Selection of Blast Design for Kofi C Pit of Endeavour Mining Corporation, Mali*

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Abstract

The Kofi Gold Mine (KGM) of Endeavour Mining Corporation in Mali needed to select one of two alternative blast designs, Blast Design 1 (BD1) and Blast Design 2 (BD2), for the fresh rocks of the deposit, both ore and waste, in their Kofi C Pit. BD1 has a burden of 3.2 m, a spacing of 3.5 m, a bench height of 5.0 m and a sub drill of 0.5 m. BD2 has a burden of 3.5 m, a spacing of 4.0 m, a bench height of 10.0 m and a sub drill of 0.8 m. Both designs have the same hole diameter of 115 mm and powder factor of 0.68 kg/m^3. The Modified Kuz-Ram Fragmentation Model was used to estimate and compare the fragmentation of the two designs. The modelling results showed that the fragmentation of BD1 would be better than that of BD2 but cost analysis revealed that the drilling and blasting cost of BD2 would be lower than that of BD1. Consequently, BD2 was modified into Blast Design 3 (BD3) to improve the fragmentation without exceeding the drilling and blasting cost of BD1. The modification was done by increasing the powder factor of BD2 by 16.18 %. Subsequent fragmentation modelling and cost analysis revealed that BD3 and BD1 would now have the same fragmentation and the same drilling and blasting cost but BD3 would give a higher productivity. It was therefore recommended that KGM selects BD3 over BD1 and BD2 for ore drilling and blasting. BD2 could be considered for waste drilling and blasting because its lower fragmentation, which is not good enough when the rock is ore, is acceptable when the rock is waste.

Keywords: Blast Design, Cost Analysis, Drilling and Blasting Productivity, Kuz-Ram Fragmentation Model

1 Introduction

Endeavour Mining Corporation (EMC) is the operator of the Kofi Gold Mine (KGM) in Mali, the location of which is shown in Fig. 1. Mining in the Kofi C Pit, the first of three pits slated for mining, is currently being done in oxidised, weathered saprolitic rock that is dug freely without blasting but fresh sandstone rocks would soon be exposed, at which time KGM would need an effective blast design for drilling and blasting the fresh rocks of the deposit, both ore and waste.

Two alternative blast designs, Blast Design 1 (BD1) and Blast Design 2 (BD2) have been proposed. BD1 has a burden of 3.2 m, a spacing of 3.5 m, a bench height of 5.0 m and a sub drill of 0.5 m. BD2 has a burden of 3.5 m, a spacing of 4.0 m, a bench height of 10.0 m and a sub drill of 0.8 m. Both designs have the same hole diameter of 115 m and powder factor of 0.68 kg/m^3 (Table 1). BD1 is being considered because it produced acceptable fragmentation when EMC employed it at their Djambaye Satellite Pit (DSP), which is 35 km away from the KGM but has similar rock properties. The advocates of BD2 also expect it to produce good fragmentation with higher productivity.

Drilling in the Kofi C Pit would be done with Sandvik Pantera 1500 diesel-powered, track-mounted drills. Blasting would be carried out by Bulk Mining Explosives (BME), who was the blasting contractor at DSP, using the same 100 % bulk emulsion explosive (HEF 100) that was used at DSP.

This paper sought to study the feasible performance of the two alternative blast designs, DB1 and DB2, in the fresh rock of the Kofi C Pit. During the study, it became clear that a third Blsat Design (BD3), which is a modification of BD2 had to be considered because both DB1 and DB2 could not produce the required fragmentation at an acceptable cost. The BD3 has a burden of 3.6 m, spacing of 4.1 m, a bench height of 10.0 m, a sub drill of 0.8 m and a powder factor 0.79 kg/m^3. The results of the study would help KGM planners to make an informed choice among the three designs.

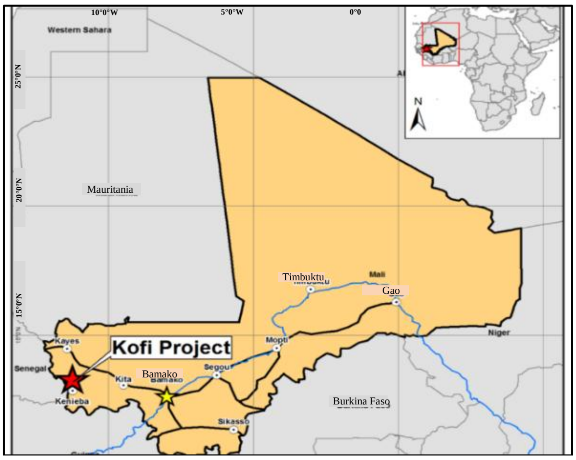

Fig. 1 Location of Kofi Gold Mine

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2 Resources and Methods Used

2.1 Data

Data from KGM and BME consisting of explosive properties and rock mass properties (Table 2) as well as drilling cost per metre and emulsion explosive cost per kilogramme (Table 4) were used for the work.

2.2 Methods

2.2.1 Fragmentation Modelling

An excel workbook version of the Modified Kuz-Ram model developed by Cunningham and being used by AEL Mining Services was used to estimate the fragmentation of the proposed alternative blast designs, BD1 and BD2 and also the fragmentation of the third Blast Design (BD3), which is a modification of BD2.

