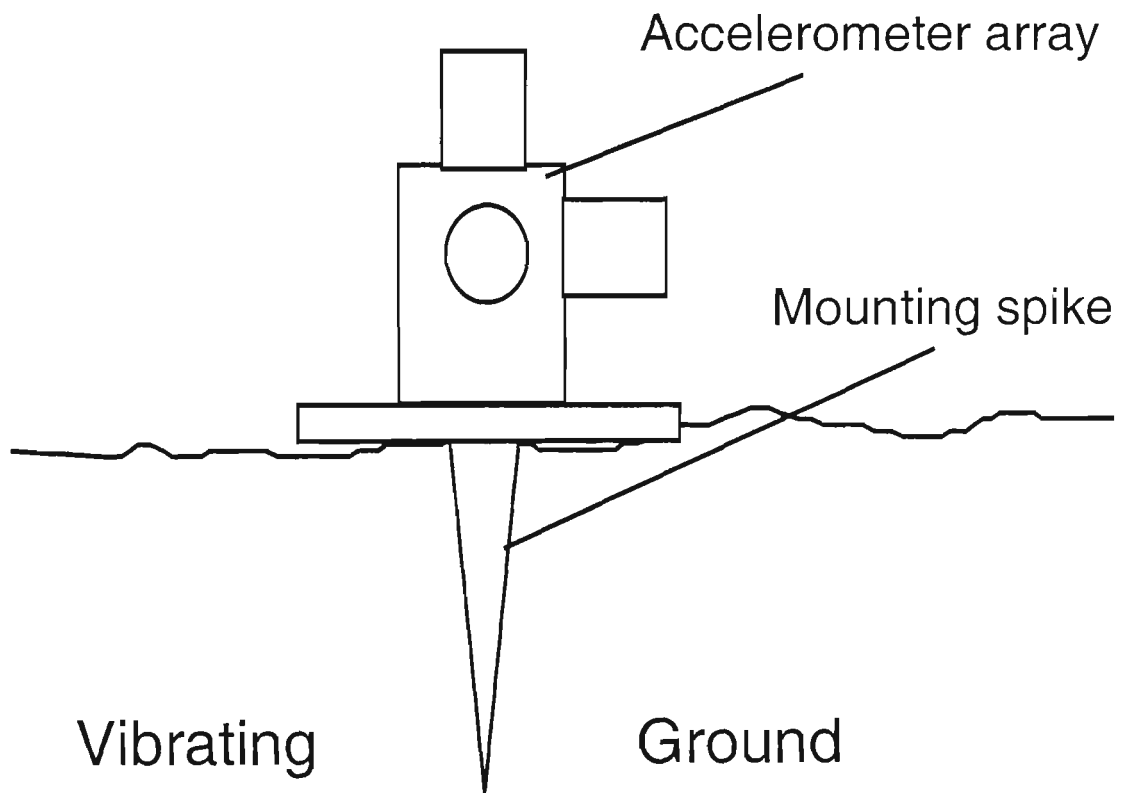


Figure 3.6 Spike mount bonding.

### 3.2.7 Deeply embedded spike bonding.

A natural extension of the small spike method was a longer spike forced into the ground with repeated blows from a sledgehammer. The ground is never consisted as far as the grain size is concerned and usually just below the surface lies hidden boulders etc. to disrupt any bonding that may be formed by forcing the spike into the ground

This method relies on a long spike (approximately 0.5 metres long) or star picket being driven into the ground and the primary sensor attached to the end of the spike protruding from the ground. The coupling of the primary sensor to the spike is usually

accomplished by bolting and the coupling of the spike to the ground relies on local compaction of the soil around the spike. The length of the spike protruding above the ground is a problem as resonant vibrations can be induced in the spike hence causing errors in the levels being measured. Because of the geometry of this method and the ease at which errors can be induced it is not recommended and will not be discussed further in this study. This method is schematically shown in Figure 3.7.

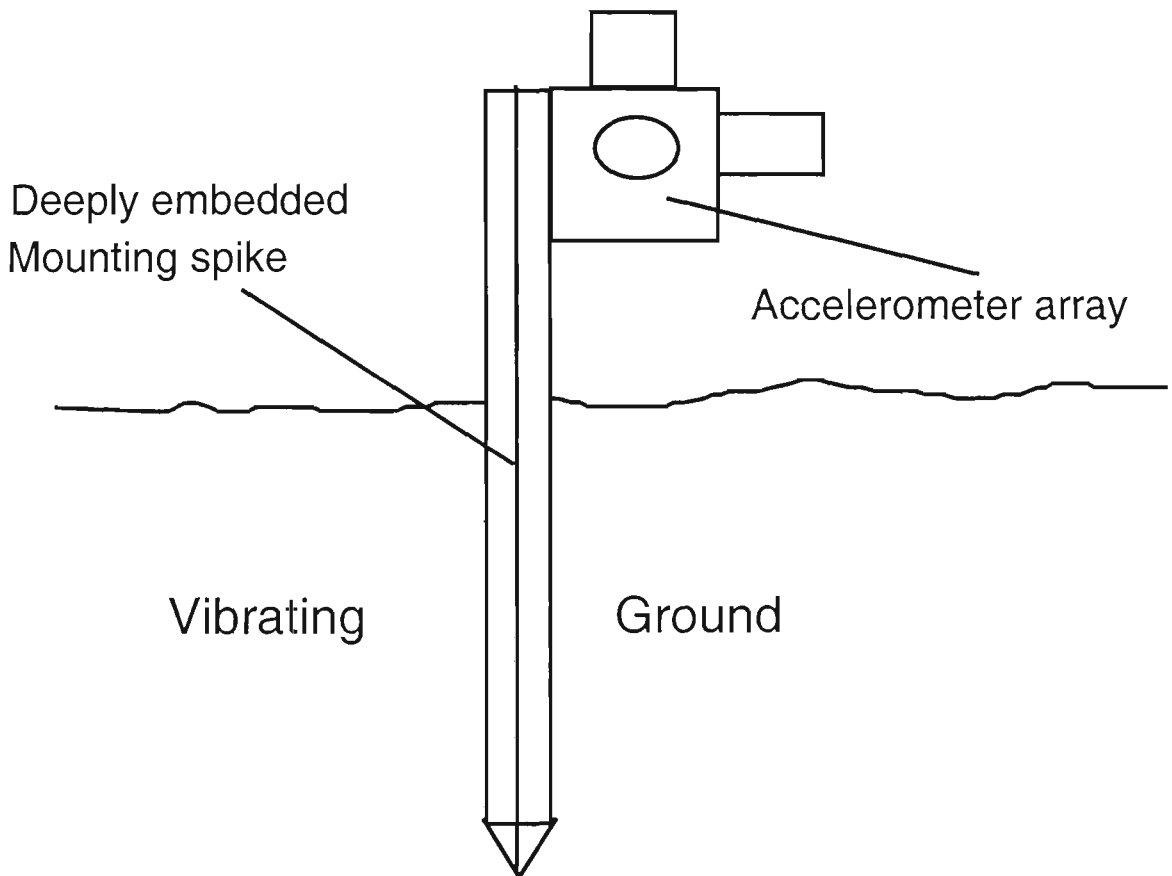


Figure 3.7 Deeply embedded spike mount bonding.

All of these methods of mounting the primary sensor to the ground (soil) have their merits but in some cases the disadvantages will completely outweigh the benefits. If it takes very little effort to embed or couple the primary sensor to the soil then there is a good chance the coupling might not be as effective as it should be. If for example the blast has duration of 6 seconds then the coupling of the primary sensor must stay intact for the entire time of the blast. If the primary sensor becomes decoupled in the middle of the blast then there will be relative movement between the primary sensor and the ground, and errors in the vibration levels will be recorded.



### 3.3 Data sampling equipment.

The effect of soil properties on the vibration measurement will be discussed in Chapter 4 and the properties of the mounting procedure will be detailed in Chapter 5. It is imperative that a scientifically based method be used to mount the primary sensor to the vibrating soil as the vibration level of the soil at the mounting point must be faithfully transmitted to the primary sensor to produce a meaningful result.

The signal from the primary sensor is of an electrical nature and is usually in analogue form. This means a change in the vibration level due to the blast produces a voltage signal somewhere between the sensor's maximum and minimum voltage level. This analogue voltage signal can often be used for displaying by meters and tape recorders but there are some drawbacks using the pure analogue signal. Storage of the signal can take up quite a large amount of space and the analysis of the signal is also quite difficult.

With the advent of the modern computer, the notebook in general use today, many of the problems associated with analogue systems have been overcome. Today the analogue signals are converted to digital signals, which are more easily handled by the computer in this digital form. Today a vibration waveform of some 10 seconds duration can be stored, as a file on a computer, in as little as 10 kilobytes of memory (depending on the resolution and sampling rate). This size file today is extremely small and can be easily handled by the subsequent analysis software that needs to be carried out to produce the "result" of the blast induced vibration at the monitoring point. A block diagram is shown in Figure 3.8 of the electronic components of modern vibration monitoring equipment.

The primary sensor, in this case is the accelerometer, is like all other instruments in that it requires a source of power. Once the power is supplied to the primary sensor a signal is sent out when the physical event occurs. This output signal, in a continuous or analogue voltage, passes to the A/D converter where the voltage signal is changed to digital format. In this digital format the original signal is easily stored in memory for latter retrieval and analysis for the final value to be displayed on the viewing screen.

Vibration monitoring equipment today is a fairly sophisticated piece of electronic hardware. However, the most important piece of this hardware is undoubtedly the primary sensor. If this primary sensor is not the correct one for the application, then no amount of electronic circuitry will be able to filter the signal to produce a result that can be relied upon. Once the primary sensor selection is fixed the next part of the vibration measurement chain is the electrical supply to the primary sensor. This, and subsequent electronic blocks are very well designed with the use of modern electronics. This electrical supply sets the primary sensor in operation mode ready to “measure” any changes that might occur as the vibration wave approaches the monitoring point. The output signal from the primary sensor (linearly proportional to the vibration wave) is sent to an analogue to digital converter. This device takes the analogue signal and compares this input signal to the maximum signal that the primary sensor can produce. A series of “bins”, representing voltage levels, is used to classify the voltage output signal which is then converted to a digital signal, the accuracy of which depends on the resolution of the analogue-to-digital (AD) converter. This digital signal is then passed to a buffer (temporary storage area) which operates on a first in last out basis. These signals are stored on a temporary basis and when the buffer is full the first sample point put into the buffer is then discarded and the new data point takes its place at the start of the buffer.

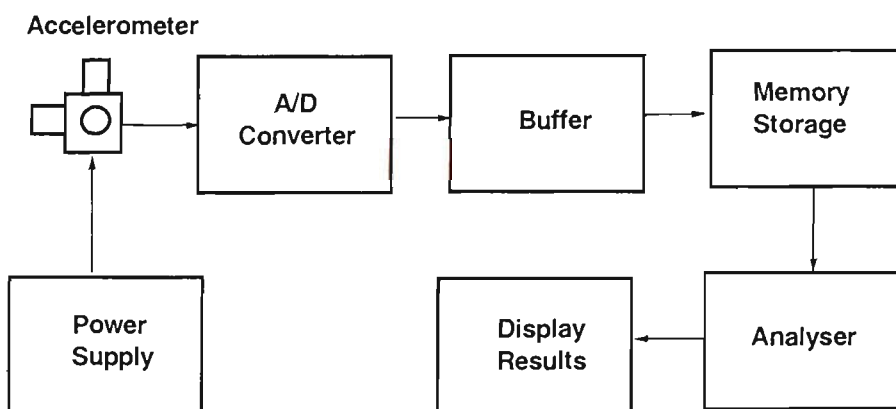


Figure 3.8 A block diagram of modern vibration monitoring equipment.

Thus, an analogue signal representing the vibration level experienced at a particular point on the ground is converted to a digital signal being placed in one end of a buffer and being discarded at the other end as time progresses. This process will continue at infinitum until some condition is met where the signals are moved into some other memory device for permanent storage. A trigger condition must be set to accomplish this permanent storage condition. Two common forms of trigger methods are used and the application will dictate which form (or even both) is to be used. The most common trigger form is the threshold, where a certain “vibration level” (which is really a voltage level) is set as the trigger condition. The data points placed in the buffer are checked against this “threshold” trigger level and while the levels are below the threshold set point the data goes into the buffer. The moment a data point is above the threshold level the direction of the data flow after the analogue to digital converter is changed and the data now flows to the permanent storage device. The other trigger device is called a wire break system. A wire break relies on an external wire circuit being broken (by a detonator) for the trigger condition to be met.

The data flow continues to the permanent storage device for a predetermined time (for example 5 seconds) where upon it is given a file name for future retrieval. The data is in the form of the output signal from the primary sensor at this stage and no analysis is carried out to determine the maximum peak level of the vibration waveform. However, the hardware is now ready to measure the next vibration wave that comes along to the monitoring point and it goes through the same process.

The data that is permanently stored in the memory now has to be analysed to give a number that represents the peak vibration level that was experienced at the monitoring point. This is where the linearity of the primary sensor’s electrical characteristics is of importance. If the calibration of the primary sensor shows that it is linear over a certain range then within this range the vibration levels can be easily measured. However, outside this range of measurement, some error component will be included which can be difficult to model depending upon the sophistication (usually the cost) of the electronics associated with the primary sensor.

The choice of primary sensors sometimes makes it difficult for an immediate result to be displayed on the output screen of the vibration monitoring equipment. The usual unit

of the vibration level is velocity in units of mm/s and this is the output from most geophone primary sensors. That is not to say that the actual output from the primary sensor is these units, but the voltage signal output from the primary sensor is calibrated (the voltage output is related to the physical event) in mm/s units. The calibration process relies on a known input from some physical event being equivalent to the voltage output from the primary sensor. With this calibration factor the physical event can be measured in velocity units that can be mathematically treated. The velocity or particle velocity evolved from some work carried out by the United States Bureau of Mines in the 40's and 50's where a damage criteria was investigated in relation to blasting operations.

The important outputs from the primary sensor is the vibration level and the frequency or predominant frequency of the blast. The blast vibration wave is a transient event and as such will decrease as time progresses. The signal in the form of a digital signal representing the primary sensor output is stored in a file in memory as stated above. This file is then processed via a computer program to determine the properties of the waveform recorded at the time of the blast. As the primary sensor consists of three sensors at the same location the main property of the blast wave that is calculated is the vector sum of these three components. The maximum vibration level is the maximum of the vector particle velocity calculated at each sample point taken. The vector particle velocity is calculated as follows:

$$VPPV \text{ (mm/s)} = \sqrt{(u_R^2 + u_T^2 + u_V^2)} \quad (3.1)$$

Where  $u_R$ ,  $u_T$  and  $u_V$  are the individual component vibration levels at the monitoring point. The subscripts are Radial (in the plane of the blast and the monitor), Transverse (in the horizontal plane normal to the Radial plane) and Vertical (in the vertical plane).

The other property is the frequency of the vibration wave that is calculated by a fast Fourier transform algorithm. This algorithm represents the vibration wave by a series of sine and cosine curves and from these "analytical" curves the frequency is determined. The frequency of the vibration wave depends to a large extent on the particular material that the wave is travelling through and also the time delay between individual hole detonations in the blast sequence.

Both of these properties of the vibration wave are calculated and must wait for the completion of the capture of the entire waveform before the respective calculation can be performed. At some time after the blast, usually less than a minute, these calculated properties are displayed on the screen of the instrument. However, as will be shown in a later chapter, these screen displays can be misleading and it is always prudent to view the entire waveform before any conclusions from the blast induced vibration waveform can be made.

### **3.4 Sample duration**

One question that is often asked is how long is the vibration wave sampled for at the monitoring point? The answer depends entirely upon the detonation time between the first hole and the last hole. The shotfirer will be able to tell how he has tied up the shot and what delays he is using in the surface initiation sequence, and this will give an indication of the time that the vibration wave will travel through the ground.

It is important to get this setting correct as sometimes there can be a series of small patterns connected to the one firing sequence or there can be a change in the firing sequence to “pull” dirt away from one section of the highwall etc. If there are larger charge weights in the latter part of the firing sequence and the time duration of the monitoring equipment is less than the duration of the blast then a lower peak vibration level could be recorded. This could result in a false vibration level being reported at the end of the blast.

#### **3.4.1 Original Analysis Work**

The detonation of explosives in the ground produces an enormous amount of energy for a very short period of time, in effect an impulse force acting on the ground. Blastholes are drilled to depths ranging from less than 5 metres for construction blasting to 15 metres for quarry blasting to 80 metres for open cut coal mine blasting. One explosive quality performance measure that is often used is the Velocity of Detonation (VoD). As the explosive detonates in the blast hole (usually initiation begins at the toe or base of the hole) the chemical reaction travels up the column of explosive until the explosive

has been completely consumed. The velocity of this reaction is termed the velocity of detonation (VoD). Commercial explosives available today have VoDs ranging from 2 km/s (low damage wall control products) to 6 km/s (for high shock and high damage products). Thus a column of explosives reacts for a finite time and the energy is imparted to the confining medium causing damage and ground motion. This energy imparted to the confining medium overcomes the inertia of the ground mass. Even though the chemical reaction has been extinguished the reaction on the ground and also by the ground continues for some time afterwards. The time for the ground to return to a stable state differs from site to site and this difference in time (from the extinguishing of the explosive reaction to the ground coming to rest again) will determine the actual time of the particular blast.

As a blast consists of a number of discrete charges of explosives detonating and each charge is initiated at some time (in milliseconds) after the preceding charge each charge will have an effect on its neighbours. The cumulation of these effects produces the vibration wave that is recorded by the vibration monitoring equipment.

However, if the sampling of the vibration wave is stopped after the last charge is initiated the ground reaction from the last charge and that of the previous six or so holes will not be recorded. In practice, after the last charge has been initiated it is best to continue sampling for a further 0.5 to 1 second depending on the number of charges detonated to ensure that the entire vibration waveform has been captured by the monitoring equipment.

By way of an example a typical overburden vibration waveform is shown in Figure 3.9. The blast initiation sequence (ie. the time of the blast) is 1687 milliseconds. If the vibration monitor was set to 1687 milliseconds then there is still ground movement or ground relaxation which contributes to the vibration wave that will not be recorded. The ground relaxation could in some circumstances (low frequency, large blasts) have a major contribution to the overall vibration level experienced at a particular location. If the vibration monitoring had continued for the extra 1300 milliseconds then the entire vibration waveform would have been recorded and its effect at the monitoring point could be analysed.

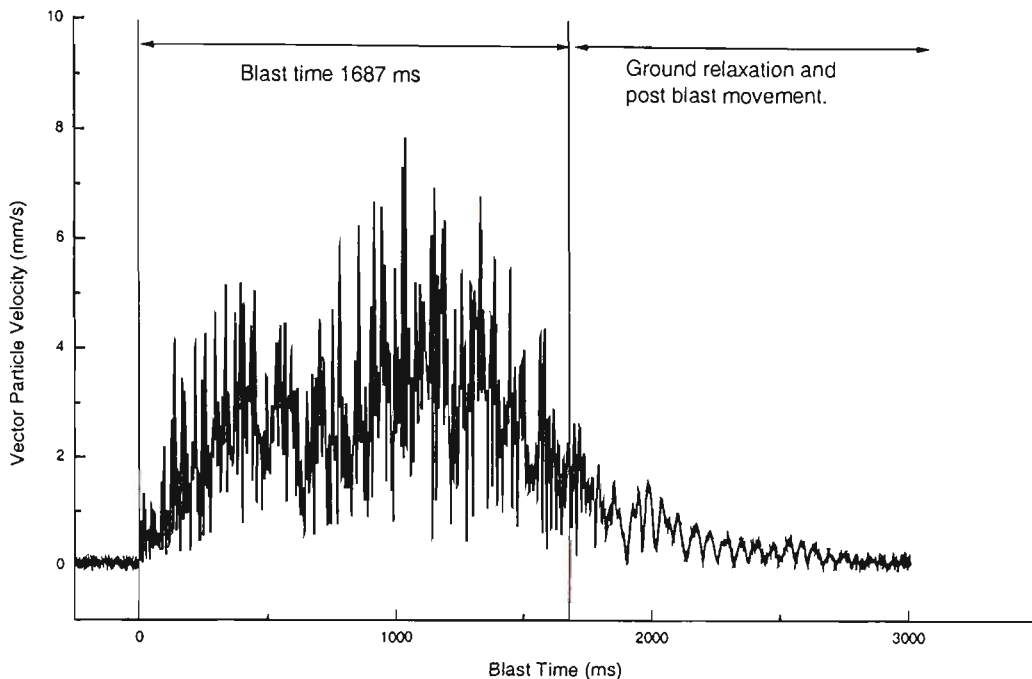


Figure 3.9 An example of the length of time to sample a vibration waveform.

Also the vibration wave recorded by the monitoring equipment is usually a combination of many different waves. Some of these waves have been discussed previously ( $p$ -wave,  $s$ -wave, Rayleigh waves and Love waves to name the most prominent) and it was shown that each wave travels through the ground at different propagation velocities.

If these propagation velocities differ, as they often do, by up to 2 km/s then the time difference at monitoring points some 2 kilometres from the blast can be quite significant. For example if the monitoring point is 2 kilometres from the blast and the  $p$ -wave velocity is 3 km/s then the first arrival (the  $p$ -wave) will trigger the monitoring equipment which begins to save the data into memory. This  $p$ -wave will arrive at the monitoring instrument 0.667 seconds after the first hole is detonated. If a Rayleigh wave is set up in the stratified ground from the blast and its propagation velocity is 0.8 km/s then this wave will arrive at the monitoring point 2.5 seconds after the first hole was detonated. Thus there is a time difference of 1.833 seconds between the first arrival of the  $p$ -wave and the arrival of the Rayleigh wave. Thus, as in the example shown in Figure 3.9, if the monitoring equipment is set to a sample duration of 1.687 seconds

then the Rayleigh wave would not be recorded at all. Sometime Rayleigh waves can have larger amplitudes than the first wave to arrive (*p*-wave).

It is difficult to predict or even model the arrival times of the vibration waves as there are many conflicting events happening at the same time. It must be remembered that as the distance from the blast to the monitoring point is increased then these conflicting events are also joined by equipment limitations. In the above example, increasing the distance to 4 kilometres increases the time difference between the arrival of these two waves to 3.177 seconds so the sample duration must be increased even further. As the distance from the monitoring point increases also the vibration level will decrease hence the trigger level must be reduced. Reducing the trigger level to a low level can cause “false” trigger events that fill up the memory with unwanted data. Eventually when the memory is full with unwanted data there is no space for the blast event when it arrives. Thus if this time difference is not taken into account when setting the sample duration then some of these waves could be missed as discussed above.

### 3.5 Sample Interval

Explosives are used in many different types of rocks to fragment the rock for further excavation. The main purpose of the explosives is to fragment the rock in order to facilitate down stream processing (milling, dumping etc.). There are rocks of many different types and no two mining sites will have the same rock properties. So, the explosives used will have different effects on the rock being fragmented. For example, the density of the rock will change from 2000 – 3000 kg/m<sup>3</sup> for some metalliferous mines to 4000 – 5000 kg/m<sup>3</sup> for iron ore mines. This density is a property of the mineral being extracted and is determined by the crystal structure and constituent parts of the ore. A high-density rock can mean that the crystalline structure is closely packed and thus the transmission rates of seismic waves through the rock (the particle to particle contact required) will be high.

However, even though the mineral can have a high density it does not necessarily mean that the vibration wave transmission rates will be high. If the in-situ rock has a lot of non-homogeneity then this will affect the transmission of the vibration waves through



the ground. This vibration wave transmission rate is the velocity of the  $p$ -wave or the first wave arrival rate with respect to time. However, in some instances both the  $p$ -wave and the  $s$ -wave arrival times can be separated. The structure of the total rock mass will basically determine the reduction in the intact rock  $p$ -wave velocity that will be measured at the vibration monitoring point. Table 3.1 shows some  $p$ -wave velocities measured at various mine sites and the corresponding  $p$ -wave velocities of the intact rock in the same area of the mine site.

Table 3.1 Comparison of In-situ and intact rock velocities.

Mine Site	In-situ Velocity (km/s)	Intact rock Velocity (km/s)
Underground Gold Mine	6.36	6.16
Surface Gold Mine	6.14	5.58
Basalt Quarry	6.21	6.12
Sandstone construction site	2.48	2.39
Sandstone Quarry	3.01	2.30
Surface coal mine	2.37	2.54

Thus the velocity of the vibration wave can be readily determined from the vibration monitoring equipment and this is the information that can be used in modelling packages to determine the effect of vibration waves on structures and rock fragmentation. But the question still remains, how quickly is the vibration wave sampled at a monitoring point?

The velocity of propagation and the frequency of the vibration are two completely separate properties. The velocity of propagation is the speed at which the wave travels through the material. This wave speed is a physical property of the material and depends on such fundamental rock properties as density, internal resistance and predominantly the structure of the in-situ rock mass. Highly weathered and fractured rock mass will offer a barrier to the transmission of the vibration wave and consequently it will have a lower velocity of propagation. The frequency of the vibration wave on the other hand is the speed of the ground displacements at the monitoring location. This frequency is also affected by the fundamental rock properties but it also relies on the competent nature of the rock mass for more efficient energy

transfer from particle to particle. This means that highly competent underground rock environments would have a higher frequency of vibrations than weathered surface rock masses. The frequency of the vibration wave is also to some extent affected by the frequency at which the individual blastholes are detonated.

This is a question that needs some careful thought because there are conflicting forces acting at different locations. The frequency of the vibration wave changes from place to place. This change is due to geometric spreading of the wave as it radiates from the source, local internal resistance of the rock mass and the local structure of the ground. Also the frequency of the vibration wave is dependent on the surface initiation sequence that was used to initiate the blast pattern. In underground operations the tendency is to fire the first part of the blast “slow” to form a space that the subsequent fragmented rock can be thrown into. This leads to a high frequency waveform, which must be sampled at high speeds if enough points are to be taken on each wave cycle to adequately define the waveform for subsequent analysis. If this waveform is not adequately sampled then wrong predictions can be made leading to possibly low vibration levels being reported. If this is the case then it is conceivable that the next blast fired in this area could possibly have increased charge mass (based on the previous low vibration level shot) in each hole, which could have devastating effects to local structures (pillars, bridges etc.).

### **3.5.1 Waveform Sampling (Original Work)**

The sampling rate (sometimes referred to as the sampling frequency) can be understood using some actual waveform examples collected in the field. The first example shown in Figure 3.10 is from an underground blasts where the rock mass was quite competent and no major faults or structure was evident between the blast and the monitoring location. The second example is that of a surface coal overburden blast, shown in Figure 3.12 where the ground between the blast and the monitoring location was fairly weathered and had a layered structure. Both of these waveforms were collected using a high-speed data logger connected to a series of accelerometers. The sampling rate of the data logger was set at 13333 samples per second (13.3 kHz) for the underground blast and a sampling rate of 15000 samples per second (15 kHz) was used in the surface blast shot.

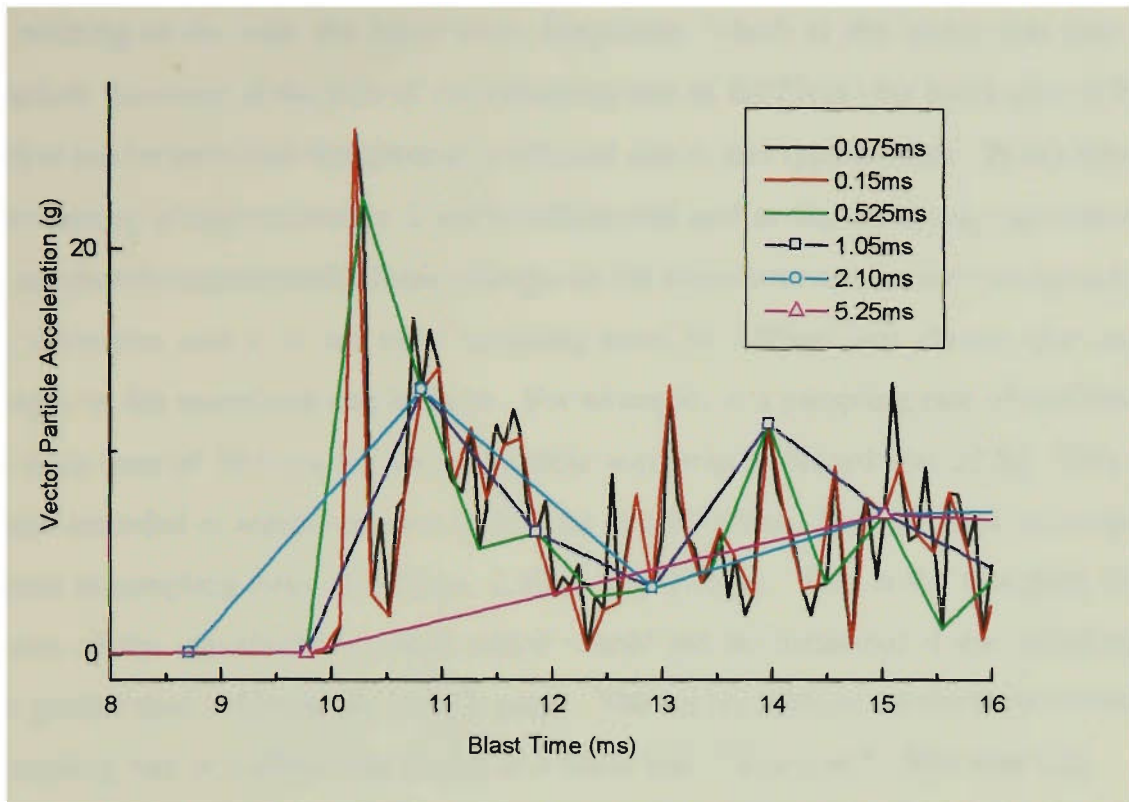


Figure 3.10 Sampling of a high frequency vibration wave (closest)

The underground blast was a series of rings (6 rings with up to 8 holes in each ring) in a narrow stope mining operation. The time delay between each hole was set at 10 milliseconds, as the entire shot had to be fired quickly to minimise damage to the surrounding ground resulting in possible explosive column cut-offs and misfires. From the waveform recorded (at 13.3 kHz samples per second) a number of “artificial” waveforms were generated. These “artificial” waveforms were made by eliminating a number of data points from the waveform sampled at 13.3 kHz to produce waveforms at 6.67 kHz, 1.90 kHz, 0.95 kHz, 0.47 kHz and 0.19 kHz samples per second. A spreadsheet was set up and sample points were selected at other sampling rates, as shown in the plot, to generate a waveform at various sample intervals. This monitoring point was approximately 30 metres from the first hole that was initiated in the blast.

As shown in Figure 3.10 the difference in the sampling times is quite remarkable. A sampling time of 0.075ms corresponds to 13.3 kHz sampling rate and as shown the number of points on each waveform is more than adequate. As this sampling point was close to the blast it was expected that high vibration wave frequencies would be experienced. As the sampling time between sample points increases a completely different waveform would be recorded at this lower sampling rate. This sampling rate

has nothing to do with the blast wave frequency, which is the event that has to be recorded. Looking at the plot of the sampling rate of 0.075ms (the black plot in Figure 3.10) it can be seen how the ground is vibrated due to this type of blast. Peaks appear to be occurring at approximately 2 each millisecond and at this sampling rate the waves are adequately represented. Some changes in the waveform can be seen as the sampling rate decreases and it is not until sampling rates of 1.05ms and slower, that marked changes in the waveform can be seen. For example, at a sampling rate of 0.075ms and at a blast time of 10.3 ms the vector particle acceleration record was 22.5g. This value is also recorded at sampling rates of 0.15ms and 0.525ms. But this peak is completely missed at sampling rates of 1.05ms, 2.10ms and 5.25ms. This is the true peak for this section of the waveform recorded which would not be measured if the sampling rate was greater than 0.525ms per sample point. The vector particle acceleration recorded at a sampling rate of 1.05ms was 21.5g, at 2.10ms was 12g and at 5.25ms was 12g.

Thus if a sampling rate of less than 1 kHz was used to sample this type of vibration wave and the peak level was used as an indication of the vibration experienced by some structure after the vibration wave had passed then erroneous results could be measured. If the sampling rate was too slow (greater than 1.05ms per point) considerably lower vibration levels would be recorded. For subsequent blasting it would be conceivable to increase the charge weights (based on the vibrations levels recorded at these low sampling rates) this would increase the vibration level. This could have possible catastrophic effects for the surrounding ground and also increase dilution of the extracted ore in this underground blasting operation.

The waveform in Figure 3.11 was obtained from the same blast as in Figure 3.10 but the monitoring location was approximately 120 metres from the blast. As can be seen the frequency of the vibration wave in Figure 3.11 is much lower than that in Figure 3.10 even though it is the same vibration wave. White (1983) when he discussed attenuation dispersion pairs alluded to this effect. At the moment of detonation of the explosive there is a finite amount of energy released by the explosive which acts on the confining rock mass. This energy radiates from the explosive source in all directions and the amount of energy at any location, or energy flux, reduces as the reciprocal of (distance)<sup>2</sup>. This function is known as geometric spreading which is the decrease of the vibration wave frequency with increasing distance from the explosive source. However,

it is not only geometric spreading that causes a broadening of the frequency but also the internal friction of the rock mass. With each oscillation of the particles there is some resistance to movement by the rock mass and internal local heating of the rock mass occurs. This process is energy absorbing and also slows down this passage of energy from particle to particle hence reducing the frequency.

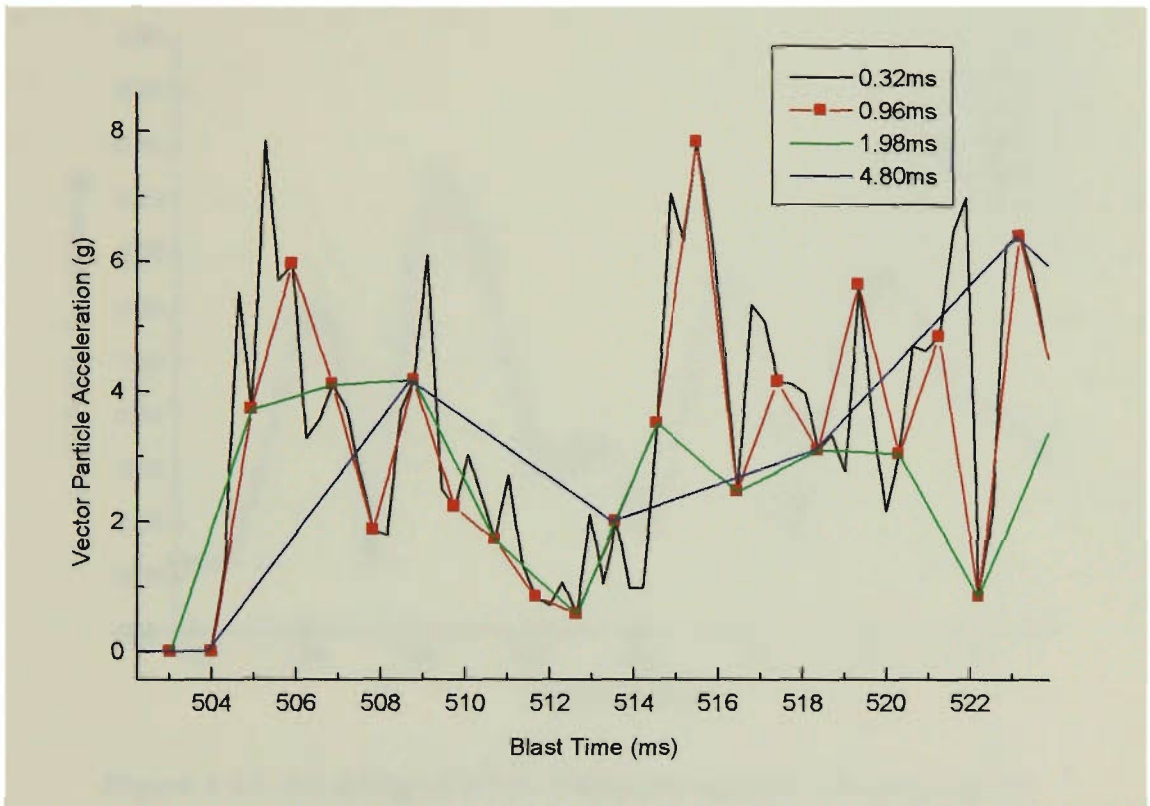


Figure 3.11 Sampling of a high frequency vibration wave (distant)

As shown in Figure 3.11 the predominant frequency of the wave at this sampling point has changed from 134.0 Hz (at 30 metres from the first hole initiated) to 37.5 Hz (at 120 metres from the first hole initiated). The sampling rate of 0.32 milliseconds per point used is shown to adequately sample the vibration wave as the shape of the waveform is different even from the waveform sampled at 0.96 milliseconds per point (compare the black and red waves in Figure 3.11). When the sampling rate is decreased even further the shape and the features of the waveform can be seen to be completely different (compare black and blue waveforms in Figure 3.11)

The surface coal overburden blast was a blast pattern consisting of 8 rows of holes with 20 holes in each row at a coal mining operation. The time delay between each hole in the row was set at 100 milliseconds and the time between rows was set at 42 milliseconds. With this initiation sequence there was only one hole per delay detonated

to minimise vibration level at a neighbouring farmhouse. From the waveform recorded at the highest sampling rate a spreadsheet was set up and points were selected at various sampling rates to produce the plot shown in Figure 3.12. The monitoring point was approximately 600 metres from the first hole that was initiated in this blast.

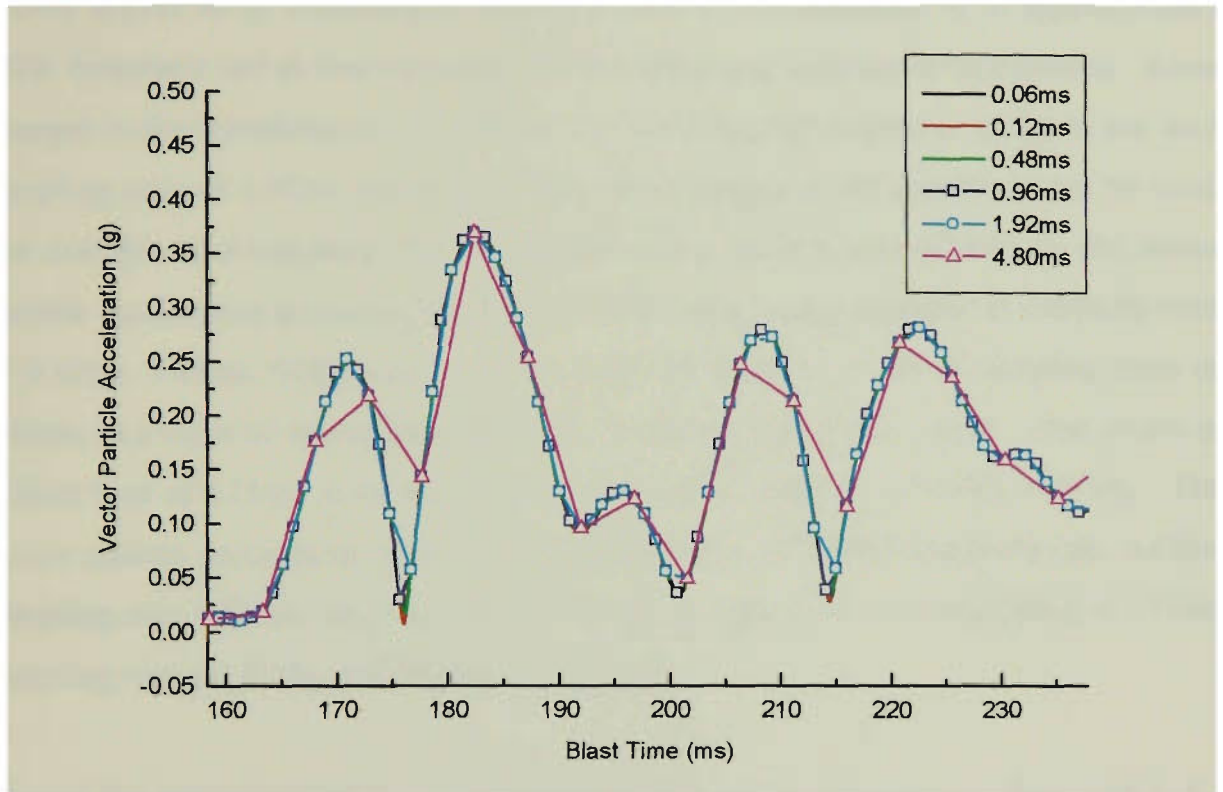


Figure 3.12 Sampling of a low frequency surface vibration wave

It was envisaged that the frequency of the vibration wave would be lower than the underground blast discussed previously. The vibration wave had to travel through stratified material of which the surface layers were extremely weathered and of a soil nature. Individual blasthole detonations were approximately 42 milliseconds (23.8 Hz) apart in time together with the attenuation and broadening effect of the weathered layered surface a significantly lower vibration wave frequency (than the underground situation) was recorded.

As shown in Figure 3.12 the difference in the sampling rates is quite similar to the effect shown for the underground blast. A sampling time of 0.060ms corresponds to 15kHz and as shown the number of points on each waveform is more than adequate. As this sampling point was a long way away from the blast it was expected that low vibration wave frequencies would be experienced. As the sampling time increases between sample points not a lot of difference is shown in the waveforms as the frequency of the

vibration wave is much lower than the underground situation. This sampling frequency has nothing to do with the blast wave frequency, which is the event that has to be recorded. If the plot of the sampling rate of 0.060ms (the black plot in Figure 3.12) is scrutinised it can be observed how the ground is vibrated due to this type of blast. Waves appear to be occurring at approximately 15 milliseconds or at approximately 65Hz frequency and at this sampling rate the waves are adequately represented. Some changes in the waveform can be seen as the sampling rate decreases and it is not until sampling rates of 1.92ms and slower that some changes in the waveform can be seen. For example, at a sampling rate of 0.060ms and at a blast time of 170 ms the vector particle acceleration measured was 0.25g. This value is also recorded at sampling rates of 0.12ms, 0.48ms, 0.96ms and 1.92ms. But this peak is cut off at sampling rates of 4.80ms to a value of approximately 0.20g. A similar loss of the “peak” value occurs at a blast time of 175ms, only this time the true value of 0g is increased to 0.14g. The vector particle acceleration recorded at 175ms was 0g at 0.06ms sampling rate, 0.12ms sampling rate, 0.48ms sampling rate and 0.96ms sampling rate but was 0.04g at 1.92ms sampling rate and 0.15g at 4.80ms sampling rate.

Thus if this instrument configuration is relied on to record the peak vibration levels at a particular location in the soil one could be fairly confident of recording the true value provided the sampling rate was kept below 1.92ms. If the sampling rate was too slow (greater than 1.92ms per point) some errors could be experienced and the resultant waveform would be unreliable for subsequent analyses. At these blast induced frequencies, at this location, reasonably accurate vibration levels would be recorded at much slower sampling rates than those needed in underground blasting as discussed.

Ideal sampling of vibration waves is an important parameter to make sure the wave being sampled is truly represented by the data stored in the vibration monitoring equipment. The sampling rate should be ideally linked to the maximum frequency of the vibration wave being sampled and this was shown in Figure 3.10 to Figure 3.12. Adopting a slow sampling rate can wrongly modify the true vibration wave.

This distortion of the input wave is referred to as aliasing whereby insufficient data points are used to represent the vibration waveform at a particular location. There are theorems in signal analysis techniques that define the optimum sampling rate. One such

technique states that to sample a waveform or a signal correctly the minimum sampling frequency should be the Nyquist frequency. All signals have a “noise” component and this noise component is usually of a high frequency nature. This high frequency noise can be instrument related and can be eliminated or minimised if a filter is placed in the signal line to stop the passage of this noise component. This is the traditional approach and hardware with a low pass frequency cut-offs of the order of 2 kHz or more can be used to eliminate any “squiggle” on the output signal from the primary sensor. These signal processing theorems (briefly discussed in Chapter 2) state that the sampling rate must be at least twice the maximum frequency of the vibration wave to prevent this aliasing or distortion of the primary event waveform. As shown by the analysis above the vibration wave frequencies are of the order of 200 Hz and as also shown sampling rates of 1 kHz were shown to be quite effective in sampling the signal output from the primary sensor.

Thus from this analysis it can be seen that the sampling rate of the waveform is critical to the information that can be extracted from the analysis of the vibration wave. Different types of ground attenuate the vibration wave at different rates and the geometric spreading effect is also affected by the type of ground. It has been shown that the frequency of the vibration wave changes with distance from the explosive source with frequencies from a typical industrial explosive changing from 300 Hz for competent underground rock to 60 Hz for stratified overburden material in coalmines.

Vibration monitoring has been carried out in a large range of rock or ground types and the frequencies measured have ranged from between 20 – 400 Hz. As stated above these frequencies are dependent to some extent on the blast initiation sequence and to sample these primary events effectively sampling rates of 1 kHz (or 1ms) per point would adequately define the primary event by the waveform recorded.

### **3.6 Resolution**

The electrical signal from the primary sensors is in the form of an analogue signal (ie. a continuous varying signal) which needs to be converted to a digital signal for



subsequent analysis. The analogue signal (the vibration wave) is converted to a digital signal by the analogue-to-digital converter. This converter samples the input analogue signal and places this voltage signal into a bin depending on the resolution of the analogue-to-digital converter.

A digital signal is easy to handle in modern electronic circuits because the signal basically consists of a “1” and a “0”. The digital signal is a 5 volt signal where 5 volts is equivalent to a “1” and a zero volt signal is equivalent to a “0”. The 1’s and 0’s make it easy to manipulate and easy to segregate into the bins mentioned above. This digital signal is now in binary form that occupies less space in computer memory when storing the data. For example an analogue file stored in binary format would occupy approximately 80% less space, so the benefit of data conversion to digital format is two fold. The number of bits used to represent an analogue voltage signal depends on the power of the analogue-to-digital converter (AD converter) used in the data capture section of the data logger. The higher the number of bits the greater will be the accuracy that can be obtained from the signal conversion.

Resolution is the division of the maximum and minimum voltage input signal into a number of “bins” (usually 2 to some power). Resolution is usually measured in bits and a good AD converter would have a resolution of 16 bits. For example (refer to Figure 3.13) an analogue sine wave is shown with a schematic representation at a resolution of 8 bits and also 16 bits. As shown by the 8-bit resolution of the digital signal a stepping function is made to represent the true analogue waveform. If however, the resolution is increased to 16 bit then an extremely accurate digital representation of the analogue signal is obtained.

The resolution of the analogue to digital converter is a function of the electronics and is a parameter that can only be selected at the time of purchase of the vibration monitoring equipment. Converters of 8-bit resolution have been on the market for many years and it has only been in the past decade that 16-bit converters have been readily available. The drawbacks in the earlier days of the 16-bit converter were the storage space required, the power consumption and the heat generated. However, all of these concerns have been overcome and 16-bit computer boards are readily available today that can be used in vibration monitoring equipment.

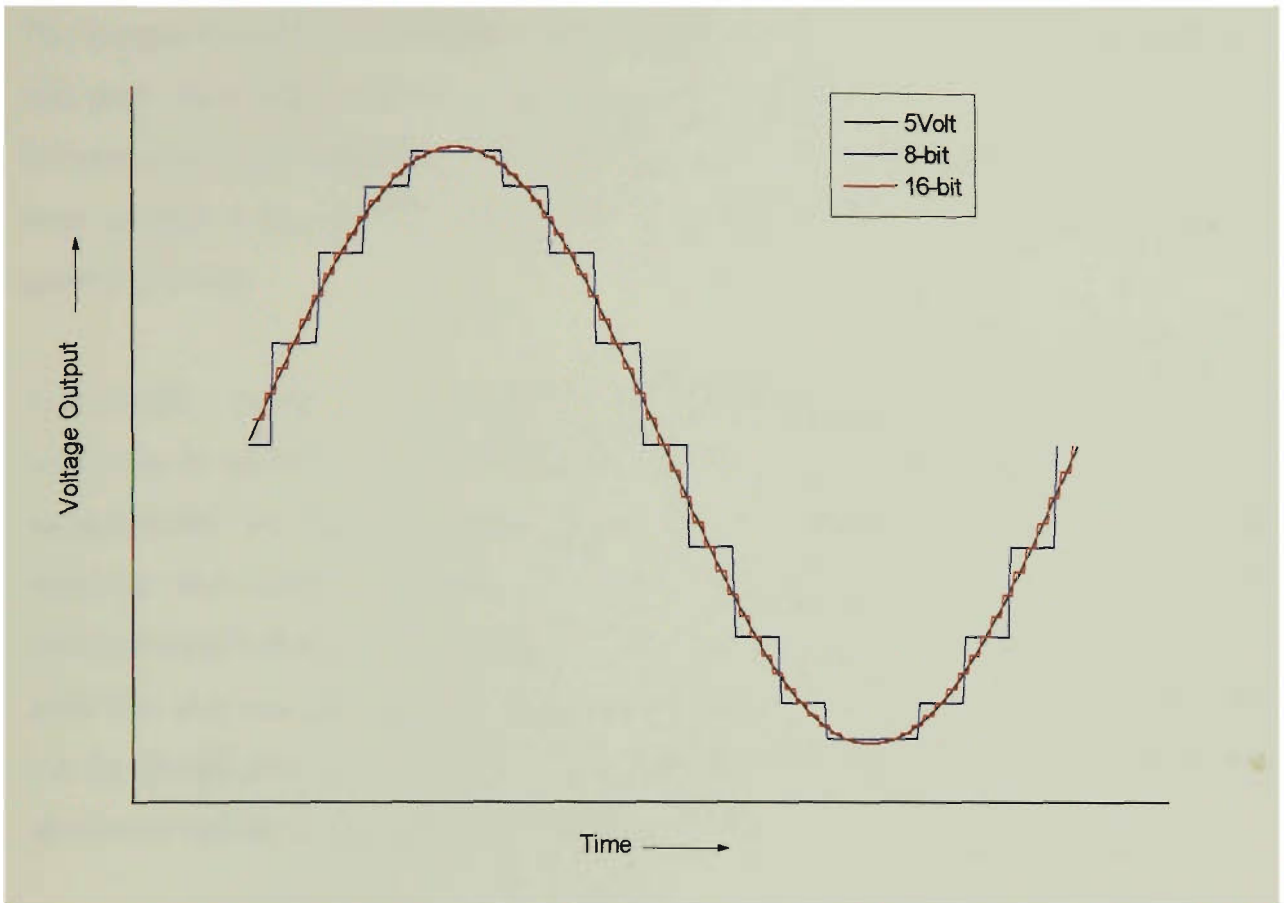


Figure 3.13 A schematic representation of the resolution principal.

### 3.7 Discussion

The different ways to mount the primary sensor to the vibrating surface was discussed. Some of the methods will be discussed in detail in Chapter 5 and the standard mounting technique will be used as the base case by which all other mounting techniques will be compared.

Mounting methods such as double-sided tape weight force and magnetic coupling should not be used when measuring blast induced ground vibrations in soil. It is the bond of the soil to the primary sensor device that is important and methods that have this soil coupling will be discussed in detail in Chapter 5.

The properties of the monitoring equipment revealed some areas that should be considered when purchasing this equipment.

The sample record time was shown to be an area where the possibility of “missing” the true peak value could occur. Although the blast timing may be set for approximately 0.5 seconds (for example) recording of the ground vibration should be maintained for at least another 1 second until the ground completely relaxes from the blast induced ground vibration.

The sample interval is possibly the most important parameter where “wrong” peak levels can be recorded. Sample intervals of at least 0.5 milliseconds per data point are recommended for high frequency blast induced ground vibrations (underground blasting) and sample intervals of at least 1.0 millisecond per data point are recommended for low frequency blast induced ground vibrations (surface blasting). A good idea is to sample as quickly as the monitoring equipment will allow as excess data can be filtered out if it is not required. Software programs and computers today can adequately handle these large size data files generated from sampling at these rates.

The resolution or accuracy of the blast induced ground vibration waveform recorded is dependent on the electronic components within the data logger equipment. Electronic equipment using 12-bit or 16-bit technology would be recommended even though more storage capacity would be required.

### **3.8 Chapter Conclusions**

- The mounting procedures used at present were discussed.
- The embedded mounting procedure has a large surface area for soil contact.
- Electronic equipment today makes many options available.
- The component structure of the data logger is discussed in detail.
- Sample duration must be long enough to capture ground relaxation.
- Sample interval must be linked to the waveform frequency.
- Underground sampling frequency must be higher than surface sampling frequency.
- Equipment resolution as high as possible will minimise potential errors.



## **CHAPTER 4.**

### **LABORATORY INVESTIGATION.**

#### **4.1 Introduction.**

This chapter will detail the laboratory study used to examine the parameters of the soil that have an effect on the vibration transmission (or attenuation of the input source) of the soil. A laboratory study was used to examine these effects as many uncontrollable parameters in the field could, to a certain degree, be controlled in the laboratory.

Sections 4.2 to Sections 4.5 discuss the soils used, the laboratory procedure developed to test different parameters of the soil and the variability in the procedure that can be expected in this study. Section 4.6 investigates the effect that moisture has on the transmission level of the vibration wave through the soil in the laboratory rig. Section 4.7 shows the effect of compaction on the coupling between the soil and the mounting block in the laboratory rig. Section 4.8 details the effect of the size distribution of the soil on the vibration transmission in the laboratory rig and the effect of large particles on the transmission characteristics of the soil. Section 4.9 shows the effect of the type of soil on the attenuation characteristics of the individual soil types in the laboratory vibration rig.

#### **4.2 External Parameters considered in Laboratory Study.**

The vibration wave transmission in the field is controlled by a number of parameters of the soil that exist at the time of monitoring. The environmental conditions at the time eg. weather, soil types etc. dictate some of these parameters of the soil that will have an effect on the vibration levels at the monitoring location. If these parameters of the soil can be controlled then their effect on the vibration levels can be quantified. A laboratory vibration rig was established which had similar mounting conditions, of the primary sensor, to that used in the fieldwork. By using the same mounting procedure in the laboratory experiments as that used in the field, errors can be minimised and these external parameters can be quantified. The effect of parameters external to the

monitoring procedure but directly influencing the performance of the monitoring procedure were investigated under controlled conditions in the laboratory. The external parameters of the soil that were investigated were:

- 1) the moisture content of the soil directly adjacent to and in touch with the mounting block.
- 2) the compaction or density of the soil directly adjacent to and in touch with the mounting block.
- 3) the particle size distribution of the soil directly adjacent to and in touch with the mounting block.
- 4) the type of soil directly adjacent to and in touch with the mounting block.

The moisture content of the soil was chosen as one of the parameters that could have an influence on the vibration level measured at a particular location. It was thought that as the moisture content of the soil increased and the interstices became saturate with water vibration wave transmission would increase. The transmission of the vibration wave relies on particle to particle contact for the continuous wave like motion to be maintained. Soil types vary, as will be discussed latter, and the number of contact points and the coupling of these contact points to the neighbouring grain will significantly influence the vibration wave transmission from grain to grain. If, however, there is an incompressible fluid such as water coating the grains then extra forces such as surface tension would aid in the grain to grain coupling and hence enhance the vibration wave transmission through out the body of the soil as the vibration wave passes through the soil. If this incompressible fluid is present in excessive quantities then a completely different mechanism will exist and the coupling between the grains could be adversely affected. Both of these conditions of the soil forming the coupling between the soil and the mounting block can occur in the field. Under normal dry conditions the moisture bond enhancement would be very low and during periods of wet weather an abundance of water between the grains is likely to occur.

