THEME 1 - REDUCING THE ENVIRONMENTAL EFFECT

REDUCING THE ENVIRONMENTAL EFFECT OF

AGGREGATE QUARRYING: DUST, NOISE & VIBRATION

Research funded through Defra’s Aggregates Levy Sustainability Fund
Sustainable Aggregates:
Aggregate resources produced from sand and gravel deposits, crushed rock or dredged from the sea contribute to the economic and social well being of the UK. Their production and supply has environmental effects.

The Aggregate Levy Sustainability Fund (ALSF) has provided funding to undertake work to minimise and mitigate these effects. This report is part of a portfolio of work that reviews ALSF and other work undertaken between 2002-2007 on ‘promoting environmentally-friendly extraction and transport’ of land-won aggregates to provide a state of knowledge account and to highlight the gaps in our understanding and practices.

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# CONTENTS

## Synopsis  

### PART 1 BLASTING VIBRATIONS AND AIR OVERPRESSURE

1. Executive Summary  
2. Foundational Concepts in Environmental Blast Monitoring  
3. Historical review of environmental blasting criteria  
5. Detailed literature review dealing with the minimisation of blast generated ground vibrations from quarries and surface mining operations.  
6. Detailed literature review dealing with the prediction and minimisation of blast generated air overpressure from quarries and surface mining operations.  
7. Areas for Future Research  

## References  

## Appendix  

### PART 2 DUST MODELLING AND VALIDATION

1. Executive Summary  
2. Modelling of the Atmospheric Dispersion of Particles  
3. Air Dispersion Models Approved for Regulatory Purposes  

Conclusion & Recommendations for Further Research  

Appendix  

References
This project as formulated had two main aims. These were to carry out a review of:-

1. All the research work funded by the Aggregates Levy Sustainability Fund (ALSF) and supervised by the Minerals Industry Research Organisation (MIRO) on behalf of the Department for Environment, Food and Rural Affairs (DEFRA)

2. All concurrent and relevant peer reviewed research carried out in the same ALSF topics areas.

The Universities of Leeds and Nottingham were selected to carry out the review as defined in Theme 1: Reducing the Environmental Effect, Sub Theme Title: Dust, Noise and Vibration.

As a consequence of the initial project meeting, it was agreed to apportion the work as follows:-

1. The University of Leeds would review the topic areas concerned with ground vibrations and air overpressure generated by blasting together with the dust monitoring.

2. The University of Nottingham would review the topic areas concerned with dust modelling and validation together with site generated noise.

A more detailed executive summary is available for each of the topic areas and can be found in the document at the commencement of each separate section. What follows is a brief overview of the work carried out under the specific topic headings

**Blasting Vibrations:** Four ALSF funded projects were considered each of which was part of the Minerals Industry Sustainable Technology initiative. The technology produced from all four projects have either been fully commercialised or has been advanced to the proof of concept phase which will enable commercialisation in the very near future. In addition after a detailed search of all the concurrent learned academic journals and conferences proceedings some 27 peer reviewed papers were selected for inclusion so as to provide a valuable source of information for regulators, operators and consultants who wished to gain an insight into the future direction of research in this topic area.

**Blasting Air Overpressure:** There were no ALSF funded projects in this area of research and thus only papers from concurrent learned academic journals and conferences proceedings were able to be considered. From the extensive list of papers discovered as a result of the extensive literature search, 17 have been considered as worthy of inclusion.

**Dust Monitoring:** Five ALSF funded projects were reviewed, all of which were part of the MIST initiative. In addition an extensive literature search identified some 27 key texts, of which 17 academic papers from journals or conference proceedings have been reviewed in more detail including work funded by English Heritage through the ALSF. The English Heritage ALSF funded projects focused on new methods for dust
monitoring, dust dispersion modelling and effects of dust on the historic environment. The review concluded that new dust monitoring protocols are needed, based on public perception of the visual impacts of minerals industry. To keep pace with environmental and public health concerns, appropriate and updated methods for air quality monitoring at minerals sites are required. New dust characterisation techniques can be applied to better attribute dust sources, and site-specific dust emission factors based on a range of quarry types are needed to provide realistic guidelines for potential dust emissions from minerals sites.

**Dust Modelling and Validation:** Three ALSF funded projects were reviewed, two that were part of the MIST initiative and one that was an English Heritage Initiative. As well as this some 78 specific papers were selected for review after an extensive literature search of learned papers both from journals and conference transactions. This was also supplement by reference to government documents and relevant web sites.

**Site Generated Noise:** There were no ALSF funded projects in this area of research and thus only papers from concurrent learned academic journals and conferences transactions were able to be considered. Some 49 specific papers and articles were selected for review after an extensive literature search of learned papers both from journals and from conference transactions. This was also supplement by reference to government documents and relevant web sites.
PART 1: BLASTING VIBRATION AND AIR OVERPRESSURE
EXECUTIVE SUMMARY

Without doubt the most contentious environmental impact experienced by residents living adjacent to quarries and surface mines are those produced by blasting. This has been confirmed not only anecdotally but also by surveys carried out by mineral planning authorities. If future projections for population increase in the United Kingdom turn out to be true, then many more homes (built from material excavated from many more quarries) will be needed, which in turn will have to be built nearer on average to those quarries that produced the aggregates. Surely a recipe for more discord rather than less.

This report begins by seeking to give an insight into what happens in a blast and how it actually breaks the intact rock to enable it to be processed. It then discussed the consequential effects of blasting in terms of the potential environmental impacts that can arise. These in turn are separated out into those levels of impact capable of damaging property and those that can give rise to allegations of nuisance.

The main thrust of the report is dedicated to assessing the research that has been done into the environmental impact of blasting. In this, the role of the former United States Bureaux of Mines is highlighted. Over many years it was at the forefront of such research. Its closure and the subsequent dispersal of its expertise was a real loss to research in this field. The British Standards are briefly discussed leading on to a brief discussion of “blasting scaled-distance” modelling (which is currently the most popular method of seeking to limit blasting induced ground vibration levels).

There then follows a brief assessment of the small number of projects sponsored by the MIST programme in this area. The research done has achieved a considerable amount. All four projects have resulted in either proven methods or products that can be used by the aggregates industry to lessen the environmental impact from blasting experienced by residents living adjacent to quarries and as such should be judged a successful use of developmental funds.

The bulk of the remainder of the report examines all the leading peer reviewed research papers that have been produced between the commencement of the MIST programme and the present day. A short discussion is given to each and an assessment made as to its efficacy in assisting commercial operations. This very substantial literature search together with the evaluation of the MIST projects has enabled an in depth assessment to be carried out regarding the way forward for research in this field.
Much has been achieved but much remains to be done. Perhaps the most disappointing aspect is the lack of enthusiasm on the part of the majority of the aggregates industry to use the standard blasting database developed as a result of the MIST project and the unwillingness of the regulators to commit the small amount of financial resource necessary for them to use it. However on the positive side certain quarry and opencast mine operators have seen the usefulness of such research and are now applying it to their operations.

The advent of fully controllable electronic detonators is set to have a major impact on the quarrying and surface mining industry. Whilst most of the effort by the manufacturers is being directed towards enhanced fragmentation, there are undoubtedly areas relating to environmental control that, with more directed research, can bring benefits to operators, regulators and local residents. The successful use of electronic detonators to control ground vibrations from blasting is a classic example of research leading on to commercial deployment for the benefit of all the stakeholders (operators, regulators, consultants and local residents) involved in the aggregates industry.
In the United Kingdom the use of explosives for mineral extraction is arguably one of the most contentious areas of surface mining. The mere thought of proposed plans for quarrying can lead to unpleasant public relations, increased number of nuisance complaints resulting in tighter restrictions and today's ever increasing litigious society render the sustainable development of many quarrying operations not viable. However for many operators, blasting is quite often the only economic means of mineral extraction.

For the majority of the United Kingdom, a vibration limit is set by the local Mineral Planning Authority. This was initially intended to prevent structural damage to adjacent properties, however nowadays they are being employed in an attempt to minimise human nuisance. Thus these values are now set at much lower levels than those based on damage criteria but still above human perception level and as a consequence complaints still arise. A statutory vibration limit will be included on a site's operational licence which must be adhered to at a specified confidence level at the nearest occupied property. The situation is further exacerbated as it is estimated that for every mainland UK mineral operation that requires the use of explosives, at least one inhabited property is within 450m of any given quarry. Kelly, Farnfield and White (1993) described an open cast coal site in West Yorkshire with more than 400 occupied properties within 200m of the blasting operation.

It is therefore vital for the industry to do all that it can to reduce the vibration levels experienced at these adjacent properties without imperilling the financial viability of the enterprise.
2 FOUNDATIONAL CONCEPTS IN ENVIRONMENTAL BLAST MONITORING

The Mechanism of Rock Breakage
When an explosive charge is detonated in a shot hole, there is a sudden release of stored energy in the form of an explosion of gas at high temperature and pressure. The effect of this sudden release of energy is to produce a high-pressure pulse to the rock surface and generate a compressive strain pulse in the surrounding rock. This pulse travels radially from the borehole and decays in amplitude as it travels outwards (White and Robinson, 1995), this is illustrated in Figure 1.1. The result of this is to produce crushed rock in the vicinity of the shot hole. Further disintegration will occur provided that the amplitude of the compressive strain pulse exceeds the crushing strength of the rock. Further from the shot hole, this will not occur instead the pulse will then travel as a seismic disturbance without causing additional breakage or fracture.

When the compressive wave reaches a free face (e.g. a quarry face or an open joint) it under goes a 180° phase shift and is reflected as a tensile waves are produced (See Figure 1.2). As the rock is far weaker in tension then in compression, it breaks away and is projected away from the face. The work done by the detonation gases is known as ‘thrust energy’ (See Figure 1.3). This is the uplifting and churning motion the expanding gases makes in the borehole and the further disintegration of the rock. For breakage to occur by the method described enough energy must be transmitted on detonation to account for:
- losses in transmission through the rock
- the energy of motion of the broken fragments
- the potential energy needed to create the facture surface.

Fragmentation by tensile fracture may be the only means of breaking the hardest rocks with explosives, although fragmentation by compression may be more important in softer and lower density rocks. Figures 1.4 to 1.7 illustrates this concept in a plan perspective.

![Figure 1.1 Explosive Detonates (Velocity 1000-6000 m/s)](image-url)
Figure 1.2 Reflection of shock waves

Figure 1.3 Gas pressure phase

Figure 1.4 Shock waves pass through the rock
Figure 1.5 The rock is first stressed compressively and then is exposed to the reflected tensile forces.

Figure 1.6 The tensile forces cause small primary cracks that expand as the pressure increases.

Figure 1.7 The tension increases in the primary cracks that expand to the surface, loosening of the rock takes place and the burden is consequently torn off.
**Effects of Blasting**

As an explosive charge is detonated in a shot hole, a rapid discharge of energy takes place within a short duration causing a tremendous rise in pressure and temperature. The majority of energy released will be exhausted in the breakage of rock, but a significant percentage is wasted. This wasted energy is dissipated away in the forms of noise, dust, heat and noxious gases together with formation a numbers of more significant environmental impacts. There are three main environmental impacts produced, namely:

- **Ground Vibration** – caused by seismic waves travelling through the ground
- **Air Overpressure** – caused by pressure waves travelling through the air
- **Fly Rock** – individual rock fragments being thrown long distances from the site by the force of the explosion

Of all the impacts, fly rock is the most serious concern due to the implications of rock matter being projected from a site, however this is primarily a safety issue and correct blast designs will significantly reduce if not completely negate the likelihood of a fly rock incident. The other two impacts, in contrast are more passive in nature, but still give rise to complaints. Induced ground vibrations are responsible for the majority of the blast related complaints directed at site operators by residents living adjacent to quarries and surface mines.

**Ground Vibration**

Ground vibrations are caused by elastic disturbances, which propagate away from the blast source. This is literally a wave motion that spreads outwards from the blast. These waves are rapidly transmitted through the solid medium, which returns back to the original configuration after their passage. The rock mass can be considered to be an elastic medium that is composed of countless individual particles. As the disturbance occurs, each of the particles are sent into a random oscillatory motion about their positions of rest, the wave being generated as each particle first receives then transmits the energy successively to the next.

**Waveforms**

There are different types of waveforms that are produced from a seismic event. There can be divided into two basic groups: Body Waves and Surface Waves.
**Body Waves**

Body waves are the waves that travel through the rock mass. Telford (1983) describes that these can be subdivided as:

1. **Primary** or **P-wave.** This is a compressive wave, which alters the volume of the body without altering its shape. In such cases the particles vibrate in the direction of wave propagation. The primary wave motion is illustrated in Figure 1.8.

![Figure 1.8 Illustration of the Primary or P-wave motion.](image)

2. **Secondary** or **S-wave.** This is a shear wave resulting in a change of shape only. Here the medium particles oscillate perpendicular to the direction of the wave propagation. The secondary wave motion is illustrated in Figure 1.9.

![Figure 1.9 Illustration of the Secondary or S-wave motion.](image)

**Surface Waves**

The body waves propagate outward in a spherical manner until they intersect at a boundary such as another rock layer, the ground surface or soil. At this intersection surface waves are produced. These waves travel along the surface and cause ground roll to occur. Telford (1983) explains that the surface wave can be subdivided into:

1. **Rayleigh** or **R-wave.** This is a longitudinal wave which gives the particle a circular or rotational movement.
2. **Love** or **Q-wave.** This is a shear wave that forms a horizontal circle or ellipse moving in the direction of propagation with no vertical component.
3. **Coupled wave.** Here the particles oscillate in an inclined elliptical motion having components in both the horizontal and vertical directions. The term ‘coupled’ implies combined P and S wave motions.
**Wave Arrival**
At small distances from a blast source i.e. (in the near field) all wave types arrive together, but as the distances from the source becomes great the slowly moving shear and surface waves begin to separate from the faster moving compressive waves. However as the majority of blasts are the combination of a number of small explosions separated by milliseconds, the difference in travel path and time delay results in the overlapping and interacting of the wave fronts and types. As the waves produce different patterns of motion in the rock particles as the pass, any structure built on or in the rock will be affected differently by each wave.

**Velocity**
There are two velocities that need to be considered when considering the passage of seismic waves. This is the ‘wave’ or ‘phase’ velocity, which describes the rate with which the disturbance propagates through the medium. (i.e. the velocity of propagation). The second is ‘particle’ velocity, which is used to describe the small oscillations that a particle executes about its equilibrium position as the wave energy excites it and passes through it (Bollinger). The wave velocity is commonly orders of magnitude larger than the particle velocity. In the analysis of blast vibrations, concern is usually given to the particle velocity and not wave velocity. From this point onwards in the manuscript, the term velocity refers to particle velocity, unless specified.

**The Measurement of Blast Vibrations**
The objective in blast vibration measuring is to detect and record the vibratory motion of the ground or structure. This motion is caused by the forces that have been previously described. They are variable in both magnitude and/or direction, transient in nature and attenuates with distance.

To describe the motion completely, three perpendicular or orthogonal components must be measured.

These are:

1. The **Longitudinal** (or Radial) component. This is the back-and-forth horizontal movement in the same direction as the travel path of the vibration wave.
2. The **Transverse** component. This is the sideward horizontal movement perpendicular to the direction of travel path of the vibration wave.
3. The **Vertical** component. This is the up-and-down movement perpendicular to the direction of travel path of the vibration wave.

The quantities measured must result in a full description of the vibratory event. This requires either particle displacement, velocity or acceleration to be recorded as a function of time. The most commonly measured quantity is velocity through the use of dedicated, ‘stand alone’ blasting seismographs.

**The Seismograph**
A seismograph is a device used for measuring ground vibrations. Typically they consist of a triaxial array of geophones that acts a motion-sensing transducer, which are usually built onto a mounting unit and in turn attached to a digital or analogue recorder. The geophones consist of a mechanical system where either a coil moved in relation to a fixed magnet or vice versa. Movement of the geophone results in a related movement between the coil and the magnet that in turn induces a voltage into the coil that is proportional to the movement. This voltage is then amplified before being recorded.

Bespoken blasting seismographs are usually portable battery operated and can be set to automatically record
a vibratory event once a pre-set trigger value has been exceeded. Seismographs are typically set to measure movement in the three perpendicular directions, previously described with two axes in the horizontal plane and one in the vertical. The horizontal alignment of the instrument is usually guided by a marked arrow on the housing, which for the most purposes will be orientated towards the blast and follows the axis for the longitudinal component. In addition, a majority of blasting seismographs also contain an extra channel that is used in conjunction with a connected microphone in order to record the air overpressure.

**Vibration Levels – Damage Criteria**

Throughout the years, there have been many investigations undertaken, both practical and theoretical, into the damage potential of blast induced ground vibration. The most prominent research authorities have been the US Bureau of Mines (USBM), Edwards and Northwood (1960) and Langefors and Kihlstrom (1963). All have concluded that the vibration parameter best suited as a damage index measure is particle velocity. With the maximum value of particle velocity in a vibration event, termed the Peak Particle Velocity (PPV) as being the most significant.

Ground vibration can potentially cause damage to structures by differential displacement. As seismic waves pass under a structure, they will rock the structure back and forth, from side to side and up and down. If the structure could move in its entirety as one whole mass then there would be no damage. However it is the differential nature of the displacement that causes the damage. This is due to structures, when subjected to ground movement, try to oppose the movement. This resistance creates differential loading, which in turn imparts stress. Usually whilst the lower part of a structure is in motion due to the vibration, the top of the structure still retains its original position at rest. This is the most common form of stress imposition and generally produces scissor cracks at approximately 45° to the horizontal and at approximately 90° to each other. The amount of motion required to damage a structure depends upon its construction method and the materials used. For example a steel-framed building can tolerate a more intense seismic wave than a residential structure with plaster walls.

Dowding (1985) suggested possible structural effects such as:

1. Structural distortion
2. Faulted or displaced cracks
3. Falling objects
4. Cosmetic cracking of wall coverings
5. Excessive instrument and machinery response
6. Human response
7. Micro disturbance

Vibration levels are often regulated to the levels that prevent the cosmetic cracking of plaster for structural response, which in turn means that under normal conditions, the first four criteria detailed above, do not usually occur. Structural response has been classified into three categories (Edwards and Northwood 1960, Siskind et al USBM RI 8507, 1980).

1. **Threshold (cosmetic cracking)** – The opening of old cracks, the formation of new plaster cracks and the dislodging of loose objects.
2. **Minor (displaced cracks)** – Superficial cracks that do not affect the strength of the structure e.g. broken windows, loosed or fallen plaster and hairline crack formation in masonry.
3. **Major (permanent distortion)** – Situation resulting in a serious weakening of the structure e.g. large cracks. The shifting of foundations or load bearing walls and major settlement resulting in distorted or weakened superstructures.

Published damage criteria generally does not differentiate between types of damage, instead gives levels to prevent the occurrence of cosmetic damage, which automatically prevents the more severe damage levels being attained.

**Vibration Levels – Human Perception**

The human body is very sensitive to vibration and as a result can be responsible for a great deal of subjective concern being expressed towards blasting activities. The majority of individuals will generally become aware of blast-induced vibration at levels around 1.5mm.s\(^{-1}\), but this can be as low as 0.55mm.s\(^{-1}\) (White and Robinson, 1995). Such vibration levels are one hundredth of the level necessary to damage structures and in comparison can be found to be far less than the levels produced by typical daily activities. Domestic activities such as walking, door closure and washing machine cycles can be found to produce significantly higher vibration levels than blasting.

There are many misconceptions about blasting and the damage caused by the resultant vibration. However, the subjective perception of ground motion can be as serious a problem as actual damage. The shaking of a residence will inevitably cause some degree of subjective reaction by the occupants. The extent of this reaction can lead to complaint of damage either real or imagined. From experience, virtually all complaints regarding blasting arise because of concern over the probability of damage to owner-occupied properties (White and Robinson, 1995).

The human response to blast induced vibration, especially within buildings is a complex phenomenon. An individual's susceptibility will vary depending on their activity at the moment the vibration arrives and will also vary with factors such as age, mental attitude and previous exposure. Other factors, which may come to affect responses and complaints, are possible biased feelings towards the business interests of the operator or by a small minority of people with the aim of purely attempting to gain compensation.

Motion and noise can be disconcerting and can lead to a search for physical evidence of damage. Often this can result in a previously unnoticed crack being discovered that will erroneously provide confirmation of the event. If a person is worried and the crack was not observed previously, the crack’s perceived significance increases over one noticed in the absence of any startling activity. These concerns are genuine and in the mind of the observer are sincere.

In typical quarry or opencast situations, the blast induced inaudible air overpressure and the audible noise following the ground motion will intensify the human response. Both ground and airborne disturbances can rattles objects and excite walls which can tend to produce more noise within a structure than outside. Occupants often inaccurately report a combination of audible and sub-audible noise, at great distances, as ground motion. A significant proportion of the complaints regarding blasting may actually relate to air overpressure and noise. This is because any impulse noise exceeding the background levels by more than 10 dB is potentially disturbing to the human consciousness. Even at a safe ground vibration levels, repeated events can instil the feeling that damage must be occurring due to the air blast effect.

Pedgen, Birch, Hosein, Rangel-Sharp and Farnfield (2007) developed a monitoring system in order to record
levels of acoustic noise within structures on different levels whilst simultaneously monitoring the levels of vibration and air overpressure, all recording were on a constant time base to determine whether the audible noise detected coincided with the arrival of the ground vibration or air overpressure. The system was designed to enable high quality sound recordings which allowed the identification of structural component generating the noise. Instrumentation and monitoring was carried out at three properties (one within the quarry, two approximately 300 and 400 metres away respectively) on different levels of the properties (i.e. ground floor, first floor, attic) and various mounting surfaces (floor of structure, wall of structure and roof of structure). Their preliminary findings showed that the acoustic response of structures can be caused by both ground vibration and air overpressure produced from blasting. However, their key finding was that there was a lack of detailed research into the generation of acoustic noise in building due to either vibrations or air overpressure. They suggest that the technology is now available to reliably investigate the acoustic response of structures and it is only through dedicated data analysis that informed judgements can be made to determine whether the cause is by vibration or air overpressure. Also, the suggestion is made that the technology could be used to perform acoustical audits of problematic residencies in order to locate and help resolve or reduce irritant sounds as a means to reduce nuisance complaints.

Air Overpressure

Air overpressure is a problem commonly encountered throughout the mining and quarrying industry when extracting minerals from the surface by blasting. It is a component of blasting which has become a regulated parameter in which is often a source of complaint from residents living in the nearby area of the mine/quarry. It is therefore paramount for all blasting practices to be well designed and monitored to ensure that air overpressure levels do not exceed the limit set by the mineral planning authority as stated in the planning application.

The pressure wave that causes air overpressure is generated from the detonation of an explosive charge which then causes the expanding gaseous reaction to compress the surrounding air and moves it outwards with a high velocity. The shock wave that is produced has a steep shock front which is closely followed by a rapidly decreasing pressure. As the surrounding air provides little resistance to the expansion of the gaseous products, they carry on expanding and reach pressures lower than the ambient atmospheric pressure.

It then travels through the air until is eventually dissipates or its path is blocked. The pressure wave's travel is dictated by the temperature of the air, the speed and direction of wind and also the presence of any obstructions e.g. trees, buildings.

Wiss and Linehan (1978) and Siskind et al. (1980) divided the causes of an air blast into several mechanisms.

- Air pressure pulse
- Rock pressure pulse
- Gas release pulse
- Stemming release pulse

Rock pressure pulse is generated by vertical vibrations of the ground. The pulse arrives simultaneously with the ground vibration. The rock pressure pulse is the first component of the air overpressure reading and is smaller than that of the air pressure pulse and will form the lower bound of the possible blast sound pressure.
Air pressure pulse is produced by direct rock displacement at a blast. The displacement in the rock transmits a pressure pulse into the surrounding air, thus producing an air pressure pulse. The air pressure pulse makes up the second section of the recorded air overpressure reading, after the rock pressure pulse. This is largely due to the lower medium propagation velocity and also has lower frequency content than the rock pressure pulse (Persson et al. 1994). This usually produces the largest amplitudes and so can be controlled by deeper charges or better confinement i.e. more adequate stemming.

The gas release pulse is caused by the escaping of gases from the explosion through fractured material, either inadequate stemming or fractured rock. This pressure pulse controls the height if the individual spikes within the readings. This is measures after the air pressure pulse and causes the most disturbances to people.

The stemming release pulse is caused by the escaping gases from the blown-out stemming. This is characterised by a high frequency wave which is super-imposed on the air pressure pulse.

The detonation of explosives causes the pressure of the surrounding air to rise instantaneously from an ambient pressure to its peak value (Persson et al. 1993). Once the pressure peaks, it then gradually decays back down to the original ambient pressure but proceeds to decay to a negative pressure value. This negative phase (also known as the suction phase) lasts longer than the positive phase however the magnitude is not as inversely proportional. The total energy of each phase will be equal. Figure 1.15 is an example of the pressure wave's two phases.

The pressure wave in Figure 1.15 was measured from a single hole blast at Newbridge Quarry. The negative phase lasts for approximately three times the duration of the positive phase.

Factors Affecting Air Overpressure

Blast Geometry:
The amount of burden that is designed for a blast is an important factor that affects the level of air overpressure produced. An excessive burden increases the ground vibrations because the explosive energy is insufficient to break the rock and so is converted into seismic energy. If the burden is too small, the explosive energy breaks the rock with surplus energy which transfers into gaseous energy that is released into the atmosphere producing air blasts. This release of gas can generate air waves of large amplitudes resulting in high levels of air overpressure.

Spacing of the holes and their delay times are other important factors. If the spacing is insufficient and is less than the distance travelled by the sound wave during the delay time between adjacent holes, then very strong
air blasts will result. This is because the pressure waves produced from each hole will superimpose and hence produce and large amplitude and thus a stronger blast wave. It is recommended that spacing divided by time interval, between delay periods, should be less than sound velocity (Bhandari 1997).

**Type & Amount of Explosive:**
The amplitude if the pressure pulse is directionally proportional to the amount of explosive used and hence, the larger the quantity of charge detonated pre delay, the larger the vibration and also larger the air overpressure.

Explosives that produce more gaseous energy rather than shock energy such as ANFO are more likely to produce an ejection of gases and therefore higher amplitude of air overpressure.

**Stemming:**
Air blast levels are a function of the amount and efficiency of stemming. Konya et al. (1981) stated that the stemming particle size should be ¼ of the blast hole diameter as this particle size provides the best confinement. They also suggest the stemming to burden ration should be 1 – 1.5.

**Priming & Initiation:**
The use of delay detonators significantly reduces the magnitude of air blasts by preventing the pressure waves from superimposing.

**Geo-mechanical Characteristics of the Strata:**
When the burden rock is highly fractured or heavily jointed then the possibility of venting of gases arises which are a main source of air overpressure. If any weak band or open joint extends from the blast hole to the free face, the gaseous energy released from the explosion will vent through and produce high air overpressures. Therefore these weak zones should be loaded by decking to reduce the magnitude of the gaseous energy produced or even use weaker explosives.

**Direction of blasting:**
When blasting, the direction of the blast should be considered in relation to sensitive areas. Air blasts are at lease 6dB higher when observed at a location perpendicular to the firing pattern rather than when parallel. (Bhandari 1997). Also an air blast behind the face is normally weaker and less noisy; this is due to the absence of high frequency components in this direction.

**Meteorological Conditions:**
Weather conditions must also be taken into account when blasting as they can greatly affect the blasting impact on the local area. If blasting is carried out during windy conditions and the wind is blowing in the direction to sensitive areas e.g. housing then the pressure wave produced, will travel further in that direction and so will have a greater impact.

Also air temperature has an effect, the higher the temperature, the greater speed of sound and so greater the distance travelled, resulting in a higher air overpressure reading. In a motionless atmosphere, the intensity of the air overpressure will reduce by 6dB as the distance doubles from the source (Bhandari 1997), however these conditions rarely exist and so the 6dB reduction may be greater in some directions and less in others.
3 HISTORICAL REVIEW OF ENVIRONMENTAL BLASTING CRITERIA

The potential connection between blast vibrations and damage to properties and structures has often been questioned. Historically, the answers that have been published are dependent on vibration levels and frequencies together with recommended maximum levels in order to prevent such criteria being exceeded.

The United States Bureau of Mines (USBM) was at the forefront of studying such effects. Over a period of 40 years, the USBM prepared three comprehensive reports which covered the aspects of vibration generation, propagation and the impacts on residential structures (Siskind 2000). These findings can be seen as the basis for many of the standards and related safe blast vibration criteria that are currently in effect.

**United States Bureau of Mines Bulletin 442**
This was the first attempt at a comprehensive review of safe blasting and was undertaken by Thoenen and Windes (1942), which resulted in Bulletin 442 (1942) for ground vibration and Windes’ Report of Investigations (RI) 3708 (1943) for air overpressure. The vibration criterion was based upon acceleration and suggested a broad “caution zone” of 0.1 to 1.0g. However, this was found to be not very well defined and consequently an attempt to precisely define safe vibration limits resulted in RI 5968 by Duvall and Fogelson (1962). Historically, this report was the first to recommend the employment of particle velocity (rather than displacement or acceleration) and the observation of 2 in.s$^{-1}$ was proposed as a safe level criterion.

**United States Bureau of Mines Bulletin 656**
Bulletin 656 published in 1971 formed the second generation comprehensive study performed by the USBM. Included were blast vibration measurements from a number of quarries plus the safe level criteria for both vibration and air overpressure (Nicholls, Johnson and Duvall, 1971). However, by the mid 1970’s questions were being raised concerning both the vibration and air overpressure criteria. Inspite of the acceptance of the USBM’s 2 in.s$^{-1}$ criteria by several states to regulate blasting activities, there were still a large number of complaints being received. Reaction by the United States government regulators, notably those in Pennsylvania and Illinois, prompted the USBM to initiate two new studies in 1974 and 1975 to address both vibration and air overpressure.

**United States Bureau of Mines Reports of Investigations 8485 and 8507**
Following Bulletin 656, two further reports were published. These two investigations comprised of additional measurements and inspections by the USBM and from other studies worldwide. This included the addition of larger open cast coal mine blasts, small construction blasts, measurements of structural response and the initial results of tests for fatigue and strength of construction materials (Siskind 2000). These two reports, RI 8485 (Siskind et al., 1980a) for air overpressure and RI 8507 (Siskind et al., 1980b) for ground vibration, recommended frequency based controls for the prevention of threshold hairline or cosmetic cracks and
reduced the long existing 2 in.s\(^{-1}\) safe criterion by a factor of 3 or 4. Figure 1.10 illustrates the suggested levels reported in USBM RI 8507, Appendix B (Siskind et al., 1980b).

Upon publication, the vibration criteria proposed by RI 8507 produced an adverse response from some industry representatives. Inspite of this, it has become widely adopted (either in whole or part) by the Federal Office of Surface Mining Reclamation and Enforcement (OSM), many US regulatory programmes, the insurance industry through the American Insurance Service Group (AISG) and the American National Standards Institute (ANSI A10.7, 1998).

British Standard BS6472

BS6472 (1992) discusses the possible effects that various types of structural vibration can have on a building's inhabitants together with how and where such vibration should be measured. Appendix C is entitled ‘Guide to the evaluation of vibration induced by blasting’. This gives information on blast induced vibration levels that may give rise to adverse comment under a given range of circumstances. This is in contrast to the possibility of actual structural damage. Consideration is given to the time of the day and to the use made of a specific occupied space in a building. Also classified are the time histories of the vibration with ‘impulsive’ vibration, such as that induced by blasting, being defined as ‘rapid build-up to a peak followed by a damped decay which may or may not involve several cycles of vibrations’. Specifically mentioned within this standard is a satisfactory vibration level of 8.5 mm.s\(^{-1}\) at a 90% confidence, with an absolute limit of 12.7 mm.s\(^{-1}\) peak particle velocity, recommended for impulsive vibration at residential properties. The recommended limit of 12.7 mm.s\(^{-1}\) can be seen to directly relate to the lower frequency threshold for plaster wall cosmetic damage as reported by USBM RI 8507 previously described as a damage limit not a nuisance limit.

In addition, the importance of a public relations program is discussed and it states that it is often the fear of building damage that leads to the concerns being expressed. It is advised that site blasting trials are undertaken followed by regular vibration monitoring in order to demonstrate compliance with the vibration limits set by the mineral planning authority.

British Standard BS7385 Part 2

BS7385 Part 2 (1993) ‘Guide to damage levels from ground borne vibration’ assesses the effect of vibration associated with structural damage and includes frequency in addition to peak particle velocity in its recommended structural damage criterion. This follows the development by Siskind et al (1980b) of a fixed curve in which the vibration levels are plotted against frequency with the results used to predict the potential for structural damage when compared to damage limit lines. The measure for frequency that
was suggested is commonly known as the ‘frequency about the peak’. This approach to assess the potential for structural damage has been widely criticised by a number of researchers, most notably by White and Farnfield (1992), yet the technique has found widespread acceptance. BS7385 Part 2 describes a transient vibration guide for cosmetic damages, which recommends peak particle velocities in frequency ranges for:

1. Reinforced or framed structures, industrial and heavy commercial buildings:
   50 mm.s\(^{-1}\) at 4 Hz and above

2. Un-reinforced or light framed structures, residential or light commercial type buildings:
   15 mm.s\(^{-1}\) at 4 Hz increasing to 20 mm.s\(^{-1}\) at 15 Hz
   20 mm.s\(^{-1}\) at 15 Hz increasing to 50 mm.s\(^{-1}\) at 40 Hz and above

This is also illustrated in Figure 1.11.

**Scaled-distance modelling**

The expected level ground vibration produced from blasting is generally arrived at by empirically equating peak particle velocity (PPV) with a scaled distance into a bivariate expression. Morris (1950) conducted a study of wave propagation and suggested that the amplitude \(a\) of the particle displacement is proportional to the square root of the charge weight \(W\) and inversely to the distance \(D\) from the blast, where \(K\) is a site constant. This is the form:

\[ a = K W^{0.5} / D \]

A generalised equation proposed by Duvall and Petkof (1959), Duvall and Fogelson (1962) and Attewell and Farmer (1964) takes the form:

\[ V = K D^A W^n \]

Where:

- \(V\) = Peak Velocity
- \(D\) = separation distance, blast to receiver
- \(W\) = charge weight
- \(K, A\) = dimensionless site constants
- \(n\) = scaling exponent

A modification of this equation forms what is now considered as the standard Scaled-Distance formula. The name derived from the scaling of distance, i.e. the separation distance between blast and receiver, with the maximum instantaneous charge weight per delay. The relationship assumes the form:

\[ V = K (D/W^n)^{-b} \]
Where:
K, B = site constants
N = scaling exponent equal 0.5 or 0.33

There are two schools of thought behind the use either n= -0.5 or -0.33, known respectively as square root scaling and cube root scaling. Work by Ambrayson and Hendron (1968) and Newmark (1968) suggests that the empirical laws should be shaped by dimensional analysis. As such dimensional analysis results in cube root scaling laws for explosions of differing magnitudes in a constant medium.

Subsequent to this further investigations were carried out by Devine and Duvall (1963) and Devine (1966). Both assumed cylindrical explosive geometry for long cylindrical charges. Through experimental they found that the square root scaling gave a better correlation coefficient than the cube root scaling. They concluded that any linear dimension should be scaled using the square root of the charge weight. This is further supported Attewell and Farmer (1964) who suggested that the peak amplitude of a particles velocity caused by an explosion should be proportional to the square root of the energy released and that under elastic conditions it should decrease with distance for body waves and as the square root of the distance for surface waves.

**Scaled-distance Regression**

The scaled distance for any location can be calculated using the following formula:

$$SD = D \times W^{-0.5}$$

Where:
SD = scaled distance (m.kg^{-0.5})
D = separation distance, blast to receiver (m)
W = maximum instantaneous charge weight (kg)

The empirical relationship then follows:

$$V = A( SD )^B$$

Where:
V = the maximum peak particle velocity (mm.s^{-1})
A, B are dimensionless site factors

The site factors A and B allow for the influence of local geology on vibration attenuation as well as for the geometrical decay of the seismic waves. The values for A and B are calculated for a specific site by least-squares regression analysis of the logarithmic plot of peak particle velocity against scaled distance. This results with a mathematical best-fit straight line \(y = mx + c\) where A is the peak particle intercept value at unity scaled distance and B is the slope of the regression line.

Figure 1.12 illustrated a typical scaled distance regression plot together with a statistical summary and derived site factors for the data set. From Figure 1.12 it is evident that there is a degree of scatter present within the data set. This is a common feature in all scaled distance models as variability will always be seen to
be present due to the numerous potential factors that can affect the source, the transmission path and the receiver.

The reliability of the prediction from the model will greatly depend on this degree of scatter that in turn is used to produce the best-fit trend line (also known as the mean or 50% confidence). In order to assess the quality of the best fit line it is usual to calculate two summary statistics to determine the models predictive capability. This is normally considered in terms of the standard error (SE) and the correlation coefficient (CC).

**Standard Error**

A standard error (SE) statistic is calculated to get a measure on the degree of scatter presented by the data set. The term ‘standard error’ is often used in various statistical applications and can be misleading as to its meaning. White, Pegden and Birch (2003) described its use when applied to a scaled distance model; the term refers to the standard error about regression. This value is used to examine the contained error in the derived model. The standard error is calculated directly from the standard deviation of the data about the least squares mean trend line. The greater the correlation, the smaller the standard deviation and consequently a smaller standard error and a tighter fit of the data about the 50% is achieved. The standard error is a measure of the spread of the data about the 50% line. A standard error value will vary between 0 and 1, with the ideal to be approaching 0. A returned standard error value of 0 would indicate a perfect data set.

From the example illustrated in Figure 1.12, that returned a S.E. value of 0.28 which is a respectable value and can be visually confirmed by the reasonably tight distribution of the data points about the mean regression line.

**Correlation Coefficient**

The correlation coefficient is the proportion of the dependent variable ($y$) that is accounted for or explained by the regression equation. A correlation coefficient value ($r^2$) varies between 1 and 0 with the ideal to be approaching 1. A returned value of 0 would mean that the equation explains none of the variation in the dependent variable, whereas a value of 1 would indicate that the equation explains 100% of the variation. The return of correlation coefficient values between the two extremes indicates the proportion or percentage...
of the \( y \) explained by the model. Poor returned \( r^2 \) values from a scaled-distance model usually reflect the consequence of clustered data points that result in a situation where the best-fit trend line could be drawn at almost any angle causing an induced error. From the summary statistics of Figure 1.12, that the returned C.C. of -0.97 is very good and can be visually confirmed by the orientation and positioning of the best-fit trend line (the negative sign only indicates the direction of the regression line). It must be noted that the correlation coefficient value returned is solely statistical and cannot be regarded as evidence of cause and effect.

