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New Blast Damage Criterion for Damage Prediction

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Abstract: There are several underground mines in India which operate in close proximity to an operating surface mine. Under such scenario, the blast induced stress waves generated due to surface blasting may be a potential source to cause instability of adjoining underground mine structures. Using seismographs, 54 blast induced vibration data were recorded at various locations in the roof, floor and pillars of the underground mine at Hingir Rampur mine of Coal India Limited by synchronizing the timing of surface blasting carried at an adjacent Samleshwari opencast mine. Results of this study show that Artificial Neural Network (ANN) has better prediction potential of peak particle velocity (PPV) and damage to adjacent underground structures due to surface blasting as compared to conventional regression methods. In order to assess and predict the impact of surface blasts on underground workings, Blast Damage Factor (BDF) has been evolved. The study shows that site specific charts can predict the blast damage class at an underground location due to surface blasting for known distances and explosive charge per delay. The severe damage in case study mine site took place when peak particle velocity exceeded 162 mm/s and PPV less than 51 mm/s had no probability of damage to underground structures due to surface blasting.

Key words: Blast damage prediction, blast damage factor, underground damage.

1. Introduction

Blasting at surface coal mines is a major safety concern for adjacent underground coal mines. In India, several underground coal mines being worked on Bord and Pillar system underlie within a depth of 30-150 m from opencast coal mines, where regular blasting is practised for removing overburden and extracting coal. Under such geological situation, blasting at surface mines may cause instability of underground structures. In order to assess the impact of damage caused by surface blasting, vibrations are monitored in underground workings, which may be termed as Surface Blasting-Underground Monitoring [1]. The various adverse effects that may damage the underground structures viz. coal pillars, gallery, junctions and roof, ventilation stoppings, isolation stoppings, water dams and other structures, may create new cracks in roof and pillars and may extend the pre-existing cracks in strata rendering them unstable [2]. There exists potential danger of spontaneous heating due to weakening of coal matrix and danger of spontaneous heating due to coal falling from pillars and roofs in goaf in underground workings due to impact of surface blasting [3]. The blast induced dynamic load absorbing capacity by the underground structures is influenced by age of the underground workings, dynamic tensile strength of the rock mass, type of support system, dimension of the bord and pillar layout, immediate roof rocks condition (whether laminated or massive), quality of the rock mass (expressed by RQD, RMR, NGI Q or density) surrounding the coal seam in which galleries are developed, induced PPV and frequency generated due to explosive loading [4]. Thus, it is very important to define the damage types and evolve technical criterion for assessment and prediction of damage with the ultimate aim of designing a safe and economic surface blasts with little or no damage to underground structures.

In general, factors which influence damage potential of underground (UG) structures due to surface blasting carried out in nearby opencast mine are enumerated below [5].

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(1) Blasting Factors

• Size of blast i.e. explosive charge/delay;

• Explosive type (emulsion, slurry or ANFO) and its characteristics;

• Delay interval;

(2) Rock Mass Factors

• Competence of rock mass and coal i.e. dynamic tensile strength;

• P-wave velocity;

• Geological strength index.

(3) Mining Factors

• Size of workings (i.e. height and width of the UG gallery);

• Support system practiced in UG mine;

• Direction of advancing face from position of UG workings i.e. face orientation;

• Parting thickness/depth of cover i.e. distance between blast site and UG structure.

2. Materials and Methods

The typical section of experimental site comprising of Samleshwari opencast mine (OCM) and Hingir Rampur UG mine showing various seams and coal layers and the positions of opencast and underground workings are shown in Fig. 1. The coal and overburden winning is done by shovel dumper combinations.

2.1 Blast Design Practiced at Experimental Site

In the Samleshwari OCM, the permissible explosive charge per delay imposed by DGMS was 1,650 kg. In this mine, only 10 holes per row were blasted in overburden benches with inter row delay of 100 ms as shown in Fig. 2. The burden relief rate of 8 ms/m was practiced for better muck profile with improved fragmentation. Bulk (emulsion) explosive was used to load all the holes. According to Director General Mines Safety (DGMS) directives and guidelines, total explosive/round was kept at 5 tonne and 30 holes were blasted in a round in overburden benches. The linear charge density of 60 kg/m was fixed for the overburden bench blast charging. The blasting details for the overburden bench of mine site are shown in Table 1.

The blast design at coal bench of Samleshwari OCM is shown in Fig. 3. A total of 10 holes were blasted for total explosive charge per delay to within 600 kg. No intra hole delay was allowed. A 50 ms delay between rows was applied. Free face condition was always ensured for improved fragmentation and

