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Application of digital image analysis for monitoring the behavior of factors that control the rock fragmentation in opencast bench blasting: A case study conducted over four opencast coal mines of the Talcher Coalfields, India

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ABSTRACT

Drilling and blasting play a very important role in driving the economy of opencast mines, as various mining activities related to strata handling are dependent on the size of the rock mass created due to blasting. Thus the analysis of fragments created from rock explosion is essential in order to monitor its compatibility with the deployed mining machineries/HEMMs (such as shovel, dumper, dragline, etc.). As over fragmentation as well as under fragmentation both tend to increase the cost of mining, the generation of fragment size in the desired range is necessary. Several factors control the rock fragmentation in blasting, such as the burden, bench height/drilling depth, stemming column, powder factor and hole diameter. The assessment of rock fragmentation with respect to the aforementioned parameters helps to enhance the blast performance and, hence, this study intends to carry out digital image analysis for monitoring the mean fragment size and boulder percentage. A highly consistent result has been obtained using forty blasting datasets carried out in the four different opencast mines of the Talcher Coalfield (India), namely Balram OCP, Ananta OCP, Lakhanpur OCP, and Lajkura OCP.

1. Introduction

Coal acts as a major driving force for the Indian economy, by serving 64% of the total primary energy requirements of the country in various forms (Mondal et al., 2017). The majority of Indian coal is mined through opencast mines (Annual production in 2013-14 through (a) Opencast mines: 426.31 Mt; (b) Underground mines: 34.36 Mt) (Ghose, 2001), which are mainly situated in Central and South Eastern parts of the country, in the states of Chhattisgarh, Madhya Pradesh, Jharkhand and Orissa, and are mostly controlled by various subsidiaries of Coal India Limited (CIL).

The economic susceptibility of an opencast mine is very much dependent on drilling and blasting activities, which is also the most common method for breaking rocks in mines. The importance of blasting in the Indian mining industry can be inferred from the heavy consumption of explosives during the production years 1976–2014 (Fig. 1). According to the Directorate General of Mines Safety (India), approximately 585.1 Mt of explosives were used in 567 coal mines in the country in various forms in 2014 (DGMS, 2014); 460 of these mines belonged to CIL and, the annual explosive consumption was about 438.4 Mt. It was also seen that the Northern Coalfields Ltd., Mahanadi Coalfields Ltd. and South Eastern Coalfields Ltd., which contained the majority of the Indian opencast mines had the highest consumption of explosives of about 126.04 Mt, 61.59 Mt and 90.02 Mt, respectively, therefore highlighting the importance of explosives and rock blasting in opencast mines.

Blasting is a very expensive operation and the explosives themselves represent 5% of the total coal production cost. Therefore, explosive costs play a vital role in maintaining the economic feasibility of opencast mines. The main objective of blasting in opencast mines is to create a muckpile of the desired fragment size, which can be easily transported using the equipment (draglines, shovels and dumpers) deployed in the mine. Therefore, the optimization of blasting is highly necessary for sustainable mining and it is said to be optimized when both the cost of blasting as well as the handling of fragmented rocks are kept to a minimum (Morin and Ficarazzo, 2006). Presently, investigations are

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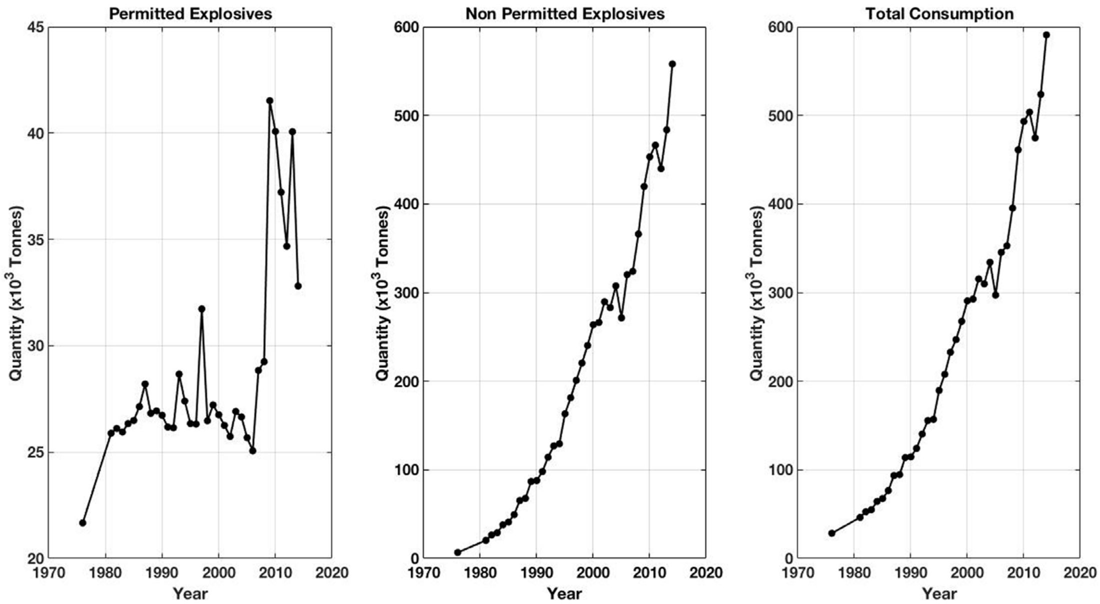

Fig. 1. Consumption of permitted and non-permitted explosives in India for the production years 1976–2014.

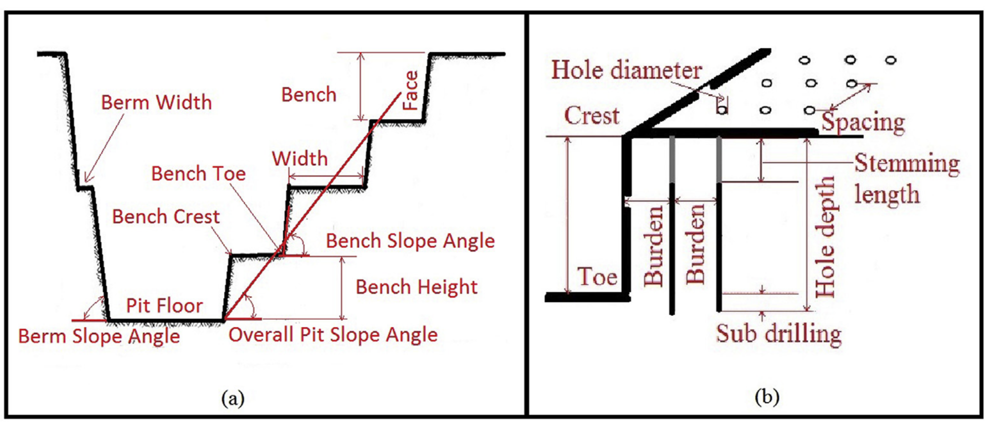

Fig. 2. (a) Layout of a bench in opencast coal mine. (b) Basic blast design parameters.

