The detection of blast damage by borehole pressure measurement

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Synopsis

The technique reported here involves measuring the air pressures generated within sealed boreholes located behind blasts. Results from twelve free face blasts in competent rock environments are presented. There were no instances of high pressure gas penetration, even at distances corresponding to less than one blast burden. Rapidly generated underpressures were measured in most holes, with the magnitudes of the peak pressures decreasing with distance behind the blasts. It has been proposed that the underpressures are the result of new volume created due to crack formation and overall rock mass dilation. The experimental evidence is consistent with this, including a correspondence of the onset times of the peak underpressures with the nominal firing times of the nearest blastholes. New post-blast cracks were observed when using borehole video cameras in the monitoring holes.

A calculation of new volume produced within the monitoring holes is proposed as an indicator of damage. While the data exhibit considerable scatter, there is a power function dependence on scaled distance, which resembles that of typical vibration data. The data also lie within the normally quoted vibration regimes for rock damage and are consistent with measured extents of damage. It is concluded that this technique may provide an inexpensive and practical comparative measure of near-field rock damage due to blasting. It is further concluded that gas penetration is not a common phenomenon. Damage appears to be mainly attributable to the nearest blastholes and the control of charge mass in perimeter blastholes is emphasized for damage minimization.

Introduction

The measurement of blast damage is important to enable the control of blast damage and ultimately the refinement of blast design for damage minimization. Due to the complexity and expense associated with most damage measurement techniques, for example cross-hole seismic techniques, their use has usually been limited to specific case studies[1,2]. For more routine use, vibration measurements are often used and the damage is inferred based on various models or criteria for rock damage[3].

Experience of measuring close to the perimeter of blasts has shown that various practical considerations may affect several of these techniques. For example, techniques that rely on the presence of boreholes, such as borehole video cameras or cross-hole seismics, may suffer from the loss of borehole integrity after the blast. It is quite common for boreholes within about one burden of a blast, (often the region of most interest when damage for the purposes of wall control is under consideration), to be partially closed or blocked, or at least deformed, after a blast. Furthermore, such holes are usually intersected by open cracks and will not hold water to enable coupling of transducers or sensors for cross-hole seismic purposes. Extensometers have been used with success to indicate rock dilation,[4,5] however they do not provide dynamic data and problems have been encountered with anchoring the instruments adequately to withstand violent and rapid motion[1]. Vibration measurements are often used, however at close proximity to a blast there is the risk of damage to the transducers, which may be expensive accelerometer arrays or the like[1].

The technique forming the basis of this work involves dynamic borehole pressure measurement and has been described previously[4,6,7,8]. Essentially, the pressures generated in the air chambers inside sealed boreholes, located in an array behind the blast, are measured.

This paper presents results obtained with this method over the past three years and suggests an interpretation of the results. It is proposed that the technique may be considered to provide a useful, practical and relatively inexpensive indication of blast damage, at least for comparative purposes. It does not suffer from the above-mentioned drawbacks as the measurement is a dynamic one which does not rely on borehole integrity after the

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blast. Also, the transducers that have been used are inexpensive and may be considered to be disposable. While it is neither a direct measurement of damage nor a highly sophisticated or precise measure, it is nevertheless proposed that it may be used to distinguish gross differences in damage behind different blast designs. Examples might include distinguishing between the damage effects from blasts that have different hole diameters or explosive densities.

Measurement technique

Details of the technique have been described previously[8]. Figure 1 shows a schematic view of the technique employed behind a typical blast. Certain conventions have been adopted, such as drilling the monitoring holes to the same depth and at the same inclination as the back row blastholes. Monitoring holes for each blast have been of equal diameter, but have varied between blasts reported in this work. It is, however, recommended that the monitoring hole diameters should be kept equal when using this technique to compare different blast designs. Smaller hole diameters are preferred, with consistent results being obtained from holes in the range 76 mm to 200 mm. Rotary drills are preferable, as the borehole walls are smoother than those obtained with percussion drills. The holes have been drilled on staggered patterns behind the blasts in a range corresponding to one-half to four burden distances. Additional practices have been to avoid locating any two monitoring holes within 3 m of each other in order to minimize interaction between holes. Where water has been present, the depth of water has not exceeded 1 m. It is not known how the presence of water influences the pressure-time profiles, but as it is likely to have some influence it is believed that this factor should be carefully controlled.

Diaphragm type pressure transducers, which had been calibrated to an accuracy of better than five per cent, were used in each monitoring hole. The holes were sealed at a depth of 1,5 m–2 m from the surface, below the level of surface damage or weathering which could render the upper section of rock to be permeable to airflow. This provided airtight chambers within the holes between this horizon and the toe of the blast. Hole sealing was achieved using inflatable airbags. Some drill cuttings were added to ensure that there were no open gaps around the edges of the bags. A multi-channel data capture unit, capable of sampling each channel at 31 kHz, as well as associated analysis software has been developed for this work.