Vibration monitoring in the field is an integral part of any mining operation today. In order to be able to measure the vibration levels at any location an instrument must be placed on the soil to faithfully, or as faithfully as possible, move as the soil moves and record the vibration wave passage with time. As with any intrusive monitoring procedure, the attachment of the primary sensor must have a minimal effect on the event

being measured. Coupling a primary sensor to soil is no easy matter due primarily to the structure of the soil itself. This coupling is best accomplished by compaction of the soil to a device to which the primary sensor is firmly attached. The compacted soil will inevitably be different to the original soil compaction state which will have some effect on the transmission of the vibration wave from the undisturbed soil through the compacted soil through the mounting block to be measured by the primary sensor. However, if the soil characteristics as far as the vibration wave is concerned are close to the characteristics of the measuring device then errors due to the measuring equipment will be minor and can be neglected on a practical scale.

Field monitoring exercises can some times be carried out in quarries or rocky soil and the coupling of this type of soil to the mounting block has often been questioned. For a vibration wave to travel through the ground there must be contact between adjacent particles. It is well recognised that vibration waves travel more efficiently through competent ground than through a broken structured type of ground. Does this also happen on a micro scale to the soil in contact with the mounting block in the field monitoring exercise, or is the soil structure (large or small particle size) the dominant feature from the point of view of the vibration wave transmission? One soil was acquired from a granite quarry enabling large particles to be obtained from this soil. The large particles were removed from the soil sample top size used in the experiments and then added back into the soil to alter the size distribution to examine the effect of “large” particles on the vibration transmission through the soil.

The laboratory section of this work investigated the effect of different types of soils on the transmission of the vibration wave. The soil types were selected from “typical” field monitoring locations and ranged from a granite quarry sample to sand type soils and predominantly clay based soils.

A procedure and an experimental set up was established to measure the effect of varying one of the four parameters mentioned above. A large container which allowed soil to be packed around the mounting block was struck with an instrumented hammer and the vibration level measured using the standard mounting procedure in the same manner as used in field trials as reported in Chapter 5. In this procedure the major variable for each test was one of the four parameters above as all other variables were reasonably

well controlled and any difference that was measured from any test could be attributed to a change in one of the four parameters above. The properties of the vibration monitoring equipment were detailed in Chapter 3 while the properties of the standard mounting procedure are investigated in typical field situations in Chapter 5.

### **4.3 Laboratory Vibration Rig Procedure.**

As with any investigation into the effects of parameters on a desired outcome a procedure had to be established so that the variation measured is a result of changes in the parameter. In this case the procedure had to be similar to the procedure that was to be used and tested in the field. Some of the components of the field procedure were the same as those used in the laboratory equipment. A laboratory vibration rig and a procedure, which could produce the same conditions each time, or as near as practically possible, was established.

The mounting procedure consisted of an aluminium cylinder, which was machined flat on each end and the circumferential surface was “knurled” to aid in the coupling of the soil to the mounting block. Knurling the outer surface of the cylinder helped to roughen the surface. One end of the mounting block was drilled and taped so that the primary sensor could be firmly secured to the mounting block. This mounting block had an aspect ratio (diameter to height) of 1 and a triaxial set of accelerometers attached to the top surface.

This orthogonal triaxial accelerometer array is the primary sensor and is the device that must move in unison with the soil. Accelerometers are transducers that change force into an electrical signal. These devices consist of a pre-stressed mass physically connected to a piezoelectric crystal. The piezoelectric crystal generates a small electric charge when a force is applied to the crystal. This small charge is conditioned and amplified and the final electrical output signal is directly proportional to the applied force. The signal from each accelerometer was sent via a cable that was connected to each accelerometer to the field data logger. The cable from each accelerometer was joined into one single plug that was connected to the field data logger.



The field data logger is an electronic device that is capable of sampling the voltage signal from the accelerometer and storing this information in digital form in the memory of the data logger. The electrical output from the accelerometer is an analogue voltage signal that ranges between  $\pm 5$  volts which is passed to an analogue-to-digital converter to “digitise” this voltage signal which is more easily handled by modern digital circuitry. This 5 volt digital signal is now in the form of binary information which is easy to store in computer memory chips for latter retrieval and interpretation.

The mounting block, the primary sensor, all described above, were all part of the equipment to convert the physical event, the vibration wave, into a form that can be recorded and retrieved for subsequent analysis. This equipment was designed to capture the vibration wave as faithfully as possible and eliminate any bias towards any element in this capture process. The next component of the laboratory procedure to test the soil properties was the container to house the soil material.

A large soil container with a volume approximately 15 times the mounting block volume, was used to accommodate the mounting block with enough space to compact the soil to bond the mounting block to the soil which was being tested. The soil container had a volume of 27.6 Litres (the mounting block volume was 1.73 Litres) and was 0.39 metres in diameter with an internal height of 0.25 metres. The soil container weighed 18.04 kilograms. The soil container was made of a fired clay material and was solid enough to withstand the continual striking during the testing of the soils.

The soil container with the soil and the mounting block attached was then located under a suspended instrument hammer which was designed to strike the outside of the container at the same location each time. The instrumented hammer was secured at one end of a rigid arm that was pivoted 1.84 metres from the surface of the soil in the soil container. The instrumented hammer was allowed to swing in a pendulum manner and strike the outer edge of the soil container and rebound. This action usually occurred four times before the instrumented hammer came to rest, touching the outside of the soil container. The soil container was aligned such that the pivot point of the instrumented hammer and the point at which the instrumented hammer struck the soil container were in the same vertical plane. The soil container was aligned in the same location for each test that was carried out. The instrumented hammer was pulled back 0.2 metres from

the outside surface of the soil container and then allowed to swing and strike the outside of the soil container. The instrumented hammer rebounded from the surface of the soil container a distance of 0.134 metres and then swung back to strike the outside of the soil container again. This second cycle of the pendulum motion of the instrumented hammer was used as the input force to the soil in the soil container. This second cycle was used as it was considered to minimise the errors in the applied force to the soil in the soil container.

The field data logger was set to record the vibration waveforms as the soil in the soil container was vibrated from the blow by the instrumented hammer. As there was envisaged errors in the positioning of the instrumented hammer before it was allowed to swing in its pendulum motion the hammer was allowed to strike the pot initially before sampling commenced. The field data logger was set to trigger on threshold of the first blow on the soil container. As the soil container was struck for the first time the field data logger began to store the output signal from the accelerometers into memory for a total of 1 second.

The main purpose of the laboratory vibration rig was to introduce a constant or near constant force to the soil in the soil container and measure any changes in the transmission or attenuation of the vibration level detected at the primary sensor. Thus any changes in the condition of the soil in the soil container should produce a change in the vibration level detected by the primary sensor. This variation could then be attributed to the change in the soil parameter. Figure 4.1 shows a schematic representation of the laboratory vibration rig and a photograph of the laboratory vibration rig is shown in Figure 4.2.

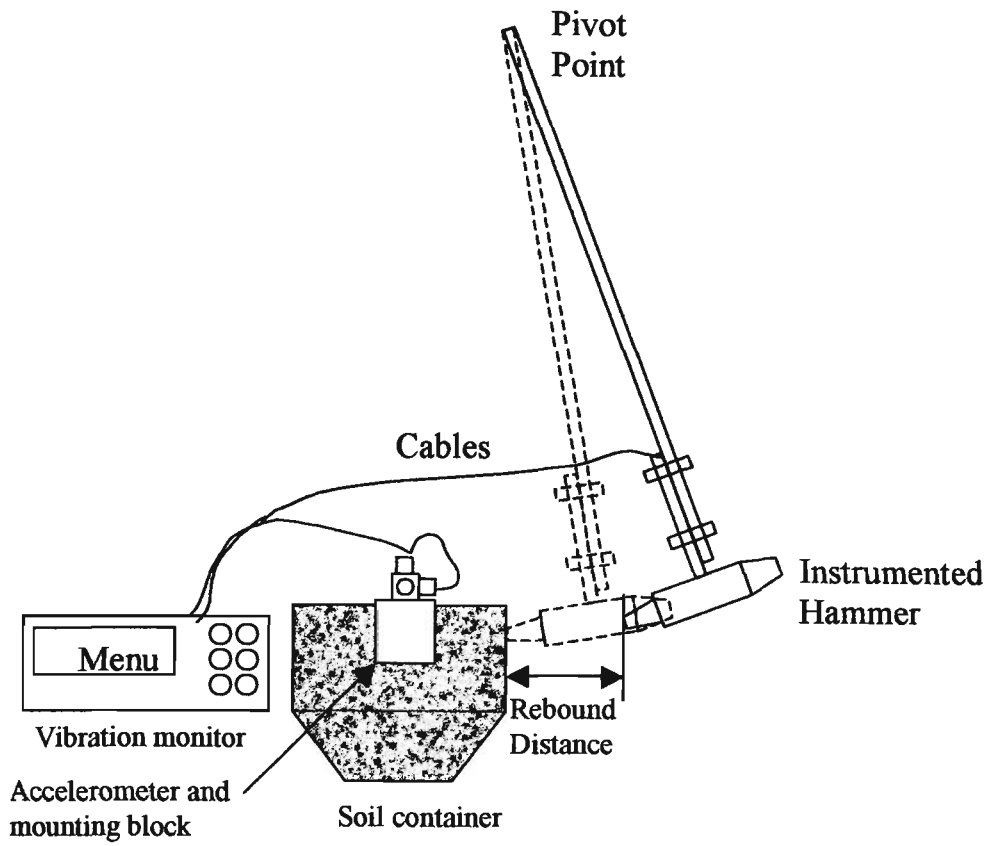


Figure 4.1 Schematic representation of the laboratory vibration rig.

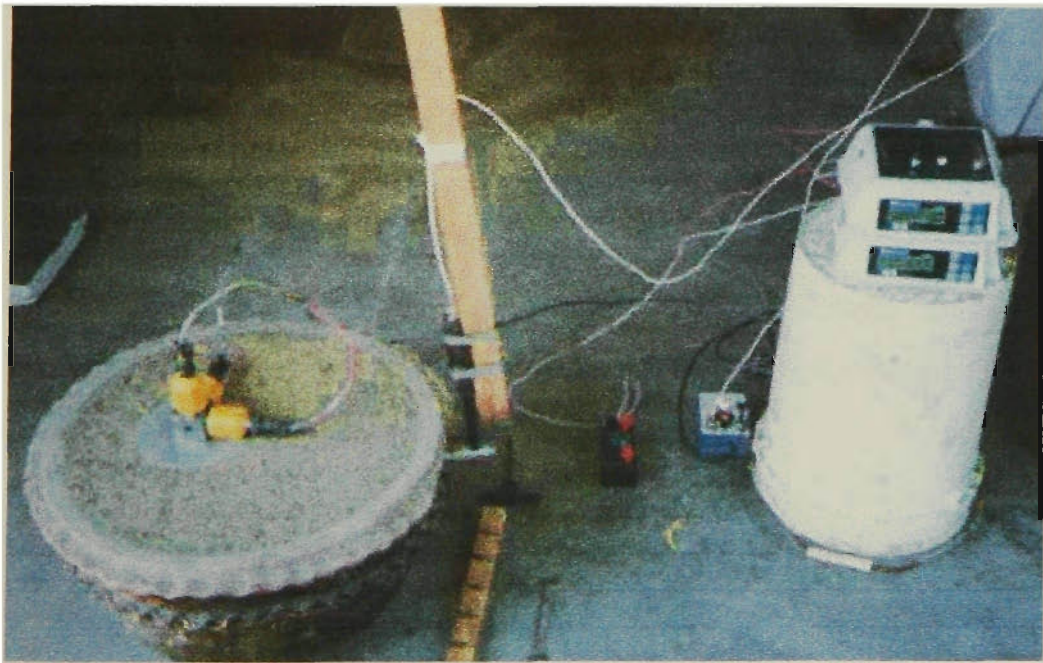


Figure 4.2 Photograph of the laboratory vibration rig.

#### 4.4 Soils used in the laboratory study.

Vibration monitoring is usually carried out in soil ie. farm paddocks, housing estates and local land fills etc. The soil types vary quite considerably and the effect of vibration transmission through each and every soil is different. Soil is a mixture of grains of many sizes and many chemical compositions. As such there are a variety of transmission rates associated with a particular soil type which all add to form a bulk transmission rate. This transmission rate varies for different soil types.

A variety of soil types were obtained to test these external parameters that affect the attenuation of the vibration level of the soil. The soil types were assumed to be typical of monitoring locations where vibration monitoring had been carried out in the field by the author over the past 10 years in the Hunter Valley, NSW. Soil consists of many individual grains which have a considerable particle size range. In this study a soil was deemed to have a particle top size of less than 8 mm and all soils were sieved on an 8 mm square mesh screen before being used in the laboratory study. There were 9 different soil types and the soils ranged from a high clay content, typically dirt, to a high silica content, typically sand.

Approximately 50 litres of each soil sample was selected from an area that appeared to be representative of each particular soil. This sample was the as received sample and all of the test work was carried out on this as received sample. Before any analysis could be carried out, each soil sample was characterised so that differences in the tests performed could be attributed to some property of the soil. Sampling particulate material such as soil is often fraught with errors and over many years standard methods have been developed in order that the sample, which is analysed for some property, is truly representative of the original as received sample.

The soil sample was first dried to remove any free moisture before any sampling was commenced. The soil was spread out on a concrete pad to a layer approximately 25 mm thick in an enclosed building to minimise any solid material losses due to wind. The sample was turned over on a regular basis to ensure all of the material was dried to atmospheric conditions. Once the sampled was dried all of the necessary sub-samples

were extracted for subsequent analysis. These sub-samples were extracted by the standard methods. A small scoop with a flat bottom 50 mm across the face was pushed into the soil sample until the concrete base was encountered. The scoop was then removed making sure to retain the soil in the scoop and this increment was transferred to a suitable container. This procedure was repeated at random locations over the entire soil sample surface until a total of 64 increments had been obtained. These 64 increments constituted a sub-sample. These sub-samples were further divided using a riffle divider especially designed to divide particulate material in an un-biased manner to produce a sample of quantity sufficient for the analysis required. All of the soils were representatively sampled and these sub-samples were analysed for both chemical and physical properties.

#### **4.4.1 Chemical Analysis of Soils.**

The chemical analysis was carried out using a scanning electron microscope (SEM). A small specially prepared sample of the soil was placed on the SEM stage, which was then placed in the electron beam of the SEM. The electron beam excites the electronic structure of the soil material and energy is released as the soil material returns to its original state. This energy is compared to known standard material of similar elemental structure and the composition of the soil material is determined. Using this method, common compounds found in soil materials were determined in order to classify the different soils used in this study. These compounds, which are typical compounds found in the soils, were:

- $\text{SiO}_2$  (silicon dioxide or silica) is a major component of sand based materials and is one of the most predominant compounds on the earth's crust.
- $\text{CaO}$  (calcium oxide) is usually an indication of the presence of limestone, which is a common compound found in soil.
- $\text{Al}_2\text{O}_3$  (aluminium oxide or alumina) which is one of the major component of clay based materials which are readily found in soils.
- $\text{FeO}$  (iron oxide) indicates the presence of  $\text{Fe}_2\text{O}_3$  and  $\text{Fe}_3\text{O}_4$  which are usually formed with other minerals and gives a brown colour to the mineral matter.

- MgO (magnesium oxide) is usually found in the carbonate form. Often chemically combined with other compounds to form common minerals found in typical soil materials.

#### **4.4.2 Physical Properties of Soils.**

The physical properties of the soils measured were chosen to highlight any differences that might occur in the shape, size and structure of the individual grains of the soil. All of the tests carried out to measure the physical properties of the soils were standard procedures used routinely in soil testing type laboratories.

##### **(a) Size Distribution**

The size distribution was determined by segregating the particles from a soil sample into fractions of decreasing physical dimensions. A sample of the soil is placed on a nest of screens of decreasing aperture, which is then placed on a vibrating table and shaken for 10 minutes. This shaking action caused the particles, which are smaller than the screen aperture to fall through the screen onto the next screen. This process is repeated until the particle is too large to pass through the screen it is sitting on. After the shaking time has been completed the segregated material on each screen is removed and weighed and a percentage retained on each screen is then calculated. These results are then displayed in graphical form and a relationship established where by parameters can be extracted to define the particle size of the sample.

##### **(b) Bulk Density of Soils.**

The bulk density is the mass per unit volume of a sample of the soil material. This measurement is carried out on the as received material and, depending on the mineral structure of the soil, is an indication of the “competency” of the individual grains. Some minerals are porous and contain air trapped within the structure and these would usually be fairly light weight. A container of known volume is filled to the brim with the soil sample and then levelled off. In this way the same volume is used each time. The container and sample is then weighed and the weight per unit volume is calculated.

The size of the container is large enough to minimise any errors due to wall effects from the particle top size of the samples used in this laboratory study.

### **(c) Particle Density of Soils.**

The particle density is the density of the mineral matter that makes up the soil. This property is determined by a water displacement technique. The sample has to be crushed to eliminate any pores within the individual grains. The sample was pulverised in a ring mill to approximately a powder consistency, which was usually less than 50 microns in size. At this particle size it was assumed that all of the pores had been crushed out of the individual grains and only the mineral matter remained for this test. A known mass of the pulverised sample was placed into a dry volumetric flask. A small quantity of water was added to the flask and the contents of the flask was gently mixed to ensure that the entire pulverised sample was wet and no air was trapped within the sample creating dry spots. Water was then added to the flask until the level was at the volume mark etched on the neck of the volumetric flask. The flask and contents were then weighed and the weight of water displaced by the dry sample was determined by difference. The density of water is approximately  $1000 \text{ kg/m}^3$  and when compensated for the temperature, the volume of the water displaced can be determined. From these calculations the density of the soil mineral matter can be determined which has been defined as the particle density in this study.

### **(d) Particle size and transmission of vibrations.**

One parameter that was investigated in this study was the effect of particle size on the vibration transmission through the soil. As one of the soil samples was collected from a granite quarry, it was easy to collect a large sample that included large sized lumps. This sample, like all of the soil samples, was screened at 8 mm to remove any coarse sized particles. For this sample the large particles were retained and further segregated on a size basis. This coarse size material was screened on a 20 mm and a 32 mm screen and the  $-32+20$  mm and  $-20+8$  mm fractions retained for future inclusion in the sample to modify the sample size distribution. These coarse size fractions were then added to the  $-8$  mm head sample in controlled amounts as required by the testing procedure. This modified size distribution sample will be discussed in section 4.8.

Table 4.1 Chemical analysis of soil samples

	SiO <sub>2</sub>	CaO	Al <sub>2</sub> O <sub>3</sub>	FeO	MgO
	(%)	(%)	(%)	(%)	(%)
Sample A	68.73	5.45	16.59	7.17	0.56
Sample B	61.91	3.88	24.69	7.21	0.81
Sample C	86.58	1.53	8.80	1.54	0.58
Sample D	85.98	2.18	7.17	1.41	2.36
Sample E	63.78	1.02	22.78	8.11	2.81
Sample F	90.21	0.32	4.75	3.48	1.02
Sample G	57.76	5.08	15.34	9.70	3.24
Sample H	93.02	0.70	1.95	1.13	0.38
Sample I	64.33	3.57	15.96	6.37	0.79

Table 4.2 Physical analysis of soil samples

	Size Distribution		Part. density	Bulk density	Comments
	Xc (mm)	n	(g/cc)	(g/cc)	
Sample A	1.54	0.76	2.648	1.407	Grey clay soil
Sample B	2.76	0.95	2.585	1.246	Coarse orange clay
Sample C	1.30	0.76	2.628	1.157	Fine grey clay soil
Sample D	0.50	0.93	2.673	1.565	Dark grey sandy soil
Sample E	0.89	0.97	2.709	1.427	Yellow sandy loam
Sample F	0.63	1.10	2.714	1.579	Brown river bed sand
Sample G	0.66	0.87	2.737	1.682	Brown black gravel
Sample H	0.84	1.82	2.676	1.307	Black sand and bark
Sample I	1.93	0.89	2.644	1.509	Granite quarry rocks
Sple I+10	2.35	0.84	2.612	1.529	Granite quarry rocks
Sple I+20	2.85	0.76	2.654	1.579	Granite quarry rocks



All of the procedures adopted in the study to measure the properties of the soils are standard techniques used by soil testing laboratories. These standard procedures have minimum bias in their outcome and have been proved over time to produce a result that can be relied upon for its accuracy and repeatability. In this way biases, usually introduced by specifically designed techniques, did not have to be identified and their effect on the procedural outcomes was negligible.

The testing regime described above was used on all of the soils to define the fundamental chemical and physical properties of each soil. These properties were used to classify the soils and highlight any differences in the chemical and physical nature of each soil. The chemical properties of the soils are shown in Table 4.1 and the physical properties in Table 4.2. The chemical analysis shown in Table 4.1 is not a complete analysis of the soil materials. Only the common substances and those appearing in large quantities were analysed as smaller elemental quantities were not considered as being relevant in this study.

The chemical analysis of each soil sample is shown in Table 4.1. As can be seen there is quite a significant difference in the chemical properties of the soils used in this study. This is a good outcome as differences in soil composition means that there is a variety of soil materials to test the validity of the mounting procedure.

**Soil A** was shown to be a moderate  $\text{SiO}_2$  based sample which had some large amounts of  $\text{Al}_2\text{O}_3$  material present. This composition is typical of clay based soils and when mixed with small quantities of water the sample appeared to be dry. Clay based soils can absorb large quantities of water and retain this water in the internal structure of the minerals that make up the soil. The high CaO level is possibly an indication of the presence of limestone type mineral indicating this type of soil is a mixture of many common minerals.

**Soil B** is similar to soil A except for two basic constituents. The  $\text{SiO}_2$  content has dropped and the  $\text{Al}_2\text{O}_3$  content has increased. This soil was obtained from the drill cuttings from a borehole drilled into the ground. The cuttings originated from subterranean levels where higher concentrations of clay material were present. Moderate amounts of CaO and MgO compounds were present and an orange stain or

colouring in the material possibly resulted from the high level of iron compounds present.

**Soil C** has a large quantity of  $\text{SiO}_2$  based compounds with a corresponding decrease in the  $\text{Al}_2\text{O}_3$  content as shown. Because of this high  $\text{SiO}_2$  content all other minerals have been decreased accordingly. This soil was grey in colour, which is a result of the low iron content, which usually gives a brown to orange colour. The low  $\text{MgO}$  and  $\text{CaO}$  levels show the small quantities of these carbonate minerals could be present in this soil sample.

**Soil D** was shown to be similar to soil C but an increased level of calcium and magnesium compounds are evident. This soil was a dark grey sandy loam type material with some evidence of clay type material present.

**Soil E** was shown to have a moderate amount of  $\text{SiO}_2$  based minerals and a high proportion of  $\text{Al}_2\text{O}_3$  minerals. This soil was a sandy loam type soil with a yellow colouring throughout. The yellow colour of the soil was a result of the high iron mineral composition and the high  $\text{Al}_2\text{O}_3$  content indicates the presence of clay based minerals. Low levels of  $\text{CaO}$  and  $\text{MgO}$  minerals are also present in this soil sample.

**Soil F** was one of the highest  $\text{SiO}_2$  content soils. This material was basically a river sand material as it was obtained from the bottom of a dry creek. There was a slight brown ting to the soil indicating the presence of small quantities of iron based minerals as measured in the sample.

**Soil G** had the lowest  $\text{SiO}_2$  level and was basically a slag based material used in road works. This is an artificially produced material and is slag material from an iron producing blast furnace. This sample is unusually high in  $\text{CaO}$  and  $\text{MgO}$  minerals which is to be expected as compounds of these elements are a necessary part of steel production in the blast furnace.

**Soil H** is another high  $\text{SiO}_2$  content mineral. This soil was a mixture of a black sand and bark and was obtained from the banks of a dry creek.

**Soil I** has a moderate amount of SiO<sub>2</sub> based minerals mixed with a high percentage of Al<sub>2</sub>O<sub>3</sub> minerals. This material comes from a granite quarry. Granite is a silica-alumina mineral together with some carbonate minerals. This was shown in the sample to be the case as the CaO level was high as was the iron level. There was not any clay material in this soil sample as the soil was quite grainy in appearance.

Only the physical properties of interest in this study are shown in Table 4.2 (page 95). As can be seen the physical properties of the soil also vary significantly from each other. The size distribution properties of the samples were determined by applying a Rosin-Rammler fit to the mass percent retained on a screen size for the soil samples. The Rosin-Rammler fit was used as it has been found to best fit granular material and is used widely in the mining and processing industry to describe granular particle size distributions. The Rosin-Rammler equation is:

$$R = 1 - [\exp -(X/X_c)^n] \quad (4.1)$$

where R is weight percent retained on screen size X, X<sub>c</sub> is a characteristic screen size related to the material and is 1/e or 36.79% of the sample weight retained on this screen size and n = is a dimensionless exponent which is a measure of the dispersion of the particles.

It is advantageous to have an equation that can relate properties of the soil so that a comparison of the different soils can be carried out. The characteristic particle size (X<sub>c</sub>) and the uniformity index (n) are shown in Table 4.2 (page 95). The characteristic particle size varied from 0.50 mm for Sample D to 2.76 mm for Sample B. When it is considered that the soil samples were screened at 8 mm, thus no particle was greater than 8 mm, then this range of characteristic sizes is quite large.

The uniformity index, the exponent of the Rosin-Rammler equation, indicated the “spread” of the size distribution data. The higher the value of n then the “closer” will be the size distribution for a particular sample. The uniformity index for these soil sample varied from 0.76 for Sample A and Sample C to 1.82 for Sample H. Samples A and C were clay based material and as such had a high percentage of ultra-fine material together with some coarse material. So the size distribution was more evenly

distributed through out the entire sieve size range used. Sample H, on the other hand, was a sandy type soil and as such had grain sizes, which were approximately the same size. This sample had very little material in the ultra-fine and the coarse sizes as most of the material was retained on the mid-sized screens used in the analysis.

The particle density shown in Table 4.2 (page 95) is related to the minerals that constitute the soil sample. All the soil samples were mixtures of different minerals and the friability of each mineral component would dictate the quantity of that mineral that would be measured in any particular size fraction. Each soil sample was crushed to a powder size to carry out this procedure so any internal porosity was eliminated and only the solid particles of the “mineral” were used in the determination. The particle density is basically the density of the mineral components, which constitute the soil sample. As shown in these results there is not a large difference in the particle density of the soil samples. The particle densities varied from 2.585 g/cc for Sample B (a clay type material) to 2.737 g/cc for Sample G (a sand type material). From the literature (Read, 1970) the density of silica or sand based minerals is approximately 2.65 g/cc while that of clay minerals is also 2.65 g/cc. The precision of this procedure was found to have a standard deviation of 0.012 g/cc so the differences measured between the soil samples is statistically significant.

The bulk density also shown in Table 4.2 (page 95) is an indication of the packing density of the loosely poured material in a container. This density is a function of both the individual particle density and the size distribution of the soil sample. The bulk densities measured had a range of 1.157 g/cc for Sample C to 1.682 g/cc for sample G. The precision of this procedure was found to have a standard deviation of 0.012 g/cc so the differences measured between the soil samples would be statistically significant. It is this packing of the individual particles in a container which will have an effect on the transmission of the vibration wave through the soil sample.

#### **4.5 Laboratory vibration rig variability.**

With any testing procedure there is some intrinsic error which means that the same result can not be recorded on any two occasions. The magnitude of the error can be

maintained at an insignificant level by making sure the physical set up is exactly the same each time the test is carried out. Whenever a measurement or action is carried out the intrinsic errors of all the parts add together to form the relative error of the overall procedure.

A series of experiments was carried out to measure the overall error that could be expected by carrying out the same test a number of times. For each test a value was recorded and for the sum of all the tests, the average, the range and the standard deviation was calculated as a measure of the expected deviation that would be experienced for this particular experiment.

#### 4.5.1 Variability with distance.

Vibration levels are known to attenuate with distance from the source and in the laboratory vibration rig this attenuation with distance was measured to determine its effect. The mounting block with the accelerometers attached was placed at different locations in the soil container so the distance between the primary sensor and the point of impact of the instrumented hammer on the outside of the soil container was varied. This is shown schematically in Figure 4.3.

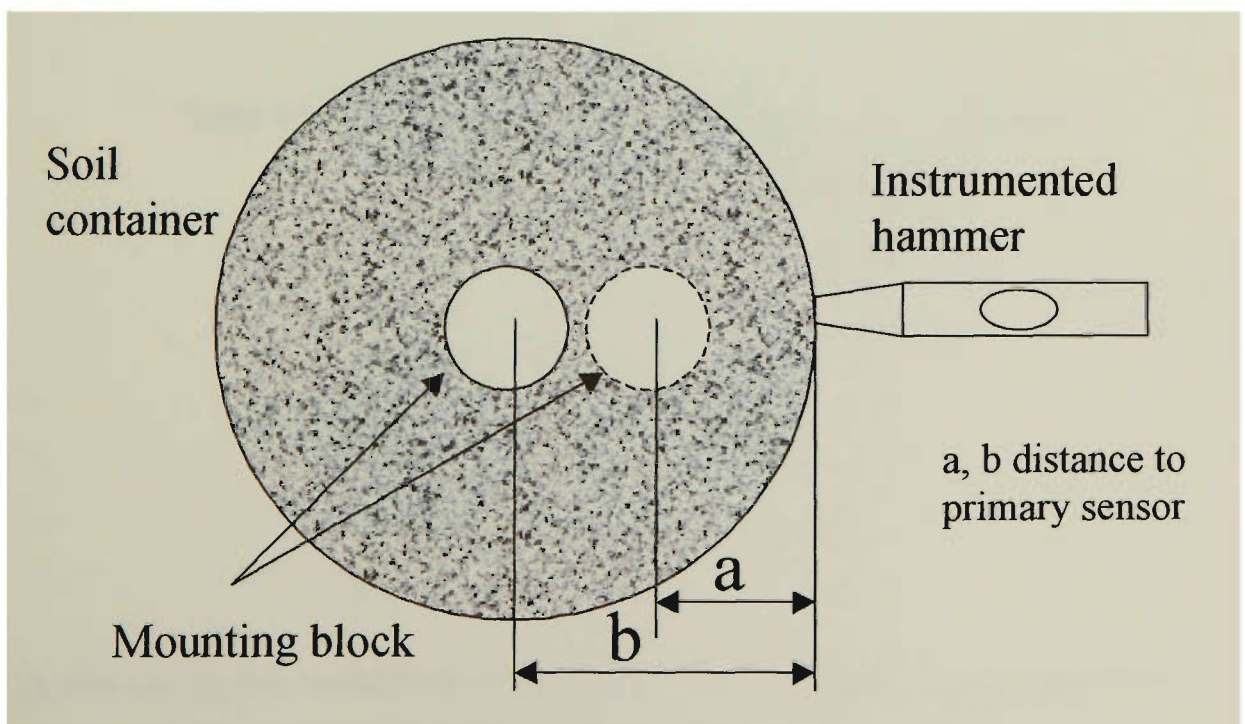


Figure 4.3 Variability with distance in laboratory vibration rig.

The experimental procedure consisted of mixing one of the soils with water to a nominal moisture content of 5%. This moisture content was chosen arbitrary to minimise the impact of moisture loss over the period that the tests were carried out. A “consistent” compaction regime in the soil container was also chosen for each test. The soil was placed in the soil container in approximately 50mm deep layers and tamped with a steel tamping device leaving the surface “loose” for the next 50mm layer. The mounting block was placed on the soil layer when the top of the block was level with the lip of the soil container. Soil was added around the mounting block and tamped until the soil was level with the mounting block and soil container lip. The excess soil was removed and the container weighed to ensure compaction levels were similar for each test. The distance between the centre of the mounting block and the point of impact was then measured and recorded. This test was carried out three times and the average results are shown in Table 4.3.

At each of the mounting block positions the instrumented hammer was raised and allowed to strike the outside of the soil container at the same point each time. As the force used to strike the soil container by the instrumented hammer will be dependent on the distance the hammer is raised it was thought the rebound distance would be more consistent. Thus the second impact on the soil contained was used as a more consistent vibration source to carry out this test.

Table 4.3 Vibration as a function of distance in the Vibration Rig

Distance	Vibration	Frequency
(mm)	(mm/s)	(Hz)
116	3.7	72.9
158	3.3	70.9
240	2.9	71.1
293	2.7	74
350	2.4	75.9

A relationship was established between the vibration level and the distance between the source and the detector. The line of best fit was constructed to determine this relationship by using the distance from the primary sensor to the impact source as the

independent variable and the vibration level recorded as the dependent variable. This is a standard statistical procedure and one that is readily available in most spreadsheet software programs today. A linear relationship was chosen to fit this data as there was only one independent variable (distance) and the applied impact force was the same (within practical limits) for all tests.

The equation for this line of best fit is called the method of least squares which minimises the sum of the squares of the errors from the data to the line of best fit. In the general case

$$y = a + bx + \varepsilon \quad (4.2)$$

If the mean error  $\varepsilon$  is assumed to be zero then

$$a = \frac{n \sum yx - (\sum y)(\sum x)}{n \sum x^2 - (\sum x)^2} \quad (4.3)$$

$$b = \frac{\sum x^2 \sum y - (\sum x)(\sum xy)}{n \sum x^2 - (\sum x)^2} \quad (4.4)$$

Solving these equations, using the data in Table 4.3, gives the following equation for the line of best fit (minimising the square of the errors).

$$\text{Vibration level (mm/s)} = 4.235 - 0.005 \text{ Primary sensor distance (mm)} \quad (4.5)$$

As these results in Table 4.3 show there is a significant difference in the vibration level recorded when the primary sensor is close to the point of the impact source (116mm) and when the primary sensor is farthest from the impact source (350mm). The data in Table 4.3 is represented graphically in Figure 4.4. Here it can be seen that there is a strong linear relationship between the primary sensor distance and the vibration level. The regression coefficient, which is a measure of the degree of fit of the data, is  $-0.992$ . This regression coefficient shows that there is a strong negative relationship between the two sets of data. This linear relationship is acceptable as the vibration source was reasonably consistent thus minimising other variables in this experiment.

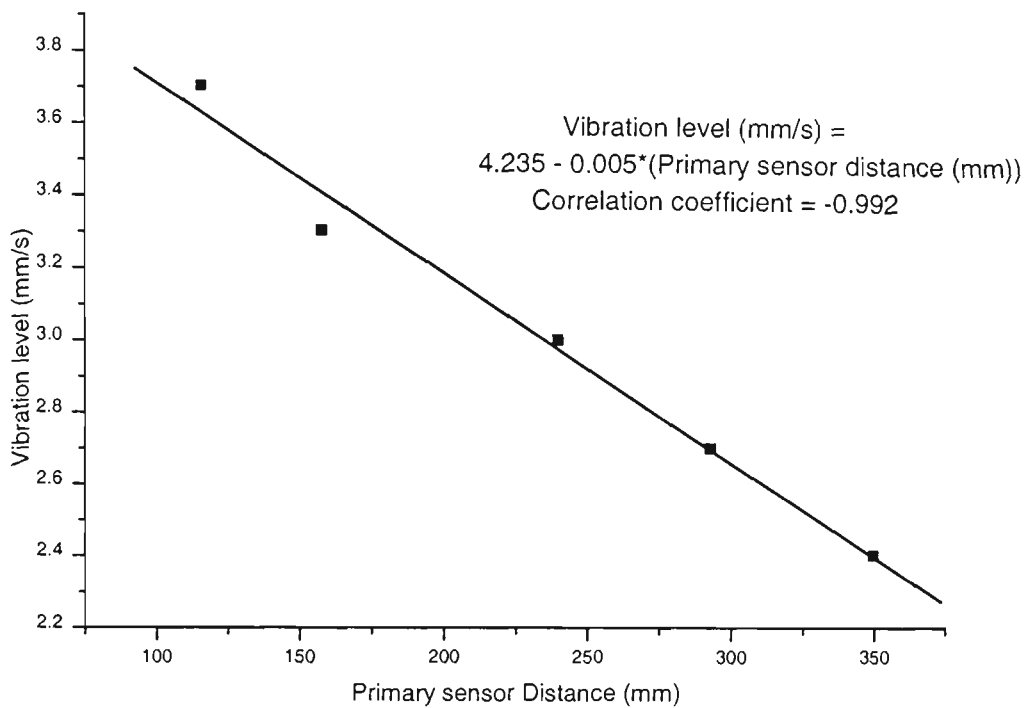


Figure 4.4 Experimental distance attenuation data and the line of best fit.

The data analysis above shows the effect of misplacement of the mounting block in relation to the vibration level recorded by the primary sensor. However for each test within an experiment the mounting block has to be placed at the same place each time. But this is practically impossible as there will always be a difference in distance between the primary sensor and the impact source no matter how much care is taken during the placement of the mounting block. This information was then used to determine the error that was associated with the placement of the mounting block.

The mounting block was placed “in the centre” of the soil contained and the soil tamped around the block as per the procedure described above. In this experiment the distance between the primary sensor and the impact point was measured. The difference in the distance between the primary sensor and the source for the standard laboratory vibration rig procedure was measured 30 times and the mean and standard deviation determined. The average distance between the primary sensor and the impact point was 181.4 mm with a standard deviation of 3.7mm. So for a 95% confidence interval (ie.  $\pm 3$  standard deviations about the mean) the variation in distance between the primary sensor and the impact point can be determined. The distance difference was found to be within  $\pm 22.2$ mm about the mean distance of 181.4 mm. This difference was then used to



estimate the vibration levels that would be expected at these distances using the linear relationship and the corresponding line of best fit as described above. The predicted vibration level at the maximum and minimum distances is shown in Table 4.4.

Table 4.4 Expected vibration range in Vibration Rig.

Block-Source distance	Predicted vibration
(mm)	(mm/s)
170.3	3.38
181.4	3.33
192.5	3.27

From this data shown in Table 4.4 it could be concluded that errors associated with the placement of the mounting block would be equivalent to 0.06 mm/s in 3.33 mm/s, or 1.80%. This shows that if the mounting block can not be placed in exactly the same location each time, then the errors associated with this misplacement are relative low at 1.80%. However there is an error associated with the procedure which must also be determined.

#### 4.5.2 Laboratory vibration rig variability.

As stated earlier there is always errors associated with any measuring technique and the main purpose of a “standard” technique is to minimise these errors. The physical parameters of the laboratory vibration rig were standardised (the instrumented hammer struck the same location each time, the soil container was placed in the same location each time etc.) in an effort to minimise any error due to the measurement procedure adopted. However, it is nearly impossible to eliminate errors all together but a measure of the certainty of a result must be determined so that some confidence can be placed in the interpretation of the results from the measurement procedure.

One of the standard methods for determining the errors associated with any measurement procedure is to carry out the same test a number of times. However, the procedure must be the same for each test. In this controlled environment only the variations, or errors, within the measurement procedure will affect the result.

An experiment was carried out in the laboratory vibration rig to measure the overall variability that could be experienced from this procedure. In this test the soil container was loaded with one of the soil samples mixed to a moisture content of 5% and compacted to the maximum compaction regime. In this way the parameters of the soil were maintained the same thus eliminating variations associated with these parameters. The soil container was aligned under the swinging instrumented hammer in the prescribed manner and the instruments activated. The instrumented hammer was pulled back 0.2 metres from the outside edge of the soil container and released and allowed to swing under the influence of gravity and strike the soil container. The hammer rebounded and struck the soil container again and it was this second striking action that was used as the applied force that produces the vibration through the soil as recorded by the primary sensor. This operation (striking the outside of the soil container) was repeated to obtain a statistically significant sample size to enable some estimation of the errors that are associated within this laboratory vibration rig.

This testing of the laboratory vibration rig was carried out a total of 30 times and the results were treated in a standard statistical manner to determine the mean, median and standard deviation. The same test procedure and the same conditions of the soil in the soil container were employed in all 30 tests so the variability of the equipment and the procedure was measured. As no other condition was changed the variation, or error, that could be expected in the laboratory vibration rig procedure was all that was measured. The results from this experiment displayed a normal distribution with some skewing to the lower level of the mean value. The median value was 3.94 mm/s compared to the mean value of 3.99 mm/s which shows the skewing of the distribution to the lower end of the scale of the measured values. All the results fell within the range of 3.67 mm/s to 4.66 mm/s. Because of the complex nature of the vibration wave transmission through soil material (multiple particulate material) this variation in the absolute values is considered reasonable small. From the average and standard deviation determinations the coefficient of variation was calculated which gives an indication of the degree of variation obtained from the laboratory vibration rig and test procedure. These results are shown in Table 4.5.

Table 4.5 Laboratory vibration rig and procedure variability.

Number of tests	Median Value	Average Value	Standard Deviation	Coefficient of Variation
	(mm/s)	(mm/s)	(mm/s)	(%)
30	3.94	3.99	0.23	5.81

As shown in Table 4.5 the variability, as measured by the coefficient of variation (the standard deviation divided by the mean), was 5.81%. The number of samples used in this test (30) is considered statistically significant and the results obtained are thus meaningful. The CoV is considered small and shows that the variation in the laboratory vibration rig and the procedure used is acceptable. It can be seen that the data is a little skewed as shown by the median value being a little lower than the mean value. This means that more than half of the results are less than the mean value thus skewing the distribution to the low values in the data range.

#### 4.5.3 Overall variation.

As stated above there is always some errors in any measuring procedure or device. The overall error that can be expected in the laboratory procedure used in the following laboratory tests is the sum of the individual errors. The errors associated with distance i.e. placement of the mounting block, were discussed in Section 4.5.1 and the errors associated with the procedure variability were discussed in Section 4.5.2.

The coefficient of variation is used as a measure of the error of the procedure as this statistic eliminates any distortion due to the absolute values measured for any particular test. The coefficient of variation also takes into account the effect of the spread of the data in the form of the standard deviation. If it is considered that a measurement is made up of the true value plus the error, for example  $X$  is the true value,  $X'$  is the measured value and  $\epsilon$  is the error obtained with measuring  $X$  then:

$$X' = X + \epsilon \quad (4.6)$$

When there are several processes and each has an error, say  $n$  total sources, then  $\epsilon_t$  the total error for all the individual processes is

$$\epsilon_t = \epsilon_1 + \epsilon_2 + \epsilon_3 + \dots + \epsilon_n \quad (4.7)$$

The overall error here for the laboratory vibration rig is considered to be made up of two processes and thus two error sources. So the total error,  $\epsilon_t$ , can be determined by the following:

$$\begin{aligned} \text{Overall error} &= \text{Distance error} + \text{procedure error} && (4.8) \\ \epsilon_t &= \epsilon_d + \epsilon_p \\ &= 5.81 + 1.80 \\ &= 7.61\% \end{aligned}$$

Thus if two results from the laboratory vibration rig vary by approximately 7.61% from each other then the parameter being investigated can be assumed to have caused the variation in the measurements recorded. It must be remembered that measuring the vibration levels in soil is fraught with problems because of the nature of the soil itself. Soil being a particulate material relies on the transfer of energy from particle to particle even though it is on a bulk basis and at each particle boundary there is the possibility of energy losses which can not be modelled let alone be predicted. It is accepted that this level of error (>10%) is extremely small for vibration measurements due to the nature of the ground material itself.

#### **4.6 Effect of moisture.**

The moisture content of the soil basically occurs in two forms. There is the inherent moisture, which is chemically bound in the minerals and does not play any role in the surface moisture effect of the soil. This moisture is part of the structure of the mineral make-up of the soil and is not released without an excessive amount of energy such as extremely high temperatures. Also associated with the moisture content is the “free” moisture that is absorbed by the soil material and at atmospheric conditions can amount to a significant quantity. Some materials absorb large quantities of water, such as clay based materials, before they become saturated and the bulk of the material is termed “wet”. The form of moisture in soil material and one that is a surface property effect of the grains is this free moisture. This free moisture attaches itself to the surface of the individual grains and under the right conditions can act as a lubrication for the grains to move or slip past one another.

The moisture content of the soil can be determined by a relatively simple procedure. As water boils or vaporises at 100°C, the sample only needs to be heated to a temperature just above this level for the “free” moisture to boil away. The “free” moisture content of the soil is the mass lost when a sample of the soil is heated to 105°C and maintained at this temperature for 4 hours. This mass loss can also include any low volatile components of the soil such as organic matter, which may be present. In this study all of the soils were devoid of any low volatile components so these constituents did not cause any concerns.

The nine soil samples and the two modified size distribution samples (Sample I+10 and Sample I+20) were all tested at four arbitrarily nominal moisture contents. The soil sample was spread out on a concrete pad and allowed to equilibrate to atmospheric conditions before sampling for the dry sample moisture content. The head sample was spread to a thickness of approximately 50 mm and turned over on a regular basis until the entire sample appeared dry. Three small sub-samples were representatively selected (multiple increments) from the soil sample and stored in air tight containers. These incremental sub-samples were then weighed and dried and the “dry” sample moisture content determined for each sample.

While the soil sample was on the concrete pad and after the dry moisture sub-samples had been extracted, the remainder of the sample were made up to the nominal moisture content required. This required moisture content was made up by mixing in a calculated mass of water with the soil. After thoroughly mixing the water into the soil sample by coning and quartering the entire sample 5 times, three representative sub-samples were taken from the entire soil sample and analysed for moisture content. The four nominal moisture contents chosen were 0% (the dry moisture content of the soil), 2%, 5% and 10%. The nominal 2%, 5% and 10% moisture levels were calculated without including the dry moisture content of the soil as it was not known at the time of testing the soil sample. It was felt that this range of moisture contents of soil would be experienced in practice in the field after periods of rain etc. In all cases the soil samples were spread out on a concrete pad inside a laboratory building protected from the elements and the inherent moisture allowed to equilibrate to atmospheric conditions (during the summer months) before testing began. No test work was carried out when the weather conditions were inclement or raining so high humidity conditions were avoided which

could adversely effect the moisture loading of the soil samples. The results of the moisture content of the soils are shown in Table 4.6.

Table 4.6 Moisture content of soil samples

	Nominal moisture content (%)				Saturation
	0	2	5	10	Level (%)
Sample A	0.68	3.51	6.05	9.55	24.99
Sample B	2.38	6.23	8.62	12.77	29.36
Sample C	3.00	5.49	8.08	12.49	32.60
Sample D	0.07	2.90	5.95	10.94	20.94
Sample E	1.95	4.15	7.17	11.79	24.90
Sample F	1.64	3.43	6.45	11.56	20.94
Sample G	0.26	3.01	4.61	8.98	18.64
Sample H	2.15	4.33	7.14	11.78	28.13
Sample I	2.16	4.72	7.16	12.86	22.15
Sample I+10	2.24	4.21	7.23	11.87	22.15
Sample I+20	1.50	3.15	6.29	11.27	22.15

As shown in Table 4.6 there is a large range in the “dry” moisture levels of the soil samples. Materials such as clays and organic matter have a naturally high moisture retention ability and this is shown in some of these samples. The clay type samples, particularly samples B and C had dry moisture levels (or 0% moisture level) of 2.38% and 3.00% respectively and samples H and I (and its hybrids) had moisture levels above 2% due to clay and organic material present in these samples. These materials have this natural moisture retention ability, or are hygroscopic. This is a property of the minerals, which make up some of these soil samples. This moisture is internal to the grain structure and would not be free moisture, which adheres to the surface of the individual grains. The remainder of the soil samples (D, E, F and G) all had dry moisture levels less than 2% and were basically silica based materials with very little hygroscopic material included in the soil. Sand based material, those comprising of high SiO<sub>2</sub> levels, do not absorb moisture but adsorb the moisture onto the grain surface. This property will be shown to affect the vibration transmission of the soil in a latter section.

The water added to make up the nominal moisture content level was assumed to be attracted to the surface of the individual grains as no salts were detected in any of the soil samples. This moisture would be adsorbed onto the surface and also the internal pores of the individual grains. A schematic representation of this surface property effect is shown in Figure 4.7 (page 119). As it can be seen, if enough water is added to the soil sample then there will be a level when the water will completely fill the voids or interstices between the grains and the whole structure would then behave like a fluid. When a small quantity of water is added and the adjacent particles have droplets of water on the surface and these droplets are attracted by other droplets then a reasonably strong bond between these grains can result from the surface tensional forces of the water. In the confines of the soil container and with this surface tension bond acting this would be the optimum condition for the transmission of the vibration wave through the soil sample. If the individual grains were completely surrounded by water there would be no air in the interstices. The water would then act as a lubricant and allow the individual grains to move or slip past one another (within the water layers between the individual grains) and aid in the differential movement between particles under an applied vibration wave load.

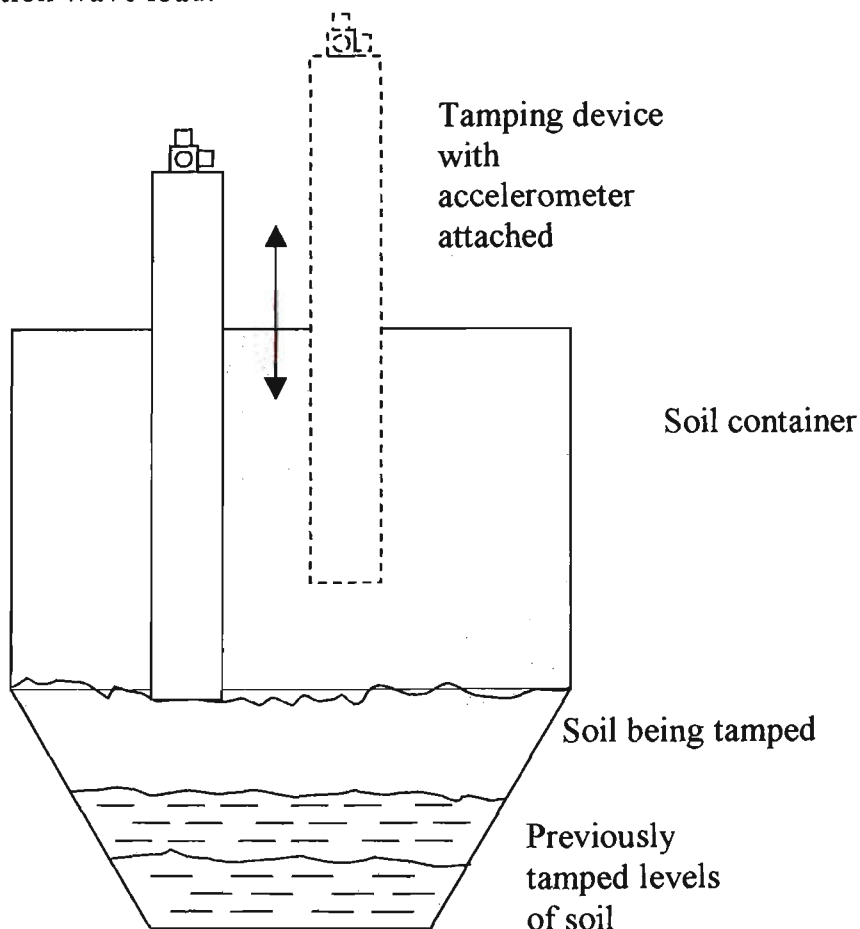


Figure 4.5 Soil compaction process.

If it is assumed that the total void space in a soil sample is filled with water then for a given soil specific or particle density the porosity of the soil sample can be calculated. It is the porosity of the sample that determines the amount of moisture that a sample can hold before it is saturated. If for example the following applies:

$$\text{Specific density (SD)} = 2.65 \text{ g/cc}$$

$$\text{Apparent density (AD)} = 1.45 \text{ g/cc}$$

$$\text{Porosity} = \frac{(SD - AD)}{SD} = 0.453$$

Thus 0.453 of the volume of the soil sample is void spaces and is available for moisture adsorption before the soil becomes saturated with water and the interstices are occupied by the water. The moisture content in this case would be:

$$\text{Density of water} = 1.00 \text{ g/cc}$$

$$\text{Particle density of soil} = 2.65 \text{ g/cc}$$

The for full saturation of the void space with water

$$\begin{aligned} \text{Density of "slurry"} &= 0.453 \times 1.0 + 0.547 \times 2.65 \\ &= 1.903 \text{ g/cc} \end{aligned}$$

Which is equivalent (in this example) to 28.3% (by mass) of water. Of course this is an ideal scenario as the moisture would never completely surround the individual grains unless the sample was completely immersed in water. More than likely air would be trapped between individual grains and this ideal moisture content would be decreased. The individual grain size distribution of the soil samples would also have an effect on this moisture holding ability of the soil samples.

To minimise any moisture losses during the testing of the vibration transmission through the soil samples the testing was carried out inside a building to eliminate losses due to wind currents and temperature fluctuations. The mixing of the moisture into the soil followed by the vibration testing was completed within 2 hours. Once the soil sample was mixed to the nominal moisture content and the moisture samples extracted the samples were loaded into the laboratory vibration rig and the testing carried out. These results are shown in Table 4.7.



Table 4.7 Vibration level at moisture content

	Nominal moisture content (%)			
	0	2	5	10
	(mm/s)	(mm/s)	(mm/s)	(mm/s)
Sample A	1.75	2.37	2.87	3.04
Sample B	1.52	1.92	2.43	2.81
Sample C	2.47	2.91	3.74	4.29
Sample D	2.15	2.76	3.12	3.58
Sample E	1.77	2.39	3.39	3.63
Sample F	2.2	2.68	3.57	3.31
Sample G	1.19	1.14	1.59	2.22
Sample H	2.20	2.89	2.46	2.03
Sample I	1.72	3.17	2.30	1.98
Sample I+10	1.57	2.64	1.86	1.63
Sample I+20	2.25	3.43	2.60	2.23

It can be seen that there is a general increase in the vibration level as the moisture content increases. This feature is noted in soil samples A, B, C, D, E and G as the maximum saturation moisture level does not appear to have been reached. Some of these soils have a clay component, which absorbs a lot of water before displaying any signs of being wet. These samples exhibit a continually increasing vibration transmission as the moisture content increased.

However, in the case of the soil samples F, H, I, I+10 and I+20 the maximum saturation moisture level appeared to have been exceeded. These samples had high  $\text{SiO}_2$  levels, except for sample I and its hybrids, which indicates that the moisture was a surface effect and the saturation level had been exceeded. Sample I was a granite material and as such would not have much clay based material even though its  $\text{Al}_2\text{O}_3$  level was high. The vibration level has reached a peak, in this last set of soil samples, and begins to fall with increasing moisture content indicating that this saturation level has been reached and the individual grains were able to move relative to one another. This saturation level appears well before the interstices are full with water, as shown previously in Table 4.7.

## **4.7 Effect of compaction.**

Compaction of the soil in the soil container, and around the mounting block in the field, will cause a large effect on the contact between individual grains. The vibration wave travels through the ground with wave like motion and particle to particle contact is essential for efficient transmission of the wave energy. The effect was measured by compacting the soil using different compaction forces and measuring the vibration transmission through this compacted soil.

### **4.7.1 Tamping pressure.**

The degree of compaction (compaction pressure) for the soils tested was varied by using three different compaction regimes. The maximum compaction pressure was attained by using a compaction device made of a solid steel bar with a flat machined end which was used to contact the soil. The medium compaction pressure was attained by using a compaction device made of a wooden block. This wooden block had a flat surface that was used to contact the soil. For the third and zero compaction pressure, the soil was poured into the soil container up to the level of the soil container and the only compaction force used was that of gravity.