being carried out to optimize the blasting for overall profitability rather than some specific operations, which is also known as the 'mine to mill' blasting approach (Grundstrom et al., 2001). The response of blasting over rock fragmentation is very complex, due to the heterogeneous and anisotropic behavior of the bench rock. Therefore it is very difficult to obtain a mathematical relation between the rock fragmentation and blast design parameters, which are broadly categorized into two groups: [a] Controllable parameters, and [b] Uncontrollable parameters (Hudaverdi et al., 2012). The blast design parameters, such as burden, spacing, hole inclination, bench height, hole depth and diameter, stemming length, sub drilling pattern, blasting initiation etc. are controllable parameters (Kulatilake et al., 2010). In opencast mining, bench design and blasting is a common method for overburden removal. The basic layout of a bench in an opencast coal mine and the blast design parameters are shown in Fig. 2a, b). The distance between the blast hole and free space is known as the burden (*B*), i.e. it is the load that is to be displaced by the explosives, whereas the distance between two consecutive blast holes is known as the spacing (*S*). The total depth of the blast hole drilled is called the hole depth (*HD*) and the extra depth drilled below the floor for obtaining clear breakage is called the subdrilling. The blast drill holes are partly filled with explosives and the remaining top end portion of the hole is filled with inert materials for storing the explosive energy for a longer period of time in order to increase rock fracturing, this portion is known as the stemming length (*T*). These are all controlled parameters, whereas the rock properties, such as rock mass structure, orientation, rock density, compressive strength (*UCS*), shear strength, elastic properties of rock, grain size, etc. are uncontrollable parameters (Kulatilake et al., 2010).

The rock fragments that result from blasting are also divided into three broad categories: [a] Oversize (further fragmentation is required in the form of secondary breaking before handling, effectively $MP_{UG} > 300$ mm; $MP_{OC} > 1000$ mm, where MP_{UG} and MP_{OC} are the mean particle sizes for underground and opencast mines, respectively), [b] Mid-range (significant particle size and easy to handle), and [c] Fines (very fine grains and difficult to handle; for coal $MP \sim 6$ mm) (Cunningham, 1996). However, the aforementioned categories may vary depending on the equipment deployed for handling the blast fragments, and the cost of mining is minimal when optimum/desired fragmentation is achieved as per the instrumentation setup and conveyor system (Mackenzie, 1967). This paper uses forty opencast bench blasting datasets from four opencast mines of India for monitoring blast induced rock fragmentation with respect to various controlled blast parameters, such as spacing, burden, stemming depth, powder factor, hole diameter and hole depth/bench height.

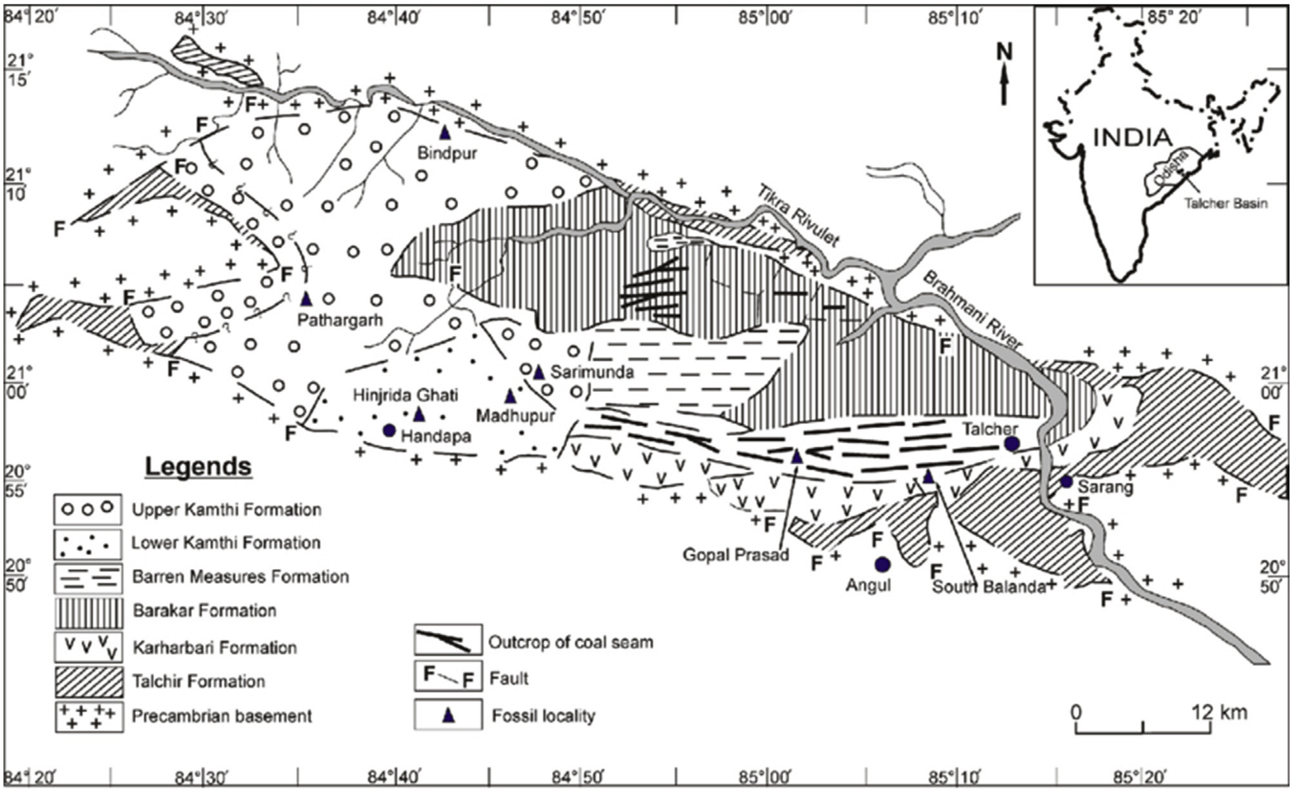

Fig. 3. Location and geology of Talcher coalfield, India (Saxena et al., 2014).

Table 1
Stratigraphic succession of Talcher coalfield.

Age	Formation	Lithology
Recent		Alluvium and laterite
Late Permian to Triassic	Kamthi	Fine to medium grained sandstone, carbonaceous shale, coal bands with greenish sandstone, pink clays and pebbly sandstone at the top (2500 m+)
	Barakar	Medium to coarse grained sandstone, a coal seam with oligomictic conglomerate at its base (500 m+)
Early Permian	Karharbari	Medium to coarse grained sandstone, shale and coal seams (1270 m)
	Talchir	Diamictic, fine to medium grained greenish sandstones, shale, rhythmites, turbidites etc. (170 m+)
		–UNCONFIRMITY–
Archaean		Granite, gneisses, amphibolites, migmatites etc.

Table 2
The bucket capacities and allowed fragment size for the four opencast mines under study.