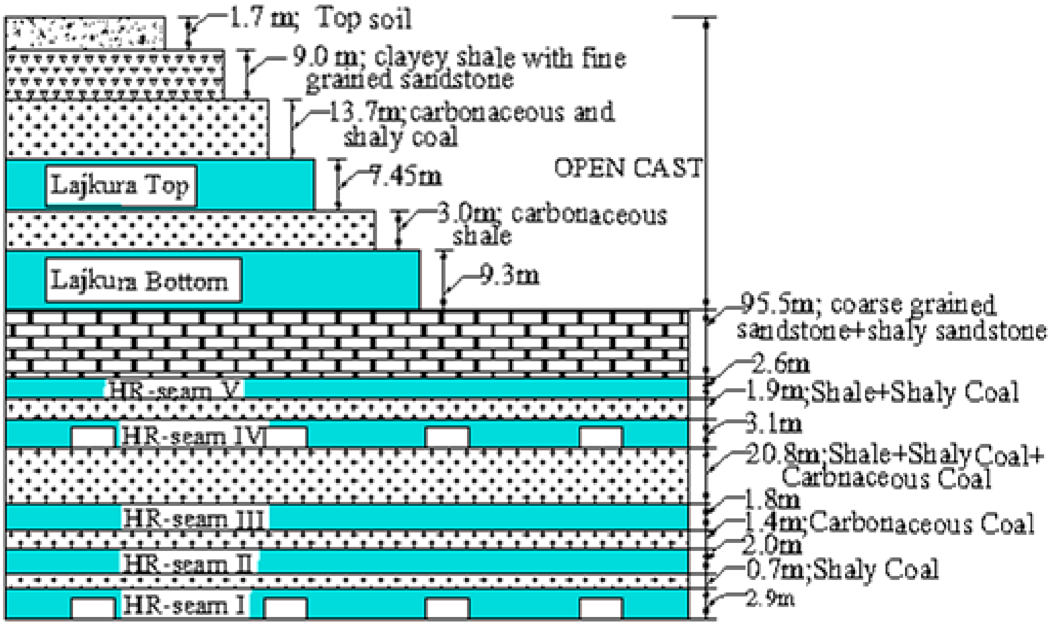


Fig. 1 Typical section showing Samleshwari OCM and Hingir Rampur UG mine.

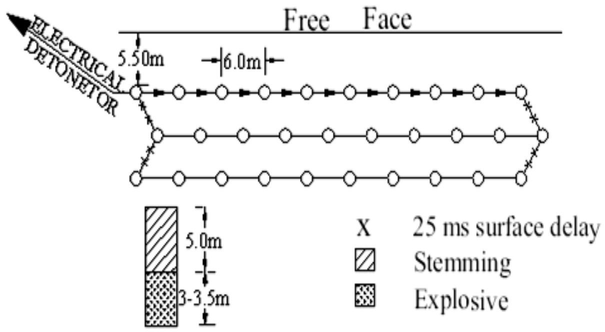


Fig. 2 Experimental blast design at overburden bench at Samleshwari OCM.

Table 1 Blasting details of mine site for OB bench.

Particulars	Description of mine site
Strata blasted	Clayey shale with sandstone overburden bench
Hole diameter (mm)	250
Hole depth (m)	9.5
Subgrade length (m)	NIL
Burden × spacing (m × m)	5.5 × 6.0
Top stemming (m)	5.0
Initiation system	Nonel and detonating fuse with cord relay
Explosive type	Emulsion
Explosive density (g/cc)	1.20
Explosive quantity per hole (kg)	162
Charge factor (kg/m^3)	0.58

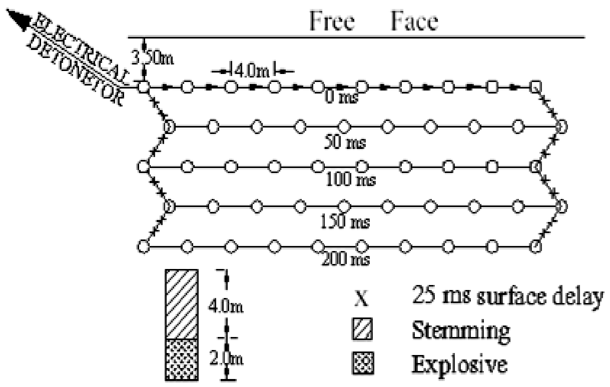


Fig. 3 Experimental blast design at coal benches at Samleshwari OCM.

less ground vibration. In the following, geometry and others blasting parameters for coal bench blasting are mentioned.

The typical drilling and blasting parameters of the blast geometry practiced at overburden bench are shown in Table 2.

Geometry and others blasting parameters for coal bench blasting are mentioned in Table 3.

The plan of the instrumented area of experimental mine site is shown in Fig. 4. Vibrations in terms of peak particle velocity (PPV) were recorded by

Table 2 Typical drilling and blasting parameters at overburden bench.

Drilling and blasting parameters	Value
Hole diameter (mm)	250
Hole depth (m)	8-8.5
Burden (m)	5.5
Spacing (m)	6.0
Stemming height (m)	5.0
Explosive charge per hole (kg)	162
Maximum explosive charge/delay (kg)	1,620
Charge factor (kg/m^3)	0.58

Table 3 Typical drilling and blasting parameters at coal bench.

Drilling and blasting parameters	Value
Hole diameter (mm)	160
Hole depth (m)	6.0
Burden (m)	3.5
Spacing (m)	4.0
Stemming height (m)	4.0
Explosive charge per hole (kg)	44
Maximum explosive charge/delay (kg)	440
Charge factor (kg/m^3)	0.52

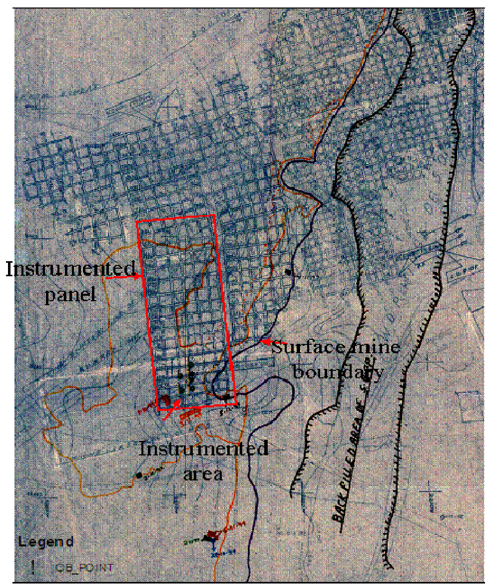


Fig. 4 Mine plan showing the opencast and underground workings at mine site.

geophones. In mine site, a total of 54 observations were recorded at different locations in the roof, pillar and floor. Apart from vibration monitoring, fall of roof, damage in permanent ventilation stoppings and spalling of pillars were also recorded underground right after surface blasting.

