Ener gy released in an explosion creates an air over pressure, commonly called an air blast, in the form of a propagating wave. If the receiver is close enough to the blast, the overpressure can be felt as a pressure front as the airblast passes. The accompanying booming sound lasts for only a few seconds. The explosive charges used in mining, quarrying and mass grading are typically wholly contained in the ground, resulting in an airblast with a frequency content below about 250Hz.

Airblast is properly measured and described as a linear peak air overpressure (ie an increase above atmospheric pressure). Modern blast-monitoring equipment is also capable of measuring peak overpressure data in terms of unweighted decibels (dB). Decibels, as used to describe airblast, should not be confused with or compared to dB(A), which are commonly used to describe relatively steady-state noise levels. An airblast with a peak overpressure of 130dB can be described as being mildly deafening.

Noise, vibration and airblast are among the most significant issues for communities located near mining/quarrying projects. 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.

**Generation of airblast**

Four sources of airblast have been identified:

- Air pressure pulse (APP): Where rock is thrown or cast from the face, a pressure pulse is created with amplitudes proportional to the initial face velocity. Frequencies are low because the rock face acts like a very large woofer. When an explosive charge in a vertical hole is fired towards a free vertical face, the resulting airblast levels are greater in front of the blast face than behind it, due to the shielding effect of the face.

- Rock pressure pulse (RPP): Vibrating ground near the monitoring location is also a sound source. Here the ground acts like an even larger woofer; however the amplitude of motion (vertical in this case) is much lower. Far more serious and controllable, in principal, is the premature release of explosive energy or breaks-outs. This can occur from two places.

- Stemming release pulse (SRP): This occurs from the bench top through ineffective stemming or holes that have been loaded too high. If stemming is insufficient there will be premature escape of gases into the atmosphere that will produce excessive airblast.

- Gas release pulse (GRP): This mechanism originates from the bench face through voids, fissures, insufficient burden, overloaded holes etc and can influence airblast over two orders of magnitude. Numerous formulae have been suggested to calculate the burden, which take into account one or more of the indicated parameters, however all the values lie in the range 25–40 x blasthole diameter, depending fundamentally upon the properties of the rock mass.

**Propagation of airblast**

As with ground vibration, airblast decays with distance because of geometric spreading. This is the mechanism whereby a finite amount of energy fills an increasing volume of space. Airblast waves travel in a fluid medium that does not transmit shear forces, making them simpler than ground vibrations. However, sound propagation, including airblast, is subject to weather conditions that can create irregular and sometimes anomalous events. Temperature inversions can refract waves back to the ground producing areas of airblast focus. An inversion can increase airblast by 10dB over the level normally expected from a given blast at a given distance. Winds enhance propagation by bending wave fronts down towards the ground and reduce the normal rate of airblast decay. A 16km/h wind blowing directly towards a site can increase airblast by 8–10dB above normal.

Weather influences on airblast propagation

When explosives are detonated in blastholes the air vibration travels as a wave front outwards in all directions from the blast at the speed of sound. The speed of sound in air increases with temperature, humidity and pressure.

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of the wave front is affected by wind (speed and direction) and by atmospheric temperature. The effect of wind velocity and air temperature can be demonstrated if the wave front is considered as a series of sound rays radiating out from the blast and perpendicular to the wave front. Among these influences, temperature inversions and wind direction and strength are significant. Both of these conditions can increase airblast above the level that would normally be expected in their absence at a given scaled distance. They do not produce additional airblast energy but they do affect its distribution. With temperature inversion warm air overlies cooler air. This is the reverse of the normal situation of steadily falling temperature with altitude. Under normal conditions airblast ray paths are bent away from the earth’s surface by the process of acoustic refraction. By contrast, when an inversion exists these rays are bent downwards in the inversion layer and can produce one or more focus points at large distances from the blast. A focus location is an area with abnormally high airblast and a relatively silent zone between it and the source.