Bucket size (m^3)	Boulder size maximum fragment size (mm)	Optimum size	
		Lower limit (mm)	Upper limit (mm)
3.0	1077	180	239
4.0	1185	198	262
4.6	1240	207	275
6.5	1390	232	308
10.0	1603	267	355
12.5	1726	288	382
20.0	2015	336	446
24.0	2140	357	474

2. Study area and methodology

2.1. Geology of the mine

The opencast mines under investigation are situated in the Talcher Coalfield of Orissa (India), which is situated in the south-eastern part of the Lower Gondwana basins within 85°28′N-84°20′N longitudes and 20°50′E-21°13′E latitudes (Pareek, 1963). The coalfield spans over an area of about 1860 km^2 and has a coal-bearing area of about 1000 km^2 (Fig. 3; Saxena, Singh, & Goswami, 2014). The geology of the coalfield was first studied by Blanford, Blanford and Theobald in 1856, and later it was carried out by the Geological Survey of India in 1963-65 and 1971-75. The stratigraphic sequence of Talcher Coalfield is given in Table 1; Singh (2016). The Talchir formation symbols the initiation of the Gondwana deposits, which rests over the basement rock and is separated by an unconformity. The coal bearing sedimentary deposits mainly belong to the Talchir, Karharbari, Barakar and Kamthi Formation, whereas basement rocks are mostly Archaean. The other components of the formations are sandstone (FG-MG/MG-CG), shale, turbidites, rhythmites, etc.

2.2. Blasting configurations used

The opencast mines used in this study belong to Mahanadi Coalfields Limited (MCL), which is one of the major coal producing subsidiaries of Coal India Limited. The majority of the coal production of MCL comes from opencast mines, and total production for the financial years 2014-15 and 2015-16 was approximately 120.10 Mt and

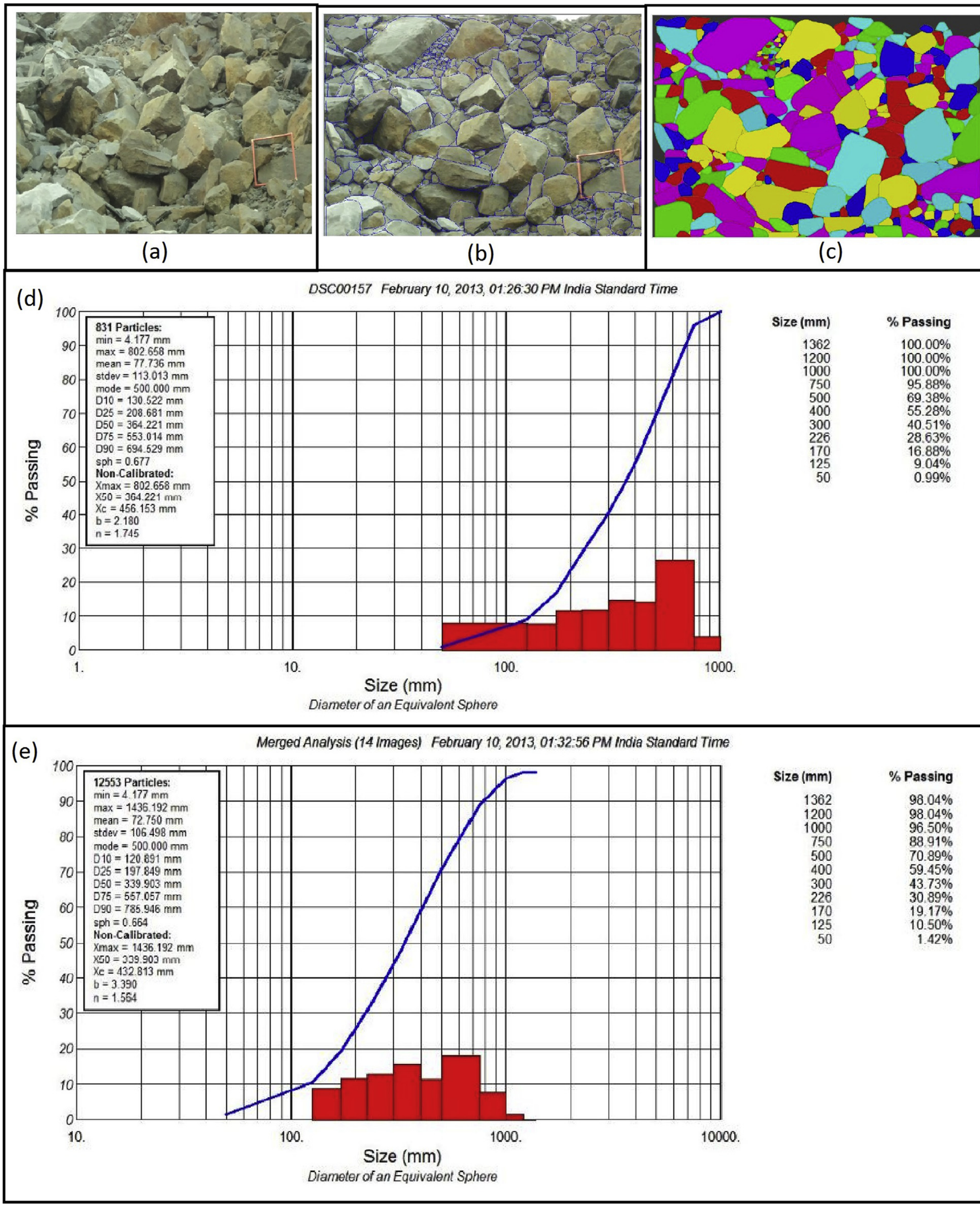

Fig. 4. (a) Muckpile created from the blast LAJ/1, (b) Netting diagram, (c) Sieve diagram. (d) Histogram analysis and cumulative curve view of the image (e) Histogram analysis and cumulative curve view of all the images taken for LAJ/1 (i.e. merged analysis for fourteen images).

136.789 Mt, respectively, where production from underground mines was only 1.28 Mt and 1.112 Mt respectively. Therefore, blasting fragment analysis played an important role in production and profitability for opencast projects. The blasting configurations used for the four opencast mines in this study are mentioned below:

[a] Balram OCP (max/min values): (i) Drill diameter (mm) – 260/160; (ii) Avg. drill depth (m) – 16.3/6; (iii) Avg. burden (m) – 5.5/3.5; (iv) Avg. spacing (m) – 6/4.5; (v) Avg. stemming length (m) – 11.3/2.56; (vi) Powder factor (m^3/kg) – 2.77/1.25; (vii) Explosives used – ANFO.

[b] Ananta OCP (max/min values): (i) Drill diameter (mm) – 260/160; (ii) Avg. drill depth (m) – 9/6.8; (iii) Avg. burden (m) – 5/3.5; (iv) Avg. spacing (m) – 6/4; (v) Avg. stemming length (m) – 6.3/3.8;

Table 3
Blasting dataset (*B*, *S*, *T*, *D*, *N*, *V*, *M*, *PF*, *E PY*, *PI* & *A*) for Balram OCP, Ananta OCP, Lakhanpur OCP and Lajkura OCP.