2.2 Classification of Observed Damage

To assess the blast damage accurately, the study area in underground mine was properly whitewashed so that the fresh fall from roof or pillar, development of new crack or extension of new crack can be visually noticed. Coal blocks detaching from roof having maximum dimension measuring up to 0.25-0.30 m^3 is assumed as "severe damage" type. The average size of coal blocks in severe damage type ranged between 0.10-0.15 m^3. Some noticeable crack extension and fresh crack development were prominently witnessed in ventilation stoppings. There were instances when small cement mortar patch detached from the ventilation stoppings wall just after surface blast in the Hingir Rampur UG mines. There were number of instances when few loosened chips detached from roof or pillar and coal dust cloud was generated after surface blast in UG workings. This type of damage is termed as "moderate damage". The instance of no spalling from roof or pillar as well as no new visible crack formation in ventilation stopping and other structures is categorized as "no damage".

The observed damage has been classified into three damage groups which are described below [6].

(a) severe damage: fall of rock/coal blocks from roof and/or pillar;

(b) moderate damage: detachment of loosened chips from roof and/or pillar, generation of coal dust after blast, formation of new/fresh visible cracks or extension of existing visible cracks etc.;

(c) no damage: no visual damage.

Visual inspections of the underground workings were carried out after each of the blasts by measuring the size of rock/coal blocks detached from the roof and/or pillars, observing the post blast dust generation and inspecting the area of spalling by measuring the penetration depth of spalling /loosening of chips. As the area under observation was properly white washed, detachment of roof/coal blocks was vividly visible and could be measured easily. The photograph showing the extent of damage in roof, pillar and a ventilation stopping is shown in Fig. 5.

2.3 *Damage Assessment by Blast Damage Factor (BDF)*

A new concept of Blast Damage Factor (BDF) is defined to assess the damage of underground mine workings caused by surface blasting [7]. Blast Damage Index (BDI) is expressed as follows.

$$BDI = \underbrace{\left[\frac{Induced\_Stress}{Damage\_\mathrm{Re}sis\tan ce}\right]} \quad (1)$$

The induced stress is a multiplicative product of peak vector sum (PVS), density and compressional P wave velocity of rock mass. The damage resistance is a multiplicative product of RMR and dynamic tensile strength of rock mass [8]. BDI does not take GSI into consideration and takes RMR as input for damage resistance calculation. The GSI is more user-friendly as compared to RMR. The BDI does not take pillar width and height into consideration which are very vital factors responsible for pillar strength. However, the pillar strength is a function of pillar width and height and may be expressed as shown in Eq. (2) [9].

$$S = S_o\left(\alpha + \beta\frac{W_p}{h}\right) \quad (2)$$

where,

S = Strength of the coal pillar;

S_o = *In situ* strength of coal pillar;

h = Height of the gallery;

W_p = Width of the pillar;

α, β = Constants.

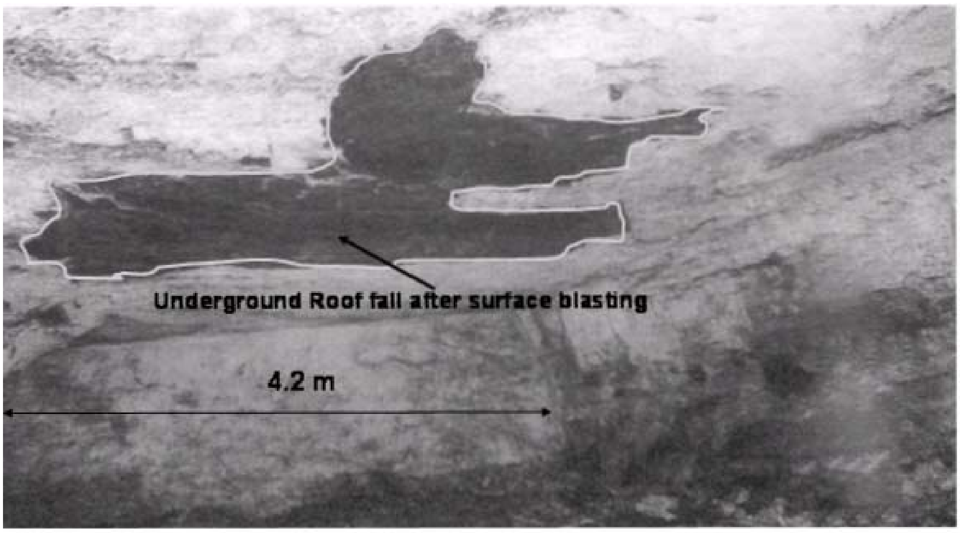


Fig. 5 Photograph showing damaged roof due to blasting (severe damage).

Eqs. (1) and (2) are considered as strength and mining factors for estimation of BDF. The proposed BDF is a dimensionless indicator of damage and expressed by considering strength and mining factors as follows:

$$BDF = \underbrace{\left[\frac{Induced\_Stress}{Damage\_Resistance}\right]}_{\text{Strength Factor}}\underbrace{\left[\frac{Pillar\_Height}{Pillar\_Width}\right]}_{\text{Mining Factor}} \tag{3}$$

$$BDF = \left[\frac{PVS \times \rho \times \mathrm{C_p}}{\mathrm{GSI} \times \sigma_{dts}}\right]\left[\frac{h}{W_p}\right] \tag{4}$$

where,

PVS = Vector sum of peak particle velocity (PPV) in mm/s;

ρ = Density of rock mass in kg/m^3;

C_p = Compressional P-wave velocity of rock mass in m/s;

σ_{dts} = Dynamic tensile strength of rock mass in N/m^2;

GSI = Geological strength index.

