New Model for Predicting Blast-Induced Overbreak in Development Drivages of Metal Mines

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ABSTRACT

Blasting is the predominant method of excavation in underground development drivages of metal mines owing to its ability to meet varying geotechnical conditions. Increasing emphasis on underground production in India, particularly in base metal deposits, has placed much pressure on faster development. Longer pulls, attempted to increase drivage rates, have often contributed to blast-induced overbreak. A number of controlled-blasting techniques (namely, line drilling, pre-splitting, smooth blasting etc) have been developed to minimise this problem. However, all these techniques essentially require additional drilling, controlled charging and detonation. An investigation has been carried out in five different horizontal drivages accomplished for the development of metal mine using burn cut to arrive at a blast-induced overbreak predictive model. Vibration monitoring close to the blast (within 13 to 63m) was carried out using accelerometers for the first time in India, to develop vibration predictors and overbreak threshold levels for individual sites. The threshold levels of PPV for overbreak was ranging from 2380 to 3300 mm/s in these five sites. The overbreak corresponding to each blast has been measured and found to be varied between 3 to 30 percent of drivage area. Combining the relevant rock, blast design and explosive parameters affecting blast-induced overbreak, a model has been developed for prediction of blast-induced overbreak using multivariate statistical analysis. This paper reports the development of the overbreak predictive model for burn cut blasting in hard rock drivages.

Keywords: Blasting; Overbreak; Damage; Drivages; Hard rock

1. INTRODUCTION

Blasting is the most popular means of excavation for underground drivages despite the rapid developments in the mechanical excavators, namely, tunnel boring machines, road headers, continuous miners etc. Faster drivage rates are possible with the recent developments in explosives (emulsion), initiating systems (Nonel, electronic detonator) and drilling (automation) systems. However, longer pulls, associated with high concentration of explosives, often lead to overbreak due to excess ground vibrations. Overbreak can become expensive phenomena in terms of extra grouting and concrete backfilling and may also give rise to additional mucking time. Most of the existing controlled blasting techniques, to reduce the blast-induced overbreak, need extra drilling, in turn, adding drilling and blasting costs and time. Blasting in horizontal drivages aims at the following objectives:

(i) Achieving longer pulls
(ii) Reducing overbreak and rock damage
(iii) Optimizing drilling and blasting cost.

It is rational to assess blast-induced overbreak in production blasting and control the same by modifying the blast design. Overbreak is largely affected by a host of rock, blast design and explosive parameters. Several researchers have attempted to study overbreak/blast-induced rock damage either based on experimental studies or relating some of the above influencing parameters. A brief discussion on the previous works is provided in the following section:

2. PREVIOUS WORK

(i) Mcknown (1984) and Singh (1992) used half cast factor as a measure of blast-induced overbreak. Half cast factor is the ratio of total visible drill mark length in the wall and roof after blast and the total drilling length.

$$HCF = \frac{\sum_{i=1}^{n} L_i}{\sum_{r=1}^{n} L_r} \tag{1}$$

Where
HCF = Half cast factor,
L_i = Post-blast drill mark length visible (m), and
L_r = Pre-blast drilled length (m).

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

(iii) Graddy and Kipp (1987) used a scalar, D, to describe the rock damage. The value D lies between 0 (intact rock) and 1 (complete failure). This can also be used to estimate the rock modulus Ed, of the damaged rock, so that

$$E_d = E\,(1 - D) \tag{2}$$

Where
E, E_d = Modulus of the intact rock and damaged rock respectively.

(iv) A method proposed by JKMRC (Australia, 1990) included the frequency, surface condition and density of discontinuities as a descriptor of damage.

(v) Forsyth and Moss (1990) devised a method of quantifying blast - induced damage. Their proposed Drift Condition Rating (DCR) comprised two components: firstly, the drift back condition (related to the rockmass integrity and the percentage of half cast visible); and secondly, the amount of overbreak. This empirical rating varied from 0 to 9.