Blast record	Date	Drill dia. (mm)	Avg. depth (m)	Avg. burden (m)	Avg. spacing (m)	Total drilling depth (m)	Total in situ volume (m^3)	Explosive (kg)	Powder factor (m^3/kg)	Specific energy (MJ/m^3)	Productive yield (m^3/m)	Area (m^2)	Stemming length (m)
BAL/1	15.12.12	260	12	3.5	5	48.5	1408.08	1122.4	1.255	2.192	29.033	117.34	7.85
BAL/2	17.12.12	260	15.5	4	5	77.5	1990.76265	1503	1.325	2.076	25.687	128.436	10.9
BAL/3	17.12.12	160	6	4.5	5	634.8	9318.12	5410.6	1.722	1.597	14.679	1553.02	2.56
BAL/4	19.12.13	260	15.6	4	5	376.3	12377.352	7111.9	1.740	1.580	32.892	793.42	11.27
BAL/5	16.12.12	160	11	4	5.5	87.8	2708.42	1412.3	1.918	1.434	30.848	246.22	4
BAL/6	18.12.12	260	12	4.5	5.5	130	3478.08	1733	2.007	1.370	26.754	289.84	8.55
BAL/7	16.12.12	160	6	4.5	5	144.6	2531.52	1232.4	2.054	1.339	17.507	421.92	4
BAL/8	16.12.12	260	16.3	4.7	6	81.5	3593.335	1703	2.110	1.303	44.090	220.45	11.3
BAL/9	19.12.12	160	10	5.5	5.5	231.1	5370.5	2504.6	2.144	1.282	23.239	537.05	5.65
BAL/10	15.12.12	160	13	3.5	4.5	258.7	5814.9	2096	2.774	0.991	22.477	447.3	7.9
ANA/1	14.12.12	260	8.9	4.5	4.5	123.9	1188.15	3075.3	0.386	7.118	9.590	133.5	6.25
ANA/2	14.12.12	260	9	4.5	4.5	119.3	1382.22	3065.2	0.451	6.098	11.586	153.58	5.8
ANA/3	15.12.12	260	9	4	4.5	125.4	2205	2885.6	0.764	3.599	17.584	245	6.3
ANA/4	16.12.12	260	8.9	5	6	124.2	2029.2	2554.2	0.794	3.461	16.338	228	3.8
ANA/5	15.12.12	260	8.8	5	6	149.3	2974.4	2925.1	1.017	2.704	19.922	338	4
ANA/6	15.12.12	260	8.9	5	6	71.3	1606.45	1312.4	1.224	2.247	22.531	180.5	4.35
ANA/7	16.12.12	160	6.8	3.5	4	95.2	1104.184	731.4	1.510	1.822	11.599	162.38	5.05
ANA/8	17.12.12	160	6.9	3.8	4	206.6	2500.422	1653	1.513	1.818	12.103	362.38	5.05
ANA/9	16.12.12	160	6.8	3.5	4	109.3	1317.092	821.6	1.603	1.715	12.050	193.69	5.15
ANA/10	14.12.12	160	7.6	4.5	5	106.7	1750.28	901.5	1.942	1.416	16.404	230.3	4.95
LAK/1	26.01.13	250	8.32	5	5.5	141.4	1971.84	2495.1	0.790	3.480	13.945	237	5.4
LAK/2	27.01.13	250	8.8	4.5	5.5	123.4	2640	2234.5	1.181	2.328	21.394	300	6.55
LAK/3	25.01.13	250	9.4	4	5.25	281.4	5969	4999	1.194	2.303	21.212	635	6.3
LAK/4	29.01.13	250	9.1	4.5	5.5	300.3	5987.8	4799.7	1.248	2.204	19.939	658	6.05
LAK/5	26.01.13	250	8	5	5.8	312.4	8120	5310.9	1.529	1.799	25.992	1015	5
LAK/6	25.01.13	250	8.8	5.5	6	219.6	6124.8	3897.5	1.571	1.750	27.891	696	6.15
LAK/7	26.01.13	160	7.1	3.5	4.5	178.7	2144.2	1272.5	1.685	1.632	11.999	302	4.9
LAK/8	28.01.13	160	5.7	4	6	200.5	3229.05	1898.5	1.701	1.617	16.105	566.5	3.4
LAK/9	27.01.13	160	6	4	5.5	161	3402	1602.7	2.123	1.296	21.130	567	3.65
LAK/10	27.01.13	160	6	4	5.5	475.8	11676	4768	2.449	1.123	24.540	1946	3.6
LAJ/1	25.01.13	260	9.6	3	4	258.5	4856.736	5410.8	0.898	3.064	18.788	505.91	5.3
LAJ/2	28.01.13	260	8.4	3.5	4	312.3	4935	5251.1	0.940	2.926	15.802	587.5	5.75
LAJ/3	28.01.13	260	8.5	4.5	5.2	253.8	4998	4269	1.171	2.349	19.693	588	5.75
LAJ/4	26.01.13	260	7.3	3.5	4	131.4	2350.6	1800	1.306	2.106	17.889	322	5.25
LAJ/5	25.01.13	160	6	4	4	305.2	4439.04	3000	1.480	1.859	14.545	739.84	4.25
LAJ/6	25.01.13	260	7.5	4	4.5	285	4687.5	3107.6	1.508	1.823	16.447	625	5.25
LAJ/7	24.01.13	160	6	3	4	324.2	4560	2945.5	1.548	1.776	14.065	760	3.75
LAJ/8	24.01.13	160	6	3.5	3.5	265.9	3960	2480.5	1.596	1.723	14.893	660	3.75
LAJ/9	24.01.13	160	6	3.5	4	472.2	7560	4383	1.725	1.594	16.010	1260	3.75
LAJ/10	26.01.13	260	7.4	3.5	4.8	88.8	2249.6	1200	1.875	1.467	25.333	304	5.25

Table 4
Equations used to calculate volume, powder factor, specific energy, productive yield, performance indicator, normalized productive yield, normalized powder factor and normalized energy.

Volume $V = A \times M$	Powder factor $PF = {}^{V}/_{M}$	Specific energy $E = 2.75 \times {}^{M}/_{V}$
Productive yield $PY = {}^{V}/_{N}$	Normalized (PF) $PF_{norm} = {}^{PF}/_{PF_{max}}$	Normalized (E) $E_{norm} = {}^{E}/_{E_{max}}$
Normalized (PY) $PY_{norm} = {}^{PY}/_{PY_{max}}$	Performance indicator $PI = (PF_{norm} + PY_{norm}) - E_{norm}$	

(vi) Powder factor (m^3/kg) – 1.94/0.38; (vii) Explosives used – ANFO.

[c] Lakhanpur OCP (max/min values): (i) Drill diameter (mm) – 260/160; (ii) Avg. drill depth (m) – 9.4/5.7; (iii) Avg. burden (m) – 5.5/3.5; (iv) Avg. spacing (m) – 6/4.5; (v) Avg. stemming length (m) – 6.55/3.4; (vi) Powder factor (m^3/kg) – 2.44/0.79; (vii) Explosives used – ANFO.

[d] Lajkura OCP (max/min values): (i) Drill diameter (mm) – 260/160; (ii) Avg. drill depth (m) – 9.6/6; (iii) Avg. burden (m) – 4.5/3; (iv) Avg. spacing (m) – 5.2/3.5; (v) Avg. stemming length (m) – 5.75/3.75; (vi) Powder factor (m^3/kg) – 1.87/0.89; (vii) Explosives used-ANFO.

The explosives used in all the aforementioned mines were ammonium nitrate/fuel oil (ANFO; also known as AN/FO), which consists of 94% ammonium nitrate (NH_4NO_3), which acted as an oxidizer, and 6% number 2 fuel oil. The bucket capacities and allowed fragment size for the opencast mines under study are provided in Table 2.

