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What 'aches' my industry?

Deviation between planned and practised blast design in opencast mines in India: a comprehensive analysis

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A comprehensive analysis of blasting data of opencast mines has been conducted for variations in basic design parameters like burden, spacing, stemming and specific charge. 354 data sets of 19 mines belonging to the coal, limestone, and metal sectors have been analysed and presented in this paper. The analysis reveals that there are strong anomalies in the design and application of blasting methods in most of the mines in India. The deviation from the calculated values of the design parameters and the observed values is beyond acceptable limits. This in turn indicates a strong compromise on production in terms of breakage or fragmentation, loading and hauling of the blasted materials. Since there are significant spacio-environmental constraints in present day opencast mines, equipment selection must be in conformity with the production which in turn should define the blast design. The study provides an insight for planners and executing agencies in Indian mining industry when a serious introspection is anticipated for equipment selection in order to achieve optimal production with safety and overall performance of blasting.

Introduction

Blasting is an integral and vital component of a mining operation. The production is precisely dependent on the blasting practice followed by a mine. The best production performance is achieved not only by the appreciation of the underlying principles of blasting but proper selection of the equipment, also. Understanding of blasting process and subsequent design for a particular geo-mining condition has a direct bearing on all the components of a mine-mill fragmentation system. An optimal blast is one which achieves the following norms of productivity and safety.

a. Optimum
   i. Fragmentation
   ii. Throw
   iii. Muck pile angle
b. Minimum
   i. Ground vibrations
   ii Air overpressure/noise
   iii. Flyrock
   iv. Backbreak/damage to next round/final pit walls
   v. Toxic fumes
   vi. Human response

Figure 1 explains the interaction,

Unlike defining the production pattern (Fig.1), the equipment selection is a unique procedure which although a decision process, has no options once selected and deployed. This means that a drilling, loading, and hauling equipment combination should be selected only after ascertaining the current and future requirements of a mine, its production, and safety.

In comparison with the above the objectives of a production pattern or blast design can be achieved when the following components of blasting are properly understood.

1. Type and nature of rock being blasted,
2. Explosive type and its properties being used,
3. Type and size of equipment used for drilling, mucking and hauling of the fragmented rock and it s conformity to the economics of the production, and
4. Rock-explosive interaction vis-à-vis, geo-mining conditions

There are host of parameters that dictate a blast design in a mine and are one way or the other related to the above conditions or norms. Out of these, the drill diameter is one of the most important parameter that dictates the blast design. The basic tenets of the blast design are bench height, burden, spacing and, stemming which are dictated by the drill diameter. These in turn determine the effectiveness of a blast. Smith and Ash (1977) explain their effect on fragmentation.

This paper attempts to analyse the blast designs in terms of above said parameters from a huge database of 354 blasts

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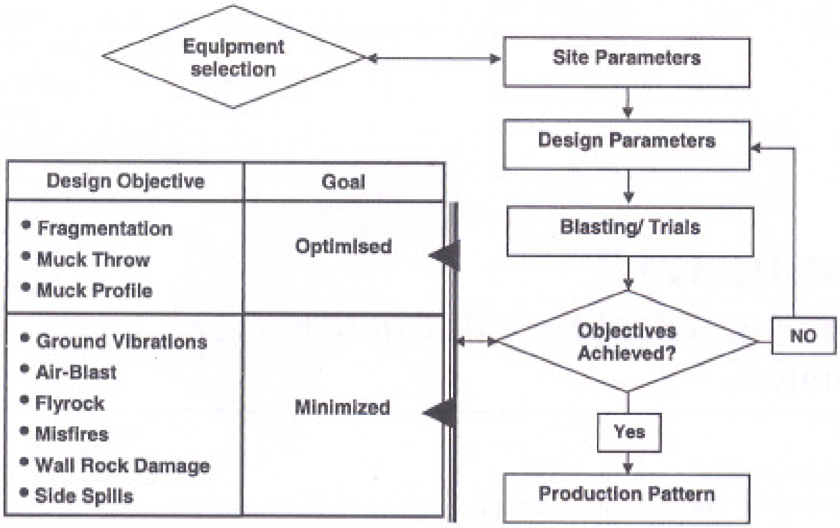

Fig.1 The objectives of blasting operations and the flow in production

generated from 19 mines of coal, limestone and metal sectors in India. The blast designs have been examined over the calculated and practised values in comparison with the theoretically desired and best practices for such mines.