To effect the compaction of the soil, a layer of soil approximately 50mm was poured into the soil container. The compaction device (steel bar or wood block) was lifted approximately 50mm from the surface of the soil and then allowed fall under its own weight force to compact the soil. This procedure was repeated until the surface was devoid of loose material and then another 50 mm layer of soil was added to the soil container. When the compacted soil was at the appropriate level, ie. when the top of the mounting block was level with the lip of the soil container, the mounting block was placed in the middle of the soil container and a 50mm layer of soil was poured around the mounting block. Compaction was then continued until the soil container was over filled with compacted soil. Finally the excess soil was removed to the level of the lip of the soil container. Thus, a constant volume of soil was used for each test and a reasonably consistent compaction pressure was used to compact the soil around the mounting block for each compaction regime.

A measure of the degree of compaction of the soil was required to see if there was a significant difference between the three compaction regimes used in this study. The tamping force of the steel bar and the wood block was determined by placing an accelerometer on one end of the compaction device and measuring the acceleration during the tamping process (Figure 4.5, page 110). This test was carried out 30 times so that a reasonable data set was obtained and the average value calculated. The maximum acceleration as the device compressed the soil was used to calculate the compaction pressure applied to the soil used in the tests. These results are shown in Table 4.8.

Table 4.8 Compaction pressure used in Vibration Rig.

Compaction	Acceleration	Mass	Area	Pressure
	(g)	(kg)	(m <sup>2</sup> )	(kPa)
Maximum	3.18	4.2	0.00196	6.81
Minimum	2.77	0.4	0.00311	0.36
Zero	0	0	0.07069	0

The compaction pressure was calculated from first principles. Pressure is directly related to the applied forces and indirectly related to the unit area over which the force is applied. The force exerted on the soil during the compaction process was calculated from the acceleration as measured by the accelerometer on the compaction device. The following relationship applies in this case and ensuring the units are satisfied the pressure applied to compact the soil is shown in Table 4.8.

$$\text{Pressure} = \frac{\text{Force}}{\text{UnitArea}} \quad (4.9)$$

$$\text{Force} = \text{Mass} * \text{Acceleration} \quad (4.10)$$

$$\text{Pressure} = \frac{\text{Mass} * \text{Acceleration}}{\text{UnitArea}} \quad (4.11)$$

In both the Maximum and Minimum compaction regimes the mass of the compaction device was easily obtained. But in the Zero compaction regime the mass of the air above the soil was neglected as it was assumed the same weight force of the air on the soil would be acting on the compaction devices used in the other two cases. As this weight force was considered to be equal in all cases and there was no compaction

device used in the Zero compaction regime a mass of zero was thought to be justified in this instance.

As can be seen from Table 4.8 there is a significant difference between the three compaction regimes. The pressure applied to the soil in the Maximum compaction regime was 6.81 kPa and was shown to be significantly different to the Minimum compaction regime. This high compaction pressure was due mainly to the mass of the compaction device, which provided sufficient pressure to form a coherent mass of soil in the soil container. This compaction procedure forced the individual grains in the soil closer together and thus minimising the interstices between the grains forming this coherent massive structure compared to the loose poured regime of the Zero compaction regime. Thus with this consistent procedure and significantly different compaction pressures, any variation recorded would result from changes in the compaction of the soil used in the experiment.

The compaction of the soil around the mounting block will, both in the laboratory vibration rig and in the field trials, will play a significant role in the transmission of the vibration waves to the primary sensor. If the material in contact with the mounting block and the undisturbed ground soil does not form an intimate bond then the primary sensor will be experiencing something other than the vibration wave travelling through the ground. The compaction of the soil in this area between the mounting block and the intact soil will provide the intimate contact required.

The mounting block, which supported the primary sensor, and the coupling of the soil to this mounting block is the most important parameter of the vibration mounting procedure. As previously discussed in Chapter 2 the passage of the vibration wave through the ground crosses many boundaries as the ground is usually stratified and made up of many layers of soil, rock and clay etc. The vibration level at any location must not be altered by the measuring procedure, which is designed to faithfully record the vibration level experienced at that location. Although a measuring device is required to record the primary event at the location, this measuring device must be as unintrusive as possible to the local conditions (of the soil, etc.). Coupling of the soil to the mounting block is accomplished by excavating a hole large enough to accommodate the mounting block and then tamping or compacting the soil around the mounting

block. The degree of compaction should not cause an increase in the vibration levels as the vibration wave travels through the soil on its way to the primary sensor.

If, for example, there was a perfect coupling between the vibrating soil and the mounting block then the primary sensor would record the true vibration level at that location. But any measuring system that has physical contact with the event being measured will cause an effect on that event. In the case of vibration measurement, there is always that chance of altering the energy passing through the ground by absorbing some of the energy from the vibrating wave. This absorption will occur even more if the soil in direct contact with the mounting block is weakly coupled to the mounting block. So the degree of compaction will have an effect on the transmission of the vibration wave through this compacted region of soil around the mounting block.

The compaction regimes of the soil were labelled Zero Compaction (loose poured soil), Medium Compaction (wood block tamping) and Maximum Compaction (steel rod tamping). The vibration test was carried out as detailed in Section 4.2 and the results are shown in Table 4.9.

Table 4.9 Compaction effect on vibration transmission

	Compaction		
	Zero	Medium	Maximum
	(mm/s)	(mm/s)	(mm/s)
Sample A	1.86	2.37	2.87
Sample B	1.55	2.34	2.43
Sample C	1.30	2.99	3.74
Sample D	2.46	2.69	3.12
Sample E	1.64	2.34	3.39
Sample F	2.30	2.88	3.57
Sample G	0.71	1.59	1.82
Sample H	1.46	1.69	2.46
Sample I	1.20	2.51	3.30
Sample I+10	1.58	1.78	1.86
Sample I+20	1.27	1.82	2.60

Table 4.10 Compaction effect on soil concentration

	Bulk density	Compaction (%solids)		
	(g/cc)	Zero	Medium	Maximum
Sample A	1.407	47.56	56.47	58.32
Sample B	1.246	44.35	51.18	53.30
Sample C	1.157	37.19	43.95	46.31
Sample D	1.565	41.69	51.48	53.93
Sample E	1.427	39.94	43.65	48.88
Sample F	1.579	40.18	46.37	51.17
Sample G	1.682	31.67	40.89	42.44
Sample H	1.307	54.98	62.92	67.31
Sample I	1.509	45.75	52.46	58.44
Sample I+20	1.519	46.32	53.85	58.53
Sample I+40	1.525	49.26	56.38	60.83

The effect of moisture was minimised by measuring the vibration levels at the same nominal moisture content for each sample. As can also be seen in Table 4.9 all vibration levels increased as the compaction regime increased. This evidence supports the statement made earlier that a better transmission of the vibration wave energy would occur when the particles are in a more intimate contact with one another. This is not to say that the maximum compaction regime increases the vibration level but merely the coupling between the soil and the mounting block is more effective and allows less “slippage” between any two surfaces.

If the vibration level transmitted through the soil is dependent on this particle to particle contact then as the compaction regime “increase” the solid concentration for a compaction regime would also increase. The solid concentration was measured for each test by weighing the compacted soil in the soil container. The solid concentration is then calculated, allowing for the moisture content of the sample, and is shown in Table 4.10. As shown in Table 4.10 there is an increase in the solids concentration for all of the soil samples when the compaction regime “increases” from Zero to Maximum compaction. If this result is compared to the increase in the vibration level, as reported

in Table 4.10, then there is some credence in the particle to particle contact causing more effective transmission of the vibration wave through the soil samples.

A plot of this data for all of the soil samples at a nominal moisture content of 5% is shown in Figure 4.6. In all soil samples the vibration level, as indicated by PPV, showed an increase for an increase in the solids volume concentration. As can be seen there is an upward trend in vibration, for all of the soil samples, as the volume of solids increases. The slopes of these lines range from 0.02 (for Sample I+20, the purple line) to 0.26 (for Sample C, the light green line). The slope of the Sample I+20 in Figure 4.6 appears to be an anomaly and when this line is “neglected” there does appear to be a more consistent slope for all of the samples. It even appears as if the rate of increase in vibration is independent of soil type and more dependent on the consolidation of the soil particles. This consolidation of the soil and its effect on the vibration transmission is shown here to have a major impact on the vibration level that can be transmitted through the soil. If the soil between the mounting block and the intact soil is loosely packed then true vibration levels will not be recorded by the primary sensor. These graphs are the actual points measured and only three compaction regimes were tested. The variation in the intercepts of these plots would in some part be due to the nature of the soil samples being used and the physical structure of the soil.

Although the soil types have an effect on the vibration transmission there is a definite increase in vibration transmission level as the compaction regime “increases”. As the vibration wave travels through the ground (the soil in the soil container in this example) it not only travels through the grain itself but as the individual grains have relatively low mass then some movement of the grains could occur. This is obviously evident at the surface where the primary sensor is “attached”. At this free surface the differential movement is allowed to occur due to the difference in density of the atmosphere and the ground. There is no weight force above the “free” surface consequently this surface allows this movement to occur.

As the soil solid concentration increases the solid particles become closer to one another and this more intimate or multitude of particle contacts help in the transfer of the wave energy from particle to particle and hence through the bulk of the soil material.

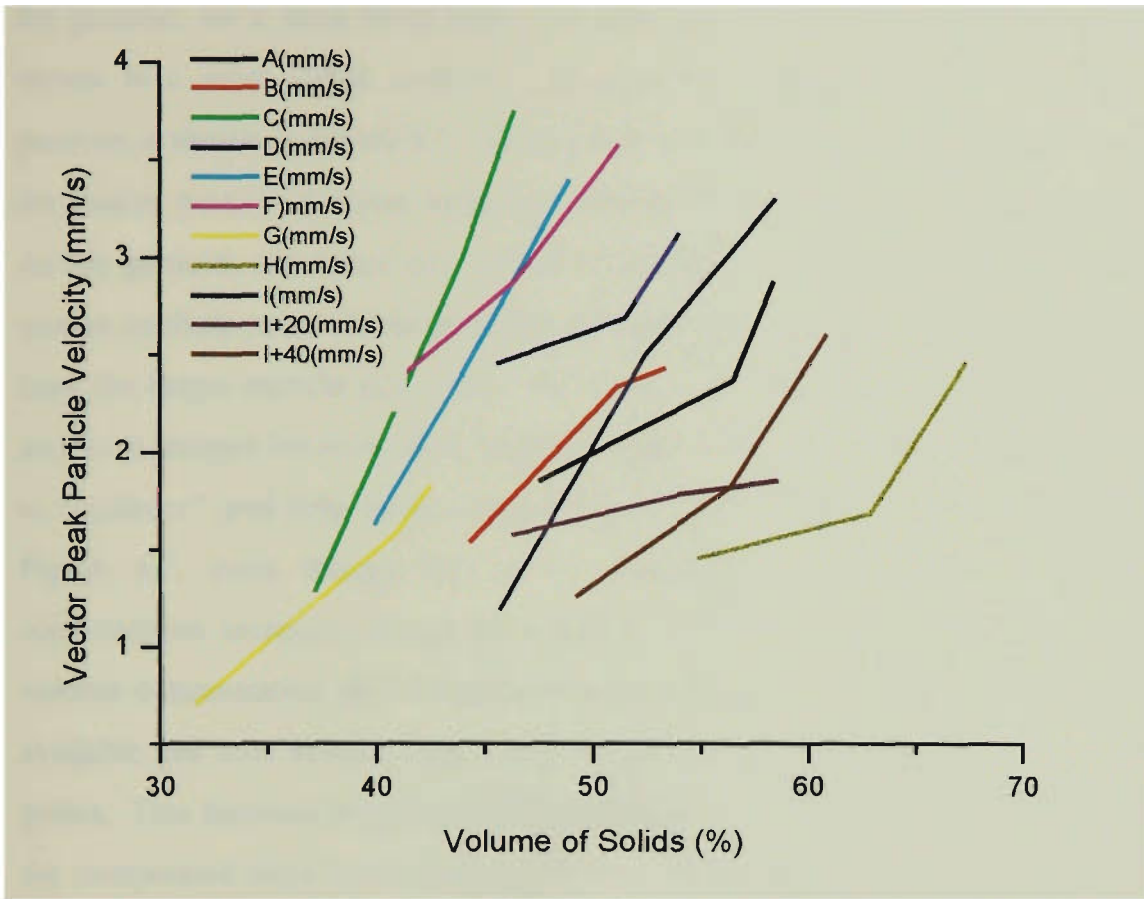


Figure 4.6 Vibration data as a function of solids concentration for all soils.

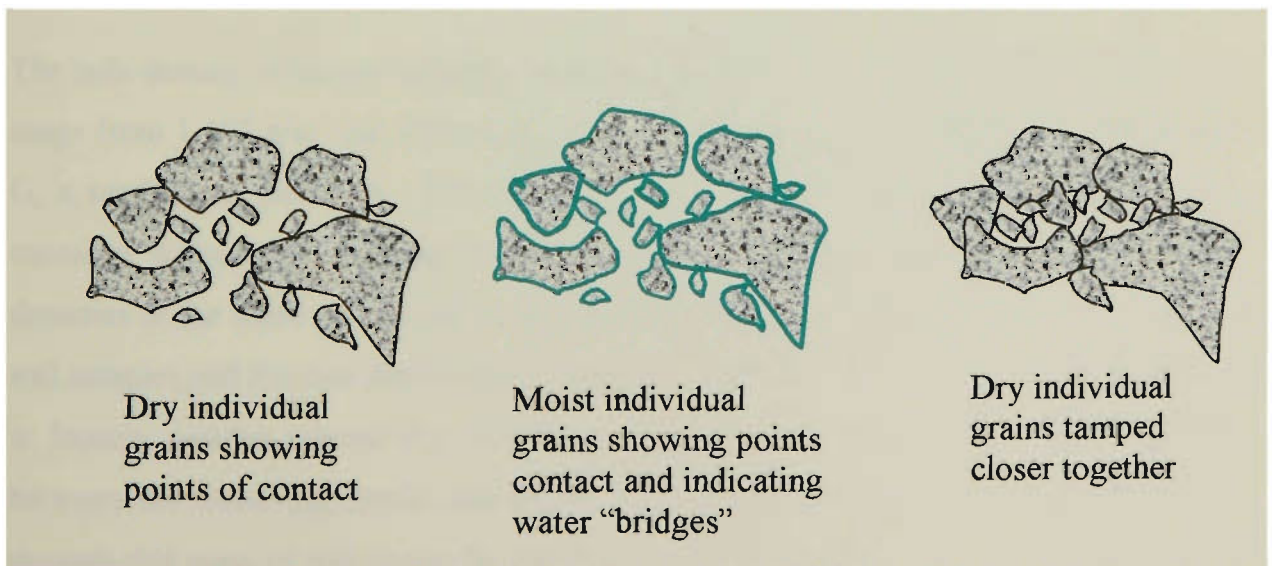


Figure 4.7 Contact scenarios for tamped and moist soil samples.



Although the compaction regimes are not forceful enough to cause particle destruction, the particle, on a local level when the tamping device is being forced into the soil, moves to a more stable position. A schematic representation of this more stable position is shown in Figure 4.7. During this movement as the soil sample is compacted the smaller particles become lodged in crevices in the irregularly shaped larger particles. As the particles are rolled and moved around they are forced into these crevices and remain in these more stable positions in relation to the larger particles. On the other hand the larger particle size grains roll about under the influence of the tamping force and form bridges between other large particles, which have spaces for smaller particles to “coalesce” and help form a more “solid” bulk material. As previously shown in Figure 4.7, even though this is a schematic representation, the solid volume concentration increases due to the tamping of the loose soil. This increase in solid volume concentration also causes a corresponding decrease in the free space volume available per unit volume required to accommodate the movement of the individual grains. This decrease in free space thus restricts the individual particle movement hence the compressed mass of soil moves as one. Thus the applied vibration load would be transmitted more faithfully through this type of soil than one of a less bulk density. But it is not only the density increase but also the increase in the contact points between individual grains that will aid the transmission of the vibration wave through the more compacted soil sample.

The bulk density of the soil samples is shown in Table 4.10 and as can be seen there is a range from 1.157 g/cc (for Sample C, a clay based material) to 1.682 g/cc (for Sample G, a sand based material). This is the density of the material loosely poured into a container without any tamping or shaking of the container. The variation in the bulk densities of the loose poured soil results from the minerals that constitute the individual soil samples and the size distribution of the soil samples. For a situation where the soil is loosely poured around the mounting block there would be very little coupling between the mounting block and the soil. The transmission of the vibration wave through this mass of soil would be interfered with and energy would be lost as particle to particle contact is limited and the vibration level would be attenuated. This would lead to a low vibration transmission level. This was measured and previously shown in Figure 4.6 and also in Table 4.10. As the individual grains move independently of each

other in this situation the primary sensor record would in no way mimic the vibration wave as it travels through the soil.

When the vibration wave passes through soil compacted to a higher density, such as the Medium and Maximum compaction regimes, there would be less free space for individual particle movement to occur. In effect the soil mass would now behave as one and the vibration wave attenuation would be less than in the loose poured situation. The higher the compaction forces used to meld the individual grains into “one” body the higher will be the vibration transmission as shown in Table 4.9. The degree of compaction can be ascertained from the change in the bulk density of the soil and the density of the compacted regimes. This change in density was measured before each sample was tested in the vibration rig by weighing the container with the compacted soil. The change in density due to compaction is shown in Table 4.10 as an increase in the percentage solids in the soil container. The effect of the increase in compaction as indicated by the percent solids on the vibration transmission is also shown in Figure 4.6.

#### **4.8 Effect of particle size distribution of soil.**

The Rosin-Rammler coefficients for the particle size distribution of the soils are shown in Table 4.2. The characteristic particle size,  $X_c$ , as discussed in Section 4.4, represents the particle size at which the fraction,  $1/e$ , of the total mass of the sample is retained on a screen aperture. While the uniformity index  $n$  represents the dispersion of the data over the screen sizes used in the particle size determination. When the mass percent retained on a size fraction is plotted against the size fraction a Rosin-Rammler or negative decay plot of the data can be formed. From this plot, which is usually a log-log plot, these size distribution coefficients can be determine. These size distribution coefficients are shown in Table 4.2 for all of the samples used in this study. In two experiments, the effect of large particles, which were thought to form bridges for the vibration wave to travel between adjacent particles, was investigated. It is obvious that once a particle is excited ie. the wave “enters” the particle, it will travel the length and breadth of the particle before leaving the particle to the adjacent particle or particles touching the original particle. Upon reaching the end of the particle it would encounter a boundary which would provide some resistance and hence reduce or attenuate the

vibration level overall. With these thoughts in mind it was expected that large individual particles would not attenuate the vibration level as much as a small particle, less contact points for large particles, hence the vibration transmission rate was expected to rise as less attenuation would be measured.

The soil sample I used in all other experiments was granite material from a quarry with the -32+8mm material removed. In this way the top particle size of the soil sample used in other experiments was maintained at 8mm. These larger sized particles were then added back into the -8mm material to produce two extra soil samples, I+10 and I+20. The size distribution properties of these samples are shown in Table 4.2 (page 95). As can be seen the Sample I had a characteristic particle size ( $X_c$ ) of 1.93 and a uniformity index ( $n$ ) of 0.89. This sample was one of the coarsest sample used in this study as only Sample B had a larger characteristic particle size at 2.76 mm. The uniformity index of Sample I was approximately in the mid-range of the nine soil samples used and for the -8mm material there was considered to be an even spread of the particle size distribution over the screen sizes used. Sample I+10, which had 10% of the -16+8mm coarse material added back into the -8mm material, had a characteristic particle size of 2.35 mm and a uniformity index of 0.84. These values were to be expected as the inclusion of the coarser particles not only increased the characteristic particle size from 1.93 mm (Sample I) to 2.35 mm (Sample I+10) but also reduced the uniformity index from 0.89 (Sample I) to 0.84 (Sample I+10). However the statistical significance of this uniformity index difference would possibly be doubtful. Sample I+20, which had 10% of the -32+16mm coarse material added back into the -16mm material of Sample I+10, had a characteristic particle size of 2.85 mm and a uniformity index of 0.76. Again, these values were to be expected as the inclusion of the coarser particles not only increased the characteristic particle size from 2.35 mm (Sample I+10) to 2.85 mm (Sample I+20) but also reduced the uniformity index from 0.84 (Sample I+10) to 0.76 (Sample I+20). There would appear to be a significant difference in the size distribution of these three samples (Sample I, Sample I+10 and Sample I+20) when both the characteristic particle size and the uniformity index are considered. Hence the assumption that large particle would form bridges for the vibration wave to travel along could be tested. The results of these experiments are shown in Table 4.11

Table 4.11 Particle size effect on vibration level

Compaction Regime	Moisture (%)	Sample I (mm/s)	Sample I+10 (mm/s)	Sample I+20 (mm/s)
Zero	0	1.99	1.61	1.39
Zero	2	2.07	2.07	1.73
Zero	5	1.20	1.57	1.27
Zero	10	0.94	1.34	3.61
Medium	0	1.75	1.41	1.89
Medium	2	3.16	2.24	1.96
Medium	5	2.51	1.78	1.82
Medium	10	1.74	1.41	1.18
Maximum	0	1.72	1.57	2.25
Maximum	2	3.17	1.64	2.73
Maximum	5	3.88	1.96	2.60
Maximum	10	3.98	3.10	1.51

As can be seen from Table 4.11, there does not appear to be any overall trend in the vibration levels for any moisture level selected. It has been shown, see Section 4.7, there is an effect with compaction and even if this is taken into account (ie. looking at the same compaction regime for each particle size distribution) there does not appear to be any significantly similar trends in any of the soil samples. It would appear that the vibration wave does not “enter” the individual particle and move through the particle but rather “uses” all of the particles as a whole body to transmit the energy through the entire sample. This hypothesis would probably be true, as work, conducted by the author of this thesis, in the field appears to suggest that damage zones (many individual particles between the vibration source and the target) do have an attenuation effect on the level of vibration. In a competent rock scenario, faulty ground could have an attenuation effect but due to the proximity of individual particles, no matter what the size, this attenuation effect would not be as pronounced as in more weathered ground. Also in competent rock even though individual particles are present and due to the pressures within the body of the earth, the spatial distance between individual rocks would be extremely small. The entire body of rock (fractured and competent regions)

would behave as one and hence the transmission of the vibration wave would be less attenuated.

In a weathered rock scenario, which is usually close to the ground surface, the forces are not as great and the contact between individual particles would not be as close. A larger gap would exist between particles allowing individual particle differential movement and hence an attenuation of the vibration wave. This weathered material is close to the surface and, as there is a major density difference between the weathered soil and the atmosphere, the surface is allowed to move. Hence structures built on the surface feel this movement greater than if the structure could be constructed within the rock mass.

From these results it can be stated that, and even allowing for errors in the procedure, for this type of material (particulate soil) there does not appear to be an relationship between particle size and the transmission of vibration waves through the soil. Apart from this lack of dependency, this finding has implications in the understanding of the effect of fractured ground barriers in attenuating blast-induced vibrations in sensitive locations. There could be a dependency on properties such as free space, particle shape, material type etc. as, overall, vibration levels are attenuated across a fracture barrier.

#### **4.9 Type of soil.**

It was shown in Section 4.2 that the soil samples used in this study were all different in chemical and physical aspects. These differences in the soils will cause each soil to transmit the vibration wave at various rates and the attenuation of the vibration wave for each soil will also be different. In many vibration monitoring exercises carried out in the field it has been found very difficult to use information measured at one site to predict events at another site with any degree of confidence. This fact is due to the local geology and structure of the ground having an effect on the transmission of the vibration wave. This should also be true for different soil types used to couple the mounting block in the laboratory vibration rig.

It has been shown that particle size does not have a significant influence on the transmission of the vibration wave so different material types with different particle size

distributions should follow in this manner. It was also shown that vibration transmission increased as the compaction regime “increased”. Thus to minimise any effects, negligible though it maybe, of particle size and to maintain a consistent “degree” of contact between individual grain the maximum compaction regime was used. Also the moisture content of the soil samples was selected at 5% as this was shown earlier to be in the region where the surface tension effects of the moisture and the individual grains was evident. Some of the soil samples had inherent moisture levels of up to 3%. As the measured moisture level was greater than 5% it was felt that this inherent moisture was trapped, in a sense, by the mineral and the moisture added was adsorbed onto the surface of the individual grains.

A total of nine different soil types were tested in the laboratory vibration rig. These soils and their chemical and physical properties were shown in Table 4.1 (page 95) and Table 4.2 (page 95) respectively. It was shown that moisture and compaction of the soil samples had an effect on the vibration transmission through the soil. To minimise these effects, the soil parameters, such as moisture and compaction were fixed at an arbitrary value and the transmission of the vibration wave through the soil was recorded. Each soil was mixed with 5% moisture and compacted to the maximum compaction regime. These results are shown in Table 4.12.

As can be seen from Table 4.12 the vibration levels ranged from 1.59 mm/s (for Sample G) to 3.74 mm/s (for Sample C). Sample G was a silica sand material with a reasonably narrow size distribution ( $X_c = 0.66$  and  $n = 0.87$ ). whereas Sample C had a somewhat different size distribution ( $X_c = 1.30$  and  $n = 0.76$ ). However, sample C was a clay based material and as such was capable of absorbing within its structure large quantities of water which causes swelling of the local grains which would aid in the compaction and hence transmission of the vibration wave through the soil. This can be seen from Table 4.12 that the clay based soils (see Samples A, B, C, D and E) compared with the sand based soils (Samples G, H, I, I+10 and I+20). This is only a generalisation and one area where more work needs to be done to define the soil properties that affect vibration transmission and hence attenuation.

The results shown in Table 4.12 also support much of the field work that has been done over the past three or four decades. Vibration measurements carried out in one mine

can be used to derive the site law parameters for that particular mine. However this site law is, as its name implies, site specific and in some cases a site law from one mine or

Table 4.12 Moisture content of soil samples

	Soil type	Moisture	Compaction	Vibration
		(%)	Regime	(mm/s)
Sample A	Grey clay soil	6.05	Maximum	2.87
Sample B	Coarse orange clay soil	8.62	Maximum	2.43
Sample C	Fine grey clay soil	8.08	Maximum	3.74
Sample D	Dark grey sandy soil	5.95	Maximum	3.12
Sample E	Yellow sandy loam	7.17	Maximum	3.39
Sample F	Brown river bed sand	6.45	Maximum	3.57
Sample G	Brown black gravel	4.61	Maximum	1.59
Sample H	Black grey sand and bark	7.14	Maximum	2.46
Sample I	Brown granite quarry rocks	7.16	Maximum	1.88
Sample I+10	Brown granite quarry rocks	7.23	Maximum	1.86
Sample I+20	Brown granite quarry rocks	6.29	Maximum	2.60

area used at another mine or area can give quite disastrous predictions. These results add weight to the fact that all materials are not the same as far as vibration transmission is concerned. It is not only the physical properties of the soil (moisture, compaction or size distribution) that determines the vibration transmission but more a fundamental property of the soil itself. The properties of the rock material itself will determine how the vibration wave is transmitted through a competent section of the rock. These properties are the density, the Poisson's ratio and the Young's modulus. All of these properties give a measure of the ability of the material that the rock is made of to allow waves to pass through. The density for example is not only the close packing of the structure of the rock material but also the mineral matter of the rock material. A high density does not necessarily mean the vibration wave will be transmitted through the rock at a higher rate than a low density material. Marble and granite with densities approximately  $2600 \text{ kg/m}^3$  can have for example  $p$ -wave velocities of approximately  $5 \text{ km/s}$  where as iron ores with a density of  $4500 \text{ kg/m}^3$  can also have  $p$ -wave velocities of approximately  $5 \text{ km/s}$ . The same applies for the Poisson's ratio and Young's modulus,

all of which are measures of the fundamental properties of the material that the soil is made of and it is these properties that will control the vibration wave transmission rate. An attempt was made to quantify any relationship that might exist between the vibration wave transmission of the soils and the particle size but there did not appear to be any relationship. This was also the case with the other parameters examined. So it appears that a soil will transmit the vibration wave at a level that of course will be dependent on the input level applied, but each and every soil type will transmit the vibration wave at a level quite different to another soil. In other words no two soil types will transmit the same applied vibration wave load at the same level. Some parameters have been shown to have an effect on the vibration attenuation of the soils but this level of vibration attenuation is primarily governed by the geological nature of the soil type itself. The vibration wave rate travelling through a particular type of rock (or soil) is a property of the rock itself and both the  $p$ -wave and  $s$ -wave velocities of the rocks are internally structurally governed and this would be different for all rock types. The vibration wave appears to move through the bulk of the soil but the wave movement is affected by particle to particle contact and the transmission properties of the soil material. Each particle of the soil is made of a mineral that has defined transmission properties for wave movement, which can not be exceeded but attenuation of the vibration level is possible due to the physical structure of individual particle and its local environment.

#### **4.10 Discussion.**

The laboratory vibration rig developed for this study proved to be an efficient device to investigate the vibration transmission through soils in a controlled environment. Because the equipment had defined alignment procedures it was capable of delivering a near constant applied vibration load to the soil sample. However, as with any measurement procedure, there are always errors and this equipment was no exception. A series of experiments was designed to check and quantify the errors that were associated with this procedure. The coefficient of variation was used to determine the magnitude of the error associated with the procedure as it eliminates any ambiguity due to the size of the absolute value of the raw data.



The errors in the laboratory vibration rig were found to be 5.81%. Also there was an error due to the placement of the primary sensor and the variation with distance from the primary sensor was included in the error analysis to remove any influence of misplacement of the mounting block. The error associated with the misplacement of the mounting block was found to be 1.80%. The overall error determined for the laboratory vibration rig was the sum of these two errors and amounted to 7.61%. This means that the result for any experiment must differ by more than 7.61% before the variation can be classified as significantly meaningful.

In field vibration monitoring exercises it is impossible to control the condition of the soil that is coupled to the mounting block. The parameters of the soil (moisture, size analysis and to a lesser degree compaction) have to be accepted at the vibration monitoring point. These parameters were studied in controlled laboratory conditions to measure their effect on vibration transmission.

The moisture content of the soil can vary significantly on a daily basis. This variation was studied by mixing soil sample with varying quantities of water to obtain moisture levels that would be experienced in the field. All the soil samples used in this experiment had varying degrees of inherent moisture, which is the moisture content of the dry soil sample. This moisture content varied from 0.07% to 3.00%. When the water was mixed with the soil and the soil was coupled to the mounting block in the laboratory vibration rig, the variation in the vibration transmission was shown to be continually increasing in the soils which had a high clay content (Samples A, B, C, D, E and G). However, for those soils which had a more sandy base (Samples F, H, I, I+10 and I+20) the variation in transmission increased to a maximum and then dropped off as more water was added to the soil. This shows that a saturation point is reached before which the water is acting in a surface tension mode and holding the soil particle together under the influence of the vibration load. Once this maximum level had been exceeded the individual particles are surrounded by water, which acts as a lubricant and the grains move more freely in relation to one another under the influence of the vibration wave.

The most important parameter that can be influenced by the operator is the compaction of the soil around the mounting block. It is this coupling between the soil and the mounting block that is most important. A bad coupling and there is differential

movement and a “wrong” result will be recorded. As the degree of compaction increased the bulk density (dry basis), the vibration transmission increased. Taken to the extreme case if the soil could be compressed to exclude all interstices then the vibration transmission would be at a maximum and very little energy would be lost. However, in a real situation coupling of the soil to the mounting block so that the soil and the block move as one ensures the primary sensor will measure the vibration level at the monitoring point as faithfully as possible.

The size analysis of the soil was shown to have very little effect on the vibration transmission. It was thought that increasing the particle size distribution would cause an increase in the vibration transmission as the larger particles would form solid bridges for the wave to travel along. However, it would appear that the vibration wave is not individual particle dependent but more of a bulk effect. As the vibration wave passes through the soil the individual grains are moving in unison with its neighbouring grains and the motion is transferred from one particle to another particle on a bulk basis not internally within each grain. The soil samples tested in this study had a top size of 8 mm. It is recommended if mounting is to be carried out in rocky ground then some fine grained material should be added to aid in the bonding (more particle to particle contacts) of the mounting block to the soil.

Under the same experimental conditions (surface moisture content and compaction regime) no two soils behaved the same under the influence of the applied vibration wave. The vibration levels ranged from 1.59 mm/s to 3.74 mm/s but it was shown that the clay based soils did transmit high vibration levels (consistently greater than 3 mm/s) than the sandy based soils (basically less than 2 mm/s). In most field monitoring situations the soil type changes from mine to mine and even from area to area within a mine. The results from one mine/operation can not successfully be used at some other mine/operation. This was shown in the variety of soil used in this study.

#### **4.11 Chapter Conclusions.**

- A vibration rig was designed to test field parameters in a laboratory environment.
- The same equipment used in the field was used in the laboratory.

- Nine different soils and a modified soil (size distribution) were used.
- Chemical and physical properties of the nine soils varied quite markedly.
- The variation of vibration with distance in the laboratory rig was determined.
- The precision of the laboratory vibration rig was acceptable at less than 10%.
- Moisture was found to have a slippage effect on the soil.
- Compaction was found to have the largest effect on the vibration transmission.
- Size distribution of the soil did not appear to alter the vibration transmission.
- All soil types transmitted a constant vibration at a different level.



## CHAPTER 5.

### FIELD MONITORING and APPLICATIONS

#### **5.1 Introduction**

It is imperative that not only the equipment be capable of measuring the signal from the primary sensors but and most importantly that the sensors are moving in unison with the vibrating ground. The many and varied mounting procedures and the parameters of an effective data logger have been described in Chapter 3.

In this chapter the reproducibility of the mounting methods is discussed. In Section 5.2 the standard mounting technique is investigated to see if the mounting method can reproduce the “same” vibration level at the “same” location. If there are any variations, what are these variations and how do these variation affect the vibration level recorded? Six data loggers using the standard mounting technique were placed at the same location for 25 typical overburden coal blasts. The variation between each monitoring set-up was measured as a degree of representative of the vibration level measured for the standard mounting technique. In Section 5.3 a selection of 5 commonly used mounting methods were compared to the standard mounting technique. Again all mounting methods were connected to the same data logger to minimise any bias (if there was a bias it was assumed to be the same for all of the data loggers). The aim was to measure the variability of the different mounting methods with respect to the standard mounting technique. In Section 5.4 the effect of the density of the mounting block of the standard mounting technique was investigated. Is a light weight mounting block going to amplify the vibration level or will a heavy weight mounting block reduce the vibration level? Six standard mounting techniques were set-up with the only difference being the density of the mounting blocks. Again 25 typical coal overburden blasts were used as the vibration source. In Section 5.5, 5.6 and 5.7 the application of blast induced vibration monitoring is discussed. The analysis of the recorded waveform has indicated what actually happened at the monitoring location and shed some light onto the possible structural concerns that might arise from the blast induced ground vibration.

## 5.2 “Standard Technique” Variability Trial

The “standard” technique, which had been extensively investigated by Blair (1995a, 1995b), was used in the field environment and tested for variability. A series of six vibration-monitoring systems that all had identical accelerometers, connectors and data loggers were used in these field trials. Each of the systems consisted of a mounting block with accelerometer bolted to the top and a cable connected the accelerometers to a field data logger. The mounting block for each system was coupled to the soil in the standard way. A range of vibration levels was required to measure the variation that could be expected from this standard procedure. For each blast monitored a total of 6 values would be recorded and the variation within these 6 values would indicate the precision of the standard technique. A local coal mine, Bloomfield Colliery, East Maitland, NSW gave permission for this work to be carried out at their open cut mining operations. This coal mine was selected because blasting operations were carried out 3-4 times each week and the variability of the ground that existed in the open pit areas.

Before each blast was monitored, a discussion was held with the shotfirer to determine the maximum charge weight in each hole, the shot initiation sequence and an area where vibration monitoring was considered safe. It was planned to measure vibration levels less than 100 mm/s as this was considered an upper limit for the “standard” mounting procedure. The basic procedure consisted of excavating a trench about 0.4 m wide and 0.2 m deep and 1.5 m long. As the variation of the mounting block and the soil coupling was being tested, all six blocks were laid in the trench and the soil backfilled into the space between the trench and the mounts. A pick handle was used in all cases to tamp the excavated soil back into the trench to form the coupling bond between the undisturbed soil and the mounting blocks. A photograph of all six mounting systems is shown in Figure 5.1 and the experimental set up in the field is shown in Figure 5.2.

As shown in Figure 5.1 the primary sensor is bolted to the aluminium block/cylinder. The bolting of the primary sensor to the aluminium cylinder ensures that there is no differential movement between the primary sensor and the aluminium cylinder. The outer curved surface of the cylinder is roughened so that the soil can form a firm bond with the cylinder and hence minimise the chance of the aluminium cylinder being decoupled from the soil. The primary sensor is attached by cable to the data logger which



Figure 5.1 The “standard” mounting equipment used in the variability trials.



Figure 5.2 Typical field set up of the “standard” mounting techniques.

is designed to accept the electrical outputs from the primary sensor and sample these signals according to the sample interval, the signal level for trigger purposes and the resolution. Modern electronic equipment (ie the field data logger) is ruggedly designed to perform these operations and it only needs the operator to be fully aware of the capabilities of the equipment for informative vibration waveforms to be recorded.

The six mounting systems are shown coupled to the soil in Figure 5.2. This is a typical set-up and the only variation from this set up for each blast monitored was the distance from the monitoring point to the blast and the location of the vibration monitors. As a variety of vibration levels was required and a total of 25 blasts were monitored the distance from each blast was measured (by normal surveying techniques). Even the maximum instantaneous charge weight (MIC) of explosive initiated in a blast varied from shot to shot and this helped to obtain a range of vibration levels monitored for this study.

The primary sensors used in all this work were accelerometers so that the output from these devices was acceleration units ( $g$  or  $m/s^2$ ). Accelerometers were used as they have a much better linearity over a wider frequency range (especially at low vibration frequencies). Constant equipment parameters were essential if variation in the recorded results were to be attributed to the mounting procedure only. The signal from the accelerometer, as stated above, is measured in units of  $g$  or  $m/s^2$ . This unit is distance differentiated with respect to time twice, so by reversing the differentiation (ie. integration) the units can be converted to velocity units of  $mm/s$ . This conversion is necessary, as the accepted industry standard unit for vibration is particle velocity and is measured in  $mm/s$ . This accepted standard has a traditional background dating back to the 1950's when some early work by USBM (Blair and Duvall, 1954) set this standard for vibration monitoring. This velocity unit is the speed at which particles are moving as the ground is acted upon by the vibration wave as it passes through the ground.

A summary of the raw data from this investigation is shown in Table 5.1 (velocity data) and Table 5.2 (frequency data) for all 25 blasts monitored. Only the vector peak particle velocity (VPPV) and the predominant frequency are shown for each monitoring system for each blast. A statistical analysis is also shown to gauge the variation of each



blast that was recorded in the field during routine vibration monitoring, carried out under very well controlled conditions.

The columns in Table 5.1 and Table 5.2 headed Mon1 through to Mon6 are the individual vibration values recorded from the blast. The statistical data columns show the Maximum value, the Minimum value and the average value. Finally the standard deviation and the coefficient of variation of this set of values is also shown in the final two columns.

As shown in Table 5.1 a wide range of vibration levels was recorded. The vibration levels ranged from 1.48 mm/s to 183.74 mm/s. For all but 4 blasts (from a total of 25 blasts monitored) records from the six monitoring systems were obtained. Open circuits causing faults in the connecting cables were attributed to this loss of data. However, it is the variation within each group that is the issue in this section. Vibration levels from different locations can be expected to change but from the same location what is the variation that can be expected under well controlled experimental conditions?

Several measures of the “spread” of the data, ie. the standard deviation and the range, were considered. However, both of these statistics are affected by the absolute value of the measurements the higher the measurement the larger will be the absolute value of the standard deviation and the range, so it is difficult to compare the spread of each set of measurements with another. However, the coefficient of variation (CoV) “gives some measure of relative importance of the standard deviation referred to the mean” (Mulholland and Jones, 1969). Also “the CoV is informative and useful in the presence of the mean and standard deviation, but abstracted from them it may be misleading” (Snedecor and Cochran, 1971).

This statistic is a function of the mean and the standard deviation which themselves have the same units. As the CoV is dimensionless (mean divided by the standard deviation) it is not affected by the absolute measured values from each data set. It is a good measure to compare data sub-sets that have large mean variations. As shown by the data the variation within each data sub-set is small but the variation between the means of the data sets is very high.

Table 5.1 Summary of VPPV vibration data for variability trials.

Individual monitor measurements (mm/s)						Statistical data				
Mon1	Mon2	Mon3	Mon4	Mon5	Mon6	Max	Average	Min	Std Dev	CoV
1.4	1.5	1.5	1.6	1.4	-	1.6	1.48	1.4	0.084	5.65
2.3	2.3	2.2	2.3	2.3	2.2	2.3	2.27	2.2	0.052	2.28
2.7	2.8	2.7	2.7	2.9	-	2.9	2.76	2.7	0.089	3.24
6.0	6.0	6.3	6.6	6.1	6.7	6.7	6.28	6.0	0.306	4.87
6.3	6.7	7.4	6.7	6.2	6.7	7.4	6.67	6.2	0.423	6.34
9.4	10.1	10.6	10.8	11.5	11.3	11.5	10.62	9.4	0.778	7.33
10.1	10.4	10.7	9.9	9.6	9.7	10.7	10.07	9.6	0.423	4.20
10.2	9.0	10.6	10.0	10.8	10.7	10.8	10.22	9.0	0.671	6.56
11.3	13.6	14.0	11.7	12.3	11.5	14.0	12.40	11.3	1.142	9.21
11.3	12.0	11.8	11.7	12.3	12.4	12.4	11.92	11.3	0.407	3.42
19.9	19.4	18.8	20.0	19.0	19.7	20.0	19.47	18.8	0.489	2.51
20.2	22.2	21.1	20.8	21.3	20.8	22.2	21.07	20.2	0.668	3.17
20.7	21.4	20.7	23.7	21.2	21.1	23.7	21.47	20.7	1.129	5.26
21.5	22.0	20.1	22.3	22.6	21.8	22.6	21.72	20.1	0.880	4.05
25.7	25.8	25.2	25.8	25.8	27.5	27.5	25.97	25.2	0.787	3.03
31.3	30.3	31.8	29.6	33.8	29.7	33.8	31.08	29.6	1.592	5.12
33.6	33.6	32.1	35.4	34.9	35.2	35.4	34.13	32.1	1.268	3.71
35.3	34.0	31.6	33.2	33.9	36.1	36.1	34.02	31.6	1.582	4.65
36.0	33.8	33.8	33.5	32.2	36.1	36.1	34.23	32.2	1.527	4.46
38.7	41.5	38.1	39.8	37.9	-	41.5	39.20	37.9	1.483	3.78
59.9	60.6	63.1	62.9	62.4	58.4	63.1	61.22	58.4	1.888	3.08
79.5	78.4	75.9	76.2	75.8	77.8	79.5	77.27	75.8	1.531	1.98
88.9	87.9	89.3	91.7	88.3	89.4	91.7	89.25	87.9	1.332	1.49
133.2	134.8	136.3	137.0	140.7	138.6	140.7	136.77	133.2	2.672	1.95
178.2	183.1	179.7	189.8	187.9	-	189.8	183.74	178.2	5.036	2.74

## Standard deviation Data

	<10 mm/s	<50 mm/s	<100 mm/s	All data mm/s	All CoV data	
Max	0.778	1.142	1.888	5.036	Max	9.21
Average	0.289	0.539	0.893	1.129	Average	4.16
Min	0.052	0.052	0.052	0.052	Min	1.49
Std Dev	0.281	0.358	0.559	1.037	Std Dev	1.84

Table 5.2 Summary of Frequency vibration data for variability trials.

Individual monitor measurements (Hz)						Statistical data				
Mon1	Mon2	Mon3	Mon4	Mon5	Mon6	Max	Average	Min	Std Dev	CoV
17.3	17.0	16.9	16.9	16.7	-	17.3	16.96	16.7	0.219	1.29
19.4	18.6	19.8	20.5	19.0	21.4	21.4	19.78	18.6	1.028	5.20
25.5	24.5	25.2	25.7	24.5	-	25.7	25.08	24.5	0.559	2.23
25.6	25.3	25.8	27.4	26.3	27.3	27.4	26.28	25.3	0.889	3.38
32.1	34.0	35.7	32.7	33.0	33.7	35.7	33.53	32.1	1.263	3.77
60.2	58.9	57.8	57.5	61.9	59.4	61.9	59.28	57.5	1.627	2.74
29.1	28.8	29.7	28.2	26.3	27.1	29.7	28.20	26.3	1.284	4.55
20.6	21.7	20.3	20.6	20.2	19.1	21.7	20.42	19.1	0.838	4.10
68.9	70.5	72.9	66.4	71.8	69.1	72.9	69.93	66.4	2.317	3.31
26.0	25.7	28.2	25.6	29.7	27.9	29.7	27.18	25.6	1.673	6.15
11.1	11.0	11.5	11.3	11.3	11.4	11.5	11.27	11.0	0.186	1.65
9.8	9.4	9.5	10.1	9.7	9.9	10.1	9.73	9.4	0.258	2.65
24.4	24.8	24.9	25.6	25.6	25.3	25.6	25.10	24.4	0.482	1.92
6.1	5.9	6.2	6.0	6.1	6.5	6.5	6.13	5.9	0.207	3.37
30.1	29.7	29.6	30.6	29.7	30.3	30.6	30.00	29.6	0.400	1.33
22.2	21.3	22.5	23.4	23.1	22.1	23.4	22.43	21.3	0.753	3.36
6.8	6.8	6.8	6.7	6.0	6.7	6.8	6.63	6.0	0.314	4.74
23.1	22.0	22.2	21.5	21.7	22.4	23.1	22.15	21.5	0.568	2.57
84.8	85.7	85.7	87.9	86.0	-	87.9	86.02	84.8	1.143	1.33
101.5	98.6	99.4	99.7	97.9	114.3	104.3	100.23	97.9	1.359	1.37
35.1	34.7	35.0	40.2	35.2	36.4	40.2	36.10	34.7	2.092	5.79
20.9	19.2	20.2	20.3	19.8	19.9	20.9	20.05	19.2	0.568	2.83
9.7	9.0	9.0	9.7	9.6	9.4	9.7	9.40	9.0	0.329	3.50
22.7	22.7	22.0	21.8	20.9	21.2	22.7	21.88	20.9	0.747	3.41
4.9	5.0	4.9	4.9	4.9	-	5.0	4.92	4.9	0.045	0.91
Standard deviation Data						All CoV data				
	<10	<50	<100	All data						
	mm/s	mm/s	mm/s	mm/s						
Max	0.329	2.092	2.317	2.317		Max	6.15			
Average	0.236	0.700	0.825	0.846		Average	3.10			
Min	0.045	0.045	0.045	0.045		Min	0.91			
Std Dev	0.114	0.527	0.620	0.617		Std Dev	1.44			

As shown in Table 5.1 the CoV ranges from 1.49% to a maximum of 9.21% with an average of 4.16%. This indicates a reasonably tight distribution showing that all the CoV values are similar. CoV values less than 10% are considered to be similar and this is supported by the low standard deviation for the experimental data. A good measure of the variability of a data set is the 95% confidence interval. This interval is  $\pm 3$  times the standard deviation about the mean value of the data set and any values that fall outside this interval would not be part of the population that the data set represents. From this data if the 95% confidence interval is applied to all blasts then a value approximately 10% about the mean value should be measured. This means that the “true” vibration level of  $\pm 10\%$  about the mean value would be expected from the six vibration monitors used to measure the vibration level.

From a practical point of view and from the data presented here it can be expected that the “standard” procedure used for vibration monitoring can be expected to measure levels with a precision of 10%. This precision can be attained if due care is taken during the bonding of the mounting block to the soil is taken and the equipment used to monitor the vibration wave is maintained in a good condition as far as calibration and serviceability is concerned. It would be difficult to obtain a precision value greater than that measured in this study due to many factors not the least being the procedure itself for measuring the vibration level in a soil environment. As stated earlier the particulate nature of soil does not lend itself mounting any measuring devices and the bonding of the soil to the mounting block has been shown to be extremely important. Thus as shown here these experiments indicate that the result measured by this procedure will be within 10% of the “true” value.

The frequency measured by the primary sensor is a function of how the explosive charges (ie. each blasthole) were initiated in the blast pattern sequence and the transmission properties of the rock material through which the vibration wave passes. The actual frequency can be controlled to a certain extent by the timing sequence used in the blast initiation. The frequency is a measure of the time that each charge is detonated and certain frequencies can be detrimental to structures (man made and natural) which experience the blast induced vibrations. The frequency reported here is the predominant frequency from the spectral plot, which is defined as the frequency at which 50% of the energy in the vibration wave occurs. The predominant frequency is a

calculated value and one that does not rely on features of the spectral plot. These features could include aberrations in the vibration waveform due to events outside the blast induced vibration loading at the monitoring point. The energy is taken as a function of the square of the amplitude, which is then summed over the entire frequency range of the vibration wave. The predominant frequency is then determined from the 50% of the area under this curve. This predominant frequency is not the frequency at the maximum amplitude, as it is felt that this frequency could occur as a spike or very sharp feature, which might not involve much energy (area under the spectral curve), and so could give a biased predominant frequency.

As shown in Table 5.2 a range of predominant frequencies from 4.9 Hz to 99.4 Hz was calculated. When the same statistical analysis as used in the vibration level analysis is applied similar results are obtained. The average CoV is a little lower at 3.1% (4.2% for vibration level) while the standard deviation of the mean values is 0.846 (1.129 for vibration level). For each test carried out there were six data points (for 21 out of the 25 blasts monitored) and although this is a small data set the variability is small. The CoV varied from 0.9% to 6.2%. This means that each mounting system (block, accelerometer and data logger) had no or little bias associated with the equipment and the random errors were maintained at an acceptable low level. Even when the complete data set (25 blasts and up to six data points for each blast) is considered the low CoV value indicates there is very little spread in the data.

From these results the “standard” mounting technique has been adequately designed to monitor blast induced vibrations within a frequency band of 5 – 100 Hz with a good degree of confidence. The CoV used to compare the average value from each data subset has shown the frequency recorded by each standard mounting block to be similar and no significant difference between the mounts occurred.

A comparison of some of the waveform captured from one of the low vibration levels recorded and one of the high vibration levels recorded is shown in Appendix 1. The component waveform and the vector sum of these components is shown for each monitoring system.

### 5.3 Variation Mounting Methods.

The results of the laboratory study were reported in this thesis where parameters of the soil itself were investigated. The parameter having the major influence was the compaction of the soil around the mounting block and it was shown that increasing the compaction enhanced the transmission of the vibration energy to the primary sensor. The moisture content of the soil was also shown to cause the vibration level to increase to a maximum and then decrease. This effect was due to the fluidisation of the soil particles (under vibration loading) as the moisture content increased. Soil type was shown to have an effect, but the size distribution did not affect the vibration transmission as much. This laboratory study has been discussed in detail in Chapter 4.

The work of Blair (1995a, 1995b) looked at the “standard” technique and the spike-mounting method. The conclusions were that the coupling of the soil to the mounting block in the “standard” technique was more effective. The methods used to mount the primary sensor to the ground have been described in Section 3.1 and some laboratory scale work has been carried out using one of the methods (see Chapter 4). However, the question still remains, what is the difference between one mounting method and another in a typical field blast-monitoring situation?

There are a variety of methods used today to bond the primary sensor to the soil experiencing the blast induced vibration loading. These methods have evolved over many years of practice and have mainly been established by equipment manufacturers. The method adopted by a particular manufacturer is one that usually suits the marketing strategy adopted by the company and in some cases is usually the easiest way of forming the soil to primary sensor bond. In this section of the work a series of six different mounting methods were trialed alongside each other. The mounting methods trialed were as follows: -

- a) the “standard” technique (“standard”) where the primary sensors are securely bolted to a mounting block which is then bonded to the soil in the prescribed manner.
- b) a modified “standard” technique (high frequency) which was similar to the “standard” technique except that the physical dimensions were changed to effectively measure higher frequency blast induced vibrations.

- c) a concrete block method (concrete) with a small disk securely glued to the top surface of a 200 mm cube of concrete which was bonded to the soil in a similar fashion to the “standard” technique.
- d) 3 circumferential spikes method (three spikes) consisted of a disk to which the primary sensors were securely bolted. On the base of this disk, three 100 mm long spikes were secured which were used to accomplish the bonding to the soil as the disk and primary sensor were forced into the soil.
- e) a central spike method (one spike) which was similar to the 3 spike technique except that only one spike was secured to the base of the disk in the centre of the disk.
- f) sand bag method consisted of a disk to which the primary sensors were securely bolted and two bags filled with fine sand were carefully placed on top of the primary sensors which were placed on a flat section of soil.

The “standard” technique was tested alongside the five other mounting methods mentioned above. A series of six vibration monitoring systems, all with identical accelerometers, connectors and data loggers was used to minimise any equipment variations. These vibration monitoring systems (primary sensors, cables and data loggers) were randomly interchanged on the mounting methods to minimise any bias that may have been present in one of the systems. Each of the systems consisted of a mounting block with accelerometer bolted to the top and a cable connecting the accelerometer to a field data logger. The mounting block for each system was coupled to the soil in the recommended way. During this section of the study the mining operations were being carried out in different areas of the pit which necessitated the movement of the systems from place to place as the blasting dictated. Monitoring locations for each blast were selected based on the type of soil available at a distance from each blast to give a desired vibration level. A range of vibration levels was required to measure the variation that could be expected. So for each blast monitored a total of 6 values would be recorded and the variation within these 6 values would indicate the precision of the mounting method compared to the “standard” technique. Each of these mounting methods is shown in Figure 5.3 and a photograph of the experimental set up is shown in Figure 5.4



Figure 5.3 Photograph of the mounting methods used in these trials. Mounting devices from left are sandbag, standard, concrete, high frequency, one spike and three spikes.



Figure 5.4 Typical field set up of all mounting methods.



This section of the research investigation was also carried out at Bloomfield Colliery. The primary sensor and data logging equipment was the same for all mounting methods and the only variation between systems was the method of coupling the primary sensor to the soil. Each primary sensor was bolted to the aluminium cylinder or aluminium disk so no differential movement was allowed. All six methods were placed in the ground at the same location as shown in Figure 5.4. In this investigation a trench some 40 cm wide and 20 cm deep and 1 m long was excavated. Three of the mounting devices (standard, high frequency and concrete) were placed in the trench and the soil tamped between the original ground and the devices. The soil was tamped to ensure an efficient bond between the mounting devices and the original undisturbed soil and extra soil was added to bring the level up to the original ground level. The one spike and the three spike mounting device were forced into the original undisturbed ground approximately 0.5 m away from each end of the trench. The sandbag mounting device in which the primary sensor was bolted to a disk was placed on the smooth ground along side the one spike device and two sandbags, filled with fine sand, were carefully placed on top of the primary sensor and disk. In this way the six mounting methods were at the same location and consequently there should not be any major variation in the soil quality (geology or structure) from one method to another. Also as the path between the mounting point for all of the mounting devices used and the vibration source (the blast) was considered to be the same there should be no variation due to the travel path of the vibration wave. Each method should receive the same vibration level and any variation measured would be as a result of the different coupling between the mounting device and the soil.