As the name suggests BDF must be inverse of factor of safety. It has two components. The Strength Factor component is a measure of inverse of factor of safety of the underground structures when subjected to blast induced dynamic loading. The numerator, the induced stress is a product of PVS, density of rock mass and compressional P wave velocity of the medium (rock mass). The denominator consists of dynamic tensile strength of intact rock multiplied by the GSI of rock mass. Dynamic tensile strength of rock mass can be approximated by $\sigma_{ci}/3.6$ where σ_{ci} is the uniaxial compressive strength of the intact rock [10]. The mining factor is inverse measure of the strength of coal pillars [11]. The mine working factor is incorporated in BDF to evaluate the contribution of pillar geometry in the stability. In general W_p/h denotes the slenderness ratio of coal pillar and has been used in pillar strength equation [12]. Hence, the composite factor will give an indicatory measure of blast induced impact assessment of surface blasts on adjacent underground structures. It may be noticed that BDF is a dimensionless indicator as shown below.

$$\text{Dimension of BDF} = \left[\frac{\left[LT^{-1}\right]\left[ML^{-3}\right]\left[LT^{-1}\right]}{\left[ML^{-1}T^{-2}\right]}\right] = 1$$

For any given mining condition, the variables $\rho, C_p, GSI, \sigma_{dts}$ may be assumed as nearly constant if the roof rock remains the same. The above parameters define the geotechnical properties of rock mass. Under such assumption, it may be inferred that BDF is directly related to PVS. It may be approximated, mathematically, that $BDF = f(PVS)$

and $PVS = h(D,Q)$ where $f(\bullet)$ and $h(\bullet)$ denote the arbitrary functions to be determined from datasets.

3. Results and Discussion

3.1 Damage Prediction by Linear Discriminate Functions

Linear discriminant analysis has been applied for predicting the damage class. Discriminant analysis is a multivariate technique for classifying different observations as well as allocating the new observations into previously defined groups. It can classify multiple multivariate normal populations with equal variance matrix as well as for unequal variance matrix. In the present study, damage has been classified into "Severe, Moderate or No damage" categories. Linear discriminant functions are estimated for these categories or damage classes using predicted peak vector sum. A class Severe or Moderate or No damage is assigned to an unknown observation (BDF) if the estimated value of discriminant function of a particular is the maximum.

Before carrying out the discriminant analysis, the total data have been divided into three parts i.e. training data, validation data and test data using Neural Network Fitting tool (NFTool) wizard of MATLAB 7.5.0 (R2007b) in ratio of 75%, 15% and 10% respectively. The total 54 vibration data recorded at roof of the Hingir Rampur mine are divided into 41 training data, 8 validation data and 5 testing data.

3.1.1 Discriminant Functions of Damage Class for Mine Site Using Artificial Neural Network (ANN) Model

The neural network is trained with 41 dataset [7]. The network architecture with network results and regression analysis of outputs and targets from ANN model are shown in Figs. 6 and 7 respectively. MATLAB (R2007b) has been used for training, validation and testing of the network. Feed forward network using Levenberg-Marquardt optimization technique has been used for training the network by keeping 37 neurons in hidden layer. Tables 4-6 list the observed damage class for the given distance (D) and explosive charge per delay (Q) in respect of training, validation and testing data respectively. The predicted peak particle velocity has been obtained from the network output and listed in Tables 4-7.

The prototype BDF for each dataset is evaluated by averaging the predicted BDF for each blast record shown in Table 4 for training datasets. Then linear discriminant functions of each damage class are obtained as given below:

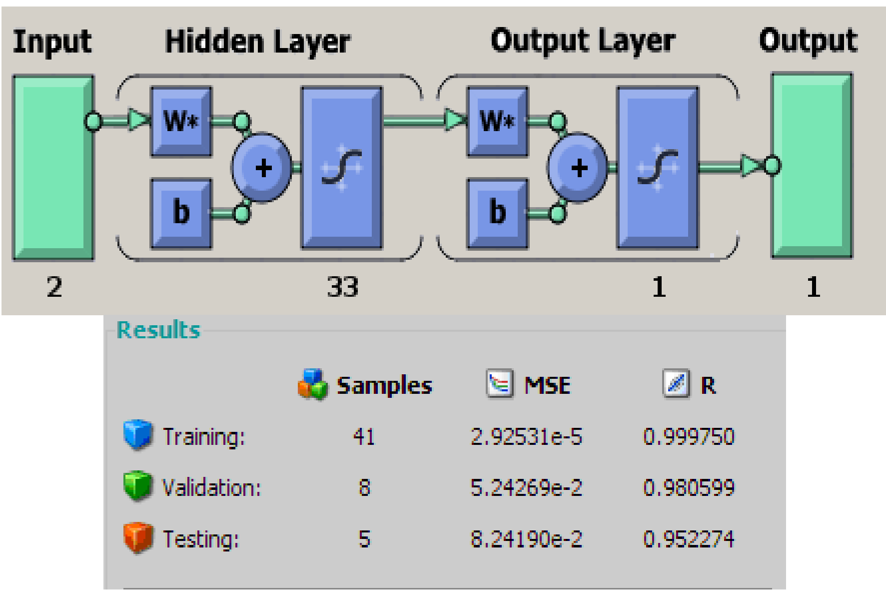
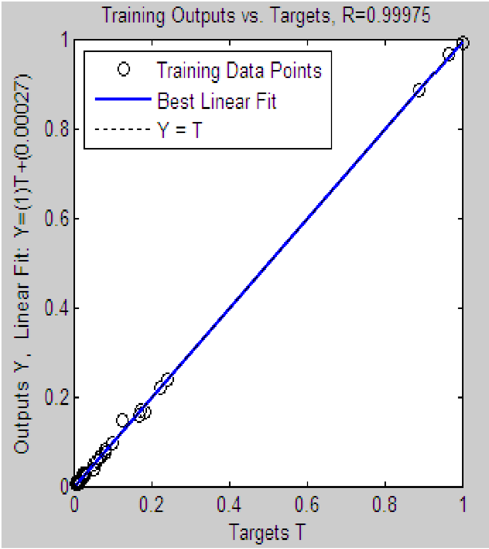
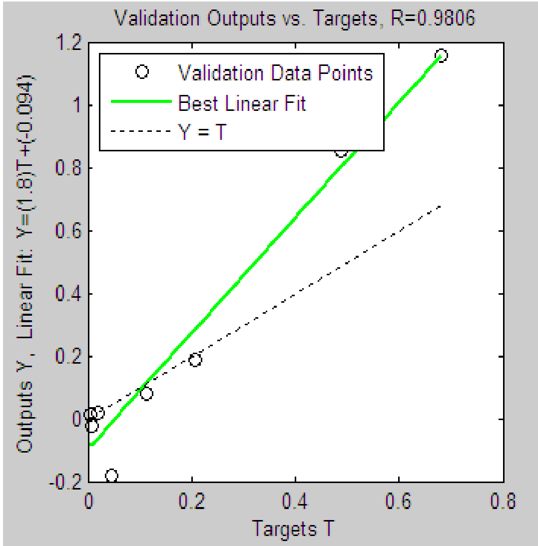


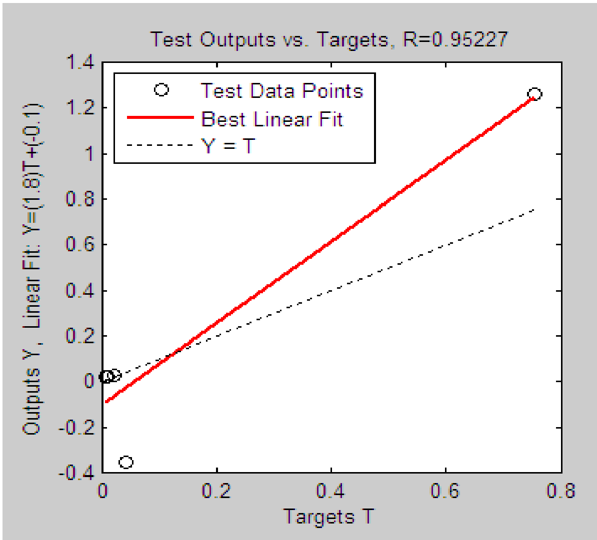
Fig. 6 Network architecture with network results for mine site.



(a) Training



(b) Validation



(c) Test

Fig. 7 Regression analysis of outputs and targets for mine site.

Table 4 Observed damage class and predicted damage class for training data for mine site using ANN model.

Sl. No.	D (m)	$PPV_{predicted}$ (mm/s)	$BDF_{predicted}$	Observed damage	Predicted class
1	143	106.88	8.07	No	Moderate
2	195	11.30	0.85	No	No
4	188	21.51	1.62	No	No
9	173	151.62	11.44	Moderate	Moderate
11	196	82.20	6.20	Moderate	Moderate
12	219	38.70	2.92	Moderate	No
13	161	136.82	10.33	Moderate	Moderate
14	194	52.86	3.99	No	No
15	399	14.02	1.06	No	No
16	418	10.74	0.81	No	No
17	185	49.06	3.70	No	No

Table 4 to be continued

19	292	9.36	0.71	No	No
22	313	13.79	1.04	No	No
23	260	8.69	0.66	No	No
24	312	8.46	0.64	No	No
25	307	28.48	2.15	No	No
26	359	10.59	0.80	No	No
27	212	283.55	21.40	Severe	Severe
28	142	341.67	25.79	Severe	Severe
29	139	344.39	25.99	Severe	Severe
30	150	333.81	25.20	Severe	Severe
33	408	28.56	2.16	No	No
34	438	16.29	1.23	No	No
36	563	6.60	0.50	No	No
37	519	4.73	0.36	No	No
38	548	4.96	0.37	No	No
39	529	4.73	0.36	No	No
40	553	5.18	0.39	No	No
41	481	6.60	0.50	No	No
43	355	38.62	2.92	No	No
44	553	4.73	0.36	No	No
45	506	5.26	0.40	No	No
46	543	4.70	0.35	No	No
47	485	5.55	0.42	No	No
48	514	4.77	0.36	No	No
49	491	5.59	0.42	No	No
50	495	5.41	0.41	No	No
51	321	11.41	0.86	No	No
52	359	19.83	1.50	No	No
53	392	26.32	1.99	No	No
54	426	14.50	1.09	No	No

Table 5 Observed damage class and predicted damage class for validation data for mine site using ANN model.