**Confidence Intervals**

The straight-line form of the model \( y = mx + c \) provides the dimensionless site factors (A and B) to define the site specific scaled-distance formula from applied least squares regression. Site factor \( A \) is described as the peak particle intercept value at unity scaled-distance and \( B \) being the slope of the regression line. An example is illustrated in Figure 1.12, the value of \( A \) is 326.151 and \(-1.19\) for \( B \) (the negative sign indicating the direction of the slope). This defines the formula for the best-fit (mean) trend line that will permit average PPV levels to be predicted at a given scaled-distance. The term ‘average’ denotes that 50% of blasts will be below that level and 50% will be above.

However for planning purposes it is standard practice for a PPV prediction, at a given scaled-distance, to observe a confidence, which will only be exceeded on a certain number of occurrences. The exact required level of confidence will be specified by the sites relevant Mineral Planning Authority (MPA) and will feature as a condition contained within the site’s operational licence. Most commonly this will be expressed in a form of words stating that all blasts must be planned so that:

“\( X\% \) of all blasts are to be below \( Y \text{ mm/s} \) as recorded at the nearest occupied premises.”

Where:

\( X = \) an imposed upper confidence limit (typically 95 or 98%) 
\( Y = \) a maximum vibration value (i.e. 6mm.s\(^{-1}\))

The site used as the example in Figure 1.12 has an associated planning confidence interval of 95% stipulated on its operation licence and this is graphically illustrated by the presence of the \( A \) (95%) confidence line on the model. The positioning of the confidence interval is determined using the models standard error statistic together with the appropriate multiplier (i.e. number of Standard Errors), obtained from conventional statistical tables.

Figure 1.13 illustrates the use of confidence intervals using the data set from Figure 1.12. For example, using the mean confidence and a Scaled Distance of 10 m.kg\(^{0.5}\), there is a mean (50%) chance that a blast would produce approximately 20 mm.-s\(^{-1}\) for that distance. Furthermore, using the 95% confidence and a Scaled Distance of 10 m.kg\(^{0.5}\), there is a 95% chance that a blast would produce approximately 34 mm.-s\(^{-1}\).

**Charge Weight Determination**

The previous described procedure is carried out in order to derive compatible maximum instantaneous charge (MIC) weights that observe the limit and probability stipulated on the sites operational licence. By substituting the required confidence intercept value (i.e. 95%) for the mean intercept value (site factor \( A \)), the scaled distance formula can be rearranged to make the MIC the subject. By then resolving the equation for the stipulated vibration PPV limit (i.e. 8mm.s\(^{-1}\)), licence compatible charge weights can be determined. In turn
these can be illustrated as a table of charge weights and/or a charge weights curve in order to direct the blasting engineer as to the MIC which should be detonated at any one time (see section 1.13.5). Figure 1.14 illustrates both a licence compatible charge weights curve and a licence computable table of charge weights for example site in Figure 1.12, that observe the sites stipulated criteria for ‘95% of all blasts to less than 8mm.s\(^{-1}\) at the nearest premises’.

By adhering to this process, it can be proven that a blast has been designed to comply with the Mineral Planning Authorities stipulated criteria. If the charge weights used exceed the recommended maximum amount, the blast has not been designed to comply with the stipulated criteria and the operator is breech of the planning consent.

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>MIC (Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>2.23</td>
</tr>
<tr>
<td>100</td>
<td>8.92</td>
</tr>
<tr>
<td>150</td>
<td>20.07</td>
</tr>
<tr>
<td>200</td>
<td>35.68</td>
</tr>
<tr>
<td>250</td>
<td>55.75</td>
</tr>
<tr>
<td>300</td>
<td>80.28</td>
</tr>
<tr>
<td>350</td>
<td>109.27</td>
</tr>
<tr>
<td>400</td>
<td>142.72</td>
</tr>
<tr>
<td>450</td>
<td>180.63</td>
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<tr>
<td>500</td>
<td>223.00</td>
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<tr>
<td>550</td>
<td>269.83</td>
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<td>600</td>
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<td>650</td>
<td>376.87</td>
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<tr>
<td>700</td>
<td>437.08</td>
</tr>
<tr>
<td>750</td>
<td>501.75</td>
</tr>
<tr>
<td>800</td>
<td>570.88</td>
</tr>
</tbody>
</table>

Figure 1.14 An example of table of charge weights and charge weights curve
Maximum Instantaneous Charge Weight Criterion
In order to prevent the possibility of wave reinforcement from consecutive detonations there is a general consensus that a delay interval of at least 8ms is required. This criterion originated from USBM RI 6551 (Duvall et al., 1963), which examined single row quarry blasts of 200lb/hole delay intervals of 0, 9, 17, and 34ms between the holes. The conclusion states that, “…except for the 0-ms delay, the length of delay and number of holes did not influence average vibration levels, for the cases of one hole per delay.” The authors therefore recommended the use of no less than 9ms to ensure vibration waves do not constructively interfere, adding together to increase amplitude. Subsequent, Siskind (2000) commented, “… their result is not surprising with typical vibration frequencies at their test sites of 30 to 40Hz, only 8ms is needed to place a second arriving wave one-fourth cycle out of phase with the previous delay.”

This conclusion can now be regarded as being reached by default as at the time in the early 1960’s, commercial blasting delays of less than 9ms were not readily available. In addition to which, considering the quality and resolution of the prevalent monitoring equipment being operated at the time, it is unlikely that if the delay periods of less than 9ms had been available that the results would proved conclusive.

Recently technological advancement has seen the appearance of electronic programmable detonator, which allows the engineer the flexibility to select any millisecond delay interval with a tenth of a millisecond accuracy. Coupled with the quality and resolution of monitoring equipment available today, subsequent research is highly likely to re-define the criterion.

Criticism of the Scaled-Distance Approach
In previous years, the scaled-distance approach to blast vibration modelling has faced some criticism. There have been two major arguments expressed against the technique, the first being that the technique over simplifies the issue and the second being that the use of a fixed scaling exponent is too rigid.

Scaled-Distance: Over Simplification Issues
Blair (1987) is highly critical and comments that the approach, “… is an oversimplification of any attenuation mechanism since it makes no allowance for the frequency content of the blast wave and assumes (incorrectly) that all frequency components are attenuated by a constant factor.”

In addition, the use of the commonly accepted scaling distance laws must be viewed with caution since such laws are not expected to be able to account for the fact that the PPV may occur in the P, S, or Rayleigh wave modes depending on the geometric relationship between the source and the detector.

Blair (1987) states that the measured surface vibration due to blasting is strongly influenced be the detector mounting environment, the blast design parameters, the scatter in the delay initiation times, the blast source radiation pattern and finally the waveform attenuation, spreading and interaction with the surface in travelling from the source to the detector. And further comments, “… thus it is not surprising that experimental PPV results traditionally exhibit a large amount of scatter about a predicted mean and it is somewhat ambitious to expect the data to be represented by a simple site law. Further more, although for certain applications, such a law might give indication of expected vibration levels, it use is basically a curve fitting exercise and the evaluating parameters give little or no information on the underlying mechanisms.”

The analytical modelling method advocated by Blair (1987) is the application of Dynamic Finite Analysis.
However this technique is highly specialised, extremely complex, very expensive, and being a simulation-based approach can require an undue computational period. There is no doubt that such an approach will provide a greater insight as to the prevailed vibration mechanism, but its use will be limited to all but the most elementary of research investigations as it provides little of the practical utility required by the industry for acceptance.

**Scaled-Distance: Fixed Scaling Issues**

Hunt et al (2003) and Wetherelt et al (2003) investigated alternative peak particle velocity analytical methods, in particular, they drew attention to the different values for site factors which can potentially be obtained through the use of different regression methods. They raise a valid question: “why continue with the bivariate, ‘log-log’ approach when the calculation of the power is now so easy with software applications such as Microsoft Excel?” In other words, why use a fixed scaling exponent when a multivariate (3 power law) site specific formula can be readily resolved. This concurs with the findings by Birch and Chaffer (1983) who also made a strong case for multivariate regression, but their calls went unheeded as the current method is so widely excepted and works in most situations.

One explanation, although not a justification, that accounts for the combined use of the square root scaled-distance rather then a 3 power multivariate relationship is that the straight line ‘log-log’ relationship is much clearer to graphically represent, which in turn makes it visually easier to examine, interpret and assess. In addition, it simplifies the process of constructing confidence lines (as these will always be parallel to the best fit trend line) and provides easier appreciated verification for blast design, monitoring and performance (White, Pegden and Birch, 2003).
Reducing the Environmental Effect of Aggregate Quarrying: Dust, Noise & Vibration
The results, outcomes and deliverables of both the previous MIST projects and the subsequent review of selected peer reviewed papers from journals and conference proceedings have been classified as:

- Very Preliminary (requiring much more work)
- Preliminary (Requiring more work)
- Proof of concept
- Potential Commercialisation
- Fully Commercialised

Four MIST projects considered blast monitoring in detail. Blast monitoring (both Vibration and Air Over pressure) is also considered within the MIST funded web site, www.goodquarry.com. The MIST research areas and projects where blast monitoring was considered were:

<table>
<thead>
<tr>
<th>MIST Research Area</th>
<th>Project No.</th>
<th>Project Title</th>
<th>Lead Partner</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knowledge Transfer project</td>
<td>MA/2/4/005</td>
<td>Development of a standard operational blasting database for use within the mineral industry</td>
<td>University of Leeds</td>
</tr>
<tr>
<td>Impact Mitigation and Management</td>
<td>MA/3/2/003</td>
<td>Feasibility project into the use of electronic detonators to control vibration from blasting</td>
<td>University of Leeds</td>
</tr>
<tr>
<td>Impact Mitigation and Management</td>
<td>MA/4/2/003</td>
<td>Full scale quarry blasting project into the use of electronic detonators to control vibration from blasting</td>
<td>University of Leeds</td>
</tr>
<tr>
<td>Impact Mitigation and Management</td>
<td>MA/5/1/001</td>
<td>Development and deployment of a novel, full integrated vibration, air overpressure and acoustic blast monitoring system for use in the aggregates industry</td>
<td>University of Leeds</td>
</tr>
</tbody>
</table>

**MA/2/4/005 - DEVELOPMENT OF A STANDARD OPERATIONAL BLASTING DATABASE FOR USE WITHIN THE MINERAL INDUSTRY**

The recording of information is critical to the blasting process, whether it be for planning purposes, statutory requirements or environmental compliance. The review and analysis of past data can play a key part in a blast’s design. Statutory records must be held to preserve operational licenses and well-maintained monitoring records are a vital defence for today’s litigious society. The aim of the project called for bespoke blasting database system to be developed to meet the requirements of today’s minerals industry. However the system proposed was not just to provide a means of information storage, but also to act as an intelligent system as an aid for blast design, charge weight determination and vibration prediction. The ‘Blast Log’ blasting database program has been designed by blasting engineers for blasting engineers as a bespoke application to provide an interactive means to assist with planning future blasts, improve performance and efficiency whilst at the same time seeking to minimize environmental impact. The database is based and structured on an
original design by the Dept. of Mining and Mineral Engineering, The University of Leeds (see Appendix B), has been written using Microsoft Access in order for it to be easily accessible to the majority of potential users without having to go to the expense and inconvenience of purchasing a third party host program. It is now freely available on CD to the UK Minerals Industry together with a comprehensive user manual.

Whilst the exercise was highly successful, the operators with one or two key exceptions have shown little interested. On the other hand a number of regulators (particularly Mineral Planning Authorities in areas of active aggregate extraction) have shown an interest, but lack of funds have prevented them from taking this further. An application was made for match funding entitled “Pilot Deployment of a Standard Operational Blasting Database for use by Minerals Planning Authorities” to the 6th MIST call for proposals but this was subsequently rejected. Fully Commercialised

MA/3/2/003 - FEASIBILITY PROJECT INTO THE USE OF ELECTRONIC DETONATORS TO CONTROL VIBRATION FROM BLASTING

A series of small scale blast were carried out at the Camborne School of Mines test mine. The aim of this project was to carry out a series of fully instrumented small scale blasts to determine the influence that the firing times of individual holes have on the resulting vibration signal and more specifically to determine whether by optimisation it is possible to consistently reduce the vibrations generated by a given blast. The key findings were that it was possible to use small scale blasts to emulate quarry shots for the purpose of analysing vibration signals. The timing accuracy of the electronic detonators was found to be extremely high. It was also found that it is possible to simulate the vibration generated from a blast with reasonably high degree of accuracy. Thus as a feasibility study it proved to be very successful. This study then lead on to the very successful full scale study one year later. Proof of Concept

MA/4/2/003 - FULL SCALE QUARRY BLASTING PROJECT INTO THE USE OF ELECTRONIC DETONATORS TO CONTROL VIBRATION FROM BLASTING

During the 18 month period of the project, 55 blasts giving rise to 526 monitoring results were monitored. The study demonstrated that electronic detonators can be used to reduce the environmental impact produced at residential properties or structures from blasting in quarries. This can be achieved by use of a protocol that was developed as part of the project, whereby a single hole vibration signature is obtained from a blast at a number of different monitoring locations representing different distances. These can then be used to develop a model using linear superposition that can accurately determine the likely level of vibration produced for a given timing delay interval for a multi-hole blast. From such a model the timing period can be selected that best suits the problem that has arisen. Thus if only a single property or structure is being considered then the timing period to give the lowest vibration level can be chosen. Alternatively if a number of properties or structures are being considered then the timing period to give the “least worst” vibration level can be selected. The project was very successful and a number of peer reviewed papers in both the proceedings of conferences and journals were produced to publicise the work. The methodology is currently being used by one of the big six aggregates companies in the U.K. to address a specific problem at one of their quarries in England. Fully Commercialised
The aim of this project was to develop a novel, full-integrated vibration, air overpressure and acoustic blast monitoring system for use in the aggregates industry. Then to test its fitness for purpose by deploying it for use in a small scale pilot study to examine the relationship between blasting complaints from local residents adjacent to quarries and the actual blasting parameters that can be measured using modern instrumentation. The prototype system was constructed and then installed at the site office at Coldstones Quarry. Two ‘Mk 1’ units were constructed and deployed at houses in Greenhow Village (Old School House and East Wayside). The data relating to each blasting event was available to download to the University of Leeds within 5 seconds of the blast being recorded. Typically each Unit consisted of three tri-axial geophone arrays with four microphones, an air overpressure microphone and a trigger transducer for signal capture. Each channel was capable of collecting in excess of 60,000 samples per second. All three units proved to be extremely reliable. Results indicated that acoustic response due to blasting can be associated with ground vibration, air overpressure or indeed both. However it was not possible to determine what controlled the manifestation of the phenomenon. Proof of Concept
Sustainable Aggregates: Reducing the Environmental Effect of Aggregate Quarrying: Dust, Noise & Vibration
5 DETAILED LITERATURE REVIEW DEALING WITH THE MINIMISATION OF BLAST GENERATED GROUND VIBRATIONS FROM QUARRIES & SURFACE MINING OPERATIONS

This following section of the report presents a review of the key academic papers presented both at conferences and in journals that are thought to be directly pertinent to the development of good practice with respect to prediction and minimisation of blast generated ground vibrations from quarries and surface mines. For each paper an assessment is made as the degree to which the findings are directly relevant to helping to reduce the environmental impact from blasting.


Research presented in this paper investigates the impact that local response can have on the correlation of scaled distance blast data and how the trend lines of each monitoring location can be modified so that they match the general trend line. Blast data recorded from a limestone quarry has been used to analyse location effects. The authors discuss the impact that location has on recorded PPV levels and how it affects the scaled distance correlation. An explanation is given of the process of modifying the trend lines of each individual monitoring location such that they are then aligned with the general trend line of the entire data set which in then results in a more realistic correlation being made. It is then shown that this allows for more accurate vibration predictions which in turn allows for use of greater MICs whilst maintaining low ground vibrations.

Proof of principle

VARIATIONS IN VIBRATION SIGNALS FROM SINGLE HOLE QUARRY BLASTS (2001) YUILL G & FARNFIELD R.

The paper describes a series of single hole blasts that were monitored and used to predict vibration levels from a production blast using linear superposition. The paper highlights the limitations inherent in the linear superposition technique when used to determine ‘optimum’ inter-hole delay times and then derive vibration predictions. Additional researching in the area is needed in order to determine a reliable method of using linear superposition with single hole blasts so that blasts can be designed with more confidence.

Preliminary

The paper presents an investigation into methods to improve the confidence of Peak Particle Velocity (PPV) predictions by reducing the scatter which should then lead to less restrictive controls on the Maximum Instantaneous Charge (MIC).

Varying statistical methods that can lead to improving the PPV predictions are discussed throughout the paper. There is a large emphasis placed on how best to attain the 95% confidence line in which all PPV predictions will be based on. The paper is concluded with a guideline on how best to predict PPV by statistical methods and also on how to account for site factors. The points discussed in this paper have proven to produce less scatter of PPV data and hence allow for more accurate predictions which will result in quarry operators being able to use greater charge weight per hole whilst still complying with the regulations. **Proof of principle**


This paper examines the use of the linear superposition technique for conducting delay-optimisation in conjunction with electronic detonators. The authors provide a detailed account of several tests which were performed in order to determine the true nature of vibration signals produced from individual blast holes. It is demonstrates the difficulties that can arise when using the linear superposition technique.

The paper provides a detailed examination into problems associated with the linear superposition technique for determining vibration signals. It implies that the fact that the “dynamic burden concept” is not as yet fully understood and hence cannot be taken into account in the model, may be responsible for the problems of prediction, however further work is required in this area as explained in the paper. **Preliminary**

THE EFFECT OF CONFINEMENT ON GROUND VIBRATION AMPLITUDE (2003) RODGERS J.

This paper investigates the effects of the burden on the resulting ground vibration amplitudes produced from a blast. The author discusses stress wave components, rock response components and time components and their interaction with the surround rock which causes the rock fragmentation. The introduction of the three components by the author provides sound background information to help out with understanding the analysis of the field experiment results. The experiment involved monitoring the ground vibrations produced from two blast holes with different burdens. A case study is also included in the paper which demonstrated the impact of reducing the burden has on reducing ground vibrations and a method of calibrating the linear superposition model was also included. **Preliminary**

In this paper, the authors investigate whether the 8ms delay time between blast holes (which has been used over the past decades as a “rule of thumb” by blasting engineers), should still be used with the introduction of electronic firing systems. The minimum recommended delay time of 8ms was introduced to minimise ground vibrations by avoiding constructive interference of blast vibration waves and hence its impact on amplitude. The authors explain how the 8ms time window has little effect on large scale blasts where frequencies are low and amplitudes are high. The recent introduction of electronic detonators which are inherently much more accurate delays (+/-0.2 milliseconds regardless of the delay period), has given the blasting industry scope to experiment in new ways that should not be hindered by old “rules of thumb”, however this research is currently at a very preliminary stage.


The paper reviews the current methods of PPV analysis that is commonly used and the validity of the assumptions that are made together with the reliability of the results that are produced. Alternative methods are proposed by the authors, which are proven to be more accurate and hence will provide greater confidence. The authors investigate residual distributions of regression data sets to show that in every log/log regression case, a positive result was not produced. It is concluded that there are doubts in the reliability of the current log/log regression approach and that more reliable approach is required such as the 3 parameter power law model discussed in the paper. The paper is at a preliminary stage as the authors have indicated that their current regression methods of PPV analysis contains a certain unreliability and so more research is required in order to establish a more reliable PPV analysis method.


The paper presents a study that was carried out to determine the ground vibration components at five sites in Turkey in order to be able to predict the PPV values of blasts with a 95% confidence level.

A summary of each site is provided and also the methodology of monitoring the blasts at each of the sites. The authors performed this study to prove that it is possible to design blasts reliably using the common PPV prediction formulae which are provided in this paper. The fact that they were able to do this is not surprising as this method has been proven many times in the past. However it is useful as the paper is in essence a summary of a series of tests performed by the authors which confirms the current methodology in PPV prediction. Proof of Principle
ENVIRONMENTAL BLAST DESIGN AND EFFECTIVE IMPLEMENTATION (2004) MOORE A.J & RICHARDS A.B

The paper investigates the sensitivity of individual factors which contribute to air overpressure, ground vibrations and fly rock. This has been done by utilising recently developed environmental design models by the authors. The intention of this research is to provide information for shotfirers relating to the key blasting parameters which if not taken into account can actually lead to significantly increasing the impact on the environment. For the case of this review, the ground vibration aspects of the paper have been reviewed.

Ground vibration generated by blasting is very briefly discussed in this paper and the key factors which influence the levels of vibrations that will be produced are explained. Wave reinforcement and the empirically derived Scaled Distance Site Law formula are both discussed. The paper gives a general summary of the environmental impacts of blasting and is divided into three sections: ground vibrations, air overpressure and flyrock. Potential Commercialisation


The paper discusses the application of the likelihood ratio test to regression data as an analytical tool to help quantify the degree of variation between sub-sets of blasting data. It is explained that this can then lead to increased prediction capabilities. Instructions on how the technique can be applied are provided in this paper together with illustrated case studies. The principle of likelihood tests are explained as clearly and simply as possible. Case studies are utilised in this paper to highlight how variations in datasets due to varying conditions can be identified and quantified. The research performed in this investigation can be of great value to regulators and operators. Proof of principle.


The paper investigates how the blast design can be optimised in order to control ground vibrations for blasting in tight situations. The author discusses how explosive energy confinement can be optimised through various methods. The remainder of the paper is a brief summary of: vibration prediction, seismic monitoring, blasting vibration in the extreme near field, public relations and project safety. This paper does not present any new ideas or theories but summarises common practices that are performed when blasting near sensitive areas. Summary

A METHOD FOR THE PREDICTION OF BLAST VIBRATIONS AND SUGGESTIONS WITH RESPECT TO UNIFORM REFERENCE VALUES FOR SHORT-TIME VIBRATIONS (2004) MUeller B & BOEHNKE R.

The paper revises the blast prediction technique whilst incorporating the momentum theory as a basis for their work in deriving a new prediction technique. The momentum theory is not fully explained but is refers the reader to the author’s previous publication. The new method of blast vibration prediction, introduced
in this paper is based upon the ejection velocities of the muck pile initially after blasting. In contrast to traditional blast prediction methods, the ‘charge per delay’ factor is not applied. It is claimed by the authors that the prediction methods offer many improvements and that the use of the momentum theory also presents further advantages.

The paper provides an interesting new ground vibration prediction method that will need to be further developed in order to provide accurate predictions from a variety of conditions. Preliminary


The paper presents an investigation by the authors into how the duration as well as the ground vibration frequencies of a blast can affect the structural response of buildings. The methodology used to monitor the blasts is fully explained. The PPV values from blasts detonated with detonator cord and by non-electric tubes were compared. An analysis of the frequency of ground vibrations was also conducted with the aid of Fast Fourier Transforms Analysis and the significance that this has on the structural response was discussed. It was found that the duration of the blast had a major impact on the structure response and a reduction in the total time period of the blast vibration was found to lessen impact on buildings.

This paper seeks to investigate an interesting aspect of blasting and then to develop a method that can help reduce the impact that ground vibrations produced by very large blasts such as cast blasts has on nearby structures. More research is needed in this area so that an optimum blast duration can be established. Preliminary.

IS THAT NORMAL? FUNDAMENTAL OBSERVATIONS FOR BEST PRACTICE BLAST VIBRATION ANALYSIS (2005) PEGDEN M, BIRCH W.J. & WETHERELT A.

This paper reviews the widely held assumption that all blasting data can be considered to be normally distributed. It seeks to investigate the normality hypothesis within the blasting context through an in-depth statistical analysis of what can be described as an ‘ideal’ data set.

The authors begin the paper reviewing the evolution of the scaled distance model. This provides background knowledge to the reader to ensure a better understanding of the intensive statistical analysis discussed in this paper. This is followed by a thorough explanation of the principles of the statistics used in the paper. The statistical analyses are applied to a blast data recorded from an opencast coal mine in West Yorkshire, England. The authors provide a detailed step by step analysis of the results to show that the number of blast need for a data set to be truly normally distributed is very large indeed.

The paper ends with a summary of the fundamental observations for best practice blast vibration analysis that have resulted from this investigation. This paper also provides recommendations in data quantity, determining normality through visual inspection, data quality and homogeneity of variance. Proof of Principle
A NEW TECHNIQUE FOR PREDICTING VIBRATION LEVELS FROM TUNNEL BLASTING (2005) BIRCH W.J, KIRKE M & HOSEIN S.

The paper describes an investigation into predicting vibrations produced from tunnel blasting underground. The paper describes the blasts that were monitored and gives an explanation of how single hole test blasts were used as a predictor for determining the MIC for the tunnel blasts using the scaled distance model. Standard regression analysis has been performed on the resultant PPV and detailed regression analysis has been carried out on the PPV data that is associated with each of the detonator time delays. This enabled the authors to identify the cause for high PPV values which will enable improved delay timings to be set. The paper concluded that electronic detonators would provide more accurate timings and hence lower levels of ground vibrations which would make tunnel blasting in urban areas more acceptable. Research into this is being conducted at this moment. The contents and results of the paper show that the work is at a preliminary stage.

ANALYSIS OF PARAMETERS ON THE GROUND VIBRATION PRODUCED BY BENCH BLASTING AT A BORON OPEN PIT MINE IN TURKEY (2005) KAHRIMAN A, KARADOGAN A, TUNCER G, OZDEMIR K & AKSOY M.

The paper describes a series of tests conducted in order to monitor ground vibrations produced from blasting and then to carry out a statistical analysis of the results. The authors describe the monitoring setup and the list the recorded PPVs. Statistical analysis is performed with the results and is fully explained which leads to determining the charge weight that can be used in order to remain within the permissible PPV limit. The paper does not introduce any new concepts but is a well drafted review of predicting PPV levels. Proof of Principle


The paper provides a description of the monitoring of blasts performed at an opencast coal mine. Videographic data, velocity of detonation and PPV data were all collected and analysed. The investigation focused on the ground motion produced by large cast blasts with MICs of up to 3 tons. Each of the blasts was monitored in the far field (2-4km). The paper concludes that the amplitude of the surface wave in front of a blast (at free faces) is not isotropic whereas behind the blast the amplitude is enhanced by a factor of 1.5 or greater. In order to gain a more detailed understanding of the increased ground motion behind a blast, the authors have acknowledged that more work is required. Preliminary


The paper begins by describing how blasting parameters can influence the level of ground vibrations produced from a blast. In order to determine what influence the burden has on the ground vibrations, blasts
at four different operations were monitored. The burdens of the blasts varied from optimum burdens to excessive burdens which are known to cause higher levels of ground vibrations. The resultant peak particle velocities \(\left( v_{\text{max}} \right) \) are correlated to the scaled distance and the influence of the burden was deduced by comparing the correlations of the optimum burden and the excessive burdens. The paper confirms that the burden is directly proportional to peak particle velocity and that the burden’s influence on frequency is not significant. The paper delivers a detailed description of the monitoring and results analysis. Although it has become known in the blasting industry that burden has a significant influence on vibration levels, this paper shows the magnitude of its influence. Commercial

APPLICATION OF 3-D PLOTS AND REGRESSIONS TO BLAST VIBRATION ANALYSIS– DEFINING A SITE-SPECIFIC FORM OF THE CHARGE WEIGHT SCALED DISTANCE (2006) YANG R

This paper presents an application of 3-D plots and non-linear regressions to define a site-specific form of the charge weight scaled distance and for analysing PPV, charge weight and distance relationships.

The author explains how site-specific data is very important for blast vibration analysis and how these site factors can be determined with the use of 3-D graph analysis. A site-specific charge weight scaled distance is explained with formulae provided. These are then utilised in a case example of blast vibration records from a coal mine which helps to illustrate the theories discussed by the author. A method of using the newly defined form of scaled distance to plot the vibration data from production blasts is briefly described with the author concluding that this form of scaled distance that has been introduced in this paper provides more accurate correlations for vibration analysis.

The author argues that analysis of 3D graphs with the use of the site-specific scaled distance is more accurate than current methods used that incorporate the standard blast analysis of plotting PPV against scaled distance. However, the author does not compare the two methods directly and has only provided one set of data to show that the site-specific scaled distance does provide more accurate correlations.

Preliminary


This paper presents an investigation into studying in detail, the application and performance of electronic detonators to improve vibration predictions. The investigation involved monitoring a series of blasts conducted at a limestone quarry whilst keeping all of the design parameters constant other than the choice of using either electronic or non-electronic detonators. A detailed description of the monitoring methods employed for all the blasts is provided as well as the blast designs. The result of the investigation showed that lower PPV levels were produced when electronic detonators were used compared to the non-electronic detonators. The authors then concluded that electronic detonators allow for greater permissible MICs.

Overall, the paper clearly describes the monitoring of a series of quarry blasts and the results from these blasts and the conclusions that have been drawn from the results are backed up by established theories.

Preliminary
INVESTIGATION OF GROUND VIBRATION INDUCED BY BLASTING AT HISARCIK BORON OPEN PIT MINE IN TURKEY (2006) KAHRI MAN A & TUNCER G.

The paper looks at a series of blasts that have been monitored for ground vibrations at 2 locations by seismographs. The recorded PPV is correlated with the scaled distance and the correlation is analysed using regression analysis. This provided the authors with a 95% confidence line for future blasts conducted at the mine. This method of predicting ground vibrations helps the operator to determine the permissible MIC for each blast without exceeding the PPV threshold.

The regression analysis is fully explained and illustrated which enables the reader to follow every step. Once the 95% confidence line is attained, a damage risk evaluation is provided from which another 95% confidence can be determined whether damage will not occur to structures within the monitored distance. This was analysed by plotting PPV against frequency.

The work presented in this paper provides a good review of how to analyse blast data using scaled distance and from this, formulate a basis for predicting PPV of future blasts. However, no new concepts are presented by the authors and this paper follows two almost identical papers which the two authors participated in. It can be said from their previous papers and from papers written by authors; White T.J, Pegden M, Birch WJ that analysis using scaled distance in order to predict PPV levels from future blasts is a commercial method.

NEAR-FIELD BLAST VIBRATION MONITORING, ANALYSIS AND MODELLING (2007) YANG R.

The paper discusses the necessity for near-field blast vibration monitoring and the differences between near-field and far-field blast vibrations and the techniques used for their assessment. The author explains how and why monitoring techniques for near and far-field ground vibrations differ and also the preferred method of recording these vibrations. It is also includes a method for calculating the charge weight distance for near-field blast vibrations.

The paper provides a clear understanding of the differences between the two types of vibration signals. Each point made by the author is illustrated with graphs and diagrams that add clarity. **Proof of Principle**

A METHODOLOGY TO CONTROL PEAK PARTICLE VELOCITY LEVELS AT MULTIPLE LOCATIONS BY USE OF ELECTRONIC DETONATORS (2007) W.J. BIRCH, M. PEGDEN, S. HOSEIN, R. FARNFIELD & D. LECKENBY

The paper describes an investigation into optimising the use of electronic detonators through a series of blasts at a limestone quarry. The series of blasts that were monitored are fully described and also an explanation of how the optimum delay time between holes were obtained using linear superposition methods from single hole test blasts. A detailed analysis of blast results proves that electronic detonators help minimise PPV levels due to more accurate delay timings. The paper is rounded off with a succinct protocol on how to make the most effective use of electronic detonators to minimise ground vibrations.
The paper provides a step by step review of how electronic detonators have been compared to non-electronic detonators. It has been shown that the use of electronic detonators can allow for larger charge weights per hole due to precise delay timings. **Proof of Principle**

**THE INVESTIGATION OF GROUND VIBRATIONS INDUCED BY BENCH BLASTING AT DIFFERENT QUARRIES AT CATALCA DISTRICT IN TURKEY (2007) OZER U, KAHRRMAN A, ADIGUZEL D, AKSOY M & KARADOGAN A.**

The paper generally repeats work from a previous paper by the authors ('Analysis of Parameters on the Ground Vibration Produced by Bench Blasting at a Boron Open Pit Mine in Turkey') however on this occasion has been applied to blasts at three quarries. Method of monitoring and regression analysis of the results are explained in depth along with methods of determining ideal charge weights of explosives by predicting future PPV levels.

The steps taken to monitor, analyse and predict PPV from bench blasting is well explained however, changes from the authors’ previous work is minimal. **Proof of Principle**

**EXPERIMENTAL TECHNIQUE TO REDUCE BLAST VIBRATION LEVEL, TOURAH, CAIRO, EGYPT (2007) KHALED M, ABDEL RAHMAN K & ABO MAKAREM A.**

This paper studies the effects of changing the initiation system in the blast design. A series of blasts were monitored at a quarry in Egypt near a place of national interest. The concept of scaled distance is briefly explained and is utilised in analysing and explained the blast results. The delay intervals and initiation sequences of the double decked holes were tested to establish which minimises ground vibrations. The paper uses a developed method of predicting PPV so that future blasts can remain within PPV constraints. The authors began investigating the effects of the initiation system however more research in this area is required. **Preliminary**


The paper investigates the causes of acoustic response to structures, as a result of quarry blasting. Air overpressure and ground vibrations were monitored at two buildings close to a quarry along with the acoustic response of the two buildings. It was found that both the ground vibrations and air overpressure can give rise to the acoustic response that occurred. The methodology of monitoring the acoustic responses inside the houses are described in great detail, with the method of operation of each of the sensors used, fully explained.

However, only two sets of results are provided in this paper and to gain further knowledge into this area, many more results are required. This has been identified by the authors and it is their intention on continuing with this research in order to fully establish the facts of ground vibrations and their effect on buildings.
There are many conflicting theories on the acoustic response of structures which has lead to great debate and misunderstanding and therefore this paper provides a ‘stepping stone’ into understanding the truth of structure response of buildings to nearby blasting. Further research in this area is much needed in order to minimise complaints of local residents. Preliminary/Proof of principle.

MODELLING AN ARTIFICIAL SCREEN FOR REDUCING SEISMIC VIBRATION (2007) BOGUNOVIC D, KRICA L & KEKOJEVIC V.

The paper delivers theoretical background and methodology into the testing of the artificial screen and its effectiveness in reducing vibration levels. The authors summarise previous work conducted in the interaction between screens and seismic waves. The methodology used in testing the screens through a series of laboratory tests is explained in detail however, testing was not conducted in the field.

The results showed that screen size has a significant effect on the effectiveness of reducing vibrations. On top of this many other parameters were vigorously tested such as the level of pulse which produces the vibration and position of the screen. It was concluded that for large pulses (i.e. when a large charge weights are to be used in each blast hole) the screen is best positioned closer to the source of vibration (blasting pattern) and for smaller pulses, the screen should be positioned further away. Through the tests performed, the results showed that vibrations were reduced from 30% to 58%.

The use of a screen is an interesting concept however, testing has not been performed in the field and so the results from a laboratory cannot be provide a precise conclusion. For this to become viable form of ground vibration control, field testing is required. Very preliminary.
6 Detailed Literature Review Dealing with the Prediction & Minimisation of Blast Generated Air Overpressure from Quarries & Surface Mining Operations

This following section of the report presents a review of the key academic papers presented both at conferences and in journals that are thought to be directly pertinent to the development of good practice with respect to prediction and minimisation of blast generated air overpressure from quarries and surface mines.


The authors describe a method that they have developed for quantifying the airblast emissions. Formulae are introduced in the paper in order to quantify the emissions of airblasts. These include calibration factors that will apply for specific sites, similar to a site factor.

An airblast design procedure is described in the paper and has been explained with clarity by being applied to a real blast, which provides a good example of how to quantify the airblast emissions from a blast in advance. Wavefront reinforcement, effects of topography and meteorological effects are all accounted for in the design procedure.

The paper shows that all significant factors to air overpressure levels must be included in the design process of a blast. The quantification methods described in the paper provide a good basis for predicting the attenuation distance of air overpressure levels from the blast. Further work has been performed in this area by the authors which has lead to the paper entitled 'Airblast Control Techniques in Open Cut Mines'. The models have been applied to additional mining operations since the writing of this paper and so the contents of this paper at the time of writing, have shown a potential commercialisation.


In this paper, the authors investigate whether the 8ms delay time between blast holes which has been used over the past decades as a rule of thumb by blasting engineers, should still be used with the introduction of electronic firing systems. The minimum recommended delay time of 8ms was introduced to minimise ground vibrations but was never intended to be applicable to controlling air overpressure. The paper is mainly focused on the delay time's effect on ground vibration and little is written about air overpressure. The authors do explain that delay time greater than 8ms still produce wavefront reinforcement and so
proving the 8ms rule as inaccurate will still not have an impact on airblast control. This is supported from air overpressure data from a previous paper of theirs and with all their previous work conducted in air overpressure wave reinforcement listed. However due to what the impact on air overpressure that such a low delay time will have, this paper has a limited application to air overpressure. \textbf{Proof of Principle}

\textbf{EVALUATING AIRBLAST DAMAGE COMPLAINTS (2004) GUBBE L.W.}

The paper sets out to predict levels of air overpressure using two different methods;

1. The Sandia Laboratories, Atomic Energy Commission method as extended by the Naval Ordinance Laboratory (NOL method).
2. The Ballistic Research Laboratory method (BRL method).

Base curves of both methods are approximated using a scaling equation which uses a ‘TNT equivalent weight of explosive’ parameter. This is not a useful parameter to incorporate when applied to blasting in quarries or mines as TNT is not used. A factor should have been included to convert the weight of explosives used to find their equivalent TNT weight.

The NOL and BRL methods are shown to predict higher levels of air overpressure than was actually produced, as these methods take into account weather conditions which largely effect the focusing of air blast waves. The blasts described in the paper did not fire during these kinds of weather conditions in order to minimise air overpressure effects. Therefore it is not shown by this paper whether or not the two methods of prediction actually produce accurate predictions. The microphones that were used for the air overpressure monitoring were not able to record readings below 10Hz and at these low frequencies, blast waves generally causes more damage to structures. Thereby monitoring and predicting air overpressure in order to prevent structural damage should include blast waves of these frequencies.

The author then describes previous research into air blast damage criteria and the final conclusions. The methods of prediction described in this paper should be applied to blasting projects in mining and quarrying operations in order to establish an effective method of predicting air overpressures. The paper explains focusing effects clearly but a more mining/quarrying specific testing is required. \textbf{Preliminary.}


The paper describes investigations into the influence that the front row burden and the initiation pattern has on the air overpressure that is produced from a blast. Blasts were monitored at four locations of which used line initiation and diagonal initiation patterns along with varying burdens. The results show that generally, air overpressure is lower as the burden of the front row is increased and that line initiation produces lower air overpressure levels in comparison to diagonal initiation.