2.3. Digital image processing using WipFrag

The use of digital image processing can be very useful for fragment analysis, and has been widely preferred in industry over traditional sieving (screening), as it is very fast and can be carried out for multiple images for analysis with very low error percentage (Maerz et al., 1996). All forty blastings created muckpiles in the desired range and the throws were also within the expected limit. The images of the muckpiles along with the scaling objecta, which were taken from a SONY digital camera, are fed into the WipFrag software in JPEG format (.jpeg). Suitable measures were taken for tilt correction (Lyana et al., 2016), as the line of observation was not perpendicular to the muckpile surface and would have resulted in improper fragment analysis. The image processing algorithms of the WipFrag software identifies the individual rock samples, and differentiate them using black outlines, also called the netting of image. The output of the software consisted of the number of particles exposed on the surface, statistical analysis of fragment size (minimum, maximum, mean, mode and standard

Table 5
PF_{norm}, E_{norm} and PY_{norm} for Balram OCP, Ananta OCP, Lakhanpur OCP and Lajkura OCP.

Blast record	Normalized powder factor (PF_{norm})	Normalized specific energy (SE_{norm})	Normalized productive yield (PY_{norm})
BAL/1	0.452198065	1	0.658484403
BAL/2	0.477429809	0.947150883	0.582609662
BAL/3	0.620771684	0.728445058	0.332928736
BAL/4	0.627322881	0.720837831	0.746025075
BAL/5	0.691254674	0.654169993	0.6996509
BAL/6	0.723419202	0.62508441	0.606814732
BAL/7	0.740420954	0.610731048	0.39707539
BAL/8	0.76055756	0.594561265	1
BAL/9	0.772903675	0.585063934	0.527077742
BAL/10	1	0.452198065	0.509806916
ANA/1	0.198994886	1.00000004	0.545367131
ANA/2	0.232261105	0.856772356	0.658909429
ANA/3	0.393577802	0.505604973	1.000000117
ANA/4	0.409192895	0.486310726	0.929163736
ANA/5	0.523741257	0.379948861	1.132996474
ANA/6	0.630462301	0.315633296	1.281346764
ANA/7	0.777579183	0.255915922	0.659619514
ANA/8	0.77910966	0.255413203	0.688290837
ANA/9	0.825683893	0.241006147	0.685306646
ANA/10	0.99999984	0.198994926	0.93289358
LAK/1	0.322719931	1	0.499991575
LAK/2	0.482464808	0.668898386	0.767059744
LAK/3	0.487596427	0.661858688	0.760532731
LAK/4	0.509442608	0.633476522	0.714911655
LAK/5	0.624352676	0.51688724	0.931934582
LAK/6	0.641723377	0.502895707	0.999999999
LAK/7	0.688096855	0.469003642	0.430210656
LAK/8	0.694554358	0.464643159	0.577431959
LAK/9	0.866810463	0.372307379	0.75761551
LAK/10	0.999999797	0.322719997	0.879852905
LAJ/1	0.478805225	1.000000091	0.741637479
LAJ/2	0.501317348	0.955094155	0.623767714
LAJ/3	0.624519441	0.766677924	0.777342394
LAJ/4	0.69659779	0.687348245	0.706140444
LAJ/5	0.789302847	0.606617942	0.574132655
LAJ/6	0.804622242	0.595068398	0.649238313
LAJ/7	0.825812935	0.579798703	0.555212905
LAJ/8	0.851592485	0.56224694	0.587874427
LAJ/9	0.920081271	0.520394539	0.631980288
LAJ/10	0.999999822	0.478805354	1.000000132

deviation) and sieve analysis (D_{10}, D_{25}, D_{50}, D_{75} and D_{90}). Similar analysis was carried out for multiple images for the same blast case study that were snapped from various directions, and the results were merged to get the final output. The working of WipFrag is described with a blast case study. Here, Fig. 4a shows the image of a muckpile that was created due to LAJ/1 (blasting no.) in Lajkura OCP on 25/01/2013. The blast used 5410.8 kg of ANFO industrial explosives in 27 boreholes with an average drill diameter and depth of about 260 mm and 9.6 m, respectively. The netting and sieve of the muckpile created by the software are shown in Fig. 4 (b & c). The analysis of Fig. 4a is shown in Fig. 4d, and it can be seen that a total of 831 particles was exposed on the surface, which were used for fragmentation analysis and the maximum, minimum and mean fragment size obtained was 4.177, 802.658 and 77.736 mm, respectively. In the same way, fourteen images were taken from different directions for LAJ/1 and similar analysis was carried out. The collective results of the all fourteen images (also known as the "merged analysis") formed the final result for fragmentation analysis for LAJ/1 (Fig. 4e). Thus, for LAJ/1 the maximum, minimum and mean fragment size obtained are 4.177, 1436.192 and 72.750 mm, respectively.

2.4. The datasets used for the study

The opencast mine used for the present study are Balram OCP, Ananta OCP, Lakhanpur OCP, and Lajkura OCP. All of these mines are situated in the Talcher Coalfield of Orissa (India), and are operated by Mahanadi Coalfields Limited. The forty blasting datasets used for the study consisted of ten blasting case studies from each of the opencast mine. The field trials and study were carried out from December 13, 2012 to December 20, 2012 (for Balram and Ananta mine) and January 23, 2013 to January 29, 2013 (for Lakhanpur and Lajkura mine). The raw dataset consisted of the following parameters: spacing (*S*), burden (*B*), average drilling depth (= bench height) (*H*), hole diameter (*D*), total drilling (*N*), total insitu volume (*V*), charge size (*M*), powder factor (*PF*), stemming length (*T*), specific energy of explosives (*E*), productive yield (*PY*), performance indicator (*PI*) and area (*A*) (Table 3). The blast parameters such as volume, powder factor, specific energy, productive yield, performance indicator, normalized productive yield, normalized powder factor and normalized energy are calculated using the formula in Table 4, and the calculated values of the normalized powder factor (PF_{norm}), specific energy (E_{norm}) and productive yield (PY_{norm}) are shown in Table 5 and Fig. 5 a, b, c & d for Balram, Ananta, Lakhanpur and Lajkura OCP, respectively. Previous studies on blasting have used ratios of the physical parameters used for fragmentation analysis, such as spacing to burden (*S/B*), drill depth to burden (*H/B*), stemming length to burden (*T/B*) and burden to hole diameter (*B/D*), and a similar approach has been utilized by this study for rock fragment analysis (Aler, Mouza, & Arnould, 1996; Chakraborty et al., 2004). Thus, the calculated values for *S/B*, *H/B*, *B/D* and *T/B* are given in Table 6. The statistical description (maximum, minimum, mean and standard deviation) of the aforementioned ratios (*S/B*, *H/B*, *B/D* and *T/B*) and powder factor (*PF*) are given in Table 7.