Temperature inversions are common in the morning and evening, as the ground surface and air get warmer and cooler at different rates. One of the reasons why some surface mines tend to blast near the middle of the day is to avoid this type of inversion. Nevertheless, it is common blasting practice not to consider temperature or humidity effects on airblast levels. Wind is another significant weather influence on airblast propagation. Examples of wind effects include a 10–15dB increase in sound level downwind compared with levels in cross- or no-wind conditions for close-in quarry blasts, and a change in the propagation decay exponent proportional to wind velocity.

**Effects of airblast on structures**

As with ground vibrations, airblasts can produce structure rattling and, in extreme cases, cracking and other damage. In contrast to ground vibration, airblast is relatively ineffective at producing whole-structure or racking-type responses in small structures such as homes. In terms of rattling response, an airblast of about 145dB is equivalent to a ground vibration of about 12.7mm/s in the structure resonance range of 4–12Hz. Few blasts reach this level. Mid-wall responses are another issue, being about six times higher than rattling responses for a given overpressure.

Mid-wall responses produce much of the secondary rattling noise and other observed effects, such as movement of pictures, clocks etc. Although not significant in terms of structural risk, these situations result in much of the perceptible noise and homeowners are often concerned that something serious and dangerous could happen to their homes. These responses also contribute to glass breakage as the initial indicators of excessive airblast. Most of the studies reported by Siskind et al. concluded that an impulsive-event sound level of 140dB represents a reasonable threshold for glass or plaster damage. A similar value is proposed by Pompetzki, whereby he equates the German threshold for glass or plaster damage of 0.6 kN/m², according to DIN 1055 (4), with a maximum level of 143dB.

**Human response to airblast**

Human response to blast vibration and airblast is difficult to quantify. Vibration and airblast can be felt or heard well below the levels that result in damage to structures. Again, the primary concern is the apprehension that damage could be occurring, which is fuelled by structural responses, as noticed by the people in their homes. Complaints from the general public about blasting almost always involve persons experiencing the vibration while in their homes rather than outside. Consequently, they are actually responding to structural motions that create rattling and rumbling noises. In reality, people often do not feel the direct ground vibration and sometimes do not even hear the direct airblast. The airblast arrives after the initial ground vibration (about 1s later over 300m of source-to-receiver distance). It is evident from figure 1 that the airblast was received by the seismograph about 1s after the arrival of the ground vibration.

A distant blast might produce a noticeable airblast response even though the airblast amplitude may be relatively low. This airblast is likely to be of very low frequency with little energy above 5Hz because the atmosphere selectively attenuates the higher frequencies. Persons inside a house may not hear or notice the direct sound. However, if a house has a natural frequency near 5Hz it will respond to the airblast and produce higher frequency secondary noise (rattling). The occupants, not hearing the direct sound, will attribute the rattling to ground vibrations. They do not realize that the low-level ground vibration arrived unnoticed several seconds earlier.
the case in fig. 1). Only in the case of near immission points and weak damping through the ground can direct ground vibration play a dominant role in blast perception.

Studies have shown that fewer blasts of longer duration will produce a less adverse human response than short blasts that occur more often. Table 1 summarizes the average human response to vibration and airblast that may be anticipated when a person is at rest in quiet surroundings. If the person is engaged in any type of physical activity, the level required for the responses indicated is increased considerably. At one extreme, there are those people who receive some tangible benefit from the blasting operation and probably would not be disturbed by any level of vibration and airblast, as long as it does not damage their property. At the opposite extreme there are people who would be disturbed by even barely detectable vibration or airblast levels.