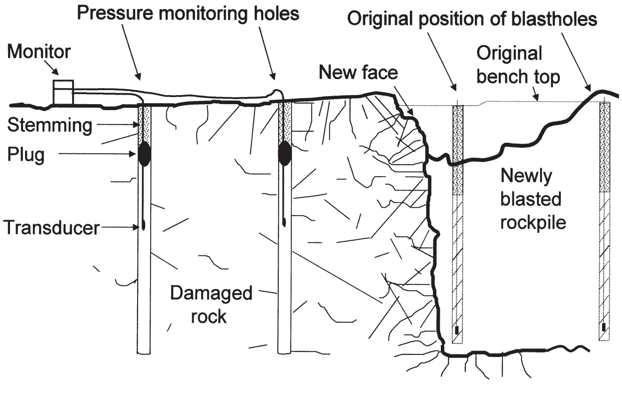

Figure 1—Schematic of borehole pressure monitoring behind a typical blast

Blast monitoring

Six full-scale unmodified production blasts and four modified limits blasts were monitored using the borehole pressure measurement technique. All blasts were fired to a free face and had not been presplit. Additionally, recent results from two single hole blasts fired to a free face located at one normal burden distance have been included. Factors such as rock type, explosive type, blasthole and monitoring hole diameter, powder factor and blasthole pattern dimensions varied considerably, as can be seen from the blast design details shown in Table I.

Results and discussion

The peak pressure data from all the blasts are summarized in Figure 2. All the peak pressures were underpressures, i.e. negative relative to atmosphere. In all of these cases, there was no evidence of high pressure gas penetration, even in holes located at distances corresponding to less than one burden behind the blasts. While gas penetration has previously been detected,[4,6,8] it is not common and appears to occur in situations of unusual blast conditions, such as in presplit blasts, or where open channels or porous seams are present. Furthermore, it is normally preceded by the rapid onset of an initial negative phase[4,6,8]. The current findings clearly show that the region of high pressure gas penetration is quite limited in extent behind most blasts.

The pressure-time traces exhibited a rapid onset to the peak and then a more gradual return to ambient after several seconds. While there were variations in shape, the general form was similar to that reported previously[8]. The magnitude of the peak underpressures decreased with distance, however from Figure 2 it is clear that the wide variety of blast and rock conditions result in a large scatter of all the data when plotted against distance from the nearest blasthole. The underpressures have previously[4,6,8] been attributed to the expansion of the air in the monitoring holes into new volume created by the opening of new or existing cracks or planes of weakness and the overall dilation of the rock mass.

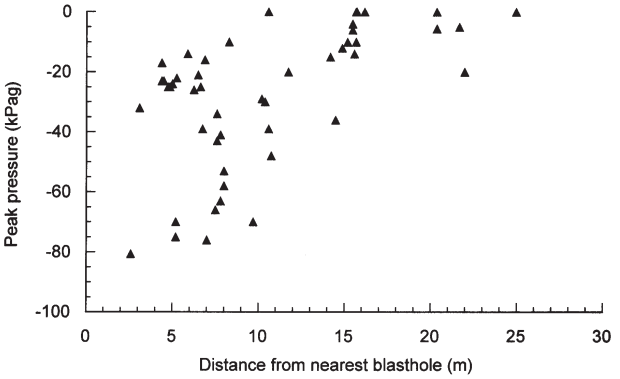

Figure 2—Summarized peak pressure data for blasts 1–12

Table I

Design details of blasts monitored with borehole pressure measurement technique

Blast no.	Blast type	Rock type	Nominal powder factor (kg/m^3)	Blasthole diameter (mm)	Burden x spacing x bench height (m x m x m)	Explosive type	Monitoring hole diameter (mm)
1	Large production blast	Sandstone	0.45	200 and 270	7 x 8 x 10	ANFO and HANFO	200
2	Large production blast	Sandstone	0.43	200 and 270	7 x 8 x 15	ANFO and HANFO	270
3	Large production blast	Sandstone	0.44	200 and 270	7 x 8 x 15	ANFO and HANFO	200
4	Large production blast	Sandstone	0.31	200 and 270	7 x 8 x 15	ANFO and HANFO	200
5	Limits blast—7 normal rows and 2 buffer rows	Breccia	0.48—normal 0.38—buffer	270—normal 165—buffer	8.7 x 10 x 10 5.2 x 6 x 10	ANFO and HANFO	165
6	Production blast—7 rows	Breccia	0.48	270	8.7 x 10 x 10	ANFO and HANFO	165
7	Trim blast—4 normal rows and 3 buffer rows	Granite and Breccia	0.68—normal 0.48—buffer	270—normal 127—buffer	7.1 x 9.6 x 10	HANFO and ANFO	127
8	Trim blast—1 normal row and 2 buffer rows	Breccia	0.48—normal 0.38—buffer	270—normal 165—buffer	8.7 x 10 x 10 5.2 x 6 x 10	ANFO and HANFO	165
9	Trim blast—2 small diameter rows only	Breccia	0.38	165	5.2 x 6 x 10	ANFO and HANFO	165
10	Large production blast	Dolerite	0.68	165	5 x 5.8 x 10	HANFO	102
11 and 12	Single hole free face blast	Dolerite	140 kg charge	165	5.2 m burden x 10 m depth	HANFO	102