The investigation involved a total of 12 blasts that were monitored for initiation pattern testing and 11 blasts monitored for front row burden testing. The air overpressures were measured behind each of the blasts but by testing the influence of front row burdens, monitoring in front of the blast would have been
more beneficial. It has been proven by Richards & Moore 2002 that the burden influences the level of air overpressure produced in front of a blast much greater than behind a blast. The results establish a trend that is common knowledge and that is the burden and air overpressure are inversely related to one another. The paper does conclude that diagonal initiation patterns produce higher air overpressure levels than that produced by line initiation patterns. Research into the effects of initiation and blasting patterns is very little and so with further research a relationship into these factors can be fully established. The research described in this paper is deemed to be at a preliminary stage.


The airblast prediction model is applied to a cast blast at an open cut coal mine in Australia. The effects of wavefront reinforcement are discussed. The authors describe the process of improving the calibration of the current model by monitoring air overpressure levels at various locations from the blast. The resulting calibration factor at each of the positions has been calculated and this has been used in predicting the air overpressure levels from a cast blast. The factors incorporate the effects wavefront reinforcement at each of the monitoring locations.

The first half of the paper applies the airblast prediction model that has already been established, to four cast blasts. The second half of the paper describes how the calibration factors vary from various locations around the blast and so an investigation into this, will lead to improvements in calibrating the airblast prediction model.

The work in this paper has lead to an improvement in the calibration factors used in the airblast attenuation prediction and so has improved the accuracy of an already commercialised prediction model and so this paper is deemed fully commercialised.


The paper investigates the sensitivity of individual factors which contribute to air overpressure, ground vibrations and fly rock. This has been done by utilising recently developed environmental design models by the authors. The intention of this research is to provide information for shot firers on how by modifying aspects of the blast due to unforeseen circumstances can actually lead to a significant increase the impact on the environment. For the case of this review, the air overpressure part of the paper has been reviewed.

The influence that burden has on air overpressure emissions is explained and graphs have been produced in order to allow shot firers understand how by increasing or decreasing the burden can influence air overpressure. The affects of topography, meteorology and wavefront reinforcement are also discussed. The effects of spacing and delay times between blast holes have on wavefront reinforcement and the extent at which a combination of the two factors has on air overpressure emissions are summarised along with an estimate of the increase in air overpressure as a direct result of a chosen combination.

Overall, the paper provides a review of the influences that different blast parameters have on the environmental impact from a blast. The graphs in the paper are designed so that they can be referred to by
shot firers in the field when modifications to the blast design are required. The information is presented effectively and concisely and the theory and data has been supported by previous research and so the contents of this paper are considered **fully commercialised**.

**MICROPHONE HEIGHT EFFECTS ON BLAST-INDUCED AIR OVERPRESSURE MEASUREMENTS (2005) ELTSCHLAGER K.K. & WHEELER R.M.**

The paper describes a series of tests performed to determine the optimum height of a microphone to monitor the air overpressure produced from a blast. The initial set of tests showed that placing a microphone on the ground records higher levels of air overpressure than a microphone placed at a height of 0.9m. The difference in recorded air overpressure was 1.2dBL. A second set of tests was conducted which showed that the height does not actually affect the levels of air overpressure recorded. The author then concludes the paper by stating that height does not influence the level measured after performing numerous rigorous tests.

Very little research has been performed in this area of monitoring air overpressures and this paper provides a useful insight that in fact microphone height is not important. This investigation is very conclusive in its results and shows that the work is ready for **fully commercialisation** if it is not already so.

**EFFECT OF METEOROLOGY ON AIRBLAST OVERPRESSURE (2005) RICHARDS A.B. & MOORE A.J.**

The paper explains the effects that meteorological conditions have on air overpressure levels produced from a blast and the rate of attenuation. The basics of meteorological effects are clearly explained and this is supported by a case study of monitoring a blast at an open cut coal mine in Australia. Assessment of different means of attaining atmospheric conditions is discussed and the authors explain that a design buffer is required in order to predict the attenuation of air blast waves.

The paper concludes with a discussion of a future funded research that will permit the effects of meteorology on airblast overpressure to be measured more accurately and so predictions of air blast attenuation rates will be predicted more accurately too.

The paper has shown that the current model used by the authors provides accurate information, regarding the effects that current atmospheric conditions will have in a particular area however, the future research that is planned will increase the accuracy of air overpressure predictions. **potential commercialised.**

**STRUCTURE RESPONSE TO TRENCH AND ROAD BLASTING (2005) ROSENHAIM V.L, DOWDING C.H & AIMONE-MARTIN C.T.**

The paper describes the effects of blasting on crack and structure response on a nearby building. Air overpressure produced from the blasts was monitored outside of the building and was compared with the structural response. The distances of the blasts from the building ranged from 232m – 368m.

The investigation concluded that the climate had a greater affect on the changes of the crack width in
the building’s walls compared to the ground vibrations and air overpressure. It is proved that the air overpressure is a poor predictor of cracks as the peak levels did not occur when the peak crack and structural response occurred. The blasts however produced low levels of air overpressure and so further research is required with blasts producing higher air overpressure levels.

The paper is primarily focused onto the effects that ground vibrations had on the structure and little was discussed on the affects of air overpressure. This may be due to the air overpressure being too low for any structural damage to have occurred. This paper is at the preliminary stage of research into this area as more monitoring is required of blasts that will produce much greater air overpressures.

CORRELATION OF PUBLIC PERCEPTION OF BLASTING AT ROCK QUARRIES TO REPORTING PRACTICES (2005) LUSK B. & WORSEY P.

The paper examines public perception of blasting operations in quarries located to nearby residential areas. The authors explain that public opinion of blasting has deteriorated over the years due to expanding suburban areas and therefore guidance limits are under more scrutiny.

The paper describes a survey that the authors performed with residents living by a quarry in Missouri, USA. The survey showed that the public are more comfortable with air overpressure levels in millibar units rather than decibels as they are much easier for someone with a non-technical background to understand and feel comfortable with. It is then concluded that the units for air overpressure should be changed to units with a linear scale (such as millibars) so that the public can understand the difference between the guidance limits and the limit of damage criteria. This would provide more confidence in the blasting operators from the public. This is an interesting concept as by proving more clear information to local residents will show that by exceeding the given limits slightly will still not affect their property. Much work is needed in this area to restore confidence back into local residents.

Much more research is needed to discover what people are most comfortable with in order to conclude whether the conversion of units used in regulatory and guidance limits should take place. Proof of principle.

PREDICTION OF BLAST INDUCED AIR OVERPRESSURE IN OPENCAST MINE (2005) MANOJ K. & SINGH T.N.

The paper discusses the use of ‘Artificial Neural Networks’ (ANN) in order to predict levels of air overpressure produced from a blast and compares these predicted levels to the predictions made by the generalised equation:

\[ \text{AOP} = a[D/(Q_{max})^{1/3}]^b \]

The results in the paper show that the predicted air overpressure levels predicted by the ANN had a much higher correlation coefficient than the levels predicted by the generalised equation. The predicted levels by the ANN are not consistently accurate as the predicted air overpressure levels can differ from the actual values by as much as 13dB.
The authors suggest that the use of ANN should be encouraged, however the results show that the system is still inaccurate and that more work is required in order to develop an accurate method of predicting air overpressure. Preliminary.

AIR OVERPRESSURE (2005) SINGH, P.K.

Gives a general discussion on air overpressure and includes; the main sources of airblasts and the effects on structures and humans along with the commonly used ‘cube-root scaling law’. The paper also includes results of air overpressures measured from 5 different limestone quarries in India. Regression analysis is performed on all of the data and a comparison of the results and the predicted air overpressure levels (using cube-root scaling law) at various intervals is made. A conclusion of the causes of the main sources of airblast is made along with recommendations for further monitoring of blasts. This paper provides a more detailed introduction to air overpressure than many papers in this area and provides detailed information into the tests that were performed. The analysis of the test results were brief and lacked detail. Preliminary.


The paper explains how air overpressure wave traces can be examined and from it, can the cause for peak results be deduced. The authors introduce a new model that takes into account confinement of blast holes to predict the level of airblasts. The model calculates the distance from the blast at which the air overpressure level will be 120dBL and incorporates both burden and stemming controlled blasts. The airblast prediction model has been developed and is used by Terrock. Wavefront reinforcement is explained in detail with the use of seed waveform analysis. This sheds light onto the importance of delay times between blast holes and the direction of initiation in blast designs. This aspect of controlling air overpressure has not been fully explained in previous papers in as much detail as in this paper and to as much success.

The blasts examined in this paper are monitored at large distances of up to 10km, however little emphasis has been placed onto air overpressure levels at much shorter distances from a blast. With this in mind, investigating the control techniques of airblasts at much closer distances will be highly beneficial in further controlling air overpressures.

The control techniques and model discussed in this paper are used in the industry and therefore shows that the content is ready for fully commercialisation.


The paper investigates whether the guidance on the level of air overpressure that is likely to cause damage is entirely accurate. The results from the tests showed that the guidance of air overpressure levels in many literatures are too low and should be higher. The study described in this paper is very limited and further
testing is required in order to prove whether current guidance levels used are too strict. Little research has been undertaken in this area and more is required in order to establish a precise conclusion. To draw any final conclusions, tests of window responses to air overpressure should be simulated in a ‘real life’ event in order to be able to recommend whether windows in buildings can withstand higher levels of air overpressure than set by the current guidance. With this in mind, the paper is deemed to be at a very preliminary stage.


The paper investigates the causes of acoustic response to structures, as a result of quarry blasting. Air overpressure and ground vibrations were monitored at two buildings close to a quarry along with the acoustic response of the two buildings. It was found that the ground vibrations were the cause for the acoustic response that occurred and that air overpressure had no effect. After subjecting the recorded traces to Fast Fourier Transform (FFT) analysis, it became apparent that the air overpressure is dominantly consisted of frequencies below 20Hz i.e. the threshold of hearing whereas ground vibrations consisted of frequencies above this range.

The methodology of monitoring the acoustic responses inside the houses are described in great detail, with the method of operation of each of the sensors used, fully explained.

However, only two sets of results are provided in this paper and to gain further knowledge into this area, many more results are required. This has been identified by the authors and it is their intention on continuing with this research in order to fully establish the facts of ground vibrations and their effect on buildings. There are many conflicting theories on the acoustic response of structures which has lead to great debate and misunderstanding and therefore this paper provides a ‘stepping stone’ into understanding the truth of structure response of buildings to nearby blasting. Further research in this area is much needed in order to minimise complaints of local residents and to regain public trust in mining and quarrying activities.

Preliminary/Proof of principle.

STUDY OF BLASTING PRODUCED AIR OVERPRESSURE IN URBAN AREA (2007) DINGXIANG Z.

The paper presents a case study of blasting activities in an urban area in Hong Kong. Air overpressure is briefly explained along with factors that influence the levels that are produced from a blast. The influence that these factors have on air overpressure levels are illustrated with statistical data that has been collected from the monitoring each of the blasts. The results of different factors on air overpressure proved to be inconclusive other than that scaled distance and air overpressure being inversely related.

This paper is concluded with methods that were taken to help control the air overpressure produced from each of the blasts and whether or not they were successful.

Overall, air overpressure is summed up and the factors that are known to influence it are investigated by
monitoring blasts that have been conducted at the project described. Most of the data proves inconclusive but this helps the author illustrate that there are many factors that influence the levels of air overpressure produced form a blast. The paper is considered at the proof of principle stages of investigations as the contributing factors have been tested and analysed but further testing is required, however the paper presents air overpressure problems associated with this particular project and is not of the author’s aim to prove which factors have the greatest influence on air overpressure.


This paper investigates the accuracy of ‘Artificial Neural Networks’ (ANN) being able to predict the level of air overpressure produced from a blast. Four parameters were incorporated into the ANN:

1. Maximum Instantaneous Charge (MIC)
2. Depth of burial
3. Total charge
4. Distance of measurement

It is made unclear by the authors what constitutes the depth of burial of the explosive charges. It is stated that it is either the length of the stemming or the distance of the charge from the free face i.e. the burden but it is not stated when it or one or the other. It might be assumed that the shortest distance of the two represents the depth of burial but this is again unclear.

A list of well known factors which affect air overpressure is provided and the most and least influential factors are stated. The authors have deemed that the orientation of initiation and delay intervals are the least contributing factors to air overpressure without proving this point or even referencing to some other work, whereas in many research papers in this field, it has been shown that these parameters can be very significant.

The predicted air overpressure by the ANN is compared to the predictions of the empirical predictor equations. The concept of ANN is very clearly explained and illustrated for a reader with no background with ANN. The paper concludes that the air overpressure predictions by the ANN are more accurate than those predicted by the empirical equations and the authors recommended further work with ANN in order to produce a method of predicting air overpressures from blasting. The results of the ANN showed that the burial depth of the explosive charges had the most influence on the air overpressure levels however it is not clarified how the burial depth is derived. This is of great importance as the stemming or burden has different effects on air overpressure levels, with the burden having a greater influence on air overpressure in particular in front of the blast. It is also not made clear in which direction the predicted and actual air overpressures are in relation to the blast.

More research is required in this area in order to establish a method of predicting air overpressure levels but the results produced from neural networks are not always definite and the results shown in this paper lack certainty. Preliminary.
7 AREAS FOR FUTURE RESEARCH

A number of areas for future research and support have been identified as a consequence of this review:

1. The successful completion of feasibility study on acoustic response should now lead into a full scale study. This should include the deployment of the relevant monitoring equipment as well as a full psychological study to assess the reaction of local residents in their own homes to the acoustic response of the structure as a result of both blasting vibrations and air overpressure.

2. The successful use of electronic detonators to reduce the magnitude of the resulting blasting vibrations now raise the question: to what extend is the improvement due to just the improved accuracy of these advanced detonators? A statistical number of conventional shock tube detonators from a number of different manufacturers should be tested and the results used to model the likely blast waves and magnitudes that could arise. This could then be compared to existing field data.

3. Financial support should be given to enable the Mineral Planning Authorities (whose regulatory areas supply significant quantities of aggregate produced by blasting) to be able to deploy the Blasting data base that was created as part of project No. MA/2/4/005.

4. Many studies have examined the effects of air overpressure and how it propagates away from the blast source, however no studies have been done to determine the actual factors in a quarry blast that determine the initial magnitude of the blast induced air pressure wave. If air overpressure is to be effectively controlled, then field studies in this area of research need to be carried out.

5. Whilst it is now possible to limit ground vibration from quarry blasts using electronic detonators, the effect on using such a method on fragmentation of the broken rock produced needs to be researched so that the full economic impact on production can be assessed.

6. The practice of splitting the total charge weight into two separate events on different detonator timing (i.e Decking) is a common method for limiting the maximum instantaneous charge in a blast. However no real science has been applied to this practice. How should a blasting engineer scale the charges in decking - i.e. is it the equivalent of halving the charge weight? Which deck should they fire first - does it make any difference? Does the timing between decks make any difference? What is the optimum split of charge weight between decks? – [most engineers favour 50 / 50 whilst other leading practitioners lean towards 40 / 60].
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**Specific blasting induced ground vibration papers reviewed**


Conference on Explosives and Blasting Technique, Nashville, Tennessee 2007 v2
International Society of Explosive Engineers.


Specific Air Overpressure papers reviewed


APPENDICES

APPENDIX I: ABSTRACTS FROM RECENT (2000 – 2007) PEER-REVIEWED BLASTING INDUCED GROUND VIBRATIONS RESEARCH PUBLICATIONS;

An Advanced Blasting Scaled-Distance Model Incorporating Individual Location Response
Birch W.J, Pegden M & West R.M.
The traditional concept of scaled-distance modelling for predicting blast induced ground vibration holds many drawbacks, not least of which is the major effect data scatter imparts on confidence determination. An investigation by the Department of Mining and Mineral Engineering, The University of Leeds, England has resulted in the development of simple but effective method of improving prediction capacity through the reduction of effective error by incorporating individual location response into a scaled-distance model.

The work is the product of an 18-month blast-monitoring campaign at a limestone quarry situated in North Yorkshire, England. The data, when presented in the form of a scaled-distance model, indicates a typical scenario where a good overall correlation becomes marred by the extent of data scatter. Examination of the individual monitoring locations however indicates that the response of the individual location is an important factor in the explanation of the large residuals. The novel approach that has been developed incorporates a series of locational site factors which when incorporated into a scaled distance model reduces the effective error and therefore improves prediction capacity. The approach is based on using a standard computer package “spread sheet” on the understanding that these are commonly available on all quarry or home computers. This approach has been validated by comparison with a more rigorous statistics method.

Due to the increased confidence, blasts designed on this basis can be seen to comply with environmental constraints with a greater degree of flexibility as regards permissible charge weights and the level of accuracy for ground vibration prediction is significantly improved. The findings are initially demonstrated in the context of a case study, but easily transferable spreadsheet calculations allow the approach to be applied elsewhere. As the concept is an extension of a world-widely accepted method, the end result is a simple, highly practical, workable solution with an appreciable outcome designed for the blasting engineer in the field.

Variations in Vibration Signals from Single Hole Quarry Blasts
Yuill G & Farnfield R
The rock blasting industry continues to be under pressure to reduce the level of vibration induced by the use of explosives.

In recent years much research and development has been directed to minimising vibration levels by controlling the delay period between blast holes.

The most commonly applied technique is known as Linear Superposition. This technique takes the vibration produced from a single-hole test shot and simulates the vibration that would be produced from a full scale-scale production blast. The simulation can be run with various delay periods and the optimum delay chosen.
The success of the Linear Superposition technique depends to a great extent on having accurate delay detonators and on the single hole test shot reliably indicating the vibration signal produced from each hole in a production blast.

A quarry-based case study is given illustrating how these assumptions are not always valid. In this case the use of electronic detonators has controlled frequency but not vibration level.

The paper goes on to describe a series of single-hole test shots in an U.K. limestone quarry. The vibration signals recorded are examined in terms of variations in free-face provision, blast geometry, explosive properties etc.

**Developments in the use of scaled-distance modelling which allow an increase in the permitted charge weights while still ensuring vibration Compliance**

*T.J. White, M.Pegden & W.J.Birch*

Scaled distance modelling is universally accepted as the method for predicting the levels of vibration from a blast and of designing blast parameters to ensure compliance with consent levels. As the modelling is a statistical method based on empirical data, confidence levels are derived using the Standard Error (assumes a normal distribution) of the data points. A high degree of scatter results in a low, and therefore more restrictive MIC (maximum instantaneous charge). Leeds University Department of Mining and Mineral Engineering have investigated a number of methods of reducing the scatter and improving the confidence of the predictions, which will result in less restrictive controls on the MIC.

1. Ensure the correct Standard Error multiplier is used in the calculation. The requirement is that a certain percentage of blasts will be below a particular level, NOT between an upper and lower limit. Therefore a single tail test is required with the appropriate multiplier.

2. Incorporate production blast data as quickly as possible if a test blast has been used. Occasionally it may be necessary to remove the test blast results. Most test blasts are carried out with no free faces and often with a single hole, so are therefore not representative of normal production blasts.

3. Take into consideration the differing geological conditions around the site. The geology surrounding a site will significantly impact the levels of vibration recorded, and if the geology varies, then this will increase scatter. By looking at particular areas rather than considering the site as a whole, the confidence of prediction can usually be significantly improved.

4. Take into consideration the differing monitoring location effects. It has been shown elsewhere that incorporating individual location response can significantly improve prediction confidence and so this method should be used wherever there is sufficient data.

5. Maintain a comprehensive blast database which will allow this type scaled distance modelling to be carried out with ease.

The above methods should be combined into a standard procedure for good practice.
Experiences with the deconstruction of multi-hole quarry blast vibration signals

R.Farnfield, G.Yuill & W.Birch

The University of Leeds and Exchem Explosives have developed a research programme with the aim of developing techniques to minimise the environmental impact of blasting operations. Initial work examined the use of delay-optimisation via the technique of linear superposition in conjunction with electronic detonators. The results of a number of quarry trials were variable and prompted the examination of some of the fundamental assumptions made with this technique. Subsequent work examined the variability of the vibration signals produced by single-hole blasts. This showed that variations in hole geometry and explosive properties had little apparent effect on the general vibration shape although vibration amplitude was closely related to the degree of hole confinement. The work described in this paper is centred on gaining an understanding of the vibration contribution from each hole in a multi-hole blast. The work has entailed detailed monitoring of a series of production blasts employing only two or three holes. Initial work with two-hole blasts suggested that the second hole produced a vibration signal similar in shape to the first but inverted and this is illustrated with two examples from limestone and chalk quarries. An additional series of two test blasts were carried out in the chalk quarry with three holes in each blast. Attempts to deconstruct these signals proved very difficult and a technique was developed based on an iterative statistical best-fit method. In common with many research programmes this work has suggested solutions to some problems but posed many new questions.

The Effect of Confinement on Ground Vibration Amplitude

Rodgers J.

There has been a longstanding acceptance that burden plays a major role in the magnitude of ground vibration amplitudes generated from surface blasting. Much of the data that this belief is based upon is empirical in nature and may or may not represent an example of false inference. Recent published reports have rightly questioned the influence of burden and confinement on blast vibration amplitude, suggesting that the fracture condition of the rock mass is a better indicator. The increased investment in electronic detonators as a tool to control ground vibration amplitudes demands an understanding of vibration production detailed enough to make use of the vastly improved timing accuracy that they provide. A more accurate relationship may be found if we strip away the assumptions of the past and search for the underlying mechanism of vibration production in surface blasting. We must answer the question: What happens at or near the borehole when an explosive charge detonates that produces ground vibrations?

In an effort to address this question in a practical way, a series of instrumented, reduced-scale, test blasts were conducted to examine the source of ground vibrations in blasting. The experiments were designed to evaluate the effect of confinement in the form of burden and rock mass condition on vibration amplitude. Attempts were made to distinguish between stress wave and rock response modes of ground vibration generation. Results and implications of the testing are discussed. To facilitate discussion of the transient vibration energy near the borehole a conceptual model is developed. A case history is also presented employing electronic detonators. Significant control over vibration amplitude and frequency content were achieved. As many might expect, the results of this application demonstrate that timing accuracy alone will not guarantee optimum, or even acceptable, vibration control, rather an approach incorporating timing, field controls and basic understanding of the response of the rockmass to explosive loading is necessary.
The Eight Millisecond Time Window Myth
Moore A.J. & Richards A.B.

Time window analysis that limits the explosive mass fired within a specified time window (commonly eight milliseconds) has been used for many years in blast design by explosives engineers.

Despite several warnings in the past that this technique has limited practical or scientific basis and, in many cases, does not effectively control vibration, almost every textbook and blasting manual refers to time window charge mass limits as a primary vibration control technique. It has become entrenched in some blast vibration management plans, despite being inappropriate for the particular situation.

With the flexible initiation timing available with electronic detonation almost a practical reality, and the 8 ms constraints in-built into the signal tube initiation system thereby lifted, it is timely to review the significance of the 8 ms time window in controlling blast vibration.

This paper re-visits the original research that led to the development of the 8 ms criteria and the non-supportive conclusion of the original researcher. Because airblast was not measured, the 8 ms time window was never intended to be applicable for airblast control. Examples of blast designs are given in this paper that comply with the 8 ms time window limit that result in substantially increased air and ground vibration, together with examples of blast design that does not satisfy time window considerations, which results in reduced air and ground vibration.

Techniques that identify wavefront reinforcement, due to the combined effect of drilling pattern and delay sequence, can assist explosives engineers to avoid high blast vibration situations that result from the inappropriate application of time window techniques and other adverse delay combinations.

The Reliability of Peak Particle Velocity Analysis Methods
P.Hunt, A.Wetherelt and N.Powell

The statistical analysis of Peak Particle Velocity (PPV) data, obtained from ground vibrations is employed throughout the surface mining and quarrying industries to monitor and control the environmental effect of blasting operations. Successful achievement of these objectives relies upon the following factors:

(a) The acquisition of sufficiently accurate and relevant, on-site PPV data.
(b) The formulation of appropriate mathematical models relating PPV, explosive charge mass and distance.
(c) Determination of ‘best-fitting’ site specific parameters for the particular models chosen.
(d) Determinations of PPV confidence levels/safety limits for the prediction of, explosive charge mass or distance.

This paper considers the current methods of analysis employed, the validity of assumptions made and the reliability of results and predictions derived; where appropriate, alternative methods are proposed which are more accurate and can be applied with greater confidence. In regard to data collection, new local blasting data has been analysed and conclusions drawn but, due to the restricted amount of space available, reference to data set A only has been made in the text. The problem of mathematical model choice is considered and results for two and three parameter power laws are compared. The very important matter of parameter determination is discussed fully, with major emphasis being placed on the comparative merits of log-log linear,
log-log planar and direct power law regression. Supporting data analysis examples are included. Assumptions regarding the normality of ‘best-fit’ regression model residual distributions are questioned and the reliability of associated safety limit determinations is discussed.

**Prediction of the Ground Vibration Attenuation Induced By Blasting For the Different Rock Masses**

*Kahriman A, Tuncer G, Gorgun S, Karadogan A & Ozdemir K.*

This paper presents the results of ground vibration measurements induced by blasting operations at five different sites located close to residential areas. Within the scope of this study, ground vibration components were measured for all blast events over a long period of time in order to predict peak particle velocity and determine the slope of the attenuation curve for five sites. During the study, while the parameters of scaled distance were being recorded carefully, suitable monitors for all blast events of five blasting sites measured the ground vibration components. At the end of evaluation of the data pairs, an empirical relation, which gives an average line at 95% confidence level, and upper bound 95% prediction line with a good correlation coefficient was established and suggested for each site.

**Environmental Blast Design and Effective Implementation**

*Moore A.J. & Richards A.B.*

Effective control of blast vibration and flyrock requires that significant factors be identified and quantified, that the blast be designed to ensure both blasting efficiency and compliance with applicable limits, and that the blast design be effectively implemented by field personnel.

Significant factors contributing to ground vibration and airblast are:

- charge mass;
- distance and direction relative to the blast;
- drilling design: burden, spacing;
- stemming height and material type;
- hole diameter and depth; and
- initiation sequence and direction.

In addition, airblast may be strongly influenced by shielding and meteorological conditions. Ground vibration is also influenced by the transmission characteristics of the ground and soil. Flyrock throw is determined by charge mass, burden, stemming height, blasthole diameter and depth.

The contribution of each of the factors has been quantified and models developed to enable the environmental outcomes of blast design to be predicted. Environmental blast design is necessary to ensure compliance with regulatory limits and the implementation of ‘safe’ exclusion zones for flyrock clearance.

This paper discusses the models used for environmental blast design and demonstrates the often significant effects that lapse during implementation of the design can have on predicted outcomes.

In practice, drillers and shotfirers are sometimes confronted with situations that require modifications to the blast design to cope with the real site situation.

Methods are presented that may be used by drillers and shotfirers to evaluate the effect of these
modifications, the tolerances that must be reached during their work practice and checking procedures, and the consequences of their actions.

**The Application of Likelihood Ratio Test to Blast Vibration Analysis**  
Birch W.J, Pegden M, West R & White T.

The dedicated documenting of blast design and vibration monitoring results forms part of the best practice methodology for today’s blasting operators. This allows regression curves to be constantly updated and in turn compatible charge weight determinations are based upon the most current data. The point can arise however when so much data becomes agglomerated that variations in blast design, geology or monitoring location response and their effects can pass unobserved and start to have an adverse effect on the forecasting capability of the regression due to a deterioration of the standard error statistic.

The simple solution would be to only compile like-for-like blasting returns, but this prospect can quickly become unworkable due to the number of potential variables. In addition it is very difficult to spot subtle variations by simply examining a standard scaled-distance curve mainly due to the intrinsic data scatter that is always present together with the logarithmic nature of the regression curve. If indeed a variation is thought to be apparent, how can the degree and magnitude of its influence to be quantified?

The Likelihood Ratio Test when applied to regression data can diagnose subtle variations between data sub-sets and provides a comparative statistic as to the degree of variation. By analysing datasets in such a way, levels of compatibility are obtained, indicating which sets can be combined in order to increase prediction capability.

This paper gives instruction on how the technique can be applied to blast vibration data, together with illustrated case studies based on the research findings of the Department of Mining and Mineral Engineering, University of Leeds, England demonstrating its performance in:

- Comparing test with production blasts
- Comparing geology variations
- Comparing Blast site areas
- Diagnosing monitoring location response

**Municipal Blasting: Blast Design, Vibration Monitoring & Control**  
Frank J. L

This paper includes research and investigation into blast design and blast optimization for vibration control in municipal and tight blasting situations, where specifications were extremely stringent.

The paper is written for the field blaster to understand and develop blast plans based on field conditions.

The paper includes blast design considerations, utilizing seismograph arrays to check and predict vibration results, and problems encountered in vibration monitoring in extremely tight situations (0-20 feet).

Blast vibration frequency, acceleration, peak particle velocities, and relative displacement are discussed with effects in the near and far fields and blast designs utilized to stay under limits.

The paper also discusses using the latest in technology for blast design to control vibration. Equipment
includes 2D and 3D laser profiling systems, digital video, fragmentation analysis, seismograph arrays, and borehole tracking devices.

Other topics are discussed such as public relations, working with regulatory personnel, unions, and other project consultants, and the problems associated with municipal blasting situations, such as, flyrock and proximity of other personnel and equipment on the project.

**A New Method for the Prediction of Blast Vibrations and Suggestions with Respect to Uniform Reference Values for Short-Time Vibrations**

_Bernd Mueller and Robert Boehnke_

This contribution presents an innovative, statistically supported method to predict blast vibrations in rock mass. For modelling the processes during and after detonation, a theory is employed which is based on linear momentum (so-called _momentum theory_), strongly supported by new measurement methods. During the course of the investigations, the following parameters have been found to dominantly influence vibrations:

- charge \( W_B \), includes geometrical factors such as borehole length and diameter (kg)
- detonation velocity \( c_d \) of the explosives used (m/s)
- distance \( r \) between the points of emission and immission (m) and the statistically determined negative exponent \( n \)
- factor \( R_M \) or \( R_S \) of the rock mass which is related to the _specific blast momentum_ and the drilling and blasting technique used and is statistically determined together with the exponent \( m \) (\( \text{mm}^2/\text{kg} \) or \( \text{kgm/mms} \))

The following regression formulas have been used:

\[
\nu_{\text{max}} = R_M W_B c_d r^{-m} \text{ for measurements of peak particle velocity}
\]

\[
\nu_{\text{max}} = R_S W_B c_d r^{-m} \text{ for strain measurements}
\]

The vibration prediction presented here is based on extensive statistical data from many open pit mines. It turns out that the borehole charge per delay is not a key factor in the vibration magnitude. Employing the above regression formulae and using the concept of _momentum theory_, enables one to:

- predict and reduce the level of vibrations with improved precision;
- improve and adjust drilling, blasting and shotfiring techniques to the respective conditions;
- increase the size of blast designs if the ignition is carried out according to the momentum theory, and
- move quarrying areas and perform blast work closer to areas where vibration sensitive structures etc are located.

In order to achieve a uniform basis for assessing the level of short-time vibrations the authors suggest new reference values on the basis of strain measurements as well as peak particle velocity. To this end, according to the building materials, structures will be classed into two groups. Strain as a directly assessable factor (in contrast to the alternative factor of peak particle velocity) depends on the conditions of the building ground of the respective structure. Ground conditions can be fixed either quantitatively by acoustic impedance or qualitatively by characterising the building ground geotechnically. The acoustic impedance can be correlated with the recorded frequency.
Low Frequency Long Duration Blast Vibrations and Their Effect on Residential Structures
Roy A.P, Sirveiya A.K & Singh P.K.

A major concern with blasting at surface mines is generation of ground vibration, air blast, flyrock, dust & fume and their impact on nearby structures and environment. A study was conducted at a coal mine in India which produces 10 million tonne of coal and 27 million cubic meter of overburden per annum. Draglines and shovels with dumpers carry out the removal of overburden. Detonation of 100 tonnes of explosives in a blasting round is a common practice of the mine. These large sized blasts often led to complaints from the nearby inhabitants regarding ground vibrations and their affects on their houses.

Eighteen dragline blasts were conducted and their impacts on nearby structures were investigated. Extended seismic arrays were used to identify the vibration characteristics within a few tens of meters of the blasts and also as modified by the media at distances over 5 km. 10 to 12 seismographs were deployed in an array to gather the time histories of vibrations. A signature blast was conducted to know the fundamental frequency of the particular transmitting media between the blast face and the structures. The faster decay of high frequency components was observed. It was also observed that at distances of 5 km, the persistence of vibrations in the structures was substantially increased by more than 10 seconds. The proximity of the frequency of the ground vibration to the structure’s fundamental frequencies produced the resonance in the structures. On the basis of the fundamental frequency of the structures, the delay interval was optimized, which resulted into lower amplitude and reduced persistence of vibration in the structures.

Is That Normal? - Fundamental Observations For Best Practice Blast Vibration Analysis
M. Pegden, W.J. Birch & A. Wetherelt

The scaled-distance model for blast vibration analysis is the standard method employed throughout the surface mining and quarrying industries to model Peak Particle Velocity (PPV) data. Although empirical, the method is widely accepted and through the simplicity of its application and ease of graphical verification is set to remain a popular option.

The validity of the technique relies principally on the fundamental parametric assumption that blasting data is normally distributed. Throughout the evolution of scaled-distance modelling, this is an issue that has most often been presumed rather than proven (most likely due to the tediousness of the calculations involved). In the few cases when normality has been given some degree of consideration, the result has been the product of a simple visual inspection of frequency distributions: clearly unsatisfactory. However recently the soundness of this assumption has been brought into question, with obvious connotations for blast modelling in general.

This paper considers this fundamental issue and seeks to investigate the normality hypothesis within the blasting context through an in-depth statistical analysis of what possibly can be described as an ‘ideal’ blasting dataset. This being a rare case study concerning an opencast coal site in England, where for the entire life of the site every single blast was monitored and recorded through the use of permanent monitoring stations. This has provided a unique ‘total population’ dataset of considerable size from which the assumptions of normality are put to the test.

Through the application of systematic parametric tests, the results illustrate:
The quantity and quality of data required for normality to be achieved
- The real effects of model instability, skewness and kurtosis on permitted charge weights
- The critical observations required for proving normality
- The relationship between proven normality and model stability.

In conclusion, the key element in achieving blasting data normality is shown to be fundamentally related to the way the data is collected in the first place and adds further credence to the importance of correct monitoring technique and the adherence to strict protocols.

**A New Technique for Predicting Vibration Levels from Tunnel Blasting**

**Birch W.J, Kirke M & Hosein S.**

Despite increasing competition from mechanical methods of tunnelling, the drill and blast method is often still the most viable method of excavating tunnels in strong and abrasive rock. To advance a tunnel using drill and blast, explosives are loaded into boreholes in the rock and detonated according to a prearranged sequence. On detonation of the explosive, the rock is fractured and displaced from its original position, leaving behind the desired void. Among the secondary effects of a tunnel blast are ground vibrations caused by elastic disturbances that propagate away from the blasted tunnel face. The possibility that such ground vibrations may cause permanent damage to property and substantial nuisance has generated significant opposition to the use of drill and blast, particularly in urban areas. It is therefore essential that the blasting engineer is able to predict Peak Particle Velocity (PPV) vibration levels at locations in the vicinity of the blast site. Such predictive capability enables the engineer to design blasts so as to ensure that ground vibrations can be kept within acceptable levels. The objective of this project was to analyse data obtained from the ground vibration monitoring program undertaken during the drill and blast excavation of a hard rock tunnel in Central England. Seismograph recordings of tunnel blasts contain a vast amount of information that cannot possibly be expressed using a single PPV value. The main focus of the study was to investigate whether predictive capability could be improved by using scaled distance models derived for selected PPV components relating to specific detonator timings in a given tunnel round. This study has established a method of analysis that can unlock this information for predictive purposes. By permitting the extraction of sub-event Peak Particle Velocity (PPV) values and allowing Scaled Distance (SD) models to be derived for individual period numbers or groups of period numbers, the method has the potential to vastly improve PPV prediction from tunnel blasting. The method established could also help diagnose blasting problems and help target blast design modifications, resulting in improved efficiency and excavation rates.

**Analysis of Parameters on the Ground Vibration Produced by Bench Blasting at a Boron Open Pit Mine in Turkey**

**Kahriman A, Karadogan A, Tuncer G, Ozdemir K & Aksoy M.**

With increasing environmental constraints on the levels of disturbance induced by blasting operations upon nearby residents, there is an increasing need to be able to design cautious blasting with greater precision. Therefore, determination of maximum amount of explosive per delay for a certain distance especially in large blasts is of great importance for the elimination of these environmental problems. Although too many research studies had been carried out in the past in order to eliminate environmental issues produced from blasting unfortunately a general approach or formula has not been established yet because of the complexity of the matter. In addition to the wave and ground motion characteristics, the complexity of blasting parameters and site factors restrict the developing a general criterion. So experimental site-specific studies
should be still done in order to predict and control blasting effects.

This paper presents the results of ground vibration measurements carried out in Espey Open-Pit Boron (Colemanite) Mine located on the west side of the central Anatolia near Kütahya province in Turkey. Within the scope of this study, ground vibration components were measured for 13 shots during bench blast optimisation studies in order to predict peak particle velocity level for this site. In blasting operations; ANFO and Powergel Magnum 600 (blasting agent), Powergel Magnum (priming) and delay electric detonators (firing) were used as explosives. Parameters of scaled distance (charge quantity per delay and the distance between the source and the station) were recorded carefully and the ground vibration components were measured for all blast events using 4 different types vibration monitors (3 White Mini-Seis and 1 Instantel Minimate Plus Models). Then, the data pairs of scaled distance and particle velocity obtained from the 38 record events were analysed statistically. At the end of statistical evaluation of the data pairs, an empirical relation which gives average line at 95% confidence level and upper bound 95% prediction line with a reasonable correlation coefficient was established between peak particle velocity and scaled distance.

The Effects of the Topographic Bench on Ground Motion from Mining Explosions
Bonner J.L, Blomberg W.S, Hooper H & Leidig M.
Understanding the effects of the bench on ground motion can improve the design of cast blasts and achieve improved blast efficiency while remaining below vibration requirements. A new dataset recorded in September 2003 from a coal mine in Arizona has allowed us to examine the excitation of short-period Rayleigh-type surface waves from four simultaneously-detonated explosions in and below a topographic bench of a mine. The explosions were recorded on a network of over 150 seismic sensors, providing an extensive understanding of the ground motion radiation patterns from these explosions. We detonated two separate explosions (~3 tons and ~1.5 tons ANFO) in the deepest pit of the mine, thus the explosions were shot to solid rock. Within 25 meters of these two explosions, we detonated two additional explosions of similar explosive yields in a bench, thus these explosions were shot to the free face. Radiation patterns and spectral ratios from the explosions show increased amplitudes (by a factor of 1.5 to 2) at azimuths behind the bench relative to the amplitudes in front of the bench. We compared these findings to seismic observations from two ~1.5 million pound cast blasts at the same mine and found similar radiation patterns. Modeling of these blasts shows that the variations in ground motion are caused by the topographic bench as a result of 1) horizontal spalling of the rock falling into the pit and 2) non-linear scattering near the free-face. We also note that shooting to a buffer (previously blasted rock) causes the azimuthal variations to be significantly reduced.