Notations have been adopted for different terminology used in the text as per the ISRM guidelines (Rustan, 1998) and relevant notations to the text of this paper is provided in Table 1.

State of art

There are substantial references available on the subject where basic design parameters of blasting have been stressed and or estimated. Major sources of the literature can be traced to ISEE (2006 – incorporating more than 200 references on the subject), Hustrulid (1999), Jimeno et al. (1995), and ISEE (2005). Most of the literature cited refers to major blast design parameters like drill diameter, burden spacing, density of explosive and charge concentration or specific charge as the major controllable parameters and rock properties like joint spacing and density as uncontrollable parameters. Some of the important references with relevant parameters stressed are given in Table 2.

Jimeno et al. (1995) has given a comparative account of design parameters used by different authors for estimation of burden (Table 3). The relative importance of major parameters has been further explained with the help of Fig.2.

It is amply clear from above table that all authors of burden formulae have used drill/ explosive diameter as the basic blast design parameter in their equations. This necessitates the introspection in terms of drill diameter adopted for a particular mining operation. Other design parameters are covariant of the 'burden'.

Comprehensive analysis of blasting practice in India

In order to evaluate the blasting practice adopted in Indian opencast mines, analysis of 354 blasts was accomplished and is presented here. Data from different mines, metal, non-metal, limestone, and coal mines was considered for analysis. The number data sets (N) used from mine-wise blasts is given in Table 4.

The data collected is exhaustive, only averages of the data observed for different parameters of the blast design have been given in Table 5. The original data presented has been analysed for different objectives earlier also and is incorporated in CIMFR reports.

Since the analysis is a comparative one, the important design parameters of blasting included viz. l_d, B_d, S_d, l_s, q have been estimated using the approach of Konya (1995). The assumptions are:

1. The analysis relates to regular opencast blasting and not to specialised blast patterns,
2. Drill diameter (d) defines the burden in conjunction with rock and explosive type,
3. Burden defines other parameters like spacing and stemming: Burden can be calculated using the equation 1 (Konya, 1995),

$$B = 0.012\left(\frac{\rho_e}{\rho_r}+1.5\right)d_e \qquad \text{... (1)}$$

Where ρ_e : density of explosive; ρ_r : density of rock and d_e : explosive diameter

4. Relevant corrections for jointing, orientation, and number of rows have been applied to find the practical burden.
5. Minimum bench height = 0.06 (d), desired bench height = 3 (B_d) and maximum bench height = 4 (B_d)
6. Desired spacing = 1.5(B_d), minimum spacing= B_d, and maximum spacing = 2(B_d)

TABLE 1: BLASTING TERMINOLOGY WITH UNITS USED IN THE TEXT

Expression	Diameter of blast hole or borehole	Bench height	Borehole length	Drilled burden	Drilled spacing
Symbol	d	H_b	l_d	B_d	S_d
Units	m	m	m	m	m
Expression	Stemming depth	Charge per hole	Specific charge	Density of rock	Density of explosive
Symbol	l_s	q_h	q	ρ_r	ρ_e
Units	m	Kg	Kg/m³	Kg/m³	Kg/m³