**Threshold limit of airblast**

Conventional noise criteria (for steady-state noise sources) and limits established for repetitive impulsive noise (such as for shooting ranges) do not apply to air overpressure from blasting. The US Bureau of Mines’ RI 8485 and the regulations issued by the US Office of Surface Mining and Reclamation Enforcement specify a safe overpressure of 133dB for impulsive airblast when recording the signal is reduced to the maximum amplitude, commonly expressed in peak pressure level (Pa or dB). In this paper, overpressures in dB are directly calculated from Pa values and hence include no time weighting. Peak amplitude can be compared either directly or after scaling the most influential parameters, namely ‘charge weight per delay’ and ‘distance to the blast’. The scaled-distance concept assumes an attenuation relationship (ie cube-root scaling for blast noise) between the weight of explosives per delay and the distance from the blast to the monitoring location. An air-transmission constant describes the transmission behaviour over decades, the scaled-distance concept has been proven to be a valid and generally applicable approach. The general equation can be used to predict sound pressure levels based on the known distance and blast design, or to evaluate a set of blast-monitoring data by comparing the air transmission factor. Air vibration levels have commonly been assessed using the following cube-root scaling law:

$$ P = K \times \left( \frac{R}{Q_{\text{max}}} \right)^b $$

where:
- $P$ = Air overpressure (Pa)
- $R$ = Distance from the closest blasthole to the monitoring site (m)
- $Q_{\text{max}}$ = Maximum explosives weight per delay (kg)
- $K$ = Air-transmission constant
- $b$ = Site-specific regression exponent

**Experimental studies**

Field experiments were conducted at five limestone quarries in India. The explosives used in most of the quarries comprised ammonium nitrate with fuel oil. Initiation was by a conventional detonating cord system. Brief details of the experimental trials are discussed below.

**Sagmania limestone mine**

Satna Cement Works’ Sagmania limestone mine has working benches in two quarries (A and C). The mine produces 7,500 tons/day to cope with the demands of the cement plant, with production achieved through drilling and blasting. The limestone deposits in the mine are horizontal to sub-horizontal with dips varying from 2° to 5°. In the eastern part of the mine the deposit is massively exposed, whereas in the western part it has been affected by weathering. Two sets of joints are encountered together with bedding planes; these are filled with clay ranging from 5cm to 20cm in thickness. A prominent bedding plane occurring 2.0–2.5m below the top bench required special attention with regard to fragmentation.

In quarry A, 16 blasts were conducted. The average burden and spacing were 4.0m and 5.0m respectively. The hole depths ranged between 7.0m and 8.0m, top stemming was 3.5–4.0m and the drill-hole diameter was 110mm. The weight of explosives detonated varied between 265kg and 2,322kg and the weight per delay ranged from 54kg to 386kg. The monitoring distances varied between 200m and 500m.

Similarly, in quarry C, 14 blasts were conducted. The average burden and spacing were 4.0m and 5.0m respectively. The hole depths varied between 9.0m and 10.0m and the drillhole diameter was 160mm. The weight of explosives detonated in a blast ranged between 700kg and 2,406kg and the weight detonated in a giant blast varied from 2,355kg to 4,700kg.

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**Table 1. Human response to airblast and ground vibration from blasting**

<table>
<thead>
<tr>
<th>Response</th>
<th>Ground vibration range, mm/s</th>
<th>Airblast range, dB lin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barely perceptible to distinctly perceptible</td>
<td>0.5–2.5</td>
<td>50–70</td>
</tr>
<tr>
<td>Distinctly perceptible to strongly perceptible</td>
<td>2.5–12.7</td>
<td>70–90</td>
</tr>
<tr>
<td>Strongly perceptible to mildly unpleasant</td>
<td>12.7–25.4</td>
<td>90–120</td>
</tr>
<tr>
<td>Mildly unpleasant to distinctly unpleasant</td>
<td>25.4–50.8</td>
<td>120–140</td>
</tr>
<tr>
<td>Distinctly unpleasant to intolerable</td>
<td>50.8–254.0</td>
<td>140–170</td>
</tr>
</tbody>
</table>
weight of explosives detonated in a plaster shooting round ranged from 25kg to 125kg. The monitoring points were near important structures and varied between 600m and 1,000m.

**Babarkot limestone mine**

At Narmada Cement Co. Ltd’s Babarkot limestone mine in the state of Gujarat, two thin bands of lateritic rock occur between Deccan trap and Tertiary sediments. Overlying the laterite are the Gaj beds (marine sediments) comprising fossiliferous yellow marly limestone with clay. Above the Gaj beds are thin beds of arenaceous limestone and clay known as the Dwarka beds.