Influence of Burden Size on Blast-Induced Ground Vibrations in Open-cast Mines
Ground vibrations have haunted blasting engineers ever since environmental concerns attained significant importance. Based on the plethora of research activity on the subject, different criteria have been designed to specify limits of blast-induced ground vibrations. In spite of the significant research, the criteria vary from one place to another and are not foolproof. This is primarily because of varied rock and blasting conditions. To augment the existing knowledge base, investigations have been carried out in three open-cast mines of Western Coalfields Limited (WCL), Singareni Collieries Company Limited (SCCL) and L&T (the Naokari limestone quarry) to establish the effect of the burden on ground vibrations and air overpressure. The study revealed that the burden has an appreciable influence on the blast-induced vibrations. Vibration data were subjected to statistical analysis for correlation of the peak particle velocity and excess burden. The excess
burden has a key influence on peak particle velocity. A vibration database specially generated for almost equal-scale distance was correlated with the peak particle velocity and the burden. The study provides an interesting insight into the influence of excess burden on the peak particle velocity of vibrations.

Application of 3-D Plots and Regressions to Blast Vibration Analysis– Defining a Site-Specific Form of the Charge Weight Scaled Distance
Yang R

This paper presents an application of 3-D plots and non-linear regressions to define a site specific form of the charge weight scaled distance.

The PPV (PPA) of single hole blasts is normally considered as a function of two independent variables - the charge weight and the distance. It is of great importance to obtain the relationship of the function accurately for a concerned site in terms of blast vibration analysis and modeling. However, in pre-computer time it was difficult to plot 3-D graphs. Consequently, a charge weight scaled distance was used to plot the PPV (or PPA) against the scaled distance as 2-D graphs. Blast vibration investigators use several forms of the charge weight scaled distances to plot data. We can exemplify them with the cube root of charge weight scaled distance, the square root of charge weight scaled distance, and other forms (Hossaini and Sen, 2004). Each of these scaled distances assumes relative contributions of the charge weight and the distance to the vibration attenuation.

For example, the charge weight is assumed to have a less contribution to vibration in the cube root scaled distance than it is assumed in the square-root scaled distance. In reality, for different sites the relative contribution of the charge weight and the distance may be different and site-specific. This may explain that in some cases, the blast vibration data plots using these charge weight scaled distances are scattered. This could be largely due to the fact that the definition of the form of the charge weight scaled distance is not adequate for the particular site condition.

At present, it is convenient to plot 3-D graphs with modern computer technology. Consequently, a better data analysis technique can be sought – 3-D plots and non-linear regression techniques. The dependence of the vibration peak values on the distance and charge weight can be examined respectively from the graphs. Using non-linear regression, a more accurate relationship for vibration attenuation against distance and charge weight can be established rather than using a conventional charge weight scaled distance as only dependent variable. A site-specific form of the scaled distance can be defined from the 3-D analysis. This paper describes the technique and its application.

The Application of Electronic Detonators to Improve Blast Vibration Predictions at Limestone Quarries
Birch W.J, Pegden M, Hosein S & Farnfield R.

Arguably, some of the most restrictive statutory blast vibration requirements attached to mineral extraction operations can be found in the United Kingdom. Such limitations are, as a rule for the UK, stipulated together with a required statistical confidence that has to be observed in the blast design process in order to ensure total planning compliance. A key element in this procedure is the effect imparted by vibration data scatter from previous blasts as this becomes reflected in the site’s operational standard error statistic and in turn directly influences the maximum instantaneous charge weights that can be justifiably employed. The greater the scatter, the lower the compliant charge weights become.

With the onus on minimising the variables that can affect the outcome and with such restrictions appearing
to become ever tighter, a great deal of interest has been generated as to the potential benefits that may be gained through the deployment of electronic detonators. It is commonly perceived that the inherent random timing scatter of conventional non-electric initiation systems is a major contributing factor to the inconsistencies observed and by design, these may be alleviated through such an alternative approach.

In order to investigate this matter, the Minerals Industry Research Organisation (MIRO) under the terms of the UK Government’s Mineral Industry Sustainable Technology (MIST) program has agreed to fund an industry wide fundamental study. Carried out by the Blasting and Environmental Research Group, The University of Leeds, England, this paper reports the initial findings in respect to blasting at limestone quarries. Such results highlight the benefits that can be achieved in terms of consistency, reduced data scatter and improved predictive capacity with tighter confidence intervals for full-scale production blasts.

Investigation of Ground Vibration Induced by Blasting at Hisarcik Boron Open Pit Mine in Turkey

Kahriman A & Tuncer G.

This paper presents the results of ground vibration measurements carried out in Hisarcik Boron open pit mine located on the west side of the central Anatolia near Kütahya province in Turkey. Within the scope of this study in order to predict peak particle velocity level for this site, ground vibration components were measured for 304 shots during bench blasting. In blasting operations; ANFO (blasting agent), gelatin dynamite (priming) and delay electric detonators (firing) were used as explosives. Parameters of scaled distance (charge quantity per delay and the distance between the source and the station) were recorded carefully and the ground vibration components were measured for all blast events using 2 different types vibration monitors (1 White Mini-Seis and 1 Instantel Minimate Plus Models). The absolute distances between shot points and monitor stations were determined using GPS. The equation of square root scaled distance extensively used in the literature was taken into consideration for the prediction of peak particle velocity.

Then, the data pairs of scaled distance and particle velocity obtained from the 565 records were analyzed statistically. At the end of statistical evaluation of the data pairs, an empirical relation which gives average line at 95% confidence level and upper bound 95% prediction line with a reasonable correlation coefficient was established between peak particle velocity and scaled distance.

Near-Field Blast Vibration Monitoring, Analysis and Modelling

Yang R.

Techniques for the study of blast vibrations, such as monitoring, analysis, and modelling are often misused between near field and far field blast vibrations. This paper discusses the differences between near-field and far-field blast vibrations in terms of these techniques.

A typical example of a near-field blast vibration problem is a blast vibration in the crest of a new highwall behind a cast blast. In such a case, the blast can be a couple of hundred feet long and the distance from the blast holes to a monitoring station may only be 100 feet or less. In this situation, the size or spatial geometry of the blast is not negligible compared to the distance from the blast to the vibration monitoring point. On the other hand, a typical example of a far-field blast vibration problem can be a quarry blast with a nearby residence house. In this case, the distance from the blast to the house may be several thousand feet. The size of the blast is less than a couple hundred feet long and negligible compared to the distance from the blast to the vibration monitoring point.
In order to accurately measure, analyze, and model the blast vibration, the near-field and far-field blast vibrations have to be treated differently.

**A Methodology to Control Peak Particle Velocity Levels at Multiple Locations by use of Electronic Detonators**

W.J. Birch, M. Pegden, S. Hosein, R. Farnfield & D. Leckenby

The use of electronic detonators to improve fragmentation is becoming universally accepted. However their use in limiting peak particle vibrations levels is still in its infancy. Most of which is anecdotal, in that few actual scientific studies have been carried and published.

This paper details the research work carried out at a limestone quarry in the County of North Yorkshire in Northern England. Here a series of blasts were carried out some used non-electric detonators whilst others used electronic detonators. The majority of blasts were carried out at the same burden, spacing and deck charge weight loadings. Initially, the key variable was the difference in detonator type and then leading on to using the electronic detonators at specific exact different detonator timing intervals. Later the study was extended to include double row as well as single row blasts.

The blasts were monitored a specific fixed locations, some buried in the ground, whilst others with mobile equipment that was established prior to the specific blast. Two single hole multi deck blasts were carried out to assess the influence of both distance and individual location response. The results obtained indicate that it is not possible to select a single electronic detonator timing interval that will give rise to the absolute lowest Peak Particle Velocity for all observation points. However what does show is that it is possible to choose the “least worst” option for all or just a number of specific monitoring locations.

From this it has been possible to establish a methodology that could be used to reduce the Peak Particle velocities at two or more specific locations by using single hole blast vibration signatures in conjunction with specific electronic detonator timing intervals. The study has concluded that this would only be possible if, as the blasting pattern encroach on specific properties, that periodically single hole signature blasts were carried to establish the shape of the relevant actual vibration envelopes. These wave envelopes could be used as the basis for choosing the specific electronic detonator timing intervals to give the lowest common peak particle velocity for the properties concerned.

**The Investigation of Ground Vibrations Induced by Bench Blasting At Different Quarries At Catalca District in Turkey**

Ozer U, Kahriman A, Adiguzel D, Aksoy M & Karadogan A.

The environmental problems arising from ground vibration has been faced and discussed frequently in various industries such as quarry, mining, civil works, shaft, tunneling, pipe line and dam construction etc. where the blasting operations are unavoidable. In bench blast design, not only the technical and economical aspects, such as block size, uniformity and cost, but also the elimination of environmental problems resulting from ground vibration and air blast should be taken into consideration. The prediction of ground vibration components plays an important role in the minimization of the environmental complaints. This paper presents the results of ground vibration measurements carried out in the quarries located on the different sides of Çatalca district in Turkey. In order to predict peak particle velocity level for this district, ground vibration components were measured for shots during bench blasting at these quarries. In blasting operations; ANFO is commonly used as blasting agent at the quarries. The type of priming and firing differed from quarry to quarry. The parameters of scaled distance (charge quantity per delay and the distance between the source
and the station) were recorded carefully and the ground vibration components were measured for all blast events by using different type vibration monitors. The absolute distances between shot points and monitor stations were determined by using GPS. The equation of square root scaled distance extensively used in the literature was taken into consideration for the prediction of peak particle velocity. In order to predict, and compare the influence grades to the neighboring buildings, and structures at the Çatalca district, the particle velocities and frequency values of all blast events are evaluated according to the United States Bureau of Mines (USBM) and German DIN 4150 Norms due to the lack of a national standard in Turkey. Then, the data pairs belonging to these quarries were gathered together to represent the district and were analyzed statistically. At the end of statistical evaluation of the data pairs, an empirical relation which gives average line at 95% confidence level and upper bound 95% prediction line with a reasonable correlation coefficient was established between peak particle velocity and scaled distance.

**Experimental Technique to Reduce Blast Vibration Level, Tourah, Cairo, Egypt**

Khaled M, Abdel Rahman K & Abo Makarem A.

There are four large limestone quarries, located nearby Cairo metropolitan. Drilling and blasting operations are used to extract limestone for the cement industries. In these quarries, the blast vibration should be kept below a certain limit. One of these quarries is Tourah Portland Cement Company (TPCC) limestone quarry which lies near important and historical large caves, within Tourah Mountain. Therefore, control of blast vibration level becomes very critical.

A series of multi-holes blasts have been performed to answer several questions about the optimum scaled distance that can be used safely to avoid caves damage, what constitutes true timing and initiation system?, and their relation to the blast vibration level?.

Four Tri-axial geophones located in a linear array, over a distance of 1.0 km (0.621 miles) from the quarry faces, they have synchronized by means of a GPS timing reference. The data retrieved from the geophones and subjected to different steps of processing and analysis.

The field tests showed that there was a significant difference in the blast vibration level between top and bottom initiation systems, containing the same explosive charge per delay intervals. In the upper bench, the results showed that the blast optimization of vibration level requires small delay intervals at distance more than 800.0 m (875 yards), between shot point and caves.

This study helped TPCC limestone quarry to remain operating since the government permitted the continuation of blasting operations. In addition, the advantages of using chock tube system in comparison with electrical detonators, could lead to convince the government to raise the permitted explosive charge per day.

**The Acoustic Response of Structures to Blast-Induced Ground Vibration: Fact or Fiction**

Birch W.J, Pegden M, Hoseins, Rangel-sharp G.D & Farnfield R.

It is widely recognised that complaints from members of the public relating to blasting operations are related to both ground vibration and air overpressure. It is also known that a complaint is more likely to be generated if the person is inside of a structure at the time of the blast. Reports relating to such complaints often refer to ‘noise’ inside the structure with terms like ‘rattling’ commonly being employed.
acoustic response is widely perceived within the blasting industry to be directly related to high levels of air overpressure although there appears to have been very little research carried out specifically related to this effect.

This paper describes the initial findings from a research project specifically designed to investigate this phenomenon, carried out by the Blasting and Environmental Research Group, The University of Leeds, England. The Minerals Industry Research Organisation (MIRO) under the terms of the UK Government’s Mineral Industry Sustainable Technology (MIST) program has funded this project.

The paper outlines the development of a monitoring system designed to record levels of acoustic noise inside structures whilst simultaneously monitoring levels of vibration and air overpressure. The system has been designed to enable high quality sound recordings to be made giving the possibility of identifying the structural component generating the noise. Initial findings from the project have confirmed that the level of structural noise is directly related to ground vibration. In the structures studied to date, there is little or no demonstrable connection between levels of air overpressure and acoustic response.

Modelling an Artificial Screen for Reducing Seismic Vibration

Bogunovic D, Kricak L & Kecojevic V.

In spite of many advantages explosives have, their usage may cause environmental problem such as seismic vibration. One of the solutions to this particular problem may be application of an artificial screen as a barrier to the seismic wave path. This paper presents the results of experimental research on the artificial screen concept, its characteristics and role in attenuation of seismic effects generated by blasting. More than 1,500 laboratory measurements were conducted with different combinations of screen sizes, positions of the screen to blasting source, and intensities of blasting impulses. The results of the study show a significant reduction of generated vibrations by employment of artificial screens.

APPENDIX 2: ABSTRACTS FROM RECENT (2000 – 2007) PEER-REVIEWED AIR OVERPRESSURE FROM BLASTING RESEARCH PUBLICATIONS;

Airblast Design Concepts in Open Pit Mines

A.B. Richards & A.J. Moore

This paper reviews factors affecting airblast levels, and describes concepts that may be used to assess and control airblast emissions from blasting in open pit mines. The paper describes methods that have been developed by the authors to quantify airblast emissions, including wavefront reinforcement and seed waveform methods. The methods permit the effect of such factors as charge mass, distance, blasthole diameter, drilling and delay pattern, and stemming height to be evaluated. The effect of the selective light-loading of blastholes to control airblast, the quantification of waveform shapes, and examples of the effect of different delay sequences are also covered. The paper concludes with an example illustrating airblast design procedure, and the combined effect of significant factors.

The Eight Millisecond Time Window Myth

Moore A.J. & Richards A.B.

Time window analysis that limits the explosive mass fired within a specified time window (commonly eight milliseconds) has been used for many years in blast design by explosives engineers.
Despite several warnings in the past that this technique has limited practical or scientific basis and, in many cases, does not effectively control vibration, almost every textbook and blasting manual refers to time window charge mass limits as a primary vibration control technique. It has become entrenched in some blast vibration management plans, despite being inappropriate for the particular situation.

With the flexible initiation timing available with electronic detonation almost a practical reality, and the 8 ms constraints in-built into the signal tube initiation system thereby lifted, it is timely to review the significance of the 8 ms time window in controlling blast vibration.

This paper re-visits the original research that led to the development of the 8 ms criteria and the non-supportive conclusion of the original researcher. Because airblast was not measured, the 8 ms time window was never intended to be applicable for airblast control. Examples of blast designs are given in this paper that comply with the 8 ms time window limit that result in substantially increased air and ground vibration, together with examples of blast design that does not satisfy time window considerations, which results in reduced air and ground vibration.

Techniques that identify wavefront reinforcement, due to the combined effect of drilling pattern and delay sequence, can assist explosives engineers to avoid high blast vibration situations that result from the inappropriate application of time window techniques and other adverse delay combinations.

**Evaluating Airblast Damage Complaints**

**Lawrence W. Gubbe,**

Air blast associated with detonation of explosives in mining, construction or military applications is often responsible for complaints by people who live or work in the vicinity of the activity. Most often, the complaints are based on the perception that vibration caused by the airblast damaged one or more residential buildings that may be located within several hundred feet or several miles from the blast site.

The potential for airblast to cause damage is related to the amplitude and frequency of the airblast overpressure wave at the receptor. Amplitude and frequency of the overpressure wave are, in turn, dependent upon the type and amount of explosive detonated; the degree of confinement; the distance the wave travels; the topography between the blast site and the receptor; and, atmospheric conditions.

It is well known that, as the result of atmospheric focusing, the amplitude of airblast overpressure that exists relatively far from the blast site may be substantially higher than the amplitude associated with the attenuated wave in an isotropic atmosphere. Two methods are available to predict baseline overpressures 1) the Sandia Laboratories, Atomic Energy Commission method as extended by the Naval Ordinance Laboratory (NOL method) and the Ballistic Research Laboratory method (BRL method). These methods are developed by different techniques, are based on different idealized atmospheres and predict widely different results. The amplification factor applied to account for the effect of focusing must be consistent with the method used to predict the baseline overpressure. Theoretically, the amplitude of the overpressure at distances several miles from the blast site could be more than 25 to 100 times the amplitude of the attenuated wave predicted by the BRL method. However, based on comparisons with measured overpressure data is probably less than approximately 3 times the amplitude of the attenuated wave as predicted by the NOL method.

This paper is based on research conducted as part of investigations of airblast damage complaints associated
with an accidental explosion near Eveleth, Minnesota and with the disposal of military explosives by
detonation at the Sierra Army Depot near Herlong, California. The techniques available for estimating
the airblast overpressure that might be generated at various distances from the blast site and criteria for
evaluating the potential for damage are examined.

**Influence of Burden on Intensity of Ground Vibrations and Aire Overpressure in
Opencast Bench Blasting**

M Ramulu, AK Chakraborty, AK Raina & AH Reddy

Burden of drill hole is third most sensitive parameter effecting the ground vibration in blasting apart from
maximum charge per delay and distance. Various types of burdens can be seen in practical bench blasting
situations. Burden can be expressed as drilled burden and initiation burden. Drill holes may have various
front row burdens (toe burden), which may be different from the designed burden. In order to ascertain
the impact of front row burden as well as the initiation burden on intensity of ground vibration and air
overpressure experiments were conducted in sandstone overburden benches of an opencast coal mine and
limestone quarry. Blast trials were carried out in cognisance of both drill and initiation burden while keeping
all other parameters constant. Effect of front row burden was also extensively studied by keeping almost all
other parameters constant. The results of the study reveal that there is substantial influence of front row
burden on the vibration and air overpressure. The statistical analysis of vibration and air overpressure data
with drilled burden and initiation burden gives significant evidence that the level of peak particle velocity of
vibration ($V_{max}$) is reduced by reducing effective burden with modification of initiation. Data analysis carried
out for air overpressure versus initiation burden shows that reducing effective burden with modification
of initiation results in increasing the level of $P$. The study reveals a qualitative assessment of the influence
of burden on the blast induced vibration and air overpressure. The study also recommends to modify the
initiation pattern to reduce the effective burden in order to reduce the vibration, without disturbing the fragmentation.

**Calibration of an Airblast Prediction Model**

R King-Siem and A J Moore

To control the airblast from blasting to regulatory limits at environmentally sensitive sites near the
Collinsville Coal Mining Operations, it has been necessary for Thiess Mining to incorporate a wavefront
reinforcement analysis model in the predictive environmental airblast design. Controlling airblast from
cast blasting 70m high faces with 2000-3000kg of explosives per hole within 700m of houses presents a
considerable challenge to the blasting personnel.

This paper describes the model used and summarises the results of an investigation designed to quantify the
increase in airblast indicated by wavefront reinforcement diagrams to further calibrate the model for future
prediction.

**Environmental Blast Design and Effective Implementation**

Moore A.J. & Richards A.B.

Effective control of blast vibration and flyrock requires that significant factors be identified and quantified,
that the blast be designed to ensure both blasting efficiency and compliance with applicable limits, and that
the blast design be effectively implemented by field personnel.
Significant factors contributing to ground vibration and airblast are:

- charge mass;
- distance and direction relative to the blast;
- drilling design: burden, spacing;
- stemming height and material type;
- hole diameter and depth; and
- initiation sequence and direction.

In addition, airblast may be strongly influenced by shielding and meteorological conditions. Ground vibration is also influenced by the transmission characteristics of the ground and soil. Flyrock throw is determined by charge mass, burden, stemming height, blasthole diameter and depth.

The contribution of each of the factors has been quantified and models developed to enable the environmental outcomes of blast design to be predicted. Environmental blast design is necessary to ensure compliance with regulatory limits and the implementation of ‘safe’ exclusion zones for flyrock clearance.

This paper discusses the models used for environmental blast design and demonstrates the often significant effects that lapse during implementation of the design can have on predicted outcomes.

In practice, drillers and shotfirers are sometimes confronted with situations that require modifications to the blast design to cope with the real site situation.

Methods are presented that may be used by drillers and shotfirers to evaluate the effect of these modifications, the tolerances that must be reached during their work practice and checking procedures, and the consequences of their actions.

**Microphone Height Effects on Blast-Induced Air Overpressure Measurements**

*Kenneth K. Eltschlager, Randall M. Wheeler*

Blasting Seismographs use microphones to measure air overpressure from blasting. The microphone height above the ground has been the object of some controversy. The current ISEE “Field Practice Guidelines for Blasting Seismographs” specify microphone placement within 1.2 inches of the ground or over 3 feet above the ground. In this study, air overpressure measurements were taken at different height intervals and compared. Blasting seismographs constructed to the ISEE “Performance Standards for Blasting Seismographs” were used to monitor construction, quarry, and coal mine blasting. Near and far field measurements were taken to obtain representative spectral and amplitude ranges. The comparative analysis shows that microphone height has negligible impact on air overpressure measurements.

**Effect of Meteorology on Airblast Overpressure**

*Alan B. Richards and Adrian J. Moore*

Airblast overpressure levels can commonly be increased by up to 20 decibels (dB) by the effects of meteorology, due to inversions and wind shear. Existing atmospheric refraction models can provide a good evaluation of the effects of meteorology, but have been limited in the accuracy of their outputs by the accuracy of the meteorological data that is available for input. This paper uses case histories from open-pit coal mine blasting in the Hunter Valley area of Australia to provide examples of increases in airblast due to inversions, wind shear, and a combination of both. It gives details of our experience of the accuracy with
which predictions and assessments can be made using meteorological data of various levels of accuracy, and on the design buffer that is required to prevent the exceedence of airblast limits. The accuracy of meteorological prediction and assessment will shortly be improved by the use of sounding equipment that gives continuous measurements of temperature and wind velocity at significant levels above the ground. The paper also gives details of an industry funded research project that aims to permit the effective use of this data at distances many kilometres (km) (miles) from the location of the sounding equipment, and to develop a short term predictive model that will permit the amount of meteorological reinforcement that will occur at firing time to be determined before a decision is made to tie up a shot.

**Structure response to trench and road blasting**


Crack and structure response to construction trench blasting was measured in a wood-frame house with a stucco exterior. Blasts at distances between 232 and 368m produced peak particle velocities (PPV) and airblast overpressures (AB) of 9mm/s and 0.02 kPa (123dB) respectively. Structure response velocities were measured at an upper corner and two mid-walls, as were changes in the width of a crack at a window corner in the east mid-wall. Structure responses were correlated with PPV and AB, which arrived simultaneously, complicating the distinction between the two. Crack responses were correlated with long-term changes in temperature and humidity as well as PPV and AB. Wall strains from out-of-plane bending and in-plane shear were computed from upper corner structure response and compared with failure strains for dry wall. As has been found in other studies, calculated strains were far lower than those required to crack dry wall, and the environmentally induced crack response from temperature and humidity was far greater than that caused by blast-induced ground motion or airblast overpressures.

**Correlation of public perception of blasting at rock quarries to reporting practices**

**B. Lusk & P. Worsey**

The paper focuses on the public perception of quarry blasting in St. Charles County, MO. This expanding urban environment has seen new legislation targeting pre-existing quarry operations that have been in place for many years. A survey was made compiling interviews conducted to gauge perceptions of persons with varying demographics. Interviews covered topics involved with quarry blasting and its reporting methods. The purposes of the interviews were to determine public perception of blasting and how best to report results of vibration measurements. Current legislation in the county is based on complaint levels rather than damage criteria. The complaints most likely not only come from ignorance to the effects of blasting on structures, but also sparse understanding of the units used to report these affects. The focus of this paper is to gauge perception of the damage criteria reported today, and to evaluate the current selection of measurement units.

**Prediction of Blast Induced Air Overpressure in Opencast Mine**

**Manoj K. & Singh T.N.**

Blasting is still considered to be the most economical technique for rock excavation and displacement either on the surface or underground. The explosive energy, which fractures the rockmass is not fully utilized and only 20-30% of the energy is utilized in actual breakage of the rockmass, and the rest of the energy is spread in the form of ground vibration, air blast, flying rock, back break, etc. Air blast is considered to be one of the most detrimental side effects due to generation of noise. A generalized equation has been proposed by many researchers but due to its site specific constants, it cannot be used in other geo-mining conditions. In the present paper, an attempt has been made to predict the air blast using a neural network (NN) by
incorporating the maximum charge per delay and distance between blast face to monitoring point. To investigate the appropriateness of this approach, the predictions by a NN are also compared with generalized equation of air overpressure and conventional statistical relations. For prediction of air overpressure, the data set has been taken from two different limestone mines for training of the network while validation of the network has been done by Magnesite mine data set. The network is trained by 41 datasets with 50 epochs and tested by 15 dataset. The correlation co-efficient determined by a NN was 0.9574 while correlation co-efficient were 0.3811 and 0.5258 by generalized equation and statistical analysis respectively. The Mean Absolute Percentage Error (MAPE) for a NN was 2.7437, whereas MAPE for generalized equation and statistical analysis were 8.6957 and 6.9179 respectively.

**Air Overpressure**

Singh P.K.

The growth in public awareness and expectations of environmental performance have led mining companies to focus their attention on the potential impacts arising from noise, vibration, and airblast generated by their activities. An attempt has been made in this paper to address the problem of airblast caused by blasting in surface mines/quarries and to highlight some remedial measures. The plaster shooting generated too much air overpressure at Sagmania quarry C. It is predicted from regression analysis. Airblast waves travel in a fluid medium that does not transmit shear forces, making them simpler than ground vibrations. The prediction of air overpressure can be made with the help of the predictor equations. FFT analysis of vibration and air overpressure event recorded at Sagmania limestone quarry is given. Field experiments were conducted at five limestone quarries in India. Measures may need to be taken to obtain suitable stemming material to contain the explosive during detonation.

**Aireblast Control Techniques in Open Cut Mines**

Alan B. Richards and Adrian J. Moore

Effective control of airblast requires that significant factors be identified and satisfied by blast design and careful implementation. Significant factors include charge mass, distance, face height and orientation, burden, spacing, and initiation sequence, stemming height and type, topographical shielding, and meteorological conditions.

This paper utilizes case histories of blasting in Australian open pit mines to demonstrate techniques that have been used to control airblast to applicable limits.

**A Classic Experiment with Air Overpressure and Windows**

Rob Farnfield, Andy Wetherelt, Charlie Adcock

The ISEE Blasters Handbook gives guidance on the level of air overpressure likely to cause occasional window breakage (151 dB) and general window breakage (171 dB). A long-term safe level of 140dB is also suggested. This guidance is widely used by demolition and other contractors to assess damage zones in the region of explosive applications employing unconfined charges.

Other reference material gives more detailed guidance relating to window area, aspect ratio and glass thickness.

Despite the guidance given in these references, complaints by members of the public regarding window breakage continue to be received by explosives engineers from air overpressure levels well below the
longterm safe limit. Such complaints are not limited to the use of unconfined charges but can even be
generated from the highly confined use of explosives in quarry blasting.

This paper describes a series of experiments with explosive charges fired in unconfined conditions close to
various window configurations. The aim of the work was to test the existing guidance levels and to extend
the knowledge base in this area. Topics covered include the role of differential pressure across windows in
the walls of an enclosed space such as a room.

**The Acoustic Response of Structures to Blast-Induced Ground Vibration: Fact or Fiction**

**Birch W.J, Pegden M, Hosein S, Rangel-Sharp G.D. & Farnfield R.**

It is widely recognised that complaints from members of the public relating to blasting operations are
related to both ground vibration and air overpressure. It is also known that a complaint is more likely to be
generated if the person is inside of a structure at the time of the blast. Reports relating to such complaints
often refer to ‘noise’ inside the structure with terms like ‘rattling’ commonly being employed. Such
acoustic response is widely perceived within the blasting industry to be directly related to high levels of air
overpressure although there appears to have been very little research carried out specifically related to this
effect.

This paper describes the initial findings from a research project specifically designed to investigate this
phenomenon, carried out by the Blasting and Environmental Research Group, The University of Leeds,
England. The Minerals Industry Research Organisation (MIRO) under the terms of the UK Government’s
Mineral Industry Sustainable Technology (MIST) program has funded this project.

The paper outlines the development of a monitoring system designed to record levels of acoustic noise
inside structures whilst simultaneously monitoring levels of vibration and air overpressure. The system has
been designed to enable high quality sound recordings to be made giving the possibility of identifying the
structural component generating the noise.

Initial findings from the project have confirmed that the level of structural noise is directly related to ground
vibration. In the structures studied to date, there is little or no demonstrable connection between levels of
air overpressure and acoustic response.

**Study of Blasting Produced Air Overpressure in Urban Area**

**Zou Dingxiang**

Rock blasting in the project of “Site Formation and Associated Infrastructure Works at Choi Wan Road and
Jordan Valley” is the largest urban blasting project in the history of Hong Kong and also is rare in the world.
More than 6.2 million of in-situ rock has to be excavated by blasting. The site is located in the center area
of eastern Kowloon peninsula, surrounded by highways, registered cut slopes, high-rise residential buildings,
MTR subways and the public utilities. The complex situations bring great difficulties and risks to the blasting
works.

As a part of the site formation, the Designed Platforms W, X, and Y are located in the southeast end of the
site and are very close to the high rising buildings of Choi Ha Estate. By the northern side of the 3 designed
platforms there is a hill of about 150m high that is to be cut for forming 7 soil and 4 rock graded slope
Sustainable Aggregates
Reducing the Environmental Effect of Aggregate Quarrying: Dust, Noise & Vibration

Three blocks of high rising residential buildings are situated adjacent to the southern side of the site. The distance between the hill and buildings is about 50 to 100 meters.

For the safety of the surrounding residents, damage free to nearby buildings and structures, effective measures have been taken to prevent any possible hazards associated with fly rock and rock falling downhill and excessive ground vibration. For controlling the effect of blasting produced air overpressure, various possible preventive measures have been tried out in conjunction to close monitoring. In this paper we try to analyze the data of air overpressure recorded in 136 numbers of blasts in order to identify those key elements that contribute most significantly to the AOP level and then tackle them accordingly.

Blast Induced Air Overpressure and its Prediction Using Artificial Neural Network
Sawmliana, Pal Roy, Singh R & Singh T

Airblast is considered to be one of the most hazardous environmental disturbances created by blasting operation. Prediction of air overpressure (AOP) generated owing to blasting is difficult due to the influence of several factors in the air wave transmission. Blast design parameters, wind direction and speed, atmospheric temperature, humidity and topography, etc. are all affecting AOP. In this paper, an attempt has been made to predict AOP using artificial neural network (ANN) by incorporating the most influential parameters like maximum instantaneous charge weight per delay, depth of burial of charge, total charge fired in a round and distance of measurement. To investigate the effectiveness of this approach, the predicted values of AOP by ANN were compared with those predicted by generalised equation incorporating maximum instantaneous charge weight per delay and distance of measurement. Air overpressure data sets obtained from four different mines in India were used for the neural network as well as to form generalised equation. The network was trained by 70 data sets and validated with 25 data sets. The network and generalised predictor equations were tested with 15 AOP data sets obtained from another two mines. The results obtained from the neural network analysis showed that depth of burial of the charges and maximum charge weight per delay were among the blast designed parameters that have most influence on AOP. Based on the ANN result, depth of burial of charge has more relative sensitivity and weight than the maximum charge weight per delay. The average percentage of prediction error for ANN was 2.05, whereas for generalised equation, it was 5.97. The relationship between measured and the predicted values of AOP was found to be more logical in the case of ANN (correlation coefficient: 0.931) than that of generalised equation (correlation coefficient: 0.867).
PART 2: DUST MODELLING AND VALIDATION

EXECUTIVE SUMMARY

Surface minerals extraction and processing operations can generate large quantities of fugitive dust which, when released in an uncontrolled manner, can cause widespread nuisance and potential health concerns for on-site personnel and surrounding communities. Typical fugitive dust emission sources may include minerals transfer points, conveyance, loading into crusher feed bins, haulage and blasting. Consequently there exists a requirement to identify, measure and monitor the cause of any impacts, and to offer and implement the necessary techniques as to abate, or eliminate these occurrences. In the past, the onus on UK site operators to implement these control techniques has been by the provisions of planning, pollution control and occupational health legislation. Although this still remains the case, site operators are now more encouraged by means of industry guidance on good practice to adopt proactive strategies as to attain sustainable development and continuous improvement in environmental performance. To increase the understanding of the dispersion of fugitive dust from such activities it is necessary to develop suitable modelling strategies.

The report presents an overview of the current modelling methodologies that have been developed to simulate and predict fugitive dust emission, dispersion and deposition from surface mining and quarry operations. A critical review of the results of recent research studies conducted to investigate the use of Gaussian plume models to provide an assessment of dust emissions from surface quarry operations in support of regulatory planning consent applications is given.

The report presents a comparative overview of the results of recent international and UK ASLF funded research projects conducted to investigate the modelling/prediction of fugitive dust emission and dispersion from surface mining operations, including quarries.

The following topics requiring further research investigation were identified:

- The execution of further field measurement and dust modelling studies to identify improved fugitive dust emission estimates to be employed in the prediction of off site dust emissions from UK quarries using the UK ADMS modelling programme.
- It is recommended that scale and full scale experimental and computational modelling studies, including computational fluid dynamics (CFD), are investigated to give a better understanding of the internal air flow regimes that may be generated within large quarry openings.

- Further research studies to investigate the development of a proactive environmental dust monitoring and mitigation management systems for quarry haul road and stock pile operations.
Surface minerals extraction and processing operations can generate large quantities of fugitive dust which, when released in an uncontrolled manner, can cause widespread nuisance and potential health concerns for on-site personnel and surrounding communities. Typical fugitive dust emission sources may include minerals transfer points, conveyance, loading into crusher feed bins, haulage and blasting. Consequently there exists a requirement to identify, measure and monitor the cause of any impacts, and to offer and implement the necessary techniques as to abate, or eliminate these occurrences. In the past, the onus on UK site operators to implement these control techniques has been by the provisions of planning, pollution control and occupational health legislation. Although this still remains the case, site operators are now more encouraged by means of industry guidance on good practice to adopt proactive strategies as to attain sustainable development and continuous improvement in environmental performance. To increase the understanding of the dispersion of fugitive dust from such activities it is necessary to develop suitable modelling strategies.

An Environmental Impact Assessment (EIA) can be conducted to determine the potential impacts of a surface mining site. An EIA explores and reports on the impacts that a site and/or installation may cause during the life-cycle period being considered. In the case of particulate matter, modelling software is capable of determining atmospheric dispersion, the localities affected by the downwind migration of the plume and the deposition flux of the particulates settling out of the plume. The results of such a modelling exercise can be employed within an EIA. Particulate matter (here also termed ‘dust’) can have detrimental impacts on both the environment and human health (Arup Environmental 1996, Amponsah-Dacosta and Annegam, 1998).

The Air Quality Strategy for England and Wales by the Expert Panel report on Air Quality Standards (Defra, 2007) estimated that 20% of the total PM-10 (particulate matter equal to or less than 10 microns in diameter) emission from anthropogenic sources in the UK in 2005 was from quarrying activities. However, the report recognised that there was a high uncertainty (±50%) in the derivation of these estimates. Dust generated from surface mining sites, as in many other industries, is the result of a force applied to bulk material, which acts to reduce the size of that material for purposes that includes easier (and sometimes more economical) extraction, handling, processing, storage and transportation. The primary sources of fugitive dust at a fully operational surface mine may include overburden removal, blasting, mineral haulage, mechanical handling operations, mineral stockpiles and site restoration. Numerous variables are accountable when considering dust generation and the potential for the emission of that dust into the atmosphere. These include the inherent material properties, method, magnitude, frequency and duration of force application, resulting material size; and the prevailing meteorological conditions.
It is for the reasons above that dust generation should be considered a site-specific issue. Nevertheless, there exist many underlying principles that apply to all surface mining sites. A blast, for example, generates a relatively large amount of dust for a short period of time, and this dust can be projected many metres into the air. In comparison, every truck on a haul road generates small amounts of dust at lower levels, but they operate for the entire working day (SPCC 1983). In both cases the dust generation mechanisms will be equivalent to comparable activities at every surface mining site.

By their very nature hard rock quarry operations involve drilling, blasting, handling and movement of significant quantities of often dry material. At almost all stages of extraction and processing there is the potential to produce and emit dust to the atmosphere. In some situations this dust can contain harmful substances such as quartz and this clearly requires special attention. In some areas of the UK fugitive dust is also a nuisance issue where residential areas are located close to operational sites. The dual concern of occupational health and air quality near quarry sites requires careful management. For quarries operating in dry or windy environments, the issue is especially challenging. Table 1 below summarises the major dust emissions that may potentially be generated during quarrying operations.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Emission Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drilling</td>
<td>Blast holes are drilled into the overburden and the mined mineral with using drill rigs. In dry conditions, this drilling operation may generate significant dust. These are often treated as point sources.</td>
</tr>
<tr>
<td>Blasting Operations</td>
<td>Dust emissions are generated as the material is blasted from the bench. Loading of the broken rock from the resultant blast pile using mechanical shovels will also create dust emissions. Emissions would be generated both from the mechanical of the rock pile and from wind blown mechanisms.</td>
</tr>
<tr>
<td>Handling of limestone (to primary crusher)</td>
<td>Once the mineral mass has been fragmented and released by blasting, it is loaded into haulage trucks. Often haulage trucks of up to 100 tonne capacity are used for the removal of the mined mineral from the open pit to the downstream processing plant. These operations will produce dust emissions during loading, unloading and during the transport of the material from the pit (from agitation of the road surface). Primarily the fugitive dust is generated, by a pick up and drop off of dust from the haulage road surface by wheels will occur. Material on the bed of the dumper will produce dust, through mechanical attrition and wind blown action.</td>
</tr>
<tr>
<td>Haul Roads</td>
<td></td>
</tr>
<tr>
<td>Mineral processing</td>
<td>The crushing and screening of the mineral into smaller size fractions produces dust emissions. A loader and gyratory crusher are often used for the primary crushing of the mineral. Here mechanical action will cause the production of a dust and fines. The crushing and screening of the ore and its subsequent transfer by belt conveyor to primary stockpiles would also be a potential source of dust generation.</td>
</tr>
<tr>
<td>Overburden handling</td>
<td>Overburden loosen by either scrapping, bulldozers or blasting is often loaded into and transported by dumper truck. Emissions will be generated from the disturbance of soil layers and the emissions related to dumper truck movement. Repositioning and unloading from the dumper truck are also likely to generate emissions.</td>
</tr>
<tr>
<td>Mound formation</td>
<td>Overburden material and low grade mineral deposits are often used to form mounds which are often levelled and shaped by bulldozers. Operation of dumpers, dozers and graders would generate dust emissions.</td>
</tr>
<tr>
<td>Storage Mounds (OB and low grade mineral)</td>
<td>Exposed surfaces of mineral storage(stockpiles generate dust due to wind erosion. Dust will also be generated due to mechanical impaction of dust dropped onto storage piles from conveyor belts. Dust emissions will depend on the height between the conveyor drop and top of the pile. Also truck tipping/loading and transport operations will generate mechanical movement of storage piles and thus produce further emissions.</td>
</tr>
<tr>
<td>Conveyor Belts</td>
<td>Transportation of various size fractions between downstream processing operations are commonly carried out using conveyor belt systems. The loading and discharge areas are likely to produce the greatest emissions. Uncovered conveyors will also suffer from wind blown and mechanical attrition dust emissions.</td>
</tr>
<tr>
<td>Movement of other quarry vehicles</td>
<td>Movement of vehicles like dumper trucks, bulldozers, tankers, water bowsers, supervisors, etc will all generate dust from the agitation of unpaved surfaces.</td>
</tr>
</tbody>
</table>

Notes: Sources used include, Chaulya et al (2001) and Arup Environmental (1995)
Dispersion modelling uses mathematical equations, describing the atmosphere, dispersion and chemical and physical processes within the plume to calculate concentrations at various locations.