TABLE 2: SELECTED REFERENCES WITH EMPHASIS THEREIN RELEVANT TO BLASTING

Author	Year	Factors	Comments/parameters stressed
Agreda	1996	All major	Influence of stochastic variables on performance
Ash	1976	Stiffness	Influence of stiffness on fragmentation
Ash	1979	Spacing	Influence of spacing on fragmentation
Bhandari	1983	Burden	Reduced burden and fragmentation
Bozic	1999	Burden	Role of burden in fragmentation
Brown	1990	Burden	Parameter influence, shot control
Chung & Preece	1999	All major	Muck profile
Cunningham	1988	All major	Fragmentation, muck profile, throw
Chakraborty et al	2002	Stemming	Fragmentation, throw and muck profile, optimisation software
Dick & Olson	1972	Drill dia	Effect on fragmentation, throw
Fletcher.	1986	All major	Flyrock
Gadberry	1981	All major	Planning
Gustafsson	1973	All major	Fragmentation, throw
Hagan	1977	All major	Fragmentation, throw
Hagan & Just	1974	Major	Optimisation
ISEE	1998	All major	Fragmentation, throw
Just	1977	Stemming	Fragmentation
Konya	1982	Stemming	Airblast
Konya	1978	All major	Role of stemming on Ground vibration
Kopp, J.W.	1994	All major	Flyrock
Langefors and Kihlstrom	1978	All major	Fragmentation, throw
L.- Pedersen and Holmberg	1973	Major	Charge geometry and flyrock
Moore	1975	All major	Empirical estimation of design through crater blasting
Morlock & Daeman	1983	All major	Airblast
Moxon et al	1993	Major	Role of design parameters on fragmentation
Nielsen	1985	All major	Sensitivity analysis of factors for optimisation
Pugliese	1972	All major	Design considerations defined H_{avg}=2.6; H_{max} =4 or more
Ramulu et al	2004	Burden	Ground vibration
Raina et al	2006	All major	Factor of Safety for Flyrock
Raina et al	2007	All major	Factor of Safety for fragmentation
Richards & Moore	2004	All major	Flyrock
Rodgers, J.	2003	Burden	Ground vibration
Rosenthal & Morlock	1987	All major	Sensitivity analysis of parameters vis-à-vis vibration
Smith	1976	Burden	Role of stiffness in blast performance
Smith & Ash	1977	All major	Role of factors in fragmentation
Thomas	1986	Drill diameter	Fragmentation
Tiddman	1991	All major	Fragmentation models/targets
Workman & Calder	1994	All major	Flyrock control

7. Desired stemming = 0.7 (B_d), minimum stemming = 0.6 (B_d) and maximum stemming = 1.0 (B_d)
8. For specific charge (q) ± 10% of the calculated value has been considered for minimum and maximum, respectively
9. The standard deviations of the major design parameters for each mine have been worked out based on the above assumptions for minimum and desired values.
10. The standard error has been worked out using the ratio of standard deviation to number of blasts recorded for each mine.

The calculations for above parameters with the above assumptions and values thus obtained have been compared to the observed values in actual blasts. Representations of desired and best configurations have also been brought out for further deductions. Graphical representation and statistics of such analysis have been used as aid to understand the practice and to draw inferences.

Bench height is the major factor determining the stiffness ratio (H_b/B_d) of a blast hole and has been compared to the drill diameter. This is in tune with the referential matter in Tables 2 and 3 wherein focus has been on the (H_b/B_d) ratio of the bench. It is clear from Table 6; (H_b/B_d) ratio is a major blast design factor that has a significant influence on the

Table 3: Parameters considered for burden calculations by different authors

Parameters used / Author/year	Andersen (1952)	Fraenkel (1952)	Pearse (1955)	Hino (1959)	Allsman (1960)	Ash (1963)	Langefors (1963)	Hansen (1967)	Ucar (1972)	Konya (1972)	Foldesi (1980)	Praillet (1980)	Jimeno ((1980)	Berta (1985)	Carr (1985)	Konya (1995)	Olofsson (1990)	Rustan (1990)
Diameter of blast hole or of charge	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Bench height								√	√			√					√	
Length of blast hole	√	√																
Stemming												√						
Sub drilling												√						
Length of charge		√						√	√									
Inclination of blast hole							√							√			√	
Rock density				√	√								√		√	√		
Compressive rock strength or equivalent indexes		√	√	√							√	√		√				
Rock constants or factors	√		√				√	√									√	
Seismic velocity of the rock mass													√	√	√	√		
Density of the explosive						√	√	√	√	√	√	√	√	√	√		√	
Detonation velocity						√						√	√	√	√			
Detonation pressure		√	√	√														
Binomial rock-explosive constant				√														
Burden/spacing ratio							√											
Strength of explosive							√										√	
Loading equipment																		

For references therein cf. Jimeno et al. (1995)- Ö - considered, blank space – not considered

