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Investigation of Blast Damage and Underground Stability

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ABSTRACT

The implications of blast damage are harmful in both economic and physical sense. To understand the mysterious nature of blast damage assessment and prediction, field work was done by driving an experimental tunnel in the bench of a quartzite quarry.

On the basis of the blast vibration monitoring records, a model was developed to predict the PPV at different distances from a blasthole. Critical particle velocity for damage and the output of the prediction model were used to delineate the extent of damage for different explosives. The predictory model was tested by designing a special blast and the burdens for the back holes have been recommended. The relationship between the critical particle velocity for "Fall Off" and the critical particle velocity for damage has been established. The existing criteria for blast damage have also been reviewed in this paper.

INTRODUCTION

Blasting is an inherently destructive and irreversible process. It is used in hard rock mines due to its economics and adaptability. Main concern during excavation by blasting is its damage to the periphery of an excavation which results in the visible alteration to the appearance of the rock structure in the form of cracking, slabbing, and overbreak. It has been observed that the significant reduction in the strength of the rock mass can take place well before the appearance of these obvious signs of damage.

If the extent of the damage and its effects on the surrounding rock can be predicted, blasts can be modified to reduce dilution and instability problems. Therefore a study was designed with the following objectives;

i) Development of a predictory model to estimate the peak particle velocity (PPV) in the vicinity of a blasthole.

ii) To determine the critical particle velocity (V_d) for damage.

iii) To test the predictory model by an actual blast.

iv) To determine the critical particle velocity (V_f) for "Fall Off".

REVIEW OF BLAST DAMAGE CRITERIA

During the detonation of an explosive charge two major energy forms develop to produce the overall damage to the surrounding rock mass. The initial form of energy is a high-intensity, short duration shock wave, followed by a high-pressure gaseous reaction. These two forms of energy sources happen somewhat simultaneously making it difficult to assess their individual contribution to blast damage. The strain produced within a rockmass during an explosive detonation is proportional to the particle velocity generated.

Most of the existing blast damage criteria relate damage to the ground vibrations resulting from the dynamic stresses induced by the blasting process.

1) Scaled Distance Concept can be used to predict the maximum peak particle velocity, V_{max} from an explosive charge, **Q**, at a known distance **R**.

$$V_{max} = K\left(\frac{R}{\sqrt{Q}}\right)^{-\beta} \quad \ldots\ldots\ldots\ldots (1)$$

where **K** and β are site constants.
The Scaled distance equation for a cylindrical charge being.

$$V_{max} = K\,(Sd)^{-\beta} \quad where\ Sd = \frac{R}{\sqrt{Q}} \quad \ldots\ldots (2)$$

2) Langefors and Kihlstrom (1973), Edwards and Northwood (1980), and several others proposed particle velocity as a blast damage criteria.

3) There was a common agreement that a Peak Particle Velocity (PPV) of less than 50 mm/sec (2 in/sec) would have low probability of structural damage to residential buildings.

4) There is a scarcity of data relating PPV to damage in underground openings.

a) Langefors and Kihlstrom (1973) have proposed the following criteria for tunnels.

PPV mm/sec (in/sec)	RESULT
305 (12)	Fall of rock in unlined tunnels
610 (24)	Formation of new cracks

b) Oriard (1982) proposed that most rock masses suffer some damage at PPV above 635 mm/sec (25 in/sec).

c) Bauer and Calder (1970) observed the following

PPV mm/sec (in/sec)	RESULT
<254 (10)	No fracturing of intact rock
254-635 (10-25)	Minor tensile slabbing
635-2540 (25-100)	Strong tensile and some radial cracking
> 2540 (100)	Break up of rock mass

5) Graddy and Kipp (1987) used a scaler, **D**, to define the rock damage. The value of D lies between 0 (for intact rock) and 1 (for complete failure). This can also be used to estimate the modulus, E_d, of the damaged rock, so that

$$E_d = E(1-D) \qquad (3)$$

where **E** = modulus of intact rock.

6) Kyoya et al (1985) proposed a damage tensor representing the results of reduced moduli which can be incorporated into finite element computation of material displacement, stress and strain.