A recent review paper by Holmes and Morawska (2006) provides a comprehensive review of the application of atmospheric models for atmospheric particulate dispersion. The authors provide an evaluation of the range of different types of dispersion models available, from simple box type models to the more complex computational fluid dynamic models. The authors discuss the suitability of the various modelling approaches to the dispersion modelling of particulates within different environments, with regard to the scale, complexity of the environment and concentration parameters are assessed. Several major commercial and non-commercial particle dispersion modelling packages are reviewed, detailing which process models are included and limitations to their use to model particle dispersion discussed.

The modelling of particle number concentration involves the incorporation of aerosol dynamics models into the dispersion models. A number of local and regional models exist that include an extensive treatment of aerosol dynamics. The majority of these are non-commercial packages that have been coupled to existing dispersion models to provide a package that is able to model changes to particle number concentration within different size groups. This means that the performance of these models depends on both the accuracy and specific processes included in the dynamics module as well as the performance of the dispersion model. It is often possible to integrate the aerosol dynamics module with different dispersion models to adapt the coupled dispersion package to better suit the objectives of the planned study. The modelling of pollutant dispersion is achieved using mathematical algorithms. There are several basic mathematical algorithms in use; the box model, Gaussian model, Eulerian and Lagrangian models (Collet and Oduyemi, 1997).

**Box models**

Box models are based on the conservation of mass. The site is treated as a box into which pollutants are emitted and undergo chemical and physical processes. These models require input data defining the simple meteorology and emissions and the movement of pollutants to and from the box is allowed. The inside of the box is not defined and the air mass is treated as if it is well mixed and concentrations uniform throughout. For this reason they are unsuitable for modelling particle concentrations within a local environment, where concentrations and thus particle dynamics are highly influenced by local changes to the wind field and emissions.

**Gaussian Plume Models**
Gaussian type plume models are widely used in atmospheric dispersion modelling, in particular for regulatory purposes, and are often nested within Lagrangian and Eulerian models. Gaussian models are based upon a Gaussian distribution of the plume in the vertical and horizontal directions under steady state conditions. The normal distribution of the plume is modified at greater distances due to the effects of turbulent reflection from the surface of the earth and at the boundary layer when the mixing height is low. The width of the plume is determined by dispersion scaling parameters that are defined by either the Pasquill thermal stability classes (Gifford, 1976) or travel time from the source. One severe limitation of plume models with regard to the modelling of particle dispersions is that since the models employ steady state approximations they do not take account of the time required for the pollutant to travel to the receptor. Therefore, aerosol particle dynamics must be calculated by performing a post processing of the results.

When using the Gaussian plume model to calculate pollutant dispersion, there are some assumptions that must be made in order for the equations to be valid: (i) the emissions must be constant and uniform, (ii) the wind direction, and speed are constant, (iii) downwind diffusion is negligible compared to vertical and crosswind diffusion, (iv) the terrain is relatively flat, i.e. no cross wind barriers, (v) there is no deposition or absorption of the pollutant, (vi) the vertical and crosswind diffusion of the pollutant follow a Gaussian distribution, (vii) the shape of the plume can be represented by an expanding cone, and (viii) the use of the horizontal and vertical dispersion coefficients requires the turbulence of the plume to be homogeneous throughout the entire plume (Beychock, 1994).

Some of the restrictions implicit in the Gaussian Plume models can be overcome by approximating the emission as a series of puffs over time, which allows for the wind speed to be varied. In this approach each puff behaves according to the Gaussian dispersion equation and the overall contribution of the source is calculated by integration of the individual puffs with respect to time and summation of the contribution of individual puffs at the receptor position.

Some further limitations of the Gaussian treatment means that Gaussian models are not designed to model dispersion under low wind conditions or at sites close to the source, i.e. distances less than 100 m. Gaussian models have been shown to consistently over predict concentrations in low wind conditions (Sokhi, 1998). Gaussian plume and puff models include along wind dispersion of the pollutants in order to better estimate concentrations under low wind conditions (Sharan et al, 1996; Thomson and Manning, 2001). A further limitation is a result of the simplified treatment of turbulence and meteorology so they are best suited to calculating hourly pollutant concentrations. Since Gaussian plume equations assume a homogeneous wind field it is not recommended that they are used for far field modelling as the meteorology is expected to change over large distances (>10km).

**Lagrangian models**

Lagrangian models are similar to box models in that they define a region as a box containing an initial concentration of pollutants. The Lagrangian model then follows the trajectory of the box as it moves downwind. The concentration is a product of the source term and a probability density function as the pollutant moves downwind. Lagrangian models incorporate changes in concentration due to mean fluid velocity, turbulence of the wind components and molecular diffusion.

Lagrangian models have been shown to work well for homogeneous and stationary conditions over flat
terrain (Oettl et al, 2001; Raza et al, 2001; Venkatesan et al, 2002; Tsuang, 2003) and for inhomogeneous and unstable media conditions for complex terrains (Du, 2001; Jung et al, 2003).

The meteorological data calculates the variance of the wind velocity fluctuations and Lagrangian autocorrelation function. Since Lagrangian particle models calculate the diffusion characteristics by the generation of semi-random numbers they are not confined by the Pasquill stability classes, as is the case with Gaussian dispersion models. If the source of emissions consists of particles, then more information must be incorporated into the function, such as the particle size distribution and the particle density (Collett and Oduyemi, 1997).

This mathematical model has limitations when its results are compared with actual measurements. This is due to the dynamic nature of the model. Measurements are generally made at stationary points, while the model predicts pollutant concentrations based upon a moving reference grid. This makes it difficult to validate the model during initial use. To compensate for this problem, the Lagrangian models are typically modified by adding an Eulerian reference grid. This allows for a better comparison to actual measurements because it incorporates a static reference grid into the model (Collett and Oduyemi, 1997).

**Computational fluid dynamic models**

Computational fluid dynamic (CFD) models provide complex analysis of fluid flow, based on the conservation of mass and momentum by resolving the Navier-Stokes equations using finite difference and finite volume methods in three dimensions. Turbulence is classically calculated using k-ε closure methods to calculate the isotropic eddy viscosity parameter present in both the momentum and pollution transport equations, which assumes that a pollutant is diluted equally in all directions. There has been a limited number of research studies promoted in this area. A recent paper by Silvester et al (2006) reports the application of CFD to the improved prediction of dust emissions from surface quarrying operations. This report concludes that the results produced by the constructed CFD models to characterise dust emissions from inpit blasting and haulage operations, clearly indicate the complex role that the internal pit ventilation flow and the confining pit geometry have on the emission, dispersion and deposition of dust within and from the pit opening. Further research to develop more comprehensive field validated CFD models of the dispersion of dust within shallow and deep quarry operations is recommended.
Sustainable Aggregates: Reducing the Environmental Effect of Aggregate Quarrying: Dust, Noise & Vibration

Introduction
During the planning of any quarry or associated processing plant the operator is required to prepare an Environmental Impact Assessment study, which includes an estimate of the potential predicted dust emissions to the surrounding environment. Most national or federal environmental regulatory authorities require the operator to submit an audit and assessment of the dust emission sources during the projected lifetime of the operation, and to detail the mitigation measures that will be enacted to minimise any off site fugitive dust emissions. The planning protocols require the quarry operator to employ a dust emission estimate for each of the static and mobile fugitive dust sources planned within the mining and the associated materials transport and downstream mineral processing operations. These estimates are based on the US EPA dust emission estimates AP-42 (EPA, 2007c). These dust emission estimate models are then included as source input data to a suitable Gaussian plume dispersion model. For defined dust loading and size distributions these models are able to predict the transport and dry and wet deposition by employing well documented and validated settling velocity and surface impaction algorithms. There are a range of suitable commercially distributed models that are approved by the national regulatory authorities including UK-ADMS, ISC3 and AERMOD. However, all of these base models are constrained in their application to surface mining operations as they employ only quite a coarse grid representation of the topography of an open pit during the various planned stages of its operations, and therefore they are unable to adequately model terrain with slopes greater than one in three. Consequently, they over predict the dust emissions experienced external to shallow open pits, due to the additional fall out, and impaction experienced by dusts due to secondary in pit air recirculation movements and the increased vertical impaction surfaces present within surface mines and quarries. A series of field experimental studies were conducted by the EPA in the US to estimate the retention of the dust emitted within shallow coal strip mines and quarries in the US concluded that between 30 – 50% of Total Suspended Particulate (TSP) matter and 5% of PM10 matter were retained within the pit due to additional dust drop out. For shallow open pit mines the Australian National Pollution Inventory protocol permits the operator to apply upper retention factors of 50% TSP and 5% PM10 for dusts emitted within the open pit or quarry.

There have been a number of Gaussian plume models developed and adopted for regulatory use within national jurisdictions. For the purpose of this review a summary of the development and application of these models is restricted to a consideration of the AERMOD (approved by the US EPA) and ADMS (approved by the UK Environment Agency) programs.

**AERMOD**

AERMOD (EPA, 2007a) is a near field steady state Gaussian plume model based on planetary boundary layer turbulence structure and scaling concepts, including treatment of both surface and elevated sources over both simple and complex terrain. This It is an improved version of the former ISC3 model developed by the US EPA. It is able to model multiple sources of different types including point, area and volume sources.
In the stable boundary layer the distribution is assumed to be Gaussian in both the horizontal and vertical directions. However, in the convective boundary layer (CBL) the vertical distribution is described using a bi-Gaussian probability density function, whilst the horizontal distribution is again considered to be Gaussian in nature. AERMOD is able to model buoyant plumes and incorporates a treatment of lofting, whereby the plume remains near the top of the boundary layer before mixing with the CBL. The atmosphere is described by similarity scaling relationships using only a single measurement of surface wind speed, direction and temperature to predict vertical power law profiles of wind speed and direction, temperature, turbulence and temperature gradient.

In general, Gaussian models are limited to treatment of flows over a simple terrain. However, AERMOD incorporates a simple method to approximate flows over complex terrains (Dunkerley et al, 2000?). AERMOD represents the concentration by a weighted combination of the concentration from a horizontal plume state, in which the plume can impact on the terrain, and a terrain following plume state, where the plume is carried over the terrain. The weighting factor depends on stability and a terrain dependent height scale. The concentration equations also require the effective source height and dispersion parameters are those for flat terrain.

**UK-ADMS**

UK-ADMS is a UK regulatory model developed to model the dispersion of buoyant or neutrally buoyant particles and gases (Carruthers et al, 1994). The model predicts the boundary layer structure using the similarity scaling approach in a similar method to Berkowicz et al (1986). The model uses an advanced Gaussian approach with a normal Gaussian distribution in stable and neutral conditions whilst the vertical dispersion is approximated by two different Gaussian distributions in the convected boundary layer (CBL). The treatment of the reflection of the plume off the surface of the earth is similar to other Gaussian models. ADMS calculates the plume rise based on the temperature differences between the atmosphere and the emitted plume and horizontal and vertical momentum fluxes including the possibility for entrainment of the plume and escape through the inversion at the top of the boundary layer.

The dry deposition of particles is modelled as a function of gravitational settling and deposition velocity with respect to aerodynamic, sub-layer and surface resistances. Wet deposition is approximated using a wash-out coefficient derived from the precipitation rate.

The changing wind flow over complex terrain is calculated using FLOWSTAR (Carruthers and Hunt, 1998), and advanced airflow model, Carruthers et al (1988) have shown that FLOWSTAR models the flow well between tens of metres up to several kilometres over terrain with gradients between 1 in 2 (upwind slopes and hill summits) and 1 in 3 locally in hill wakes. This will have an important bearing on the modelling of particulate emissions within operating quarries. ADMS calculates a perturbed mean and turbulent velocity field using the linear flow model FLOWSTAR. The deflection of the mean streamline through the source can then be determined and it is this height which appears in the concentration equations. The turbulent velocity field is used to prescribe the dispersion coefficients.

A recent comparative review of the performance of the AERMOD and ADMS dispersion modelling packages when applied to the modelling of a series of case study pollutant emission and receptor studies is given by Hall et al, 2000.
Dust dispersion models for surface mining operations

A recent MIST sponsored research project (MA/2/3/007, Petavratzi et al 2005), collated a comprehensive review of the fugitive dust emissions that may be generated from surface mining operations and summarises the range of conventional mitigation technologies and strategies that may be applied to control these emissions. This report presents a summary of the potential dust sources and mitigation strategies, and also presents a detailed overview of the current UK and International environmental and health and safety legislation governing mineral dust emissions. Petavratzi et al, 2006 documents the results of an investigation into the development of a laboratory testing protocol that may be adopted to assess the propensity of a quarried hard rock mineral to generate fines and dust during each stage of the extraction, transport and processing. The application of this assessment method is illustrated by application to a major limestone quarry operated by Tarmac Ltd (MA/2/3/007). In addition English Heritage sponsored a parallel project (EH-ALSF, 2005) that considered the environmental impact on historic heritage, which included an assessment of the potential impacts of dust emissions from quarry operations.

Reed (2005) has recently produced a comprehensive review of the dust dispersion models that have been developed or applied to the prediction of dust from surface mining operations including quarries. The dust dispersion models used to predict emissions from surface mining operations are generally adapted from existing regulatory industrial air pollution models.

A major challenge to the modelling the dispersion of fugitive dust emissions from deep surface mines or hard rock aggregate quarries is the influence of the in pit meteorology. As most Gaussian plume dispersion models have been developed to model downwind dispersion of dust from sources across a flat or undulating terrain, these models cannot account for the influence that the complex flow regimes that exist within quarry openings. As fugitive dust emissions within a quarry are transported and dispersed by the local airflow field within the quarry, there is a need to develop transport and deposition models that reproduce the local effects produced by these flows.

The airflow regime within a deep quarry opening is produced by the combined action of the mechanical shear of the atmospheric boundary layer across the surface opening and the thermal buoyancy forces created by the differential heating of the quarry surface by the passage of the sun during the day. In addition, the occurrence of thermal temperature inversions at night may also assist trapping the dispersion of the dust emissions from within the quarry. The combination of these forces creates: (1) an external flow field across the surrounding terrain and across the interfacial quarry opening that is governed by the atmospheric boundary layer (ABL), and (2) an internal flow field driven by the combination of the mechanical shear of the atmospheric boundary layer across the surrounding terrain and the airflow within the quarry opening, and the thermal effect created by the differential heating of the internal quarry surfaces by the sun (see Figure 1). To improve the understanding and modelling of these processes requires the adoption of a multi-scale modelling approach; this is discussed in a following Section 6.

Thus, a fugitive dust emission within a quarry will be transported and dispersed by this locally generated flow field. The creation of this chaotic, and often recirculatory in-pit flow regime within the quarry will increase the residence time of the entrained dust particles within the confines of the quarry. As the deposition of particles is governed by Stokes Law, any increase in the dust residence time within the quarry may allow
either; (1) allow the settlement of many of the dispersed dust particles or (2) increase the probability of their removal by impaction on the internal surfaces of the quarry. Consequently, only a fraction of the fugitive dust emitted and dispersed within the confines of the quarry will cross the interfacial layer defined between the quarry opening and the atmospheric boundary layer to be dispersed and potentially deposited downwind across the surrounding terrain. The fraction of the dust emission which crosses the interfacial layer between the quarry opening and the ABL will form an equivalent areal emission source whose downstream dispersion may be modelled by conventional Gaussian plume models.

The existence and effects that these internal pit flows have on the retention of dust emitted within the quarry opening was recognised by research work conducted by Cole and Fabrick (1984). The authors note that the earlier work of Shearer concluded that for shallow open pit mines that approximately one-third of the fugitive dust emissions from mining activities escape the open pit. This is a very simplistic model that is representative of the box model algorithm. Further discussions are provided for a Gaussian plume model described by Winges. This model calculates the mass fraction of dust that escapes an open pit in terms of an mathematical expression containing the particle gravitational settling velocity (determined from Stokes’ Law), the vertical diffusivity, and the depth of the open pit (Reed, 2005). The resulting mass fraction estimate was employed to scale the areal dust emission factor employed within a Gaussian plume dispersion model to predict the particulate deposition downwind.

Cole and Fabrick, (1984) also proposed an open-pit retention model based upon the interfacial wind velocity at the top of the open pit. This model was again employed to scale the areal dust emission factor employed within a downwind Gaussian plume dispersion model. A comparison of both models with emission and deposition data of a published study by Shearer gave good agreement, concluding that one third of the dust emitted escapes from the open pit (Reed, 2005).

The report by TRC Environmental Consultants (1995) conducted for the US EPA, summarizes the results of research investigations conducted to better understand the dispersion and transport of particulate matter released within surface coal-mine pits. Data previously collected at four surface coal mines were used in this investigation. This report describes the analysis and interpretation of those data sets, examines the relationship between meteorology and smoke puff behaviour, and compares mine pit escape fraction (that portion of the dust emitted in the pit that leaves the pit) with those predicted by existing equations. Two independent techniques were used in conjunction with assumed particle-size distributions and the onsite data, to infer values of escape fraction. These values were then used to determine the predictive ability of two widely used model algorithms (Cole and Fabrick, 1984).

Atkinson et (1997) detail the development of the improved area-source dust emission models included in the EPA recommended Gaussian plume the Industrial Source Complex (ISC) emission code to replicate the area dust emissions from open pit sites. This model employs a combination the results of the scale wind tunnel studies of Perry et al, (1994) and the algorithms of Petersen and Perry (1995) to simulate the scaled emission and dispersion of dust from the open area of the surface mine.

The US EPA recommends that dust dispersion modelling from surface mining operations required for regulatory compliance and operation of mineral workings is performed using the Gaussian plume AERMOD program, which has replaced the application of the former ISCST3 (Industrial Source Complex Short Term 3 model) (EPA, 2007b). Open pit algorithms are used to model particulate emissions from open pits, such
as surface hard rock quarries. These algorithms simulate emissions that initially disperse in three dimensions with little or no plume rise. Open pit algorithms are available in some refined models such as ISCST3. In the ISCST3 model, the open pit algorithm uses an effective area for modelling pit emissions based on meteorological conditions. The algorithm then utilizes the numerical integration area source algorithm to model the impact of the emissions from the effective area sources. The following parameters are needed to model open pit sources: open pit emission rate (emission rate per unit area), average release height above the base of the pit, the initial length and width of the pit, and the volume of the pit. The source of fugitive dust emissions within surface mining operations are typically, blasting, loading, haul road operations, tipping and wind blow from stockpiles. The modelling of dust dispersion at surface mining operations generally focuses on PM10, although attention is now turning to PM2.5.

There have been relatively few studies completed to determine the ability of the ISC ST3 model to accurately predict PM10 dispersion from surface mining operations (Reed, 2005). The EPA conducted a large scale field study at a surface coal mine in Wyoming. This study was carried out in three reporting stages (EPA 1994a,b; 1995) and considered all of the potential dust emission sources across the mine site. The dust emissions from each of the potential sources was estimated using the appropriate emission factor (EF) models contained within the EPA AP-42 source emission catalogue for surface mining operations (EPA, 2007c). These emission sources were then input to the ISCST3 model to compute the predicted dust dispersion downwind of the open pit site. To validate the computed dispersion models a total of nine PM10 ambient dust sampling stations were positioned across the site of the mining operation. The sampling stations were located on both the upwind and downwind directions of the major excavation operations. Detailed meteorological data was recorded on site using a dedicated weather station. A detailed log of the mining activities on site was recorded across the two month period of the field experiments. The dust dispersion models were used together with the dust emission models and weather data to create sequential event dust dispersion and deposition model predictions over the dust sampling period. The model predictions were compared against the measurements recorded across the network of sampling stations. The researchers concluded that the ISCST3 models significantly over predicted the PM10 emissions measured by the dust samplers (EPA 1995). The researchers were unable to determine the source of the over prediction of the PM10 particulates. Consequently, it is not known whether the over prediction was caused by the AP-42 emission estimation methods (EPA, 2007c) or by the dispersion model (EPA, 2007b).

Cole and Zapert (1995) conducted a study to investigate the application of the ISC3 dust dispersion model applied to three hard rock stone quarries. These studies followed a similar methodology as to that conducted by the parallel EPA sponsored studies described above (EPA 1994 a,b; EPA 1995). However, these studies appear to have employed a much sparser network of PM10 dust samplers. A comparison of the modelled and measured dust dispersion measured at the samplers concluded that the models over predicted the measured samples by up to a factor of 5 times. The researchers suggested two potential causes of this discrepancy: (1) that the ISC3 model did not adequately replicate the deposition of the particulates, and (2) that the linear time, averaged method of modelling the emission of dust from haul trucks on the unpaved haul roads over predicted the actual emissions experienced on site. The haul road was highlighted as being responsible as it was concluded from an analysis of the on site dust inventories that haul road emissions contributed between 79-96% of the PM10 emissions at each of the quarries. The EPA has been conducting further research studies to improve the deposition models contained within the new substitute model to ISC3, AERMOD, no publications detailing validation of these new methods have been found.
Reed et al (2001) conducted a study to investigate the application of the ISC3 model to a hard rock quarry operation. The authors concurred with the findings of Cole and Zapert (1995) that haul road emissions made the major contribution to the dust emission inventory. However, the authors also concluded that another feature of that characterized these major dust sources was that they were mobile sources. The authors suggested that the representation of the haul truck emissions as a liner time averaged source could also lead to an over prediction of the resulting emission and deposition. Therefore, the authors proposed the development of a dynamic dust source model along the identified haul roads. Subsequent research studies by Reed (2002; 2003) developed a dynamic dust emission source model. This application of this model was validated at a series of two field studies conducted at a hard rock quarry and a coal mine. Reed argues that the over prediction of the dust dispersion by the ISC3 model is due to a large degree to the form of emission model suggested by the EPA AP-42 guidance notes (EPA, 2007c). The suggested AP-42 model is constructed by applying the total emissions of the mobile haul truck sources to a specified areal source that represents the passage of the truck along the unpaved haul road from the loading point at the blasted bench to the tipping point at the primary crusher. The emission is time averaged over the sampling period modelled. From actual field observations and measurements the emissions from haul trucks are not uniform, but dynamic following the passage of the trucks. The model proposed by Reed simulates the truck emissions as moving point sources. It was concluded that the application of the dynamic haul truck emission model within the ISC3 model gave a much improved prediction of the emission sampled at the chosen receptor/sampling points (Reed, 2003). It was conceded that further field test validation was required to demonstrate the accuracy and consistency of this model. A further section of the review details a discussion of recent research studies that have attempted to give an improved understanding to the modelling and prediction of dust emissions from unpaved haul roads within quarries.

A number of recent studies reported in the literature have investigated the generation of fugitive dust emissions from limestone quarry operations (Chulya et al 2001), Chakraborty et al 2002, Chang 2004, Bhandari et al 2004 and Organisack and Reed, 2004.

The US National Stone, Sand and Gravel Association (NSSGA, 2007) in conjunction with Trinity Consultants, has developed a new guidance document to assist in improving the accuracy of the modelling of pollutant emissions from aggregate operations, this guidance makes use of actual emission data generated by the aggregates industry. This document includes an extensive compilation of all current state and federal modelling policy and guidance. The guidance document also identifies states that lack comprehensive aggregate industry air modelling guidance, provides consistent guidance for those states backed by appropriate technical theory and creates a single guidance document for all aspects of how to model an aggregate facility.

Many regulatory agencies require aggregate facilities to complete air quality dispersion modelling analyses before issuing permits. One of the most subjective and time-consuming aspects of air dispersion modelling is the modelling of sources that are fugitive in nature like those found at a typical aggregate facility. Fugitive sources can include fugitive dust from conveyor transfer points, haul roads and open storage piles, as well as emissions from crushers/screens and truck loading and unloading. The current EPA air dispersion models, Industrial Source Complex Short-Term Version 3 Model (ISCST3) and AERMIC Model (AERMOD 2) are able to estimate ambient concentrations from these types of fugitive sources. The models allow for categorization of fugitive sources into point, area, volume, or open pit sources (open pit sources are only available in ISCST3).
Methodologies for correctly characterizing fugitive sources are necessary due to the model’s sensitivity to certain input parameters and the lack of guidance for modelling fugitive sources. Incorrect characterization of fugitive sources can lead to unrealistic model-predicted concentrations.

The NSSGA Air Quality Dispersion Modelling document provides methods for appropriately characterizing fugitive sources such that the modelled parameters, and thus calculated concentrations, accurately reflect the sources in question. Discussions on regulatory guidance are included, as well as summaries of the data and technical theory used to develop the suggested methodologies. The set of fugitive source modelling methodologies presented in this document was developed by a combination of data research, review of modelling guidance documents, and practical knowledge of modelling fugitive sources. These modelling methodologies can be adapted to fit site specific characteristics. It is recommended that a research study should investigate the applicability of the NSSGA dust emission and dispersion models to UK quarries.

Case Study Applications
A series of two recent MIST sponsored research projects (MA/2/3/007 and MA/4/1/002) have conducted a series of preliminary dust dispersion measurement and modelling studies at a major UK limestone quarry. The modelling software employed in these investigations was the UK Atmospheric Dispersion Modelling System, ADMS 3, developed by Cambridge Environmental Research Consultants (CERC 2001). ADMS is approved for use by the UK Environmental Agency and is typically employed in assessments supporting Pollution Prevention and Control (PPC) applications, to determine suitable discharge conditions such as stack height, requirements for pollution control systems and for safety planning (Timmis et al 2000). The aim of these studies was to develop a modelling strategy to simulate dust dispersion from blasting events and haul roads applicable to UK hard rock aggregate quarries.

The initial research study (MA/2/3/007 and Appleton et al, 2005), was the first research investigation to employ the ADMS3 model to simulate fugitive dust dispersion from surface mines and quarries in the UK. As the UK has not developed an independent dust source emission inventory, the researchers employed the US EPA AP-42 (EPA, 2007c) emission models to estimate the dust emissions predicted from blasting events, loading operations and truck emissions from unpaved haul roads.

A major assumption in the construction of all of these models was that the atmospheric boundary layer was assumed to penetrate the shallow depressed workings of the quarry and to be primarily responsible for the subsequent dispersion of the modelled dust emissions from the quarry. Representative values of dust quantities released by in-pit activities were obtained from literature published by the USEPA (USEPA 1995, 1998) and a detailed annual meteorological record for the area was obtained from the local UK Met Office located at Manchester Airport. A representative limestone dust particle size distribution (PSD) obtained from preliminary fugitive dust sampling studies was employed in the construction of the ADMS 3 dust dispersion models.

The simulation of bench blasts
Wei et al (1999), discusses a computer model created at Kalgoorlie Consolidated Gold Mines Pty Ltd, Western Australia to determine dust dispersion from blasting operations. The program uses inputs such as meteorology, bench height, blast design information, and rock density to predict the behaviour of dust from blasting and its subsequent dispersion to impact nearby towns. It also accounts for absorption and reflection
of dust off the pit walls with the dust concentrations estimated using settling velocities for different particle sizes and densities. Kumar and Bhandari (2002) also created a model for predicting dust dispersion from blasting operations. In their model, they made use of the Eulerian mathematical algorithm. This model considers atmospheric stability and wind velocity and direction for computing dust concentrations at different distances from the blast. However there is no mention of any field validation studies.

An analysis of these studies highlighted two observed stages in the formation and dispersion of the resulting dust emission, namely: (i) the development of an initial cloud initiated by the detonation and blast of the bottom of the bench, followed by (ii) the formation of a second dust cloud dispersion created by collapse of the material forming the top of the blasted bench. Consequently, a number of visual characterisation studies were carried out at the Old Moor Quarry to confirm the validity of these observations, and to form the basis of subsequent modelling studies. Digital video cameras were placed at two locations along the pit boundary to obtain front and side elevation views of a series of quarry blasting events. A review of the footage was undertaken to understand the physical processes that occur during the collapse of a bench and how dust cloud is subsequently generated.

These models were used to investigate the predicted dispersion of the dust clouds from the quarry under a range of seasonal weather conditions experienced by the quarry.

**The simulation of unpaved haul road emissions**

In the ADMS 3 model simulations performed, fugitive haul road dust emissions were represented by a line of areal point sources that overlap to represent the continuous emission of an areal line source. The emission rate being determined from the EPA AP-42 model guidance notes (EPA, 2007c) for haul trucks. A series of dust emission predictions exercises were performed to simulate the dust emissions from these haul roads during the transport of rock from surveyed blasted benches to the primary crusher plant external to the quarry. A summary of recent haul truck generated research projects is contained within Appendix 1.

An analysis of the dust emission and dispersion modelling exercises performed confirmed the strong influence of the site specific meteorological conditions and both the in-pit and surrounding terrain upon the levels and direction of the predicted dust dispersion and deposition.

The location of the emission source, the terrain formation and the prevailing meteorological conditions complexly interact to determine the degree of impact experienced beyond the pit boundary. Impacts off-site are reduced by:

- The source of emission being located more centrally and deeper within the pit;
- A greater exposure to the surface of the terrain located downwind of the emission source; and
- Less dispersive meteorological conditions.

The current restriction of ADMS to model terrains that contain gradients of greater than 1:3, greatly restricts the ability of the modelling package to replicate the influence of steeply changing terrain.

The modelling strategy and model simulations developed as part of this study were qualitatively verified by observational studies conducted during the course of the project. To gain greater confidence in the accuracy of the model predictions it was recommended that a dust deposition sampling network be established at the quarry. The data provided by this network could then be used to verify the accuracy of the modelling studies.
A further MIST sponsored research project (MA/4/1/002; Docx, 2007) performed a further data collection and dust monitoring regime required to provide validation of the ADMS modelling tool. The execution of this project was again based upon the Old Moor Quarry of Tunstead Works, Buxton, Derbyshire. An inventory of the potential dust emission sources within the quarry concluded that blasting events and haulage road operations were the major source of fugitive dust emission.

To monitor and give a quantitative assessment of the long term contribution of these operations to dust emission a comprehensive network of dust deposition gauges was established around the working perimeter of the quarry. The dust deposited in these gauges was collected and analysed on a monthly cycle. The analysis of the dust deposition data collected identified the strong influence of the local weather conditions on the extent of the dispersion experienced throughout the quarry. In particular, blasting events located on the exposed upper benches contribute significantly higher measured and predicted offsite dust deposition and fluxes, than blast events occurring at deeper locations within the quarry.

To improve the understanding of the dust generated and dispersed during bench blasting, the project included the development and design of a prototype high volume sampling device, to collect a sample of the dust cloud emanating from the blasted benches. These sampling exercises enabled the determination of the size distribution and mineralogy of the collected dust to be established. The initial high volume sampling protocol developed as part of the study required the continuous monitoring of the local wind regime within the vicinity of the blast. The blasting events included in the study were also video recorded and the resultant video footage analysed to assist the understanding of the formation and directional dispersion of the dust cloud liberated by the blast.

The ADMS Gaussian plume dispersion models are able to simulate a number of cumulative fugitive dust emission, dispersion and deposition scenarios. The data collected by the dust deposition gauge network was subsequently compared against the dust deposition and dispersion predicted by ADMS simulation models.

A comparative analysis of the measured and predicted dust deposition data concluded that the predicted results tend to overestimate the measured deposition by factors of between 2 to 10 times over the sampling periods. This over prediction supports the observations made in earlier modelling studies (EPA 1994a,b; EPA 1995).

It is concluded that the over predictions made by the recommended regulatory plume dust dispersion models could be due to a combination of two principal effects:

1. the potential overestimation of the dust emitted from the dust emission events (e.g. blasting and unpaved haul road emissions) as predicted by the US EPA AP-42 models (EPA, 2007c)

2. the ADMS Gaussian plume model/terrain models are not able to accurately replicate the actual near source emission, dispersion and deposition mechanisms, due to:
   a. the influence of in-pit generated flow regime that may conflict with the prevailing wind direction effecting the plume dispersion
   b. the mobile nature of the truck generated dust sources, and the complex flow fields generated around these emission sources
   c. the influence of the internal quarry surfaces to promote an impact removal of the emitted dust within the quarry boundary.
It is recommended that further field measurement and dust modelling studies be conducted to identify improved dust emission estimates to be employed in the prediction of off site dust emissions from UK quarries using the UK ADMS modelling programme.

It is also recommended that alternative fluid flow simulation models, including computational fluid dynamics (CFD), are investigated to give a better understanding of the internal air flow regimes that may be generated within large quarry openings. The development of such validated models will also assist in the development of more accurate dust emission, dispersion and emission models that may be used to predict potential on-site visibility issues due to dust emission on haul roads, and to improve off dust site emission estimates to be employed in the regulatory Gaussian plume dispersion models.
4 CONCLUSIONS & RECOMMENDATIONS FOR FURTHER RESEARCH

**Improved dust emission and dispersion modelling studies**
- It is recommended that further field measurement and dust modelling studies be conducted to identify improved dust emission estimates to be employed in the prediction of off site dust emissions from UK quarries using the UK ADMS modelling programme.
- It is recommended that further field based and modelling studies be conducted to better characterize the dust emissions experienced by vehicle movements on unpaved haul roads. These studies should also consider the construction and validation of more detailed 3D Computational Fluid Dynamics (CFD) flow models, to study the wake characteristics responsible for the generation and dispersion of the haul road dust plumes within and from the quarry boundaries.
- It is recommended that scale and full scale experimental and computational modelling studies, including computational fluid dynamics (CFD), are investigated to give a better understanding of the internal air flow regimes that may be generated within large quarry openings. The results of the studies will help to identify and quantify the influence of these internally generated flow regimes on the generation and dispersion of dust within and from quarry operations. The development of such validated models will also assist in the development of more accurate dust emission, dispersion and emission models that may be used to be used to predict potential on-site visibility issues due to dust emission on haul roads, and to improve off dust site emission estimates to be employed in the regulatory far field Gaussian plume dust dispersion models.

**Haul Road Dust Management**
- To address this current industry problem the development of a proactive environmental dust monitoring and management system is required. Ideally, a system would be developed that could detect the onset of a dust problem, its specific location and be able to mobilise the required mitigation measures. This proactive system would provide quarry operators with a vital tool to mitigate the onset of dust problems prior to the actual emission.
- It is recommended that an extensive series of UK field trials be conducted at a number of representative quarry operations to provide bench mark studies that may subsequently used to develop an optimised, proactive haul road wetting strategy that may be adapted by UK quarries. These studies should encompass where appropriate the issues of water additives including bitumen emulsions used in both South Africa and Australia. These investigations should consider the appropriate use of field located and/or remote sensing technologies to identify the on set of potential adverse haul road dust emissions to assist in the initiation of wetting operations. The development and implementation of such a proactive haul road wetting strategy would (1) reduce offsite dust emissions, (2) improve Health and Safety and (3) optimise water consumption, and (4) reduce lost production time due to the necessary cessation of haul truck operations due to either, visibility restrictions or road over wetting.
A. UN PAVED HAUL ROAD FUGITIVE DUST EMISSIONS

Introduction
Recent US EPA (2007c) guidelines have identified that haul roads can contribute up to 93.3% of the total emissions from open pit operations including quarries. In addition, recent research studies (Reed, 2001; MA/4/1/002) have concluded that the current US EPA AP-42 emission model (EPA, 2007c) proposed to simulate in pit haul road dust emissions may severely over predict both the mechanism and the quantity of dust emission. Consequently, this section presents a review of recent research studies that has been conducted to quantify and improve the understanding of the mechanism of dust emissions from unpaved haul roads.

Haul road dust management
The understanding of unpaved haul road emissions and their control is currently not well characterised. In addition, the effective environmental management and control of these dust emissions from these sources is not often achieved. Current management practices are often based upon reactive control measures, triggered by the experience or interpretation of the mine operatives to the on site emissions, and to the availability of dust suppression equipment and staff. Furthermore, it is common place for the application of wet dust suppression methods to be applied to the whole of the unpaved travelled quarry road network, rather than targeting specific identified problematic areas. This can have significant economic and environmental costs on quarrying operations, by unnecessary water usage or increased dust emissions.

To address this current industry problem the development of a proactive environmental dust monitoring and management system is required. Ideally, a system would be developed that could detect the onset of a dust problem, its specific location and be able to mobilise the required mitigation measures. This proactive system would provide quarry operators with a vital tool to mitigate the onset of dust problems prior to the actual emission.

Background to the Problem
The need to develop and effective and economic control of haulage road dust emissions also addresses a number of the other major problems facing current quarry operators:
1. Water minimisation
2. Off site emissions of nuisance Dust
3. Off and on site health effects of dust
4. Onsite safety
5. The environmental benefits produced by alternative onsite layout of extraction, haulage, transport, processing and storage operations.

Water Minimisation
One of the major challenges facing the modern quarry industry is the need to reduce the amount of water it abstracts from ground and surface water sources, for dust suppression, downstream wet mineral processing, and general plant and hygiene use.
The use of automated water sprays and water bowsers on haulage roads is a common industry practice, one which has rarely questioned the supply of its raw material; water. However, many mines and quarries can now no longer rely on a constant, ‘free’ supply of water. With increased competition from, local communities, industries and agriculture coupled with more demanding regulatory standards, quarry operators are under increased pressure to reduce primary water abstraction and usage (Lowndes et al, 2006).