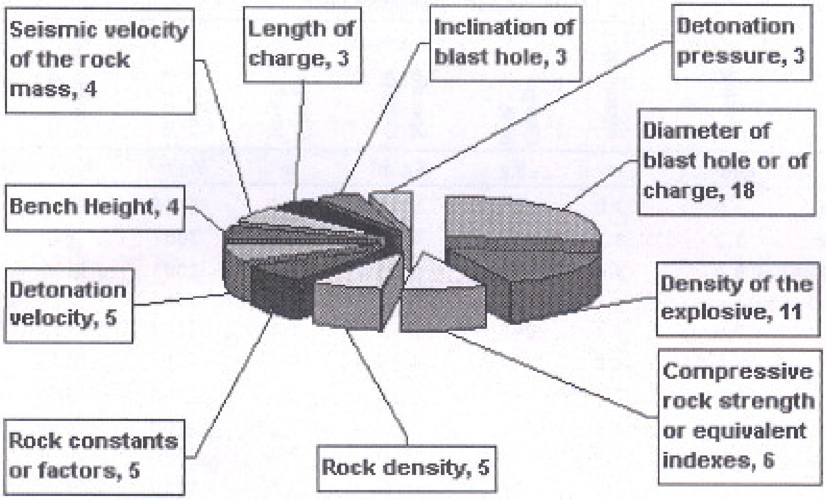

Fig.2 Pie diagram of design parameters used for burden calculations

fragmentation, flyrock, ground vibration, and air blast. Moreover, since burden has a limited range of variation, bench height assumes a major role in defining the blast performance.

A plot of bench height vs. drill diameter has been given in Fig.3 along with trend-lines of minimum, desired, and best values for different drill diameters.

The percentage data for different stiffness ratios is also included in Table 6 in order to make a comparison. The figures indicate that only 21% of the data has the best stiffness configuration.

A significant departure of measured values in bench height is depicted from the above plot. A minor fraction of the data is observed to occupy the space between desired and best bench limits.

Drill diameter has also been plotted vs. calculated and observed values of B_d (m), S_d (m), l_s (m) and q (kg/m^3) in Figs. 4 (a, b, c, d), respectively. Significant deviations from calculated values of the major blast design parameters are observed from the exploratory analysis of the data from the figures.

The individual variation of observed B_d, S_d, l_s and q is amply clear from their plot against the calculated values shown in Figs. 5 (a, b, c, d). The scatter in data is also amply clear from the observed and theoretical values of individual parameters. Not only does it point to the variation in calculated and observed values in relation to the drill diameter used, but there is a significant scatter in the data for each drill diameter used in the field. The figures are quite implicit and point towards a poor consideration for blast design and its implementation.

TABLE 4: DETAILS OF MINE(S), RELEVANT DETAILS AND NUMBER OF BLAST OBSERVATIONS

	Mine type	Number of blasts observed (n)	Size of equipment used (T)	
			Loading (m^3)	Hauling (T)
1	Coal	20.0	4.0	50
2	Coal	15.0	4.0	50
3	Coal	19.0	10.0	50
4	Coal	26.0	10.0	50
5	Coal	17.0	10.0	50
6	Coal	37.0	4.0	50
7	Coal	15.0	10.0	50
8	Coal	25.0	10.0	50
9	Coal	10.0	10.0	50
10	Limestone	12.0	2.4	35
11	Limestone	27.0	2.4	35
12	Limestone	16.0	2.4	50
13	Limestone	14.0	2.4	50
14	Limestone	32.0	2.4	50
15	Limestone	11.0	2.4	50
16	Mn-Ore/OB	23.0	2.4	35
17	Mn-Ore/OB	10.0	1.6	10
18	Cu-Ore/OB	23.0	10.0	50
19	Fe-Ore/OB	2.0	2.4	20
	Total (N)	354.0		

The anomalies observed above are not within acceptable limits of the statistical error. This also necessitates an individual analysis of different mines so that there is clear demarcation of blasting practice observed by different mining sectors.

Discussion

The descriptive results of the predicted and observed values given in Figs. 4 and 5 can further be analysed in terms of percentage of data that fits in desired or best category of major blast design parameters as discussed above. This is helpful in evaluating the status of the blasting practice in mines in India, which is distributed over wide area in the country.

A summary table of the results for different parameters observed in the said mines vis-à-vis minimum, desired, and best values for the said parameters have been worked out from the data and is given in Table 7. The least number in this case indicates less deviation as is found in case of stemming. Percentage of the data for parameters considered that is below the desired levels is also given in the said table.