Again, as in Section 5.2, the accelerometers used were all the same and the output from these accelerometers was in acceleration units ( $g$  or  $m/s^2$ ). The raw data from the data loggers was initially filtered to remove any unwanted high frequency and low frequency electronic noise. This noise is basically caused by the electronics used to capture the signal from the primary sensor. A Butterworth band pass filter is used to remove these unwanted high frequency and low frequency aberrations so that a smooth signal is used in the integration stage. After the raw data is filtered the data must be integrated to convert the raw data into an acceptable format. Integration is accomplished by using the trapezoidal rule. If velocity is differentiated with respect to time then the

acceleration of the event is obtained. Conversely, if acceleration is integrated with respect to time then the velocity of the event will be obtained. The acceleration raw trace (which has been filtered at this stage) is a transient event with respect to time and if the height of the trapezoidal bounded by two consecutive time points is determined; the velocity with respect to time can be calculated. This particle velocity will be used through out this study. Mathematical analysis carried out on the recorded values converted the acceleration units to velocity units (mm/s), the industry accepted units for vibration monitoring.

A summary of the raw data from this investigation is shown in Table 5.3 for all 25 blasts monitored. Only the vector peak particle velocity (VPPV) and the predominant frequency are shown for each unit for each blast. The vector peak particle velocity is one of the important properties of blast induced vibrations and the one value that must be controlled. This property has been related to blast damage and the limits set by local restriction or country standards use this property as the control variable for blasting operations. The predominant frequency has been also linked to blast damage by other workers as there are certain frequency bands that promote structural resonance in buildings. It is only over the last couple of decades that the frequency of the blast induced vibrations has been given the attention that it deserves and blasting operators are designing their blasts accordingly. A statistical analysis is also carried out to measure the variation of each blast that was recorded in the field during routine vibration monitoring under well controlled conditions.

As can be seen in Table 5.3 and using the “standard” as the base case (to compare all other procedures) the vector PPV levels for all monitoring systems had a range from 2.4 mm/s to 592.6 mm/s. Although this is a large range, it occurred due to the monitoring point being set up at different distances from the blasts being monitored. Each blast that was monitored had different charge weights in the blasthole. Each blast also was designed with an initiation sequence so that there were a minimum number of holes firing at the same time to reduce the vibration level at the local residence. Consequently a different maximum instantaneous charge weight (MIC) was detonated for each blast.

Table 5.3 Summary of VPPV vibration data for mounting trials

standard	Individual monitor measurements (mm/s)					Statistical data				
	High freq	Concrete	3 Spike	1 Spike	Sandbag	Max.	Average	Min.	Std. Dev.	CoV
2.5	2.4	2.5	2.6	2.9	2.5	2.9	2.6	2.4	0.15	5.91
2.6	2.5	2.6	2.7	2.8	2.6	2.8	2.6	2.5	0.10	3.69
3.7	3.7	3.7	4.1	4.5	3.5	4.5	3.9	3.5	0.37	9.69
4.4	4.6	4.6	4.5	4.4	4.4	4.6	4.5	4.4	0.10	2.13
5.2	5.7	4.6	6.9	5.3	5.8	6.9	5.6	4.6	0.77	13.67
7.5	7.2	7.5	6.4	8.0	6.2	8.0	7.1	6.2	0.70	9.76
13.5	13.5	11.9	12.2	12.5	11.7	13.5	12.5	11.7	0.78	6.21
14.1	18.5	19.4	24.3	18.5	14.9	24.3	18.3	14.1	3.65	19.97
17.4	17.2	17.2	18.3	19.9	16.1	19.9	17.7	16.1	1.31	7.39
19.6	20.5	18.4	--	21.1	18.4	21.1	19.6	18.4	1.24	6.33
21.7	20.9	20.4	22.1	20.5	24.6	24.6	21.7	20.4	1.57	7.24
21.9	19.4	18.2	17.7	20.3	16.6	21.9	19.0	16.6	1.91	10.04
26.0	27.0	28.2	27.6	35.5	26.4	35.5	28.4	26.0	3.53	12.42
35.8	36.0	33.6	34.9	36.2	35.7	36.2	35.4	33.6	0.97	2.74
37.2	37.3	35.5	35.9	38.9	33.2	38.9	36.3	33.2	1.93	5.31
40.9	--	50.0	49.1	54.0	41.6	54.0	47.1	40.9	5.68	12.05
58.9	50.7	55.0	53.6	58.6	53.8	58.9	55.1	50.7	3.17	5.76
61.3	61.9	70.6	69.5	64.4	53.0	70.6	63.5	53.0	6.40	10.08
73.3	--	77.1	76.9	79.3	--	79.3	76.6	73.3	2.50	3.26
75.0	--	74.4	88.4	73.7	h	88.4	76.8	72.6	6.53	8.50
76.5	52.7	71.5	41.1	47.6	55.9	76.5	57.5	41.1	13.78	23.95
128.5	135.2	114.1	167.5	--	111.2	167.5	131.3	111.2	22.54	17.17
143.1	121.8	146.6	150.5	126.1	89.9	150.5	129.6	89.9	22.60	17.43
152.3	145.1	152.3	152.7	160.5	140.9	160.5	150.6	140.9	6.82	4.53
431.3	395.1	456.8	592.6	393.6	283.6	592.6	425.5	283.6	100.99	23.74

Soil mounting of the primary sensor is primarily be used for levels less than 100 mm/s as the coupling between the soil and the primary sensor is not expected to remain in tact at higher vibration levels. Rowe et al, 1999, used soil mounting to monitor single hole vibration levels at distances from 5 metres to 50 metres from the single blast hole detonations and found that the mount had been disturbed after the hole was fired at vibration levels greater than 100 mm/s. For levels greater than 100 mm/s it is recommended that the primary sensor be coupled to bedrock by using a rigid two-part resin to glue the primary sensor to the bedrock.

The mining and construction industry encounters structures that need to be protected when blasting operations are close by. Design parameters for these structures (concrete dams, power poles for major transmission grids and residential buildings) as far as blast induced vibrations are concerned have been determined by the manufacturers or relevant standards. As the vibration levels monitored in this section had a very large range it was thought prudent to divide this range into more meaningful categories. Some typical ranges used in monitoring blast induced vibration levels in mining and construction applications have been set at 100 mm/s for large constructions (such as concrete dams), 50 mm/s for electricity power poles carrying high voltage electric power and 10 mm/s for residential and commercial buildings. It is with these ranges in mind that the data measured was divided into the following four categories: -

- 1) all levels monitored during this study
- 2) all levels less than 100 mm/s (large structures)
- 3) all levels less than 50 mm/s (power poles)
- 4) all levels less than 10 mm/s (residential and commercial buildings)

The analysis of the data was carried out by making the assumption that the “standard” mounting procedure would give the “true” vibration level. All other mounting methods would be compared to the “standard” and any variation measured was due to the coupling of the soil to the mounting block, spike or ground. Hence the detection of the vibration level variation from the standard procedure would be an indication of the errors due to bonding of each of the techniques used in this experiment.

Firstly, the actual vibration level was examined. The vector peak particle velocity (VPPV) in mm/s was the maximum level experienced at the monitoring point for any

particular event. This in effect is the one single number that is traditionally used to describe the vibration level from a blast. Even though the timing of a blast will range from 0.5 seconds up to 10 seconds and in some cases the waveform can be complicated, it is the one maximum peak level that is used to describe the vibration level. In order to compare one mounting method to another this peak level for the “standard” was used as the independent variable. A graph was constructed with the peak vibration level for all mounting methods as a function of the “standard” peak vibration level. If there is no significant difference between the mounting methods, then a straight line of best fit with a regression value of 1 and a slope of 1 and passing through the origin should result. Deviations from these parameters of the line of best fit (regression coefficient, slope and y-axis intercept) would indicate poor coupling between the primary sensor and the soil in comparison to the “standard”. This assumption was considered reasonable as the only variable between the systems was the soil to mounting device coupling as all systems used the same measuring equipment which was randomly rotated to minimise any bias that may be present.

The second vibration waveform parameter and one which is often overlooked in blast vibration monitoring is the frequency of the waveform recorded. This frequency is termed the predominant frequency of the recorded waveform. For this study the predominant frequency is defined as the frequency at which 50% of the energy (area under the frequency spectrum) resides. This predominant frequency will be different from the frequency at which the maximum amplitude occurs because it is a measure of the total energy in the entire waveform spectrum. It is best to compare frequency content of a blast on the entire spectrum and in this instance the maximum frequency limit is fixed by the time between each sample in the waveform record. The frequency range is divided into areas of equal spacing (bins) and the frequency spectrum is plotted against these bin values. In this way the amplitude of each bin (frequency range) can be cumulated for all of the blasts (in a given vibration level range) and a meaningful comparison to the “standard” technique obtained.

### **5.3.1 All vibration vector peak particle velocity values.**

The VPPV data is also summarised in Table 5.3. From 25 blasts monitored, the highest vibration level measured (“standard” technique) was 431.1 mm/s. A plot of all

mounting methods compared to the “standard” technique is shown in Figure 5.5a. The equation for each line of best fit and the regression coefficient is also shown on the plot. As shown by the slope of these lines of best fit, the mounting methods vary from 1.33 to 0.67 when compared to the “standard” technique. Due to the high number of data points in the low end of the range, and a few large valued data points at the top end of the range, the line of best fit is strongly influenced by these few data points at the top end of the range of all data points. This deviation of the data from the standard technique can be explained by the fact that the only variable in the system was the coupling of the mounting device to the vibrating.

The comparative vibration results are shown in Figure 5.5a along with the equations of the lines of best fit and the linear regression coefficient. As can be seen the linear regression coefficients are very close to 1 indicating a good linear fit (in all cases) over this large data range. The concrete block has a slope of 1.05 and an intercept of  $-1.73$ , which shows that this data is very similar to the “standard” mounting technique data over this large data range. The high frequency mounting method and 1 spike mounting method have y intercepts close to zero but the slope of the line of best fit was close to 0.9 indicating a deviation from the “standard” mounting technique data. The 3 spike mounting method and sandbag mounting method both deviate strongly from the expected values and had slopes of 1.33 and 0.67 respectively, hence exhibiting a large deviation from the “standard” mounting technique.

The frequency data is summarised in Table 5.4. This frequency data is the cumulation of all blasts on a frequency bin basis. These plots as shown in Figure 5.5b indicate a comparison of each mounting method to the “standard” technique. This is a better way to view the data as it shows the extent of coverage of the frequency plots for each mounting method. A single line of best fit would not highlight the features of the frequency spectrum to show the difference in the mounting methods as far as frequency is concerned.

The predominant frequency values are shown in Table 5.4. If a similar analysis as that carried out in Section 5.1 is applied to this data the results can be quite confusing. For example the coefficient of variation (CoV) ranges from 1.45% to 22.46%. Thus it is difficult to get a meaningful interpretation of the results by standard statistical methods.

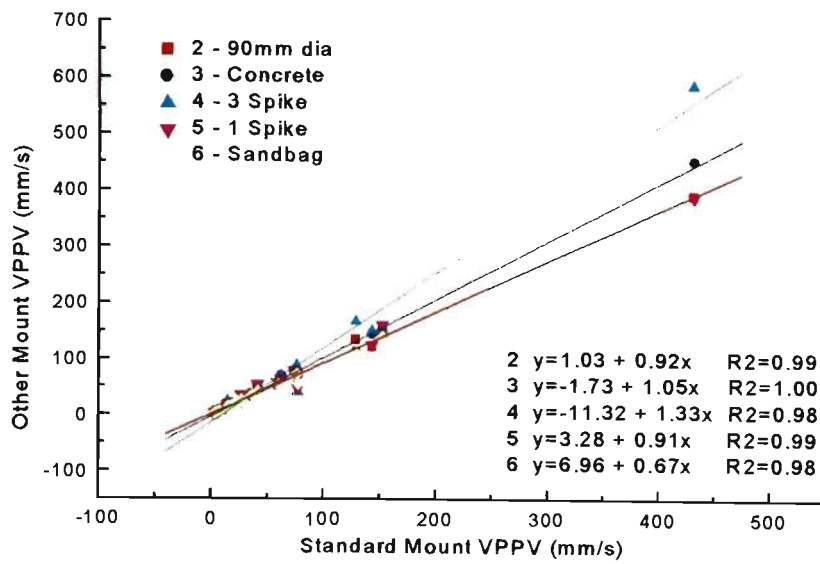


Figure 5.5a Plot of VPPV for all mounts compared to standard mount.

All data. .

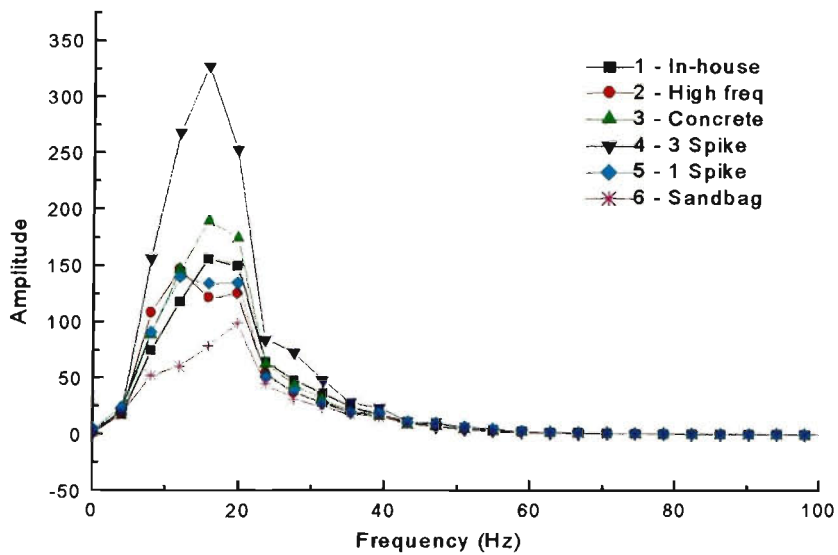


Figure 5.5b Frequency plot of all mounting blocks.

All data

Table 5.4 Summary of frequency vibration data for mounting trials

standard	Individual monitor measurements (Hz)					Statistical data				
	High freq	Concrete	3 Spike	1 Spike	Sandbag	Max.	Average	Min.	Std. Dev.	CoV
-	60.4	66.1	60.8	40.4	-	66.1	56.9	40.4	11.32	19.88
33.5	31.9	41	42.6	34.8	31.9	42.6	36.0	31.9	4.69	13.04
22.3	23.2	23.9	27.4	22.6	23.2	27.4	23.8	22.3	1.86	7.84
24.8	33.3	26.5	33.4	32.7	22.8	33.4	28.9	22.8	4.77	16.50
32.6	32.6	34.8	34.7	37.7	34.3	37.7	34.5	32.6	1.88	5.45
18.7	17.2	19.2	19.8	20.1	17.6	20.1	18.8	17.2	1.17	6.24
33.6	30.1	34	31.6	32.4	29.2	34.0	31.8	29.2	1.90	5.98
23.5	23.3	23	23.1	25	23.7	25.0	23.6	23.0	0.73	3.10
17.2	16.9	16.3	15.9	25.8	17.5	25.8	18.3	15.9	3.74	20.46
15.4	15.2	15.2	15.2	15.7	15.6	15.7	15.4	15.2	0.22	1.45
21.2	30.1	-	28.4	35	23.3	35.0	27.6	21.2	5.50	19.94
30.2	28.8	30.5	28.6	31.7	27.9	31.7	29.6	27.9	1.42	4.80
26.3	26.8	25.5	27.2	31.6	26.4	31.6	27.3	25.5	2.18	7.99
17.9	10	18.4	18.1	21.6	16.8	21.6	17.1	10.0	3.85	22.46
15.7	15.9	16.9	17.4	16.4	17.1	17.4	16.6	15.7	0.68	4.11
34.2	41.4	31.1	36.4	43.4	43.7	43.7	38.4	31.1	5.23	13.64
35.9	36.2	34.5	35	38	33.8	38.0	35.6	33.8	1.48	4.17
13.8	14.5	14.5	16.6	15.4	13.2	16.6	14.7	13.2	1.20	8.20
27.3	30.2	-	28.6	26.6	-	30.2	28.2	26.6	1.58	5.62
35.6	36.5	35.5	33.9	34.6	28.5	36.5	34.1	28.5	2.89	8.46
43.6	44.4	42.7	45.8	40.9	42	45.8	43.2	40.9	1.75	4.05
27.4	24.8	27.8	25.7	-	21.8	27.8	25.5	21.8	2.40	9.43
22.1	22.3	21.6	21.5	21.9	20.8	22.3	21.7	20.8	0.53	2.46
26	25.7	26	26.8	21.4	20.8	26.8	24.5	20.8	2.63	10.75
21.2	19.4	19.2	18.1	20.7	24.0	24.0	20.4	18.1	2.07	10.13



This difficulty results from the fact that each blast had a frequency content that differed quite significantly. If the frequency component from each blast is divided into bins of a known frequency level and each blast is accumulated into each bin over the all of the blasts in this experiment a more meaningful description of the frequency component of the blast induced vibration can be displayed. Thus, if a graph is constructed as shown in Figure 5.5b then the relative merits of each mounting method as far as frequency is concerned can be seen. The 3 spike mounting method results stand out from all others with an excessive high amplitude peak at approximately 20 Hz. As this graph is a cumulation of all 25 blasts of the value measured for each blast it could possibly be due to one excessively large vibration level for one blast. The concrete block mounting method levels are higher than the “standard” mounting technique values but the general shape of the graph is similar and could be influenced by the odd high or low level recorded. All other graphs have a similar structure but lower values than the “standard” mounting technique with the sandbag mounting method showing a distorted shape compared to the “standard” mounting technique.

A comparison of some of the waveforms captured from one of the low vibration levels recorded and one of the high vibration levels recorded is shown in Appendix 2. The component waveform and the vector sum of these components is shown for each mounting device tested.

### **5.3.2 Vibration Vector Peak Particle Velocity <100 mm/s**

This VPPV data is summarised in Table 5.3 (page 145). In this group all blasts with vibration levels greater than 100 mm/s (“standard” mounting technique) were removed. There were 21 blasts monitored and the highest vibration level measured (“standard” technique) was 76.5 mm/s. A plot of all mounting methods compared to the “standard” technique is shown in Figure 5.6a. The equation for each line of best fit and the regression coefficient is also shown on the plot. As shown by the slope of the line, the mounting methods differ by 1.01 to 0.81 from the “standard” mounting technique. The data values are more evenly spread within the data range and a more indicative comparison is obtained. These results do not appear to be skewed one way or the other owing to the even spread of the “standard” mounting technique data in this data range.

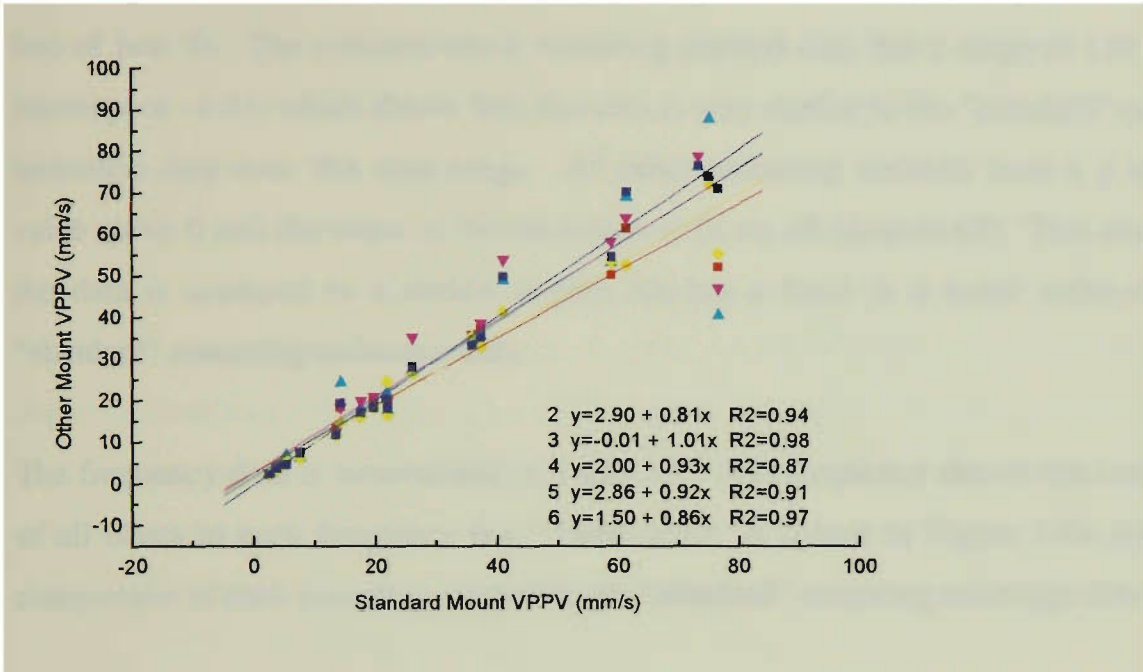


Figure 5.6a Plot of VPPV for all mounts compared to standard mount.  
Data less than 100 mm/s

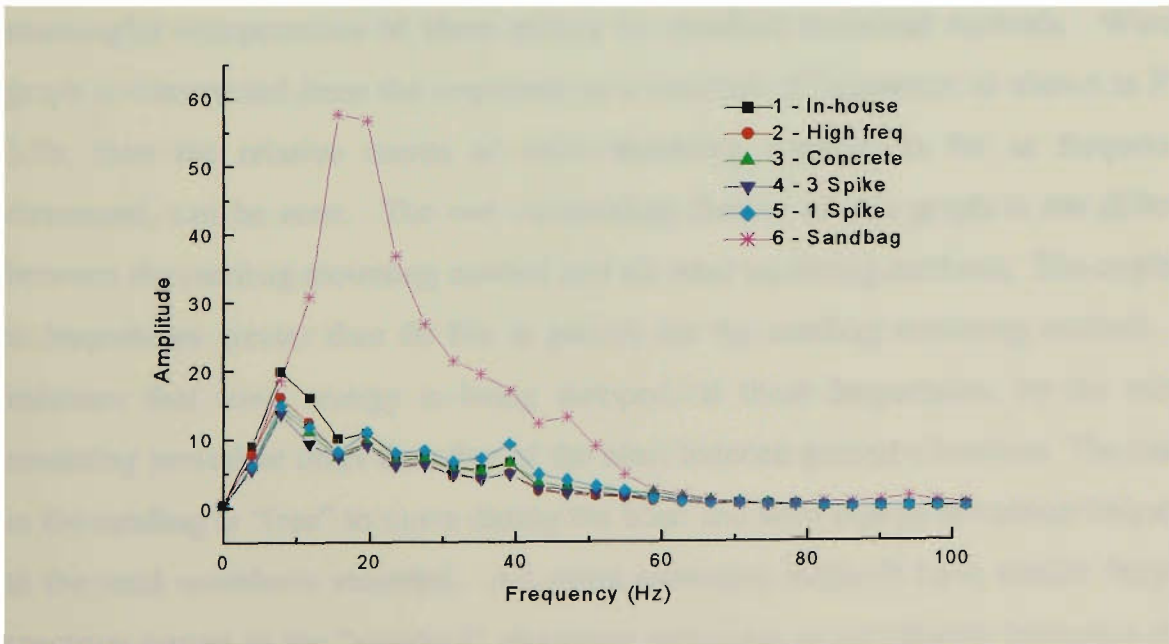


Figure 5.6b Frequency plot of all mounting blocks.  
Data less than 100 mm/s

The comparative vibration results are shown in Figure 5.6a along with the equations of the lines of best fit and the linear regression coefficient. As can be seen the linear regression coefficient deviates from 1 indicating the data is more dispersed about the line of best fit. The concrete block mounting method data has a slope of 1.01 and an intercept of  $-0.01$ , which shows that this data is very similar to the “standard” mounting technique data over this data range. All other mounting methods have a y intercept value about 0 and the slope of the lines of best fit are all close to 0.9. This shows that the data is scattered to a certain degree but has a trend to a lower value than the “standard” mounting technique data.

The frequency data is summarised in Table 5.4. This frequency data is the cumulation of all blasts in each frequency bin. These plots, as shown in Figure 5.6b, indicate a comparison of each mounting method to the “standard” mounting technique data.

The predominant frequency values are shown in Table 5.4. Again, if similar analysis as that carried out in Section 5.2 is used an ambiguous interpretation results. There is a marked difference between the mounting methods as shown by the CoV. The coefficient of variation (CoV) ranges from 1.45% to 22.46%. Thus it is difficult to get a meaningful interpretation of these results by standard statistical methods. When the graph is constructed from the amplitude as a function of frequency, as shown in Figure 5.6b, then the relative merits of each mounting method, as far as frequency is concerned, can be seen. The one outstanding feature of this graph is the difference between the sandbag mounting method and all other mounting methods. The amplitude, at frequencies greater than 60 Hz, is greater for the sandbag mounting method. This indicates that some energy is being dumped, at these frequencies, by the sandbag mounting procedure other than that of the blast induced ground vibrations. The material in the sandbag is “free” to move during the blast and adds energy at various frequencies to the total waveform recorded. All other mounting methods have similar frequency spectrum curves to the “standard” mounting technique so no adverse frequency effects have shown up in this data range for these mounting methods.

### 5.3.3 Vibration Vector Peak Particle Velocity <50 mm/s

In this group all blasts with vibration levels greater than 50 mm/s (“standard” mounting technique) were removed. The VPPV data is summarised in Table 5.3. There were 16 blasts monitored in this group and the highest vibration level measured (“standard” technique) was 40.9 mm/s. A plot of all mounting methods compared to the “standard” technique is shown in Figure 5.7a. The equation for each line of best fit and the regression coefficient is also shown on the plot. As shown by the slope of the line, the mounting methods vary from 1.16 to 0.97 from the “standard” mounting technique. The data values are more evenly spread within the data range and a more indicative comparison is obtained. These results do not appear to be skewed one way or the other due to the even spread of the “standard” mounting technique data in this data range.

The comparative vibration results are shown in Figure 5.7a along with the equations of the line of best fit and the linear regression coefficient. As can be seen the linear regression coefficient deviates from 1 indicating the data is dispersed about the line of best fit. This linear regression coefficient varied from 0.94 to 0.99, which shows that there is good linear agreement between the individual mounting methods and the “standard” mounting technique. The concrete block mounting method data has a slope of 1.05 and an intercept of  $-0.62$ , which shows that this data is very similar to the “standard” mounting technique data over this data range. All other mounting methods have a y intercept value close to 0 (all less than the absolute value of 1 away from 0) but the slopes of the lines of best fit varied from 0.97 to 1.16. The 1 spike mounting method (slope of 1.16) displayed the maximum difference from the “standard” mounting technique, which indicated that the 1 spike values would tend to be higher than the “standard” mounting technique. Again there is scatter in the data as shown by the regression coefficients but the scatter has diminished considerably.

The frequency data is summarised in Table 5.4. This frequency data is the cumulation of all blasts in each frequency bin. These plots as shown in Figure 5.7b indicate a comparison of each mounting method to the “standard” mounting technique data.

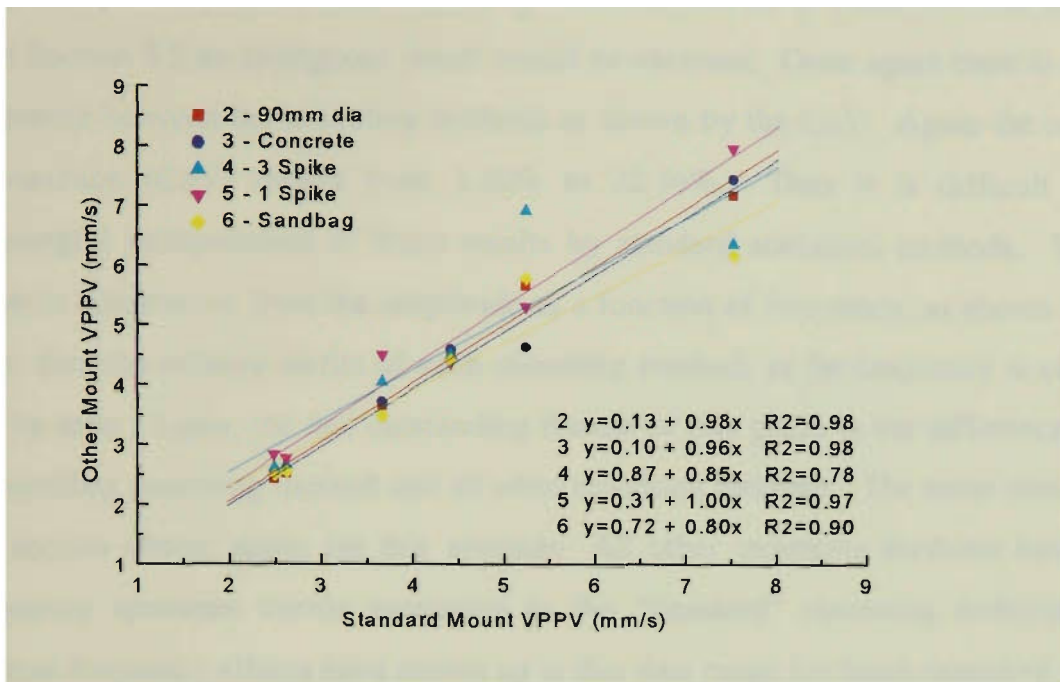


Figure 5.7a Plot of VPPV for all mounts compared to standard mount.  
Data less than 50 mm/s

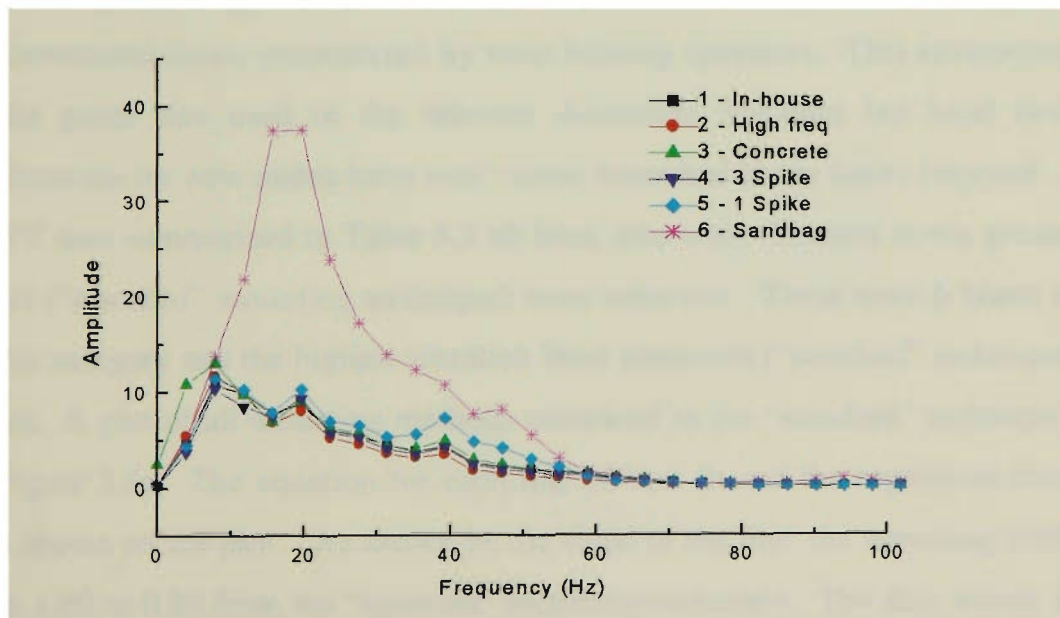


Figure 5.7b Frequency plot of all mounting blocks.  
Data less than 50 mm/s

If the analysis of predominant frequency values as shown in Table 5.4 was carried out as in Section 5.2 an ambiguous result would be obtained. Once again there is a marked difference between the mounting methods as shown by the CoV. Again the coefficient of variation (CoV) ranges from 1.45% to 22.46%. Thus it is difficult to get a meaningful interpretation of these results by standard statistical methods. When the graph is constructed from the amplitude as a function of frequency, as shown in Figure 5.7b, then the relative merits of each mounting method, as far frequency is concerned, can be seen. Again, the one outstanding feature of this graph is the difference between the sandbag mounting method and all other mounting methods. The same reasons, as in the section above, apply for this anomaly. All other mounting methods have similar frequency spectrum curves compared to the “standard” mounting technique so no adverse frequency effects have shown up in this data range for these mounting methods.

#### **5.3.4 Vibration Vector Peak Particle Velocity <10 mm/s**

This category is probably the most important as this is the range of typical environmental limits encountered by most blasting operators. This environmental limit is the guide line used in the relevant Australian Standard but local development applications for new mines have over recent times had lower limits imposed. From the VPPV data summarised in Table 5.3 all blast data with vibration levels greater than 10 mm/s (“standard” mounting technique) were removed. There were 6 blasts monitored in this category and the highest vibration level measured (“standard” technique) was 7.5 mm/s. A plot of all mounting methods compared to the “standard” technique is shown in Figure 5.8a. The equation for each line of best fit and the regression coefficient is also shown on the plot. As shown by the slope of the line, the mounting methods vary from 1.00 to 0.80 from the “standard” mounting technique. The data values are evenly spread within the data range.

The comparative vibration results are shown in Figure 5.8a along with the equations of the lines of best fit and the linear regression coefficient. As can be seen the linear regression coefficients deviate considerably from 1 (0.98 for the high frequency and concrete mounting methods to 0.78 for the 3 spike mounting method).

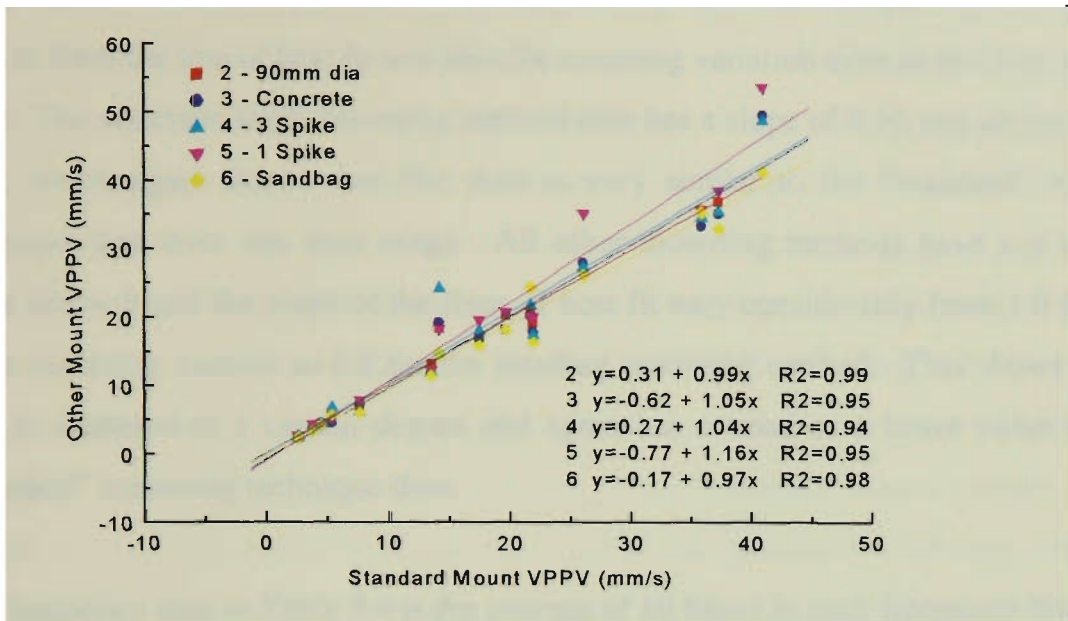


Figure 5.8a Plot of VPPV for all mounts compared to standard mount.  
Data less than 10 mm/s

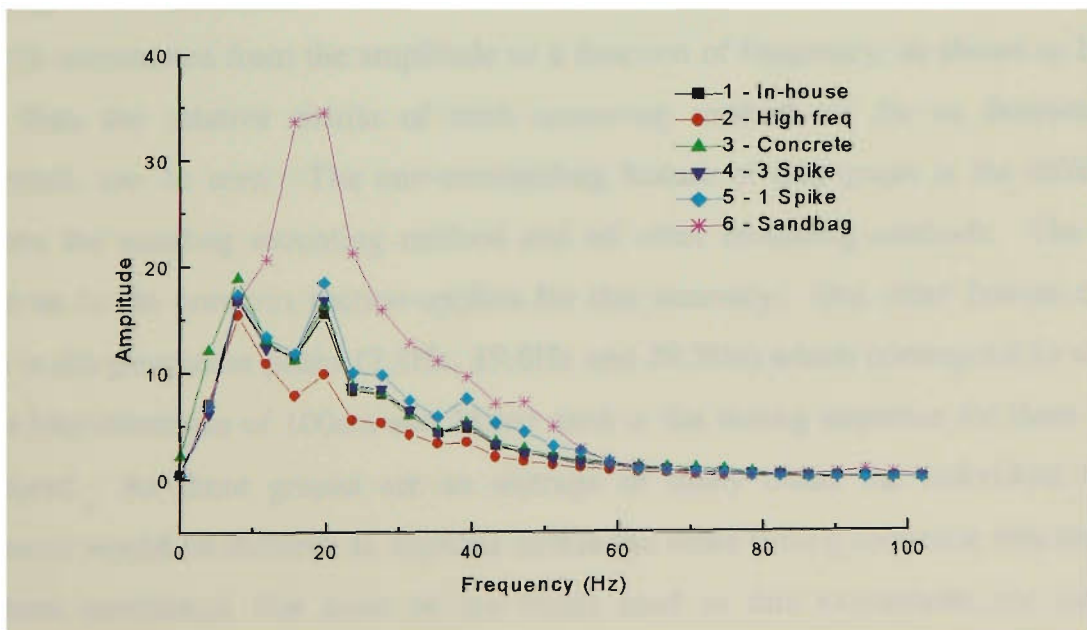


Figure 5.8b Frequency plot of all mounting blocks.  
Data less than 10 mm/s

This variable nature of the data is possibly due to the small number (6) of data points used to form the line of best fit and also the coupling variation even at this low vibration level. The concrete block mounting method data has a slope of 0.96 and an intercept of 0.10, which again shows that this data is very similar to the “standard” mounting technique data over this data range. All other mounting methods have a y intercept value above 0 and the slope of the lines of best fit vary considerably from 1.0 for the 1 spike mounting method to 0.8 for the sandbag mounting method. This shows that the data is scattered to a certain degree and again has a trend to a lower value than the “standard” mounting technique data.

The frequency data in Table 5.4 is the average of all blasts in each frequency bin. These plots as shown in Figure 5.8b indicate a comparison of each mounting method to the “standard” mounting technique data. If an analysis as that described in Section 5.2 was used an ambiguous interpretation of the data would result. Once again Table 4 shows a marked difference between the mounting methods as indicated by the CoV. The coefficient of variation (CoV) ranges from 5.45% to 19.88%. Thus it is difficult to get a meaningful interpretation of these results by standard statistical methods. When the graph is constructed from the amplitude as a function of frequency, as shown in Figure 5.8b, then the relative merits of each mounting method, as far as frequency is concerned, can be seen. The one outstanding feature of this graph is the difference between the sandbag mounting method and all other mounting methods. The same reason as in the previous section applies for this anomaly. One other feature of this graph is the prominent peaks (7.8Hz, 19.6Hz and 39.2Hz) which correspond to surface delays (combinations of 100ms and 25ms) used in the timing sequence for these blasts monitored. As these graphs are an average of many blasts the individual timing sequences would be difficult to separate unless the same timing sequence was used for all blasts monitored. For most of the blasts used in this experiment the standard initiation sequence was a combination of 100 ms, 42 ms and 25 ms. The choice of the delay sequence depended on the geometry of the blast pattern and the location of free faces. All other mounting methods have similar frequency spectrum curves to the “standard” mounting technique so no adverse frequency effects have shown up in this data range for these mounting methods.



This section detailed the comparison of the “standard” technique with some other common mounting methods and the effects and errors at different vibration levels. Armstrong and Sen (1999) have summarised some of this work in their paper. The conclusions from this work were that there are differences between the “standard” mounting technique and the other mounting methods and errors of up to 33% could be attributed to bad coupling of the primary sensor to the ground. In this thesis a concrete block and an aluminium cylinder (typical “standard” mounting techniques) were compared and these mounting methods were within 5% of each other at various peak vibration levels. This small variation between the “standard” mount and the concrete mount was within the errors found when only the “standard” technique was tested against itself. Thus these two techniques could be used in place of each other without causing any added errors than those shown by the “standard” technique.

As the transmission of the blast induced vibration waves is a natural phenomenon through the ground, it is difficult or nearly impossible to expect two measurements even at close proximity to be the same. In this section of the work the monitoring locations were changed for each blast so there was no fixed path for the vibration wave to travel through consequently variation due to the travel path of the vibration wave would be quite high. This could also introduce more errors. Thus, two points, which have a measured value within 5%, would be considered to be the “same”.

The comparison of all mounting methods was shown to approach the “standard” mounting technique value as the vibration level was reduced. However, errors of 20% were still measured at these low vibration levels. This indicates that if it is easy to mount the primary sensor to the soil, then it is easy for the coupling to be detached and hence erroneous results will be recorded. The extra effort taken to bury the primary sensor in the ground will ensure that the measured values are those that are actually occurring in the soil from the blast and not some artefact of the mounting procedure.

The use of spiked mounts must be discouraged as these mounts might “feel” coupled to the soil upon testing, but even the slightest upward relative movement during the testing can cause decoupling of the soil to the spike leading to erroneous results. If the vertical vibration component is high, there is the possibility (under the right amplitude level and

frequency) that the bond can be broken and the primary sensor will be left “dangling in the breeze” so to speak.

The use of sandbags must also be discouraged due to the fact that the material in the sandbags is loose and under vibration loading this loose material will move independently of the vibration wave. This movement of material in the sand bag will be detected by the primary sensor hence adding energy from an outside source to the vibration waveform. So, in the final analysis what is really being measured?

#### 5.4 Influence of Mount Density.

One of the aspects of the “standard” mounting cylinder that was investigated by Blair (1995a) was the mass of the cylinder/block. Blair in his work stated that the mass factor  $b$  ( $\text{mass}/(\text{soil density} * \text{radius}^3)$ ) must be less than 1.5 to have negligible influence on the resonance frequency of the soil. This was determined from the shaker table studies, which had a finite mass of soil on the shaker table. In a half space situation the mass of the soil is infinite and hence the resonance frequency of the soil could be difficult to excite. Thus, the mass and hence the density of the mounting block/cylinder should not influence the vibration level at the monitoring point.

Warburton (1957) presented a theory of vertical vibration of structures on layers of soil under earthquake loading and discussed the mass factor, also used by Blair, for a mount (or structure) sitting on the soil surface. Blair placed masses on the primary sensor and concluded that mass factors of up to 50 would not affect the mount coupling with the soil when subject to vibration loads in the vertical plane.

The mass factor ( $b$ ) is a function of the mass of the primary sensor (primary sensor and mounting block) divided by the product of the soil density and the radius<sup>3</sup> of the base (mounting block) resting on the soil. If the mass factor is applied to this work the following parameters apply.

a) Primary sensor mass	0.75 kg
b) Mass of mount	2.0 – 14.0 kg
c) Radius of mount	0.065 m
d) Soil density	1500 kg/m <sup>3</sup>

e) Mass factor range                    10.0 – 53.7

But this theory was applied to structures (tall buildings in earthquake prone areas) sitting on the surface of layers of soil of finite thickness. So if the primary sensor bonded to the soil by embedding in the soil then limits of the mass factor must be increased to account for the embedment of the block/cylinder and the increased coupling of the soil to the mount block/cylinder. This hypothesis was tested by trialing a series of mounting blocks with different densities and the same geometric dimensions with the same vibration load applied to each system.

The density of the mount (aluminium block with the primary sensor attached to the top) was thought to affect the transmission of the vibration wave through the mount, similarly it was thought that large monolithic rocks would behave the same way and consequently differential movement could be experienced. After all if a mount of infinite mass were bonded to the soil then it would be expected to transmit very low levels as the vibrational energy would be insufficient to overcome the inertia of the infinite mass mount. Does the density of the mounting block, in a practical sense, have any effect on the vibration level measured?

The “standard” technique was tested along side five other modified “standard” mounting blocks. A series of six vibration-monitoring systems all with identical accelerometers, connectors and data loggers were used to minimise any equipment variations. The only difference for each of the six systems was the density of the mounting block that was bonded to the soil. A range of vibration levels was required to measure the variation that could be expected. So for each blast monitored a total of 6 values would be recorded and the variation within these 6 values would indicate if any trends as a function of the mounting block/cylinder density existed. Each of these mounting methods is shown in Figure 5.9 and a photograph of the experimental set up is shown in Figure 5.10

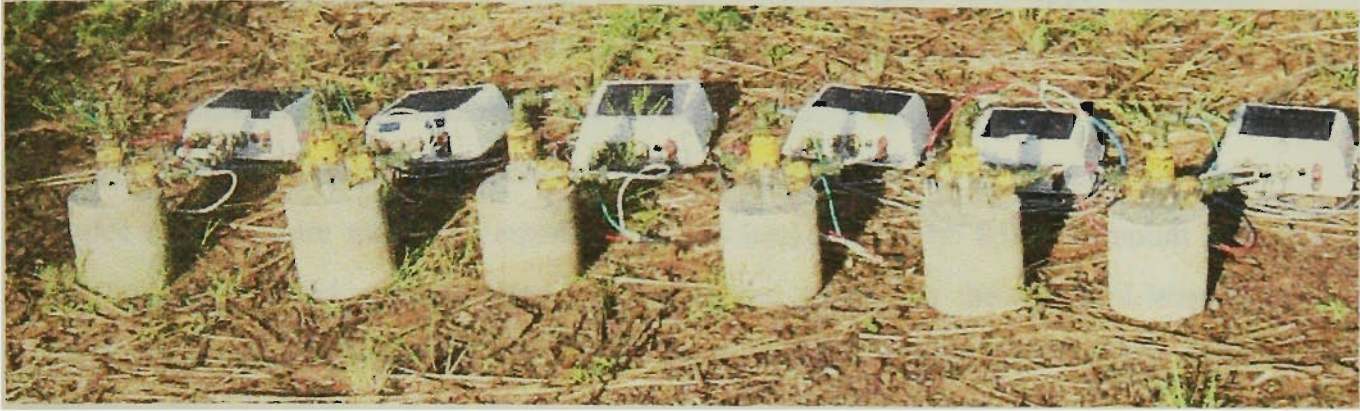


Figure 5.9 The variable density mounting methods used in the trials.



Figure 5.10 The variable density mount field set up.

Mounting blocks having the same geometric dimensions as the “standard” mount were made up using cement, sand, polystyrene, steel and lead shot. The densities chosen were 1.0 g/cc, 1.7 g/cc, 2.6 g/cc, 4.0 g/cc, 5.0 g/cc and 8.0 g/cc. The upper and lower limit were arbitrarily chosen so that the range would cover expected soil density values in typical monitoring exercise usually carried out by mining operators. The 1.0 g/cc and the 1.7 g/cc mounts were made of cement, sand and polystyrene. The 2.6 g/cc, 4.0 g/cc, 5.0 g/cc mounts were made of cement, sand and lead shot. The 8.0 g/cc mount was made of steel. These mounts were coupled to the ground in the standard way by excavating a trench, placing the mounts in the trench and back filling the dirt while tamping. The top of the mount was level with the ground so no vertical swaying of the mount could occur. A small aluminium disk was bonded (with Plastibond) to the top of each mount so that the primary sensor could be bolted to the mount. This set up was to be a semi-permanent arrangement and a place at the edge of the mining lease away from all mining operations was chosen.

The main reason behind this phase of the study was to investigate the thought that varying densities could cause differential movement between, for example, adjacent rock particles. Of course as is the case throughout this study the practical aspects of vibration monitoring is the driving force behind all of this work. It was felt that the range of densities of the vibration mounts covered what was considered to be a range of soil densities and competent rock particle densities encountered in most mine vibration monitoring situations.

The blasting operations at the mine had started in a new strip area and the direction of mining was planned to be consistent for approximately 12 months. This type of operation was considered to be ideal as a consistent path to the vibration monitoring point would minimise any complications of the vibration waveform due to directional changes. The blasting operations were also planned to have a variety of charge weights as the depth of mining from the surface increased. Thus the vibration levels would vary due to both the variation in charge weight and also the change in distance from the monitoring location. These monitoring conditions and the variations that were expected were ideal for this part of the study and the monitoring location was selected so that vibration levels were mainly in the “environmental range” as far as residential buildings were concerned.

This location was also ideal in that the mounts would not be moved between blasts thus eliminating the possible errors in coupling variation that might occur during bonding the mounting blocks to the soil. One of the sources of errors when comparing the mounting blocks even if the blocks are exactly the same physical characteristics is the bonding of the soil to the mounting blocks. Each time the block is bonded to the soil there is a chance, small though it may be, that the coupling will not be the same for all the mounts used in this experiment. Coupling errors were eliminated by placing the six different density mounts at the same location for each and every blast in this section of the study. The mounts were inspected before each blast and after a period of about one month it was noted that the soil immediately around the mounting blocks had similar physical characteristics (appearance and structure) to that of the soil at some distance from the blocks. Weather conditions had made the compacted soil more consistent with its immediate environment.

A range of vibration levels was required and as this location was at a permanent point at the boundary of the mine where low vibration levels were expected. The closest residence was approximately 300 metres from the monitoring point and the vibration level at this residence had to be maintained less than 5 mm/s. The vibration levels measured ranged from (average values) 0.4 mm/s to 16.4 mm/s with the majority of the measurements less than 10 mm/s. A total of 29 blasts were monitored in this section of the work.

A summary of the raw data from this investigation is shown in Table 5.5 (velocity data) and Table 5.6 (frequency data) for all 29 blasts monitored. Only the vector peak particle velocity (VPPV) and the predominant frequency are shown for each unit for each blast. A statistical analysis is also shown to gauge the variation within each blast that was recorded in the field during the vibration monitoring carried out under well controlled conditions.

As shown in Table 5.5 a wide range of vibration levels were recorded. For all but 1 blast (from a total of 29 blasts monitored) records from the six density mounts were obtained. Electrical faults in the connecting cables were attributed to this loss of data. However, it is the variation within each group that is the issue in this section.

Table 5.5 Summary of VPPV vibration data for density mounting trials.

1.0 g/cc	1.7 g/cc	2.6 g/cc	4.0 g/cc	5.0 g/cc	8.0 g/cc	Max.	Average	Min.	Std. Dev.	CoV
0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.3	0.3	0.04	12.89
0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.4	0.4	0.04	9.80
0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.04	8.45
0.6	0.6	0.5	0.6	0.5	0.5	0.6	0.6	0.5	0.05	9.96
0.6	0.6	0.7	0.7	0.6	0.7	0.7	0.7	0.6	0.05	8.43
0.7	0.7	0.6	0.6	0.7	0.6	0.7	0.7	0.6	0.05	8.43
0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.00	0.00
0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.00	0.00
0.9	0.9	0.8	0.9	0.9	0.9	0.9	0.9	0.8	0.04	4.62
1.2	1.1	1.1	1.1	1.1	1.2	1.2	1.1	1.1	0.05	4.56
1.6	1.5	1.4	1.5	1.4	1.4	1.6	1.5	1.4	0.08	5.57
1.5	1.6	1.5	1.5	1.5	1.6	1.6	1.5	1.5	0.05	3.37
1.4	1.7	1.8	1.7	1.8	1.6	1.8	1.7	1.4	0.15	9.03
1.8	1.9	1.8	1.7	1.8	-	1.9	1.8	1.7	0.07	3.93
1.9	1.8	1.8	1.8	1.9	1.8	1.9	1.8	1.8	0.05	2.82
1.7	2.2	2.0	2.0	2.0	2.0	2.2	2.0	1.7	0.16	8.08
2.1	2.0	2.1	2.1	2.2	2.3	2.3	2.1	2.0	0.09	4.36
3.3	3.1	3.1	3.2	3.0	3.0	3.3	3.1	3.0	0.12	3.75
3.5	3.5	3.5	3.2	3.4	3.4	3.5	3.4	3.2	0.12	3.42
3.5	4.0	3.9	3.9	3.9	3.9	4.0	3.9	3.5	0.18	4.57
4.6	4.0	3.8	4.0	4.0	4.3	4.6	4.1	3.8	0.29	6.94
4.1	4.6	4.4	4.3	4.4	4.6	4.6	4.4	4.1	0.19	4.31
5.5	6.1	5.9	5.9	5.9	5.9	6.1	5.9	5.5	0.17	2.95
7.0	7.6	7.4	7.4	7.3	7.2	7.6	7.3	7.0	0.19	2.59
9.3	9.7	10.0	10.5	10.4	10.2	10.5	10.0	9.3	0.45	4.53
10.5	9.7	9.4	9.6	10.5	10.5	10.5	10.0	9.4	0.52	5.20
9.8	10.1	11.1	10.1	9.7	10.1	11.1	10.2	9.7	0.50	4.90
12.4	12.7	12.7	12.7	13.3	12.7	13.3	12.7	12.4	0.33	2.56
16.2	16.4	16.1	17.2	17.4	17.2	17.4	16.8	16.1	0.58	3.45
									Max.	12.9
									Average	5.3
									Min.	0.0
									Std. Dev.	3.02

Table 5.6 Summary of frequency vibration data from density mounting trials.

Individual monitor measurements						Statistical data				
1.0 g/cc	1.7 g/cc	2.6 g/cc	4.0 g/cc	5.0 g/cc	8.0 g/cc	Max.	Average	Min.	Std. Dev.	CoV
14.8	14.1	14.4	14.6	14.4	14.5	14.8	14.5	14.1	0.23	1.62
22.2	21.4	21.8	21.9	21.7	22.1	22.2	21.9	21.4	0.29	1.32
7.8	7.8	7.5	7.7	7.9	7.8	7.9	7.8	7.5	0.14	1.78
20.1	19.0	19.7	19.5	19.9	20.4	20.4	19.8	19.0	0.49	2.47
7.1	6.4	6.9	7.0	6.5	6.9	7.1	6.8	6.4	0.28	4.16
20.5	20.8	20.0	20.9	19.3	19.2	20.9	20.1	19.2	0.74	3.69
16.3	15.8	15.6	15.8	15.9	15.9	16.3	15.9	15.6	0.23	1.46
19.9	20.0	19.6	20.2	20.6	21.0	21.0	20.2	19.6	0.51	2.51
19.6	19.2	19.4	19.2	19.2	19.3	19.6	19.3	19.2	0.16	0.83
19.7	18.4	18.4	18.3	19.3	19.4	19.7	18.9	18.3	0.62	3.27
12.9	12.6	12.6	12.5	12.2	12.7	12.9	12.6	12.2	0.23	1.84
20.0	19.8	20.0	20.0	20.0	20.0	20.0	20.0	19.8	0.08	0.41
18.4	19.2	19.2	19.0	19.0	19.1	19.2	19.0	18.4	0.30	1.58
18.9	18.9	19.2	19.0	19.0	-	19.2	19.0	18.9	0.12	0.64
20.3	20.0	19.8	20.0	20.0	20.0	20.3	20.0	19.8	0.16	0.80
19.4	19.5	19.6	19.5	19.6	19.6	19.6	19.5	19.4	0.08	0.42
22.0	21.5	21.7	21.8	22.0	22.2	22.2	21.9	21.5	0.25	1.14
18.2	17.9	18.1	18.0	18.1	18.0	18.2	18.1	17.9	0.10	0.58
18.3	18.1	17.5	18.1	17.8	17.8	18.3	17.9	17.5	0.29	1.60
16.5	16.1	16.1	16.2	16.4	17.4	17.4	16.5	16.1	0.49	3.00
20.2	20.1	19.7	19.9	19.9	20.1	20.2	20.0	19.7	0.18	0.92
18.0	17.7	17.4	18.0	17.6	17.5	18.0	17.7	17.4	0.25	1.43
9.3	9.3	9.1	9.2	9.2	9.3	9.3	9.2	9.1	0.08	0.88
9.1	9.1	8.6	9.0	9.1	9.1	9.1	9.0	8.6	0.20	2.22
11.7	11.7	11.5	11.7	11.7	11.7	11.7	11.7	11.5	0.08	0.70
7.5	7.0	7.9	7.0	7.6	7.8	7.9	7.5	7.0	0.39	5.20
15.1	14.7	14.7	14.7	15.0	15.7	15.7	15.0	14.7	0.39	2.62
11.0	10.7	10.7	10.8	10.8	10.8	11.0	10.8	10.7	0.11	1.01
7.9	8.0	7.8	7.3	7.6	7.2	8.0	7.6	7.2	0.33	4.28
									Max.	5.2
									Average	1.9
									Min.	0.4
									Std. Dev.	1.27



How is the vibration levels affected by changing the density of the material of the block/cylinder? As the block is rigid there is no differential movement between the primary sensor and the block on any of the six mounting systems used in this section of the study.