Borehole video cameras were used in several of the monitoring holes before and after the blasts. Randomly orientated new cracks and apertures were clearly visible in most cases where underpressures had been recorded. Figure 3 shows an example of new cracks in a hole behind Blast 10.

The onset times of the peak underpressures were estimated from several of the traces and were seen to correspond closely, usually with delays of several to tens of milliseconds, to the nominal firing times of the nearest blastholes. This correspondence and time scale are believed to be consistent with a proposed mechanism of rapid crack formation and rock dilation and the rapid expansion of air into the new voids.

The underpressure data clearly reflect a disturbance to the rock mass and as such may be used to provide a measure of the disturbance in a comparative fashion behind different blast designs. The underpressure data has been used in this way to assess various limits blast options for wall control at one particular mine site.

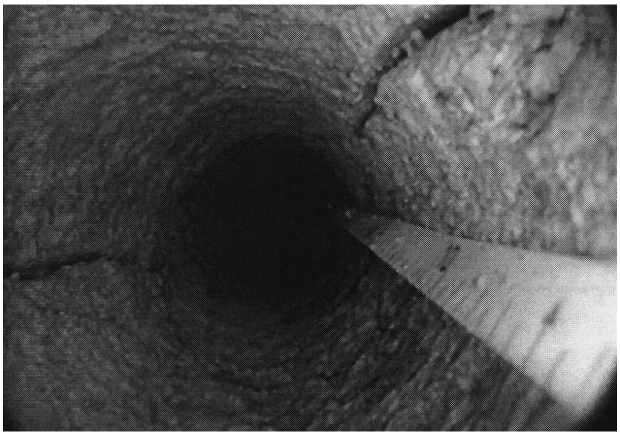

Figure 3—Example of cracks viewed by borehole video camera in a monitoring hole

Furthermore, if it is assumed that the underpressures are the result of new volume creation, such volume may be readily calculated. Based on a rapid adiabatic expansion of the air in the monitoring holes, the following relationship is derived from thermodynamic gas laws:

$$V_{new}/V_{hole} = (P_{atm}/P)^{1/\gamma} - 1$$

where, V_{new} = Maximum extent of new volume created within hole (m^3)
V_{hole} = Original volume of hole (m^3)
P_{atm} = Atmospheric pressure (kPa)
P = Absolute pressure in monitoring hole at negative peak (kPa)
γ = Adiabatic expansion coefficient for air (1.4).

It is proposed that the new volume created per unit original volume of monitoring hole, i.e. the term V_{new}/V_{hole}, may be considered to be an indicator of the damage created in the rock mass at the monitoring hole location. This ratio has been calculated for all the data of Figure 2 and plotted in Figure 4 against the scaled distance often used for vibration data. The scaled distance used here is the commonly adopted one of distance to the charge divided by the square root of the charge mass. It may be fitted to a power function in a similar fashion to that routinely used for blast vibration data. The scatter is high and reflects the wide variety of blast and rock conditions. It is comparable to that obtained for vibration data under widely differing conditions, see for example the collection of US Bureau of Mines data as presented by Persson *et al.*[9].

The data for blasts 1-4 only are plotted in Figure 5 and similarly the data for blasts 11 and 12 only are plotted in Figure 6. Each of these independently represents a series of blasts of fairly similar design and rock type. It is seen that the scatter in the data and the fit to the power function are improved from that of all the data of Figure 2, indicating that much of the scatter may be attributable to variations in blast design and geology.