3. Results and discussion

The digital image analysis (using WipFrag) of the muckpile created from blasting was used to calculate the mean fragment size and the boulder percentage, and their variation with respect to *S/B*, *H/B*, *B/D*, *T/B* and *PF* for the four opencast mines are collectively shown in Fig. 6 and Fig. 7. The results of the study are discussed below:

3.1. The effect of spacing to burden ratio (S/B)

The spacing (*S*) and burden (*B*) are essential parameters of rock blasting. The large burden tends to minimize rock displacement along with increase the workload of the explosives, reduce the penetration of explosion gases into the rock fractures and also increase the vibration levels. However, a smaller burden induces excessive crushing and pushing of rock fragments in an uncontrolled manner, which might result in higher muckpile throw. Depending on the bench rock characteristics, the burden length can be 20–40 times the diameter of the blast drill hole (Ash, 1963). The spacing (*S*), which is the distance between two successive blast holes depends on burden (*B*), delay timing (Δt) between blast holes and the initiation sequence. Large spacing leads to insufficient fracturing between the blast holes, which results in irregular faces with toe problems. On the other hand, smaller spacing causes excessive crushing and superficial crater breakage (Singh et al., 2016). Thus, an increase in both spacing and burden tends to increase the fragment size. The variation of the mean fragment size and boulder percentage with respect to *S/B* ratio are shown in Figs. 6a and 7a. The results show that there is a decrease in mean fragment size with an increase in *S/B* for Balram, Lakhanpur and Lajkura OCP. Hence, it can be inferred that this shows that the effects from the burden have dominated the results, as lower burden (corresponding to higher *S/B*) has resulted in lower fragment size. On the other hand, there is an increase in fragment size with an increase in *S/B* for Ananta OCP. Therefore, it can be inferred that the effects from spacing have dominated the result as a higher fragment size is obtained with higher spacing. The boulder percentage has shown a random variation with respect to *S/B* hence no inferences can be made.

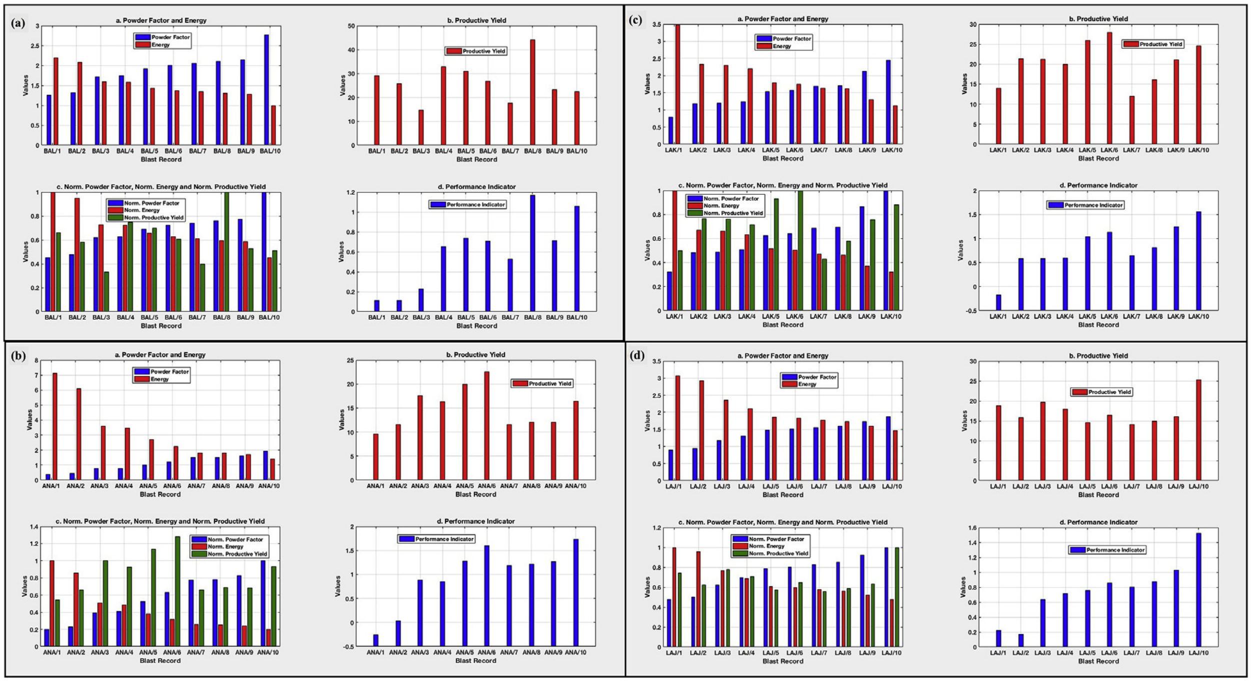

Fig. 5. Powder factor (PF), specific energy (E), productive yield (PY), performance indicator (PI), normalized productive yield (PY_{norm}), normalized powder factor (PF_{norm}) and normalized energy (E_{norm}) for (a) Balram OCP, (b) Ananta OCP, (c) Lakhanpur OCP and (d) Lajkura OCP.

Table 6
Calculated values for *S/B*, *H/B*, *B/D* and *T/B* for Balram OCP, Ananta OCP, Lakhanpur OCP and Lajkura OCP.

Sl. No.	Blast record	*S/B*	*H/B*	*B/D*	*T/B*	Sl. No.	Blast record	*S/B*	*H/B*	*B/D*	*T/B*
1	BAL/1	1.428571429	3.428571429	13.46153846	2.242857143	21	LAK/1	1.1	1.664	20	1.08
2	BAL/2	1.25	3.875	15.38461538	2.725	22	LAK/2	1.222222222	1.955555556	18	1.455555556
3	BAL/3	1.111111111	1.333333333	28.125	0.568888889	23	LAK/3	1.3125	2.35	16	1.575
4	BAL/4	1.25	3.9	15.38461538	2.8175	24	LAK/4	1.222222222	2.022222222	18	1.344444444
5	BAL/5	1.375	2.75	25	1	25	LAK/5	1.16	1.6	20	1
6	BAL/6	1.222222222	2.666666667	17.30769231	1.9	26	LAK/6	1.090909091	1.6	22	1.118181818
7	BAL/7	1.111111111	1.333333333	28.125	0.888888889	27	LAK/7	1.285714286	2.028571429	21.875	1.4
8	BAL/8	1.276595745	3.468085106	18.07692308	2.404255319	28	LAK/8	1.5	1.425	25	0.85
9	BAL/9	1	1.818181818	34.375	1.027272727	29	LAK/9	1.375	1.5	25	0.9125
10	BAL/10	1.285714286	3.714285714	21.875	2.257142857	30	LAK/10	1.375	1.5	25	0.9
11	ANA/1	1	1.977777778	17.30769231	1.388888889	31	LAJ/1	1.333333333	3.2	11.53846154	1.766666667
12	ANA/2	1	2	17.30769231	1.288888889	32	LAJ/2	1.142857143	2.4	13.46153846	1.642857143
13	ANA/3	1.125	2.25	15.38461538	1.575	33	LAJ/3	1.155555556	1.888888889	17.30769231	1.277777778
14	ANA/4	1.2	1.78	19.23076923	0.76	34	LAJ/4	1.142857143	2.085714286	13.46153846	1.5
15	ANA/5	1.2	1.76	19.23076923	0.8	35	LAJ/5	1	1.5	25	1.0625
16	ANA/6	1.2	1.78	19.23076923	0.87	36	LAJ/6	1.125	1.875	15.38461538	1.3125
17	ANA/7	1.142857143	1.942857143	21.875	1.442857143	37	LAJ/7	1.333333333	2	18.75	1.25
18	ANA/8	1.052631579	1.815789474	23.75	1.328947368	38	LAJ/8	1	1.714285714	21.875	1.071428571
19	ANA/9	1.142857143	1.942857143	21.875	1.471428571	39	LAJ/9	1.142857143	1.714285714	21.875	1.071428571
20	ANA/10	1.111111111	1.688888889	28.125	1.1	40	LAJ/10	1.371428571	2.114285714	13.46153846	1.5