**Nuisance Dust**

The problems associated with dust emissions are not just confined to the health impacts resulting from PM10 and PM2.5s. ‘Nuisance dust’, described as the coarse airborne dust fraction, is also a significant problem for quarry operators, causing both environmental and operational problems. The inherent nature of nuisance dust emissions makes it visible and an aesthetic nuisance, often resulting in complaints regarding the soiling of property and amenities from local inhabitants. Consequently, along with odour emissions, this makes nuisance dust emissions two of the greatest causes of complaints with respect to local air pollution (Hall et al, 1993). Nuisance dust can also have a number of other impacts on the local environment. Depending on the type and content of the dust, it can affect soil chemistry, wildlife, vegetation, local microclimate conditions and vegetation (Arup Environmental, 1995; Balkau, 1993).

**Dust Health Effects**

Exposure to any dust in excessive amounts may create adverse health problems including respiratory problems (HSE, 1997). Various factors influence the health risks posed to the exposed party, including, particle size, dust concentration, dust composition, deposition site with in the respiratory tract and the exposure duration (SIMRAC, 1996). Therefore, the control of haulage road dust emissions is of major concern, to protect both the health of both onsite workers and nearby off site residents.

**Onsite Safety**

Haulage trucks can often weigh over 200 tonnes fully laden, and travel at up to 30mph on often narrow inclined and interconnecting haul roads. For safety reasons it is important that the drivers maintain excellent driver visibility, to avoid truck collisions and avoid the trucks steering off haul road. During periods of dry weather, these safety concerns are often compounded by increasing haulage road dust emissions, further reducing driver visibility and making conditions extremely problematic. In particular, hot and dry weather can result in very high evaporation rates, resulting in ineffective dust suppression programme. A study by Thompson and Visser (2002) found that in a South African surface mine, water suppression (provided by a mobile water bowser) was required every 21 minutes to prevent the onset of hazardous driving conditions due to reduced driver visibility. This highlights the need for the development of an environmental monitoring and management system capable of constantly monitoring the road conditions ensuring site safety is never compromised.

**Changing Onsite Layout**

The nature of quarrying means that the depth and lateral extent of the extracted open pit terrain is ever changing as more of the mineral reserve is exploited within the mineral planning boundary of the deposit. In response, to the movement of the location of the mineral extraction operations the haulage road network is constantly adapted to allow the haulage trucks access to the blasted material. This would make the use of a paved haul roads and static monitoring or water suppression systems ineffective and possibly uneconomic in order to combat haul road dust emissions.

The following sections summarise the current state of knowledge of haul road dust management, sampling
and characterisation documented in the literature. This section also presents a review of the potential technologies that exist for the online measurement or prediction of haulage road dust emissions.

**Characterising Haul Road Emissions**

Vehicle generated fugitive dust from unpaved roads can be both a localised nuisance and a significant contribution to regional air quality (Veranth et al 2003). Fugitive dust generated along unpaved haulage roads from truck traffic can disperse over site boundaries and may expose workers or near by residents to airborne or deposited dust when downwind of the haulage roads. As well as being a nuisance, the production of PM10 size particulates can also be a health and safety concern in the immediate area. The generation of fugitive dust clouds on haul roads can also present a significant operational safety hazard by reducing the visibility of the truck drivers along the length of the travelled haul roads and ramps. The results of a recent US based studies have indicated that haul truck operators record one of the highest respirable dust exposure levels amongst the cross section of the workforce employed at quarries (Organiscak and Reed, 2004).

Typically, unpaved road surfaces may be characterised as a graded and compacted roadbed, usually created from the parent soil/rock-material. A vehicle traveling along an unpaved road will impose large impaction forces on the wheel/road contact surfaces causing disturbance and pulverization of surface material. In addition, a zone of highly turbulent air (wake) is formed immediately behind and in the vicinity of the vehicle characterized by the imposition of strong unsteady surface wind shear effects capable of entraining surface particulates and causing diffusion of re-suspended particulates (Gillies et al 2005; Baker 2001). Baker (2001) classifies this wake as comprising two zones – the near wake and the far wake. The near wake is characterised by strong unsteady turbulent flow structures whilst the far wake is characterised by stable flows subject to a gradual decay to background conditions. Wake characteristics are well documented for bluff body flows in the form of the generic car shape typified by the fastback configuration. The near wake is shown to consist of two trailing opposing vortices the strength or clarity of which is known to increase with increased body streamline (Duell et al 1999). Duell (1999) demonstrated a significant drop in the strength and definition of these vortices according to the increased ‘bluntness’ of the rear of the vehicle noting, in terms of dimensionless distance from the vehicle rear, a decrease in near wake definition of approximately half compared to a more streamlined body. Baker (2001) noted a similar relationship between a streamlined fast moving train and a lorry. The haul road truck represents an extreme in terms of body ‘bluntness’ since aerodynamic performance is entirely irrelevant in their design. The combined influence of their extraordinary size and large body drag would suggest the generation of a short lived wake characterised by large, poorly defined vortices experiencing rapid decay. Although haulage trucks have not been subjected to the same level of aerodynamic analysis as the classic on road car based bluff body flows it is clear that the combined effort of tyre/road interaction and wake turbulence is sufficient to cause significant particulate emission and subsequent dispersion.

Emissions from unpaved haul roads are typically quantified using the US EPA ‘Emission Factors’ that define a rate of emission through a simple function (equation 1) typically incorporating operational and site variables such as vehicle speed, vehicle load and surface characteristics such moisture and/or silt content.

\[ E = A \times EF \]  

(Equation 1)

The emission factor for a given situation will therefore provide an emission rate for a specific situation in
terms of mass per unit distance travelled. The United States Environmental Protection Agency (USEPA) has published data defining specific emission factors for industrial/mining related activities in the context of US geological and meteorological conditions derived from field sampling studies and back calculations based upon Gaussian formulations (USEPA, 1998). These emission factors are recognised as being of variable quality (Veranth 2003; Venkatram 2004) and consequently roadside sampling research is still highly active as evidenced in Etyemezian et al 2003a,b, Kuhns et al 2003, 2001 and Zhu & Hinds 2005). A significant amount of research work has been previously conducted to provide a more fundamental understanding of the mechanisms that may create and control haul road dust emissions. Through the AP-42 research project programme, the US EPA (1998) sponsored a large number of research projects in this field, with the aim to improve the predictive modelling of road dust emissions.

The US EPA AP-42 document (US EPA, 1998) concludes that the emission of particulates from unpaved haul road surface was due to three major processes:

1. The force of the wheels on the surface of the road causes the pulverisation of the surface material.
2. These crushed particles are lifted and dropped from the surface of the road through the rolling action of the wheels across the road surface, and are also lifted by the strong air currents in turbulent shear with the road surface.
3. Finally the passing wake generated behind the moving vehicle further acts on the road surface to increase the liberation of the surface material (US EPA, 1998).

These processes are further influenced by a number of other contributory factors, which combine to determine the amount of dust liberated. These main factors are:

- **Vehicle Movement**: Quantity of dust emissions is observed to vary linearly with the volume (frequency) of the haul road traffic (US EPA, 1998). This is subject to two main correction factors:
  - **Road Condition**: This is related to the compaction of the road surface, cohesiveness and bonding of the surface material, durability of the surface material and the amount of imported fines (spillage) on the road (Thompson and Visser, 2002)
  - **Volume and speed of traffic**: The findings of a recent research project report funded by the US EPA, (1998) documented a direct correlation between the speed of traffic and the quantity of dust emitted. As the speed increases the resulting emissions get greater.

- **Vehicle Characterisation**: Vehicle weight, number of wheels and load are all factors that can influence the amount of fugitive dust released. For example, the shape of a vehicle can have a significant impact on the wind shear across the road.

- **Climatic Conditions**: Frequency and amounts of precipitation, solar radiation, wind conditions are all influencing factors
- **Silt Content**: Dust conditions have been found to vary directly with the fraction of silt (<75µm). The greater the silt content, the greater the haul road emission
- **Moisture Content**: This has been found to be one of the most significant factors in the reduction of haul road emissions (USEPA, 1998). This factor is discussed further below.

### Moisture Content

The maintenance of sufficient surface moisture on haul roads has been found to play an integral part in the level of dust suppression required on unpaved haul roads. The action of adding water to the haul road surfaces causes the finer material, the cause of dust emissions, to conglomerate, increase in mass and thus
reduce its potential to be suspended into the air. The dominant factors that influence the effectiveness of the addition of water to haul roads may be summarised under four main categories (US EPA, 1998).

1. The amount of water (per unit area surface road) added during each application
2. The period of time between applications
3. The weight, speed and number of vehicles travelling over the road during the period of application
4. Meteorological conditions (temperature, wind speed, cloud cover, etc) that effect evaporation during that period

The graph below relates the moisture ratio with the control efficiency. The first portion of the graph, with the moisture ratio between 0 and 1 illustrates the situation where no control has been added thus producing 0% control efficiency. The next section (moisture ratio between 1 and 2) reveals that a small increase in the surface moisture ratio provides a large increase in control efficiency, with a doubling resulting in 75% efficient control. The final section then illustrates that passed this level an a doubling of the moisture ration produces significantly less dust control, with an increase in efficiency of only 15%.

Haul Road Dust Emission Sampling
For the design of an effective dust management system, correlations need to be drawn on the amount and effects of dust emissions experienced on haul roads under varying operational, weather and control conditions. This therefore leads to the need for accurate emission quantification in order to assess the optimum conditions for dust control. The use of process emission factors for the accurate modelling of dust emissions has resulted in a significant number of studies aimed at quantifying haulage road emissions.

The field sampling of haul road dust emissions can be subdivided into two main categories: (1) the horizontal flux method and (2) the source sampling method.

Horizontal Flux Method
The horizontal dust flux method is based on the principle that an accurate measure of the upwind mass flux (prior to the road) and the downwind mass flux (after the emission) the source emission can be determined (Venkatram, 2004). This method is based on the main assumption that the concentration variation normal to the wind is negligible. Thus, the horizontal flux can be determined by measuring the vertical profile of the emission plume at varying downwind distances (see Figure 2).

The sampling approach involves sampling the dust concentration and wind speed at varying heights within the dust plumes. As a result both a wind speed profile and dust concentration profile can be determined and the emission rate inferred. The calculation of the source dust emission rate from this data may be determined using one of three computational methods (Venkatram, 2000):
1. Mass balance method
2. Dispersion model method
3. Tracer method
Mass Balance Method

The mass balance method assumes that an accurate profile of both the upwind and downwind dust plume may be determined and interrogated. Using the sampling approach discussed above, and combining the measured wind speed and dust concentration profiles the horizontal flux may be determined from the evaluation of the following integral (Venkatram, 2000):

\[ \text{Horizontal Flux} = \int (uC) \, dz \]
Where;
U = instantaneous velocity normal to the plane
C = the simultaneously measured concentration
Z = vertical height
均价 = averaged over the sampling period

A research study undertaken by Veranth et al (2003) included the execution a field survey of the road dust emissions and the subsequent calculation of the horizontal dust flux. The sampling survey involved the use of seven portable DustTrack™ particulate analysers configured for PM10 sampling. The DustTrack™ samplers are laser light scattering samplers with a range of 0.001-100mgm$^{-3}$. These were positioned on two sampling towers, located at around 4.5m and 95m downwind of the emission source. The near source tower had samplers position at heights of 0.9, 1.7 and 3.7m and the far tower had samplers positioned at heights of 1.8, 4.6, 9.1 and 18.3m. The wind profile was also measured at each of the sampling towers, using a number of sonic anemometers. The horizontal flux of the dust was determined from the product of the dust concentration times the wind speed integrated from ground level to the top of the dust cloud. From an analysis of the results produced from his study Veranth et al (2003) concluded that in order for a more accurate measurement of dust flux to be achieved a better characterisation of the dust concentrations and wind speed near to the ground is required. In a recent paper by Venkatram (2004) he highlights that another problem with the mass flux method is the inability to accurately demarcate the extent of the vertical dust. This is especially important when the dust concentrations measured at the highest sampling height are relatively high in comparison to the rest of the plume measurements. They suggest that alternative horizontal flux measurements may combine simultaneous dust concentration and wind velocity vector data associated with individual truck haul trips to gain a better insight into the emission profile.

A number of other studies have also utilised the mass balance technique to quantify the emission of dust from unpaved roads. A study by Tsai and Chang (2002) found that calculated emission factor values varied considerably with a change in the environmental conditions, including wind speed, moisture content, silt content and traffic volume (frequency). This paper also highlighted the short comings of the mass balance method to accurately calculate the resultant dust fluxes experienced during calm wind conditions.

**Dispersion Model Method**

The aim of the dispersion model method is to fit the measured upwind-downwind concentration profile to a dispersion model, by treating the emission rate as the unknown parameter. This method allows for the backward calculation of the emission rate from the measured downwind plume concentration profile. Venkatram (2004) undertook a study to calculate the horizontal dust flux measurements via the dispersion model route, by using the monitored dust data collected by Veranth et al (2003). This allowed them to undertake a comparison with the similar the mass balance method. Form the study Venkatram (2004) concluded that there is a need to model the actual dispersion measured and not simply adopt a plausible concentration profile, as suggested by Veranth et al (2003). They conclude that the use of a dispersion model allows the investigator to explicitly account for the length of the source and wind direction when performing an estimate of the emissions from the measured concentration data. Venkatram (2000) identified fluctuating background levels and source characterisation as potential drawbacks of the dispersion model approach. The influence of these factors should be reviewed prior to an application of the dispersion model approach.
Tracer Method
The tracer gas method adopts the same sampling arrangement as used in the mass balance and dispersion methods, to monitor the tracer gas concentration profiles of the downwind dust plume. However, with this method the addition of a tracer gas, of known concentration, to the emission source is carried out (Claiborn et al, 1995). As a result, the ratio of the downwind tracer concentration to the source tracer concentration can be applied to the associated measured PM downwind concentration. For example, if a road were to be investigated, a known concentration of tracer would be applied to the road and the resultant emission measured downwind. The downwind concentration would then be indicative of the actual PM concentration and the tracer ratio could be applied to the particulate emissions. The study undertaken by Claiborn et al (1995) investigates the use of SF$_6$ as an emission seed to determine the emission factors from a number of road experiments. However, the study did not assess vertical profiles and so it is not possible to present an accurate comparative assessment of this method with those discussed above.

Semi-Quantitative Approach
As well as studies aimed towards determining haul road emission factors a number of studies have taken a more qualitative approach. Organiscak and Reed (2004) undertook a haul road fugitive dust sampling program which investigated the characteristics and variation of the dust emissions. The study aimed to measure the size characteristics, concentrations and source attenuation in order to assess the potential human health and safety impacts of haulage road emissions.

The sampling method adopted was not concerned with the measurement of the vertical concentration profile of the emission plume, but the concentration at the typical human height exposure level (taken to be up to 1.5m). Dust monitoring stations were spaced at three downwind locations, next to, 15.2m and 30.5m away from the haul road emission. At each monitoring station three 37mm PVC filter cassette type personal samplers were located, measuring the total, thoracic and respirable dust concentrations respectively. The sampling program also incorporated a number of instantaneous light-scattering dust samplers and multi-stage impactors to examine the real-time dust behaviour and relative size distributions of the collected dust. In addition, the meteorological conditions (wind speed, direction, solar radiation), the truck speeds, various road surface parameters and dust silica content was measured. The road surface moisture content was measured by performing a gravimetric analysis on collected road samples, whilst the surface silt content was determined through mechanical sieving. This sampling was undertaken inline with the guidelines laid out in the American Society for testing and materials (ASTM C117, 2001a: ASTM D2216, 2001b: ASTM D854, 2001c). The US EPA also provides well documented guidelines as part of the AP-42 documentation on the sampling and analysis of haul road dust loadings (USEPA, 1993a: USEPA, 1993b).

Organiscak and Reed (2004) concluded that the downwind dust concentrations were primarily effected by the wind conditions, sampling distance and haul road conditions. The study found that haul roads could generate high concentrations of fugitive dust, but that the dust concentration levels were found to decrease to almost background levels at a distance of 30.5m downwind of the haul road. The vast majority of the fugitive dust captured was found to be non-respirable (<10µm), with at least 80% of airborne dust sampled >10µm. Instantaneous, real-time, sampling illustrated how an individual truck dust plume decayed as it dispersed away from the emission source. A further analysis of the collected dust samples concluded that the dust plume initially had a peak concentration which decayed with time, with the peak level notably diminished by the 30.5m sampling station. The instantaneous measurements also demonstrated
the effectiveness of road wetting at reducing the amount of fugitive respirable dust generated by truck movements.

An analysis of the dust sampling survey data, without calculating emission flux rates, related the haul road, metrological and truck movement conditions with the levels of human dust exposure. This study puts forward the argument that in order to assess the effective control of haul road dust emissions the actual emission rate is not actually required. Instead of this it is possible to infer dust control effectiveness by assessing the level of plume attenuation and its respective size distribution, with the benefit of a simpler sampling survey.

A recent research MIST sponsored research study report (MA/4/1/002, Docx et al 2006) presents an analysis and discussion of field experimental data collected during an unpaved road side particulate emission sampling study conducted within a major UK limestone quarry. The particulate samples were collected using a total of six cylindrical adhesive pad type collectors located symmetrically, at equally spaced intervals upwind and downwind of an unpaved truck haul road. A total of three sampling studies were conducted, each representing approximately 1 hour of road activity and comprising of between 6 to 8 vehicle passes. The first two sampling periods were conducted on an initially unwetted haul road. The third sampling period was conducted following road wetting by a bowser. The surface characteristics of the haul road surface were obtained by the collection of a series of swept surface material samples. An analysis of these samples collected prior to and during each of the sampling periods established the surface moisture and silt content of the unpaved road surface. Weather data was obtained using a permanently sited metrological station located on a hill above the quarry, together with a portable weather station located upwind of the haul road to providing accurate localised data. The dust samples collected on the adhesive pads were sized using an Image Analysis (IA) based method. The IA method employed advanced image enhancement functions to characterise the captured particulates in terms of, total count, captured mass, particle aspect ratio and size distribution. These characteristics were compared for each collector sample over each of the three sampling periods.

The study concluded that the IA method was able to provide a useful and consistent range of sample characteristics, although the limit of the resolution of the sizing of the particulates sampled was found to be approximately 5µm. It was found that there was minimal variation in the sampled particulate size distribution and aspect ratio up to a collection distance of 29m from the road side in the downwind direction. A clear attenuation in the capture of particles was identified in terms of particle count and total captured mass reporting to measured upwind background levels at 29m from source. The directionality of the particulate concentrations collected on the pads was found to vary significantly. It was concluded that IA offers a viable method for the analysis of samples collected from cylindrical adhesive pad collectors.

The variance in emission capture directionality warrants further investigation. Road emissions are inevitably subject to high levels of turbulence near source and it is likely that this turbulence, manifested in random short lived large eddies, may in the absence of contamination, contribute to the variations in the collected samples.

Following a comparative analysis of the directionality of the external pit wind direction and that recorded by the local in-pit weather station it was concluded that a localised in-pit weather system was generated within quarry openings. It was proposed that the complex in pit flow regime observed could potentially influence the dispersion, transport and deposition of the dust emitted from mobile and stationary sources within the quarry.
Source Sampling Methods
A three part study undertaken by Etyemezian et al (2003a, b and c) describe the results of an investigation to study the use of a novel sampling technique for the determination of road dust emissions. Etyemezian et al (2003a) proposes that the emission of a vehicle can be measured by sampling in front of and behind a vehicle’s tyre, with the difference in PM concentration relating to the emission. The sampling system, known as TRACKER (testing re-entrained aerosol kinetics from roads) measures PM$_{10}$ and PM$_{2.5}$ road dust emissions. This analysis is achieved by pumping the collected dust samples through DustTrack™ dust samplers which use a 90° light-scattering mechanism to provide real time dust concentrations. Entymezian et al (2003a) reports that the Tracker system is calibrated using the emissions measured via the upwind/downwind tower based horizontal flux method (as discussed previously). The study found that TRACKER has the ability to measure road dust emissions, with reasonable repeatability. The TRACKER has been calibrated over a small range of conditions, including unpaved roads with vehicle speeds of 5-20km/h but has concluded that the emissions factor generated was proportional to vehicle speed.

In a further study, Etyemezian et al (2003b) reports the results of a study to examine the use of the TRAKER system to identify the effects of precipitation, wintertime road standing and the use of street road sweepers on the resultant road dust emissions. Studies undertaken indicated that paved road dust emissions reduced by over 50% during the winter (3 weeks sampling in Treasure Valley, Idaho). They also conclude that an analysis of the TRAKER results indicated that winter rainfall events can suppress unpaved road dust emissions for a week or longer. The paper also investigates the effect of road sweeping on haulage roads, concluding that the vacuum sweepers tested were ineffective at removing PM$_{10}$ emission in the short-term. The investigators also found that PM$_{10}$ emissions increased by 40% immediately after road sweeping. However, they suggested that the longer-term effects may be beneficial. This may be due to the fact that by removing the larger particulate matter, which may evolve into smaller PM10 matter, you are actually removing the potential for further PM$_{10}$ emissions.

The third part of the TRAKER study (Etyemezian et al, 2003c) investigated the effects of speed, traffic volume, location and season on road dust emissions. The results and conclusions of this study, concerned solely with paved roads, is less applicable to unpaved haulage road emissions. However the paper does raise some interesting points, notably a comparison of emissions calculated using generic AP-42 data and that by TRAKER emissions. When using the ‘average day’ silt loadings from the AP-42 documentation the silt loading emissions were found to be much lower than those measured by both the TRAKER and via onsite measurement.

The studies undertaken by Etyemezian et al (2003 a, b and c) propose a new method with which to estimate haulage road dust emissions. The papers also highlight the possible use of laser sizing techniques as a method of carrying out online road surface monitoring. The possibility of calibrating PM$_{10}$ samplers to effective control conditions is an area worth investigating further.

B. CURRENT HAUL ROAD DUST MANAGEMENT SYSTEMS

A semi-quantitative approach
Research work undertaken by Thompson and Visser (2002) developed two empirically derived models to assist in the management of haulage road dust emissions experienced at South African open cast coal mining operations. The first model proposes a link between the levels of haul road dustiness to the frequency of
dust suppression activities. The second model draws correlations between the level of dustiness experienced to both the haul road surface material and the speed of the operating vehicles.

The models developed by Thompson and Visser (2002) were derived from a series of sampling study undertaken at a large open pit coal mine in South Africa. The objective of this study was to quantify the onsite conditions, and to identify a scale of dust emission levels. Due to the number of different factors that can influence haul road dust emissions Thompson and Visser (2002) simplified their approach by identifying the principal contributory factors. The resulting calculation methods allowed for a variation in these factors whilst holding the remaining variables constant. The empirical models developed hold true for the South African region in which the sampling studies were carried out, and where the moisture evaporation rates are assumed constant. This assumption was based upon a classification of the regional climatic conditions of South Africa, which categorised South Africa into areas of similar climatic conditions (Weinert et al, 1988). Haul road traffic volume were recorded throughout the sampling study, allowing this variable also to be held constant.

This dust modelling approach based on the determination of the principal contributory parameters required a relatively low cost dust measurement method to allow subsequent technology transfer and industrial implementation. This precluded the use of the complex and expensive plume profiling approach discussed previously. Instead, a semi-quantitative approach was adopted with the aim to relate dust emissions directly to the identified principal contributory parameters governing the intensity of the dust plume. The development of the dust sampling method aimed to develop a generic benchmark ‘dust-defect’ score, which categorised the haul road emissions based on the deficiency in the functional performance of the haul road. The study used a single dust measuring instrument that could measure the PM$_{10}$ concentration of the road’s dust plume, which in turn could be compared to a qualitative ‘dust-defect’ benchmark value. The ‘dust-defect’ classification adopted was as follows (see Table 2):

In order to develop the benchmark ‘dust-defect’ benchmarks the measured PM$_{10}$ measurements were assigned a descriptive visual interpretation based upon the opinions of the mine personnel (see table 2). Thompson and Visser (2002) further proposed a dust emission intervention level, which related to the degree level where remedial action would be required. A dust defect degree of two was assigned as the intervention level based on visual effects and driver discomfort, rather than health implications.

The monitoring program undertook a number of tests measuring the time it took for measured dust levels to return to baseline conditions after a measured dust suppression event. From these test, dust-time curves were generated which revealed that dustiness increased with each vehicle pass (immediately following spraying) from dust degree level one to dust level four after 90 minutes. Using these findings regression analysis was carried, out over various monthly evaporation rates, to find the time to zero palliation, using:
\[ X_0 = 286.8 - 0.73E_m, \text{ where;} \]

- \( X_0 \) = time to zero palliation (min)
- \( E_m \) = average monthly evaporation rate (mm), for climatic region outlined in Thompson and Visser (2002)

If \( X_0 \) was only dependent on the monthly evaporation rate then this formula could be used directly to calculate the time required between haul road suppression in order to keep it below ‘dust-defect’ degree two. As it is well known that this is not the case, Thompson and Visser (2002) went on to draw a second model to account for the other major the other influencing factors.

The second model involved three equations to relate the dustiness as a function of tyre wearing course material and vehicle speed. The first equation related the mass of the loose dust on the haul road with the various anticipated dust size fractions. The second equation considered the type of truck operating on the haul road surface, relating this to the dust quantity generated by a single truck pass. The third and final equation quantified the effect of vehicle speed on the total amount of dust emitted. In combination, these equations provided an initial estimate of the dustiness associated with a particular wearing course material.

By combining the dust-suppression and dustiness models Thompson and Visser (2002) were able to predict the water bowser spray dust-suppression application interval for the site study. For example they concluded that under summer conditions at 77% palliation the water bowser needed to suppress the haul roads every 21 minutes. This time interval would thus keep the ‘dust-defect’ level below two, the identified intervention level.

The models set up have provided a structured and semi-quantitative approach to the management of haulage road activities. They have also developed a mechanism to which an assessment of differing haul road palliatives can be assessed. This has formed the scope for further work undertaken by Thompson and Visser (2000) that have investigated and reported on the issue.

<table>
<thead>
<tr>
<th>Dust defect degree</th>
<th>Associated Hund peak dust level (mg/m³)(^1)</th>
<th>Qualitative dust defect degree description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degree 1</td>
<td>&lt;3.50</td>
<td>Minimal dustiness</td>
</tr>
<tr>
<td>Degree 2</td>
<td>3.51 – 23.50</td>
<td>Dust just visible behind vehicle</td>
</tr>
<tr>
<td>Degree 3</td>
<td>23.51 – 45.00</td>
<td>Dust visible, no discomfort to driver of oncoming vehicle, good visibility</td>
</tr>
<tr>
<td>Degree 4</td>
<td>45.01 – 57.50</td>
<td>Notable amount of dust, windows closed in oncoming vehicle, visibility just acceptable, overtaking hazardous</td>
</tr>
<tr>
<td>Degree 5</td>
<td>&gt;57.51</td>
<td>Significant amount of dust, windows closed in oncoming vehicle, visibility poor and hazardous, overtaking not possible</td>
</tr>
</tbody>
</table>

\(^1\) Approximate value of peak dustiness for -10µm dust, mg/m³, for per haul-truck pass

Table 2: Dust-Defect classification table (after Thompson and Visser, 2002)
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PART 3: DUST MONITORING

EXECUTIVE SUMMARY

This section of the report is a review of MIST research projects from 2002 - 2006 relating to dust monitoring and relevant peer-reviewed research from 2000. The MIST projects are evaluated in relation to other studies published during this period and the report highlights future areas for research into dust monitoring that were identified by the projects.

Three MIST research projects considered dust monitoring in detail, and dust monitoring is also considered in www.goodquarry.com, the outcome of 2 linked MIST projects. 17 recent peer-reviewed dust monitoring research publications are discussed in relation to the MIST projects. In addition to current regulatory guidance there appears to have been relatively limited research published relating to (new) dust monitoring methodologies aimed at the minerals industry. The abstracts from the other research publications are included as an appendix to the report, together with the titles of 9 official guidance documents published since 2000.

Nuisance dust monitoring, either as the development of new methodologies or to validate dispersion models, was the primary focus of the MIST research projects although PM$_{10}$ dust (dust with an average diameter up to 10 micron) was also considered. Recent parallel research studies tended to concentrate on specific categories of dust, such as PM$_{10}$, either for environmental monitoring or occupational health monitoring although new nuisance dust monitoring methods were also applied.

Whilst standard methods for nuisance dust monitoring exist, these appear to have been found inadequate as different dust monitoring methods were developed and applied according to the requirements of the sampling objective. Where agreed standards exist, (e.g. for PM$_{10}$ dust), research appears focused on testing the effectiveness of existing equipment or new applications of the method. Where standards are not agreed (e.g. nuisance dust) research and development has been to the methodologies. The measurements obtained by the different methods are generally not interchangeable and where they are tested against one another, correlation may be limited. It is generally accepted that the British Standard methods for measuring nuisance dust by deposition or flux have a number of limitations yet are supported in current guidance.

Therefore there is an opportunity to seek more widely acceptable standard nuisance dust monitoring methods to replace outdated techniques. However new dust monitoring methods cannot be developed satisfactorily without validating nuisance dust criteria. The minerals industry needs reliable criteria as well as measurements for nuisance; these could be investigated and promoted by the industry itself as part of good environmental governance.
The report concludes with recommendations for future research that were identified as a consequence of the review:

- Criteria for dust nuisance that can be applied across the minerals industry
- Protocols for nuisance dust monitoring based on perception of nuisance
- Testing public perception to the visual impacts of minerals industry
- Refined sticky pad monitoring to include particle recognition
- Methods for directional quantification of \( \text{PM}_{10} \) at quarries and the impact of fine dust on local air quality
  to keep pace with environmental and public health concerns
- Dust characterisation to better attribute dust sources
- Site-specific dust emission factors based on a range of quarry types to provide regulators and operators
  realistic guidelines for potential emissions
INTRODUCTION

The University of Leeds contributed to a project for the Aggregates Levy Sustainability Fund (ALSF), ‘Reducing the Environmental Effect, Sub-theme C: Dust, Noise and Vibration’. The ALSF enabled research towards reduction of the environmental impacts of minerals extraction through the Minerals Industry Sustainable Technology (MIST) programme.

This section of Sub-theme C considers MIST research projects relating to dust monitoring and publications of other research into dust monitoring. Recommendations for further research work are proposed.

MIST research projects were carried out in five areas in relation to minerals extraction; essentially these were environmental assessment, impact mitigation, site operation, knowledge and technology transfer and resource optimisation. Projects were selected by a review panel from tender applications submitted by industry, academic institutions, research organisations and consultancies in response to six calls for proposals.

Dust is defined as particulate matter 1 – 75 µm (micron) diameter and is produced by abrasive forces acting on materials. It is carried by moving air when there is sufficient energy in the airstream and is removed through gravitational settling (sedimentation), washout (such as during rainfall or by wetting) and through impaction on surfaces. Settled dust can be re-suspended where conditions allow, either by wind blow from bare surfaces or by disturbance such as vehicle movement.

Whilst dust is generated by natural processes such as weathering and erosion of rocks, significant quantities of dust are produced by a wide range of human activities such as agriculture, heavy industry, materials handling as in waste management and quarrying, and road use. The public perception of dust settlement and emissions from such processes is recognised as dust ‘nuisance’.

Increasing attention is being paid to the impacts of dust on human health, as finer particles can be inhaled and breathed into the lungs and cause harm. It is generally recognised that dust up to 10µm can be inhaled beyond the larynx and dust up to 4µm can be breathed into the lungs. The UK has introduced National Air Quality Standards (NAQS) for ambient pollutants such as dust up to 10µm, which is commonly referred to as PM$_{10}$. Target objectives for finer particles (PM$_{2.5}$) are included in the 2007 Air Quality Strategy. Whilst PM$_{10}$ is measured to agreed standards there are no official standards (such as NAQS) for dust nuisance.

The environmental and social impacts of dust generated by mineral workings have long been recognised. Planning conditions applied to quarry developments have specified various methods of assessing dust emissions, but in the absence of a standard method for measuring dust nuisance a range of methods to assess dust nuisance have been applied. The measurements from different methods are generally not interchangeable. Therefore it has not been straightforward to compare the environmental performance of
different minerals sites either against each other or in relation to other potentially dusty activities such as agriculture and road transport.

This report is a review of MIST research projects carried out between 2002 and 2006 relating to dust monitoring and a review of peer-reviewed research relating to dust monitoring from 2000 to date. It evaluates the MIST projects in relation to other studies published during this period and identifies gaps in the research and highlights future areas for research into dust monitoring that were identified by those projects.
2 REVIEW OF MIST-FUNDED DUST MONITORING RESEARCH PROJECTS (2002 - 2006)

For this review, MIST-funded dust research projects were classified as:

- **Review based projects**: studies based on new analysis of existing information leading to improved understanding, better guidance, increased information availability or innovative design criteria.

- **Technology development projects**: conceptual and practical development of new tools & technologies to minimise the environmental impact of mineral extraction.

- **Site based demonstration activities**: site scale demonstration of new approaches and technologies for impact minimisation or management.

The results, outcomes and deliverables of the previous MIST projects have also been classified as:

- **Very Preliminary** (requiring much more work)

- **Preliminary (Requiring more work)**

- **Proof of principal**

- **Potential Commercialisation**

- **Commercial Exploitation Realised**

Three MIST research projects considered dust monitoring in detail. Dust monitoring is also considered within part of the outcome of two linked projects, www.goodquarry.com. The MIST research areas and projects where dust monitoring was considered were:
<table>
<thead>
<tr>
<th>MIST Research Area</th>
<th>Project No.</th>
<th>Project Title</th>
<th>Lead Partner</th>
<th>Project Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impact mitigation and management</td>
<td>MA/1/2/009</td>
<td>Establishment of a reliable &amp; non-subjective measure of nuisance dust using low-cost, multi-directional dust monitoring and processing techniques</td>
<td>Geoffrey Walton Practice</td>
<td>Technology and development</td>
</tr>
<tr>
<td>Impact mitigation and management</td>
<td>MA/2/3/007</td>
<td>Cleaner Quarries - optimising environmental performance</td>
<td>Nottingham University</td>
<td>Review - based</td>
</tr>
<tr>
<td>Environmental assessment procedures and tools</td>
<td>MA/4/1/002</td>
<td>Cleaner Quarries: Methods to reduce the environmental impact of quarry operations</td>
<td>Nottingham University</td>
<td>Review – based, site-based</td>
</tr>
<tr>
<td>Knowledge and technology transfer</td>
<td>MA/2/4/004</td>
<td>Open access website for promoting good environmental practice in the UK minerals industry</td>
<td>MIRO</td>
<td>Review - based</td>
</tr>
<tr>
<td>Knowledge and technology transfer</td>
<td>MA/4/4/001</td>
<td>Extending and promoting the goodquarry.com open access website and disseminating examples of good environmental practice in the minerals industry</td>
<td>Leeds University</td>
<td>Review - based</td>
</tr>
</tbody>
</table>

The outcome of MA/1/2/009 Establishement of a reliable & non-subjective measure of nuisance dust using low-cost, multi-directional dust monitoring and processing techniques was a report booklet that described the field testing and validation of a newly-developed method for directional dust monitoring. The project was carried out with support from a number of industrial partners in the opencast, waste management and quarrying sectors. The DustScan method was originally developed at the University of Leeds and had been commercialised by the Geoffrey Walton Practice with support from the DTI.

The report can be regarded to be in essentially 2 parts. The first part of the report introduced the requirement for a new method for directional dust monitoring at minerals sites and described how the new method was developed. The second part of the report set out and discussed the results of a series of field trials in which the new method was trialled against existing dust monitoring techniques. Some ideas for further work regarding geochemical analyses of the directional dust samples were introduced in this part of the report.

The need for the minerals industry to accurately apportion dust movements at and around sites was set out. Deposited dust can be re-suspended and ‘recycled’ thus primary sources of dust can be difficult to identify. Dust nuisance can be perceived to have occurred as a consequence of mineral workings whereas it may have arisen from off-site activities such as arable farming or road transport.

Distinctions between ‘nuisance dust’ and dust that can have impacts on human health were pointed out. Nuisance dust is commonly regarded as a coarser fraction, typically greater than 20 µm (micron), although there is no standard definition. Dust particles between 20 – 50 µm tend to settle rapidly and can be seen as deposits on clean surfaces such as car paintwork and window ledges.

The project reviewed a range of dust monitoring equipment which was categorised in terms of active, passive and flux monitoring methods. The different monitoring methods were tabulated and compared in terms of cost and practicality.

The DustScan system was described in illustrated text. The equipment comprised a rigid stand, a cylindrical...
dust sampling head with replaceable adhesive dust collection slides (sticky pads) and a protective carrying flask for the sampling head. Dust was collected on an exposed area of a sticky pad; the dust sampling area was determined by pre-scoring of the removable backing paper. The sticky pads were pre-punched to ensure correct orientation on the cylindrical sampling head. The sticky pads were sealed after sampling to provide a permanent, encapsulated record of the dust sample.

Dust coverage on the sticky pads was assessed by computer analysis of a scanned image of the sealed dust collection slide. The exposed sampling area of the sticky pad was compared with the unexposed reference area. The computer software masked extraneous matter such as seeds and insects from the image. Levels of directional dust coverage were determined by the software at better than 1° resolution and summarised at 5 – 15° intervals.

The results of the computer analyses were given in 2 measurements. Absolute Area Coverage (AAC%) was a measure of the dust coverage irrespective of colour. Effective Area Coverage (EAC%) was a measure of the colour of the dust in terms of the difference in its colour intensity. Results of these dust measurements were normally tabulated and presented as rose plots to indicate the scale and direction of dusting.

The project noted that there were currently no legislative and policy standards for defining, monitoring or measuring nuisance dust at mineral workings. In the absence of regulatory standards ‘custom and practice’ guidelines were commonly applied.

The second part of the report sets out the results of a series of field trials where the DustScan system was used in a range of site settings alongside other, more established dust monitoring methods.

From the findings of the report and from other studies new directional dust thresholds based on AAC% and EAC% were proposed.

The report concluded with some results of geochemical analyses of directional sticky pad dust samples. It was suggested that such techniques might be beneficial to the minerals industry as a means of ‘fingerprinting’ dust samples to discriminate between dust sources (such dust generated by a minerals site and dust arising from other, off-site activities).

**MA/2/3/007: Cleaner Quarries - optimising environmental performance** was a report in 4 sections, preceded by an introductory section. This section of the review considers Section 2: Review of dust issues in the minerals industry only.

The project sought to demonstrate that there would be advantages to the minerals industry from ‘cleaner production’. Whilst improvements in production efficiency would increase profitability through reduction of waste at source, there would be other benefits such as reduced emissions to air and water and consequently a reduction in the human and resource costs that pollution can cause.

Section 2 of the report considered definitions of dust and its effects, regulatory limits and standards for dust pollution, dust monitoring, control and mitigation measures, and dust modelling.