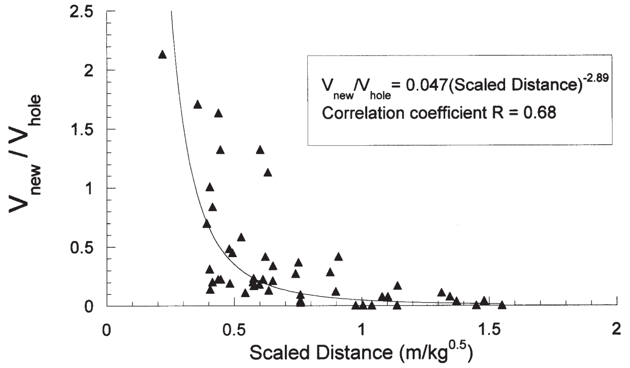

Figure 4—Plot of calculated new volume per unit original volume of monitoring holes versus scaled distance

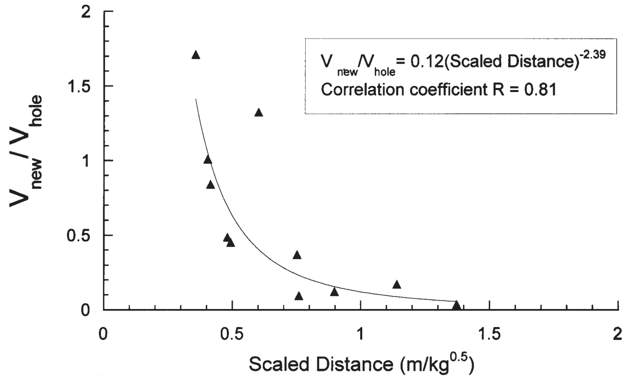

Figure 5—Data for blasts 1–4

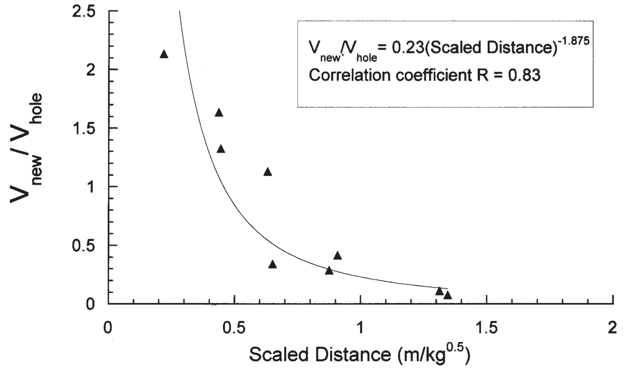

Figure 6—Data for blasts 11 and 12

While vibration levels in the form of peak particle velocities may not alone provide adequate descriptions of damage[10], it is instructive to examine commonly quoted vibration threshold values for rock damage. Singh[3] quotes, from various sources, vibration levels believed to damage intact rock as being in excess of 635 mm/s. Persson *et al.*[11], have quoted values of 700–1000 mm/s as incipient levels for new crack formation in hard rock. They also present[9] a large body of vibration data from various sites and blast conditions attributed to the US Bureau of Mines. While this data is generally from far field situations, it can be seen that vibration levels in excess of those quoted above would be attained at scaled distances of about unity or less. Liu and Ludwig[5] present experimental near field vibration data showing levels in excess of 600 mm/s at scaled distances of about 1,3 m/kg$^{0.5}$. Yang *et al.*[1] measured near field vibration levels in excess of 800 mm/s at scaled distances corresponding to about 0,4–1,3 m/kg$^{0.5}$. From Figure 4 it is clear that our data lie within this regime, with significant volume expansion occurring at scaled distances below about 1,3 m/kg$^{0.5}$. This is consistent with the assertion that the data represents actual, and indeed quite extensive, rock damage.

Directly measured extents of damage behind blasts are also consistent with the data. For example, Zhang and Song[2] measured the zone of microcracking around several single hole ANFO blasts in weak granite using crosshole seismic tomography. Their results show that the outer limit of the cracked zones lay in a radius of scaled distances corresponding to 1,2–1,8 m/kg$^{0.5}$.

Conclusions

Measurement of the air pressure generated within sealed boreholes behind conventional blasts has shown that gas penetration is not commonly detected, even at distances corresponding to less than one blast burden. Instead, underpressures usually occur. These have been attributed to volume expansion caused by blast damage to the rock mass. It is thus concluded that the technique provides a comparative measure of such damage. In current work it is being used to assess damage behind a series of controlled single hole blasts with varying amounts of burden. In this application it is providing conclusions consistent with those achieved using multiple accelerometer arrays for near field vibration measurements.

It is a relatively inexpensive technique, simple to implement and without many of the drawbacks of other damage measurement techniques. A calculation of the new voidage, which would give rise to the observed pressure reductions in the monitoring holes, has been proposed as a damage indicator. A scaled distance dependence of this voidage, similar to that of typical vibration data, is shown. The scaled distances for these data are within the regimes for rock damage that have been quoted in the literature.

An apparent scaled distance dependence of the data underlines the importance of the explosives charge mass in producing these effects. All results to date have pointed to increased underpressures, and hence increased damage, from larger charges. Furthermore, the close correspondence of the onset times of the peak underpressures with the firing times of the nearest blastholes has indicated that the major damage originates from these blastholes. The importance of controlling explosive charge masses in the perimeter blastholes for the minimization of damage in final limits blasting is thus emphasized.

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