3.2. The effect of bench height (drilling depth) to burden (H/B)

As subdrilling was negligible, bench height was almost equal to the drilling depth. The drill depth/blast hole depth (H) is another highly important parameter in blasting and it is dependent on spacing (S). Ideally, the spacing should not be greater than one half of the blast hole depth, i.e. $S < 0.5H$. The ratio of bench height (H) to burden (B) is also referred to as stiffness. High stiffness either results from deeper drill depth or smaller burden length. Therefore, high stiffness leads to easier deformation. Moreover, shallow drill depth or larger burden length tends to lead to smaller stiffness, thus resulting in poor fragmentation (Ash, 1985). The variations in the mean fragment size and boulder percentage with H/B are shown in Figs. 6b and 7b. The results show that fragment size has decreased with an increase in H/B for Balram, Ananta and Lajkura OCP, which shows that high stiffness (due to greater hole depth and lower burden) has resulted in better fragmentation. It can also be seen that higher boulder percentages are obtained for lower stiffness values.

3.3. The effect of burden to hole diameter (B/D)

Drill hole diameter (D) is an important parameter in the optimization of blasting, as several other controlled parameters, such as burden and stemming length, are dependent on it. The drill hole diameter plays an important role in blast design. Smaller drill diameter reduces the amount of explosives that can be loaded in to the blast hole, which in turn reduces the explosive energy per hole. Usually, it is believed that a smaller drill hole diameter results in finer fragments, but in this case study higher borehole diameters have been used, i.e. 160, 250 and 260 mm. Therefore variation in the B/D ratio is mostly due to variation

Table 7
The statistical variation (maximum, minimum, mean and standard deviation) of *S/B*, *H/B*, *B/D*, *T/B* and powder factor (*PF*) for Balram OCP, Ananta OCP, Lakhanpur OCP and Lajkura OCP.

Blast Record	Parameters	Max	Min	Mean	Standard deviation
BAL/1-10	*PF*	2.7740	1.255	1.9049	0.4355
	S/B	1.4286	1	1.2310	0.1281
	H/B	3.9	1.3333	2.8287	1.0177
	B/D	34.375	13.4615	21.7115	6.9458
ANA/1-10	*PF*	1.942	0.386	1.1204	0.5224
	S/B	1.2	1	1.1174	0.0772
	H/B	2.25	1.6889	1.8938	0.1639
	B/D	28.125	15.3846	20.3317	3.7056
LAK/1-10	*PF*	2.449	0.79	1.5471	0.4842
	S/B	1.5	1.0909	1.2644	0.1309
	H/B	2.35	1.425	1.7645	0.3046
	B/D	25	16	21.0875	3.2436
LAJ/1-10	*PF*	1.875	0.898	1.4047	0.3222
	S/B	1.3714	1	1.1747	0.1316
	H/B	3.2	1.5	2.0492	0.4758
	B/D	25	11.5385	17.2115	4.5245

in burden. Hence, increasing *B/D* will result in higher fragment size and boulder percentage. The variations of mean fragment size and boulder percentage with *B/D* are given in Figs. 6c and 7c. The mean fragment size increased with an increase in *B/D* for Balram, Ananta and Lajkura OCP. Thus, it can be concluded that the effect of burden has dominated the results, as higher burden (corresponding to high *B/D*) has resulted in higher mean fragment size. Whereas, for Lakhanpur OCP, there is a decrease in mean fragment size with an increase in *B/D*. Here it can be concluded that the effect of the borehole diameter has dominated the result, as a lower borehole diameter (corresponding to higher *B/D*) has resulted in better fragmentation. The results also show that higher boulder percentage was obtained for higher *B/D*.

3.4. The effect of stemming depth to burden (T/B)

The proper capping of a drill hole is essential so that as much of the energy obtained from the explosives can be utilized in rock breakage, and also to mitigate the hazards of fly rock. Thus, stemming length is a very important parameter in blast rock fragmentation analysis, especially when the collar zone of the blasting hole contains hard rock. Usually, the stemming length is almost equal to burden ($T \approx B$), but can be up to 1.5 times the burden to avoid the fly rock problem ($T \approx 1.5B$). The stemming length also depends on the borehole diameter (*D*). Further dependence on the burden rock type and explosives, leads to the use of a minimum stemming length, i.e. 25 times the hole diameter (*D*) i.e. $T > 25D$ (Jimeno et al., 1995). Long stemming columns are often suggested when the burden rock has natural fractures, while for large compact burden rock the stemming length can be kept shorter. Higher values of *T/B* can be achieved by increasing the stemming length, i.e. reducing the explosive charge column in drill holes, which might result in poor rock breakage. The variations in the mean fragmentation size and boulder percentage with respect to *T/B* are shown in Figs. 6d and 7d. The data collected from the opencast mines shows that there is a decrease in mean fragment size with an increase in *T/B*. The dataset agreed with the expected results as higher stemming depth and lower burden (corresponding to higher *T/B*) has resulted in reducing the fragment size, and therefore higher boulder percentages were seen for lower values of *T/B*.

3.5. The effect of the powder factor (PF)

The powder factor (*PF*) is the amount of explosives required to break 1 m^3 or 1 tonne of rock, and is the ratio of the quantity of rock broken to the total amount of explosive used (Jimeno et al., 1995). The powder factor is related to the geology of the rock and acts as a deciding parameter for the choice of the amount of explosive to be used and also its initiation sequence. Thus, it helps to maintain the cost effectiveness of mining operation. Soft/sedimentary formations usually have a lower powder factor (soft laminated rock: 0.1–0.25; med-hard sandstone: 0.3–0.45), whereas harder formations have relatively higher values of powder factor (quartzite/granite: > 0.65; dolerite: 0.9–1.2). However, if an explosive with the same density is used, then it can be seen that higher powder factor (*PF*) will result in oversized boulders, whereas lower powder factor (*PF*) tends to lead to more crushing of the rocks. The variations of mean fragmentation and boulder percentage with powder factor are shown in Figs. 6e and 7e. The results obtained from the four opencast mines show that high mean fragment size are