The project noted differences in commonly applied definitions of dust. BS6069 Part 2 effectively defines dust
as particulate matter up to 75 µm diameter; some industry guidance includes material up to 2 mm diameter. The importance of other physical properties of dust and the significance of the aerodynamic diameter of particles was emphasised. Smaller dust particles may be monitored specifically. For example those with a 10 µm median aerodynamic diameter are commonly referred to as PM$_{10}$.

Means of dust generation and propagation at minerals sites were considered. The scale of potential dust emissions from specific processes at minerals sites was tabulated. Dust generation, propagation and deposition are not straightforward to predict, although it is generally accepted that coarse particles are deposited sooner (and hence nearer to a source) than finer particles.

The legislative context for dust was described. In the UK these focus on public health (known as local air quality), which is assessed by local authorities with respect to the National Air Quality Standards set out by central government; and occupational health, which is assessed by employers with respect to Occupational Exposure Limits set by the Health and Safety Executive.

A rationale to dust monitoring was described. A dust monitoring strategy should be planned following analysis of the minerals processes taking place at the site, site personnel and dust control measures in place. Environmental influences such as weather conditions should be recorded.

Section 2 of the report concluded by noting that dust is generated at mineral sites by a range of processes including site preparation, excavation, stockpiling, loading, transport and mineral processing. The amount of dust that arises from the different stages and operations at a minerals site are variable and not straightforward to quantify. There is limited air quality legislation specific to the minerals industry; this may be due to a scarcity of specific dust monitoring data. In common with other industries occupational health legislation relating to dust applies to the minerals industry and dust management at minerals sites is best achieved through a site-specific dust assessment procedure.

Sections 3, 4 and 5 of the report consider atmospheric dispersion modelling, comminution flow sheet modelling and a visualisation of the limestone quarry studied in this report, respectively.

**MA/4/1/002: Cleaner Quarries: Methods to reduce the environmental impact of quarry operations** was a report in 3 sections, preceded by an executive summary. This review considers *Section 2: Methodology for Improved Dust Emission* only.

The overall aim of the project was to build on the concept of ‘cleaner production’ where environmental benefits such as reduced dust emissions could be obtained by minimising waste through improved production methods. Dust emissions at quarries can have a significant impact on communities in the vicinity of the workings.

It was considered that a major proportion of dust emissions from quarries are fugitive, from area sources such as haul roads, blasting and stockpiles, where the source could not readily be identified. Therefore it was recognised that methods to predict potential dust emissions from quarrying would be of benefit to the industry.

A comprehensive programme of dust monitoring was undertaken to validate a modelling method to predict fugitive dust emissions at quarries.
The principal aim of Section 2 of the report was to provide dust emission estimates and models for the UK quarrying industry. This was to be achieved through understanding patterns of dust movement at a large limestone quarry, observed using depositional and directional dust monitoring.

Definitions for dust were discussed. Dust is a generic term to describe fine particulate matter suspended in air. Nuisance dust affects the appearance of the environment but doesn’t automatically cause harm. Inhalable dust is up to 10 µm diameter and respirable dust is up to 2.5 µm diameter. British Standards define Total Suspended Particulates (TSP) as all particulate matter up to 75 µm diameter.

Dust occurs naturally in the atmosphere at varying concentrations. It arises from a range of natural and anthropogenic processes such as combustion, minerals handling and processing, industry, sea-salt and volcanic activity.

Dust can be characterised by size fraction and is generally defined by its aerodynamic diameter. Dust monitoring programmes often concentrate on fine dusts, such as sub-2.5 µm (PM$_{2.5}$) and sub-10 µm (PM$_{10}$). However coarser dust can affect amenity and cause nuisance.

Dust is generated at minerals sites due to crushing and abrasive forces on materials. It is emitted through saltation or suspension and entrainment in an air stream. A range of activities take place at minerals sites that can lead to dust generation.

A dust emissions inventory for quarrying was given. Drilling, blasting, initial handling, and rock processing had high significance dust emissions. Overburden handling and emissions from stockpiles had moderate significance dust emissions. Dust emissions from conveyors, vehicle movements on unmade surfaces and construction of stockpiles were considered to have low significance.

Dust from unmade haul roads was considered in some detail. There can be significant emissions of dust both as PM$_{10}$ and coarser; nuisance dust, from unmade haul roads.

2 programmes of dust monitoring at the study site were drawn up. Firstly, a long-term programme was set up to obtain dust samples to validate a dispersion model for fugitive dust emissions in the UK quarry industry. Secondly a short-term programme was set up to enhance estimates of dust emissions from quarrying activities.

For the long-term sampling programme it was recognised that any sampling strategy at the study site would be a balance between representative sampling and practical considerations. Monitoring equipment had to be located according to manufacturer’s guidance and there were normal budgetary constraints on the project.

It was considered that dust emissions at the site would be best evaluated by boundary monitoring of dust deposition and direction. Frisbee-type gauges were identified as the most suitable method for dust deposition monitoring and co-located sticky pads were chosen for directional monitoring. The duration of depositional and directional dust sample intervals were taken in accordance with apparently available guidance and methodologies.

The short-term sampling programme focused on assessing dust emissions from vehicles on unmade roads.
Samples were taken upwind and downwind of a haul road using directional sticky pad samplers. Data from the site weather station were used to inform correlation analyses.

The sticky pads were analysed using a combination of optical microscopy, digital photography and computer software. A series of digital photomicrographs were taken along the length of the sticky pad. Particulate size and shape were analysed using computer software and reported as absolute area coverage (AAC). It should be noted that this value of AAC was different to that measured by DustScan (see MA/1/2/009, above).

It was noted that in some circumstances particle size distribution of dust samples on sticky pads could be obtained by image analysis. Heavily dusted sticky pads could not be analysed in this manner as the area of touching particles could not be assessed. The output of the analysis was in a spreadsheet format identifying each particle measured, the image in which it was located, its area in µm² and its maximum and minimum dimensions. Thus the sticky pad samples could be analysed to obtain a significant body of information about the dust sampled. The data were reported at approximately 1° resolution and presented on a radar plot according to direction.

A programme to evaluate blast dust emissions was prepared following consideration of different sampling methods. A prototype high-volume, powered, sampler featuring a cyclone derived from vacuum cleaner design was prepared and tested although its performance was not evaluated for this stage of the report.

The results of dust monitoring at the quarry were set out and evaluated for the modelling sections of the report.

www.goodquarry.com was launched on 11 February 2004 as a freely accessible information and advice resource for anyone with an interest in the UK aggregates industries. It was developed by the University of Leeds in collaboration with the minerals industry, mineral planners and consultancies, regulatory bodies and educational and advisory bodies.

Dust monitoring is considered in the Air Pollution pages of www.goodquarry.com thus the topic is readily accessible from the home page. The Air Pollution pages also discuss definitions and sources of dust, dust emission from minerals sites and the impacts of dust on ecology and agriculture, as nuisance dust and on personal and public health. Popular thresholds and statutory limits for dust are given and discussed, and examples of good practice with regard to dust for minerals planning, dust assessment studies and quarry design.

The dust monitoring pages of www.goodquarry.com note that estimation of dust emissions from minerals sites is problematical due to the complexity of mineral workings and variations in dust dilution and dispersion from them. Quantification of dust emissions from minerals sites and the impacts of dust at offsite receptors is not straightforward and requires long-term, comprehensive, monitoring.

Offsite dust receptors may be affected by dust from sources other than neighbouring quarry workings. Therefore effective dust monitoring to discriminate between sources is required to ensure appropriate source apportionment. This may be achieved through directional monitoring, especially where dust colour can be assessed; dust characterisation to identify through geochemical analyses may also be appropriate. Correlation of dust monitoring data with site-specific weather information is also recommended.
Dust monitoring methods differ according to their application and can be considered as ‘active’ and ‘passive’. Active monitoring methods are more sophisticated than passive ones, measure over relatively short timescales such as minutes, hours and days and are applied to occupational dust monitoring. Passive systems are suited to longer sampling intervals such as weeks or months and are used for environmental and nuisance monitoring.

It is noted that there are no standards or definitions for nuisance dust and there is no universal method for its monitoring. The type and frequency of monitoring at minerals sites are generally agreed between the operator and relevant regulatory bodies. Directional methods may be most appropriate where there are multiple dust sources and offsite receptors; where dust levels are low and there are few receptors, non-directional methods may be suitable.
Sustainable Aggregates Reducing the Environmental Effect of Aggregate Quarrying: Dust, Noise & Vibration
3 REVIEW OF RECENT (2002 - 2006) PEER-REVIEWED DUST MONITORING RESEARCH PUBLICATIONS

Full references to, and abstracts from, the publications discussed (numbered in the text) are given at Section 6 (Appendices) below.

In addition to current regulatory guidance there appears to have been relatively limited research published relating to (new) dust monitoring methodologies aimed at the minerals industry. This review considers published research into dust monitoring methods that may be applicable to the minerals industry as well as wider contexts.

Impacts of dust on historic environments were considered by Blades et al (1, 2). Aggregate production from hard rock quarrying occurs at significant levels in or near National Parks, such as the Peak District National Park. Dust generated by quarrying can affect the built environment either through soiling or chemical reactions between certain mineral dusts (e.g. limestone) and building materials. Research was undertaken near limestone quarries in North Yorkshire and in Derbyshire. Dust was monitored using passive and active methods. 11 mm diameter adhesive tabs attached to scanning electron microscope (SEM) stubs and mounted at different heights on vertical surfaces indoors and outdoors. Concentrations of ambient dust were also monitored using real-time dust monitoring equipment indoors and outdoors at the locations where passive monitoring was carried out. The passive dust samples were analysed by the British Geological Survey using SEM and XRF (X-ray fluorescence spectrometry). Passive samples taken at 1 m from ground level were also examined by automated petrographic image analysis. Dust concentrations were found by passive monitoring to be generally higher outdoors than indoors. Ambient dust concentrations were generally higher on weekdays than at weekends. It was considered that the elevated dust levels outdoors and on weekdays were largely due to traffic associated with quarrying. Peak dust concentrations had higher proportions of coarse dust than background dust concentrations and it was considered that coarse particles were resuspended by quarry traffic. It was noted that present-day dust concentrations due to quarry traffic are likely to be lower than in the past due to mitigation measures such as sheeting and wheel washing. It was pointed out that buildings near limestone quarries can be constructed of local stone, hence dust from nearby quarrying is likely to be chemically similar thus unlikely to react with such outdoor masonry.

Limited work has been undertaken recently on the public perception of visual nuisance. Brimblecombe and Grossi (3) report the outcomes of a survey of 900 respondents at nine different sites that tested their perception of discoloration of public buildings. The significance of maintaining up-to-date assessment criteria for nuisance is emphasised; standards for cleanliness tend to increase as pollution levels decrease. The paper suggests that public responses to visual pollution can provide information regarding acceptable levels of ambient pollutants.
The development of the DustScan methodology from its inception at the University of Leeds to a commercial method was set out by Datson and Birch (4). Sticky pad dust monitoring was developed in the 1980s and 90s. The method was developed to standardise sampling and subsequent computer analysis. A field trial showed that monitoring intervals of 7 – 14 days were generally appropriate to avoid saturation of the sticky surface although where dust levels were low this could be extended to up to 4 weeks. Enhancements to the original software had been carried out to increase image resolution and to provide a measurement of EAC% correlated to another method, the Sticky Pad Reader (supplied by Ian Hanby, www.hanby.co.uk).

A method for directional dust characterisation using geochemical analyses of sticky pad samples was developed by Datson and Fowler (5). Samples were analysed for a suite of elements using ICP-OES (Inductively Coupled Plasma-Optical Emission Spectrometry) and ICPMS (Inductively Coupled Plasma Mass Spectrometry). Dust was not physically removed from the sticky pads and the mass of dust was low in relation to the substrate. Samples were prepared for the analyses by ‘total’ digestion of the dust on the sticky pads using strong acids. Rigorous ‘blank correction’ was required as some elements were at significant and variable concentrations in the materials of the sticky pads themselves. The method was refined to indicate the residual mass of dust on the sticky pad; from this, the duration of sampling and the ‘wind run’ it would be possible to estimate the average directional concentrations of elements analysed during the sampling interval.

Cylindrical sticky pad gauges set on tripods were used by Docx et al (6) to measure dust emissions from vehicle movements on unpaved haul roads. 6 gauges were located symmetrically upwind and downwind of an unsurfaced quarry haul road. Samples were taken before and after wetting with a bowser over relatively short intervals, representing 6 – 8 vehicle passes. The sticky pad samples were analysed using optical microscopy and digital imaging. The digital images were processed for clarity to improve measurement of individual particles. Visible characteristics of the dust particles, such as circularity, were measured and the mass of dust was estimated using a nominal density factor of 2.6. Dust particle count and mass was found to attenuate with distance downwind from the haul road. Dust directionality was determined as the percentage obscuration on the sticky pad caused by the dust.

Dust emissions from opencast coal mining in India were estimated by Ghose and Majee (7) using active (powered) air quality monitoring equipment upwind and downwind of the study site. Very high levels of dust emission were observed and recommendations to control dust propagation at opencast coal sites were made. Particle size, benzene content and sulphate, nitrate and chloride ion content of dust produced from opencast coal mining in India were also assessed by Ghose and Majee (8). Air quality is very poor in the vicinity of the opencast coal sites due to dust emissions from the workings and higher standards of dust control were recommended to reduce harm to human health and vegetation.

A range of passive and active dust sampling equipment was calibrated in controlled conditions and in the field by Goossens and Offer (9). Gauges measuring horizontal dust flux and vertical deposition were calibrated against a powered isokinetic sampler. A range of absolute efficiencies of the samplers was found; the modified Wilson and Cooke (MWAC) sampler was found to be the most efficient horizontal dust flux sampler, at 75% to above 90% efficiency in wind speeds from 1 – 5 ms⁻¹.

Dust sampled within and near an opencast coal site in South Wales was characterised by Jones et al (10). Dust was collected on polycarbonate filters using active samplers. The dust samples were examined using a range of scanning electron microscopy techniques to determine particle size, shape, mineralogy and
chemical composition. A high proportion of PM$_{10}$ dust originated from diesel vehicle exhaust emissions; it was considered that off-site sources such as road transport contributed to the ambient PM$_{10}$ dust that was sampled. The mass of dust collected was greater within the opencast than beyond due to the increased proportions of coarser (and mainly non-respirable) dust within the site. Coal was a minor component of the dust, between 10 – 20%.

Low-cost active (powered) dust samplers for workplace monitoring are discussed by Kenny et al (11). Porous foam inserts are routinely used as size-selective media for dust sampling; different fractions of dust could be monitored simultaneously by adapting commonly available equipment.

Significant quantities of dust can be generated by bulk handling of materials. Where such activities are spatially concentrated, for example at ports, dust levels can be sufficiently high to adversely affect local air quality. Moreno et al (12) sampled ambient PM$_{10}$ near a major harbour in north-east Spain and used a range of analytical techniques to assess particle size distribution, morphology, mineralogy and chemical composition of dust sampled. The results of the investigation provided an inventory of characteristics that can be used to indicate source provenance of dusts in a range of settings; dust arising from road transport was also assessed.

Deposition of Saharan dust was monitored by O’Hara et al (13) who used dust ‘traps’ to assess dust propagation in a range of environments. The dust traps comprised a shallow circular tray with an Astro-turf inset to reduce dust blow-out. At the end of the study period the samples were returned to the UK for analysis. Dust mass, particle size distribution and bulk mineralogy were determined and analysed in relation to local soils and weather data. Coarse material (greater than 60 µm) was generally locally derived; finer dust had travelled greater distances.

Dust generated by vehicular activities on unmade roads was monitored using sticky samplers by Padgett et al (14). Growth in recreational vehicle use is leading to increased rates of erosion and deterioration of unmade roads. Dust from road surface erosion damages ecological structures and may harm human health. Dust was sampled alongside unsurfaced roads at 2 locations using real-time (active) dust monitors and purpose-made (passive) sticky samplers. The real-time gauges measured concentrations of PM$_{2.5}$ dust; the sticky gauges assessed total dust. Dust levels on the sticky samplers were determined from changes in mass before and after sampling and were expressed as mass per unit area. The authors used a proprietary insect trap solution applied to the base of Petri dishes; unexposed control samples lost small but consistent weights thus results were adjusted accordingly. Most of the dust sampled with the passive samplers was of coarser fractions; finer dust travelled further than coarse dust. The study supported previous estimates of soil erosion from recreational vehicle traffic as approximately 2000 kg ha$^{-1}$ year$^{-1}$.

The light-scattering technique for dust monitoring is discussed by Sharma and Prasad (15). Suspended dust is illuminated by a light source and the intensity of scattering light is measured to indicate the size distribution of the dust. Whilst the theory of assessing particle concentrations in air by this method is well-established various revisions have been applied. The angle of measurement of light scatter in relation to the incident light to an air stream affects the detection sensitivity of equipment that uses this technique. Equipment where the light scatter is measured perpendicular to the light source is easier to construct but is less sensitive than equipment with the sensor at approaching 180°. Consequently it is proposed that such ‘forward angle scattering’ equipment is more suitable for measuring airborne dust than ‘right angle scattering’ devices.
The performance of portable ‘direct-reading’ dust monitoring equipment was tested in controlled conditions by Thorpe and Walsh (16). Direct-reading equipment has many advantages over more established gravimetric equipment as they can provide rapid on-site measurement of dust concentrations, enabling straightforward identification of dust sources and speedy assessment of control measures. However calibration of direct-reading instruments is problematic as this depends on the physical properties of the dust measured. Therefore a controlled assessment of direct-reading dust monitors in relation to gravimetric equipment in standardised conditions was carried out. There was generally a linear relationship between direct-reading instruments to a gravimetric standard method where particle size distribution of the test dust was constant. Monitor response tended to increase as the mass mean particle size increased and with air velocity according to dust type.

Dust deposition in and around quarries is considered by Walton et al (17). Quarries are perceived to be major sources of dust nuisance by regulatory authorities yet other activities such as road transport and agriculture may also cause significant levels of dust generation. Quarry operators should consider: whose dust it is, how much dust there is and what its composition is. Different nuisance dust monitoring methods are discussed and more than three years’ data from 4 co-located frisbee-type deposition gauges and DustScan sticky pad directional gauges at a minerals site in East Anglia are considered. Deposited dust levels varied across the site over the study period and the highest inferred average mass deposited was 122.4 mg m$^{-2}$ day$^{-1}$. The directional data indicated that high levels of dust arose from off-site as well as on-site directions. A correlation exercise found no better than moderate levels of correspondence between dust mass and dust soiling rate; correlation coefficients increased where the numbers of dust sources decreased. It was considered that this was due to increased homogeneity of dust sampled and it was noted that the study indicated that significant amounts of dust can arise from off-site as well as on-site directions. Relationships between wind, rainfall and dust were examined and no strong relationships were found between such environmental factors and dust either in deposition or soiling. Thus it was considered that highly localised factors such as short-term gusting and sporadic rainfall may influence dust events at a site. Dust samples and ‘as dug’ mineral samples were analysed using ICP-AES and relationships between concentrations of abundant elements such as aluminium and iron were examined. It was noted that the Fe:Al ratio of ‘as dug’ mineral was near unity yet in the dust samples the ratio was nearer 1:1.5, indicating that mineral dust from the site was not the primary source of dust sampled. Therefore it was concluded that quarry site operators should treat planning conditions based on non-directional dust mass alone with caution as these may not take off-site sources into account. Correlation between dust deposition and dust flux appears limited, probably due to differences in the properties of dust being sampled. Quarrying can lead to dust generation but as this dust is likely to comprise comminuted rock from a fixed source it should be recognisable in dust samples through geochemical analyses. Directional dust monitoring is appropriate for distinguishing between on-site and off-site dust sources thus to enable proper attribution of dust measured at quarries.
Dust, and dust monitoring, can be considered in terms of ‘health’ and ‘nuisance’. The former includes public and occupational health. The latter is less readily categorised, and there are no standard definitions for nuisance dust.

With regard to public health the National Air Quality Strategy, set out by DETR (18) and Defra (19, 20), has clearly-defined standards for ambient pollutants including PM₁₀; for occupational health the Health and Safety Executive publishes guidance documents setting out workplace exposure limits (WELs) for many dusts as well as standard sampling methodologies (21, 22).

With regard to nuisance dust Section 79 of the Environmental Protection Act 1990 describes ‘statutory nuisance’ as dust or smoke from various processes such as industry which may be considered a health risk or a nuisance and a local authority is empowered to serve an abatement notice if appropriate. However Defra (20) states that the approach to dust nuisance is not ‘standards-based’. The expression relates to a range of effects from the long-term soiling of surfaces to the physical and visual impact of dust clouds, which can be transitory (Quality of Urban Air Review Group, 1996).

Nuisance dust monitoring, either as the development of new methodologies or to validate dispersion models, was the primary focus of the MIST research projects relating to dust monitoring. Health dust was considered, although generally as a secondary issue. However the recent parallel research studies paid considerable attention to finer particulates, such as PM₁₀, either for environmental monitoring or occupational monitoring.

As noted in the MIST research projects (and in the official guidance publications below) standard methods have long been available for monitoring nuisance dust. However these appear to be lacking, as it can be seen from the MIST research projects and parallel studies that a considerable amount of research has been carried out into developing new techniques or refining existing equipment. Consequently in the apparent absence of suitable methods, different dust monitoring methods have been developed, and applied, according to the requirements of the sampling objective.

Therefore it may be considered that until standards for nuisance dust are generally agreed there are limited opportunities for development of standard methods (and the related investment). Where agreed standards
exist, such as for health dust, research appears focused on testing the effectiveness of existing equipment or new applications of the method. The standard (e.g. in this case ‘PM\textsubscript{10}') is not in question. Where standards are not agreed (e.g. ‘nuisance dust’) research and development has been to the methodology – hence the divergence in the types of gauge and equipment that can be used to monitor nuisance dust. Yet the measurements obtained by the different methods are generally not interchangeable and where they are tested against one another (e.g. Walton et al) correlation may be limited. This finding is not surprising, as the directional gauge measures dust flux and the gauge measures fall-out, i.e. ‘not flux’.

It is generally accepted that the British Standard methods for measuring dust deposition and dust flux are of limited value; yet these are promoted in current guidance. The opportunity exists, therefore, to seek acceptable nuisance dust monitoring methods to replace outdated methods.

However as noted above new methods cannot be developed satisfactorily without validating nuisance dust criteria; Brimblecombe and Grossi (3) point out the essential feature of testing public perception to visual nuisance – and that the findings must be reviewed on a regular basis to avoid out-dated criteria being applied. The minerals industry needs reliable criteria as well as measurements for nuisance; these could be investigated and promoted by the industry itself as part of good environmental governance.
5 AREAS FOR FUTURE RESEARCH

A number of areas for future research have been identified as a consequence of this review:

1. Criteria for dust nuisance that can be applied across the minerals industry are required

2. Protocols for nuisance dust monitoring based on perception of nuisance are required

3. Testing public perception to the visual impacts of minerals industry is required

4. Refined sticky pad monitoring, to include particle recognition could be achieved by combining DustScan with Nottingham University’s particle recognition approach; or others such as BGS

5. Methods for directional quantification of PM$_{10}$ (and below) emissions at quarries and the impact of fine dust on local air quality are required to keep pace with environmental and public health concerns

6. Dust characterisation can be developed to better attribute dust sources: particle size, shape, mineralogy and composition – to target particular dust types (e.g. silica sand, asbestiforms)

7. Site-specific dust emission factors based on a range of quarry types should be developed to provide regulators and operators realistic guidelines for potential emissions.
ABSTRACTS FROM RECENT (2000 – 2006) PEER-REVIEWED DUST RESEARCH PUBLICATIONS


The overall aims of this one year project, which was funded by English Heritage through the Aggregates Levy Sustainability Fund, were to propose a methodology for investigating the impact of aggregates extraction and transport on the English historic environment, including monuments, buildings and associated collections in order to inform future work, to contextualise the impact of aggregate extraction on the historic environment and to involve and inform the many different communities affected or interested in this activity. It studied the effects of both quarrying and road and rail transport of aggregates focusing in particular on the impact of dust, noise and vibration.


Annual production of crushed rock aggregates across Europe is currently 3000 million tonnes, a figure which is expected to increase over the next few decades with increasing demand for building material. For geological reasons many sources of aggregates occur in upland areas often within areas of great natural beauty with vulnerable cultural landscapes, archaeological sites and historic buildings. This paper describes research to investigate the physical impacts of extraction and transportation of aggregates on the fragile historic landscapes of England. The impacts of noise, vibration and dust on buildings and the quality of the environment are investigated at two case study sites, representing areas where large aggregate quarries are operating in close proximity to historic villages and landscapes.


This work investigates public perception of the blackening of light coloured stone historic buildings in some European countries. It used on-site questionnaires to explore the perceived lightness of the façades in terms of opinions that the building is dirty or needs cleaning. There was a clear relation between opinions about the dirtiness of a building and views that it should be cleaned. Visitors to buildings found the assignment of colour or a grey scale value to buildings relatively easy despite the fact that they are typically made up of many shades. There was a strong relationship between the perceived lightness of a building and the opinion that it was dirty. This relationship was used to establish potential levels of blackening that may be publicly...
acceptable and propose some aesthetic thresholds. Such thresholds suggest approaches to setting limit values for elemental carbon in the air, such that significant buildings do not become unacceptably discoloured. Developments of this kind contribute to the regulation of non-health aspects of air pollution and aid decision making in the management of significant buildings.


Dust monitoring using sticky pads was popularised in the 1980s. The discolouration caused by dust adhering to white adhesive material was measured with a smoke stain reflectometer. This loss of reflectance was expressed as the percentage effective area coverage (EAC%) per day. EAC% can be used as a measure of nuisance caused by dust. EAC% may also be measured with a hand-held Sticky Pad Reader (SPR). Sticky pads can be mounted on flat or cylindrical surfaces to measure dust by deposition or in flux. An alternative method was developed in the 1990s that measured total dust coverage using computer-based scanning. DustScan used a transparent adhesive film wrapped around a vertical cylinder with magnetic north marked. The sticky pad was sealed with another transparent sheet before scanning at 50 dots per inch (dpi). Dust levels were assessed by comparing the grey-scale values of pixels in the exposed area with an unexposed reference area. Insects and other extraneous material could be ‘masked out’ from the computer analysis. Dust coverage was expressed as percentage absolute area coverage (AAC%). DustScan has subsequently been developed commercially. A limited trial indicated that monitoring periods of 7 – 14 days were preferred to avoid dust saturation of the sticky pad. A method for calculating EAC% has been developed and shown to have a high degree of correspondence with an SPR. A trial for the Minerals Industry Research Organisation (MIRO) made comparisons between DustScan and other dust monitoring methods. Dust nuisance limits based on AAC% and EAC% are proposed.


DustScan is a method of sampling ambient dust. It was developed at the University of Leeds as a low-cost technique for directional nuisance dust monitoring. It is a passive system that uses self-adhesive ‘sticky pad’ collection slides mounted on cylinders to collect dust in flux at quarries, waste facilities, etc. After typically 1 - 2 weeks the sticky pads are sealed with a transparent film then scanned on a flatbed scanner linked to a computer. Directional dust levels are quantified using specific software as Absolute Area Coverage (presence of dust irrespective of colour, AAC%) and Effective Area Coverage (darkness of dust, EAC%). National Air Quality Standards (NAQS) require particular elements in air (e.g. Pb) to be assessed. Concentrations are usually determined using active monitoring equipment where dust, typically at a size convention (e.g. PM$_{10}$), is drawn onto a filter. Such methods may be non-directional and require a power supply. This paper describes the development of methods to characterise DustScan samples using ICP-OES and ICPMS, including determination of indicative elemental mass concentrations in air. Dust is not readily removed from the sticky pads and its mass is low in relation to the substrate. Sample preparation is based on ‘total’ digestion of the dust in using HF and HNO$_3$. Rigorous blank correction is important as some elements are at significant and variable concentrations in the sticky pads themselves. The analytical method has been refined to determine the mass of the mineral residue of the sample after ignition at 550°C. From this, plus duration of sampling and average wind speed, it is possible to estimate average concentrations of specific elements in ambient air by direction.

Demand for increased aggregates extraction combined with ongoing pressure to adhere to existing and future environmental regulatory requirements requires sustained research and investigation into associated particulate emissions. Open pit quarries commonly operate ‘blast and haul’ extraction methods, implying that any increase in production will lead to increases in quarry traffic and hence unpaved haul road particulate emissions. This paper presents an analysis and discussion of experimental data collected during a roadside particulate emission sampling study conducted within a major UK limestone quarry. The particulate samples were collected using a total of six cylindrical adhesive pad type collectors located symmetrically, at equally spaced intervals upwind and downwind of an unpaved truck haul road. A total of three sampling studies were conducted, each representing approximately 1 hour of road activity and between 6 and 8 vehicle passes. The first two sampling periods were conducted on an initially unwetted haul road. The third sampling period was conducted following road wetting by a bowser. The surface characteristics of the haul road surface were obtained by the collection of a series of swept surface material samples. An analysis of these samples collected prior to and during each of the sampling periods established the surface moisture and silt content of the unpaved road surface. Weather data were obtained using a permanently sited metrological station located on a hill above the quarry, together with a portable weather station located upwind of the haul road to providing accurate localized data. The dust samples collected on the adhesive pads were sized using an image analysis (IA) based method. The IA method employed advanced image enhancement functions to characterize the captured particulates in terms of total count, captured mass, particle aspect ratio and size distribution. These characteristics were compared for each collector sample over each of the three sampling periods. The study concluded that the IA method was able to provide a useful and consistent range of sample characteristics, although the limit of the resolution of the sizing of the particulates sampled was found to be approximately 5 µm. It was found that there was minimal variation in the sampled particulate size distribution and aspect ratio up to a collection distance of 29 m from the roadside in the downwind direction. A clear attenuation in the capture of particles was identified in terms of particle count and total captured mass reporting to measured upwind background levels at 29 m from source. The directionality of the particulate concentrations collected on the pads was found to vary significantly. It was concluded that IA offers a viable method for the analysis of samples collected from cylindrical adhesive pad collectors.


The Indian reserve of coking coal is mainly located in the Jharia Coalfield (JCF) of Bharat Coking Coal Ltd. (BCCL). The reserves which are 19 339 Mt, have been exploited intensely over the last 80 yr. Resulting air pollution is increasing in the area due to large-scale opencast (O/C) mining. But no well-defined method of estimating the generation of air pollutants is used due to different mining activities. An investigation has been conducted to evaluate the air pollution due to a large O/C coal project. The mining project under study is one of the largest opencast projects (OCP) of BCCL and the details have been described. Ambient air monitoring stations were chosen considering the dominant wind directions (upwind and downwind) and covering industrial, residential and sensitive zones. The air quality survey was carried out for four seasons and the methodology adopted has been described. The data revealed a high air pollution potential and are in respect of suspended particulate matter (SPM) and respirable particulate matter (RPM) in the project area as
well as in the surrounding locations. Impacts on the air quality have been assessed on the basis of upwind and downwind concentration of air pollutants.


Surface coal mining creates more air pollution problems with respect to dust than underground mining. An investigation was conducted to evaluate the characteristics of the airborne dust created by surface coal mining in the Jharia Coalfield. Work zone air quality monitoring was conducted at six locations, and ambient air quality monitoring was conducted at five locations, for a period of 1 year. Total suspended particulate matter (TSP) concentration was found to be as high as 3,723 µg/m³, respirable particulate matter (PM₁₀) 780 µg/m³, and benzene soluble matter was up to 32% in TSP in work zone air. In ambient air, the average maximum level of TSP was 837 µg/m³, PM₁₀ 170 µg/m³, and benzene soluble matter was up to 30%. Particle size analysis of TSP revealed that they were more respirable in nature and the median diameter was around 20 µm. Work zone air was found to have higher levels of TSP, PM₁₀, and benzene soluble materials than ambient air. Variations in weight percentages for different size particles are discussed on the basis of mining activities. Anionic concentration in TSP was also determined. This paper concludes that more stringent air quality standards should be adopted for coal mining areas and due consideration should be given on particle size distribution of the air-borne dust while designing control equipment.


The efficiency of six aeolian dust samplers was tested via wind tunnel experiments and field measurements. In the wind tunnel, four samplers designed to measure the horizontal dust flux and one sampler designed to measure the vertical dust flux (in the downward direction, i.e., deposition) were calibrated against an isokinetic reference sampler. The horizontal dust flux samplers were: the big spring number eight sampler (BSNE), the modified Wilson and Cooke sampler (MWAC), the suspended sediment trap (SUSTRA), and the wedge dust flux gauge (WDFG). Vertical deposition flux was measured using a marble dust collector (MDCO). A modified Sartorius SM 16711 dust sampler with adjustable flow rate (SARTORIUS) was used as isokinetic reference sampler. In the field experiments, the WDFG was replaced by a Sierra ultra high volume dust sampler (SIERRA). Wind tunnel calibrations were carried out at five wind velocities ranging from 1 to 5 m s⁻¹. Field calibrations were conducted during seven periods of two weeks each. The most efficient samplers are the MWAC and the SIERRA, followed by the BSNE and the SUSTRA. The WDFG is more effective than the BSNE at velocities below 3 m s⁻¹, but its efficiency drops quickly at higher wind speeds. The most recommendable sampler for field measurements is the BSNE, because its efficiency varies only very slightly with wind speed. In the absence of horizontal flux samplers, the MDCO collector can be used as an alternative to assess horizontal dust flux and airborne dust concentration provided the appropriate calibrations are made.


Airborne particulate matter has been collected from within, and proximal to, an opencast coal mine in south
Wales. This work forms the first part of a three year project to collect and characterise, then determine the possible toxicology of airborne particles in the south Wales region. High-resolution Field Emission SEM has shown that the coal mine dusts consist largely of an assemblage of mineral grains and vehicle exhaust particles. SEM-EDX has shown that the mineralogical make-up of the PM$_{10}$ is complex, heterogeneous, and constantly changing. These findings are supported by analytical TEM-EPXMA. However, patterns can be determined relating the mineralogical composition of the airborne particles to collection locations and mining activities within the opencast. At our study opencast, Park Slip West, quartz, which has known health effects, never exceeded 30% of the total collection mass, and average levels were much less. Vehicle exhaust emissions was the largest source in terms of particle numbers. The mass of airborne particulate matter within the pit averaged approximately twice that of outside the pit: importantly however, this higher mass was due to relatively large, and non-respirable, mineral grains. This study demonstrates that the physicochemical and mineralogical characterisation of airborne particles from mining and quarrying is essential to quantify the respirable fraction, and to identify potentially hazardous components within the PM$_{10}$.


Porous polyurethane foams provide a low-cost method for separating dust into health-related fractions in accordance with recognized sampling conventions. A number of dust sampling instruments that make use of foam selectors have been described in recent literature, but practical experiences of using these instruments in real workplaces have not been widely reported. An IOM inhalable dust sampler incorporating a respirable-fraction selector foam was evaluated in a range of industries, for general occupational dust monitoring. The key issues addressed were those that determine the practicability of the instrument, such as limitations on particulate loading, losses or movements of particles during transportation of samples, and equivalence with conventional respirable dust sampling methods. The new sampler was found to be satisfactory in all these respects. The minor problems experienced have been addressed during the design of the production version of the foam cassette, which is available as an accessory for the existing IOM inhalable dust sampler. The key advantage of the new dust sampler is that it measures both inhalable and respirable dust concentrations in a single sample (hence the name: dual-fraction dust sampler). Therefore, it saves both time and money in industries where both inhalable and respirable dust are routinely monitored.


Harbour activities such as loading, unloading and transport of dusty loose materials may be an important source of atmospheric particulate matter (PM). Depending on the materials, the type of operation and the meteorological scenarios, these activities may have an impact on the levels of ambient air PM around harbour areas. Moreover, air quality at harbours may be affected by nearby urban and industrial emissions. The aim of this work is to compile an inventory of the main characteristics (chemical, morphological, mineralogical and grain size parameters) of the bulk cargo materials and of the material emitted during different port operations for possible use as tracers of the fugitive PM emission sources. For all cases, the tracer characteristics determined for each bulk material were also identified in the corresponding PM material emitted. This inventory could assist the harbour authorities to identify the origin of high PM events recorded by air quality monitoring networks in harbour areas, and could also help modellers to predict the
impact of harbour activities on ambient PM levels. The harbour of Tarragona (north-east Spain) was selected for this study given the high volume of solids in bulk handled. To this end, 12 handling operations of selected materials (clinker, phosphate, pyrite ash, Mn mineral, fine Si–Mn, coke (coal), bituminous coal, tapioca, soybean, alfalfa, corn, andalusite) were selected for the characterisation of suspended and deposited PM. In spite of the coarse grain size distribution of these bulk cargo materials, with a very low % in the fraction <10 µm, manipulation of these materials during harbour operations may result in high emissions of PM10 with relatively high levels of potential toxic elements. Furthermore, ambient PM10 in the area with the highest traffic density of the harbour was also sampled and characterised.


North Africa is the largest global source of atmospherically transported desert dust. Advances in satellite technology allow dust plumes to be spatially and temporally monitored, but little is known of near-surface dust deposition, as field-based studies are rare. This paper presents results from a year-long field-based dust monitoring study of three zones across Libya, ranging from the Mediterranean coast to the Sahara desert. Monthly deposition rates are compared with meteorological data, particle size distribution and mineralogy to establish potential source areas. Comparison of annual dust deposition rates with previous studies in North Africa shows that areas of Libya have the highest dust deposition rates on record.


Vehicles traveling on dry, unpaved roads generate copious quantities fugitive dust that contributes to soil erosion, and potentially threatens human health and ecosystems. The purpose of this study was to develop a low-cost technique for monitoring road dust that would enable land managers to estimate soil loss. The “sticky-trap” collectors developed were evaluated at the Turkey Bay off-highway vehicle (OHV) riding area on the Land Between the Lakes National Recreation Area, in western Kentucky. The results showed that the dust plume created by vehicle traffic was heterogeneous: larger particles were in the lower part of the plume and deposited closer to the source, smaller particles were carried higher in the plume and traveled at least 100 m away from the source. Collection of particles parallel to the source was also heterogeneous, suggesting that measurements taken at a single point may not be appropriate for estimating erosion losses. Measurements taken along two trails indicate that when large numbers of riders are present, dust concentrations may reach unhealthful conditions for riders, but that it is unlikely that fugitive dust is harming native vegetation, given frequent rainfall. The study demonstrated that OHV traffic contributes to substantial erosion of roadbeds because of aeolian transport.