Statistically, a 10% error from the desired values could be considered normal but in present case not even a single parameters is within said limit. Instead, all the parameters are

Table 5: Average of the parameters observed in the field for different mines

Mine type	Hole diameter	Bench ht	Hole depth	Burden	Spacing	Stemming	Charge/ hole	Specific charge	Charge length	Density of rock	Density of explosive
	m	m	m	m	m	m	Kg	Kg/m³	m	Kg/m³	Kg/m³
Coal	0.150	6	5.8	2.6	3.0	3.0	26	0.57	2.7	2134	980
Coal	0.150	6	5.7	2.4	3.2	3.1	26	0.56	2.5	2007	960
Coal	0.258	18	18.8	8.3	9.6	5.4	827	0.55	13.5	2005	1115
Coal	0.150	8	8.1	4.6	6.4	3.1	80	0.33	5.0	2187	1125
	0.250	10	10.3	5.7	7.0	4.4	269	0.77	5.9	2249	1120
Coal	0.250	13	13.4	6.1	8.2	4.2	327	0.52	9.2	2236	1123
Coal	0.150	5	5.9	5.2	5.7	1.7	37	0.26	4.2	1900	980
Coal	0.160	7	6.6	3.8	4.2	4.4	50	0.48	2.2	2100	1050
	0.250	8	7.4	5.1	5.4	4.0	92	0.41	3.4	2100	1050
Coal	0.160	7	7.0	3.9	4.7	4.0	76	0.62	3.0	1940	950
	0.250	17	18.1	6.1	6,2	4.6	477	0.68	13.5	1940	950
Coal	0.260	28	27.9	7.3	7.7	7.2	1038	0.66	20.7	2000	950
Cu_ore	0.165	13	13.7	3.3	4.2	5.1	157	0.95	8.7	2450	1100
Fe-Ore	0.110	4	4.2	2.5	3.0	2.1	17	0.59	2.0	2425	980
Limestone	0.110	8	8.5	3.4	4.1	2.8	39	0.36	5.7	2383	985
Limestone	0.100	6	6.6	2.8	3.8	2.2	19	0.32	4.5	2383	915
	0.150	7	7.4	4.1	5.8	3.0	63	0.39	4.4	2352	899
Limestone	0.150	9	9.3	3.9	6.3	3.7	63	0.29	5.6	2449	925
Limestone	0.115	5	5.4	2.9	3.9	2.3	22	0.36	3.1	1979	961
Limestone	0.110	9	9.4	3.8	5.0	3.6	58	0.35	5.7	2400	1000
Limestone	0.102	5	5.4	3.5	4.2	2.1	27	0.34	3.3	1777	1000
	0.110	4	4.3	3.2	3.8	2.1	20	0.44	2.2	1777	1000
Mn-Ore	0.110	7	6.7	2.0	2.4	2.8	17	0.71	3.9	2637	906
Mn-Ore	0.100	5	5.3	1.4	2.5	2.9	13	0.79	2.4	2430	980

Table 6: Relation of blast performance to bench stiffness (after Konya, 1995)

Stiffness ratio (H_b/B_d)	1	2	3	4
Fragmentation	Poor	Fair	Good	Excellent
Air blast	Severe	Fair	Good	Excellent
Flyrock	Severe	Fair	Good	Excellent
Ground vibration	Severe	Fair	Good	Excellent
Comments	Severe back-break and toe problems Do not shoot. Redesign	Redesign if possible	Good control and fragmentation	No increased benefit by increasing stiffness. ratio above 4
Indian mining scenario (Data%)	4%	38%	37%	21%

well beyond the desired limits. The greatest value 79% is that of the bench height which happens to be a defining parameter in blasting.

Bench height for a blast is defined by:

1. The drill diameter, it is evident that there is a mismatch of drill diameter in most of the cases in the above data.
2. Stipulations in tune with the loading equipment or slope.

Since condition 2 above is a safety concern and cannot be overruled or changed, we are left with a serious introspection on selecting the drill size.

In order to ascertain the mine-wise error in the major blast design parameters, the standard error from the theoretical values of desired/best have been calculated and are presented in Table 8. The calculations from the data have been made in the following manner.

a. Data from all mines is organised with the parameters under consideration,

b. Difference from minimum calculated and minimum desired and the observed value is calculated,

c. Standard deviations for both the conditions are worked out to further ascertain the standard error of the means.

d. The standard error is averaged, giving equal weight to all 5 parameters (B_d, S_d, l_s and q and d) considered and plotted for each mine (Fig.6).