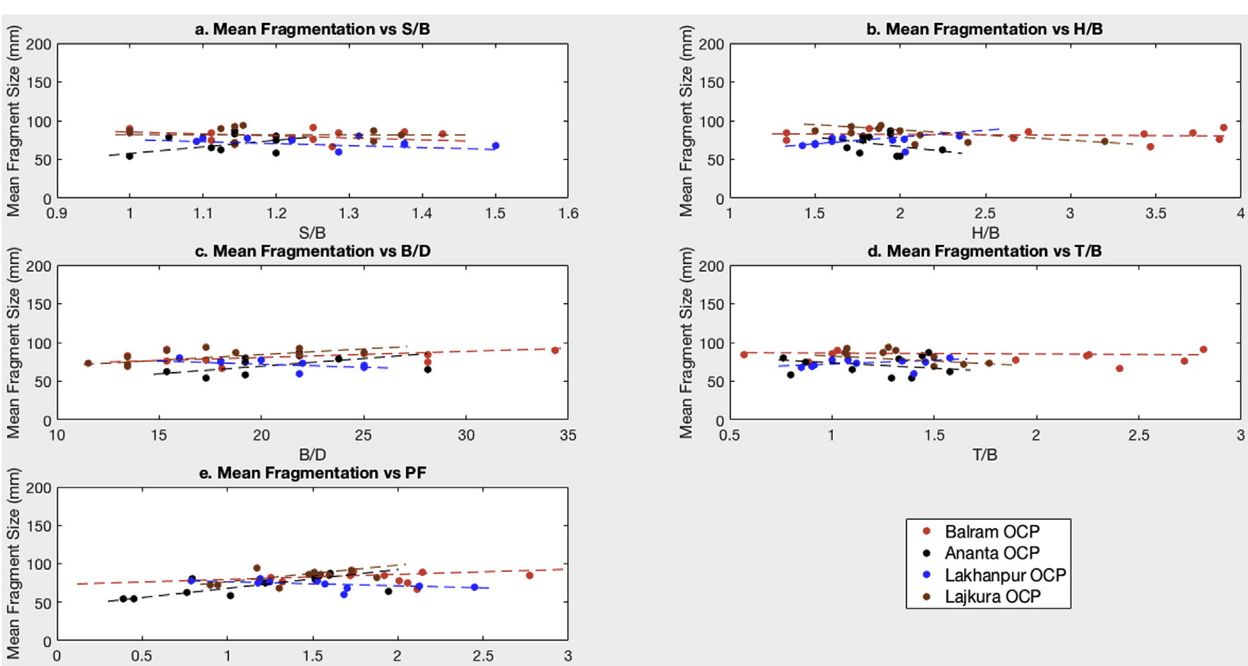

Fig. 6. Variation of mean fragment size (mm) with respect to (a) *S/B*, (b) *H/B*, (c) *B/D*, (d) *T/B* and (e) *PF*.

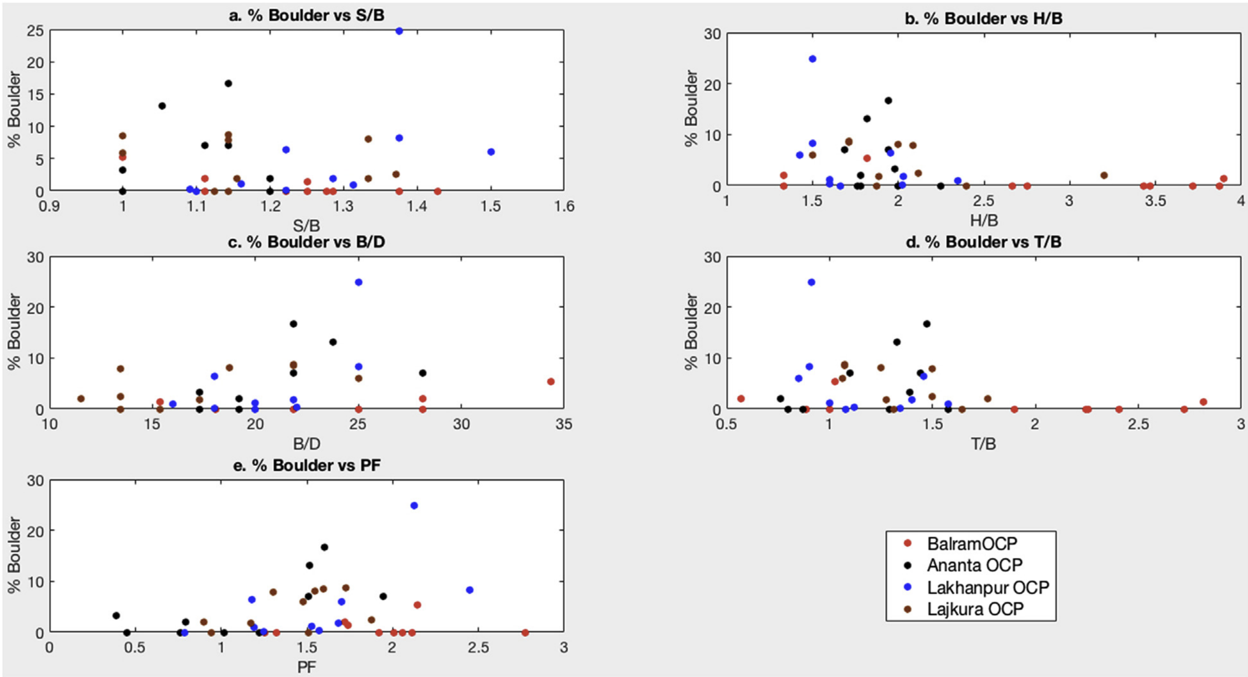

Fig. 7. Variation of boulder percentage with respect to (a) *S/B*, (b) *H/B*, (c) *B/D*, (d) *T/B* and (e) *PF*.

obtained for higher values of powder factor. Also, high boulder percentages are seen for higher values of powder factor.

4. Conclusions

The following conclusions can be drawn:

(i) The mean fragment size is directly proportional to both spacing and burden. Hence dependence of fragment size on *S/B* is governed by the individual effect of the aforementioned parameters. As for Balram, Lakhanpur and Lajkura OCP the effect of burden has resulted in a decrease in mean fragment size with an increase in *S/B*. Whereas for Ananta OCP, the effect of spacing has resulted in higher fragment size with an increase in *S/B*.

(ii) As high *H/B* corresponds to higher borehole depth and lower burden, the combined effect of borehole depth and burden has resulted in low mean fragment size for higher values of *H/B*. In addition, high boulder percentage can be seen for lower values of *H/B*.

(iii) The effect of burden has resulted in high mean fragment size with an increase in *B/D* for Balram Ananta and Lajkura OCP, as high burden leads to poor fragmentation. Whereas in Lakhanpur OCP, the effect of the borehole diameter tends to lower fragment size as *B/D* increases, as smaller borehole diameter leads to better fragmentation. High boulder percentages were obtained for higher values of *B/D*.

(iv) The combined effect of stemming depth and burden has resulted in lower fragment size for higher values of *T/B*, as high stemming depth and lower burden reduces the fragment size. Therefore, high boulder percentages were seen for lower values of *T/B*.

(v) The results obtained from the opencast mines show that the means fragment size was directly proportional to the powder factor. Thus, higher fragment size and boulder percentage were obtained for higher values of powder factor.

Conflict of interest

The authors state that there is no conflict of interest.

Ethical statement

The authors state that the research was conducted according to ethical standards.

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