Several measures of the “spread” of the data, ie. the standard deviation and the range, were considered and both of these parameters indicate the “spread” about the mean of the measured data. However, both of these statistics are affected by the absolute value of the measurements and the higher the measurement the larger will be the standard deviation and the range. So it is difficult to compare the spread of each set of measurements against another. However, the coefficient of variation (CoV) is a function of the mean and the standard deviation which themselves have the same units. The CoV is dimensionless and thus is not affected by absolute measured values from each set.

As shown in Table 5.5 the CoV ranges from 0% to a maximum of 12.9% with an average of 5.3%. This indicates a reasonably tight distribution showing that all the CoV values are reasonably similar. CoV values less than 10% are considered to be similarly distributed and the CoV is a means of comparing different but similar samples. Samples where the CoV is greater than 5% occur where the values are less than 5mm/s, which could be expected since small deviations in the value measured can cause large deviations in the CoV statistic computed (ie. 0.1 deviation in 5 is equivalent to 2%).

From a practical stand point and from the data presented here it can be expected that the density of the mount does not have a significant effect on the variation of the vibration levels measured. There was not any trend with density highlighted from this work which shows that provided the mount is made of the one material, a density similar to the density of the soil would provide the least interference. Some standards have included a density stipulation to minimise an errors due to this density difference.

The frequency measured by the primary sensor is a function of how the explosive charges (ie. each blasthole) were initiated in the blast pattern sequence and the physical properties of the ground through which the vibration wave travels. The frequency of the

vibration wave can be “channelled” into specific frequency bands by proper design of the initiation sequence. However it has been found (recent work by author) that this frequency channelling has more to do with the vibration transmission through the ground or rock type than the initiation sequence used. The vibration frequency can be controlled to a certain extent by the timing sequence used in the blast initiation and monitoring at sensitive location can give some indication of the frequency that is transmitted by the ground at that location. The frequency is a measure of the number of times a charge is detonated which can be highlighted in the spectral trace or the “speed” at which the energy is transmitted from particle to particle. Certain frequencies can be detrimental to structures (man made and natural) and these frequencies can be determined by attaching primary sensor to these structures that will experience the blast induced vibrations.

As shown in Table 5.6 a range of predominant frequencies from 7.5 Hz to 21.9 Hz was calculated. When the same statistical analysis as used in the vibration level analysis is applied similar results occur. The average CoV is lower at 1.9% (5.3% for vibration level) while the mean standard deviation is 1.27 (3.02 for vibration level).

From these results it can be concluded the density of the block/cylinder does not have any adverse effect on the transmission of the vibration wave through the block. If the density of the mounting block is similar to the soil density less “stress” would be placed on the soil to block coupling bond. Thus there would be less unwanted movement and a more faithful representation of the vibration wave would be recorded.

A comparison of some of the waveforms captured from one of the low vibration levels recorded and one of the high vibration levels recorded is shown in Appendix 3. The component waveform and the vector sum of these components is shown for each density mounting block used in this trial.

## **5.5 Waveform Frequency**

When an explosive charge (point source or column source) is detonated an impulse force is set up and is radiated in all directions from the point or column source. The impulse force acts on particles of the confining medium and produces a shock wave

which propagates through the medium. This shock wave propagates in all directions and produces a variety of wave types depending on the medium and its structure. The wave movement is accomplished by adjacent particles vibrating in simple harmonic motion about their equilibrium position and transmitting motion to neighbouring particles. Of course this is a simplistic view of wave propagation in elastic medium as the elastic medium is by no means homogenous in all of its properties. Intact rock structure itself can vary and this can cause resistance to rock particle movement as does in-situ rock structure. Planes of weakness and cracks can cause hurdles for the vibration wave to overcome and hence cause local energy losses which all adds (or subtracts from) to the vibration waveform recorded at a particular monitoring point.

Even though the rock structure is considered an elastic medium (ie. moving particles return to an equilibrium point) the transmission of the vibration wave through the ground attenuates with time and distance from the explosive source. As will be shown in a later section an empirical method is available to measure this vibration level attenuation as a function of charge weight and distance from the explosive source (see section 5.6.4). However, it is not only the vibration level that is important at a particular monitoring location but also the frequency of the vibration at the monitoring point which can cause some serious problems. For example a local coal mine was blasting close to a main road bridge over a creek. Monitors were placed on the bridge (in the centre of the span), on the bridge footings and on the ground a short distance from the bridge footings. The analysis of the vibration waveform showed that the bridge had a natural frequency of approximately 4 Hz. It is imperative that the design of the blast initiation sequence be such that this frequency 4 Hz (or 250 milliseconds) be avoided if the resonance frequency of the bridge was not to be excited.

The frequency of the waveform is governed by a number of rock properties but also the design of the blast initiation sequence will have a major effect on the frequency of the vibration waveform measured at a particular location. All vibration monitoring equipment record the vibration waveform as a transient signal in the time domain (ie. each sample point is taken at a particular point in time). This transient signal in the time domain can be converted to a signal in the frequency domain by the Fourier integral where the time function is expressed as a function of angular frequency  $F(\omega)$ :

$$f(t) = (1/2\pi) * \int F(\omega)e^{i\omega t} d\omega \quad (5.1)$$

So from this integral the time function of the vibration waveform recorded by the vibration monitoring equipment can be transformed to a function in the frequency domain. The frequency waveform can show where any major concerns could arise such as frequency at major amplitude spikes, the shape of the frequency trace and the energy distributed within frequency bands.

A series of single holes were detonated in a trial at a greenfield site to gather some information about the vibration frequency expected at sensitive locations on this site. Six vibration monitors were set up for each test hole and a detailed analysis of the effect of the vibration waveform on the ground was conducted. A vibration prediction program was used to estimate the vibration wave frequency that was to be expected at a particular location. An example of the single test hole signature vibration waveform close to the holes (21 metres away) is shown in Figure 5.11 (red waveform) and for the same hole but further away (206 metres) shown also in Figure 5.11 (green waveform).

The blast hole was 89 mm in diameter, drilled to a depth of 13 m and loaded with 76 kg of explosives. Approximately 4 m of crushed rock was used as stemming material to lock in the explosive forces. As shown in Figure 5.11 the time domain waveform (signature wavelet) close to the blast (red waveform) is a short quick pulse and the entire waveform is over in less than 100 milliseconds. Whereas the signature wavelet for the same single hole at a distance of 206 m was completely different in that the waveform was spread out and it took some 700 milliseconds for the waveform to completely die down. The frequency for the waveform at the closest monitoring point (the red waveform in Figure 5.11) was 36.5 Hz compared to 19.4 Hz for the waveform at a distance of 206 m from the single test hole (green waveform in Figure 5.11).

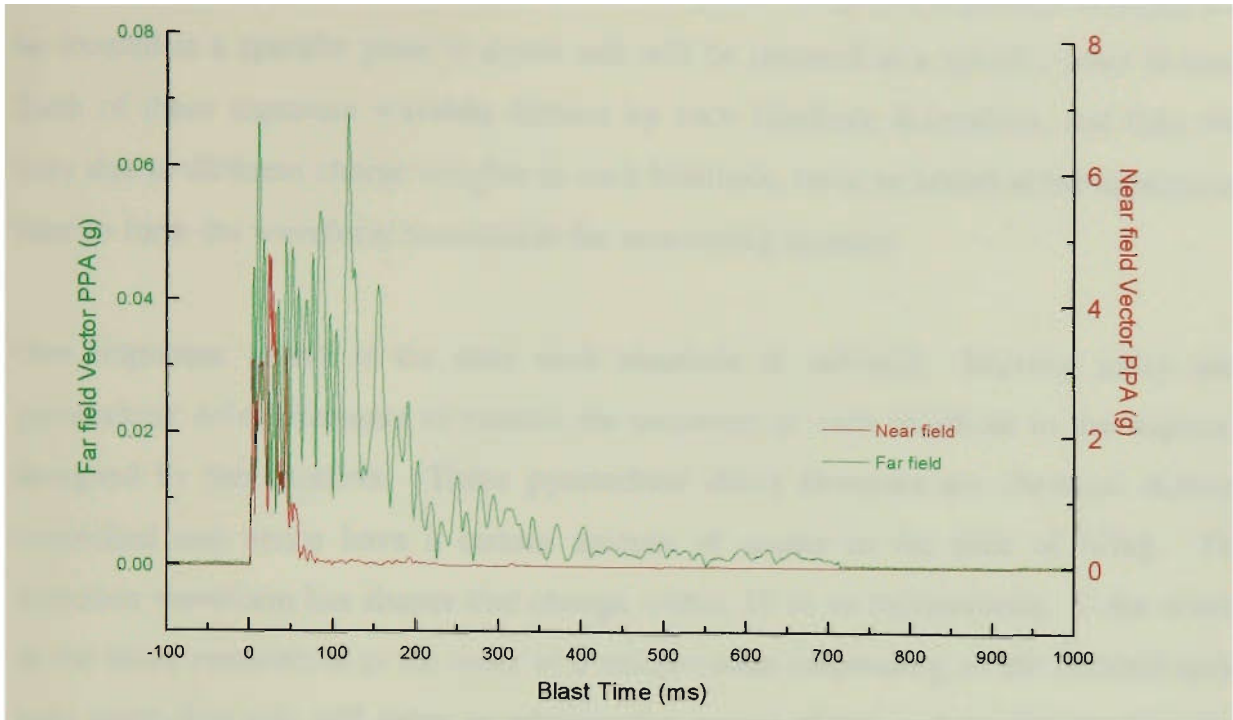


Figure 5.11 Signature vibration waveforms at various distances

White (1983) stated even though a great deal of work has been done on attenuation and dispersion of seismic waves there is no consensus as to the dominant mechanism. White discussed some of the mechanisms that have been proposed but all have their limitations. Sliding friction contributes above a certain limit but below this limit are observed frequency independent values. Fluids filling voids, cracks have shown attenuation to vary as the square of frequency but the magnitude of attenuation depends on crack geometry and computed attenuation values were entirely negligible at frequencies  $<1$  kHz.

Blair (1996) tested large blocks with hydrophones at different locations with two sonic sources, one on each side of the block, to measure the attenuation of the input wave. Blair (1996) concluded that geometric spreading, at these high input frequencies, was frequency independent and elastic scattering and intrinsic attenuation were the major causes of input wave attenuation. Thus any changes in frequency measured at different locations can be attributed to either the scattering of the wave by the in-situ rock during its journey to the monitoring point and the intrinsic attenuation of the rock material.

However, the signature wavelet for a single hole is not the waveform that is experienced at a monitoring point for a typical blast. A blast pattern consists of a collection of single

blastholes. Each blasthole will have its own depth or height of explosive column, will be located at a specific point in space and will be initiated at a specific point in time. Each of these signature wavelets formed by each blasthole detonation, and they will vary due to different charge weights in each blasthole, must be added at the appropriate time to form the waveform recorded at the monitoring location.

One important aspect is the time each blasthole is initiated. Blasting today uses pyrotechnic delay elements to control the initiation of each blasthole in the sequence designed by the shotfirer. These pyrotechnic delay elements are chemical reaction controlled and hence have a certain amount of scatter in the time of firing. The vibration waveform has shapes that change within 10 or so milliseconds. If the scatter in the delay elements is in the order of 2 milliseconds (depending on the nominal delay time used) then this will delay or advance the arrival of this and subsequent signature wavelet at the monitoring location. When all of these signature wavelets are added together the vibration waveform at the monitoring location would be the result. An example is shown in Figure 5.12 of predicted waveforms at a monitoring location, where the time scatter of the delay elements is taken into account, of two different firing sequences for the same blast pattern.

A monitoring exercise was carried out using single blastholes in a sandstone quarry. Multiple holes and multiple monitors were used to capture waveforms at various locations and various charge weights. The single test holes were all drilled in sandstone and the sandstone extended to within 0.5 m of the surface of the hole ie. only 0.5m of broken ground or backfill above the sandstone. All single holes were stemmed with enough material to completely contain the explosive reaction in the ground and no stemming was ejected from the holes. A range of signature wavelets were recorded as shown by two examples in Figure 5.11 and one of the signatures was chosen that best represented the location of interest (a building, a bridge etc.) at a distance from the proposed blast site. From this signature wavelet the waveforms in Figure 5.12 were constructed. The vibration level decreased as a result of geometric spreading and inherent resistance within the rock mass and rock structure, both providing some form of resistance to the transmission of the vibration level through the rock.

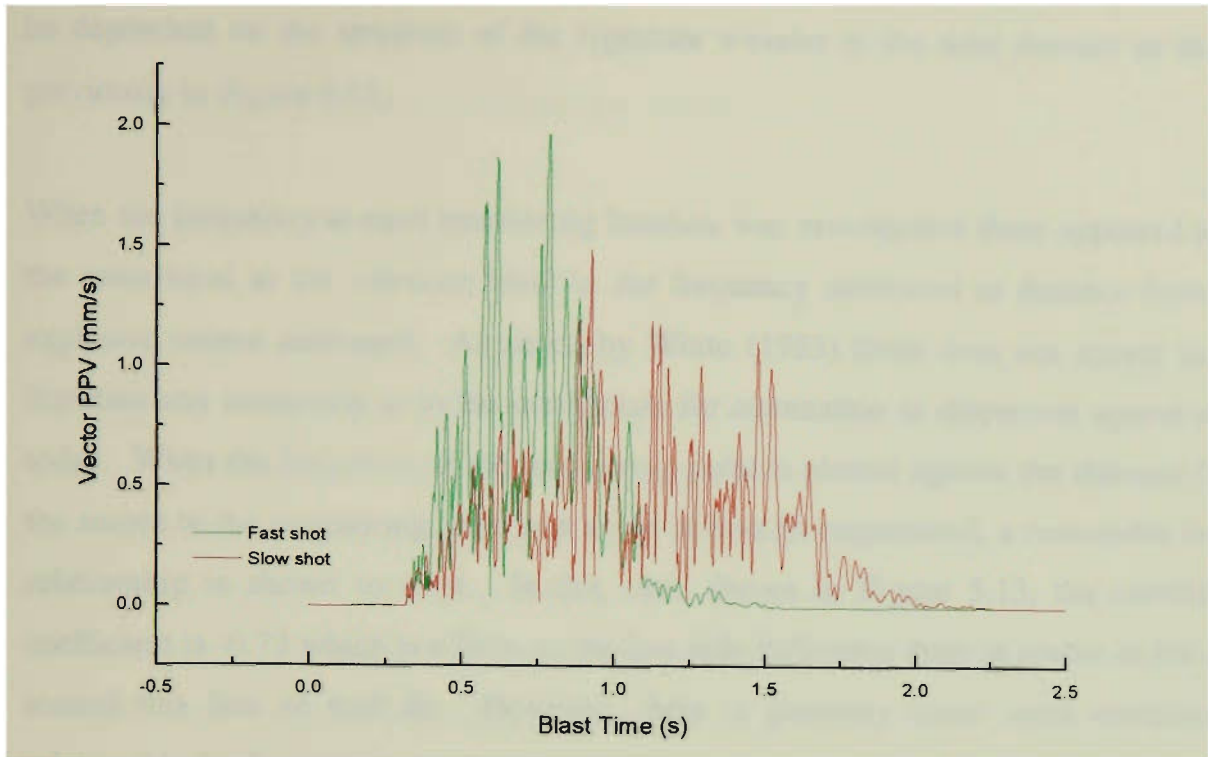


Figure 5.12 Predicted waveforms of a “slow” and a “fast” blast

However, at a particular location it is not only the vibration level but also the frequency of these vibrations that can cause some concern. High frequency vibrations of a certain level (say  $F_L$ ) are known to cause less structural damage than the same vibration level at a much lower frequency ( $F_L$ ). Siskind (1986) has shown that housing structures have a natural frequency of approximately  $<30$  Hz, which should be avoided when designing a blast that is likely to infringe upon this type of structure.

Each monitor (for each single hole) recorded a signature wavelet for the explosive that was detonated. The frequency at each monitoring location was shown to be different for the detonation of the same single hole. The vibration waveform for the fast blast in Figure 5.12 under ideal conditions, would have a frequency of 58.8 Hz (basically all holes initiated 17 milliseconds apart). However, due to scattering and intrinsic attenuation the frequency of the predicted waveform was 37.5 Hz. The slow blast had a frequency reduction from 15.8 Hz, for the ideal situation, to 14.0 Hz for the predicted waveform. This difference between the fast blast, ideal and predicted values, is much greater than the frequency difference for the slow blast. This is due to the longer time delay employed in the slow blast allowing time for each signature wavelet to dissipate and not have a significant effect on subsequent signature wavelets. However, this will

be dependent on the structure of the signature wavelet in the time domain as shown previously in Figure 5.11.

When the frequency at each monitoring location was investigated there appeared to be the same trend as the vibration level ie. the frequency decreased as distance from the explosive source increased. As stated by White (1983) there does not appear in the literature any consensus as to the mechanism for attenuation or dispersion agreed upon today. When the frequency at the monitoring point is plotted against the distance from the source to the monitoring point and a line of best fit constructed, a reasonable linear relationship is shown to exist. In this case, shown in Figure 5.13, the correlation coefficient is -0.73 which is a little on the low side indicating there is scatter in the data around this line of best fit. However, there is probably some more complicated relationship for frequency attenuation with distance as it is highly unlikely that a change in the basic structure of the vibration wave would be as simple as a linear relationship with distance. This experimental data does show that distance is an important parameter and this empirical relationship can be used to estimate the frequency change as the distance from the source varies.

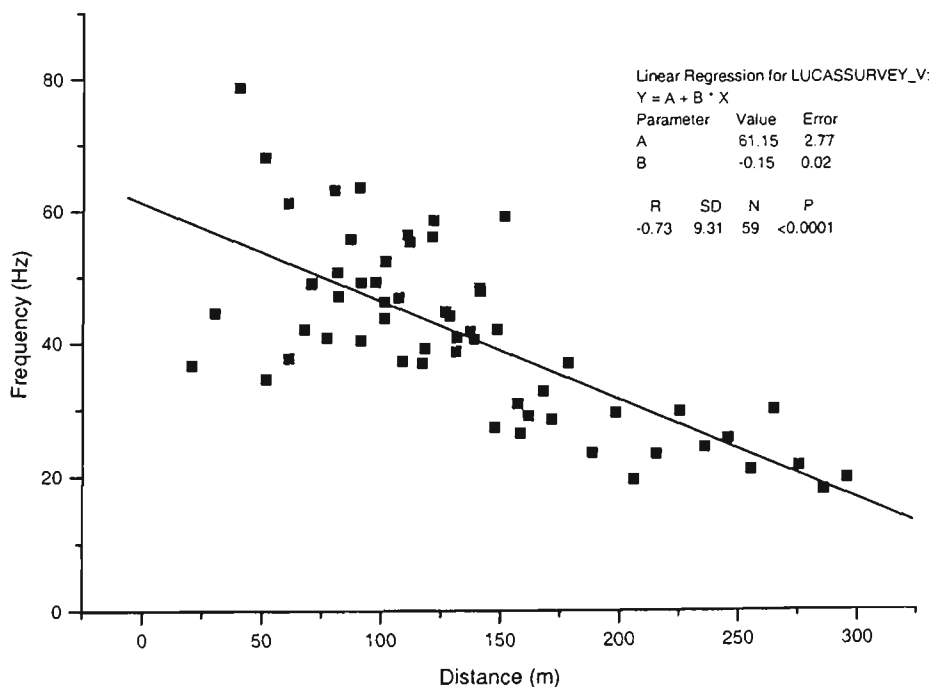


Figure 5.13 Vibration waveform frequency variation with distance



## 5.6 Blast Induced Vibration Monitoring Applications

### 5.6.1 Underground Blasting.

In an underground mine the fragmentation of the ore seams is usually accomplished by blasting. It is the control of this blasting process that is critical to the underground mining operations if ore grades are to be maintained (ie. no removal of gangue or mullock material close to the ore/gangue interfaces to cause dilution). Also the safe operation of the mine is inherently based upon smooth wall blasting techniques if over break and hence unstable walls are to be eliminated. It is the measurement of blast induced vibration but more precisely the analysis of the vibration waveform at sensitive locations that can help blasting operators to control the level of damage caused by blasting. A typical underground blast induced waveform is shown in Figure 5.14. The monitoring point was approximately 300 metres from the centre of the blast. The blast consisted of a series of single holes fired at 200 millisecond intervals to open up a slot followed by 4 rings with approximately 8 holes in each ring. The holes in the rings were delayed by only 20 milliseconds as high speed blasting was considered conducive in minimising damage to the surrounding rock hence leaving more stable walls.

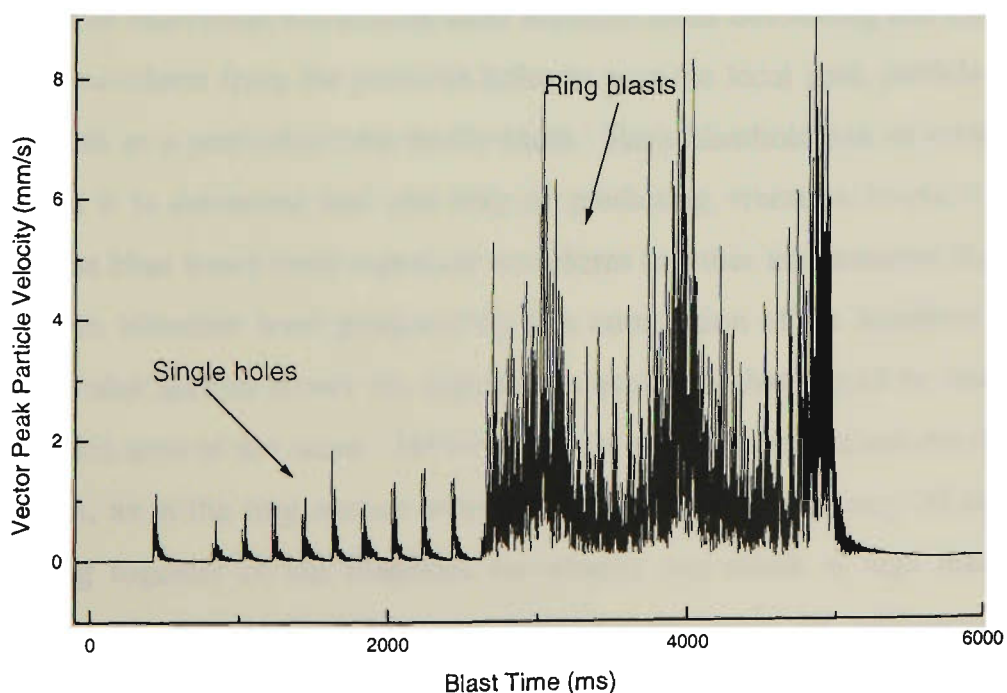


Figure 5.14 An example of a fast underground blast vibration waveform

The rock structure at the mine was competent layered chalcopyrite copper ore with the stratifications less than 0.3 metres thick. Fragmentation was not an issue but dilution and over break needed to be controlled. The features of the waveform recorded for this blast can be seen in Figure 5.14.

The slot section (up to 2000 milliseconds into the blast) contained individual holes initiating every 200 milliseconds, which gives the rock time to move and form the slot. Each hole was charged with approximately 100 kg (ranging from 80 kg to 115 kg) and the peak vibration levels were expected to be similar. However, what was of interest from this shot was that each hole detonation produced two peaks and in some instances the second peak was higher than the first peak. The second peak was approximately 20 milliseconds after the first peak. When the analysis was carried out it was determined that the first peak was the arrival of the *p*-wave (primary wave) and the second peak was the arrival of the *s*-wave (shear wave). The *p*-wave had a velocity of 6.5 km/s and the *s*-wave had a velocity of 3.5 km/s. It is unusual to see this separation of the *p*-wave and *s*-wave components due to the particle to particle interaction of the ground and the less than competent nature of the ground usually encountered in blasting operations.

The ring section of the vibration waveform shows a completely different feature and one that was similar for faster firing of blastholes. The vibration waveform is a combination of individual waveforms from separate holes detonating and each blasthole adds to the waveform from the previous holes to give the local peak particle velocity or vibration peak at a particular time in the blast. Each blasthole has its own “signature wave” when it is detonated and one way of predicting vibration levels is to add (in relation to the blast time) these signature waveform together and measure the maximum and minimum vibration level produced by this cumulation of the blasthole signatures. In effect the slot section shows the signature waveforms that would be obtained from blasting in this area of the mine. However, if the time between blasthole initiations is short enough, as in the ring section when blasthole separation is only 20 milliseconds, the crowding together of the blasthole waveforms can result in high blast vibration levels. As the delay time between hole firings was 20 milliseconds, which corresponded to the *p*-wave and *s*-wave separation times (at this location) then the *p*-wave level would add to the preceding *s*-wave level producing a high total vibration level. This information can help in the future planning of blasts as the firing can be

altered to move the following *p*-wave to a later point in time to reduce the overall vibration level from the blast.

An example of a more “cluttered” waveform is shown in Figure 5.15. In this blast the rings in an underground shot were initiated with a delay of 10 milliseconds between each hole. The rock type was a calaverite gold bearing ore and was more massive than the ore body in the previous example. The blastholes were similarly charged but this shot was loaded with an emulsion explosive (ANFO was used in the previous example).

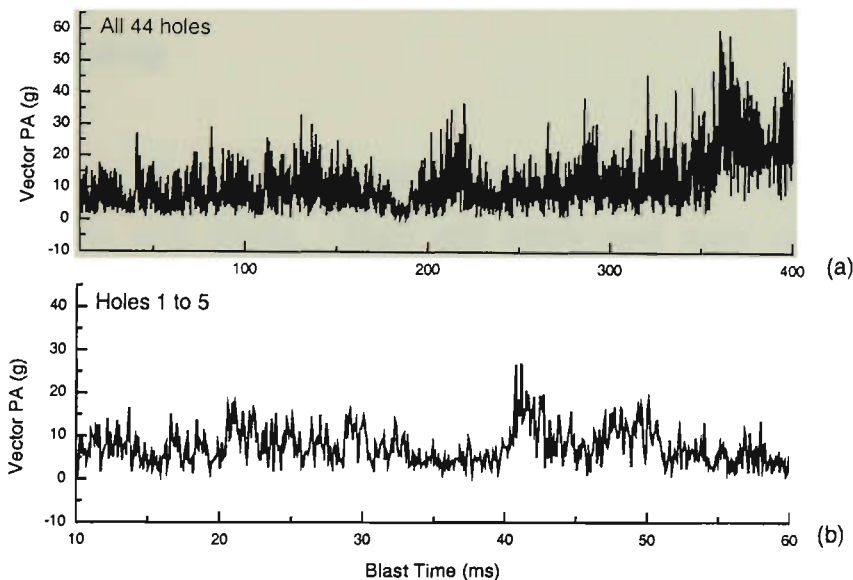


Figure 5.15 An example of a “cluttered” underground blast vibration waveform

The resulting waveform should have a lower peak for the same column length (same blasthole diameter). As can be seen in Figure 5.15 it is difficult to separate the next hole detonating but also the *p*-wave and *s*-wave components could not be separated. In this section of the waveform approximately 44 blastholes were initiated with only 10 milliseconds between each blasthole. The expanded waveform shown in Figure 5.15b has a charge detonating at each 10 millisecond interval and as shown the hole separation is extremely difficult if not impossible at times to separate. Again as each blasthole detonation has its own signature effect on the ground as it detonates, the waveform is a combination of all of these signatures (as in superposition of two waves). So as the first hole has detonated and the explosive is completely consumed in approximately 5 milliseconds the ground begins to relax. Then the second blasthole detonates and the reaction continues for approximately 5 milliseconds (depending on charge length). So

in effect the base line for the subsequent charges has been moved away from zero (in either the positive or negative direction) so adding to the vibration level expected by the next blasthole detonating.

In both of these examples above, the detonation of the charged holes occurred at a precise time because electronic delay detonators were used. So any scatter in the initiation time has been eliminated as far as interfering with the arrival time of the *p*-wave and *s*-wave from each blasthole is concerned.

### 5.6.2 Surface Blasting

The other main area where vibration monitoring is used is as a quality control tool in surface blasting in coal mines. Each and every coal mine operator has certain environmental limits to operate within and blast induced vibrations are no exception. The operator has limits such as 5 mm/s at the nearest neighbour and when the size of some open cut blasts are considered this limit can be quite restrictive. These mines are operating a blasting campaign, which can have up to 3 tonnes of explosives in a single blasthole. So with these high charge weights some indication of the expected vibration level before the shot is fired is a good mining practice. Changes to the charge weight can be done before loading to make sure the vibration level is within the environmental limits if a reliable predictor is available.

One method of predicting the change in vibration level with change in charge weight also takes into account the distance from the explosive source to the monitoring location. It is a well known fact that the vibration level decreases with increasing distance from the explosive source. Also the vibration level decreases with a decrease in charge weight detonated for a fixed distance from the source to the monitoring point. Both of these facts can be combined into an attenuation decay power law to provide a means of estimating the vibration level at a particular point for a given charge weight and distance. A typical vibration attenuation decay power law is shown in Figure 5.16.

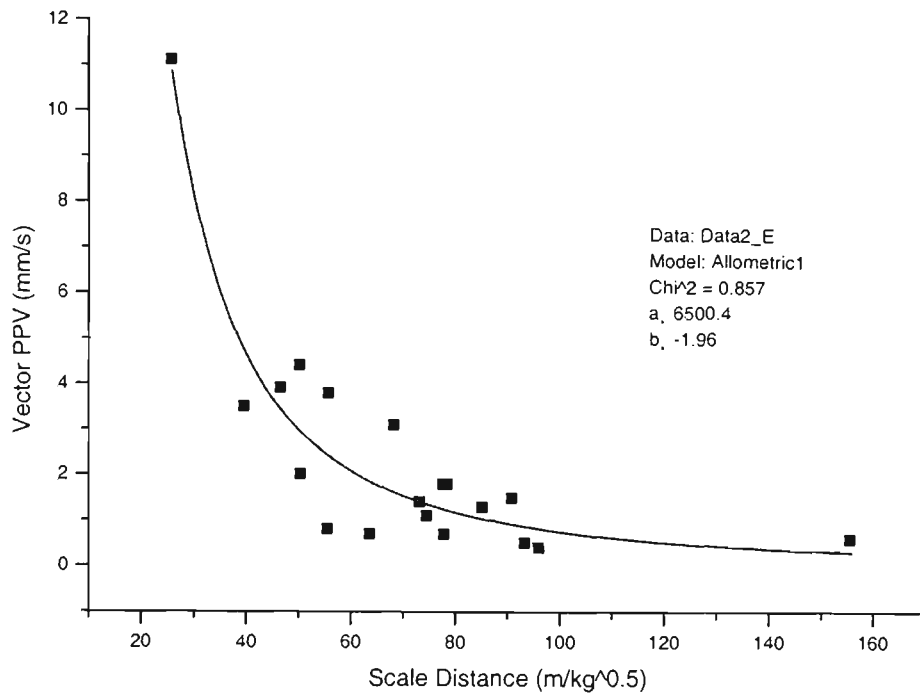


Figure 5.16 An attenuation site law used for vibration prediction

A series of vibration monitors are placed in a line between the explosive source and the point of interest. One monitor is also placed beyond the point of interest so that interpolation of the data does not introduce any errors. A number of blasts are monitored and the charge weight of each blasthole is recorded. Thus after a number of blasts the effect of vibration on the ground at this particular operation will be known and the site attenuation law can be constructed. The abscissa is the scaled distance (distance divided by the square root of the charge weight) and the ordinate is the vector peak particle velocity that was recorded. A line of best fit of the form

$$\text{Vector Peak Particle Velocity (mm/s)} = a * [\text{Scaled distance (m/kg}^{1/2}\text{)}]^{-b} \quad (5.2)$$

is constructed around these points resulting in an equation, which can be used as a predictor of vibration as a function of scaled distance. The site parameters  $a$  and  $b$  are determined by experimental techniques for each site using various charge weights and various distances between the explosive source and the monitoring location.

This site attenuation law describes the relationship between the vector peak particle velocity and a term called the scaled distance. The vector peak particle velocity is

calculated from the waveforms recorded from the three orthogonal primary sensors placed at the monitoring point and is the measure of the particle motion due to the vibration wave loading at the monitoring point (or any other point). As stated previously this vector peak particle velocity level has been related to damage and environmental limits are placed on blasting operations to maintain acceptably low levels. The vector peak particle velocity levels measured at the monitoring point have been obtained from both changes in the charge weight detonated and the distance from the charge weight detonated to the monitoring location. As can be appreciated both of these parameters will have an effect on the vibration level. For example if 100 kg of an explosive is detonated at a distance of 100 metres from a monitoring location the vibration level will be lower than a charge weight of 200 kg detonated at the same point. Conversely if 100 kg of an explosive is detonated at 100 metres distance from a monitoring location the vibration level will be higher than if the same charge weight is detonated some 500 metres from the monitoring location. Intuitively speaking increasing the charge weight or decreasing the distance will cause an increase in the vibration level at a particular point. Hence the scaled distance parameter which encompasses the effect of both of these parameters. To define a relationship between two properties it is usual to have the dependent variable (VPPV in this case) either increasing or decreasing with an increase in the independent variable. However in this case the VPPV (dependent variable) decreases with distance and increases with charge weight. To counter this conflicting situation the scaled distance property is defined as the distance (in metres) divided by the square root of the charge mass (in kilograms).

Both square root scaling relationships and cube root scaling relationship have been used but traditionally the square root scaling relationship has been employed (also in this study). The square root scaling relationship is based on the geometric facts that the charge weight is a column of explosives of certain length, hole diameter and constant density. Thus the hole diameter is proportional to the square root of the charge weight. The scaled distance is based on the distance divided by the square root of the charge weight and so a comparison of the ratio between two lengths can be appreciated. The square root scaling law is more conservative than the cube root scaling law for scaled distances  $<30$  and as conservative estimates are on the safe side for blast predictions one of the benefits of using the square root scaling law is demonstrated.

The site attenuation law is at best a conservative predictor of the vibration levels that would be experienced at a particular location. The decay power law will indicate a 50% chance of predicting the outcome to be above a certain level as it uses only peak levels to form the curve. No attempt is made to look at the basic blast parameters and their effect on the vibration level from a blast using this predictor.

### 5.6.3 Environmental Vibration Monitoring

The majority of vibration monitoring exercises is carried out to determine if the blasting operations are operating within environmental limits that apply to the mine/quarry operations. In these cases the mine operator usually has a local farmhouse or domestic residence where a permanent monitoring point has been established. The primary sensor is securely coupled to the soil and the monitor is turned on before the blast. The waveforms recorded are manually retrieved or transmitted via a telephone or radio link back to the mine office.

More often than not the vibration monitoring equipment will calculate the peak levels on all channels and also calculate a vector sum of the three vibration channels. These peaks are usually all that is reported. Thus for a rather complicated blast pattern one number is all that determines the success or failure of the blast as far as environmental limits are concerned. For example, the monitoring point is near a tree, as they often are, and a branch is dislodged by the blast (or weather condition). The branch falls on top or near the primary sensor, this results in a very large “vibration” level being detected by the primary sensor. This level could be well above the actual blast induced vibrations. An example of a typical surface coal mine blast being within environmental limits together with a “branch spike” is shown in Figure 5.17.

If analysis is not carried out on the waveform, which is the normal practice at most operations, an extremely high vector peak particle velocity would be reported as shown in Figure 5.17. But if the waveform is examined and the “spike” (which is obviously not blast induced) removed from the analysis a more meaningful waveform of the actual blast will result. The total waveform VPPV had a value of 5.9 mm/s (including the spike) whereas the blast induced waveform had a VPPV value of 4.8 mm/s. Also the frequency of the blast induced waveform is also important as the spike (very short

duration high frequency) would not be felt by structures (houses, bridges etc.) as it would only be local to the primary sensor. The frequency of the blast induced vibration was calculated to be 18.3 Hz but the frequency of the total waveform was 18.4 Hz. This small frequency increase would probably not affect the interpretation of the effect of the blast induced vibration on any structure of interest. This is due to the area under the frequency spectrum curve for this high frequency spike would be small compared to the total energy in the vibration waveform.

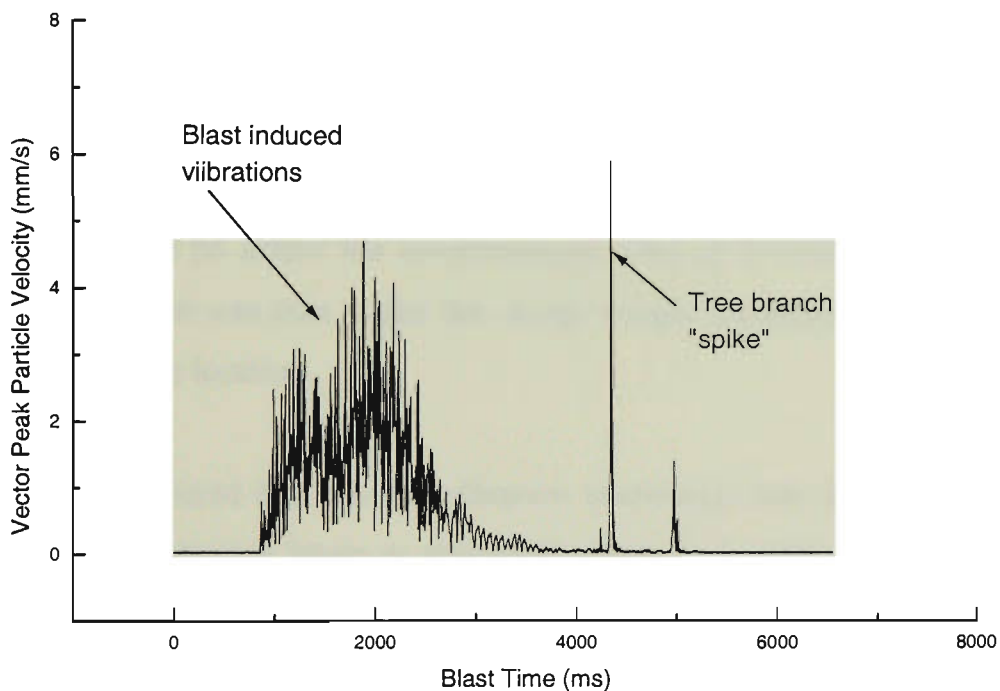


Figure 5.17 An example of a “spike” causing an error.

#### 5.6.4 “Greenfield Site” Blast Monitoring

When a development application is put up to a local council to establish a mine or quarry some scientific background has to be included in all areas of environmental limits (blasting, water quality, air quality etc.). Blasting is no exception and in the case of a “greenfield site” where no history (existing mine operation or neighbouring mine operation) is available some small scale testing should be carried out to provide an estimate of the vibration level at particular points for the proposed blasting operation.

Again a vibration attenuation decay law is established for the area of the proposed mine/quarry. As there are no existing blasting operations, a series of test blastholes at



large spacing is drilled and loaded with explosives. Charge weights similar or just exceeding those planned for the mining operation should be used and vibration monitors are placed at sensitive locations and around these test blastholes at various distances to cover the entire planned operation area.

Even though single holes are used and the firing conditions would not be the same as a typical blast pattern (no free face, no burden relief etc.) these holes will give an over estimation of the vibration level and any prediction should be on the conservative side. These single holes are repeated and monitors are moved to locations of interest as required. If this procedure is adopted for a number of single holes, confidence in this predictive site attenuation law increases. In the case above (see Figure 5.18a, Figure 18b and Figure 18c) it was shown that at a scaled distance greater than  $25 \text{ m}/\sqrt{\text{kg}}$  the VPPV level would be below the environmental limit of 5 mm/s. Using this scaled distance the shotfirer can then adjust the charge weight according to the distance from the nearest sensitive location.

It must be remembered that the site vibration attenuation law developed from single hole in normal production blasts or greenfield single hole trials can be limiting in the results calculated. The expected vibration level from any blast is very difficult to predict and the peak level can occur at any time in the blast sequence. There are many blast parameters that can have an effect on the vibration level and the prediction of the peak level becomes a statistical problem because of the variability of these parameters.

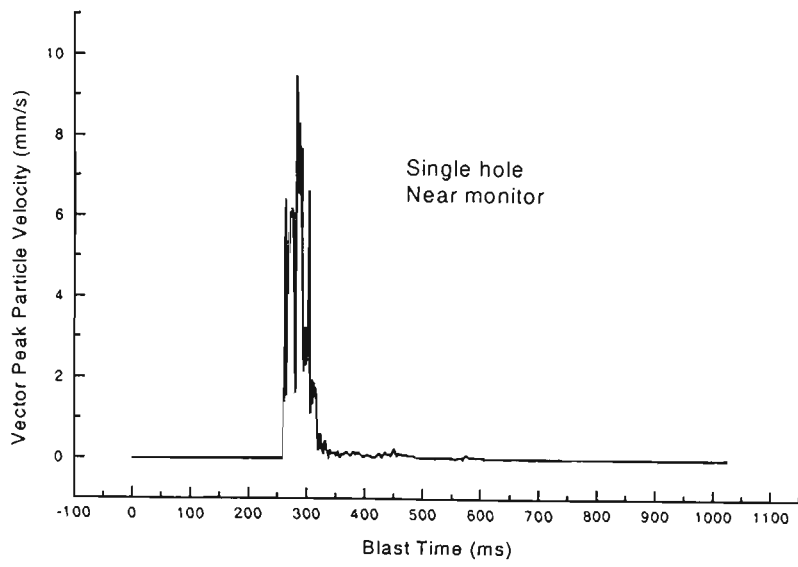


Figure 5.18a Near field single hole vibration waveform.

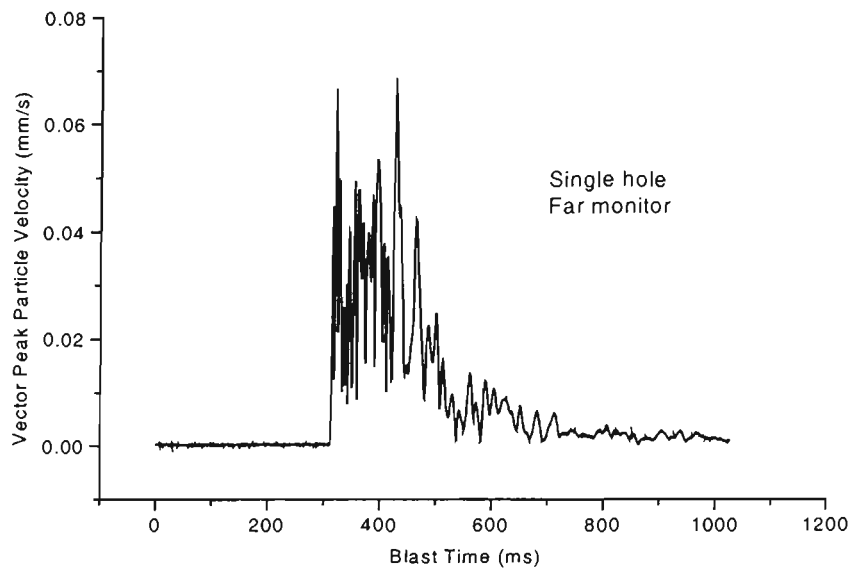


Figure 5.18b Far field single hole vibration waveform.

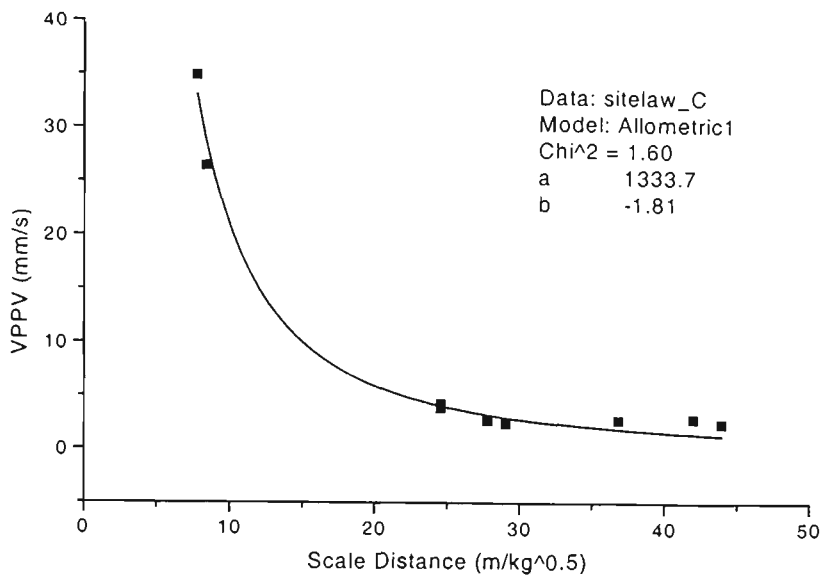


Figure 5.18c Greenfiled vibration attenuation site law

The initiation sequence is designed to initiate each hole at a precise time using what is known in the blasting industry as delay detonators. These delay detonators have a pyrotechnic element or chemical compound that burns at a specified rate. This reaction rate is controlled by the composition of the delay element, the diameter and also the length. All of these properties can of course be varied from the ideal value required which results in a variation in the time that these delay elements burn. Although this delay element time variation is extremely small, usually quoted as less than 2% by the initiation explosive manufacturers, these errors can accumulate. For instance consider a blast with 200 holes and each hole is designed to initiate some 42 milliseconds (a standard time interval used in delay detonators) apart. Towards the latter part of the blast the waves from each blasthole begin to overlap and reinforce each other consequently two or more holes can be initiated at the same time thereby increasing the vibration level from this blast. This phenomenon can be accounted for in a statistical sense as the actual detonation times will be statistical “know”.

The charge weight is another blast parameter that is not exactly known. The amount of explosives delivered into a blasthole can be accurately measured again to within 2% of that required. Some explosive suppliers aim to deliver accurately to 1-2 kilograms of

that required. But again there is some error associated with the actual quantity delivered down the blasthole and this variation can be quite large in some instances. This parameter can also be represented in a statistical sense.

The location of each and every blasthole can be determined by conventional surveying techniques and the actual location in a 3D coordinate system is known very accurately. Some systems quote an accuracy to the nearest millimetre. However, the distance from each hole to the monitoring location is not the same and this variation can in some cases, if the monitoring location is close to the blast, be quite significant.

These factors and also the passage of the vibration wave through the ground all have an effect on the vibration level that will be experienced at a particular location. But it is the maximum vibration level experienced at the monitoring location that is of interest and this level must be controlled within certain limits. Predictive programs can help in estimating this vibration level if reliable data is used as inputs to these predictive programs.

One unfortunate drawback to this procedure is that the test holes fire in a totally confined condition, which can lead to an overestimation of the vibration level. Single holes in a blast pattern at the beginning or end of the shot have been trialed with limited success due to the creation of possible neighbouring column cut-offs due to the extended time between the blast pattern and the single holes firing. However, in a greenfield situation there is no blast pattern to fire and this procedure can be confidently used before production blasting has commenced to gauge the vibration level that would be produced.

## **5.7 Discussion**

The variability of the standard mounting technique was measured by six identical vibration monitor set-ups used to monitor 25 typical coal overburden blasts at various scaled distances. One blast could not be compared to any other blast as the vibration levels were different due to the distances and charge weights used. The variation within each blast was found to be a measure of the reproducibility of the standard mounting

technique. The means to measure this variability, realising that each blast produced a different vibration level at the monitor location, was the coefficient of variation, CoV, (standard deviation /mean). If the CoV was less than 5% (18 of the 25 blasts) the standard mounting technique was reproducible over the range of vibration levels recorded. The CoV of the 25 blast was in the range from 1.4% to 9.2% when the average vibration level for the 25 blasts was in the range from 1.48 mm/s to 183.74 mm/s. The predominant frequency of the blast induced ground vibration recorded in these trials was in the range from 4.9 Hz to 100.2 Hz with a CoV range of 0.9% to 6.2%. As the block used in the standard mounting technique was designed for frequencies less than 200 Hz this frequency range did not introduce any spurious frequencies into the waveforms recorded.

The different mounting methods showed how variable the science of measuring blast induced ground vibrations can be. When five other methods were compared to the standard mounting technique the difference is clearly shown. The predominant frequency of the blast induced ground vibration recorded was in the range of 14.7 Hz to 56.9 Hz which is typical of the frequencies measured in coal overburden blasting operations and was well within the range of the standard mounting block. The concrete mounting block method showed a regression line with a slope less than 1 for all four vibration ranges selected with the slope values in the range of 0.81 to 0.99. The high frequency mounting method showed a similar trend in the slope of the regression line with values in the range of 0.96 to 1.05. This mounting block was similarly constructed to the standard mounting block but designed to handle higher frequency blast induced ground vibrations. However, the other three mounting methods exhibited fluctuating values of the slope of the regression line about the expected value of 1. For the 3 spike mounting method the slope of the regression line was in the range of 0.85 to 1.33 which could indicate a loosening of the bond hence a poor coupling of the soil to the spikes. The 1 spike mounting method showed the regression line slopes were in the range of 0.91 to 1.16 which also showed significant variability. The sandbag mounting method showed a large range in the slope of the regression line from 0.67 to 0.97 which could indicate the sandbag is acting as a damper on the system. However its frequency plot showed that there is energy being dumped over a wide frequency range which could be due to the loose material in the sandbag moving slowly due to the vibration event and this movement being detected by the primary sensor.

The variable density of the mounting block in the standard technique did not show any deviations from the standard mounting block. As these mounting blocks were all the same physical dimensions (the density of the concrete was changed by adding polystyrene balls or lead shot) and the weight varied for 2 kg to 16 kg. The predominant frequency was in the range 6.8 Hz to 21.9 Hz due to the distance between the monitoring point and the blast. The CoV varied from 0% to 12.9% with the higher CoV values resulting from extremely low peak vibration levels (less than 1 mm/s). In this situation a small numerical change in the individual values caused a large change in the CoV calculation. For example 5 values at 0.3 mm/s and 1 value at 0.4 mm/s gave a CoV of 12.9%.

Probably the most important issue in vibration wave analysis is understanding the frequency effect of the blast induced ground vibration at the monitoring location. It was shown that the frequency decreases with distance from the explosive source, a function attributed to dispersion and intrinsic attenuation. A modelling technique (see Figure 12) showed how a low frequency waveform could have a lower peak vibration level when compared to a higher frequency waveform (under the same conditions). Experimental data from field trials where a single hole was detonated in a sandstone quarry showed the effect of distance on the frequency of the blast vibration waveform. An attempt was made to define a linear relationship but any relationship would appear to be much more complex. A linear regression of the predominant frequency as a function of distance had a regression coefficient of  $-0.73$  which indicates some scatter of this data about the regression line.

Vibration monitoring was shown to be a useful tool to analyse what has actually happened to the ground during a blast. An example was shown of an underground blast where a mixture of slow firing slot holes and fast firing ring holes were monitored in the same blast. In all underground blasting operations a cavity or void must be created for the fragmented rock to be thrown into. Slow firing of the blastholes allows time for the fragmented material to move into the cavity. This then creates more space near the adjacent blastholes for the subsequent fragmented material. Another example showed a blast that was fired with 10 millisecond delay between holes firing and the “cluttered” nature of the waveform was shown. It was difficult to isolate one hole from another in

this example. Firing times such as 10 milliseconds delay between holes aids in fragmentation of massive ore bodies and minimises the chance of holes cut-offs due to ground movement.

The problems that can occur when relying on the information on the front screen of the monitoring equipment was also shown. Rogue peaks could result from falling branches, rocks etc. close to the monitor when in effect the blast induced ground vibration wave has passed several seconds earlier. Analysis of the record is an important part of any responsible mine/quarry operator.

Greenfield site, new quarries or mines, do not have the luxury of historic data to predict vibration levels from proposed blasting operations. A procedure was detailed where a reliable predictor can give valuable information from the detonation of a small number of single blast holes. A vibration attenuation site law can be constructed from these single holes and the vibration peak levels measured at various locations. The configuration of the blastholes must be similar to the planned blastholes as far as charge weight is concerned to enable a reasonably accurate site law to be determined.

## 5.8 Chapter Conclusions

- The variability of the standard technique was shown to have a precision of 10%.
- The standard mount design adequately handled frequencies up to 100 Hz.
- The differences between the mounting methods was clearly shown.
- The density of the standard mounting block was practical insignificant.
- Blast timing was shown to change the vibration waveform frequency.
- Underground blasting generates different types of waveforms.
- Modelling can predict vibration levels with some degree of confidence.
- Greenfield site blast monitoring was techniques were discussed.





## CHAPTER 6.

### CONCLUSIONS.

#### **6.1 General Conclusions.**

Blast induced vibrations are a result of mining practices that occur on a regular basis. The mining industry benefits society in many ways. The products from the mining industry touch our lives daily. But that is not to say that society will be slaves to the mining industry but more that society shall control the mining industry. A by-product of the mining industry is blasting and the environmental concerns that it brings. Blast induced vibrations, is one that causes a lot of problems (real and perceived). Blast induced vibrations do cause damage, after all if the explosive did not fragment the rock then it would not be performing the task required of it. But the effect of these vibrations is immediate, not like the damage that occurs over a long period of time from normal climatic conditions and settling of the ground on which houses are built. But with all of this damage, perceived or real, it must be managed if society is to prosper and grow.

##### **6.1.1 Vibration monitor set up.**

Blast induced vibration must be quantified and the properties of the instrument used to measure these blast induced vibration waves must be defined before monitoring can take place. The sample duration is the total time that the samples are taken over and was shown to have a bearing on the structure of the waveform recorded. For example, see Figure 3.9, where a blast was connected up to fire for a total time of 1687 milliseconds. If the sample duration was also set at 1687 milliseconds then all of the blast induced vibration wave would not have been recorded. The ground reacts to the blast induced vibrations in complicated ways and as shown the ground is still moving due to relaxation and post blast movement after all the holes had detonated. So it is imperative that the total time the signal from the primary sensor is sampled is a couple of seconds longer than the blast is designed for eg. for a 4 second blast the vibration monitor should be set to sample for 8 seconds. This will allow all of the holes to

detonate and ample time for the ground relaxation and post blast movement to subside and come to rest.