Sl. No.	D (m)	Q (kg)	$PPV_{predicted}$ (mm/s)	$BDF_{predicted}$	Observed damage	Predicted class
1	156	121	78.62	5.93	No	Moderate
2	204	882	63.90	4.82	Moderate	Moderate
3	212	882	49.06	3.70	Moderate	No
4	210	373	20.35	1.54	No	No
5	303	506	10.44	0.79	No	No
6	170	2,077	340.11	25.67	Severe	Severe
7	188	2,077	333.73	25.19	Severe	Severe
8	504	421	4.85	0.37	No	No

Table 6 Observed damage class and predicted damage class for testing data for mine site using ANN model.

Sl. No.	D (m)	Q (kg)	$PPV_{predicted}$ (mm/s)	$BDF_{predicted}$	Observed damage	Predicted class
1	359	291	31.61	2.39	No	No
2	414	291	18.23	1.38	No	No
3	183	882	119.11	8.99	Moderate	Moderate
4	326	442	20.73	1.56	No	No
5	501	110	5.33	0.40	No	No

$$g_{Severe}(BDF) = 24.60\ BDF\ -\ 302.46 \quad (5)$$

$$g_{Moderate}(BDF) = 7.72\ BDF\ -\ 29.83 \quad (6)$$

$$g_{No}(BDF) = 1.30\ BDF\ -\ 0.85 \quad (7)$$

By comparing the observed and predicted class mentioned in Tables 4-6, it is found that 2 out of 41 and 2 out of 8 data are misclassified in training and validation dataset respectively. There is no misclassification in respect of test datasets.

The predicted BDF has been computed by using Eq. (4). The geotechnical parameters for computing the BDF are shown in Table 3.

3.2 Discriminant Functions of Damage Class for Mine Site by Analytical Model

In this case, predicted PPV for given D and Q is estimated using Eq. (8) obtained by generalized vibration predictor equation where SD shows the scaled distance.

$$PPV = 52301\left(\frac{D}{Q^{0.26}}\right)^{-2.008} = 52301\left(SD\right)^{-2.008} \quad (8)$$

Using the training data mentioned in Table 7, predicted BDF is computed for each dataset. The required geotechnical parameters are taken from Table 1. The prototype BDF for each damage class is determined by averaging the predicted BDF of that class. Linear discriminant functions are then formulated as given in Eqs. (9)-(11) for Severe, Moderate and No damage classes respectively.

$$g_{Severe}(BDF) = 7.69\ BDF\ -\ 29.60 \quad (9)$$

$$g_{Moderate}(BDF) = 3.57\ BDF\ -\ 6.39 \quad (10)$$

$$g_{No}(BDF) = 0.78\ BDF\ -\ 0.31 \quad (11)$$

Then for each dataset given in Table 7 the predicted damage class is determined and listed in Table 7. By comparing the observed and predicted damage class it is found that 3 out of 41 are misclassified in training dataset. There is no misclassification in respect of validation and testing datasets (Tables 8 and 9). As before, majority of the misclassification has no adverse impact on safety as the predicted class has jumped to higher safety band as compared to observed class.

Table 7 Observed and predicted damage class for training data for mine site using analytical model.

Sl. No.	D (m)	Q (kg)	$PPV_{predicted}$ (mm/s)	$BDF_{predicted}$	Observed damage	Predicted class
1	143	65	21.73	1.64	No	No
2	195	65	11.66	0.88	No	No
4	188	121	17.35	1.31	No	No
5	359	291	7.49	0.57	No	No
6	414	291	5.62	0.42	No	No
7	183	882	51.67	3.90	Moderate	Moderate
9	173	882	57.85	4.37	Moderate	Moderate
10	212	882	38.46	2.90	Moderate	Moderate
12	219	882	36.03	2.72	Moderate	Moderate
13	161	561	52.77	3.98	Moderate	Moderate
14	194	561	36.29	2.74	No	Moderate
16	418	819	9.47	0.71	No	No
17	185	373	32.26	2.43	No	Moderate
18	210	373	25.01	1.89	No	No
20	326	442	11.30	0.85	No	No
21	303	506	14.05	1.06	No	No
22	313	506	13.16	0.99	No	No

Table 7 to be continued

25	307	1,705	25.80	1.95	No	No
26	359	1,705	18.84	1.42	No	No
27	212	2,778	70.01	5.28	Severe	Moderate
28	142	1,653	119.37	9.01	Severe	Severe
29	139	1,654	124.64	9.41	Severe	Severe
31	170	2,077	93.70	7.07	Severe	Severe
33	408	63	2.60	0.20	No	No
34	438	63	2.26	0.17	No	No
35	504	421	4.59	0.35	No	No
36	563	421	3.68	0.28	No	No
37	519	240	3.23	0.24	No	No
38	548	240	2.90	0.22	No	No
39	529	275	3.34	0.25	No	No
40	553	275	3.05	0.23	No	No
42	501	110	2.31	0.17	No	No
43	355	47	2.96	0.22	No	No
44	553	47	1.21	0.09	No	No
46	543	69	1.54	0.12	No	No
47	485	250	3.78	0.29	No	No
49	491	168	3.00	0.23	No	No
51	321	883	16.73	1.26	No	No
52	359	883	13.36	1.01	No	No
53	392	281	6.16	0.46	No	No
54	426	281	5.21	0.39	No	No

Table 8 Observed and predicted damage class for validation data for mine site using analytical model.

Sl. No.	D (m)	Q (kg)	$PPV_{predicted}$ (mm/s)	$BDF_{predicted}$	Observed damage	Predicted class
1	399	819	10.39	0.78	No	No
2	292	442	14.10	1.06	No	No
3	312	786	16.67	1.26	No	No
4	150	1,654	106.97	8.07	Severe	Severe
5	188	2,077	76.55	5.78	Severe	Severe
6	481	110	2.50	0.19	No	No
7	514	250	3.36	0.25	No	No
8	495	168	2.95	0.22	No	No

Table 9 Observed and predicted damage class for testing data for mine site using analytical model.