7) Mckown (1984) and Singh (1992) used half cast factor as a measurement of blast damage.

8) Scott et al (1968) used geophysical techniques like seismic refraction and electrical resistivity to assess and describe the blast damage.

EXPERIMENTAL WORK

The field work was performed in an abandoned quartzite quarry. A 2.4m X 2.1m (9' X 8') experimental tunnel was driven into a bench of the quarry. Nine 1.8m (6') long drift rounds were drilled and blasted using a variety of blast design parameters.

Test Site Characteristics:

The quarry was initially mined for the high quartzite/quartz sandstone content. The rockmass structure was intact, blocky and columnar with a grain size that varied from fine (0.2-0.6mm) to very fine (<0.2mm). Geological mapping of the area identified four major joint sets having a spacing of 0.6-2.0m in length. The P-wave velocity and compressive strength of the rock was 4800m/sec. and 250 MPa respectively, with a moisture content of low to nil.

Blast Design Parameters:

In most of the drift rounds ANFO was used in the holes except the perimeter holes. The perimeter holes were broken into three areas, left, right, and back holes. To obtain relative blast damage potential the explosive charge in the back holes was kept constant for each round. Both sets of side holes however were charged with a variety of explosives with different energy partitioning characteristics. The different explosives used and their general characteristics are listed in Table 1.

Table 1 Explosive Characteristic

TYPE OF EXPLOSIVE	DENSITY (Kg/m^3)	VELOCITY OF DETONATION (m/sec.)
HIGH STRENGTH DETONATING CORD		5500
SEMI-GELATINE DYNAMITE	1320	2800
HIGH STRENGTH EMULSION	1170	4600
LOW STRENGTH EMULSION	1140	5100
DILUTED ANFO	700	2500

Assessment of Blast damage

To assess the damage created by blasting in the experimental tunnel the following methods were used.
a. Vibration Monitoring
b. Percentage Overbreak
c. Half Cast Factor

Vibration monitoring is one of the most important tools in understanding blasting. Each of the nine rounds in the experimental tunnel were monitored with seismographs (Instantel DS-377, OMNI PROBE 1200) along the vertical axis of the drift. Complete seismic records of each blast were recorded and subsequently analyzed.

Visual condition of the remaining rock wall and back (roof) is a crude but sometimes a reliable method of determining blast damage, but quantifying tools such as Half Cast Factor and % Overbreak are more reliable means.

Percentage Overbreak is a measure of the amount of rock that was removed from the periphery of an excavation beyond the planned limit. Percentage Overbreak is determined by comparing the designed profile with the after blast profile.

Half Cast Factor is a measure of the remaining half casts (half barrels) left on the rock walls and back. Half Cast Factor assessment does not take into account any error of borehole alignment. If the drill hole alignment has deviated from the designed pattern, overbreak measurements will calculate this as damage. But using the Half Cast Factor assessment, it is possible to determine that damage was created by drilling error rather that from blasting.

Half Cast Factor is determined using the following formula:

$$\frac{(\sum \textit{visible blast hole lengths (after blast)})}{(\sum \textit{perimeter blast hole lengths (before blast)})} \times 100$$

RESULTS AND DISCUSSION

Development of the Vibratory Model:

During the excavation of the experimental tunnel, particle velocity records for each round were monitored from the upper bench above the drift (figure 1).