(vi) Paventi (1995) reviewed the development of a field procedure for damage monitoring through an empirical blast induced damage index, D_M given by,

$$D_M = I * II*III * IV*(V_A + V_B) \tag{3}$$

Where
I: considers the reduction in intact rock strength due to micro-fracturing.
II: evaluates the extent of the exposed excavation surface area remaining in place using the post scaling half cast factor.
III: determines the drift condition by assessing the drumminess of the back with a scaling bar.
IV: accounts for the amount of scaling arising from damage.
V_A & V_B: considers the direction of structure with respect to drift direction to account for the anisotropy potentially caused by structural features at meso and macro scales.

(vii) Yu and Vongpaisal (1996) proposed a new blast damage criteria based on dynamic tensile strength, compressional wave velocity (P-wave), density of rockmass and peak particle velocity of the blast. The proposed damage criterion is as follows:

$$BDI = \frac{V \times \rho_r \times C_p}{K_r \times DTS} \tag{4}$$

Where
BDI = Blast damage index,
V = Vector sum of peak particle velocity (m/s),
ρ_r = Density of rock (g/cc),
C_p = Compressional wave velocity (km/s),
K_r = Site Quality constant (0 – 1.0) ,
= (RMR – Ground support adjustment)/100, and
DTS = Dynamic tensile strength (MPa).

Based on the blast damage index the rock may be categorized as given in Table 1.

Table 1 - Blast damage index and damage type (Yu and Vongpaisal, 1996)

BDI	Type of damage
≤0.125	No damage to underground excavation
0.25	No noticeable damage
0.5	Minor and discrete scabbing effect
0.75	Moderate and discontinuous scabbing damage
1.0	Major and continuous scabbing failure
1.5	Severe damage
≥ 2.0	Major caving

Singh (2000) studied the roof damage in underground mine due to surface blasting. Based on underground instrumentation and far-field vibration monitoring, it was found that the BDI value of less than 1 referred to no damage condition and BDI value of more than two referred to severe damage condition, whereas BDI value in between 1 to 2 referred to a minor damage condition.

(viii) Ibarra, Maerz and Franklin (1996) proposed perimeter charge factor (PCF) as the controlling parameter for the blast induced rock damage assessment. Perimeter charge factor is defined as the ratio of weight of explosives in the perimeter blast holes and the next row divided by the volume of rock within this annulus, ignoring the lifters in the invert. Analysis of the blast data of Aquamilpa Hydroelectric Project, Diversion Tunnel No.2, revealed a relationship between Overbreak/Underbreak with log of Barton's Q index. A linear relationship between the underbreak/overbreak and PCF has been established. An increase in PCF indicates an increase in overbreak therefore a decrease in underbreak. A composite relationship including both PCF and Q value for the prediction of overbreak/underbreak was established. Although, these relations are site-specific, it is easy to establish using multiple regression analysis.

$$\begin{aligned} \text{Overbreak}\,(\%) &= -K_{o1} + K_{o2} \times \text{PCF} - K_{o3} \times \log(Q) \\ \text{Underbreak}\,(\%) &= K_{u1} - K_{u2} \times \text{PCF} + K_{u3} \times \log(Q) \end{aligned} \tag{5}$$

Where
K_{o1}, K_{o2} = Site-specific characteristic constants for overbreak, and
K_{u1}, K_{u2} = Site-specific characteristic constants for underbreak.

The above review clearly brings out that the damage models suggested relate the damage/overbreak with either a single or a couple of influencing factors. It was felt that the inclusion of predominant factors of representing rock, blast design and explosive could lead to a more rational overbreak predictive model. The major contributing parameters identified are given below:

(a) Rock parameters: Dynamic tensile strength, rock density, Poison's ratio and threshold level of PPV for overbreak.
(b) Blast design parameters: Confinement and advance factor
(c) Explosive charge parameters: Perimeter charge factor

Thus, experimental blasts have been designed such that the above-mentioned rock, blast design and explosive charge parameters could be covered as described in the following sections:

3. DESIGN OF EXPERIMENTAL BLASTS

The rock and rock mass properties were determined from the field and laboratory investigations. Poisson's ratio was computed from the measured P-wave and S-wave velocities in the laboratory. Post-blast drivage cross sectional area was measured using telescopic overbreak measuring rod (Fig. 1) which had been designed and fabricated in Indian School of Mines, Dhanbad, under the supervision of the authors. Overbreaks were computed using planimeter after plotting telescopic offset measurements on a graph paper. The overbreaks are expressed in percentage of drivage area. Peak particle velocities and accelerations were monitored as near as possible to the blast face using accelerometer and triaxial-geophone-based seismographs (Minimate Plus and Minimate 077 of Instantel Inc Canada). The fixing arrangement of the accelerometer sensors has been shown in Fig. 2. The sensors used in the study with their broad specifications are mentioned in Table 2. The measured accelerations are integrated to PPV. Vibration predictor equations between PPV and cube root scaled distance (Eqn. 6) as proposed by the Ambraseys and Hendron (1968) were developed for each site. To arrive at the overbreak threshold levels of PPV, the established predictor equations were extrapolated upto the overbreak distances (Murthy and Dey, 2003).

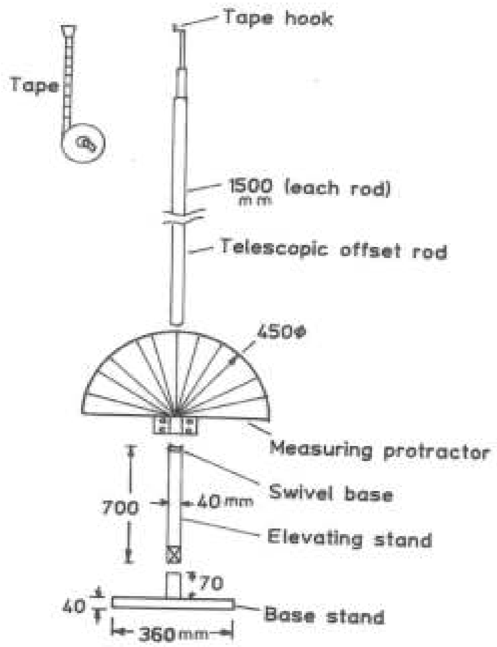


Fig. 1 - Telescopic overbreak measuring rod

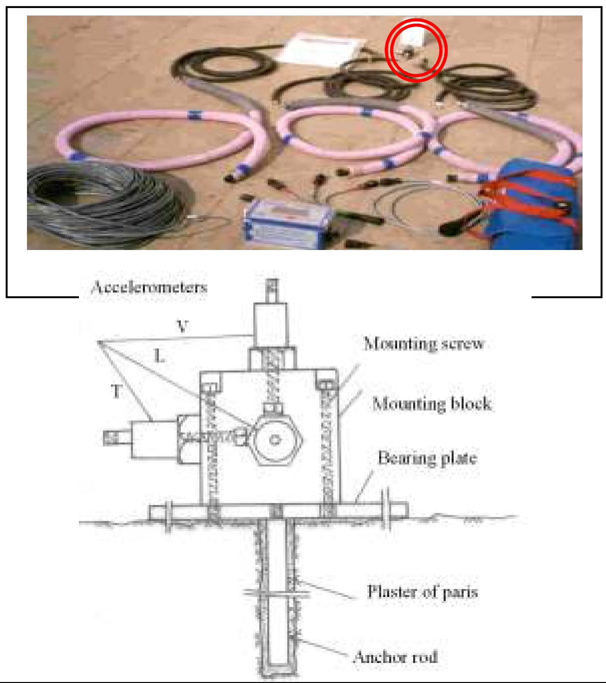


Fig. 2 - Fixing of sensors of the accelerometer

$$SD = R/(W)^{1/3} \quad (6)$$

Where
SD = Scaled distance,
R = Distance from the blast to monitoring point (m), and
W = Maximum charge per delay (kg).