Sl. No.	D (m)	Q (kg)	$PPV_{predicted}$ (mm/s)	$BDF_{predicted}$	Observed damage	Predicted class
1	156	121	25.24	1.91	No	No
2	204	882	41.55	3.14	Moderate	Moderate
3	196	882	45.02	3.40	Moderate	Moderate
4	260	786	24.04	1.81	No	No
5	506	69	1.77	0.13	No	No

3.3 Interpretation of Results

Linear discriminant functions of Severe, Moderate and No damage classes of a given dataset with known D and Q have been determined based on the analytical and neural network models. The major idea is to forecast the blast damage class at an underground location due to surface blast for known D and Q. The results given above can be used as a guideline to determine the damage class. The working chart for mine site based on Q versus D plots for different PPV and BDF is shown in Figs. 8 and 9 respectively. From these figures, estimated value of PPV or BDF can be obtained if D and Q are known. Once BDF is known, damage class can easily be ascertained to ensure safe and economic surface blast.

Further, threshold values of PPV and BDF are also estimated from discriminant functions. The threshold BDF/PPV of the measured data is very close to the threshold PPV/BDF derived from predicted PPV of ANN Model as compared to the threshold PPV/BDF derived from Analytical/ Regression Model as shown in Table 10.

The threshold values of PPV and BDF for Severe, Moderate and No damage in respect of mine site are mentioned below:

The threshold values of BDF are given as follows.

- Severe damage: BDF $\geq$ 12.30;
- Moderate damage: 3.86 $\leq$ BDF < 12.30;
- No damage: BDF < 3.86.

The threshold values of PPV are given as follows.

- Severe damage: PPV $\geq$ 162 mm/s;
- Moderate damage: 51 mm/s $\leq$ PPV < 162 mm/s;
- No damage: PPV < 51 mm/s.

The severe damage in mine site will take place when PPV will exceed 162 mm/s. Moderate damage is expected if PPV ranges between 51 mm/s and 162 mm/s. PPV less than 51 mm/s will have no damage to underground structures.

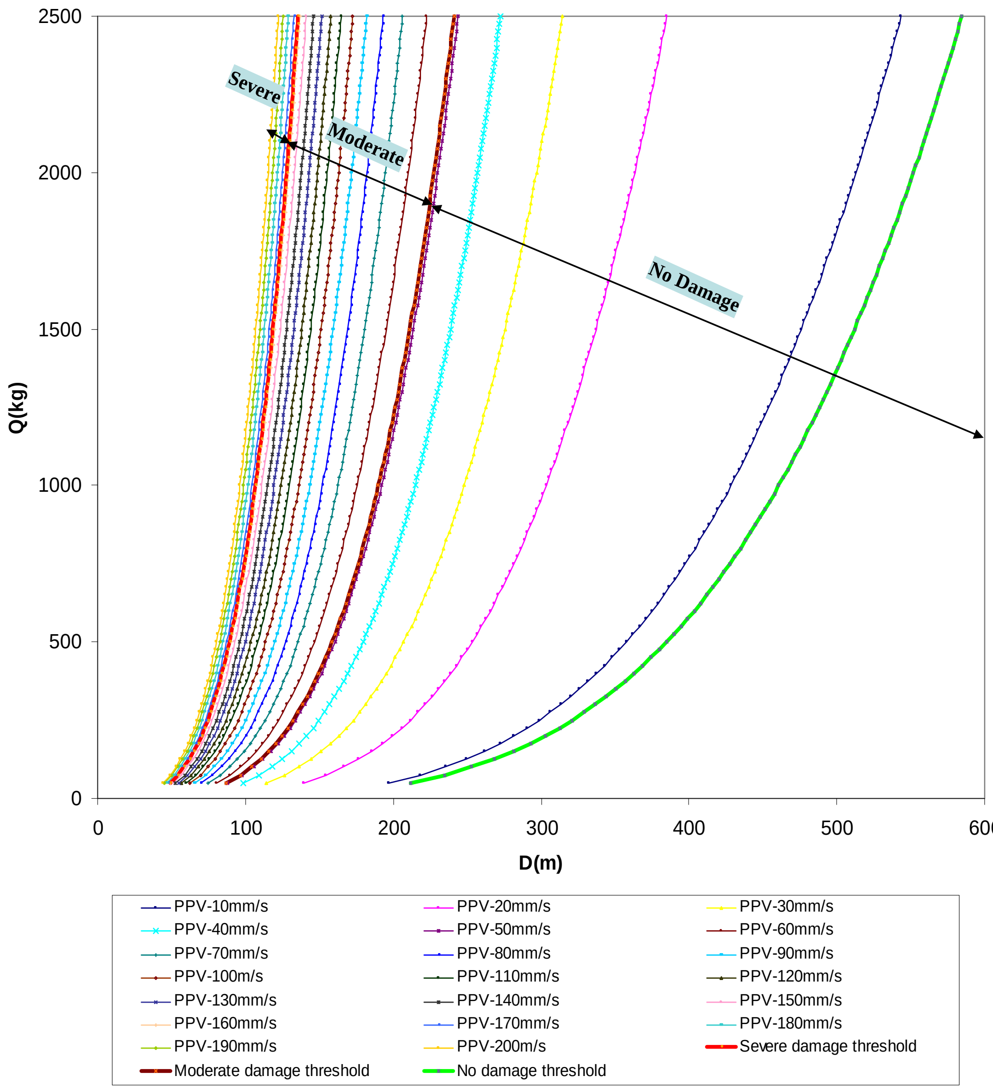


Fig. 8 Relationship between Q and D for different PPV.