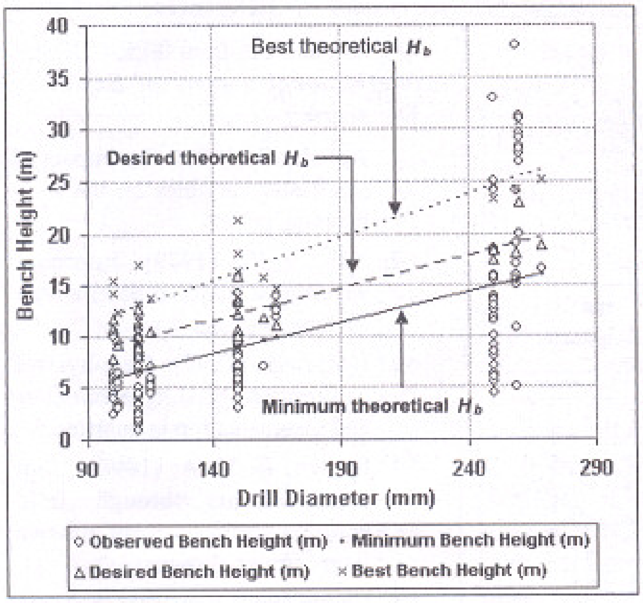

Fig.3 Bench height vs. drill diameter used in some mines in India

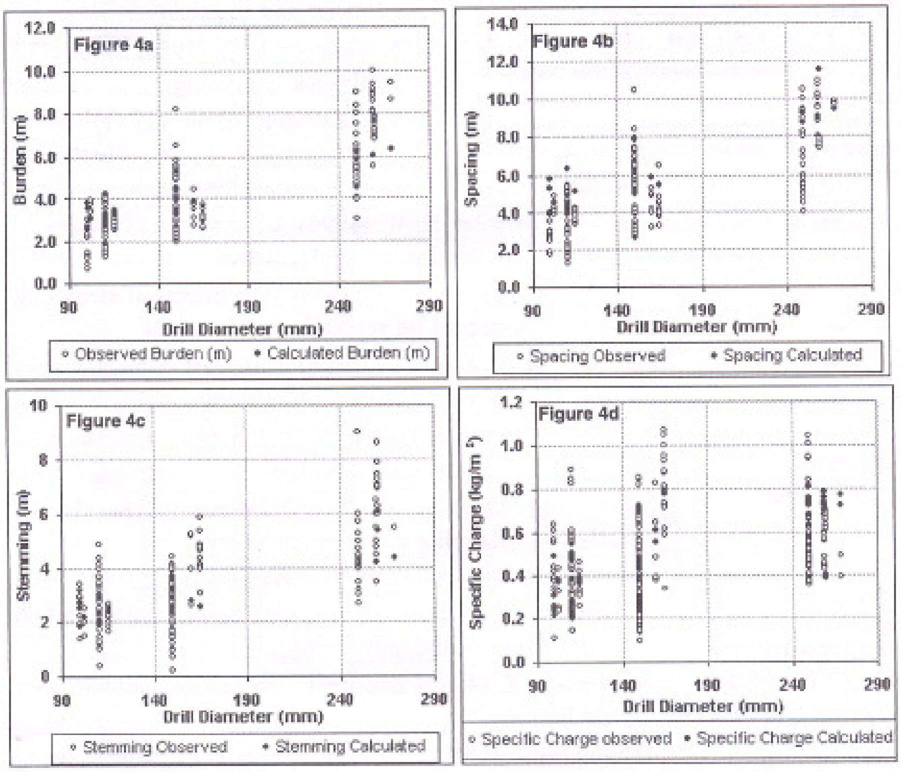

Fig.4 (a to d) Observed and calculated (theoretical) values of B_d, S_d, l_s and q vs. d, respectively

A sector wise classification has been made in Fig.6 for coal, limestone, and metal mines and is also presented in Table 9.

The errors presented above are quite indicative of the fact that there is significant error in the blast design from the calculated one. The relatively best practice adopted in Indian mining scenario is that of the limestone sector which records least error in contrast to the metal and the coal sectors. A further look at Table 6 gives an insight into the overall picture of our blasting practice. There are still some blasts which may not be considered safe, most of the blasts are working in the fair and good category and a only 21% blasts qualify for the best category.