Table 2 – Major specifications of seismic sensors used in the study

Parameters	Accelerometer	High frequency geophone	Triaxial geophone
Frequency range	1 Hz to 3 kHz	1Hz to 2 kHz	2 to 300 HZ
Acceleration range	Upto 500 g (4903 m/s^2)	Geophone natural frequency: 28Hz	Upto 254 mm/s

Dynamic tensile strength has been estimated using the following formula proposed by Tezuka et al. (1997).

$$\sigma = (\rho \times c \times v)/960.4 \tag{7}$$

Where

σ = Dynamic tensile stress (MPa),
ρ = Rock density (g/cm^3),
c = P - wave velocity (m/s), and
v = PPV (m/s).

In the above equation, substituting the v with threshold level of PPV, dynamic tensile strength of rock is estimated. Confinement, the ratio of drilling depth and tunnel area, have been measured for every blast, because it has a significant impact on the overbreak. Similarly, Advance factor, the advancement achieved per unit drilling in a blast round i.e. the ratio of advance and drilling depth, has also been computed.

4. FIELD INVESTIGATIONS

Field investigations have been carried out in five horizontal drivages through hard metamorphic rocks representing different geotechnical conditions. The blasts investigated are the regular production blasts with burn cut carried out in development drivages referred as Site-1 through Site-5. The details of rock properties and experimental blasts are provided in Tables 3(a) and 3(b). Near-field vibrations were monitored to establish ground vibration predictor equation for each site. The predictor equation has been extrapolated upto the overbreak distance to estimate the threshold level of PPV for overbreak. The predictor equations and estimated vibration threshold levels for overbreaks are shown in the Fig. 3.

Table 3(a) - Rock properties of the five investigating sites

Parameters	Site-1	Site-2	Site-3	Site-4	Site-5
Dynamic tensile strength (MPa)	34.87	41.46	49.44	42.47	65.16
Threshold level of PPV (mm/s)	2380	2725	2665	2502	3300
Rock density (g/cc)	2.78	2.87	3.24	2.98	3.35
P-wave velocity (km/s)	5.06	5.10	5.50	5.47	5.66
S-wave velocity (km/s)	2.86	2.82	3.32	3.43	3.41
Poisson’s ratio	0.266	0.280	0.213	0.242	0.215

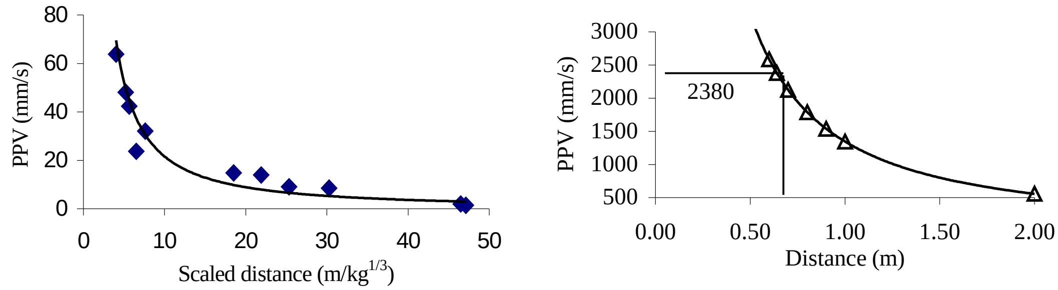
5. DEVELOPMENT OF OVERBREAK PREDICTIVE MODEL

A predictive model has been developed for estimation of overbreak from rock parameters, blast design parameters and explosive charge parameters (Dey, 2004). Dynamic tensile strength (DTS), Poisson’s ratio (μ), rock density (ρ) and threshold level of PPV (PPV) have been taken as the rock descriptors. Perimeter charge factor (PCF) has been taken as the charge descriptors. Here, to determine the PCF, the perimeter holes are considered only. Advance factor (AF) and confinement (Cn) are considered as blast design descriptors.