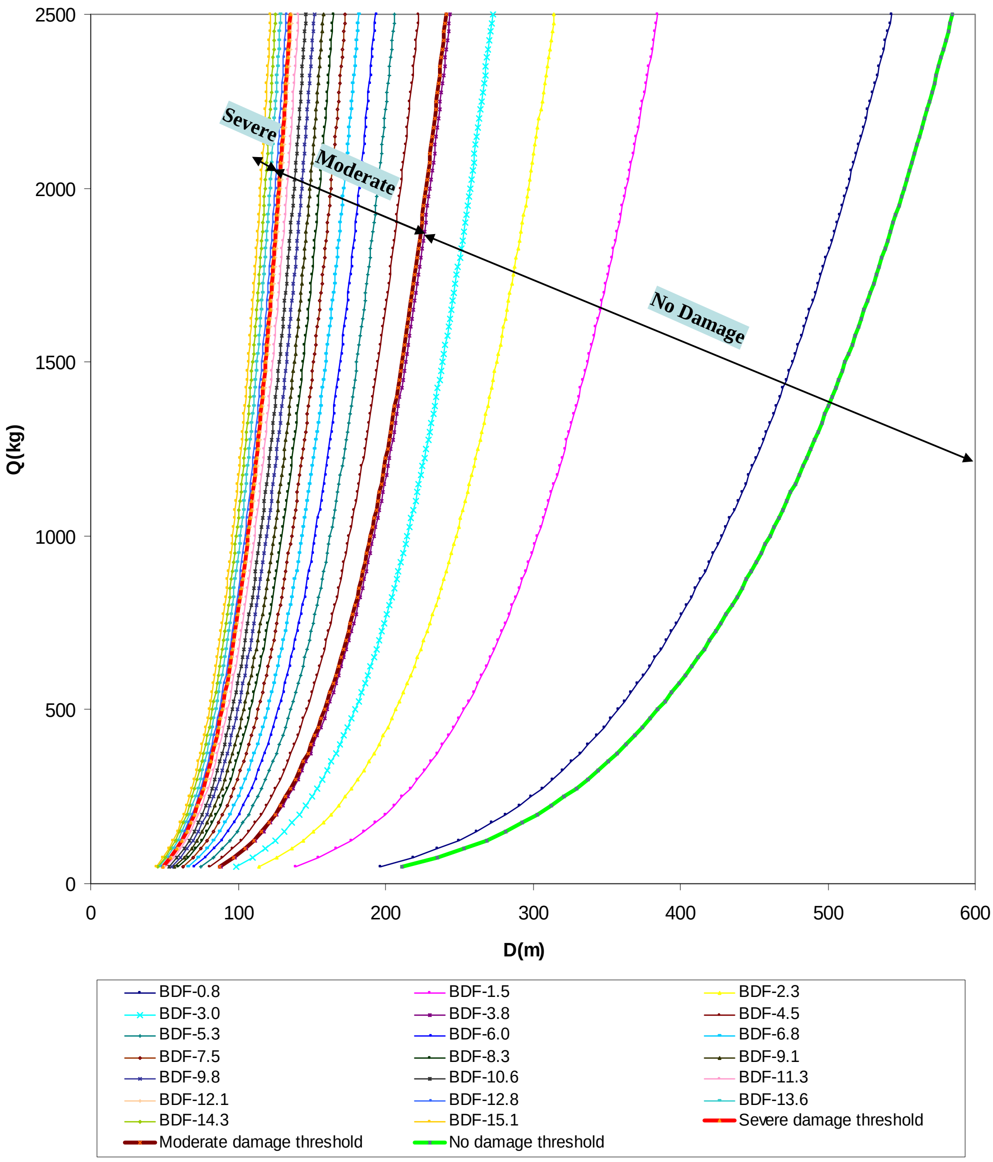


Fig. 9 Relationship between Q and D for different BDF.

Table 10 Threshold PPV and BDF for mine site.

Threshold PPV/BDF derived from measured PPV data			
	Severe	Moderate	No
Threshold PPV (mm/s)	155.64	47.17	5.12
Threshold BDF	11.75	2.81	0.39
Threshold PPV/BDF derived from predicted PPV of ANN model			
	Severe	Moderate	No
Threshold PPV (mm/s)	162.93	51.17	8.64
Threshold BDF	12.30	3.86	0.65
Threshold PPV/BDF derived from predicted PPV of analytical model			
	Severe	Moderate	No
Threshold PPV (mm/s)	50.97	23.68	5.19
Threshold BDF	3.85	1.79	0.39

4. Conclusions

In this study a new concept of Blast Damage Factor has been evolved for damage assessment and prediction. A site specific chart has been developed to predict the blast damage class at an underground location due to surface blast for known distances and explosive charge per delay. It was also observed that the threshold BDF/PPV of the measured data is very close to the threshold PPV/BDF derived from predicted PPV of ANN Model as compared to the threshold PPV/BDF derived from Analytical/Regression Model. Thus, it can be stated that the prediction of ANN models should be used for prediction of PPV in comparison to regression models for better accuracy and reliability in prediction. PPV less than 50 mm/s will have no damage to underground structures however PPV more than 162 mm may lead to severe damage to the underground structures for the case study mine site. The site specific charts should be used by practicing blasting engineers as handy tool for carrying out safe and economic surface blast with no damage potential to underground workings.

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