Conclusions

It is imperative from the study of the blast design for a large data from 19 opencast mines that the blast designs are significantly deviating from the acceptable statistical levels. This is demonstrated by huge design and implementation errors brought out over here. The anomalies may be representative of random, initiative based blast designs rather than a scientifically thought and experimented ones.

Despite of the fact that limestone mines show a relatively less error that points to a better thought blast designs, the overall scenario is not up to the mark. The coal sector that is a major mining industry in India records far more error in the blast design and practice. There is practically a need to grow in terms of the design and practice of blasting as most of the blasts observed reckon in fair to good categories of blasting expressed in terms of parameters of concern for optimisation (Fig.1 and Table 6).

It is hence concluded, for 2 cases viz.,

1. Existing mines, should consider revising the blasting practice by conducting a thorough investigations into the blast designs, equipment compatibility – particularly of drill diameter. This shall include economical evaluation, feasibility of the equipment available vis-à-vis spatial and environmental constraints, optimisation studies and blast auditing for optimal performance and maximum system utilisation. Steps like changing the drill diameter in future should be considered.
2. Mines that are at planning stage should consider all aspects of blasting, environment, pit slope, and stipulations while simulating conditions over a period of life of the mine. A comprehensive analysis of these parameters should be conducted and equipment selected accordingly which in turn should match the blast design or practice.

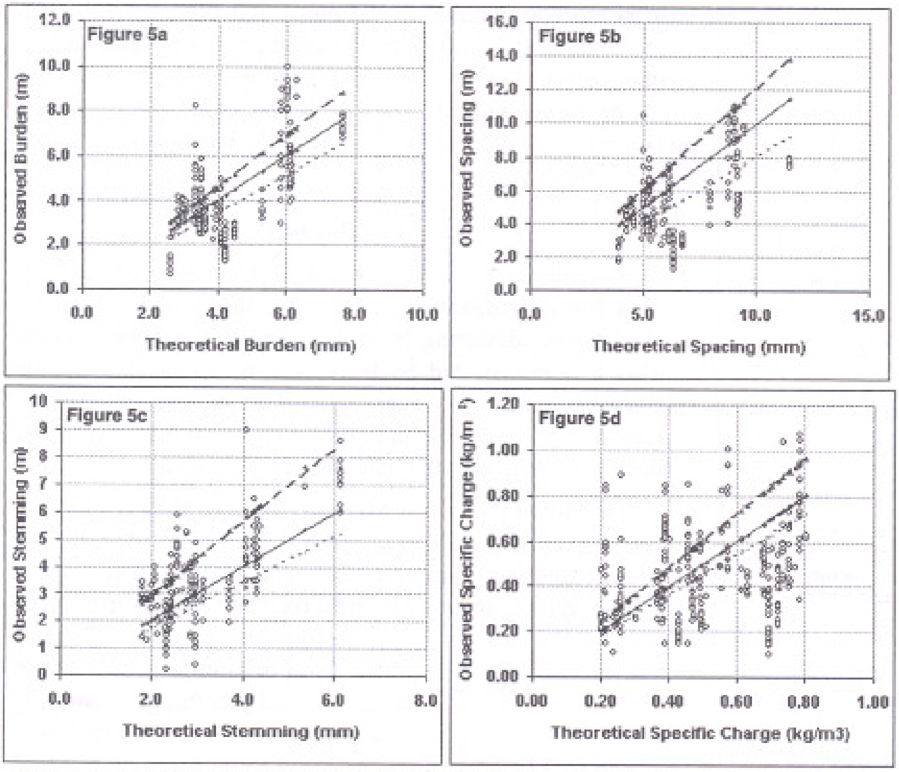

Fig.5 (a to d): Observed and theoretical values of B_d, S_d, l_s and q, respectively (the lower, middle and upper straight lines represent minimum, desired and best values of the parameters, respectively)

TABLE 7: SUMMARY TABLE OF OBSERVED PARAMETERS IN RELATION TO CALCULATED VALUES

	Parameter	Number of observations where value is less than (N=354)			
		Minimum	Desired		Best/ maximum
			Number	%age	
1	Bench height	216	280	79	336
2	Burden	133	202	57	235
3	Spacing	173	253	71	319
4	Stemming	77	125	35	262
5	Specific charge	169	206	58	258

It is recommended that procedures given in various blasting manual for such exercise should be adopted. Some software(s) that are commercially available like CMRI_Visfot may be considered for blast optimisation in order to define the production pattern.