Probably the single most important property of any vibration monitoring equipment is the sample interval time or time between successive samples being collected. This time is measured in milliseconds and was shown to be linked to the frequency of the blast induced vibration at the monitoring point. In competent rock structure when blast induced vibration wave frequencies are generally 100-200 Hz then to obtain enough data points for a smooth curve, a sampling interval of 0.075 milliseconds was required (see Figure 3.10) to capture the vibration wave including all of the peaks. Compare the vibration waves sampled at 0.075 ms to that sampled at 1.05 ms. Peak levels of 22.5 g were recorded at 0.075 ms whereas at a sample interval of 1.05 ms a peak level of only 12.0 g was recorded. This shows that the true peak levels can be seriously underestimated at these slower sample intervals. However when the frequency of the blast induced vibration wave is much lower for example less than 100 Hz (see Figure 3.12) then the sample interval can be reduced while still maintaining accuracy in the vibration waveform sampled. When the sample interval of 1.92 ms is chosen some of the peaks and troughs are just missed but when a sample interval of 0.96 ms is used to sample this waveform none of the pertinent points on this waveform are missed.

The next property of the monitoring equipment is the bit resolution of the analogue to digital converter. The primary sensor is an analogue device in that a continuous variable voltage signal is output from the primary sensor as the primary event is encountered. The analogue to digital converter changes this analogue signal to a digital signal, which is easier to store and process. The analogue to digital converters are 8 bit ( $2^8$  or 256 parts) and up to 16 bit ( $2^{16}$  or 65532 parts). If the maximum voltage input to the analogue to digital converter is  $\pm 5$  volts then for the 8 bit converter each bit is equivalent to 0.039 Volts whereas in the 16 bit converter each bit is equivalent to 0.00015 Volts. As shown in Figure 3.13 the 8 bit converter would have more of a stepped waveform than the 16 bit converter which approaches the analogue input signal.

### 6.1.2 Waveform frequency.

The blast induced vibration waveform frequency was shown to effect the predicability of modelling programs because of the spreading out with distance from the blast hole. As shown in Figure 5.11 even single hole vibration waveforms can have a significant difference in the waveform as the distance increases. At a close monitoring point a total waveform length of less than 100 ms is shown whereas at a larger distance the waveform length was increased to 700 ms (see Figure 5.12). The predicted waveform frequency was shown to decrease when the shot time was increased as shown in Figure 5.12. From this predicted waveform the frequency decreases from 37.5 Hz for a fast blast to 15.8 Hz for a slow blast. So not only does the firing sequence affect the blast induced vibration frequency produced but also the ground itself has a broadening effect with distance on the frequency of the blast.

An attempt was made to define a linear relationship for the decrease in frequency with distance. This linear relationship had a regression coefficient of 0.73 indicating that there is some scatter in the data but did show that a linear relationship is possible.

### 6.1.3 Applications.

Monitoring applications show the type of waveform that was examined in this study. All blasting applications produce different types of waveforms and this was shown in Figure 5.14 and Figure 5.15. Underground blasting has a section of the waveform where individual hole detonation can be identified. This part of the blast occurs when the opening is being formed for the subsequent material to be thrown into. Even at 20 ms delay between holes detonating, individual hole waveforms can be identified. But when the intra-hole delay is 10 ms a more cluttered waveform is evident.

Surface blasting techniques produce one of an environmental concern because the blasts are larger both in number of holes (hence the duration of the blast) and also the charge weight per hole being initiated. Some means of predicting the likely outcome of a blast is always needed and a site law can be established which can be used as first approximation to the likely vibration outcome. This prediction can be used also in

environmental blasting applications but possible traps were eluded to with rogue spikes from falling debris close to the primary sensor was shown in Figure 5.17.

Blasting in new mines/quarries or in greenfield sites always causes concern, as the vibration levels of previous blasts are not known thus there is no history to help predict future vibration levels. Single hole blasts, from which a site law is developed, was shown as one cause of responsible action that could be taken.

#### **6.1.4 Laboratory study.**

The parameters of the soil affecting the vibration transmission to the primary sensor were investigated in a laboratory study. A laboratory vibration rig was constructed which allowed a near constant vibration source to be applied to a container full of the soil and the primary sensor attached to a mounting block. The precision of the equipment was defined by repeating the same test a number of times and was found to have a coefficient of variation of 5.81%. One of the major sources of error was seen as the placement of the block in the soil or more precisely the distance between the primary sensor and the vibration source. A test was repeated a number of times by placing the block in the centre of the soil container and determining this distance. The vibration level was then determined at various distances from the vibration source and this error was calculated to be 4.14%. The overall error for the test rig was the sum of these two errors or 9.95% which means that values that are greater than 9.95% apart would be considered to be significantly different. The parameters of the soil affecting vibration transmission were tested in this laboratory vibration rig.

Moisture of the soil was thought to be a major contributor to attenuation of the vibration signal through the soil. It was shown that clay based soils which have a capacity to absorb large quantities of water before they 'appear' wet have an increasing transmission effect with moisture content up to 10% moisture. However, soils which have a sand based material exhibit a maximum transmission with increasing moisture content followed by a reduction in transmission as the moisture content approached 10%. It appears that a moisture saturation point is reached for these soils where surface tensional forces are overcome by the excessive quantity of moisture around the individual grain particles.

The compaction of the soil around the mounting block was shown to exhibit the largest influence on the vibration transmission through the soil. Soil in the ground has had time to compact to a natural packing density due to weather and normal ground movement. When the mounting block is embedded in the soil a bond must be formed between the undisturbed soil and the mounting block. This bond is accomplished by tamping the loose soil between the original soil and the mounting block. This soil should be tamped or compressed as much as physically possible to form a bond between the soil and the mounting block that will be permanent for the duration of the vibrating wave.

The particle size distribution of the soil in contact with the mounting block did not show any effect on the vibration transmission through the soil. It was thought that solid bridges would aid in the vibration transmission so, one soil had large lumps added to significantly modify its original size distribution. But it appears that the vibration transmission through the soil is a bulk effect rather than an individual particle effect, this assumption is also supported by the results shown in the compaction section of this study.

#### **6.1.5 Field studies.**

Vibration monitoring exercises in the field have shown that results from one mine/quarry can not be used at another mine/quarry with any degree of confidence. This phenomena was investigated using 9 different (mineralogical, chemical and physical) soil samples. Under the same vibration loading conditions there was not any correlation from one sample to another. This lack of correlation shows that the entire solid transmits vibration waves at a rate fundamental to the soil and the structure itself (geological and physical) and that no two soils will behave the same under the same vibration loading. These soils tested ranged from sand type soils to clay based soils and no comparison between soils could be found.

The results of the laboratory study and parameters of the monitoring equipment were used to define the operating parameters of the mounting procedure to be used in the field. Vibration sources for this section of the study were typical blasts used in coal

mining operations. As it was impossible to apply the same vibration loading on any two occasions, six identical vibration monitoring set ups were used for each blast.

The variation within the 6 set ups was used as a measure of the precision of the procedure. The coefficient of variation was used as the measure of precision of the procedure, as the magnitude of the vibration level varied for each trial and the coefficient of variation eliminated any ambiguity due to absolute values of the vibration levels being compared. In this procedure each set up had the same data logger, primary sensor and mounting block and care was taken to ensure all six mounting blocks were bonded by the same method to the soil surrounding the mounting block. A trench was dug to place all six mounting blocks in and the excess soil tamped around each mounting block. In this way it was felt that the six set ups were identically installed. However even for practically identical set ups the results obtained will not be the same due to small irregularities in the set ups, this is also the case in this part of this study. The variation in the field was shown to have a precision of 9.95% as determined by the coefficient of variation.

Many methods are used to bond the primary sensor to the vibrating soil. Several popular bonding methods used in practice today were trialed along side the standard method. The standard method had a scientific background engineered into the design and the properties can be traced back to testing to determine the optimum conditions. The bonding methods compared in this section of the study were sandbagging the primary sensor to the ground, spiking mounts being forced into the ground and as the blast vibration frequency varied due to operating conditions a mounting block designed to handle higher frequencies was also compared. All of the embedded mounts showed discrepancies of less than 10% at all vibration levels tested and so were classified as the same as the standard mounting block. However, the spike mounts showed a variation greater than 30% and so are not a recommended procedure. The sandbag mount did have some similarities to the standard mounting block, but at the lower vibration levels the material in the sandbag appeared to settle during the blast and add energy to the primary sensor which was detected as changes in the frequency content of the sandbagged waveform. This mounting procedure is also not a recommended procedure.

Increasing the soil compaction around the mounting block was shown (in the laboratory section of this study) to increase the vibration transmission through the soil. At field mounting sites the soil is compacted due to climatic conditions and time to form a stable state. The density of this stable state would be fairly consistent. The effect of the density of the mounting block was trialed as it was thought to that local high mass concentrations would affect the vibration transmission to the primary sensor. But this was not the case as shown by the consistency of the vibration levels for the mount densities varying from 1.0 g/cc to 7.9 g/cc. Again this effect supports the hypothesis that the vibration transmission is not within a particle basis but more on a bulk system basis and local density concentration, ie. large boulders etc. would vibrate the same as the surrounding ground.

Monitoring of blast induced vibrations has become an integral part of mine/quarry operations today. The mine/quarry needs to be reassured that the method they are using is actually measuring how the ground is moving under the influence of the blast induced vibration loading. The vibration monitoring procedure investigated here has been shown to have sound scientific knowledge engineered into the design and was shown to be a repeatable method to monitor blast induced vibrations. The main concerns of any operator using this procedure should be the bonding of the mounting block (and hence the primary sensor) to the soil. The primary sensor **MUST** move in unison with the soil to faithfully record the vibration waveform at the monitoring location.

#### **6.1.6 Conclusions Summary.**

- The understanding of the monitoring equipment was shown to be important if meaningful records were to be captured on this equipment.
- Sampling interval was shown to be linked to the vibration waveform frequency. Slow sampling time for high frequency waveform can result in low peak levels being measured.
- Different equipment set ups are required for different applications.
- Non blasting events (rocks, branches etc) can cause erroneous results.
- Greenfield sites need special attention.

- Laboratory study showed that:
  - Moisture can effect the vibration level by allowing the grains to slip.
  - Compaction was shown to have the greatest effect on vibration transmission.
  - Vibration transmission was insensitive to particle size.
  - No two soil types responded the same to the vibration loading.
- The standard procedure had a precision within 10%.
- When compared to the standard procedure the concrete block proved statistically the same. The sandbag and the spike mounting procedures were statistically different and are not recommended for compliance monitoring.
- The density of the mounting block was statistically the same for all densities tested.

## **6.2 Future research.**

During the course of this study and the preparation of this document areas where more knowledge is required to better understand the measurement of the vibration effect on the ground were found. The literature study showed that a lot of work has been carried out on the vibration transmission through the ground and also a lot of work into structural effects caused by the vibrating wave. Some work has also been carried out into the different mounting scenarios in soil. Soil is a difficult medium to measure the vibration level in as it is comprised of many individual particles and the bonding between each particle and its neighbours can be quite different. In this study soil was defined as granular material less than 8 mm particle top size and as such covered material from sand to quarry fines.

### **6.2.1 Moisture effect.**

The moisture content of the soil was shown to affect the vibration transmission through the soil and a mechanism was postulated. This mechanism was supported by the results which showed that as the moisture increased the structure of the moisture/soil matrix went from a surface tension support mode to a fluidisation mode. In the surface tension mode the grains are held together not only by the particle packing but also by the surface tensional forces of the water at the points of contact of neighbouring grains.



When the moisture content exceeds a certain level the surface tension forces become less dominant and the moisture content between neighbouring grains is sufficient to allow movement between neighbouring grains. This mechanism should be defined more precisely as this can have an effect on the vibration levels that are measured in inclement weather for example. Also tidal water areas where mine/quarry operations are near the shoreline will cause water saturation between neighbouring grains, which will allow for particle to particle slippage and different vibration levels will be obtained at different times of the day for similar blasts. An understanding of how this water mechanism affects the vibration transmission through the ground could aid in the production of water curtains for example in the ground between vibration sensitive areas and the explosive source. Protecting the local community from blast induced vibrations from mine/quarry operations will be a major concern in years to come as previously isolated mine/quarry operations are encroached upon by the urban sprawl and their operations become ever more scrutinised.

It was postulated in this study that the vibration effect through the soil was a bulk effect and not the passage through individual grains to neighbouring grains. This postulation was supported by the moisture content hypothesis above and also by the particle packing density. So as the particles become closer together their vibration transmission characteristics increase and more energy is transmitted through the soil. But as shown the particle size distribution appears to have very little effect on the vibration transmission but the compaction caused a significant increase. The particle density or more likely the more particle to particle contacts will help increase the vibration transmission. Now this has a major effect in ensuring the true vibration level at a monitoring point is being measured. But can this compaction or particle to particle contact point density increase actually amplify the blast induced vibration input?

### **6.2.2 Particle density effect.**

The converse of particle density increase could have beneficial effects in reducing blast induced vibration levels between vibration sensitive areas and the explosive source (similar to the water curtain postulation). If a fractured barrier is placed between the explosive source and the vibration sensitive site then energy attenuation could occur between particles as the vibration energy is transmitted through the bulk of the fractured

ground. Is there a particle size distribution that best attenuates the energy and how can such a barrier be formed to alleviate the communities concerns near mine/quarry operations?

What really causes the difference in the vibration levels for one soil compared to that of another soil? Is it an inherent property of the material that makes up the soil or is it some physical property of the particles or number of particles? These are some of the questions that lend themselves to some intensive research as the knowledge of vibration wave travel through particulate material can possibly lead to ways of controlling the blast induced vibration through soil.

But what must be remembered in any continuation of this study is that the blast induced vibration wave is a complicated physical characteristic of not only the material that is supporting the vibration wave but the blast induced vibration wave itself. The explosive source when detonated sets off a shock wave in all directions in the confining medium, in this case the ground. When it comes to a major change in density, at a free surface for example, this is where the damage to structures can occur and this is where the blast induced vibration level is measured. So an understanding of what is happening at this free surface is information that can be of benefit to the mine/quarry operators to control their operations within community accepted environmental limits.

### **6.2.3 Recommendations Summary.**

- The effect of moisture on the vibration transmission through the soil should be investigated more thoroughly. This understanding will help to explain ambiguous vibration results that are at times difficult to interpret.
- Vibration transmission through different materials is not completely understood and a more thorough understanding of the transmission properties of materials is required.



## REFERENCES

- Armstrong L.W.**, 1999, Vibration evaluation of low energy development product BB607 at Bulga Mine., Internal Report , ORICA Australia Pty. Ltd., pp. 1-10
- Armstrong L.W. and Brodbeck A.**, 1998, Monte carlo vibration prediction modelling at the proposed Basalt Hill Quarry, NSW., Internal Report No.57923, ORICA Australia Pty. Ltd., pp. 1-17
- Armstrong L.W. and Sen G.C.**, 1999, The measurement of blast induced vibrations in soil. Explo '99, Kalgoorlie, WA, 7-11 November, pp. 99-104.
- Atlas Powder Company**, 1987, Explosives and rock blasting. Atlas Powder Company, Dallas, Texas, USA, pp. 321 - 410.
- Australian Standard AS 2187.2 – 1993**, Explosives – Storage, transport and use. Part 2: Use of Explosives.
- Blair D.P.**, 1989, Ground coupling of vibration detectors., CSIRO Division of Geomechanics, Institute of Mineral Energy & Construction, External Report No.1, September, pp. 1-45
- Blair D.P.**, 1991, Field testing of the dynamic compliance for blast vibration mounts., CSIRO Division of Geomechanics, Institute of Mineral, Energy & Construction, Internal Report – New Series No.92, October, pp. 1- 38
- Blair D.P.**, 1995a, Soil-embedded detector mounts for seismic monitoring., Geophysics, Vol. 60, No.1 (January – February), pp. 120-133
- Blair D.P.**, 1995b, Blast vibrations in soil and on large resonant structures., Explo '95, Brisbane, Qld., 4 – 7 September, pp. 315-322.

**Blair D.P.**, 1996, Estimates of seismic attenuation using vibrational resonance and pulse transmission in four large blocks of rocks., Geophysics J. Int., No.126, (January – February), pp. 135-146

**Blair B.E. and Duvall W.I.**, 1954, Evaluation of gages for measuring displacement, velocity and acceleration of seismic pulses., US Bureau of Mines Report Investigations 5073

**Bollinger G.A.**, 1971, Blast Vibration Analysis., Southern Illinois University Press, USA.

**Brochu R.R. and Eltschlager K.E.**, 1999, Proposed draft of the ISEE seismograph performance specifications and general guide lines for seismograph field use., Proceedings of the 25<sup>th</sup> Conference on Explosives and Blasting Techniques, International Society of Explosive Engineers, Nashville, Tennessee, 7 – 10 February, pp. 279-285.

**Bullen K.E.**, 1954, Seismology, Methuen's Monographs on Physical Subjects, John Wiley & Sons, New York

**Crouse C.B., Liang G.C. and Martin G.R.**, 1984, Experimental study of soil-structure interaction at an accelerograph station., Bull. Seismological Soc. America, Vol.74, No.5, October, pp. 1995-2013.

**Dowding C.H.**, 1985, Blast vibration monitoring and control., Prentice-Hall Inc., Englewood Cliffs, New Jersey, USA, pp. 6-40.

**Ester Z. and Vrkjan D.**, 1999, Seismic monitoring during blastings of building pit for WTC at RIJEKA., Proceeding 25<sup>th</sup> Annual Conference on Explosives and Blasting Techniques, Nashville, Tennessee, USA, 7-10 February, pp. 369-377.

**Ghosh A. and Daemen J.J.K.**, 1991, Validation of exponential decay blast vibration predictor with case studies., SME Annual Meeting, Denver, Colorado, February 25-28, pp. 1-9

- Grogan A.**, 1998, A review of suggested geophone attachment methodologies from commonly referred to mounting standards., Proceedings of the 24<sup>th</sup> Conference on Explosives and Blasting Techniques, International Society of Explosive Engineers, New Orleans, Louisiana, 8 – 11 February, pp. 105-113
- Jaeger J.C. and Cook N.G.W.**, 1976, Fundamentals of Rock Mechanics., Chapman & Hall Ltd., London, UK.
- Krohn C.E.**, 1983, Geophone ground coupling., Geophysics, Vol.49, No.6, June, pp. 722-731.
- Kjartansson E.**, 1979, Constant Q-wave propagation and attenuation., J Geophys., Vol. 84, pp. 4737-4748
- Kolsky H.**, 1963, Stress waves in solids., Constable & Co., London, England.
- Levenspiel O.**, 1972, Chemical reaction engineering., John Wiley & Sons Inc., New York.
- Luco J.E. and Wong H.L.**, 1982, Response of structures to nonvertically incident seismic waves., Bull. Seism. Soc. Am., Vol 72, pp. 275-302
- Miller D.K. , Yancey B. and Matheson G.**, 1999, Vibration and airblast standards for underwater blasting in Virginia., Proceeding 25<sup>th</sup> Annual Conference on Explosives and Blasting Techniques, Nashville, Tennessee, USA, 7-10 February, pp. 65-71.
- Moore P.J.**, 1985, Analysis and Design of Foundations For Vibrations., A.A.Balkema, Rotterdam, Netherlands, pp. 157-193
- Mulholland M. and Jones C.R.**, 1969, Fundamentals of Statistics., Butterworth & Co., Australia, pp. 93-110

**Obert L. and Duvall W.I.**, 1957, "Micro-seismic method of determining stability of underground openings", US Bur Mines, Bul. no. 573, 17p

**Persson P-A, Holmberg R. and Lee J.**, 1994, Rock blasting and explosives engineering, CRC Press, Florida, USA, pp. 105

**Read H.H.**, 1970, Rutley's Elements of Mineralogy, George Allen & Urwin Ltd., London, England, pp. 199-219

**Rossmann H.P. ed.**, 1983, Rock fracture mechanics., No. 275, Int. Centre Mech. Science, New York, pp. 229-251

**Rowe J, Blair D., Molloy K. and Armstrong L.W.**, 1999, Bayswater Coal Mine trial evaluating development product BB 509., Internal Report No. 58108, ORICA Australia Pty. Ltd., pp. 1-25

**Sen G.C., Yang H-S and Ju J-S**, 1996, Ground vibration generated by blasting and construction equipment – A comparison., J. Explosives Engineering, V.13, No.4, Jan-Feb, pp. 25-32

**Siskind D.E.**, 1986, Frequency analysis and the use of response spectra for blast vibration assessment in mining., Proceedings of 12<sup>th</sup> Annual Symposium on Explosives and Blasting Research, Orlando, Florida, 4-8 February, pp.1-11.

**Siskind D.E.**, 1998, Site procedures for a blast vibration program and impact assessment., Proceeding 25<sup>th</sup> Annual Conference on Explosives and Blasting Techniques, Nashville, Tennessee, USA, 7-10 February, pp. 287-296.

**Snedecor G.W. and Cochran W.G.**, 1971, Statistical Methods., Iowa State University Press, Iowa, USA, pp. 32-65.

**Toomik A. and Tomberg T.**, 1998, Blast vibrations in oil shale underground mining., Estonian Academy of Sciences, Institute of Chemistry, Oil Shale, Vol.15, No.1, pp. 65-

**Warburton G.B.**, 1957, Forced Vibration of a body on an elastic stratum., Appl. Mech., V24, pp. 55-58

**White J.E.**, 1983, Underground sound. Application of seismic waves., Elsevier Science Publishing Co. Inc., New York, USA, pp. 83-138

**Wolf J.P. and Somaini D.R.**, 1986, Approximate dynamic model of embedded foundation in time domain., Earthquake eng. struct. dyn., Vol 4, pp. 683-703



## BIBLIOGRAPHY

**Armstrong L.W.**, 1998, Evaluation of vibration wave velocity at Bulga Mine., Internal Report , ORICA Australia Pty. Ltd., pp. 1-10

**Armstrong L.W., Blair D.P. and Nagarajan M.**, 1998, Control blasting near electricity power poles., Internal Report No. 57777, ORICA Australia Pty. Ltd., pp. 1-25

**Armstrong L.W., Law T.M. and Brodbeck A.**, 1999, Vibration monitoring and blasting close to residential buildings. Cleary Bros Bulky Goods Store Shellharbour, NSW., Internal Report No. 58118, ORICA Australia Pty. Ltd., pp. 1-15

**Berg E.**, 1974, Rayleigh waves from high gain long-period stations : signal extraction; amplitude determination; and separation of overlapping wave trains., USAF Air Force Office of Scientific Research, Contract No. AFOSR-74-2612.

**Blair D. P. and Armstrong L.W.**, 1996a, The use of ground vibration for the assessment of explosive product performance., Internal Report No. 57359, ORICA Australia Pty. Ltd., pp. 1-34

**Blair D. P. and Armstrong L.W.**, 1996b, The 12 massfire within the Charlotte Deeps orebody., Internal Report No. 57465, ORICA Australia Pty. Ltd., pp. 1-32

**Blair D. P. and Armstrong L.W.**, 1996c, Vibration assessment of a presplit with regard to open pit wall control., Internal Report No. 57479, ORICA Australia Pty. Ltd., pp. 1-25

**Blair D. P. and Armstrong L.W.**, 1998a, Environmental monitoring and modelling for Ebenezer Mine., Internal Report No. 57775, ORICA Australia Pty. Ltd., pp. 1-24

**Blair D. P. and Armstrong L.W.**, 1998b, Vibration assessment of presplits and pit wall response in the Fimiston Operations., Internal Report No. 57898, ORICA Australia Pty. Ltd., pp. 1-52

**Blair D. P. and Armstrong L.W.**, 1999a, Measurement and simulation of blast for the control of vibrations to the pit wall in KCGM's Fimiston Operations., Internal Report No. 58102, ORICA Australia Pty. Ltd., pp. 1-32

**Blair D. P. and Armstrong L.W.**, 1999b, The spectral control of ground vibration using electronic delay detonators., Internal Report No. 58106, ORICA Australia Pty. Ltd., pp. 1-32

**Blair D. P. and Armstrong L.W.**, 1999c, The spectral control of ground vibration using electronic delay detonators., International Journal of Blasting and Fragmentation 3: 1-32.

**Blair D.P. and Jiang J.J.**, 1995, Surface vibrations due to a vertical column of explosive., Int. J. Rock Mech. Sci. & Geomech. Abstr. Vol.32, No.2, pp. 149-154.

**Brent G.F. and Armstrong L.W.**, 1999, Trial of electronic delay detonators in a presplit at Mt. Thorley Mine., Internal Report, ORICA Australia Pty. Ltd., pp. 1-10

**Brent G.F., Blair D. P., Armstrong L.W. and Smith G.E.**, 1997, Assessment of presplits formed using electronic delay detonators at Mt. Thorley Mine., Internal Report No. 57663, ORICA Australia Pty. Ltd., pp. 1-33

**Coonan G.R.**, 1982, Transient vibration and complaints an empirical study of coal mine detonations., Proceedings 8th Conference on Explosives and Blasting Technique, SEE, Montville, Ohio, pp. 203-216

**Dowding C.H.**, 1999, Vibration control by direct measurement of crack response., Proceeding 25<sup>th</sup> Annual Conference on Explosives and Blasting Techniques, Nashville, Tennessee, USA, 7-10 February, pp. 349-357.

**Favreau R.F.**, 1969, Generation of strain waves in rock by an explosion in a spherical cavity., J. Geophysical Research, V. 74, No. 17, August 15, pp. 4267-4280

**Foster G.A.**, 1981, Structural response and human response to blasting vibration effects – is there a connection., Proceedings of the Seventh Conference on Explosives and Blasting Technique, Annual Meeting, Phoenix, Arizona, January 19-23, pp. 10-26

**Froedge D.T.**, 1995, Anomalies in blast vibration propagation., Sixth High Tech Seminar, Blasting Technology Instrumentation and Explosives Applications, Boston, Massachusetts, July 8-13, pp. 71-82.

**Halliwell G.**, 1980. Using Fourier transform analysers to investigate component vibration., Nuclear Engineering International, March, pp. 42-45

**Hashiba T. and Whitman R.V.**, 1968, Soil-structure interaction during earthquakes., Soils and Foundations, Vol. 8, pp. 1-12

**Hole L.R., Kaynia A.M. and Madshus C.**, 1998, Measurement and simulation of low frequency impulse noise and ground vibration from airblasts., J. Sound and Vibration, V. 214, No.2, Article No. sv981562

**ISRM**, 1992, Suggested method for blast vibration monitoring., Int. J. Rock Mechanics and Mining Sciences & Geomechanics, V. 29, No. 2, March, pp. 143-156

**Johnson C.F.**, 1962, Coupling small vibration gauges to soil., Earthquake Notes, Vol.33, pp. 40-47

**Kahrman A. and Tuncer G.**, 1999, Prediction of ground vibration produced from bench blasting., Proceeding 25<sup>th</sup> Annual Conference on Explosives and Blasting Techniques, Nashville, Tennessee, USA, 7-10 February, pp. 379-386.

**Kamperman G.W.**, 1980, Human response to blasting noise and vibration., Inter.Noise 80, Miami, Florida, USA, 8-10 December, pp. 979-984.

**Keil L.D., Burgess A.S., Neilsen N.M. and Koropatnick A., 1977, Blast vibration monitoring of rock excavations., J. Can. Geotech., Vol. 14, pp. 603-619.**

**Kolsky H., 1963, Stress Waves in Solids., Dover Publications, New York.**

**Leong E.C., Cheong H.K. and Pan T.C., 1996, A device for the measurement of sub-surface ground vibrations., Geotechnical Testing Journal, GTJODJ, Vol. 19, No. 3, September, pp. 286-296.**

**Madshus C., Bessason B., Stordal A. and Jenssen A., 1996, Dynamic shock wave measurements in coarse saturated rock fill., Norwegian Geotechnical Institute, No.195, 14p.**

**Mendecki A.J., 1997, Seismic Monitoring in Mines., Chapman & Hall, University Press, Cambridge**

**Romberg T.M., Cassar A.G. and Harris R.W., 1984, A comparison of traditional Fourier and maximum entropy spectral methods for vibration analysis., Transactions of the ASME, V. 106, January, pp. 36-39.**

**Sames F., 1995, Vibration controlled blast timing optimization using the seed waveform modeling concept., Sixth High Tech Seminar, Blasting Technology Instrumentation and Explosives Applications, Boston, Massachusetts, July 8-13, pp. 25-34.**

**Sames F. and Hivick R., 1999, Techniques to assess the influence of blast design parameters on airblast and blast vibration., Proceeding 25<sup>th</sup> Annual Conference on Explosives and Blasting Techniques, Nashville, Tennessee, USA, 7-10 February, pp. 297-307**

**Siskind D.E. and Stagg M.E., 1987, Blast vibration measurements near structures., Information Circular, USBM 9135, Washington, DC, pp. 46-50**

**Sperber A., Schildberg H-P. and Schlehlein S.,** 1996, Investigations on vibrations of a pipe caused by acetylene detonations using laser velocimetry., Proceedings of SPIE – The International Society for Optical Engineering, V.2868, pp. 275 – 284.

**Stagg M.E. and Siskind D.E.,** 1984, Effects of blast vibration on construction material cracking in residential structures., Proceeding 17<sup>th</sup> Annual Conference on Explosives and Blasting Techniques, Nashville, Tennessee, USA, 7-10 February, pp. 32-45

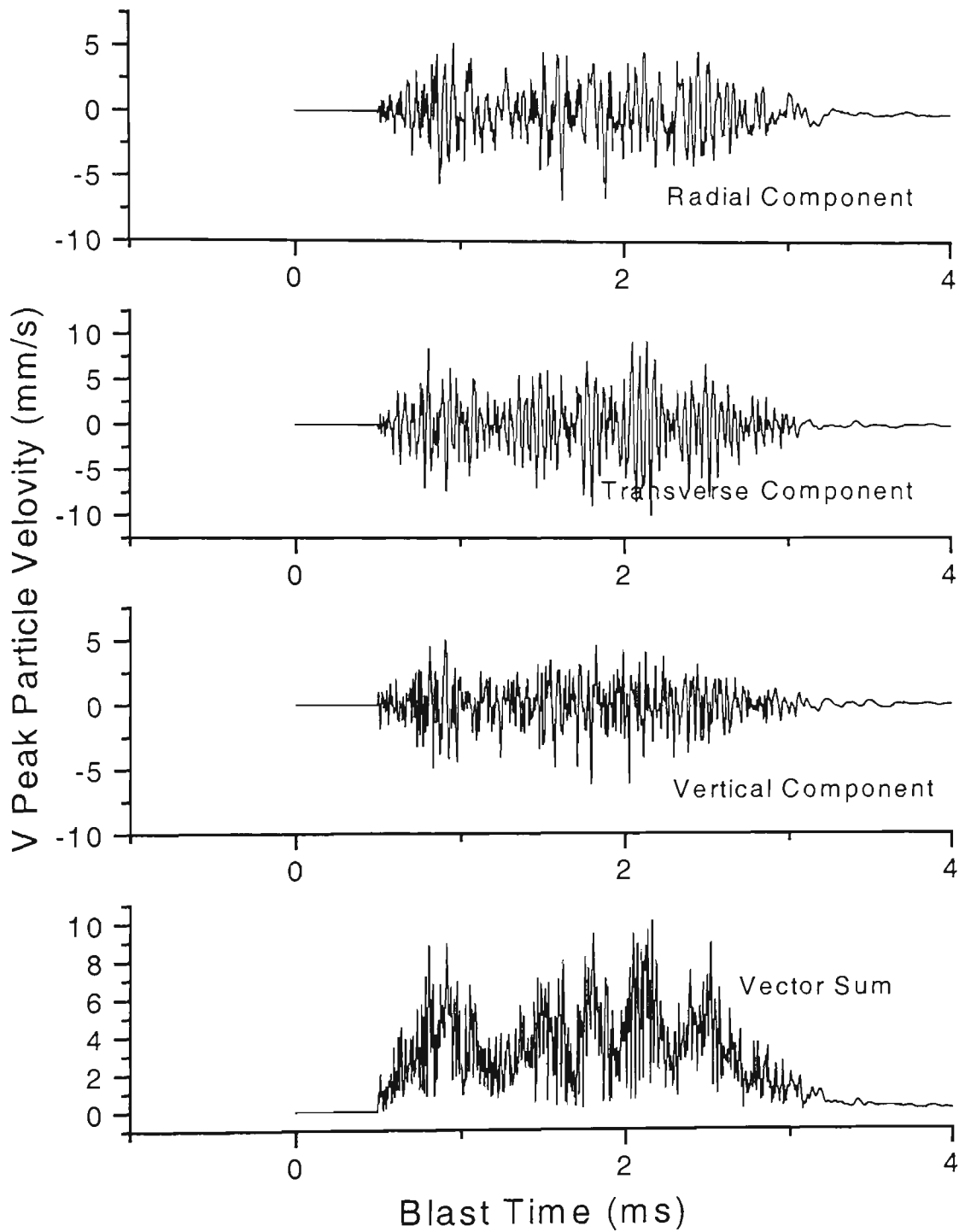
**Yang R., Bawdwn W.F., Talebi S. and Rocque P.,** 1993, An integrated technique for vibration monitoring adjacent to a blast hole., CIM Bulletin, V. 86, No. 972, July – August, pp. 45 – 52.

**Yang Y.,** 1985, A time domain identification technique: the oversized eigenmatrix (OEM) method., J. Vibration, Acoustics, Stress and Reliability in Design, V. 107, January, pp. 53-59.



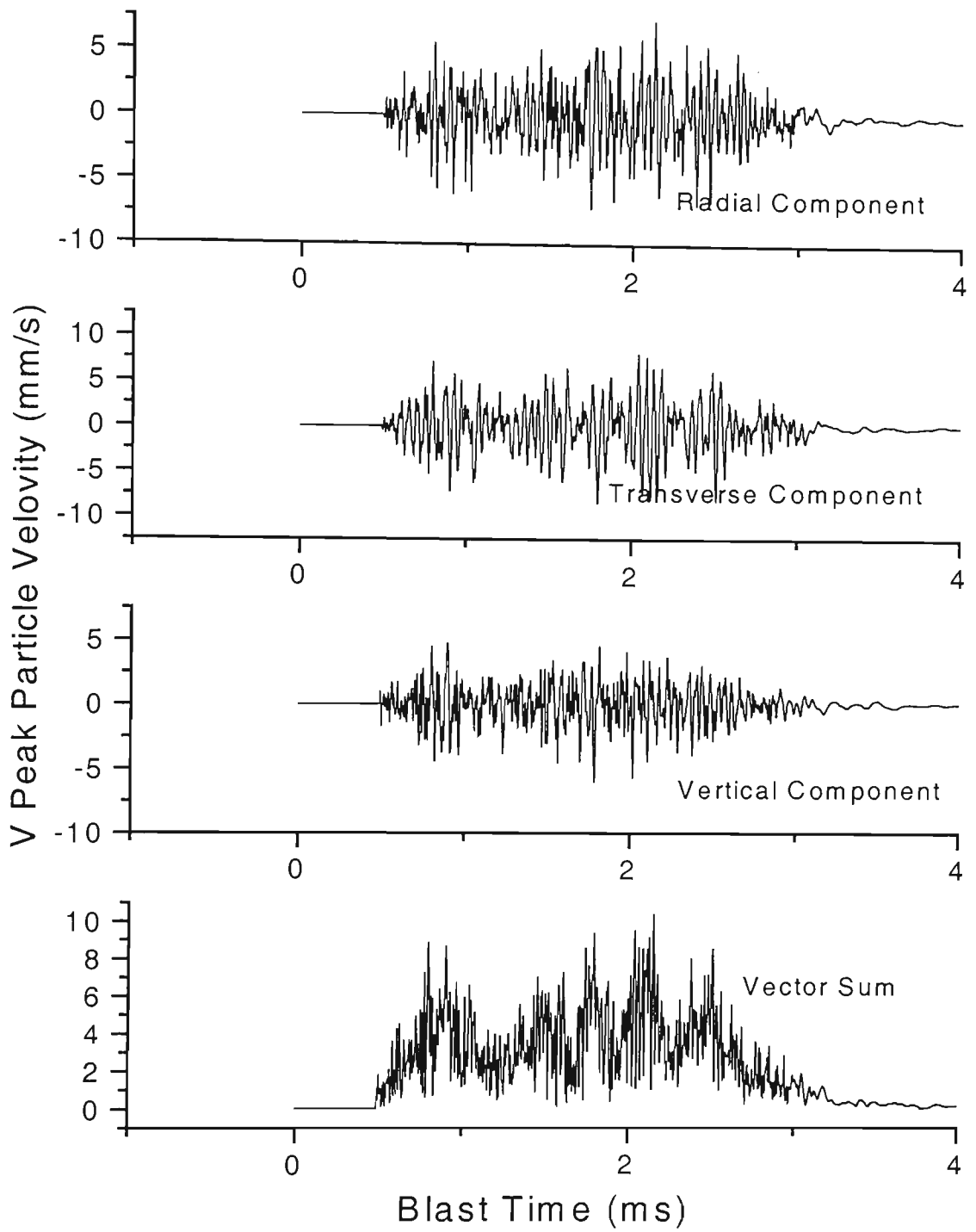
## APPENDICES

- Appendix 1. Vibration mount variability
- Appendix 2. Vibration mount comparison
- Appendix 3. Vibration mount density

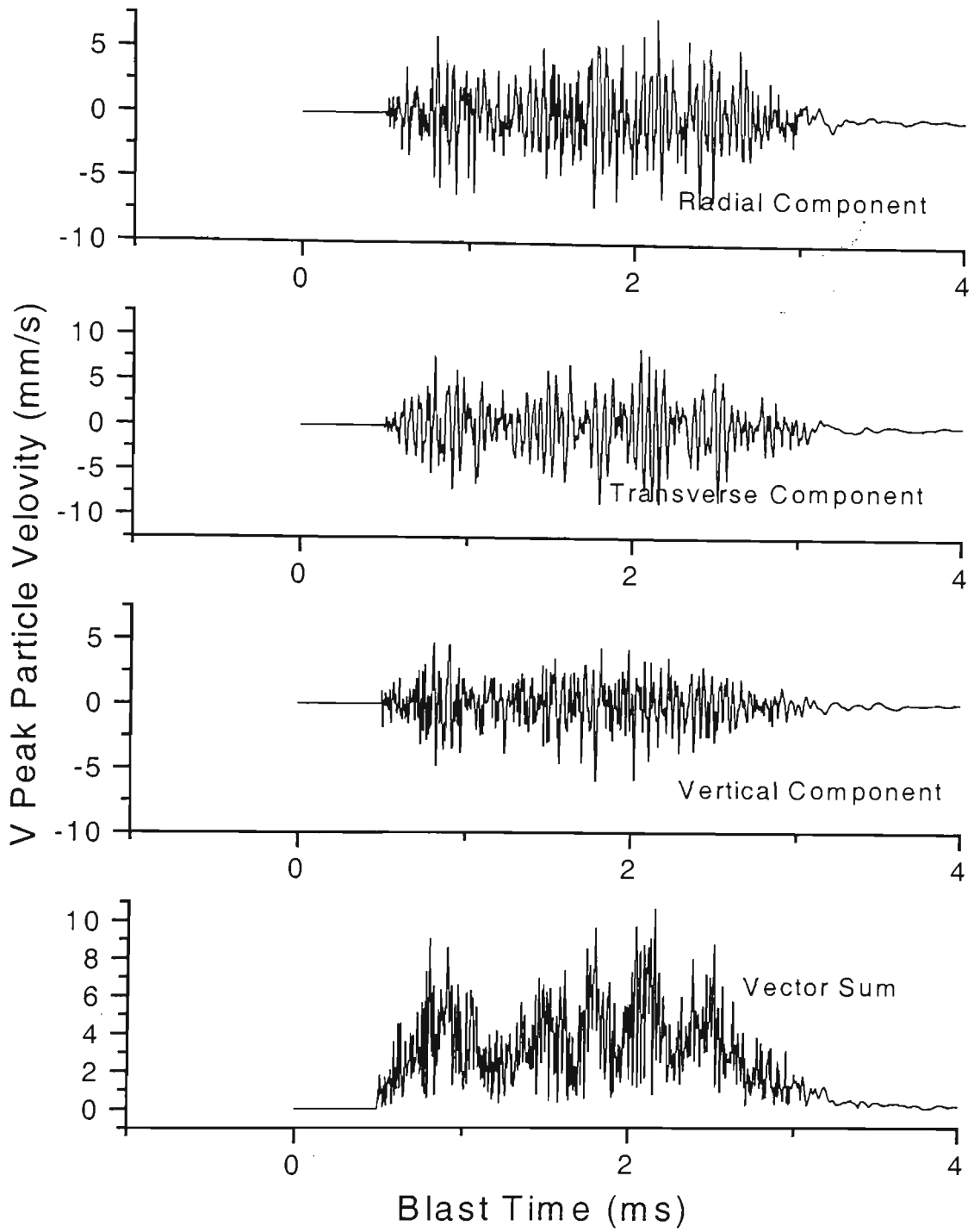


Appendix 1.1 Low vibration level – Monitor 049 – Mount variability

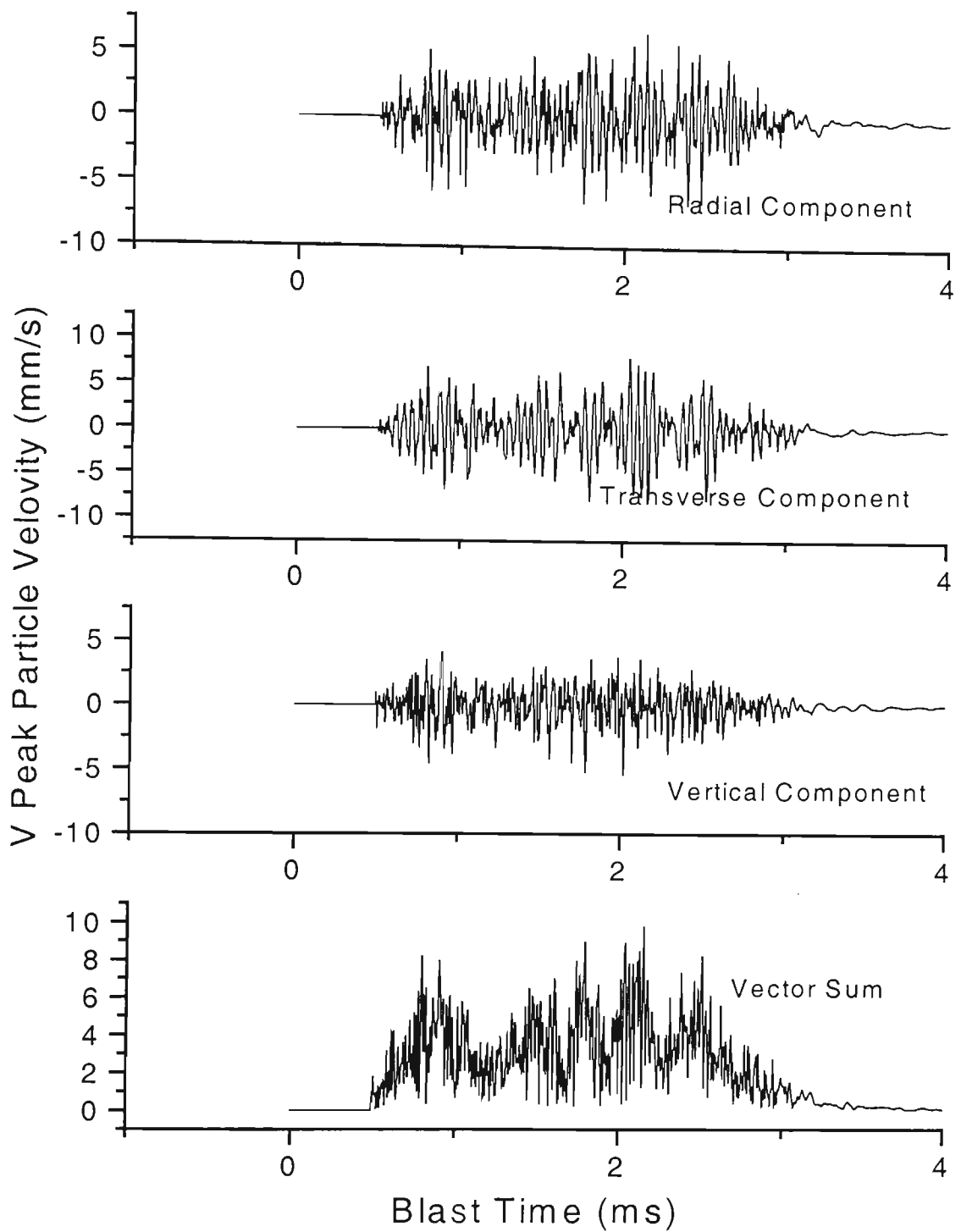




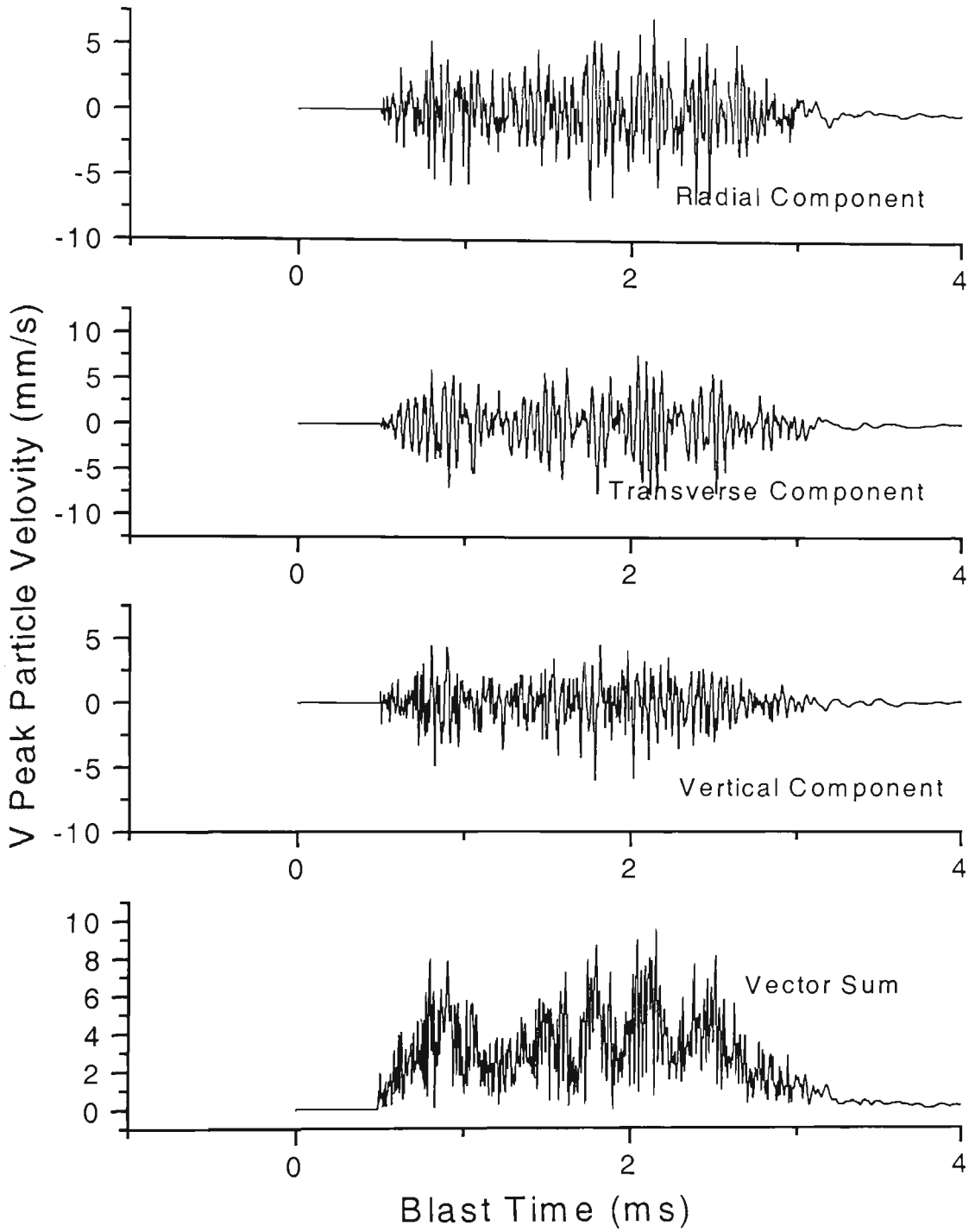
Appendix 1.2 Low vibration level – Monitor 050 – Mount variability



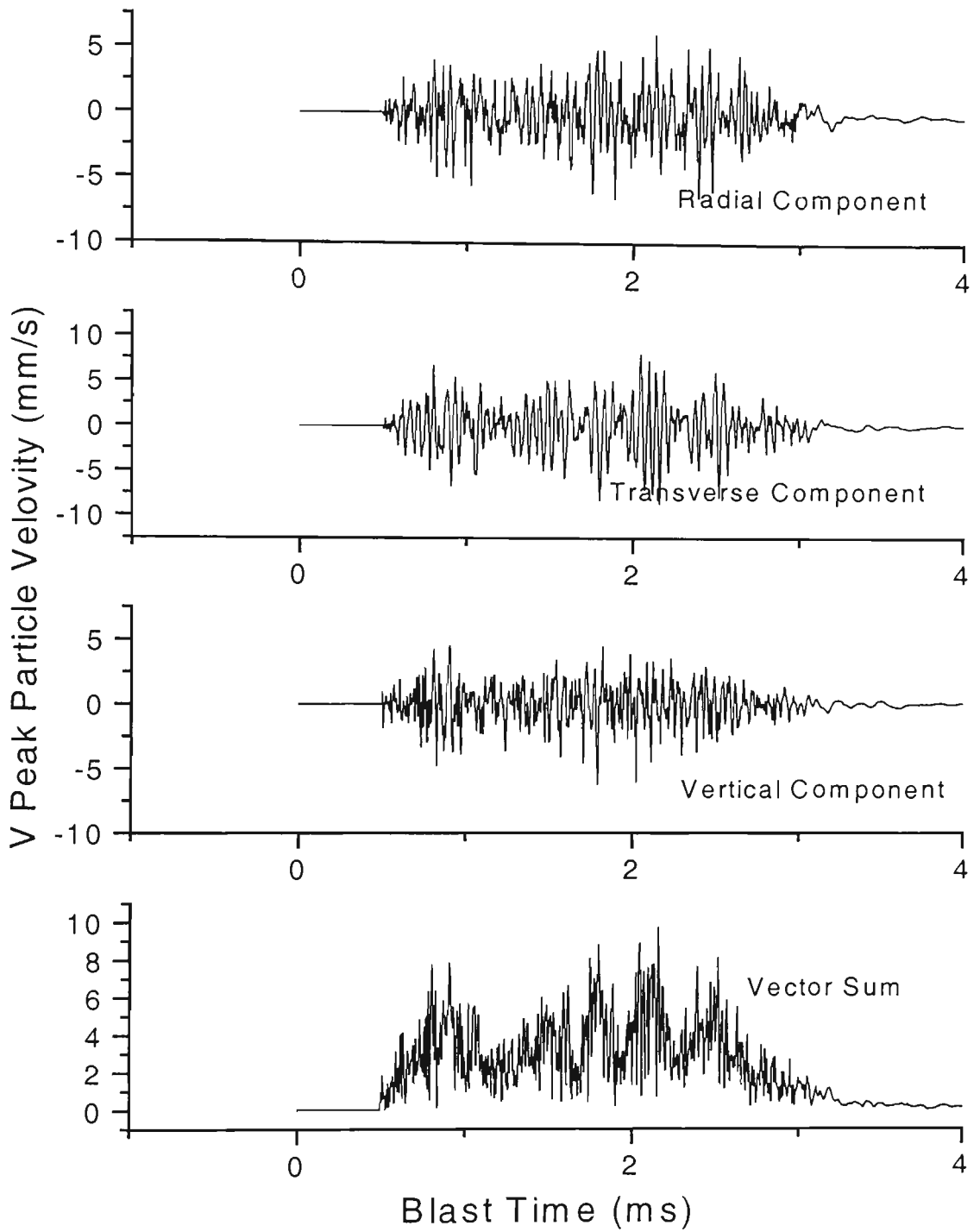
Appendix 1.3 Low vibration level – Monitor 074 – Mount variability



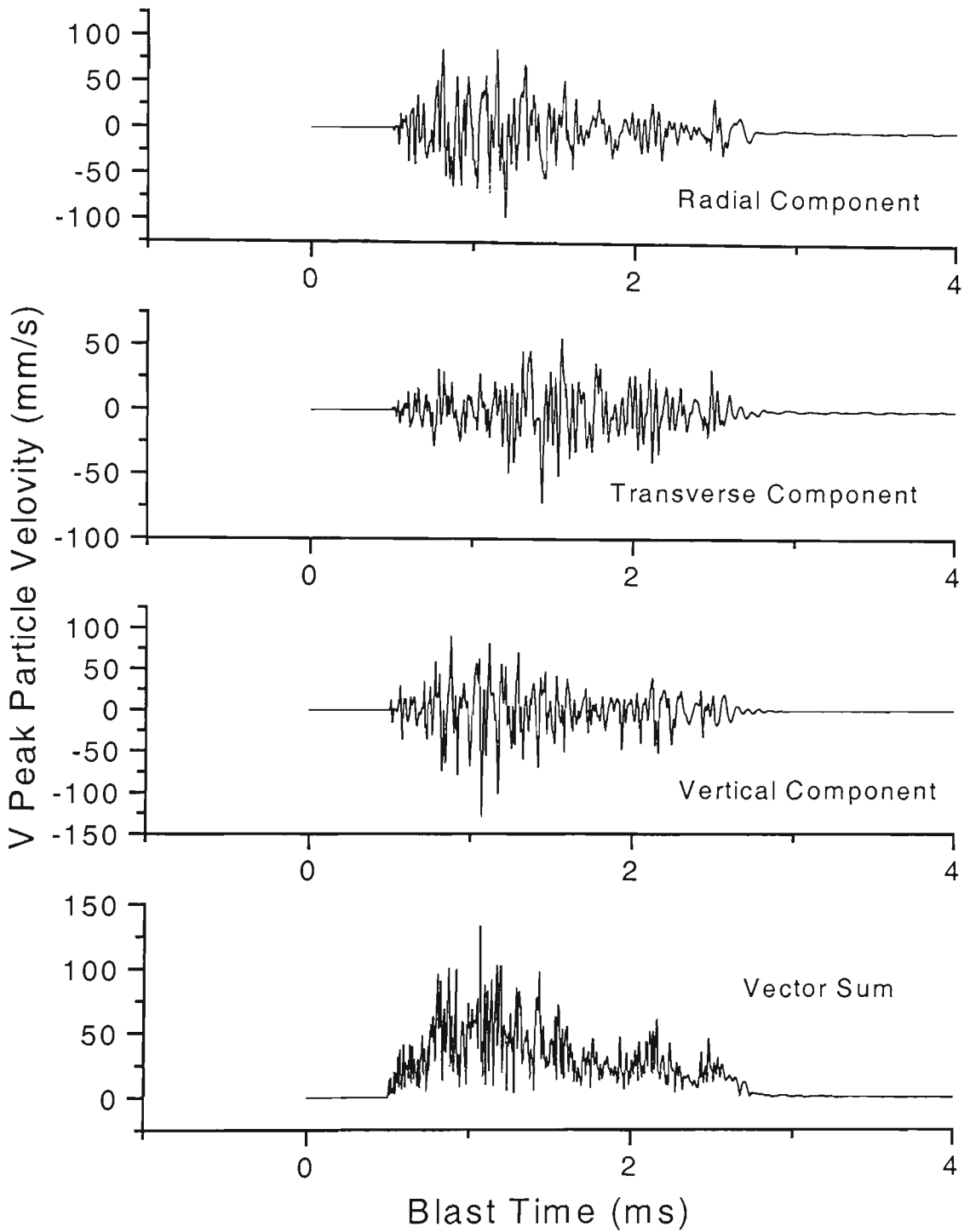
Appendix 1.4 Low vibration level – Monitor 075 – Mount variability