Table 3(b) – Details of experimental blast results

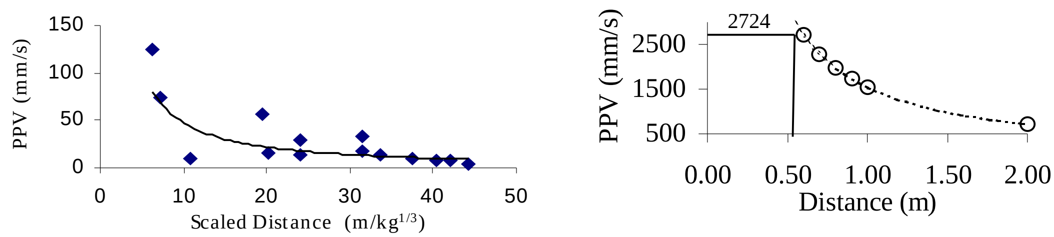
Sl No.	Drill depth (m)	Perimeter charge factor (kg/m^3)	Overbreak (%)	Advance (m)	Face area (m^2)	Advance factor (m/m)	Confinement (m/m^2)
Site-1							
1	3.2	N.A.	14.24	2.6	14.4	0.81	0.22
2	3.2	1.34	5.83	2.8	14.4	0.88	0.22
3	3.2	1.22	17.01	2.0	14.4	0.63	0.22
4	3.2	1.34	18.8	2.0	14.4	0.63	0.22
5	3.2	1.19	18.43	2.0	16.0	0.63	0.20
6	3.2	N.A.	14.24	2.4	14.4	0.75	0.22
7	3.2	1.03	26.55	1.8	16.0	0.56	0.20
Site-2							
1	1.3	2.31	3.99	1.2	12.0	0.92	0.11
2	3.2	1.16	24.17	2.1	16.0	0.66	0.20
3	3.2	1.25	19.66	2.5	16.0	0.78	0.20
4	1.5	1.59	17.9	1.2	12.0	0.80	0.13
5	1.5	1.32	18.2	1.2	12.0	0.80	0.13
6	1.5	2.14	16.55	1.25	12.0	0.83	0.13
7	1.5	1.62	7.78	1.3	12.0	0.87	0.13
8	1.7	1.74	17.69	1.4	12.0	0.82	0.14
9	1.3	1.31	10.75	1.18	12.0	0.91	0.11
10	1.7	1.36	14.73	1.5	12.0	0.88	0.14
11	3.2	1.13	22.2	2.4	16.0	0.75	0.2
Site-3							
1	1.6	1.41	18.44	1.2	6.25	0.75	0.26
2	1.6	1.34	15.42	1.4	6.25	0.88	0.26
3	1.6	1.40	18.38	1.3	6.25	0.81	0.26
4	1.6	1.24	22.36	1.25	6.25	0.78	0.26
5	1.6	1.44	21.48	1.25	6.25	0.78	0.26
Site-4							
1	1.6	1.31	18.99	1.3	6.25	0.81	0.26
2	1.6	1.48	12.21	1.35	6.25	0.84	0.26
3	1.6	1.48	29.97	0.9	6.25	0.56	0.26
4	1.6	1.31	27.22	0.9	6.25	0.56	0.26
5	1.6	1.41	24.45	1.2	6.25	0.75	0.26
Site-5							
1	1.6	1.41	21.15	1.2	6.25	0.75	0.26
2	1.6	1.17	17.92	1.35	6.25	0.84	0.26
3	1.6	1.32	22.91	1.2	6.25	0.75	0.26
4	1.6	1.45	22.93	1.2	6.25	0.75	0.26

The related data pertaining to each site has been statistically analysed using multivariate statistical software (SPSS ver 6.0) in order to test the significance of the relationship. For the statistical validation of the model, due to low index of determination, t-test and F-test have been conducted. The results are given in Table 4.