Six blasts were conducted with an average burden and spacing of 3.0m and 4.0m respectively. Hole depths were between 7.5m and 8.5m, the drill diameter was 105mm and the collar stemming was 2.3–2.5m. The weight of explosives detonated ranged from 20kg to 2,880kg and the weight per delay ranged from 20kg to 345kg. The air overpressure monitoring stations ranged from 50m to 250m. The regression plot of data is depicted in figure 4.

**Langiberna limestone mine**

In M/s Orissa Cement Ltd’s Langiberna limestone mine in Orissa state there are two almost parallel bands of limestone running east–west separated by a band of dolomitic limestone about 200–300m wide. The southern limestone band is 100–200m wide and fairly steeply dipping (60–85°). The northern band is 300–400m wide and dips more gently (25–40°). The quality in the southern band is generally good; the limestone here appears to have been less affected by metamorphism/replacement and has a higher carbonate content.

Seventeen blasts were conducted with explosives ranging in weight from 30kg to 1,240kg, with the weight per delay ranging from 22kg to 338kg. The burden was 2.2–3.5m and the spacing was 2.5–3.8m. Hole depths ranged from 4.0m to 9.0m with a diameter of 115mm. The monitoring points ranged from 50m to 580m. The regression plot of recorded air overpressure data is shown in figure 5.
Khatkurbahal limestone quarry

Khatkurbahal is a semi-mechanized limestone quarry of M/s Shiva Cement Ltd in Orissa state. The area is part of the Archean Complex of Precambrian age and comprises deformed meta-sediments including limestone, dolomite, sandstone, quartzite and quartz-mica schist. These have been thrown into an easterly plunging synclinorium with both the northern and southern limbs inverted in places. The rocks exhibit dips ranging from 25° to 85° towards both the north and south.

Holes were drilled by jackhammers to depths of 1.5–2.5m. The burden and spacing were 0.6m and 1.4m respectively. The collar stemming ranged from 1.0m to 1.5m. The explosives were detonated instantaneously and ranged between 5kg and 12.5kg in weight. The air overpressure monitoring stations were close to the quarry at between 50m and 240m. The regression plot of recorded air overpressure data is shown in figure 6.

Results and analysis

It was observed that all the mechanized quarries generated higher air overpressure. If the measurements had been made near the blast site, the magnitude would have been higher. The maximum air overpressure recorded at each quarry is shown in table 2. The corresponding blast-design parameters and weight of explosives detonated are also shown in the table. It is evident from the table that the maximum air overpressure of 146dB was recorded at Babarkot quarry at 120m from the blast site when 120kg of explosives were detonated in a delay, whereas at Sagmania quarry C the maximum air overpressure recorded was 142dB at 115m from the blast face when 726kg of explosives were detonated in a delay. Higher air overpressure was recorded at Babarkot due to the wind effect (the quarry is situated near the coast of the Arabian Sea where high wind velocities often increase blast air overpressure). Another blast at Babarkot was performed with 990kg of explosives and a greater weight per delay of 192kg. The air overpressure recorded at 120m was 135dB. However, at the time of this blast the wind velocity was lower, indicating that wind has