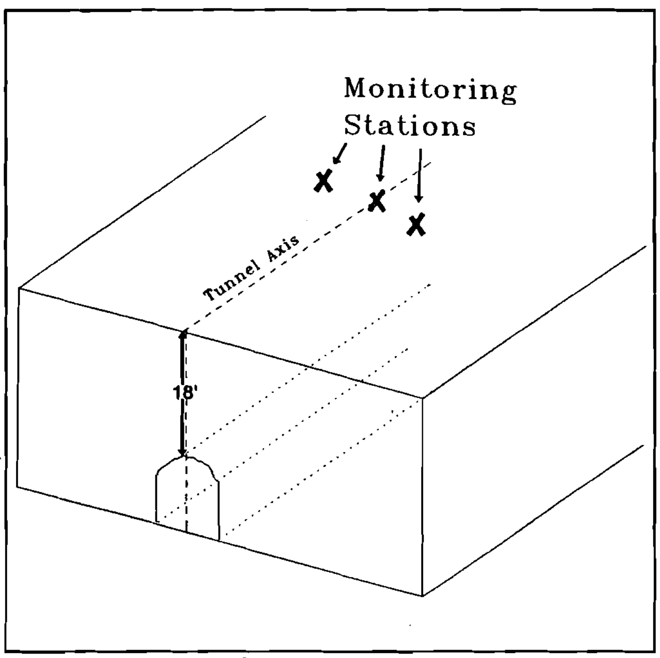


Figure 1 Location of vibration monitoring stations.

The monitoring stations for each round were surveyed with respect to the perimeter holes in that round. Accurate distances D in meters, and known quantities of explosives Q kg/delay were tabulated for the determination of the site constants K and β. A log-log plot of measured peak particle velocity PPV vs their respective scaled distances, produced a visual representation of all recorded data. Upper and lower limit lines were drawn to envelope all plotted values. The equation of these lines had the form

$$\log V = \log K - \beta \log (Sd) \cdots\cdots\cdot (4)$$

A range of site constant values K and β were determined from the upper and lower limit lines. The Y-axis intercept equalled K_{lower} and K_{upper} with the negative slope of each line representing β_{lower} and β_{upper}.
These values were as follows

Constant	Range
K	770-2334
β	1.3-1.7

Once a range of values were determined, a statistical analysis was performed with the goal of optimizing the constants to best fit the data. The best fit representation of this site produced a vibratory model which looked as follows

$$V = 1077 \left(\frac{D}{\sqrt{Q}}\right)^{-1.6} \cdots\cdots\cdots\cdot (5)$$

giving values for K and β of 1077 and 1.6 respectively.

Near Field Vibratory Model

When questions of blast damage are raised, values of peak particle velocity at close distances to the blasthole are the main concern. Holmberg and Persson (1979) developed an equation which allows determination of PPV levels at distances less than or equal to the explosive column length. By integrating over the length of the column H, prediction of PPV can be achieved, for a given quantity of explosive Q, at a desired distance D . Using the near field equation, PPV for a known charge can be computed at different distances from the blast (figure 2).

Critical Particle Velocity for Damage

Blast damage is a result of the induced dynamic stress (s) during detonation. The induced dynamic stress can be calculated for an elastic medium as a function of peak particle velocity (V) and longitudinal wave velocity (V_p).

$$s = \left(\frac{V}{V_p}\right) \cdots\cdots\cdots\cdots\cdot (6)$$

During the detonation of an explosive charge the magnitude of the dynamic stresses that develop around the blasthole will be large enough to induce primary cracking in the rock mass. The critical particle velocity (V_d) at which