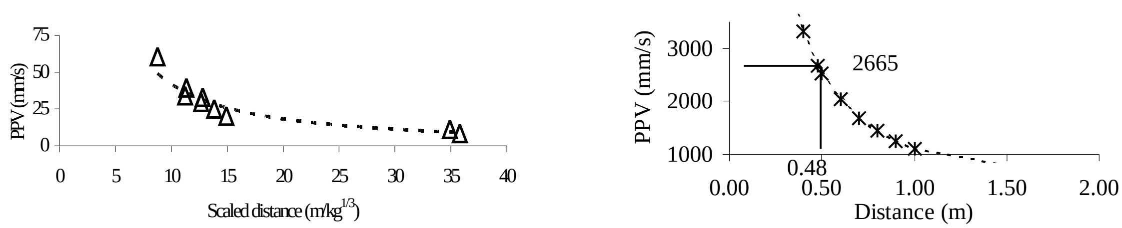
(a) (b)

Fig. 3(i) - PPV predictor for site 1 and extrapolation upto overbreak distance



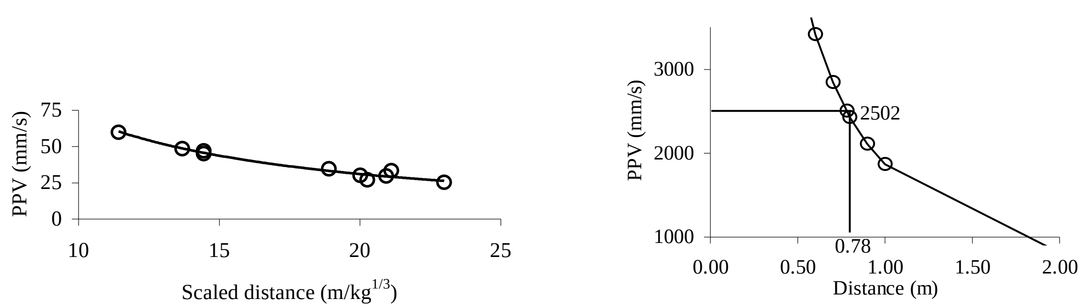
(a) (b)

Fig. 3(ii) - PPV predictor for site 2 and extrapolation upto overbreak distance



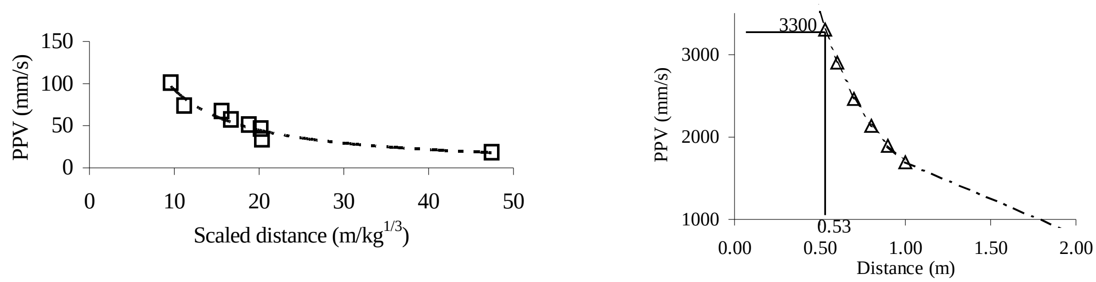
(a) (b)

Fig. 3(iii) - PPV predictor for site 3 and extrapolation upto overbreak distance



(a) (b)

Fig. 3(iv) - PPV predictor for site 4 and extrapolation upto overbreak distance



(a) (b)

Fig. 3(v) - PPV predictor for site 5 and extrapolation upto overbreak distance

Table 4 - Statistical validation of the proposed overbreak prediction model (BIRD)

Dependent variable	Independent variable	r	$t_{calculated}$	t_{table} (5% Sig.)	$F_{calculated}$	F_{table} (5% Sig.)
Overbreak (%)	Rock descriptor Design descriptor Charge descriptor	0.713	3.21	2.228	2.763	4.07