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TABLE 8: STANDARD ERROR OF MAJOR PARAMETERS FROM THE THEORETICAL VALUES

	Mine	Bench height		Burden		Spacing		Stemming		Specific charge	
		Min	Desired	Min	Desired	Min	Desired	Min	Desired	Min	Desired
1	Coal	3.30	7.71	1.94	2.61	3.78	5.13	0.33	1.50	0.25	0.20
2	Coal	3.03	6.21	1.76	2.37	3.00	4.23	0.78	1.20	0.18	0.15
3	Coal	7.77	7.23	2.49	1.68	1.07	1.55	1.62	1.32	0.23	0.37
4	Coal	4.99	6.50	1.59	1.57	2.01	2.69	1.05	1.35	0.34	0.47
5	Coal	2.34	5.73	0.37	1.04	1.05	2.87	0.50	2.04	0.19	0.32
6	Coal	3.67	4.64	2.04	1.61	1.78	1.63	1.02	1.79	0.45	0.58
7	Coal	5.57	8.57	0.98	1.70	3.23	4.82	1.53	2.02	0.20	0.32
8	Coal	8.64	8.70	1.36	1.64	3.07	4.78	0.77	1.59	0.21	0.21
9	Coal	12.62	5.71	0.51	1.57	3.79	6.09	1.31	0.87	0.27	0.19
10	Limestone	1.94	1.50	0.66	0.40	0.34	1.05	0.80	0.26	0.23	0.33
11	Limestone	2.18	8.38	1.20	1.93	2.17	3.63	0.75	2.18	0.11	0.09
12	Limestone	1.26	3.44	0.51	0.95	0.69	1.22	0.90	0.54	0.20	0.28
13	Limestone	1.60	4.98	0.62	1.10	1.36	2.37	0.32	1.20	0.05	0.10
14	Limestone	2.25	0.52	0.91	0.52	0.68	0.54	1.59	0.73	0.14	0.23
15	Limestone	2.57	5.08	0.50	0.41	0.77	1.60	0.33	1.11	0.10	0.14
16	Mn-Ore	3.86	7.19	2.29	2.91	4.05	5.31	1.25	1.87	0.31	0.28
17	Mn-Ore	1.65	3.05	1.29	1.66	1.47	2.22	1.23	0.66	0.12	0.16
18	Cu-Ore	2.69	1.63	0.51	1.00	1.44	2.47	2.61	1.59	0.28	0.36
19	Fe-Ore	3.07	4.57	0.21	0.62	1.07	1.88	0.85	1.01	0.06	0.17

Min – Indicates minimum

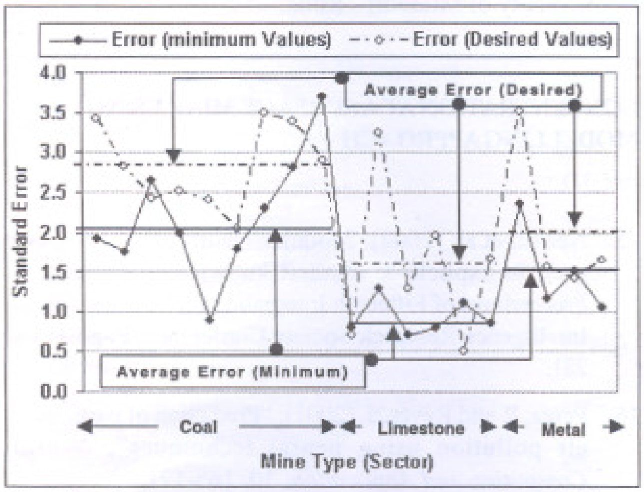

Fig.6 Standard error (averaged over 5 parameters) from minimum and desired values of parameters

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TABLE 9: SECTOR-WISE AVERAGE STANDARD ERRORS

Rank	Mine sector	Standard error average of 5 parameters	
		Minimum	Desired
3	Coal	2.20	2.82
1	Limestone	0.92	1.56
2	Metal	1.52	2.03

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