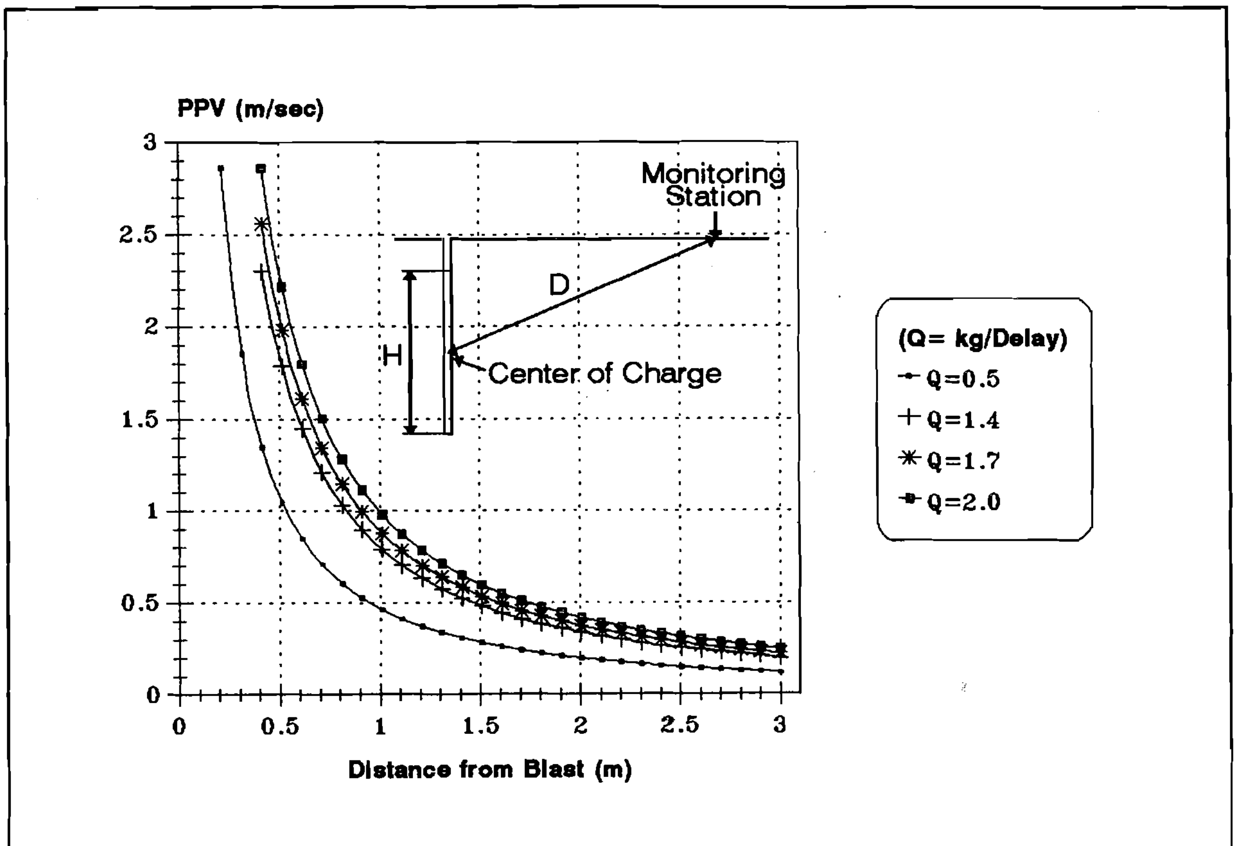


Figure 2 PPV vs Distance from blast for different charge concentrations.

the damage occurs can be calculated with the following equation.

$$V_d = \left(\frac{V_p \cdot T_s}{E}\right) \quad \ldots\ldots\ldots\ldots (7)$$

where T_s = tensile strength of the rock
E = Young's modulus

For the test site, the range of critical particle velocity was found to be 1500-2000 mm/sec with an average value of 1750 mm/sec.. With the aid of the Near field equation, critical particle velocities can be predicted and the zone of probable damage can be delineated. To illustrate this zone of probable damage figure 3 outlines the three main boundary lines; Designed Profile, Final (after blast) Profile, and the predicted Extent of Damage. The Extent of Damage at PPV=1500 mm/sec is calculated to be the distance from the designed profile outward into the intact rock. Final tunnel profile is also shown in figure 3 and its determination is described later in the paper.

Testing the predictory Model

In order to test the validity of the predictory model, a special drift round was designed. The burden for the back holes (the distance between the back holes and the baby arch holes) was calculated with the predictory model and the critical particle velocity for damage to be 0.6 meters for an explosive charge of 1.4 kg/delay . The predicted zones of damage from the baby arch and back holes are shown in figure 4

All the holes except the back holes were blasted. The damage to the back holes was found to be minimal thus proving the validity of the model. All the back holes were successfully charged and blasted. On the basis of this finding, the distances between the first-row-in holes (charged with ANFO in hard rock) and the perimeter holes are suggested in table 2.

Table 2. Suggested burden for perimeter holes when the first-row-in holes are charged with ANFO.