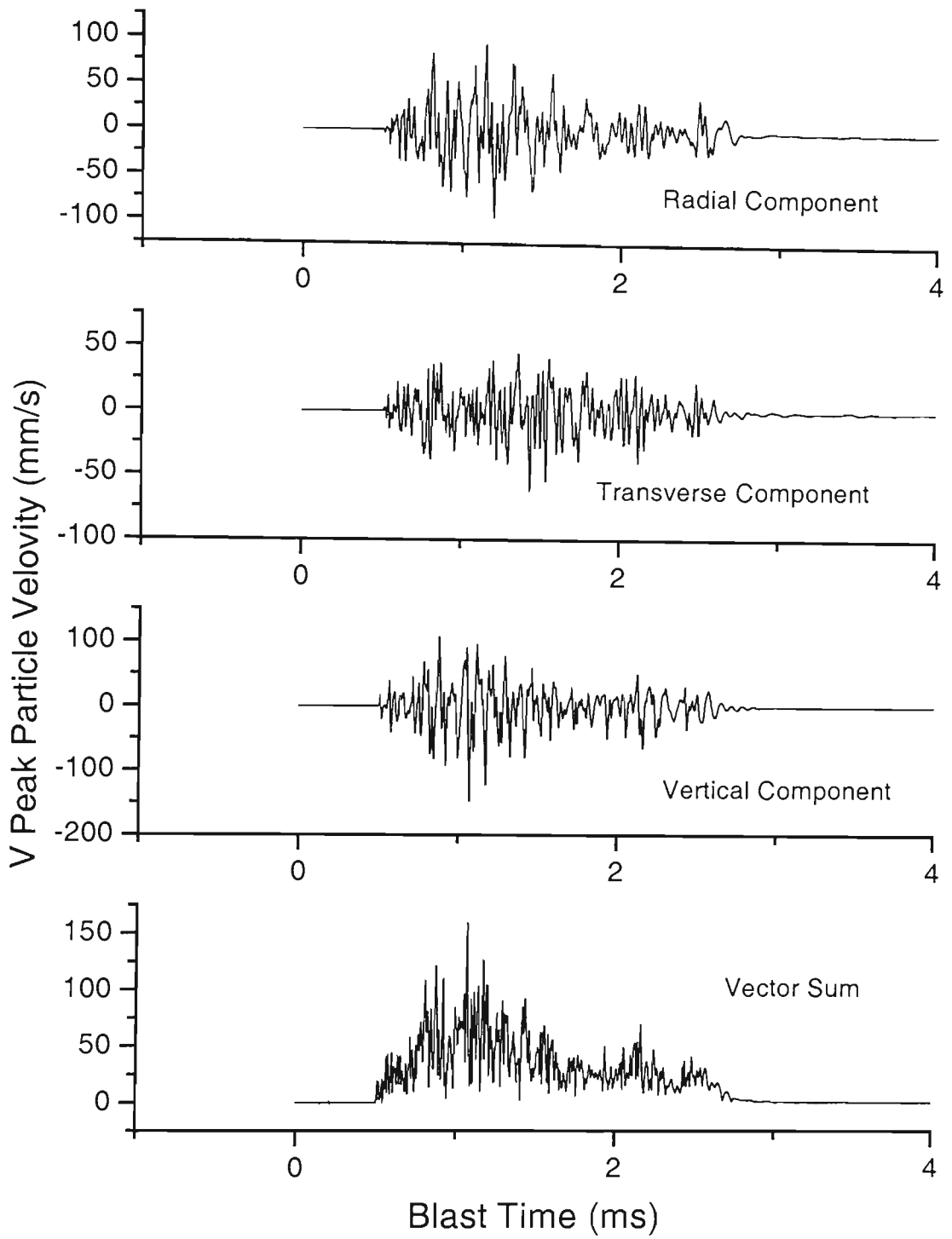
Appendix 1.5 Low vibration level – Monitor 132 – Mount variability



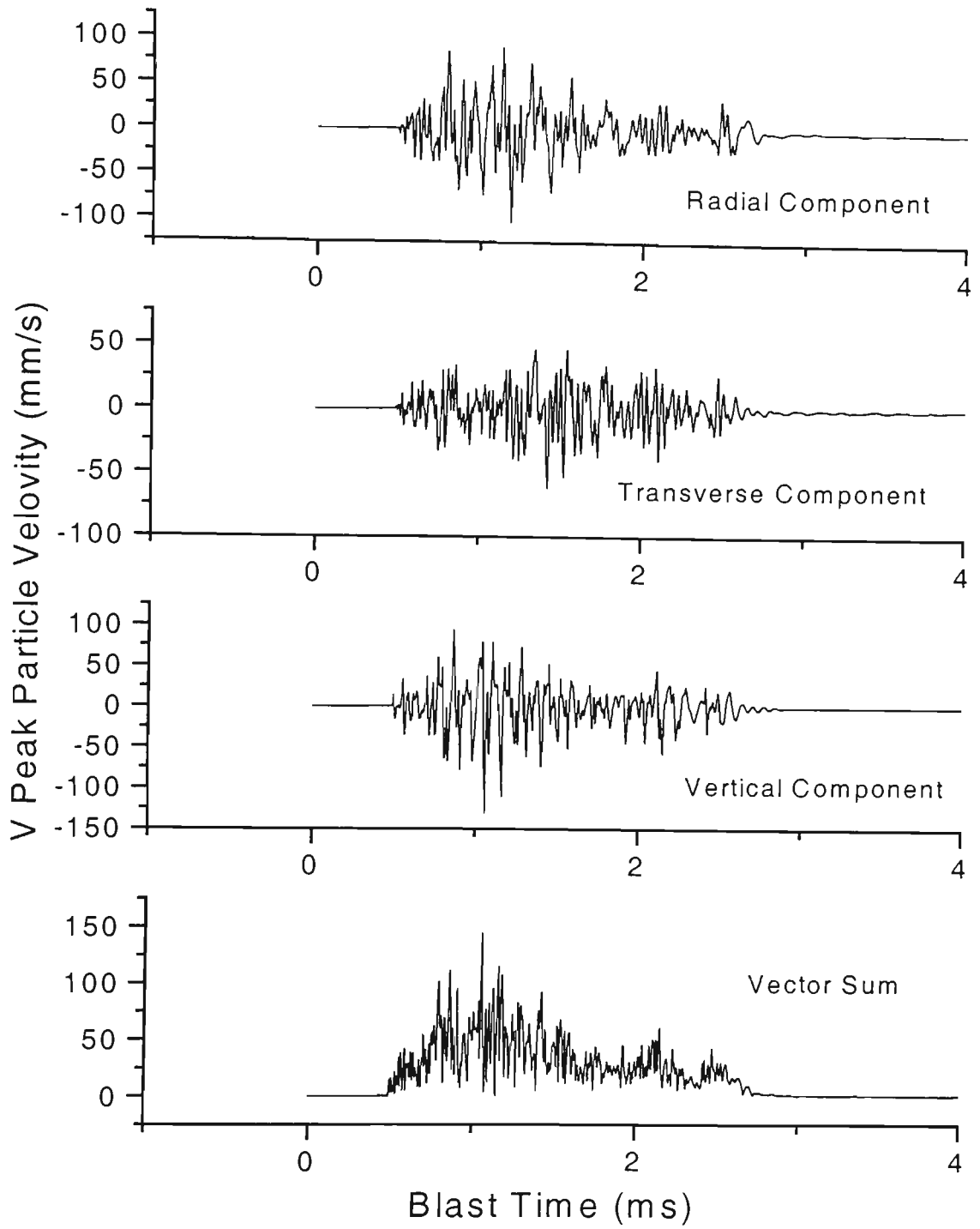
Appendix 1.6 Low vibration level – Monitor 153 – Mount variability



Appendix 1.7 High vibration level – Monitor 049 – Mount variability

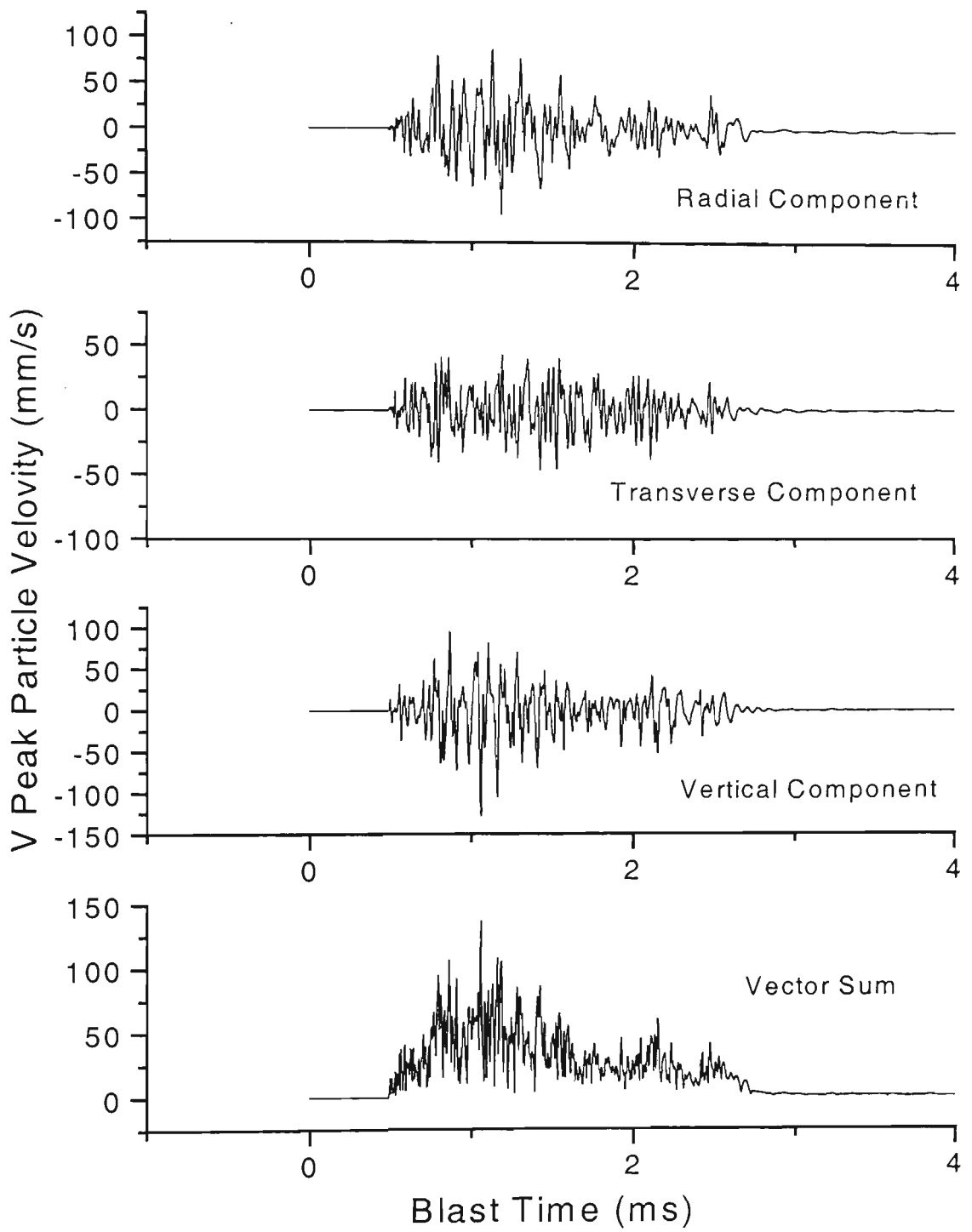


Appendix 1.8 High vibration level – Monitor 050 – Mount variability

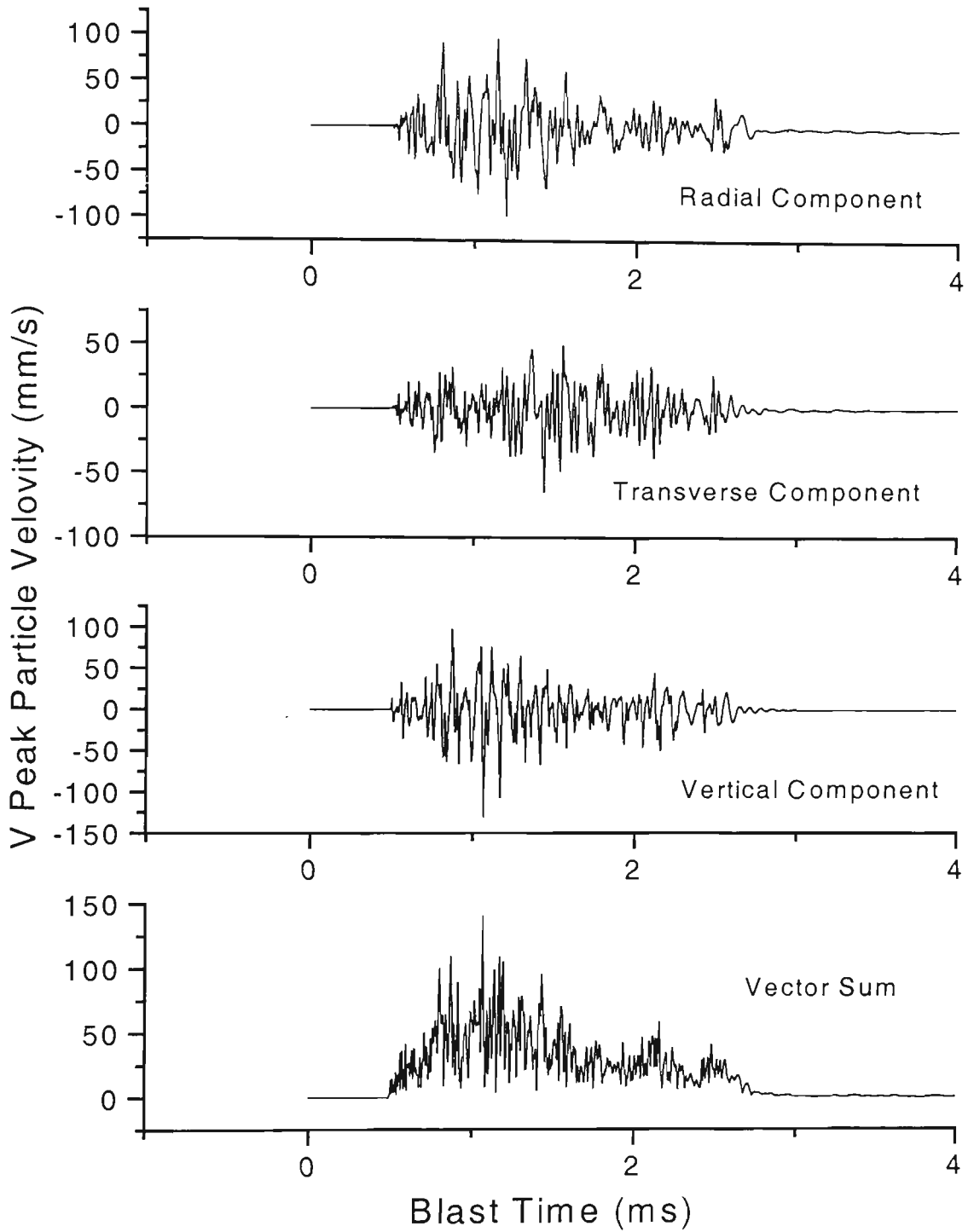


Appendix 1.9 High vibration level – Monitor 074 – Mount variability

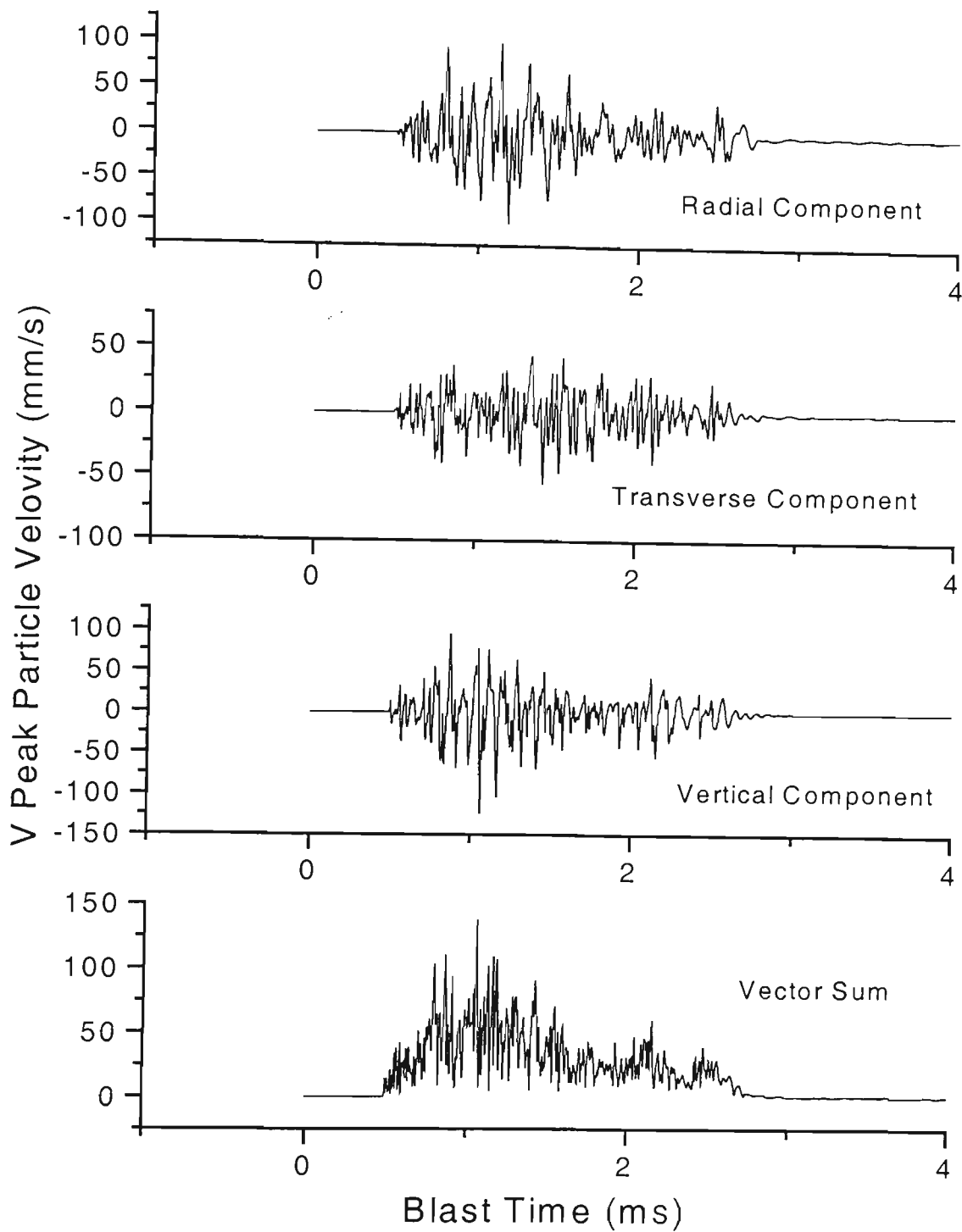




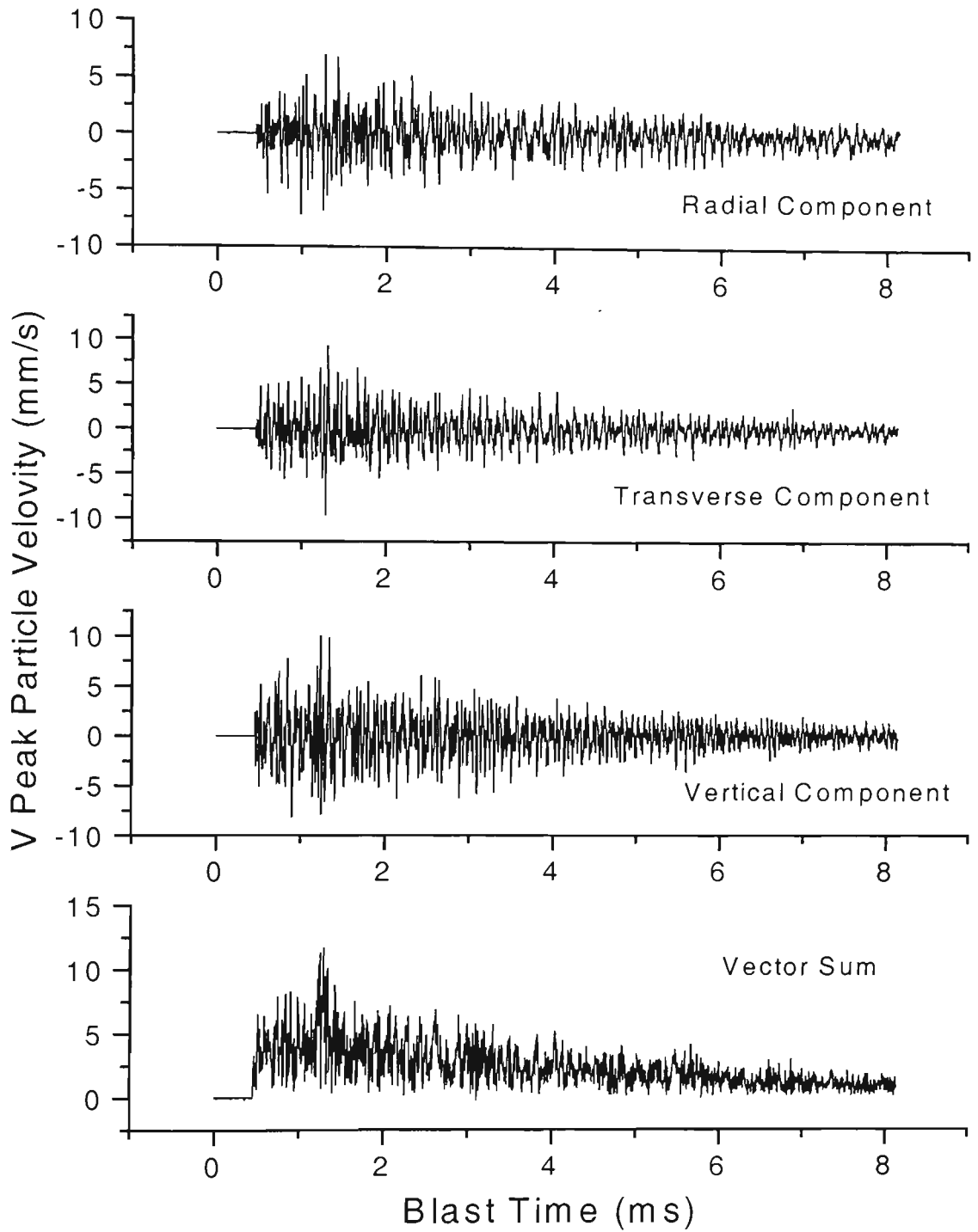
Appendix 1.10 High vibration level – Monitor 075 – Mount variability



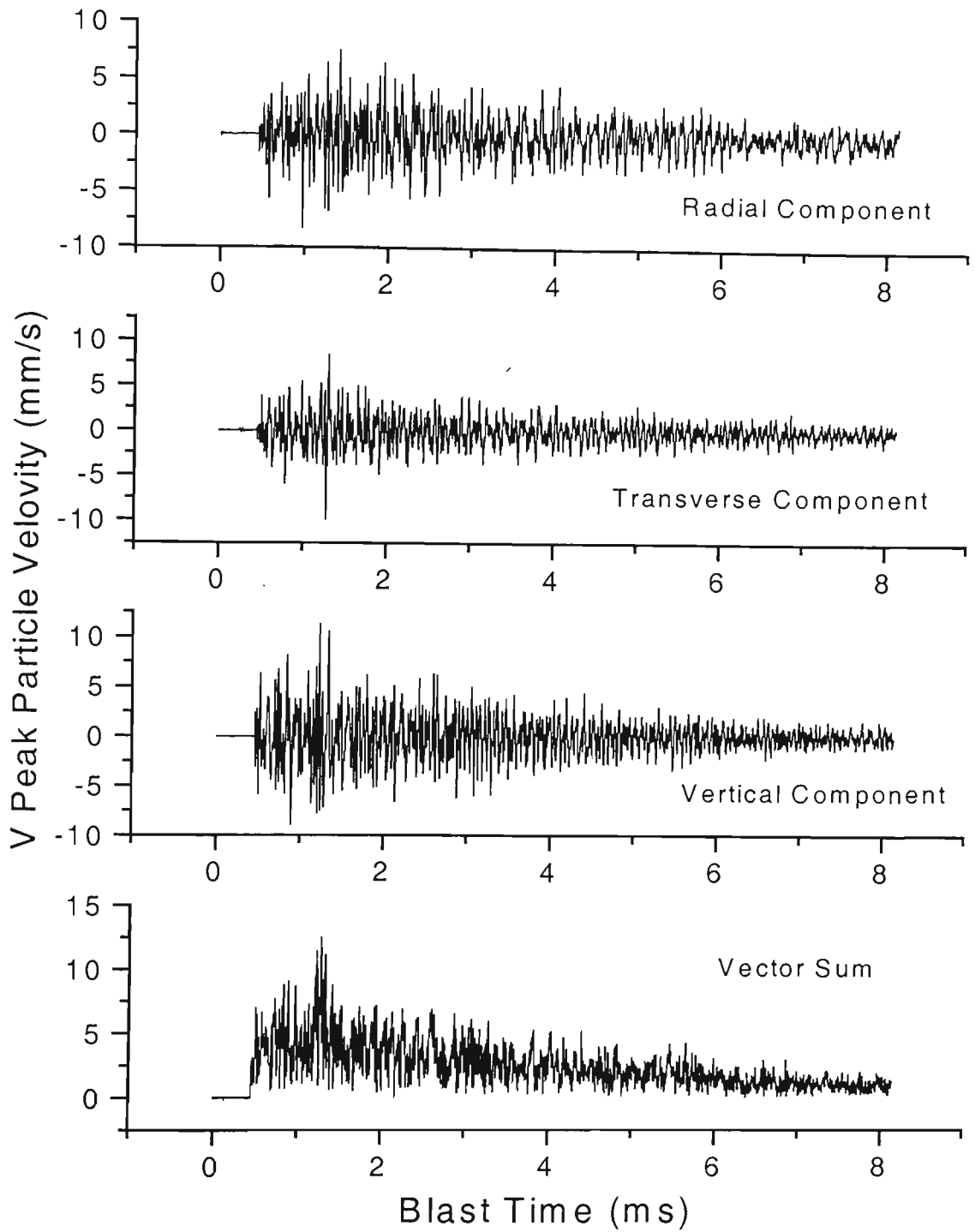
Appendix 1.11 High vibration level – Monitor 104 – Mount variability



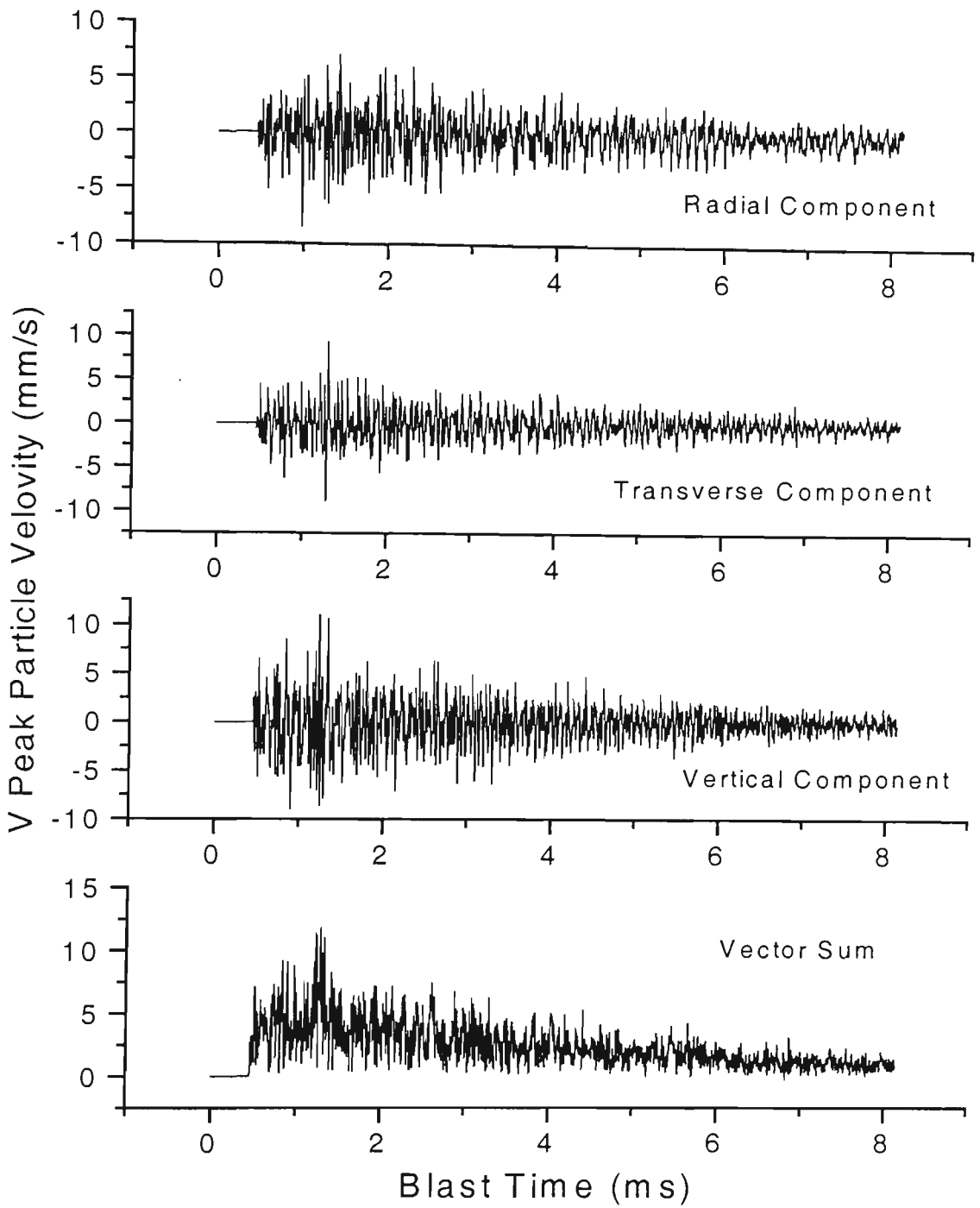
Appendix 1.12 High vibration level – Monitor 153 – Mount variability



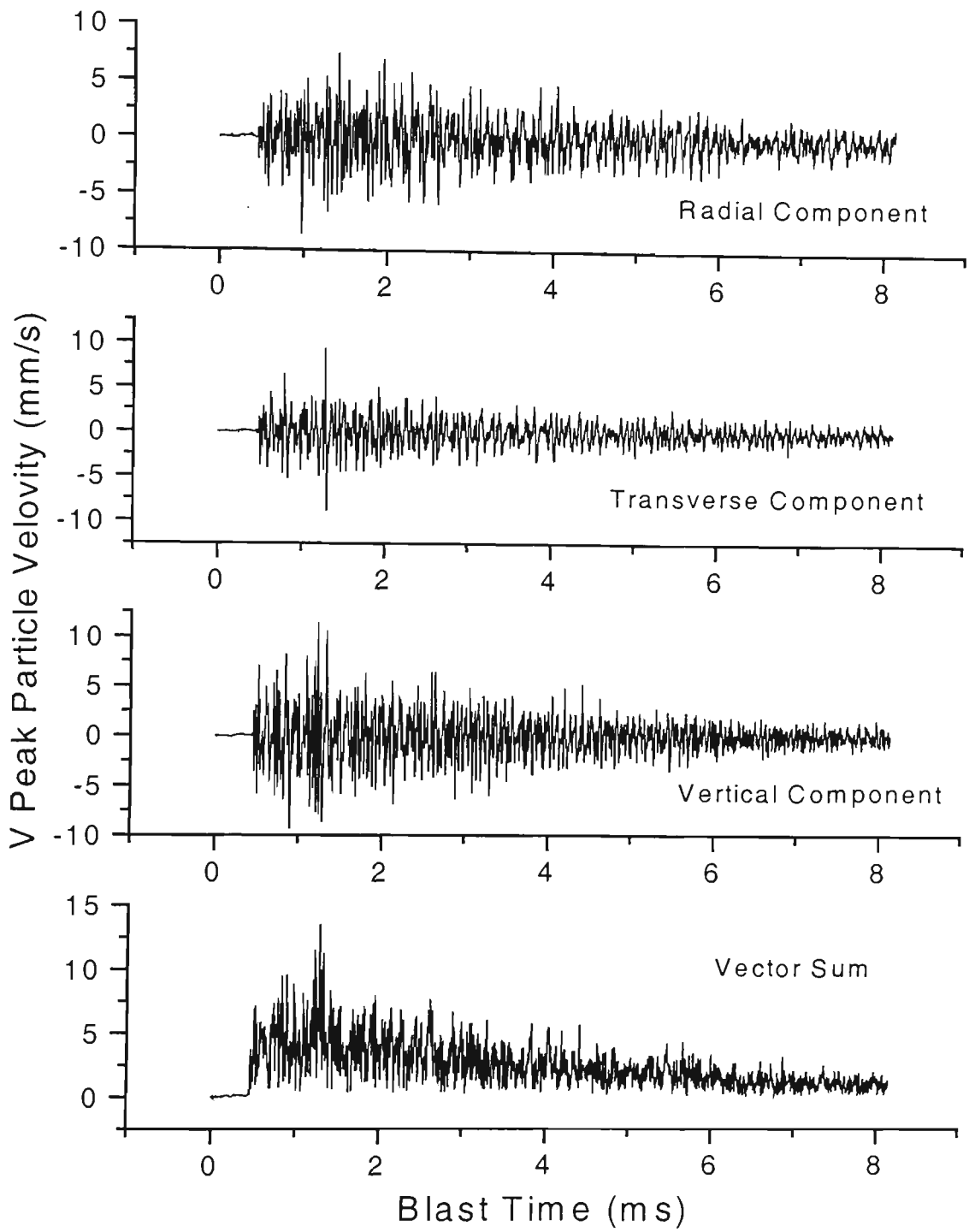
Appendix 2.1 Low vibration level – Sandbag mount – Mount comparison



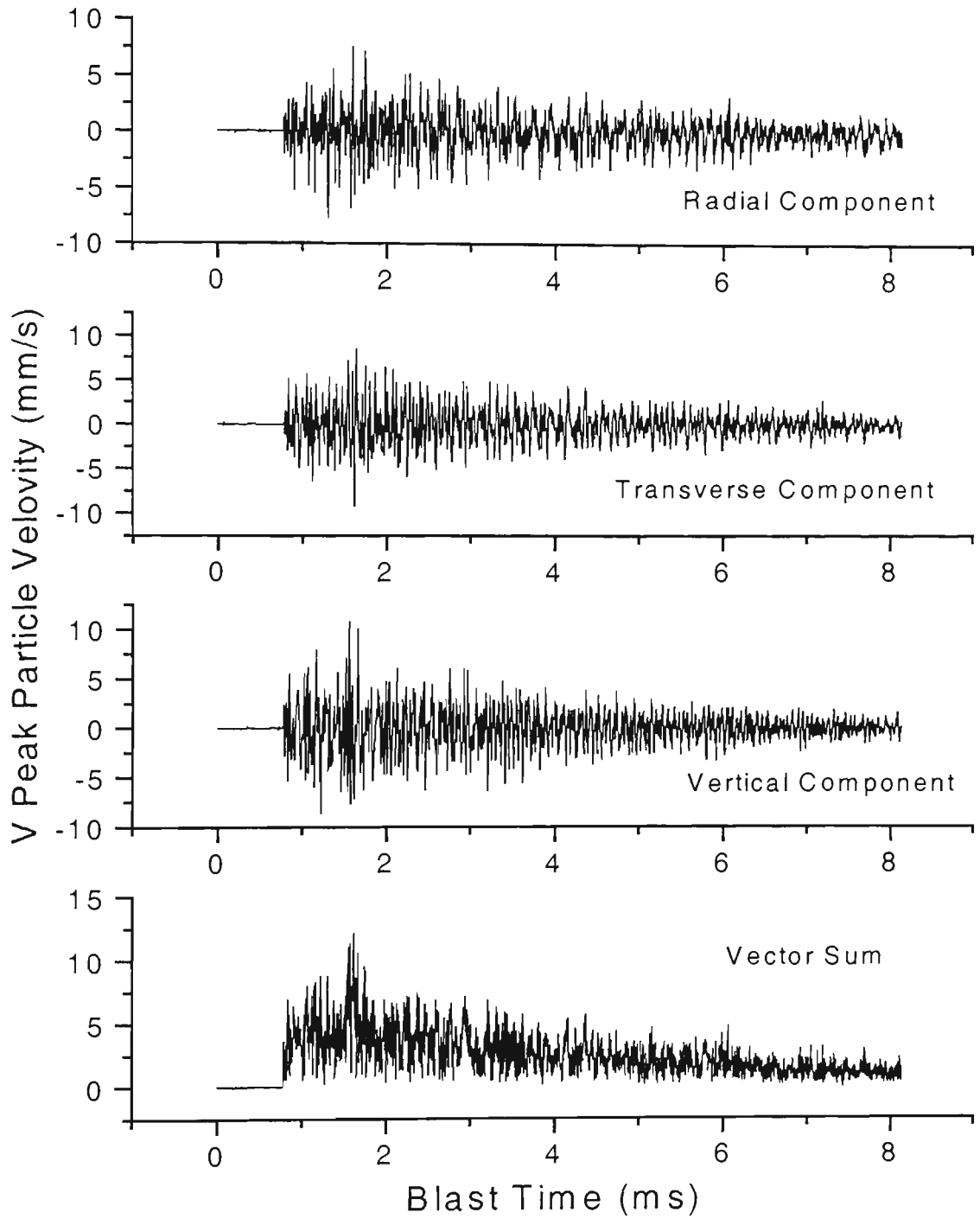
Appendix 2.2 Low vibration level – 1 Spike mount – Mount comparison



Appendix 2.3 Low vibration level – Concrete block mount – Mount comparison

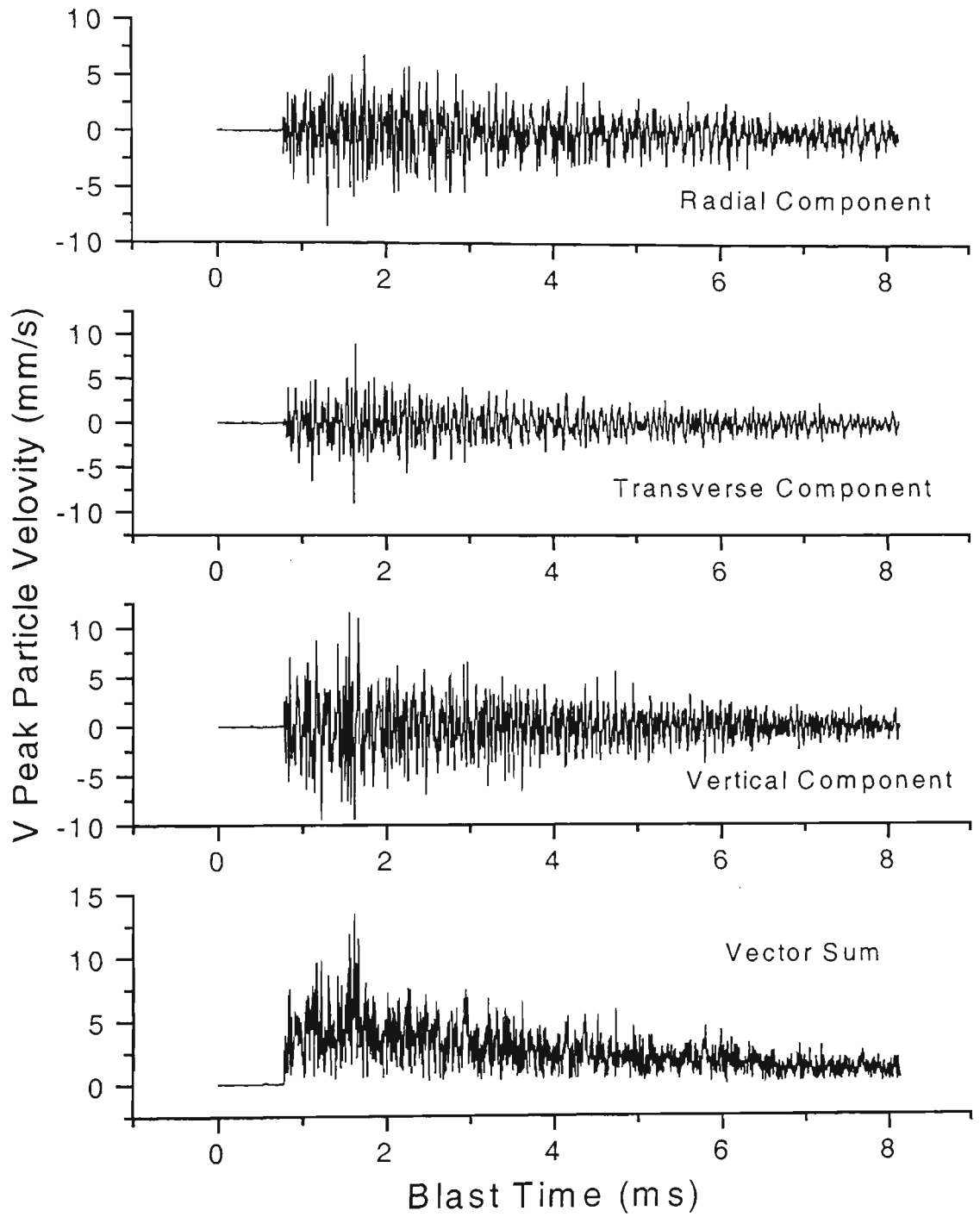


Appendix 2.4 Low vibration level – Standard mount – Mount comparison

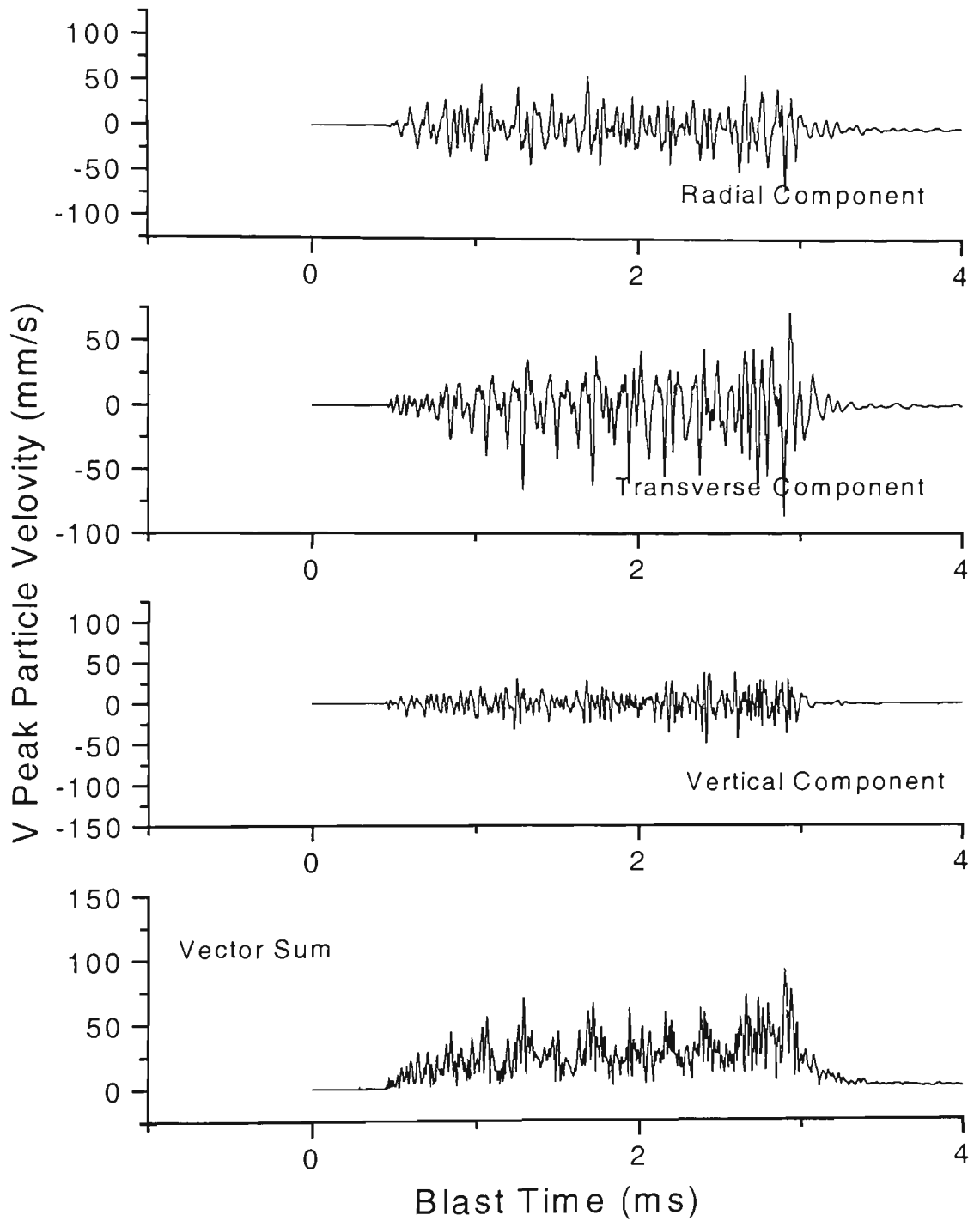


Appendix 2.5 Low vibration level – 3 Spike mount – Mount comparison

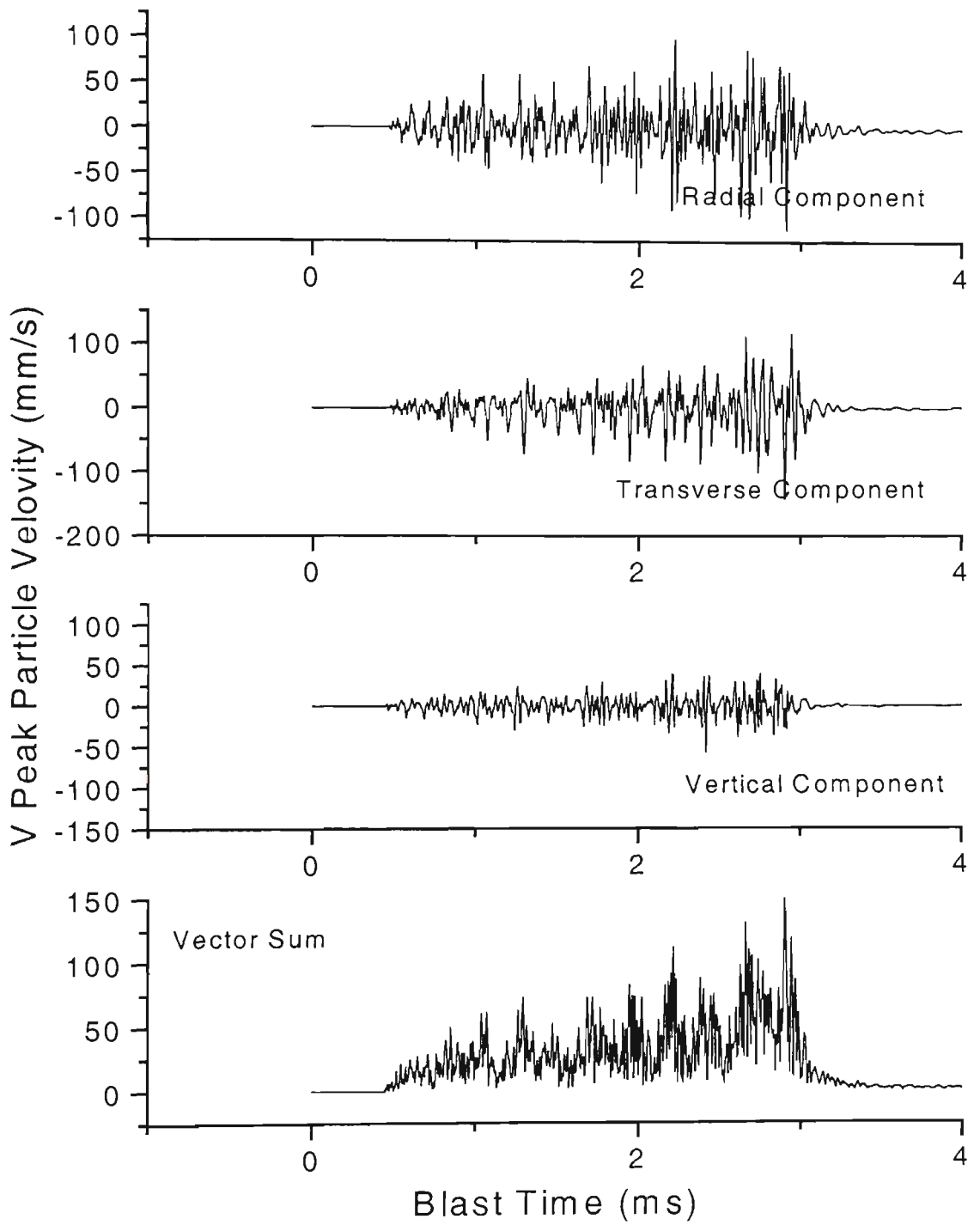




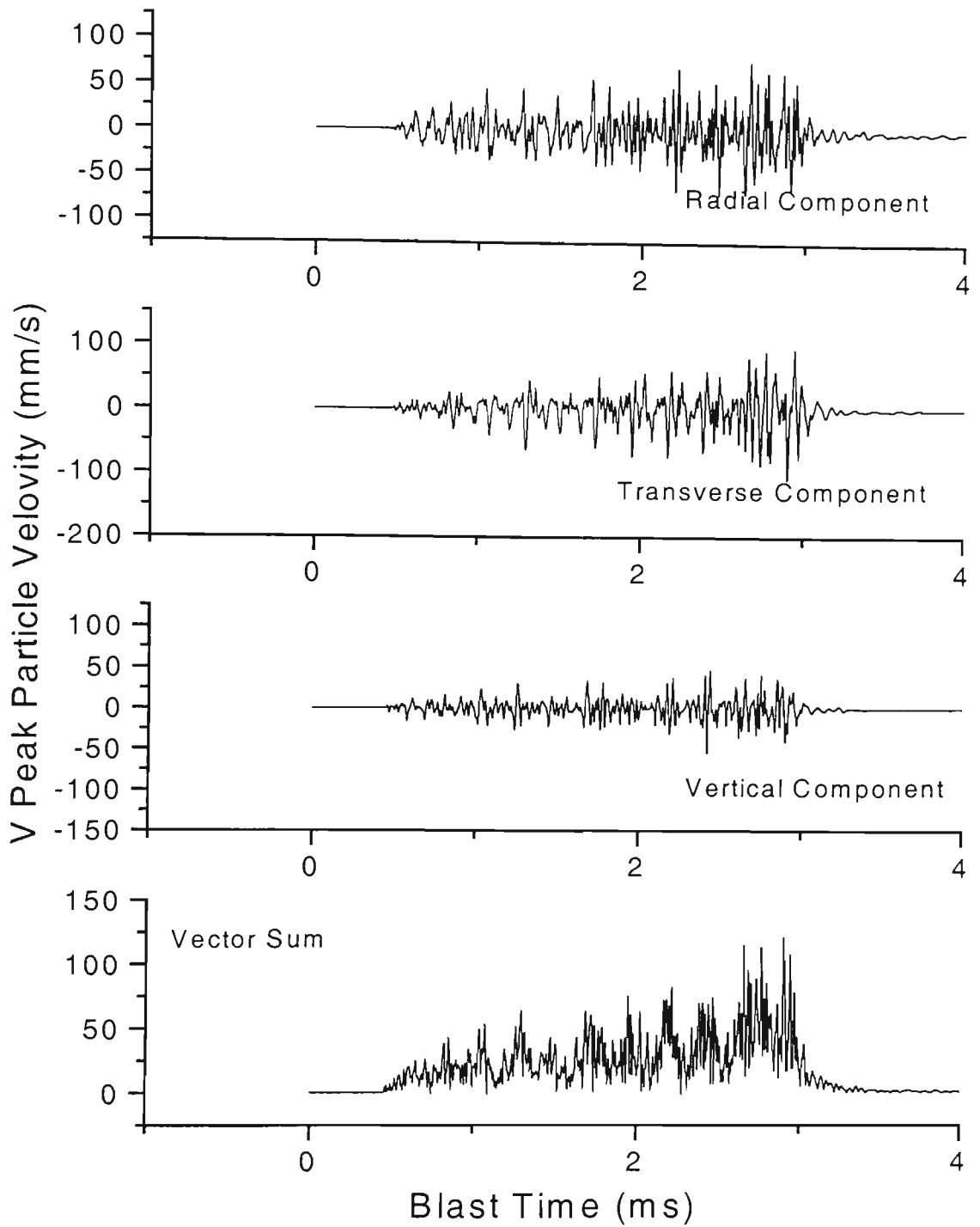
Appendix 2.6 Low vibration level – High frequency block – Mount comparison