<table>
<thead>
<tr>
<th>Quarry</th>
<th>Burden, m</th>
<th>Spacing, m</th>
<th>Hole depth, m</th>
<th>Collar stemming, m</th>
<th>Explosives detonated, kg</th>
<th>Explosives weight per delay, kg</th>
<th>Monitoring station from blast, m</th>
<th>Air blast, dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sagmania A</td>
<td>4</td>
<td>5</td>
<td>8</td>
<td>3.5</td>
<td>1,178</td>
<td>340</td>
<td>204</td>
<td>137</td>
</tr>
<tr>
<td>Sagmania C</td>
<td>4.2</td>
<td>5.1</td>
<td>9.5</td>
<td>3.2</td>
<td>2,406</td>
<td>726</td>
<td>115</td>
<td>142</td>
</tr>
<tr>
<td>Babarkot</td>
<td>2.5</td>
<td>4.0</td>
<td>6.5</td>
<td>2.0</td>
<td>810</td>
<td>120</td>
<td>120</td>
<td>146</td>
</tr>
<tr>
<td>Langiberna</td>
<td>2.5</td>
<td>3.0</td>
<td>5.0</td>
<td>2.0</td>
<td>778</td>
<td>195</td>
<td>110</td>
<td>142</td>
</tr>
<tr>
<td>Khatkurbahal</td>
<td>0.8</td>
<td>1.3</td>
<td>1.6</td>
<td>0.8</td>
<td>12.3</td>
<td>12.3</td>
<td>50</td>
<td>133</td>
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<tr>
<td>Plaster</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>shootings</td>
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<td></td>
<td></td>
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</tr>
</tbody>
</table>

Table 2. The maximum air overpressures recorded together with the respective blast-design details.
Drilling, Blasting & Breaking

Fig. 7. FFT analysis of vibration and air overpressure event recorded at Sagmania limestone quarry

an enhancing effect on air overpressure. The frequencies of the vibration were in the range 10–40Hz, whereas the frequencies of air overpressure varied between 3Hz and 74Hz. The FFT analysis of a blast event is shown in figure 7.

The air overpressure data recorded in the quarries are grouped together for statistical analysis. The best-fit empirical equations have been established for the quarries, correlating the explosives weight in a delay (Q max in kg), the distance of the monitoring station from the closest blasthole (R in metres) and recorded air overpressure. The predictor equations for each upper bound of the 95% prediction interval are given in table 3.

The prediction of air overpressure can be made with the help of the predictor equations given in table 3 for various distances for the respective quarries. The safe air overpressure of 133dB recommended by the US Bureau of Mines has been taken as the threshold limit and the explosives weight per delay has been computed for each quarry for various distances that will meet the threshold limit of 133dB, as shown in table 4. If the higher threshold of 143dB derived by Pompetzki had been used, the explosives weight values in table 3 would increase by a factor of \( \sqrt{1000} \), which is, for example, 6.9 for Sagmania quarry A.

Predicted charge weight per delay indicated that the range of monitoring of data in the field influences the predictability of the equations. As the charge weight per delay in Khatkurbahal quarry was very low and monitoring stations were very near, the equation prediction at smaller distances is very much in agreement with the recorded data but is not applicable for longer distances. Similarly, at Sagmania quarry A and Langiberna, the monitoring stations were at shorter distances, so the prediction for shorter distance is in agreement with the recorded data. The recording of data was varied at Sagmania quarry C and Babarkot quarry, so the prediction of air overpressure is more or less in agreement with the recorded data for near as well as longer distances. It is concluded that, for reliable prediction of air overpressure at the distances concerned, the number of air overpressure data to be recorded should be greater and at a range of varying distances.

The plaster shooting generated too much air overpressure at Sagmania quarry C. It is predicted from regression analysis that even some 6kg of explosives detonated for plaster shooting may generate 133dB of air overpressure at 500m. Air overpressure of about 140dB may be anticipated 1,000m from the detonation of 100kg of explosive for rock breakage by plaster shooting. The quarry operators should therefore think about changing the practice of plaster shooting. The rock breaker may be used for breaking boulders, or pop shootings may be performed with suitable precautions for flyrock.

Conclusions and recommendations

The mechanisms relating to airblast generation also suggest means to control airblast. Sufficient burden to ensure good fragmentation and to control flyrock will also help to reduce the air pressure pulse. Where strong face motion is desired, such as in cast blasting, some air pressure pulse is inevitable. Voids, mud seams and fissures should be stemmed through. Explosives should be weighted to avoid overloading the holes. Burdens should be carefully controlled with adjustment for fractured, sloping and/or irregular faces. These measures should eliminate or minimize the gas release pulse. Both air pressure pulse and gas release pulse are directional, coming from the front face. Where possible, the bench should be oriented to avoid line-of-sight conditions between the face and critical structures.