Diameter of blast hole (mm)	Explosive type in first-row-in holes	Perimeter hole burden (m)
32	ANFO	0.55-0.65
38	ANFO	0.65-0.75
45	ANFO	0.75-0.90

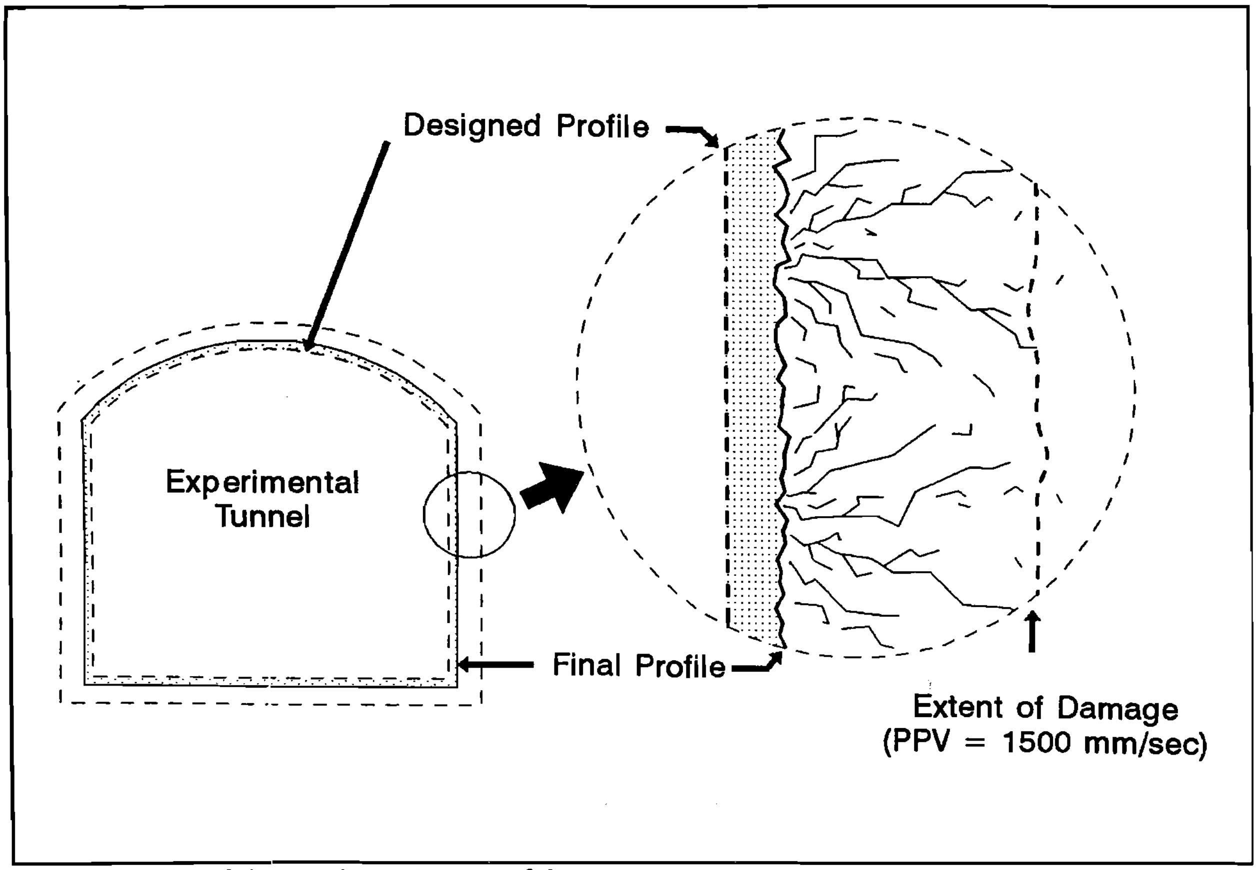


Figure 3 Profiles of the opening and extent of damage.