For the validation of the model, t-test has been conducted to test the significance of r (correlation coefficient). The null hypothesis (H_0) is that the r is not significant and as opposed to alternate hypothesis (H_1), where r is significant. The calculated t-value ($t_{calculated}$), which is a function of r, n (number of samples) was found to be 3.21, and is larger than t-value (t_{table}) at 5% significance level (i.e. 2.228 from student t-table). Thus, it can be concluded that the alternate hypothesis (H_1) is valid. It means r is significant. F-test has also been done to test the variances of regression and residuals whether they were alike or not. The calculated F ($F_{calculated}$) is to be 2.763, which is lesser than the F-table (F_{table}) value at 5% significance with 3 and 8 degrees of freedom. In this case, the null hypothesis is valid. In other words, there is no significant difference between variances of regression and residual. Thus, the model proposed is valid and applicable. The proposed model considers rock, blast design and charge parameters, hence it is more rational and applicable for blast design to control overbreak. The explosive characteristics have been kept the same for all the cases. Thus, the proposed composite model is statistically and conceptually acceptable and hence can be used for blast-induced rock damage assessment in horizontal drivages. The composite model developed, named as BIRD, is given below:

$$OB = 27.91 + 0.97 \times PCF - 1.53 \times \frac{(DTS \times \mu)}{(DPPV \times \rho)} - 1.89 \times \frac{AF}{Cn} \quad (8)$$

Where

OB = Overbreak (%),
PCF = Perimeter charge factor (kg/m^3),
DPPV= Threshold level of PPV for damage (m/s),
DTS = Dynamic tensile strength,
μ = Dynamic Poisson’s ratio,
ρ = Rock density (g/cm^3),
AF = Advance factor (m/m), and

Cn = Confinement (m/m^2).

Accuracy of BIRD model has been tested for 4 blast events recorded in Site-2, which were kept aside for testing and not used in the development of the predictive model itself. The results are given in Table 5. From the table, it is clear that the percentage error in the prediction varied between 3 and 9 and could be considered as within acceptable limits of prediction. Thus, the BIRD model is validated.

Table 5 - Comparison of the observed and predicted overbreak using BIRD model

INPUT				
	Blast-1	Blast-2	Blast-3	Blast-4
Perimeter charge factor (kg/m^3)	1.49	1.46	1.32	1.58
Dynamic tensile strength (MPa)	41.46	41.46	41.46	41.46
Poisson's ratio	0.28	0.28	0.28	0.28
Density (g/cm^3)	2.87	2.87	2.87	2.87
Threshold level of PPV for overbreak (mm/s)	2725	2725	2725	2725
Pull (m)	1.6	1.5	2.0	1.4
Face size (m^2)	14.40	14.40	14.40	14.40
Drill depth (m)	3.2	3.2	3.2	3.2
OUTPUT				
Actual overbreak (%)	24.73	23.60	19.97	24.91
Predicted overbreak (%)	22.83	22.93	21.32	23.45
Percentage error (±)	7.68	2.83	6.78	5.86

6. CONCLUSIONS

Blast-induced overbreak has been investigated from the experimental blasts and ground vibration monitoring using state-of-art seismography. The overbreak measurements have been utilized to establish peak particle velocity thresholds. An overbreak predictive model has been developed considering the rock parameters (dynamic tensile strength, Poisson's ratio, estimated damage threshold levels in terms of PPV, density of rock), blast design parameters (advance factor and confinement) and an explosive parameter (perimeter charge factor).

The composite overbreak model (BIRD) developed is found to be statistically significant for the cases investigated. It has been noticed that the overbreak threshold levels decrease (from 3300 to 2500mm/s) with the increase in advance factor (from 0.4 to 0.9). An increase in the confinement (from 0.1 to 0.25) resulted in increase in the overbreak. With the increase in the perimeter charge factor (from 1.0 to 3.5kg/m^3)) the percentage overbreak increased from 6 to 30. Under the influence of the above stated parameters, the percentage overbreak varied from 3 to 30. From the above results obtained and comparison of BIRD model with the existing models, it can be concluded that the proposed overbreak model (BIRD) is adequately representative and rational as it considers the critical rock, design and charge parameters influencing overbreak. From the testing of BIRD model with 4 blast datasets, it has been found the model could predict overbreak within a percentage error of 10 (Table 4). Thus, this approach can be considered useful for overbreak prediction in horizontal drivages/tunnels.

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