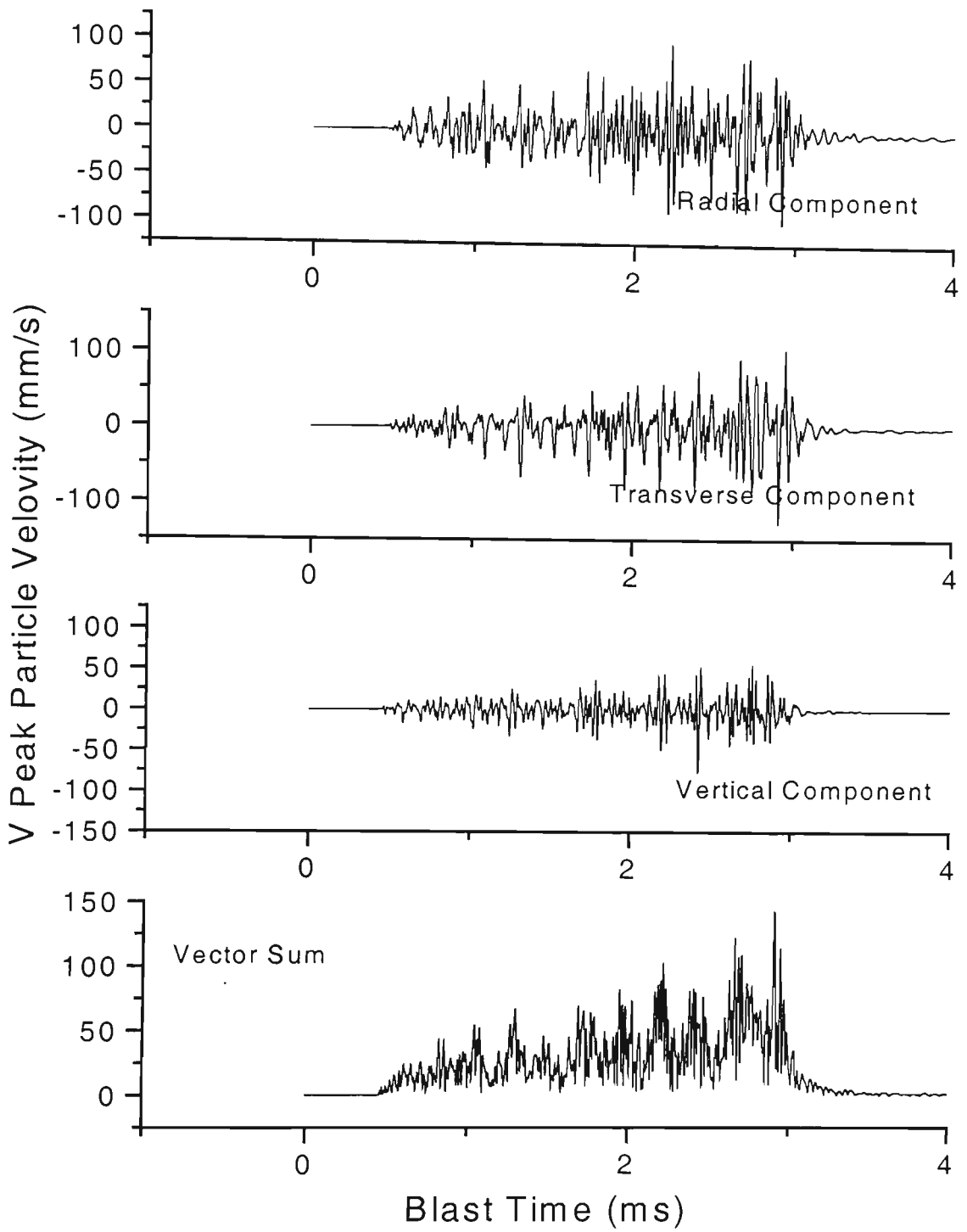
Appendix 2.7 High vibration level – Sandbag mount – Mount comparison



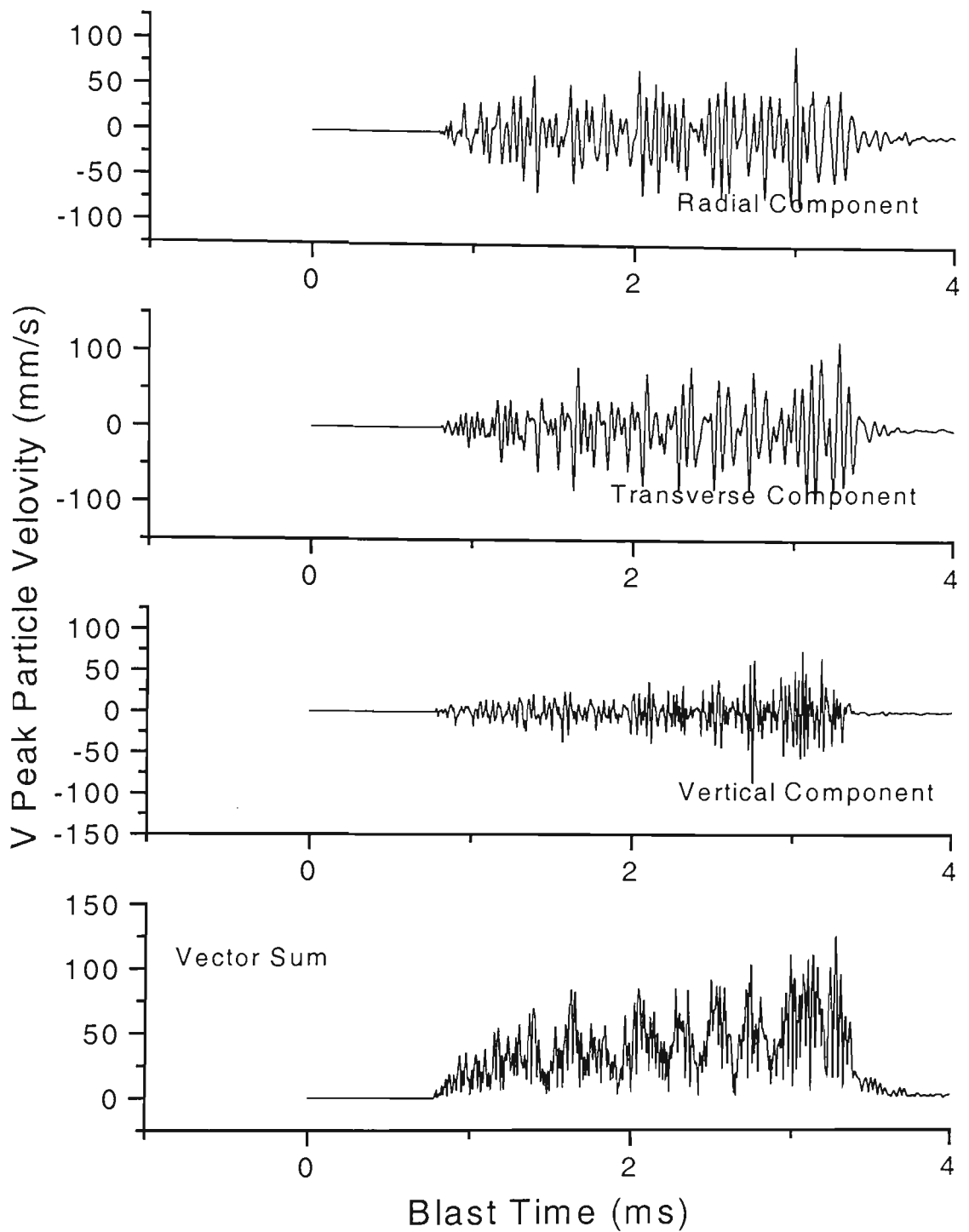
Appendix 2.8 High vibration level – 3 Spike mount – Mount comparison



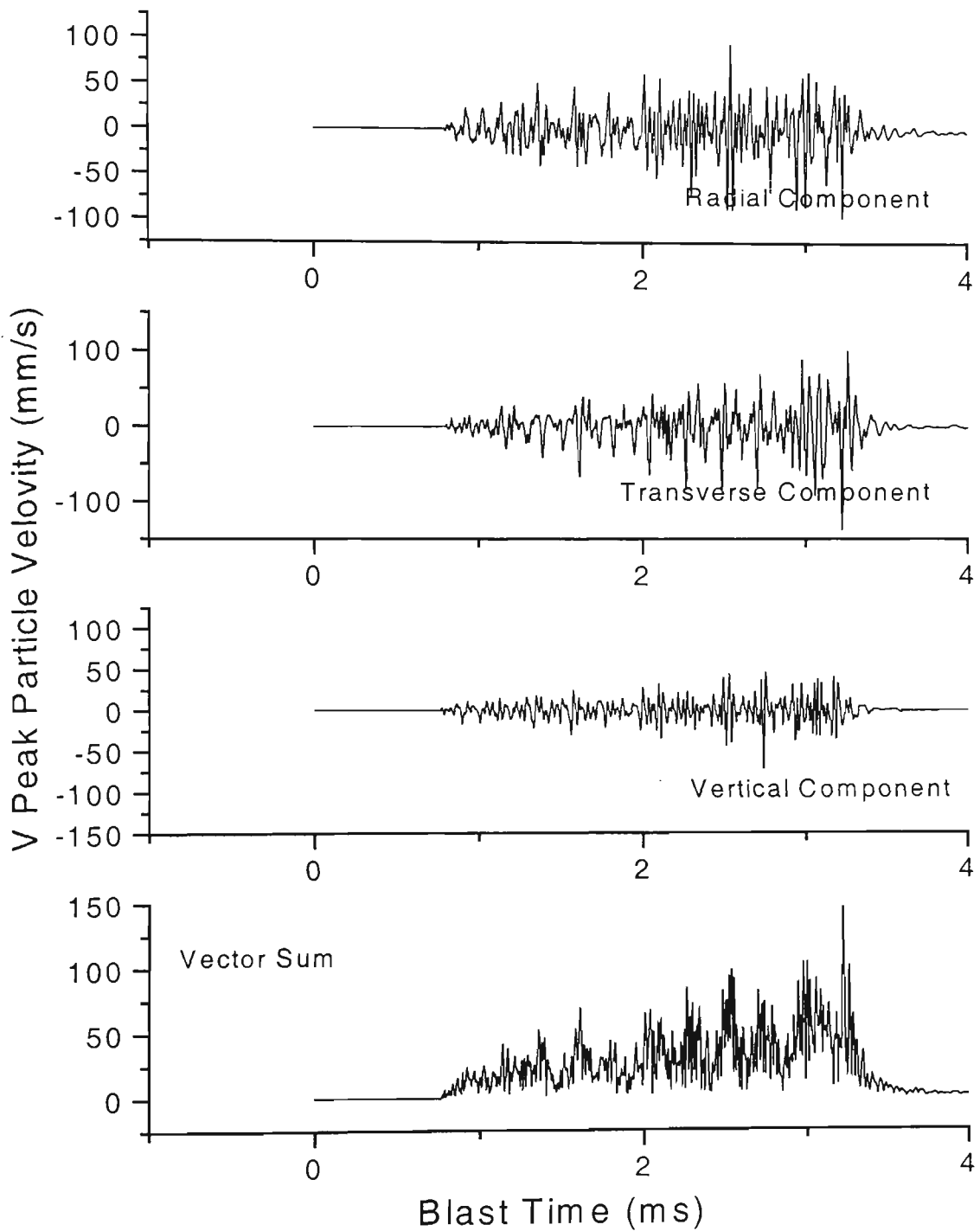
Appendix 2.9 High vibration level – High frequency mount – Mount comparison



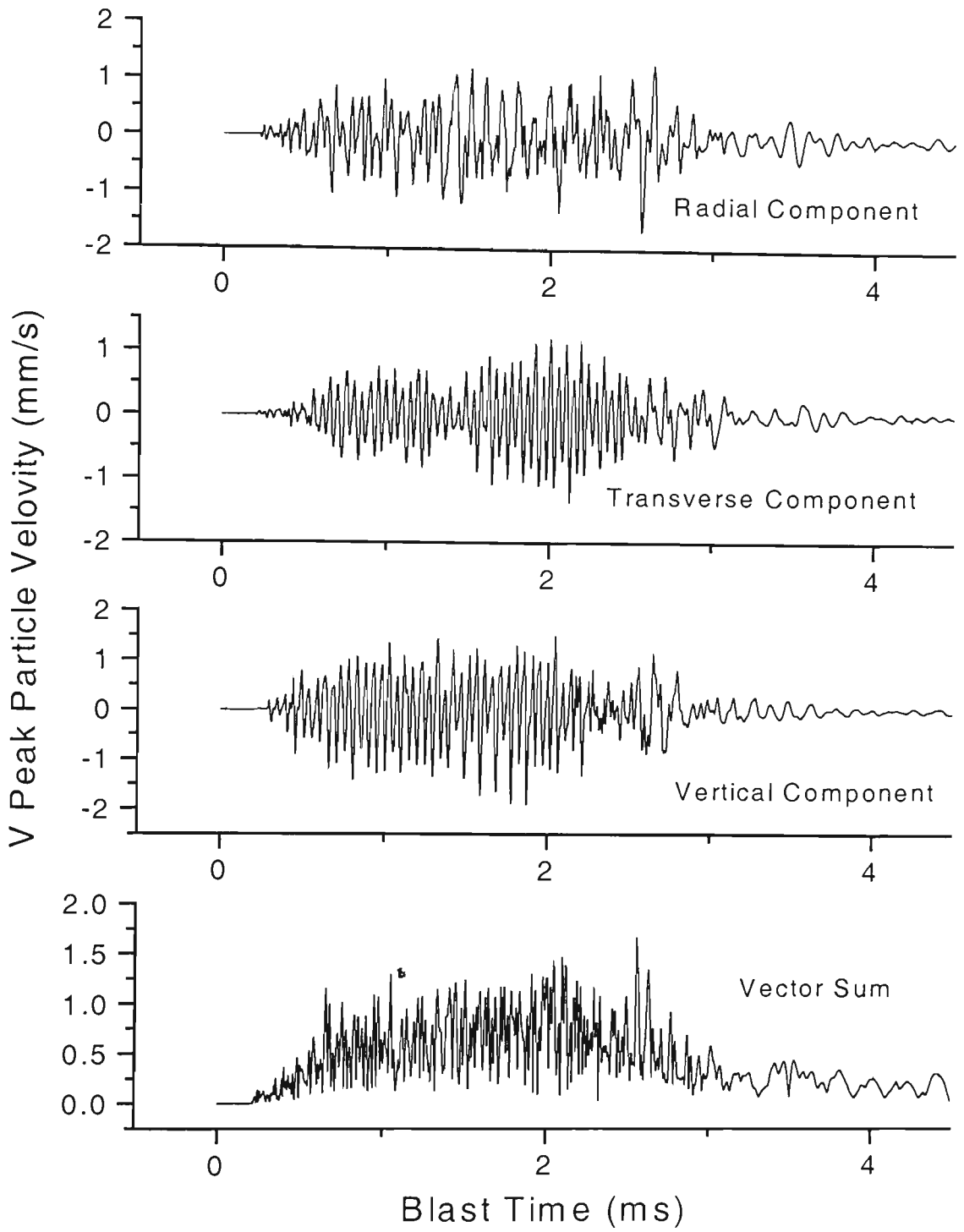
Appendix 2.10 High vibration level – Standard mount – Mount comparison



Appendix 2.11 High vibration level – 1 Spike mount – Mount comparison

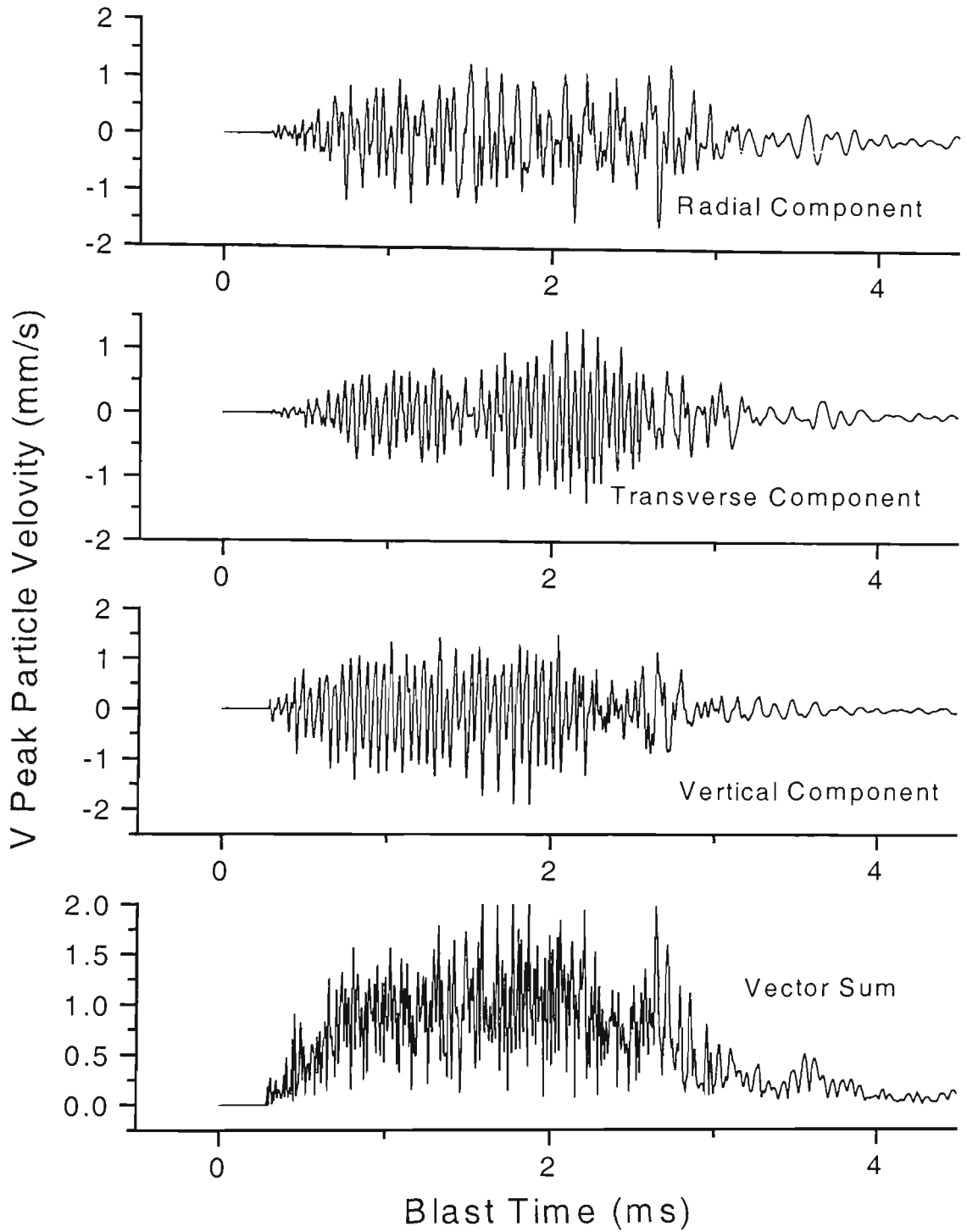


Appendix 2.12 High vibration level – Concrete block mount – Mount comparison

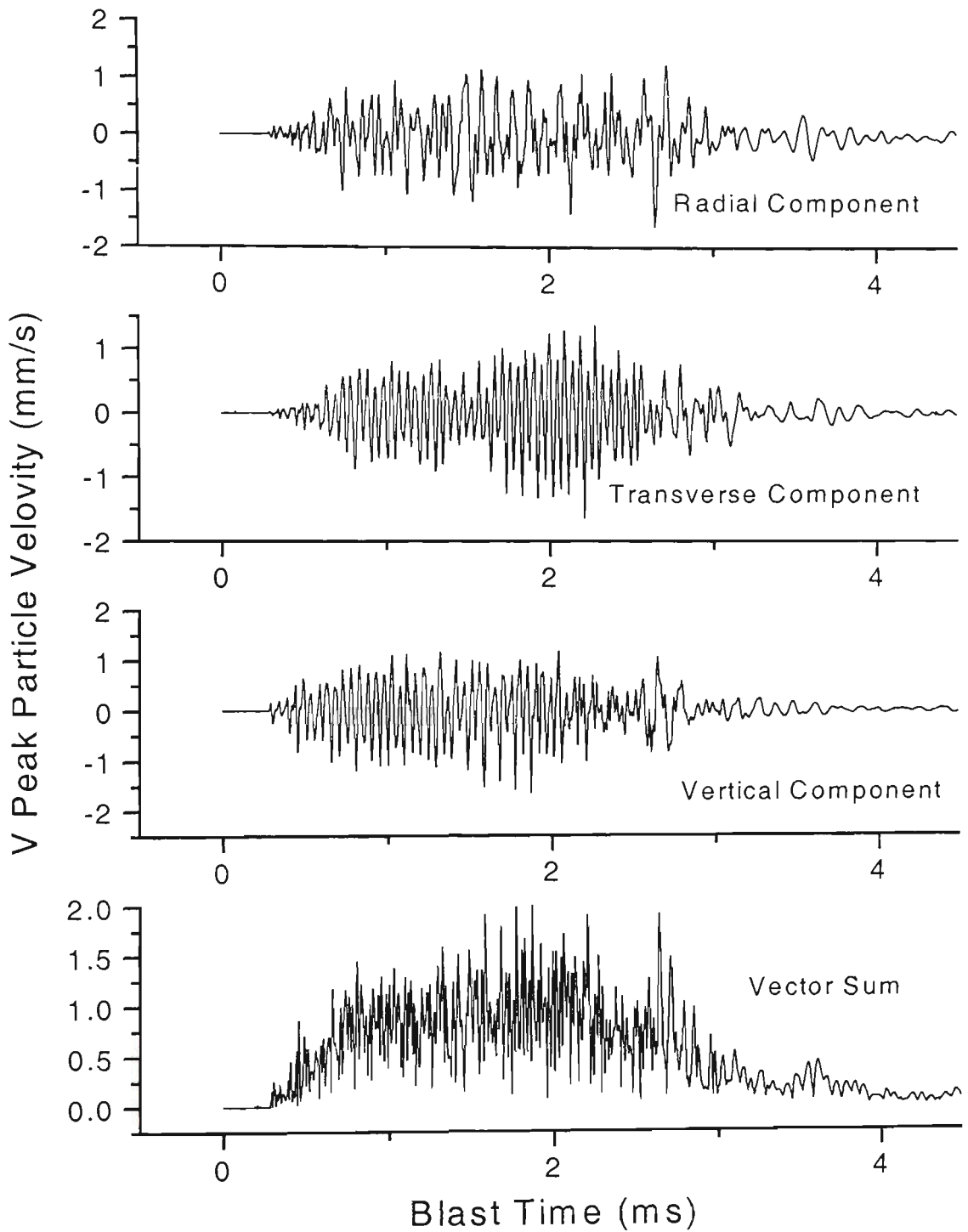


Appendix 3.1 Low vibration level – Mount density 1.0 g/cc

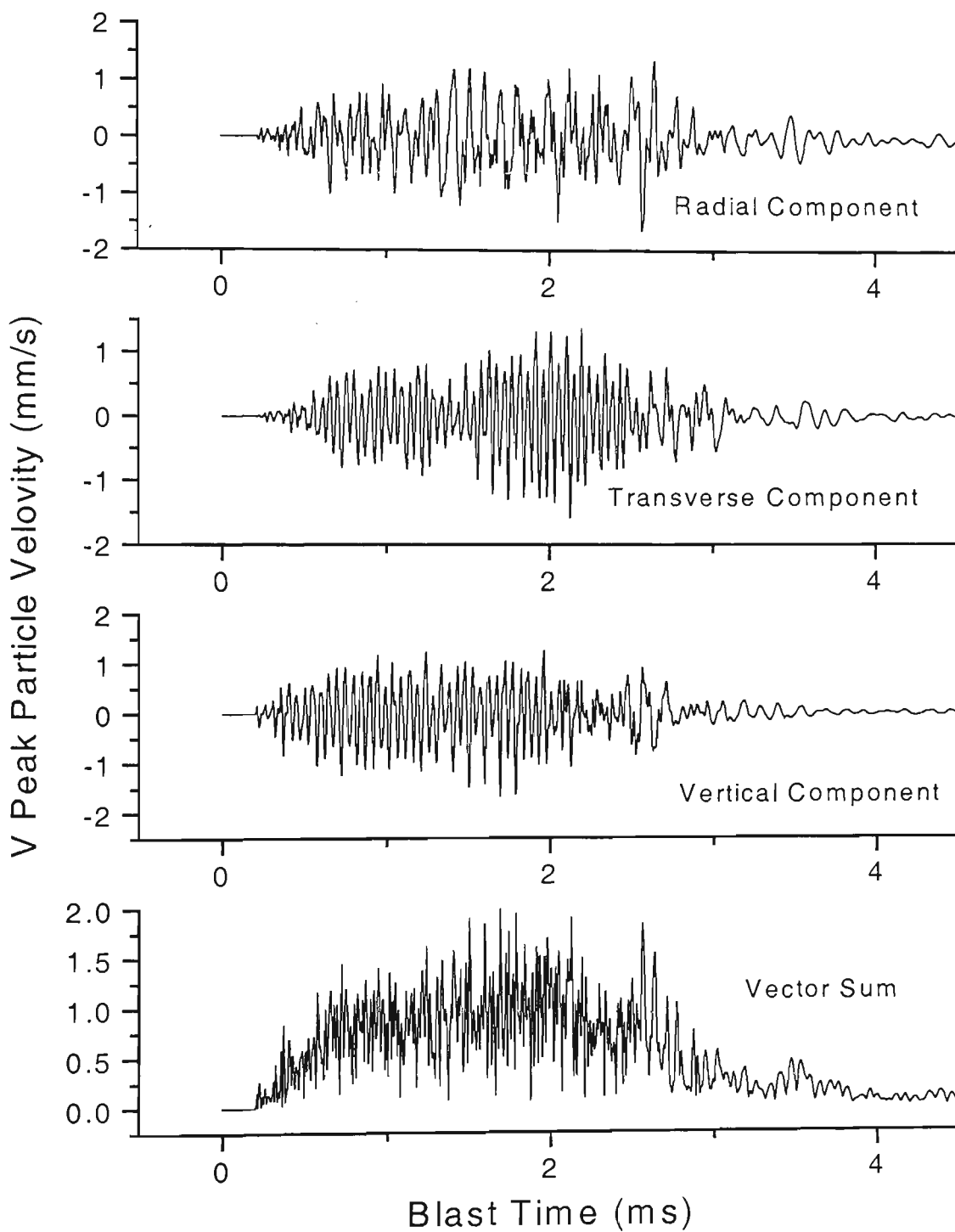




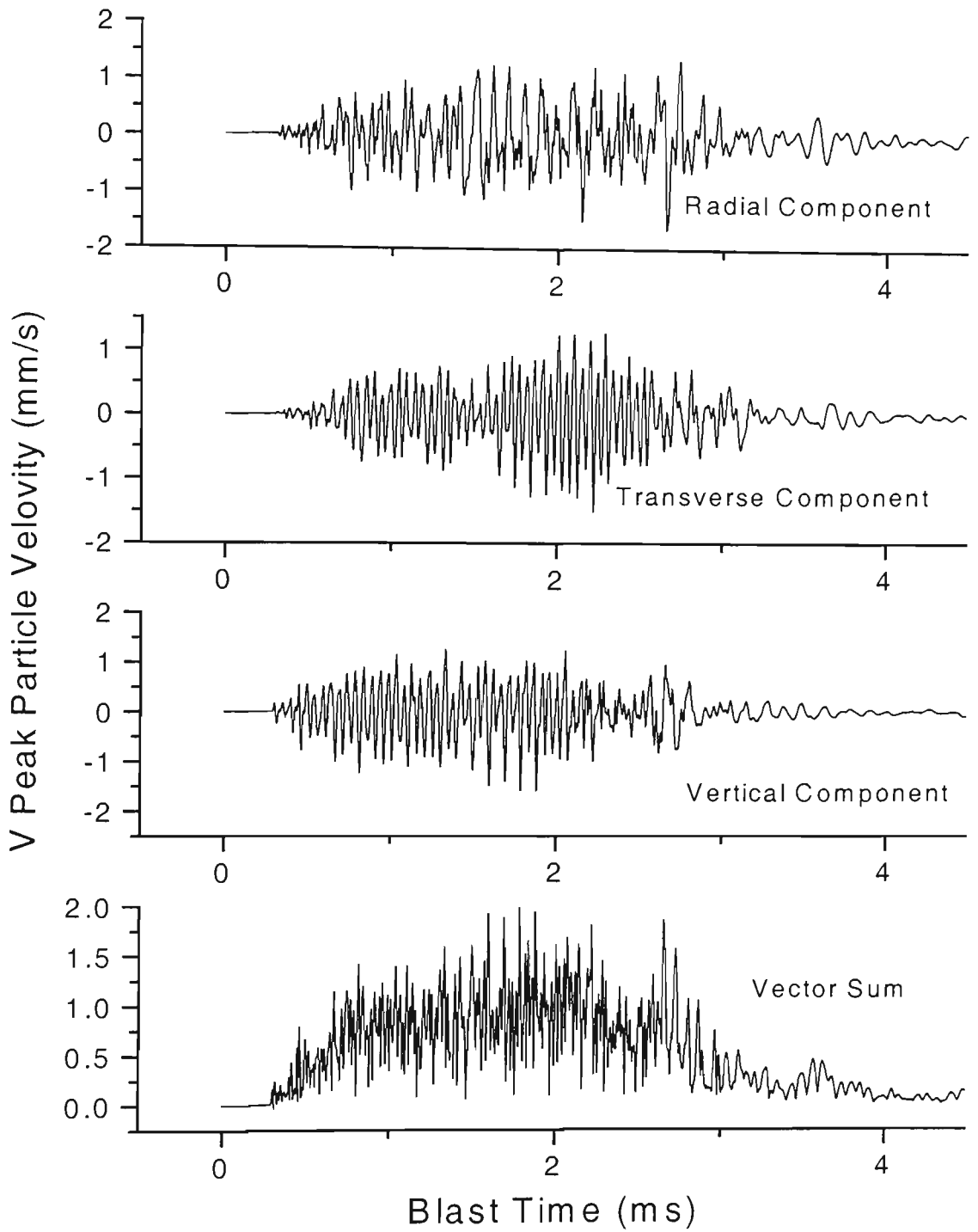
Appendix 3.2 Low vibration level – Mount density 1.7 g/cc



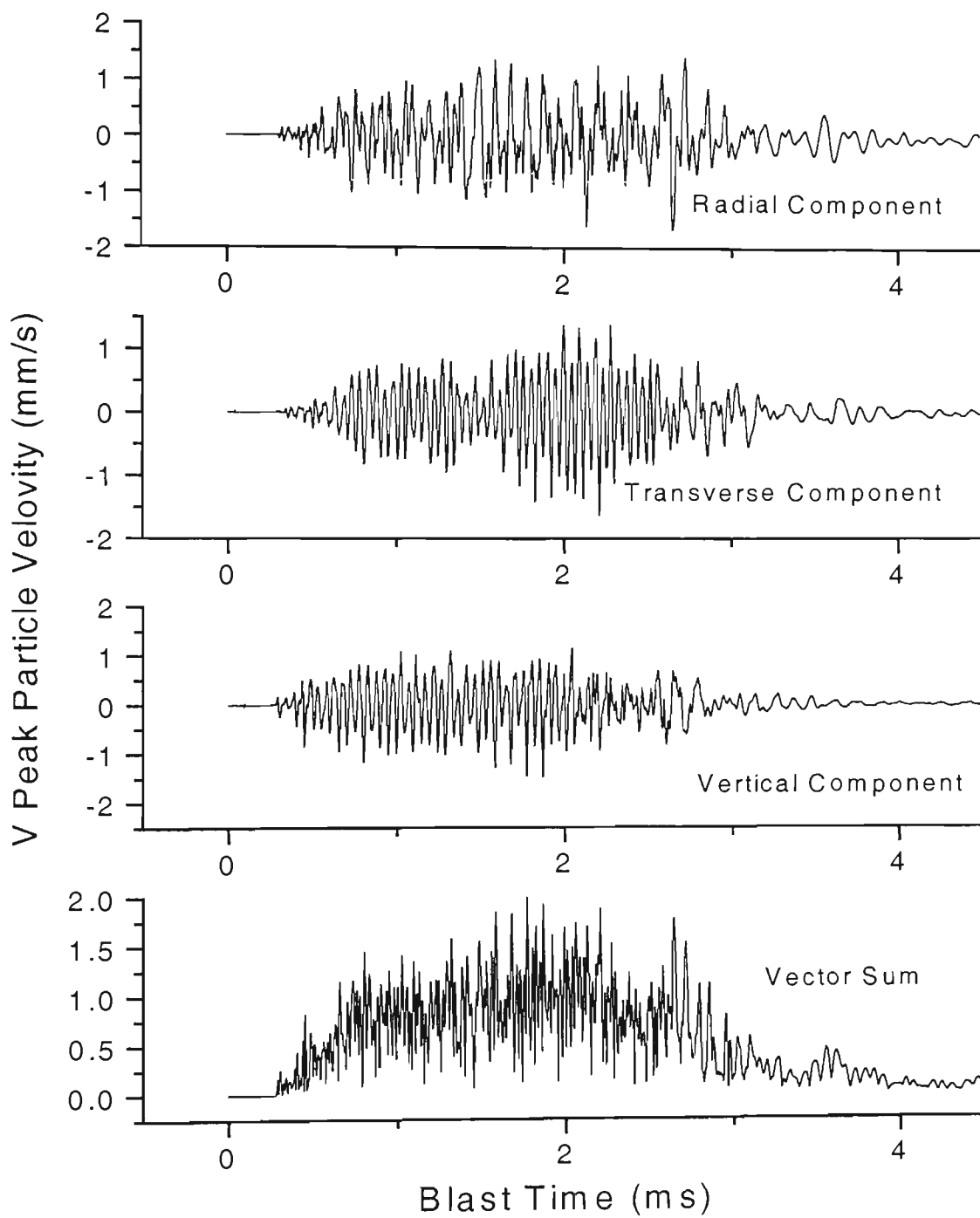
Appendix 3.3 Low vibration level – Mount density 2.6 g/cc



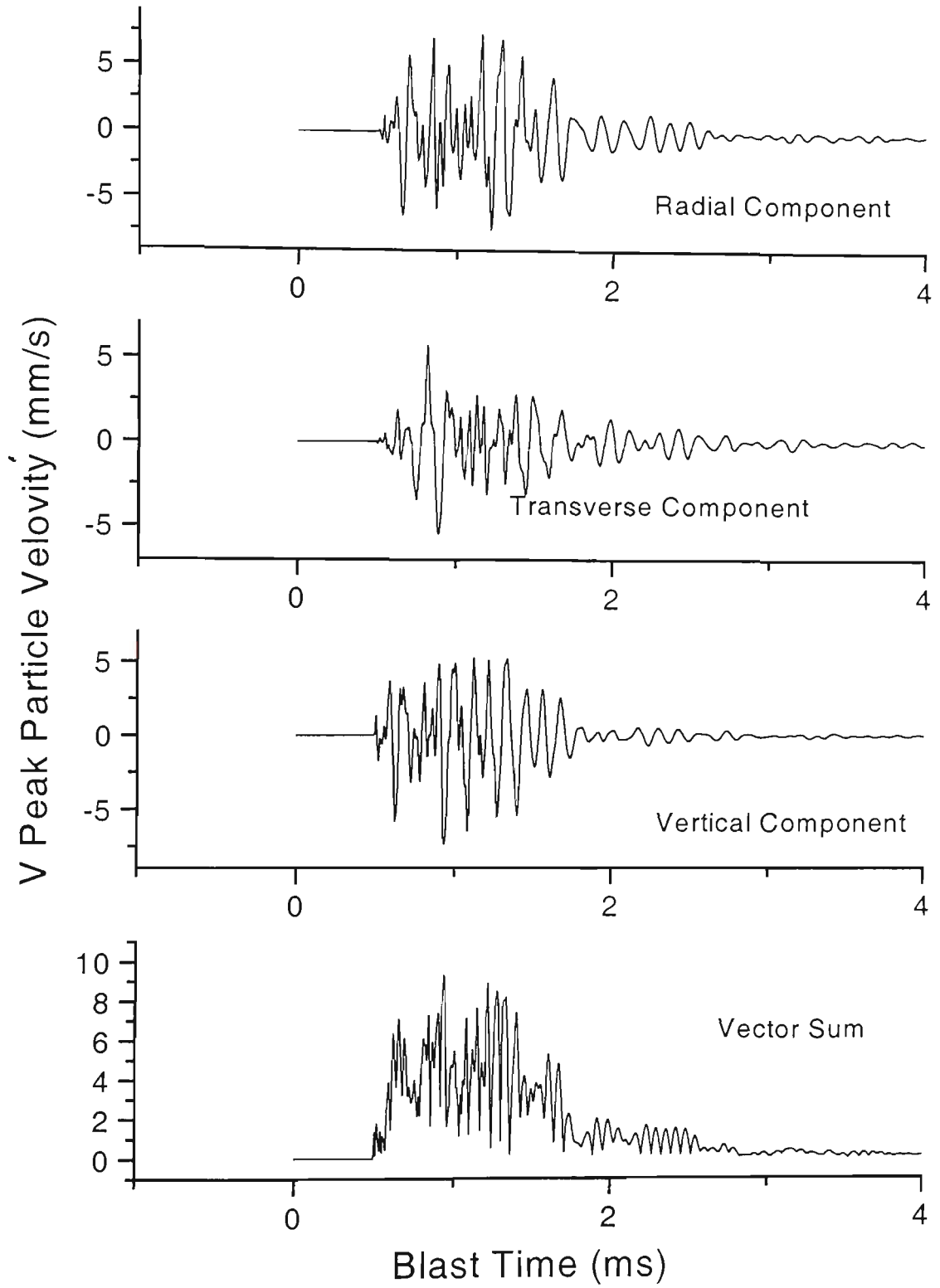
Appendix 3.4 Low vibration level – Mount density 4.0 g/cc



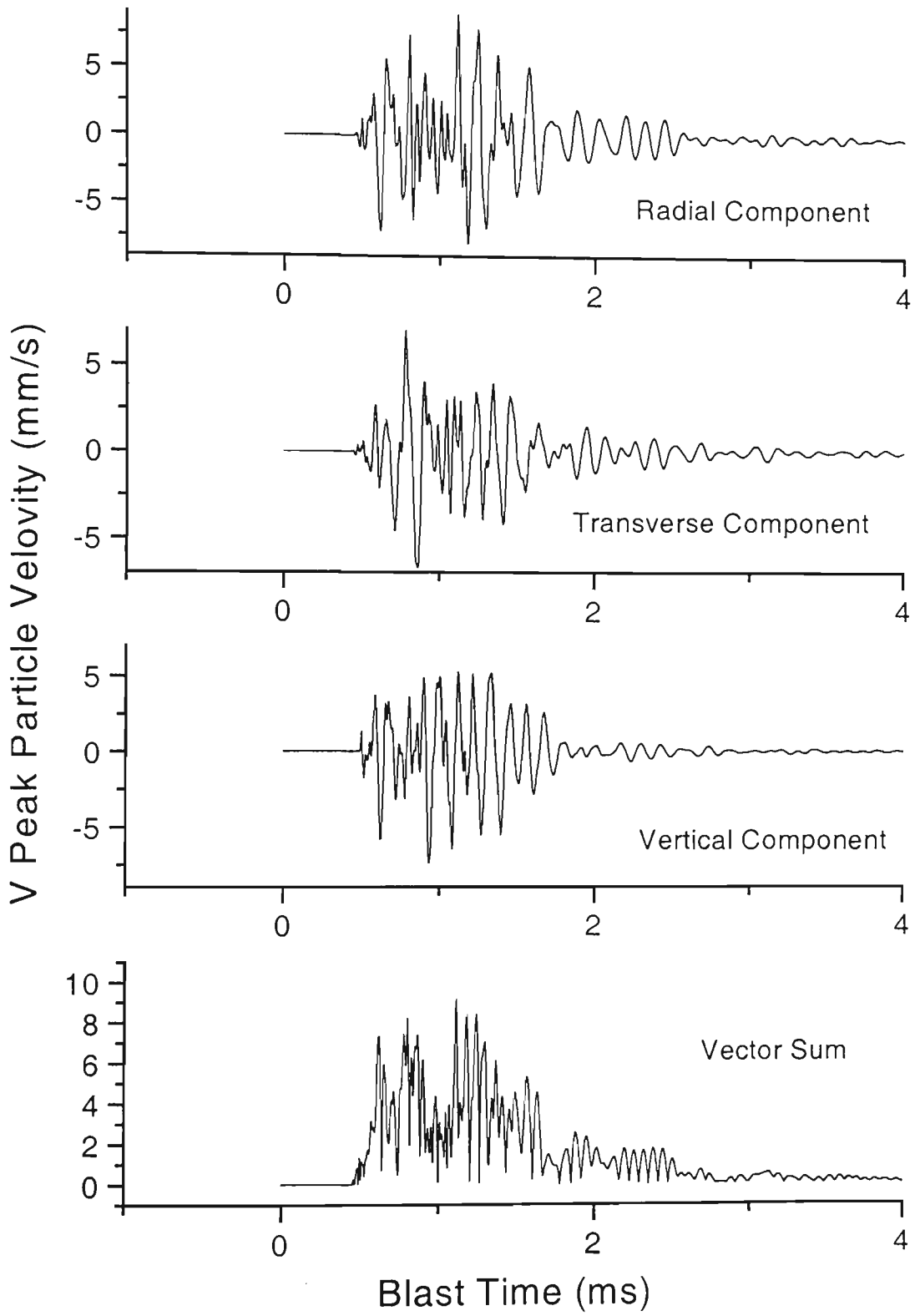
Appendix 3.5 Low vibration level – Mount density 5.2 g/cc



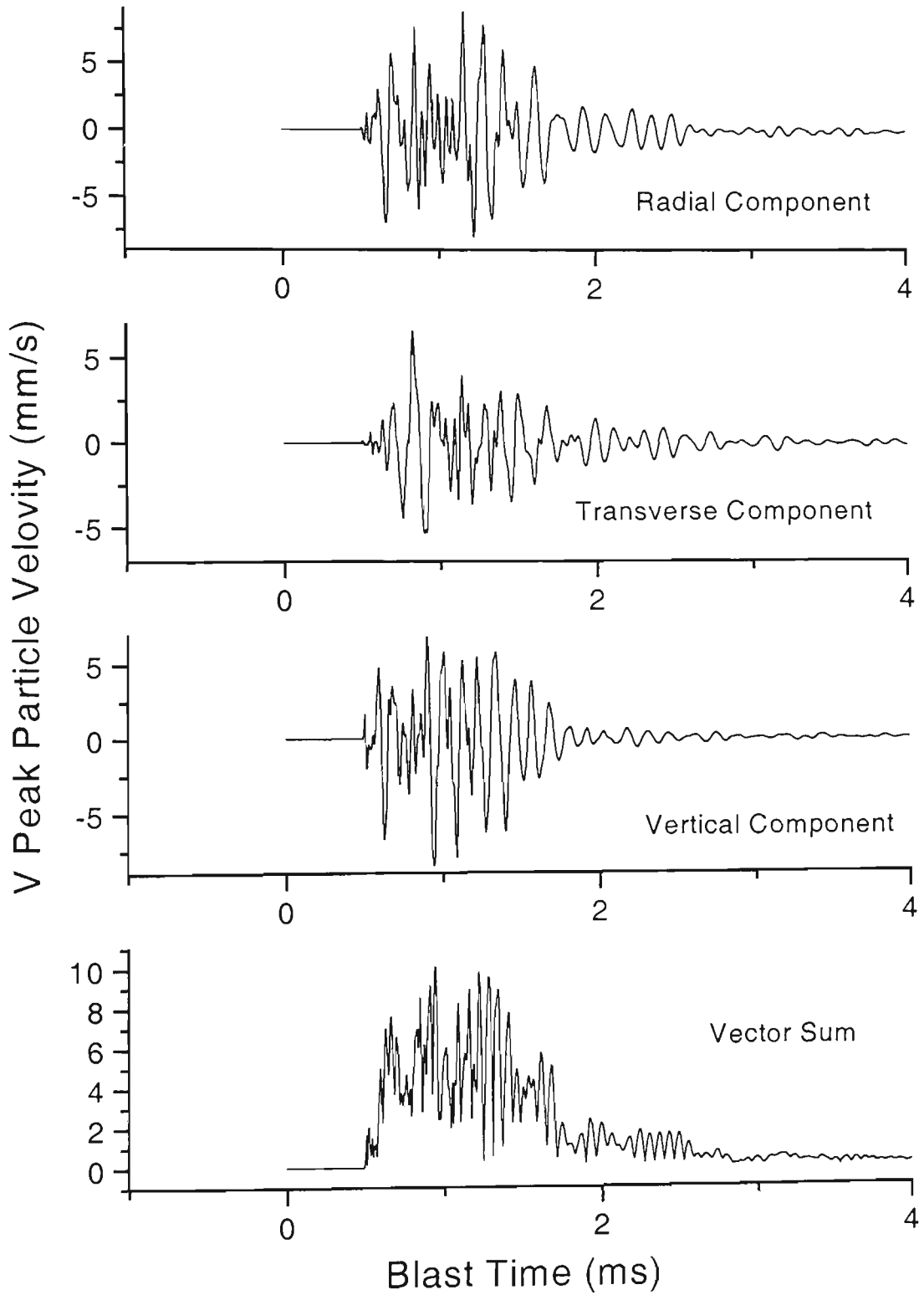
Appendix 3.6 Low vibration level – Mount density 8.0 g/cc



Appendix 3.7 High vibration level – Mount density 1.0 g/cc

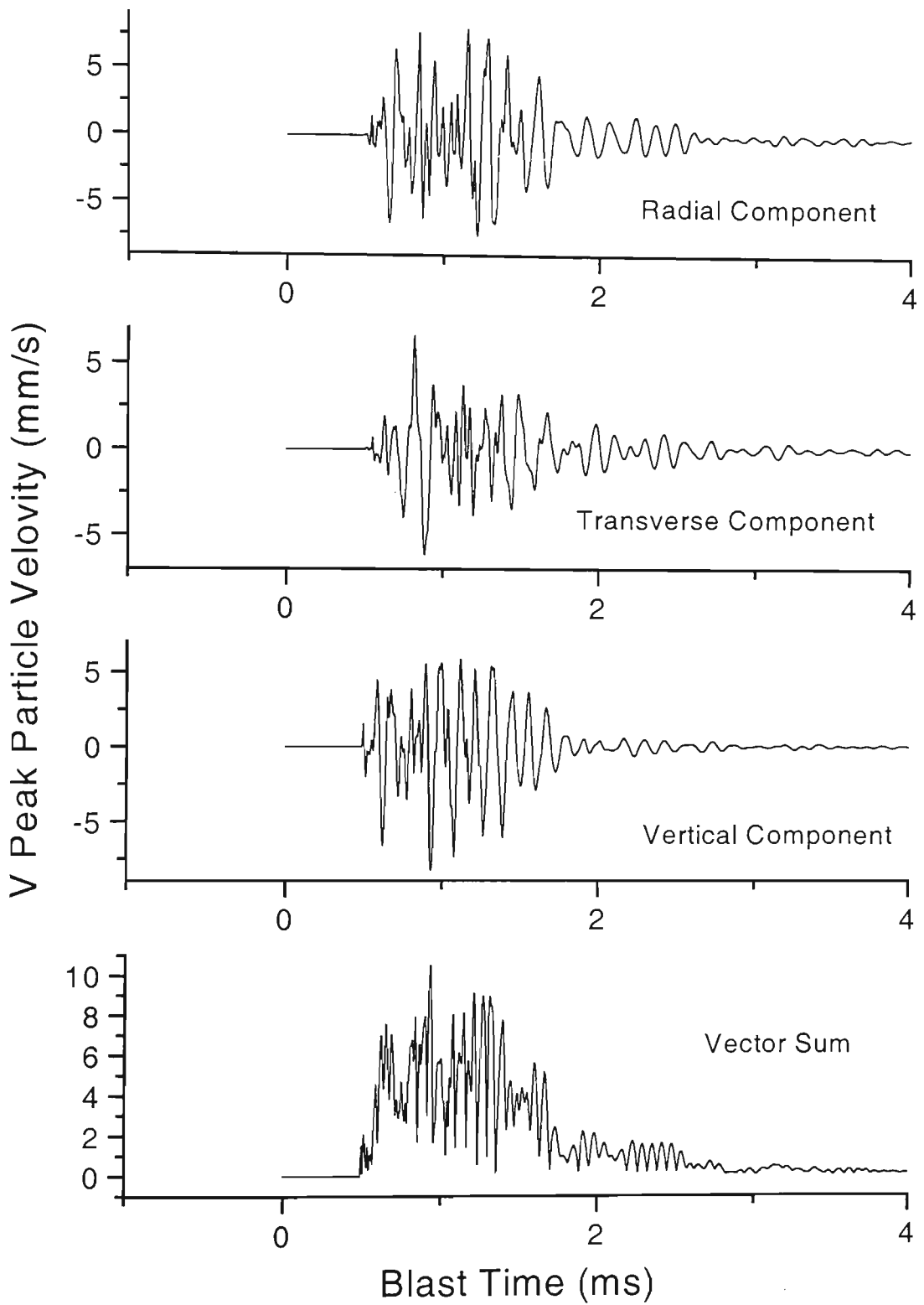


Appendix 3.8 High vibration level – Mount density 1.7 g/cc

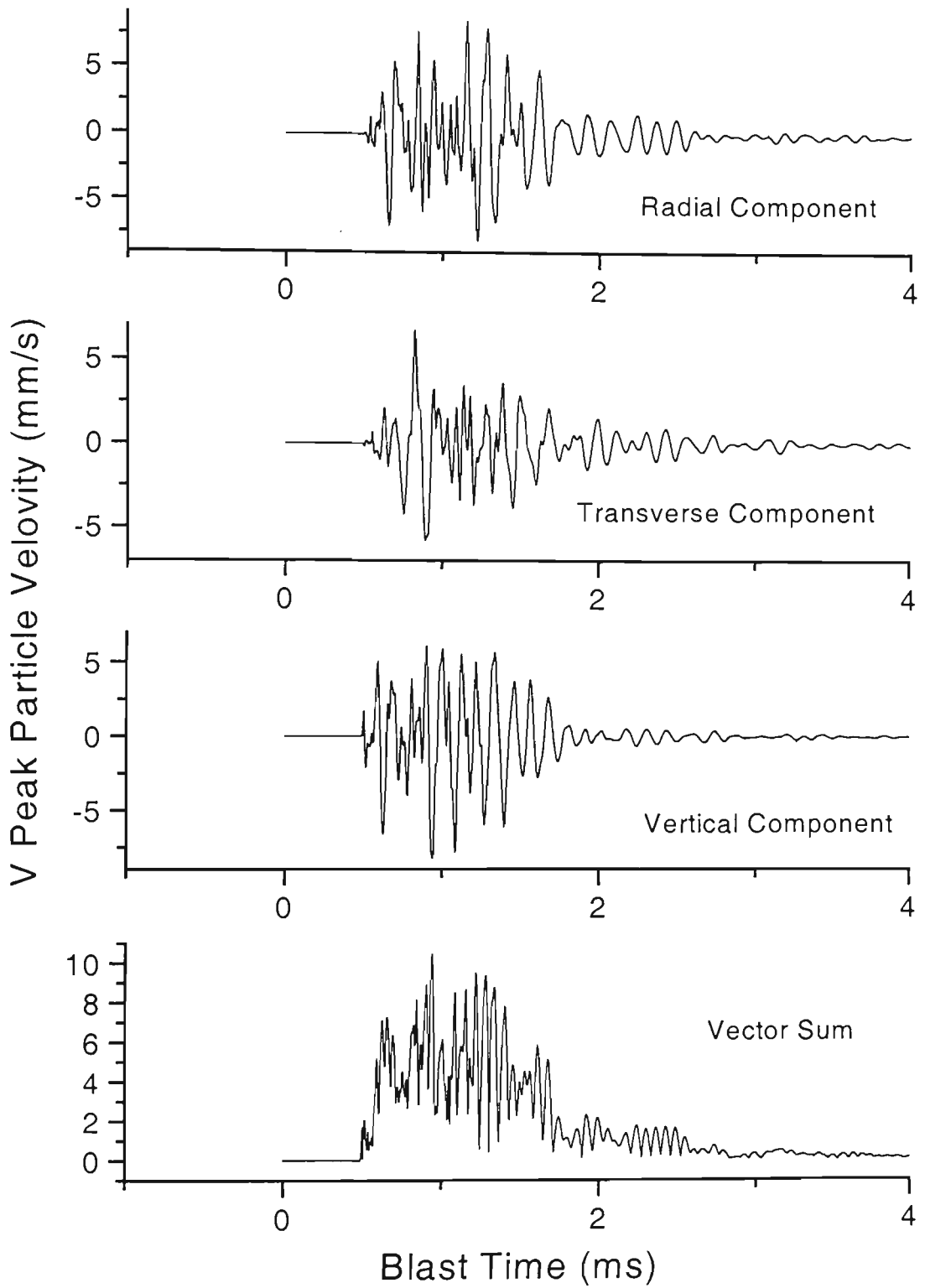


Appendix 3.9 High vibration level – Mount density 2.6 g/cc

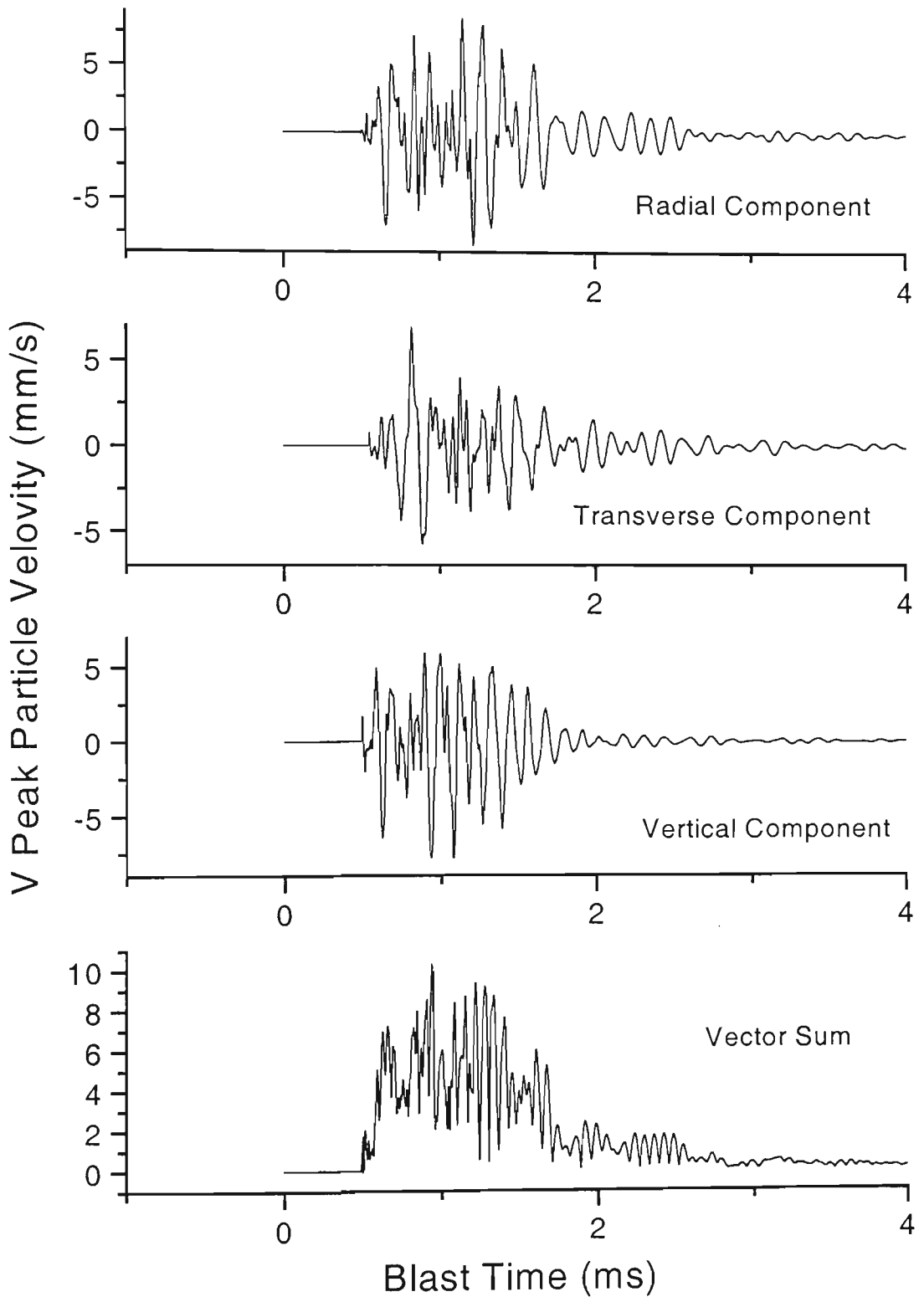




Appendix 3.10 High vibration level – Mount density 4.0 g/cc



Appendix 3.11 High vibration level – Mount density 5.2 g/cc



Appendix 3.12 High vibration level – Mount density 8.0 g/cc