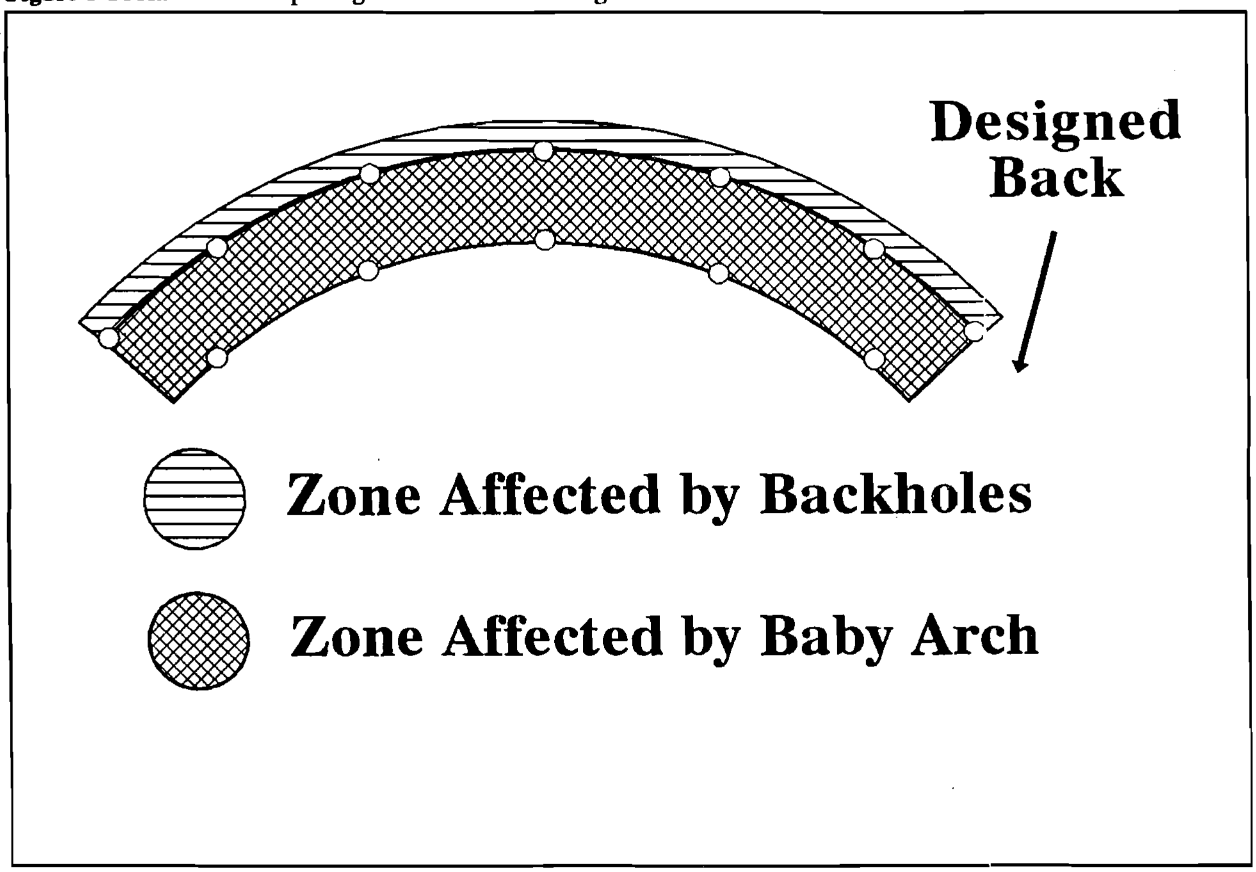
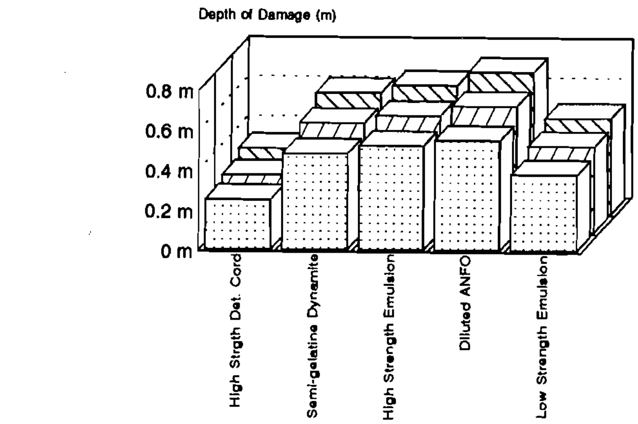


Figure 4 Damage Zones from Baby arch and Back holes.

Figure 5 shows the maximum, minimum and average values of predicted depth (zones) of damage for the explosive types used at the test site.