The paper briefly describes an electro-optical system for counting of dust particles, which is based on the scattering phenomena. Utilizing the scattering of light by various size particles present in the environment, various particle counting techniques have been developed in order to measure the scattered intensity of light. Light scatters in all directions but much more in the so-called near forward direction 17° off axis, at 163°
from the light source in the visible range. On the basis of two techniques, the right angle and forward angle scattering, opto-mechanical systems have been developed which measure scattered intensity and particulate matter. The forward scattering Nephelometer is more sensitive and therefore is more suitable for pollution monitoring than the right angle scattering Nephelometer. Whereas the right angle scattering Nephelometer has the utility in extremely low concentration in ppb level owing to the excellent light trap efficiency in comparison to forward scattering Nephelometer. In this paper measurement techniques and measurement results associated with design and development of a real time particle analyzer are also discussed.


Three portable direct-reading dust monitors were tested in a recirculating dust tunnel and a calm air dust chamber against a range of industrial dusts with different size distributions to investigate sources of variation in their responses. Responses were found to be linear compared to reference gravimetric respirable samplers over a range of concentrations for a particular particle size distribution. Their calibration factors were dependent on particle size, particle composition and air velocity. If particle size and air velocity do not change significantly then the calibration factor can be applied to the monitor readings to give an accurate measure of dust concentration. The DataRam and HAM, factory calibrated against respirable dust concentration, were found to agree closely, whereas the Microdot gave higher readings, having been factory calibrated against total suspended particulate concentration. The calibration of the DataRam was significantly altered by either contamination of the optics with dust or by cleaning the optics. This was not observed with either the Microdust or HAM, since both monitors include a reference calibration element.


This paper considers the use of depositional and flux dust monitoring at quarry and mineral processing plants with particular reference to a quarry in East Anglia. The findings suggest that arable farming can be a major source of dust, reaching nuisance levels and at times significantly exceeding dust concentrations from properly managed quarry operations. Other adjacent activities including major roads and railways may also contribute considerable quantities of dust at the boundaries of operating sites. Conventional depositional monitoring methods fail to detect such dust movements unless very carefully correlated with meteorological information. Deposition rates should not be used as the basis of nuisance prosecutions. The provenance of dust can be detected by flux monitoring and checked with a range of analytical methods and equipment to assess and fingerprint the chemistry and mineralogy of source materials. Examples of these methods are included in the paper.

A number of official guidance documents have been published since 2000:


Guidance. LAQM.TG (03). DEFRA.

21. Health and Safety Executive (2005). Workplace Exposure Limits: Containing the list of workplace
exposure limits for use with the Control of Substances Hazardous to Health Regulations 2002 (as amended).
HSE Books.

14/3: General methods for sampling and gravimetric analysis of respirable and inhalable dust. HMSO.

Environment Agency, Bristol.

recycled and secondary aggregates production. ODPM.


environmental effects of mineral extraction in England; Annex 1. Dust. ODPM.
PART 4: ON SITE NOISE PREDICTION AND MITIGATION

EXECUTIVE SUMMARY

The current world economic growth has increased the demand for the production of construction, metal and energy minerals that are capital and energy intensive operations. These operations are increasingly required by legislation to adopt measures to minimise and control their environmental footprint in terms of pollutant emissions to land, water and air including noise (Kumar et al., 2006). Consequently, quarries and surface mining operations are faced with the management of on site noise created by the use of large capacity drilling, loading, mobile earth moving machinery and downstream transport and processing plant (Vardhan et al, 2006). The use of such machinery generates different types and levels of noise, which eventually affect the ambient noise environment of the immediate neighbourhood (Pathak et al, 1997).

Several approaches, including the use of natural and engineered solutions together with the adoption of good practice have been employed at different quarry/mine sites to minimize noise emission levels and its effects on the surrounding neighbourhood. This study provides a review of recent national and international research studies concerned with on-site noise prediction, mitigation and best practices to reduce the impact of quarry noise on the immediate environment. It is noted that no noise mitigation research studies have been funded from the MIST programme to date. However, a parallel research project funded by English Heritage (EH-ALSF, 2005) considered the potential environmental impacts of quarry operations on historic heritage, which included an assessment of the potential impacts of noise emissions from quarry operations.

The following areas of potential future research were identified:

- Research focused on the applicability of both conventional and engineered noise control measures in quarries.
- Bench mark case studies are conducted to assess the efficiency of the existing noise control measures currently being used in mine and quarry sites.
- Hybrid noise predictive models should be developed, which account for the complex quarry design and the mobility of noise sources in quarries to improve noise prediction in quarries.
Bench mark field and modelling studies be conducted to assess the applicability and effectiveness of vegetated bunds to attenuate off-site noise at quarry sites.
INTRODUCTION

Surface mining and quarry operations produce a complex noise field that changes with time and is affected by the in-situ changing meteorological conditions ((Pal et al, 2000; Durucan and Korre; 2000). These often excessive levels of noise are encountered due to the large capacity of the extraction, transport and processing machinery used within large and extensive quarry operations. This creates a challenge to quarry operators to design noise and vibration mitigation measures to produce a low-noise and vibration environment for workers (Sensogut and Cinar, 2007). Prolonged exposure of workers to adverse noise and vibration levels may result in permanent or temporary loss of hearing; it can also act as physiological stressor, and result in reduced productivity. Noise also creates of large source of nuisance to the population living or working in the areas surrounding working quarries (Vardhan et al, 2006). The existence of these potential negative noise effects coupled with the need to be compliant with environmental noise regulations requires the quarry management to take the measures necessary to mitigate the noise levels experienced on site.

In recent years, control measures have been developed and applied in different parts of the world to attenuate noise levels emitted from surface mining/quarry operations. A number of these control measures mainly emphasize the engineering control of the major noise sources. However, the applicability of many of these measures is only possible in the planning of a new quarry or the major reconstruction of old quarry workings Pal et al, (2000).

English Heritage has recently sponsored a parallel research project (EH-ALSF, 2005) that has considered the environmental impact on historic heritage, which included an assessment of the potential impacts of on and offsite noise emissions as the result of quarry operations.
Reducing the Environmental Effect of Aggregate Quarrying: Dust, Noise & Vibration
2 NOISE PROPAGATION

NOISE

Sound can simply be considered as any variation in air pressure that is detected by the human ear. The simplest definition of noise is “unwanted sound”. In the context of mining and/or quarry operations, sound (hereafter referred to as noise) is an inevitable consequence of the working of minerals, which becomes environmental noise or noise pollution when it impinges on people outside the site. Noise pollution is human or machine created sound that disrupts the environment. Almost all materials found within a surface mine/quarry environment serve as a media for noise propagation, the degree of contribution being a function of that medium’s physical and chemical properties. A sound field generally originates from a single or multiple sources and propagates at the speed of sound. When it propagates, the sound field transports energy, and the amount transported in a second through $1m^2$ is termed as the intensity of sound which is proportional to the square of the pressure amplitude (Vardhan et al, 2006). Noise level of any location can be measured in terms of sound pressure level (SPL) which changes with time depending on the nature of source. However, in the context of environmental noise, it is expressed in terms of broad band average of A-weighted SPL (Pathak et al, 1997). A technical overview of fundamental noise theory applied to quarries has been conducted by Hepworth Acoustics (www.goodquarry.com). Hepworth Acoustics have recently produced an updated noise data base for quarries on behalf of Defra (Defra, 2006).

Outdoor Noise Propagation

The noise generation source, the path, and the receiver are the three main parameters commonly used to define outdoor noise propagation. The source emits sound power that can be measured in the vicinity of the source. The emitted sound levels diminish as the sound propagates outward along the path from the source to the receiver. Finally, the sound levels from all sources combine at the receiver (Beranek and Ver, 1992). Figure 1 presents a schematic of the mechanisms of outdoor sound/noise propagation. The following general observations can be made regarding the propagation of noise:

- Noise diminishes with distance as it diverges from its source which may be directional
- Atmospheric absorption attenuates the noise along its path
- Ground reflections interfere with the direct noise, causing further attenuation
- Heavily wooded areas provide attenuation as do man-made and natural barriers
- Tree top scattering may sometimes reduce barrier effectiveness
- Vertical gradient of both wind and temperature refract (bend) the noise path up or down causing noise shadow zones which may modify the effectiveness of noise/sound barriers.

The propagation of noise in the quarry environment, or any area close to any surface mining operations is affected by different factors. At the source, the geometrical spread and ground effect are known to have major influence on noise propagation. Whereas air absorption, refraction and scattering by atmospheric turbulence must be taken into account when considering propagation away from the source (Roman, 2006). Penton et al (2002) report that, for relatively short source-receiver distances, meteorology and terrain effects are small hence generally ignored. However, the failure to include meteorological and terrain effects when considering noise impact from large quarry operations may result in a severe over prediction or
underestimation of off-site sound levels. For example during days of major temperature inversions and low cloud cover noise propagation can be accentuated by reflection (Penton et al 2002).

**Sources of quarry noise**

Noise may be generated from several domestic and industrial sources, including such as airports, major roads, surface quarries, forest machinery, cement works chemical and manufacturing plants. This study focuses on the noise that may be generated from quarries or surface mining operations. It has recently been reported that the noise levels encountered from many quarries or surface coal mines are second only to that encountered near to jet engines at airports (Sensogut and Cinar, 2007).

At almost every single part of the extractive and downstream processing stages of a quarry operation some level of noise may be generated. For instance, even in the preparatory stages of a quarry, during the construction of the infrastructure such roads/rails access, site office and processing plants all these activities will contribute to the level of noise generated on-site. The extractive sequences of overburden removal and storage, drilling and blasting, loading and transportation (by dump trucks or conveyor belts) of the quarried minerals to the processing plant will all generate both mobile and static noise sources. The normally static processing plant consisting of the primary crushing and secondary processing of the mineral products will also present a source of noise. Large scale extractive and processing operations can only be economical with the use of high powered diesel earth moving machinery (such as drills, bulldozers, dumpers, shovels etc) and explosives, which will create a potentially high level noise that may be transmitted to the immediate surroundings causing nuisance to near residents. Recent research studies have highlighted that mobile plant, including bulldozers, dumpers, excavators/shovels and front-end loaders and haulage trucks are major noise sources in opencast mines (Vardhan et al, 2006). The chart below summarises the major contributors to on-site quarry/opencast mines noise levels identified by these studies.

**Noise Prediction in Quarries**

The prediction of environmental noise in and around industrial complexes including quarries involves the determination of the normal and peak sound power level of the noise sources, the evaluation of the attenuation factors (e.g. the ground, ambient air conditions and the in pit bench face attenuation) and their combined analysis for a given noise propagation path (Pathak et al, 1998 and 2000). As the environmental noise levels experienced in and around mining complexes are combinations of long-term averages of the various types of noise source, and the actual prevailing propagation conditions over the period being considered, it is important to conduct baseline statistical noise data from existing similar quarry sites before proceeding with a noise prediction exercise. In addition, the sound pressure levels at a potential receiver will fluctuate due to changes in the density, relative humidity, and the temperature of the volume of air in the atmosphere between the source and the receptor. Therefore any noise prediction and control system must also model the complex behaviour of the acoustic waves under a representative range of atmospheric conditions (Pathak et al, 1998).

A review of the recent research literature has shown that, there have been a number of research studies conducted to evaluate optimal methods to predict noise propagation. However, very few studies have focussed on the surface mining and quarrying industries. This could be attributed to the complexity of the types, characteristics and sources of noise levels that are generated within open pit mining operations.

The activity accounting technique (AAT) developed by Pathak et al, (1999) is one of the few noise prediction
models developed recently that have found application within surface mining or quarrying operations. The AAT relies on the identification of the different potential noise emitting activities in the quarry and the determination of their noise duration and frequency spectra for the purpose of noise quality predictions. The AAT methodology may be used without the use of a frequency analysis to determine broad band noise levels. It also claims to work well for the determination of the SPL at specific locations within a specified working zone. A major requirement for the application of this technique is the development of a field verified acoustic database for the various activities involved in the surface mining or the quarry operations (Pathak et al, 1999).

Another noise prediction model applicable to surface mines or quarries is the development of the air attenuation model by Pathak et al (2000) which has been validated by field measurements taken in a working quarry. This model predicts the noise attenuation due to absorption in air and also accounts for both the prevailing temperature and relative humidity conditions in the area. The method also includes the evaluation of the noise ray path curvature directly from long-term experimental wind velocity and temperature data. To make the model more applicable to the quarry environment, a procedure was developed to determine the ray path curvature due to temperature and wind velocity gradient between noise source at the pit bottom and the receiver positions outside the quarry boundary.
3 COMPUTER AIDED NOISE PREDICTION MODELS

The inception and recent exponential growth in digital personal computers have played a significant role in the development of computational models to predict environmental noise propagation and attenuation from industrial complexes. These environmental noise prediction models are used to construct noise assessments as part of an Environmental Impact Assessment study to support the planning application of a new or extension to an existing quarry or surface mining operation. These computer aided noise prediction models, require the user to define the sound power level (SPL) data obtained from previous field measurements obtained from similar items of mobile equipment, fixed processing plant and equipment, transportation (road and rail), blasting, construction (Defra, 2007). This data is input to the models and adjusted where necessary to account for attenuation and other factors. The computer models allow the user to conduct a series of simulations to predict the noise propagation to be expected during the normal extraction and processing activities at a quarry, and to compute the overall maximum noise emission levels experienced at selected sensitive receptor locations internal and external to the quarry boundary across the working day. These predicted emission levels are subsequently used together with measured to assess the potential noise impact throughout the projected quarry life cycle.

SiteNoise™ is a noise modelling software package developed by WS Atkins (Anon, 2007) (Reference place on reference list www.wsanoise.com). The noise propagation and attenuation models used are based on the guidance given in British Standard BS 5228 (Part 1: 1997 'Noise and vibration control on construction and open sites'). Static, mobile on-site and haul roads are the three main sources of noise considered in the BS 5228. SiteNoise™ permits all these three noise sources to be defined and positioned anywhere on a generated terrain map defining the quarry site. The SiteNoise™ noise prediction model simulation require the user to specify the following information:

- Digital map of the site, showing the locations of site activities (i.e. location of static plant, haul roads and mobile activities generating noise).
- Elevation data particularly for all activities taking place above and below ground level.
- Ground topography, especially height of noise barriers, noise control bunds and fences, baffle banks etc.

With the above information well defined and entered correctly, SiteNoise™ is able to perform noise
predictions calculations and create noise level contour maps across and near site, and predict noise pressure levels experienced at specified receiver locations.

SoundPLAN™, is a noise modelling software package developed in Germany by Braunstein & Berndt GmbH that has been written to implement various internationally recognised noise prediction codes (Reference). Supplied with the relevant sound emission data for both mobile and static quarry plant the SoundPLAN™ models generate the predicted noise emission levels across and oof site in the form of SPL contours taking into account such influencing factors as; source sound power levels and location, distance attenuation, ground absorption, air absorption, acoustical shielding methods employed, meteorology as observed by Pathak et al, (1998, 2000).

Another well known and used noise modelling software approved for use by the Australian and New Zealand Environmental Council (ANZEC) is the Environmental noise modelling (ENM) package developed by RTA Technology Pty Ltd (Environment Australia, 1998 and Tonin, 1984). The ENM has been developed based on the three principal noise forecasting models (OCMA, VDI and CONCAWE) used extensively in Europe.

Another useful noise modelling software is the Engineering Noise Control™ (ENC™) software developed by Casual Systems Pty in Australia (Casualsystems, 2007). The ENC software is based on the computational noise prediction models and modelling procedures outlined in Bies and Hansen’s (2003) established noise engineering and control reference text book on engineering noise control. The modelling package offers the additional flexibility to run several site based noise prediction exercises and to plot on same site layout plan. This flexibility helps the user to explore the changing effect produced by varying the location of various noise generating sources to achieve more quickly a desired goal.
4 NOISE CONTROL

Noise can be controlled in several ways however; the effective conventional way to control noise is to devise a strategy that limits both its generation and propagation. Practically, to develop a best solution for noise control would involve three major activities that are very much interconnected. This is illustrated in figure 3.

The first step is to identify and list all the potential noise sources followed by categorisation into either mechanical, aerodynamic noise source etc. The next stage after categorisation is to rank the contributions from each noise source. The ranking process involves establishing the relative contributions from each source to the total noise produced by the process. The dominant sources must be tackled and treated first to achieve effective noise control. It is only when listing, categorisation and ranking of noise has been completed, that noise control techniques can be applied to the remaining noise. Noise control at source, use of silencers (mufflers), enclosures, barriers, vibration isolation and damping are few of the control techniques that are conventionally employed to control noise (www.hse.gov.uk). The application of these methods are discussed in detail in the following sections.

Barriers (Screens)
Noise barriers or screens are materials that are employed or used outdoors to reduce the level of noise from such sources as roads/rail traffic or industrial operations (Fahy, 1998). In other words, noise barrier is any large object that blocks the line of sight between the noise source and the receiver including the ground itself, if it protrudes upwards through the line of sight (Bies and Hansen, 2003). Practically, the performance of barriers depends on such factors as:

- Barrier geometry (height, length and cross-sectional form)
- Presence of sound that matters noise absorbing materials on the barriers
- Aperture size in the barrier
- Form and frequency spectrum of the noise source
- Source and receiver locations relative to the barrier position
- Topographic and acoustic impedance of the ground between the source and receiver positions
- Micro-meteorological conditions, particularly wind speed and direction
- Presence of nearby reflecting/scattering objects (Fahy, 1998).

A common form of barrier is a wall which may be very high or long enough to limit the diffraction of noise over and around it respectively. Bies and Hansen (2003), report that, barrier attenuation can be increased up to 8dB by lining the source with absorptive material to control the noise generated at source before it is propagated. Shimode and Ikawa (1978) observed that, existing buildings may sometimes serve as barrier to noise achieving high attenuation of noise due to the double diffraction experience at the two edges of the building. A similar effect can be achieved by using two thin barriers separated by a gap (Foss, 1979). More practically in quarries, similar results are obtained with the use of earth mounds, with the effective barrier
width being the width of the top of the earth mound. Tree top scattering from vegetative bunds achieve fairly
good noise attenuation results however, they fail to contribute significantly to barrier attenuation, when they
are planted on earth mounds (Bies and Hansen, 2003).

Acoustical barriers are one of the most common and efficient noise control measures in use today (Ming,
2005). This has therefore attracted numerous studies to understand the diffraction of sound around barriers,
to predict their performance and to develop more efficient designs (Watts et al., 1994 and Crombie et
al., 1995). Acoustical barriers are used mostly for the noise mitigation of transportation systems such as
highways, railways, airports etc. (Watts, 1996; May and Osman, 1980). Since the nature of tonal noises is
different from that of traffic noises, the design of a tonal noise barrier is different from that of a traffic noise
barrier. Ming (2005) however, reports the design of a novel absorptive acoustical barrier. The absorptive
acoustical barrier proposed, is for the mitigation of tonal noises based on the principle of the Helmholtz
resonator and its performance has been assessed in situ in a gearbox station of a mining site. Besides being
effective among reflecting barrier and absorbent barrier, it gives a better sound absorption at the tonal
frequencies of interest as well as protects the inside absorption layer from deterioration due to harsh
weather (Ming 2005).

It is an established fact that over flat ground the spectra for single-noise screens have significant marked
differences for propagation over absorbing ground where the screen obstructs surface wave attenuation
over the absorbing ground cover (Peplow, 2006). Quarry/surface mine operations produce noise from
sources that are often contained in open pits at a lower elevation surrounded by an absorbing ground source
defined by the quarry benches. This however makes it quite complex to mitigate the noise generated from
the pit with screens. A recent research study paper by Peplow (2006) presents a new approach to modelling
approach that may be adapted to reflect the complexities that may be encountered in open pit operations.
Although the study was conducted to simulate noise generated from a road traffic environment, the
technology could be extended into quarry environment for noise control. Peplow’s study was an extension
to the phenomenon for screens adjacent to cuttings or dips surrounded by absorbing ground. This study was
based on a numerical model using boundary element techniques that enables the excess attenuation and
insertion loss for various noise barriers and cuttings of complex profile and surface cover to be calculated.
The model was applied to both single-foundation and double-barrier configuration noise barriers. It was
therefore concluded that a short noise barrier located near to a cutting may be more efficient than a taller
barrier located further from a highway cutting. It was however observed that, modifications of noise barrier
designs located near and far from the source in cuttings have little effect on sound attenuation beyond the
barrier foundations. This noise control technology could however be applied to control the propagation of
quarry noise off site that may cause an environmental nuisance to neighbouring communities.

**Mufflers (Silencers)**

Mufflers are devices for reducing the amount of noise emitted by a machine, for instance on internal
combustion engines, the engine exhaust blows out through a muffler or silencer. They are common used
to reduce noise associated with internal combustion engines, high pressure gas/stream vents, compressors,
fans etc and may function in any one or combination of these three ways: They may either suppress the
generation of noise, attenuate an already generated noise or carry/redirect noise away from sensitive
areas (Bies and Hansen, 2003). Mufflers can be dissipative or reactive depending of how their acoustic
performance is determined. A dissipative muffler is one whose acoustical performance is determined by the
presence of sound absorbing material, whereas a reactive mufflers’ acoustical performance is determined
by its geometrical shape (Magrab, 1975). Mufflers are typically installed along the exhaust pipe as part of the exhaust system for an internal combustion engine of a vehicle or stationary machine to reduce to reduce its exhaust noise. They achieve noise reduction or cancellation with a resonating chamber specifically tuned to cause destructive interference leading to noise cancellation. The use of a silencer is prompted by the need to reduce the radiated noise of a source, but in most practical applications, the final selection is based on the trade off between the predicted acoustical performance, mechanical performance, volume/weight and the cost of the resulting system (Beranek, 1992).

**Vibration Isolation**

Vibration isolation involves the physical separation or isolation of an object such as a piece of equipment/machine from the source of vibration is another effective way of ensuring noise reduction in machines. Thus the transmission of vibratory motions or forces from one structure to another is when a relatively flexible element is inserted between the vibratory structures. Bies and Hansen (2003), observed that, for the purpose of noise control, it is very imperative to control all possible structural path of vibration as well as airborne sound.

**Vegetated Bunds**

A recent body of active research effort has focused on the development of vegetated green belts in and around surface mining operations to attenuate ambient air and noise pollution. In addition to their observed effectiveness, vegetative bunds or green belts have become regarded as one of the cheapest and aesthetically pleasing methods of pollution control in the developing countries Pal et al (2000).

Tree planting has proved to be an effective method to check the environmental pollution and maintain the ecological balance of the region. Noise levels are reduced to about 33% around industrial complexes surrounded by tree plantation (Padma et al, 2004).

The use of vegetated belts, including vegetated bunds has received considerable attention due to their effectiveness to control noise. However, much of its applications have focused on road and rail traffic rather than quarry noise control (Tyagi et al, 2006). Several types of tree plantations (vegetation), such as grassland, cultivated areas, green belt of differing width and height have been used to examine noise reduction. Attenborough et al, (2000) observed that, the propagation of sound over an absorbing surface is influenced by the impedance of the surface and the locations of the source and the receiver. This therefore suggests that, the orientation, height and thickness or width of vegetation belt is essential to the percentage of noise reduction achievable.

The application of vegetated bunds for noise reduction has received considerable recent attention in road and railway noise reduction studies. However, similar studies have not been conducted for quarry operations. This can in part be attributed to the topographical disruption caused by surface mine/quarry operations that make it difficult to identify sufficient stretches of land within the quarry boundary that are suitable for tree planting to attenuate noise. In spite of these complexities, a number of recent research studies have focused on the application of vegetated bunds for noise attenuation at surface mining operations. Pal et al (2000), focused on the use of green belts for noise controlling in mining complexes. In this study, the average trend of total noise attenuation (in percentage) at different depths of the green belt was evaluated to compute the minimum desired thickness of green belt for different locations at surface coal mining operations as shown in the Table 1.
Previous studies by Fricke (1984) and Aylor (1972) established that vegetation is only effective to attenuate noise at higher frequencies (i.e. $f>2000\text{Hz}$) due to the absorption of sound energy by the foliage. However, recently Martınez-Sala et al (2006) observed that, vegetation becomes transparent to sound at frequencies lower than $1000\text{Hz}$ and therefore, the impedance of the ground becomes the dominant factor for attenuation. Martınez-Sala et al (2006) also found that noise could be scattered by the leaves and branches of trees rather than absorbed that could produce a significant attenuation of mid frequency noise. It is important to note that vegetation belts in the range of tens of meters thick are required to attain significant noise attenuation Kragh (1981).

Recent research has shown that vegetated green belts can have a significant effect on the efficiency of the noise attenuation. Previous, more fundamental research investigations focused on the use of periodic array of scatterers (cylindrical rods) which have the capacity to inhibit sound transmission due to a periodicity in the density of the area they covered (Martınez-Sala, 1995; Sigalas and Economou, 1996 and Kushwaha, 1997). Subsequent research studies were conducted to assess the influence of such factors as the type of array structure used and the density of scatterers within each array structure (Sanchez-Perez et al 1998 and Caballero et al, 2001). In a more recent research study conducted by Martınez-Sala et al (2006), it was demonstrated that, a belt of trees organised in a periodic array produces peaks of attenuation at low frequencies ($f<500\text{Hz}$) not as a consequence of the ground effect but as a result of the destructive interference of the scattered waves. The results further revealed that with this type of arrangement effects a greater attenuation than that achieved with classic tree belts using less width. It was however emphasized that, future investigations be conducted by varying such factors as the type of array or the species of trees chosen.

Chih-Fang and Der-Lin (2003) investigated the noise reduction effects with 35 evergreen tree belts in which case a map showing the relationship between visibilities together with width was plotted. The map provides some practical suggestions concerning design of tree belts for noise reduction. Chih-Fang and Der-Lin (2005) further examined the effects of noise reduction with six different tree belts. This included Casuarina nana Sieber (ex Spreng), Casuarina equisetifolia, Duranta repens (“Golden leaves”), Ficus microcarpa L.f. (“Golden leaves”), Hibiscus rosa-sinensis, and Hibiscus rosa-sinensis. Visibility, height, and width of the tree belt, height of receiver and noise source, and the distance between noise source and receiver, were the parameters considered in this study. A model demonstrating the order of importance of the five parameters in relation to relative attenuation was developed and transformed into a three dimensionless parameters consisting of receiver and noise source height/tree height ($h'$), distance between noise source and receiver/tree height ($d'$), and belt width/visibility ($m'$). A three-dimensional map of noise reduction by tree belts was formed by plotting the relative attenuation on the coordinate axis of $h'$, $d'$ and $m'$ and curve fitting. This map can be used as guidance in designing three belts for noise reduction in environmental planning.
NOISE MANAGEMENT STRATEGIES

The established noise mitigation or noise management strategy used usually employs the hierarchy of source control, path control, receptor control or a combination of any of these to reduce environmental noise. Source, path and receptor are the three most important parameters that control noise emissions levels, propagation to the immediate environment to cause nuisance. Once, any of these parameters is controlled or eliminated, the emission of noise would either be below ambient levels, or cannot be propagated to affect the immediate surroundings.

Although, all these parameters are important to effectively mitigate or completely eliminate offensive noise levels, source control is usually highly prioritized in most noise control strategies and method. This is because, besides being the most effective form of controlling noise emission levels, source controls mitigate noise by eliminating noise source before it is allowed to emit an offensive noise levels capable of causing environmental nuisance. Source control in noise mitigation is also the easiest to oversee in either static or dynamic operations in a quarry or construction site. Example of on site noise source control measures usually employed are; time constraints which prohibit certain operations during sensitive night time hours, equipment restrictions that limits the type and number of equipment necessary for operations, emission restrictions specifying stringent noise emission limits, method substitution, thus using quieter methods and/or equipment, noise compliance monitoring which involves having technicians on-site to ensure compliance etc.

Ensuring all static and mobile diesel powered equipment have high quality noise mufflers installed.

Path control measures on the other hand are designed and implement only when source control alone is insufficient to avoid noise impact. With the path control, intervening path ways over which quarry or construction noise propagates to sensitive receptors are interrupted with noise barriers, curtains or enclosures. To effectively control noise using this approach, the barriers used must be able to completely block the line of sight between the noise source and the affected receptor. Increased distance between noise source and receptor, where noisy activities are performed farther away from the receptors is another effective way of controlling noise propagation.

Receptor control measures which are usually the last resort and are designed and implemented when source and path control measures are not feasible or sufficient enough to mitigate noise emission to acceptable limits. This is because; they normally involve having to relocate either the operations causing the noise emissions or the affected receptor.

It should be noted that the use of bunds, acoustic walls and new trees may have a major impact on the
Historic Environment as these strategies may destroy archaeological evidence and hence the application of the usual impact assessment and mitigation methods would have to be employed as part of the planning process.

Different quarries and open cast mining sites will implement different site specific strategies to abate noise emissions from their operations, but all will follow the hierarchical source, path or receptor control strategy. The following section focuses on a review of noise control and mitigation measures that have been employed in quarries, open cast mines and construction sites supported with case studies.
6 NOISE CONTROL MEASURES IN QUARRIES, MINES & CONSTRUCTION SITES

As mentioned earlier, all the notable noise emission sources in quarries and construction sites can be categorized as being emitted from; mobile equipment, fixed processing plant and equipment, transportation (road and rail), blasting and construction.

Fixed and Mobile Heavy Duty Machinery
Heavy earth moving machinery (HEMM) such as bulldozers, dump trucks, front end loaders, drills, shovels/excavators and compressors are the equipment that falls under this category. A review of literature reveals that this class of equipment are some of the major noise sources in quarry operations, mines and construction sites. Various forms of control techniques have been employed to reduce if not eliminate the noise from HEMM. The installation of windshield, engine exhaust mufflers and sound absorption material has been reported in several literatures as being effective for reducing dozer related noise (Daniel et al, 1979, Barthalomae and Bobick 1983 and Vardhan, 2006). The use of noise reduction kits, properly designed silencers and fitting of noise absorbent acoustical panelling to the sides of engine compartments and to the radiator of cooling fans has also been reported to achieve reasonable noise reduction in HEMM (Tomlinson, 1985). Turner (1986) reports a noise reduction of about 8 dB with exhaust silencers and noise absorbent damped panels around engines. This technology was later used by Mukherjee (1987) retrofitted to the engines of dozers that resulted in a reported noise reduction away from the dozer. The use of exhaust silencers and fitting acoustical panels to the rear of dump trucks has been reported to reduce noise level (Mukhopadhyaya and Dey 1998 and 1999). A noise reduction of about 11 dB has been achieved on dump trucks with the use of damping sheet, sound barriers materials and acoustically absorptive materials at the engine bulkhead, floor panels and cab interior respectively (HSE, 1995). The HSE (1995) also document noise reduction of about 14 dB when the beds of dump trucks are lined with abrasion-resistant rubber whereas about 15 dB noise reduction is expected when crushing bins are lined with abrasion-resistant rubber.

Workshops and Processing Plants
Hammering, riveting, pneumatic chipping, scaling, grinding which are the typical operations in quarry and surface mine workshops are minor sources of noise that combine to generate high level of noise on site. Vardhan et al (2006), reports that the impact of the arm/piston, the impact of chisel on casting, expelled air and work piece resonance are the sources of noise from pneumatic chipping. Such noise sources could be reduced by 15dB (A) through the use of either internal damping methods or constrained layer treatment. The study also reports that mufflers could be used to effectively reduce air-exhaust noise with an acoustically treated booth being effective to in containing noise around the work area (Vardhan et al, 2006). Baffles of
sound absorbent materials hung from the roof girders has been reported to reduce noise reflections in workshops (Vardhan et al. 2006 and NIOSH, 2007). Acoustical curtains and fibreglass blanket isolating has been used to isolate high noise areas (NIOSH, 2007).

Processing and screening plants on the other hand has been identified as one of the major sources on noise on quarry and surface mine sites (Vardhan et al. 2006). Typically noise is created in processing and screening plants by the diesel engines which create the hydraulic pressure, material impacting metal hoppers, chutes and screen decks. Crushers also generate considerable from the impact of the jaws/hammers on the materials whereas in screens, the motion of materials across the screen surface can also cause undesired noise levels.

Numerous strategies have been reported to reduce or mitigate noise levels from crushing and screening plants. Among such control measures are: lining chutes with resilient materials (HSE, 1995 and Vardhan 2006), use of acoustically designed booth to contain noise and construction of noise fences and bunds in the line of sight of the noise source and the receptor to prevent noise from propagating beyond the quarry boundaries (HSE, 1995). Installation of energy absorbing resin (EAR) on screens has been reported to achieve noise reduction of about 3dB (A) whereas a noise reduction of 4dB is achieved with the installation of rubber screen cloth on top of screen decks (Vardhan et al. 2006). Moreover, noise reduction of about 15dB (A) magnitude screens has been reported by using hybrid decks consisting of two types of steel which vibrates at different frequencies, so that the vibrations damp one another by being out of phase (Turner, 1986).
7 BEST PRACTICE NOISE CONTROL STRATEGY & CASE STUDIES

In addition to the application of engineering noise control technologies, there are several best practice noise control strategies that have been employed at several quarry and mine sites to reduce noise emission or attenuate the level of noise reaching residential areas. Among such practices are:

- Ensuring adequate separation between operations and residential developments.
- Locating haulage roads sufficient distances from residential areas and with maximum screening by hills and ridges where possible and maintaining roads.
- Minimizing the distance between loading and emptying dragline buckets.
- Using rubber lining in chutes, dumpers, trucks and transfer points (www.goodquarry.com).
- Enclosing high noise producing machinery within acoustic enclosures.
- Constructing earth mounds along or around high noise areas. (Driussi and Jansz, 2006).
- Limiting operating hours - adequate scheduling of the noisiest operations should occur during the day when the impacts are less significant.
- Minimizing the drop height of materials to loading trucks, crusher bins and plants.
- Keeping noise control hoods/shields closed when machines are in operation.

Outlined below are few case studies supporting the above best practice noise control measures.

**Noise Control Scenario-Case Studies**

At the Oberon Quarry in New South Wales, Australia, several noise management techniques were employed from the design stage through the extractive process and the processing operations. The enclosed nature of the open pit design shields the quarry operations and enables mobile equipment to stay in less acoustically screened positions for a shorter period. Moreover, the design also incorporates the use of overburden earth bunds to visually shield the quarry operations from sensitive receptors. The crushing and processing plants were located adjacent to an 8m high wall of undisturbed material together with an additional constructed acoustic bund 2m high and 80m long to attenuate noise from the crushing and processing facilities. The primary and secondary crushers have been located within acoustic screen enclosures to further reduce the noise emissions. The noise associated with transportation is kept low by a constant maintenance of haul roads. Noise associated with drilling has been considerably reduced by use of modern and efficient hydraulic drilling equipment. With the above best practice noise control design measures, construction and operations, it is reported that, negligible noise impact has occurred at the nearby residential locations (Environment Australia, 1998).

The design and implementation of best practice noise control strategy has also been applied to assist the Kalgoorlie Consolidated Gold Mines (KCGM) to operate one of the largest open pit gold mining project in far closer to the residential area of Kalgoorlie-Boulder than would normally be permitted (Environment Australia, 1998 and Driussi and Jansz, 2006). At KCGM, the normal reversing alarm on trucks and mobile
plants were changed to ‘smart alarms’ that adjust to the noise output during reversing to no more than 10 dB (A) above the ambient noise level, making it far less intrusive at night. Another best practice noise control measure implemented successfully at KCGM is the provision of screening around primary crushers and exploration drilling rigs together with construction of earth mounds along and around noise areas. Moreover, a 20m high noise control barrier constructed between the mine and the residential areas has been reported as very effective in reducing noise levels from the KCGM surface operations.
8 CONCLUSIONS

There is no doubt that both construction and quarry/surface mine operations have the potential to generate high levels of noise which if not managed will adversely affect neighbouring communities. Most of the on-site noise sources have been identified in the literature as emanating from the mobile heavy duty extraction and transport machinery and the associated crushing and screening plants deployed for different operations.

During the planning of new surface mine and quarry operations and extension applications, there is a need to incorporate designs that limit at source or include enclosures or barriers to minimise the propagation of on-site generated noise off-site. Thus, the high pit walls/benches, overburden bunds and stockpiles may act as barriers to limit the propagation of noise in favourable weather conditions. However, in the presence of adverse meteorological conditions such as temperature inversions and low cloud cover, the quarry operational layout design may offer limited influence on the attenuation of noise leaving the site or source.

Theoretically different noise control methods are available. However, in practice the choice of noise control methods will be limited depending on the cost, effectiveness and feasibility. Depending on the source type and the magnitude of noise generated different control measures have been used and reported to achieve significant noise reduction. A number of these control measures mainly emphasize engineering control for major noise sources. The common control measures that appear in literature are the use of acoustic barriers, mufflers, vibration isolation and vegetation belt with acoustic barriers and vegetation belts still attracting research attention. However, it is worth noting that, the applicability of most these noise control measures were only possible in the planning of new mines or involving a major redesign of existing surface mine/quarry operations.

The most effective way of reducing on-site noise is either through redesign of equipment if possible and the adoption of best practices that ensure that noise levels are kept to a minimum. The alternative option which may be expensive is to use conventional methods of noise control such as provision of enclosures or acoustic barriers for noisy machinery where possible, relocation of noise source, the fitting of silencers, and the damping of vibratory structures, the construction of earth bunds/fences and the use of vegetated bunds and green belts to attenuate the noise leaving the surface mine/quarry sites.
9 RECOMMENDATIONS FOR FURTHER WORK

Based on the experimental and theoretical research presented in literature shows that, much work has been done to in the area of mechanisms which control the propagation of noise in the atmosphere which has set the foundation for future research studies. However, very little has been done to improve the existing conventional and engineering methods of noise control and its application in the quarry industries.

It is therefore recommended that:

- Research is focused on the applicability of both conventional and engineered noise control measures in quarries.
- Bench mark case studies are conducted to assess the efficiency of the existing noise control measures currently being used in mine and quarry sites.
- Hybrid noise predictive models should be developed, which account for the complex quarry design and the mobility of noise sources in quarries to improve noise prediction in quarries.
- Bench mark field and modelling studies be conducted to assess the applicability and effectiveness of vegetated bunds to attenuate off-site noise at quarry sites.
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Figure 1: Mechanisms of outdoor noise propagation (adapted from Beranek and Ver, 1992)
Figure 2: Classification of noise sources from surface mining/quarry operations (adapted from www.goodquarry.com)
Noise Source/Location | Observed noise level (leq) dB (A) | Permissible noise level, dB (A) | Desired minimum thickness of green belt (m)
--- | --- | --- | ---
Along roads | 75-80 | 65 | 40
In rural settlements | 60-65 | 55 | 30
Near surface mines | 70-80 | 75 | 10
Near processing plants | 80-90 | 75 | 30
Near shaft | 80-87 | 75 | 30
Near mine exhaust fan | 80-87 | 75 | >50

Table 1: Desired minimum thickness of green belts for different locations of coal mining complexes (adapted from Pal et al, 2000)