Table 3. Established predictor equations for upper bound of 95% prediction interval for the experimental sites

<table>
<thead>
<tr>
<th>Quarry</th>
<th>Propagation equation</th>
<th>Correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sagmania A</td>
<td>( \frac{R}{\sqrt{Q_{max}}} )</td>
<td>0.798</td>
</tr>
<tr>
<td>Sagmania C</td>
<td>( \frac{R}{\sqrt{Q_{max}}} )</td>
<td>0.762</td>
</tr>
<tr>
<td>Babarkot</td>
<td>( \frac{R}{\sqrt{Q_{max}}} )</td>
<td>0.84</td>
</tr>
<tr>
<td>Langiberna</td>
<td>( \frac{R}{\sqrt{Q_{max}}} )</td>
<td>0.771</td>
</tr>
<tr>
<td>Khatkurbahal</td>
<td>( \frac{R}{\sqrt{Q_{max}}} )</td>
<td>0.836</td>
</tr>
</tbody>
</table>
Drilling, Blasting & Breaking

Airblast off the bench top is created by uplift and, more seriously, by failure of the stemming. Measures may need to be taken to obtain suitable stemming material to contain the explosive during detonation. This may mean something better than drill cuttings as well as eliminating exposed detonating cord. If explosive detonating cord is to be used to detonate the blastholes, it should be covered with suitable aggregate material. It is always advisable to use a Nonel initiation device to help reduce airblast generation.

As is the case with ground vibration, the selection and use of delays can strongly influence the airblast, because sound in air propagates much more slowly than ground vibration (at approx. 330m/s). The effective delay interval can directly superimpose and reinforce air overpressure. Correction of normal delays for travel time differences for different holes is most important. Too short an effective delay interval should be avoided.

Wherever possible blasting should be confined to midday to minimize the noise-enhancing effects of temperature inversions, and avoided entirely when the wind speed is too high.

Table 4. The predicted explosives weight per delay (in kg) detonated in a blast that will generate air overpressure of 133dB at the distances shown at respective quarries

<table>
<thead>
<tr>
<th></th>
<th>50m</th>
<th>100m</th>
<th>150m</th>
<th>200m</th>
<th>250m</th>
<th>300m</th>
<th>350m</th>
<th>400m</th>
<th>500m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sagmania A</td>
<td>1.73</td>
<td>13.90</td>
<td>46.80</td>
<td>111.00</td>
<td>217.00</td>
<td>374.00</td>
<td>594.00</td>
<td>887.00</td>
<td>1,733.00</td>
</tr>
<tr>
<td>Sagmania C</td>
<td>0.76</td>
<td>6.08</td>
<td>20.50</td>
<td>48.70</td>
<td>95.10</td>
<td>164.00</td>
<td>261.00</td>
<td>389.00</td>
<td>761.00</td>
</tr>
<tr>
<td>Babarkot</td>
<td>0.88</td>
<td>7.07</td>
<td>23.80</td>
<td>56.50</td>
<td>110.00</td>
<td>191.00</td>
<td>303.00</td>
<td>452.00</td>
<td>883.00</td>
</tr>
<tr>
<td>Langiberna</td>
<td>1.15</td>
<td>9.18</td>
<td>31.00</td>
<td>73.40</td>
<td>143.00</td>
<td>248.00</td>
<td>394.00</td>
<td>587.00</td>
<td>1,147.00</td>
</tr>
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<td>Khaskurbahal</td>
<td>7.28</td>
<td>58.20</td>
<td>197.00</td>
<td>340.00</td>
<td>910.00</td>
<td>1,148.00</td>
<td>2,497.00</td>
<td>2,722.00</td>
<td>3,316.00</td>
</tr>
<tr>
<td>Plaster shootings</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.394</td>
<td>0.77</td>
<td>1.33</td>
<td>2.11</td>
<td>3.15</td>
<td>6.16</td>
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References