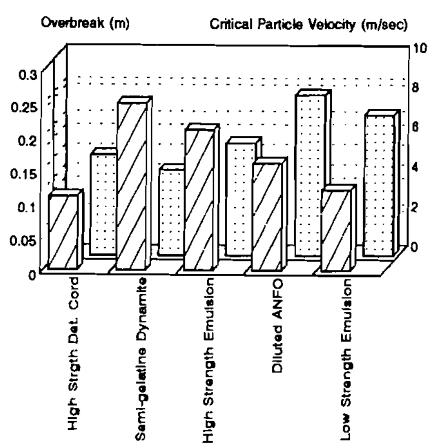


Maximum Damage	0.32 m	0.6 m	0.64 m	0.71 m	0.48 m
Average Damage	0.28 m	0.54 m	0.58 m	0.63 m	0.43 m
Minimum Damage	0.25 m	0.48 m	0.52 m	0.55 m	0.38 m

Figure 5 Zones of predicted damage

Critical Particle Velocity for "Fall Off"

After each round was blasted, measurements were taken to determine the maximun thickness of overbreak on each side of the drift. Again using the near field equation, and the overbreak measurements, the critical particle velocity for "Fall Off" was determined. The critical particle velocities at the points of maximum overbreak have been given in figure 6.



Max Overbreak (m)	0.11	0.25	0.21	0.16	0.12
Critical PPV (m/sec)	5	4.25	5.6	8	7

Figure 6 Critical PPV at maximum Overbreak.

Critical particle velocity for "Fall Off" was approximately 2-3.5 times the critical particle velocity for damage. This range is dependent on the energy partitioning characteristic of the explosives being used. It was observed that with high shock energy explosives, the V_f is higher where as with high gas energy explosives the V_f is lower due to the increased overbreak by the assistance of gas pressure.

Half Cast Factor and Overbreak

Half cast factor and % overbreak were used as a measuring tool for exterior damage. The results for these damage indicators have been given in figure 7.

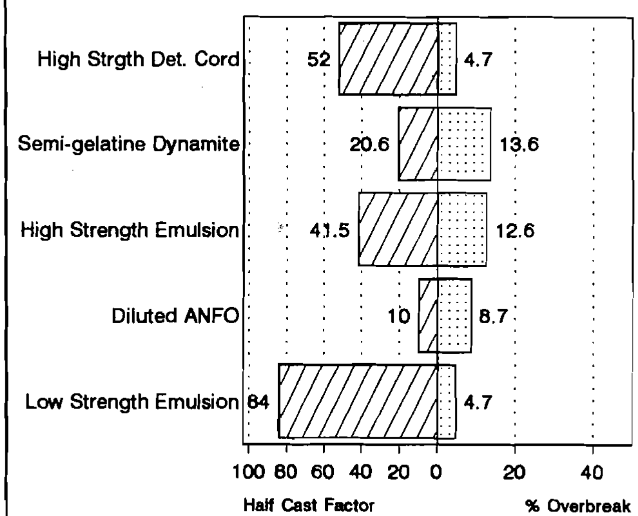


Figure 7 Half Cast Factor and Percent Overbreak.

Percent Overbreak and Half Cast Factor need to be used in conjunction with each other. Half Cast Factor value of 100% does not necessarily mean no overbreak. Drill hole alignment may cause the overbreak beyond the designed profile. It has been observed that Low Strength-High VOD explosives cause minimum exterior damage. High Strength explosives cause the most excessive damage to the tunnel profile.

CONCLUSIONS

Blast damage in underground mines can cause ore dilution, stability problems and unsafe working conditions. The most common damage criteria is based upon the ground vibrations induced by the dynamic stresses of the blast. On this basis using blast vibration monitoring, a predictory model for the site can be developed to determine the extent of damage. The critical particle velocity for "Fall Off" was 2-3.5 times the critical particle velocity for damage depending on the energy partitioning characteristic of the explosives being used. On the basis of vibration monitoring and critical particle velocity for damage, optimum burdens for the side and back holes can be determined.

All numerical results such as site constants, critical particle velocity for "fall off" and "damage", are site specific, and can not be literally applied to other mine sites. However the approach can be successfully applied for the optimisation of blast design providing safe and stable excavations.

ACKNOWLEDGEMENTS

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