Although the Kuz-Ram model is widely used in the estimation of fragmentation from blasting (Hawke, 2011; Akinbinu and Sellers, 2014; Hudaverdi and Akyildiz, 2016), Cunningham (2005) notes that the Modified Kuz-Ram model which incorporates a timing algorithm is an improved model that should be of considerable help in guiding Blasting Engineers in their attempt to improve blasting.

The Modified Kuz-Ram model uses the Rosin-Ramler equation to determine the fragment size distribution. The Rosin-Ramler equation is given in Equation (1):

$$R_x = \exp\left[-0.693\left(\frac{x}{x_m}\right)^n\right] \quad (1)$$

where R_x is mass fraction retained on screen opening x; x_m is mean size; and n is uniformity index.

The mean size, x_m is given in Equation (2):

$$x_m = AA_TK^{-0.8}\,Q^{\frac{1}{6}}\left(\frac{115}{RWS}\right)^{\frac{19}{30}}C(A) \quad (2)$$

where A is rock factor; K is powder factor, kg/m^3; Q is mass of explosive in hole, kg; RWS is weight strength relative to ANFO; 115 is RWS of TNT; C(A) is rock correction factor; and A_T is timing factor.
The uniformity index (n) is given in Equation (3):

$$n = n_s\sqrt{\left(2-\frac{30B}{d}\right)}\sqrt{\frac{1+{S}/{B}}{2}}\left(1-\frac{W}{B}\right) \times \left(\frac{L}{H}\right)^{0.3}C(n)\left(\frac{A}{6}\right)^{0.3}g \quad (3)$$

where B is burden, m; S is spacing, m; d is hole diameter, mm; W is standard deviation of drilling precision, m; L is charge length, m; H is bench height, m; n_s is timing scatter factor; C(n) is correction factor for known uniformity; A is rock hardness factor; g is geometry factor.

2.2.2 Cost Analysis

The drilling and blasting costs of BD1, BD2 and BD3 were estimated and compared. Only the variable drilling and blasting costs were considered in the cost analysis because the fixed costs would be the same irrespective of the blast design selected. Explosive costs were considered to be the only variable blasting costs. The drilling and blasting costs of the blast designs were compared using drilling and blasting cost per BCM of blasted material.

3 Results and Discussion

3.1 Results of Fragmentation Modelling

Table 1 shows the blast design parameters for the proposed blast designs while Table 2 shows explosive properties, timing delays and rock mass properties that were used to estimate the fragmentation of the blast designs.

Figs. 2 and 3 respectively show inputs of blast parameters in the Modified Kuz-Ram software and inputs of explosives and rock data in the Modified Kuz-Ram software.

Blasting effectiveness is often described in terms of parameters or moduli of the distribution. The most commonly used fragmentation moduli are (a) the screen size through which 80% of the blasted material will pass, (b) the 50% passing size, and (c) the characteristic size from the Rosin-Rammler distribution function (Lownds, 1997). For these reasons, the fragmentation moduli used in this work are the screen sizes through which 50% and 80% of blasted material pass. The fragmentation modelling results are shown in Figs. 4, 5 and 6, for fragmentation curves of the blast designs, zoom view of 50% section of fragmentation curves and zoom view of 80% section of fragmentation curves respectively. A summary of the fragmentation of the designs at 50% and 80% passing are presented in Table 3. The results show that BD1 would produce better rock fragmentation than BD2 in the Kofi C Pit. Whereas the difference in fragmentation of the designs at the 50% passing would not be very noticeable (only 2.5 cm difference), there would be noticeable difference in their fragmentation at 80% passing (7.4 cm).

From fragmentation modelling results, the lower drilling and blasting cost per BCM of BD2 (see Table 4) would be at the expense of poorer fragmentation. BD2 would however give a higher drilling and blasting productivity than BD1. A blast hole in BD2 would yield 140 BCM of blasted rock, whereas a blast hole in BD1 would yield 60.8 BCM of blasted rock. For a given blasting area, BD2 would yield more BCM of broken rock per blast than BD1 and this is mainly due to higher bench height of BD2.

As noted by Nielsen (1985), each blasting design will result in a degree of fragmentation that will influence the productivity and costs of the subsequent operations in the following way:

(i) increased fragmentation will necessitate higher combined costs for drilling and blasting.

(ii) the shovel loading capacity must be expected to increase with finer fragmentation, and the costs for wear parts and maintenance will be reduced.

(iii) Increased shovel capacity means shorter loading time per truck and decreased cycle time. Transportation costs are therefore reduced. In addition, finer fragmentation will reduce truck body wear.

(iv) Improved fragmentation will lead to reduced costs for secondary blasting and less time lost due to handling of boulders.

Finer fragmentation will also lead to less wear of the crusher. The crushing time per truck load will decrease, and this will lead to less waiting time for the trucks at the crusher. Shorter cycle time for the trucks may again lead to better utilization of the shovel capacity. Now, since some costs will increase with finer fragmentation and some will decrease, an optimal fragmentation must exist.

Selecting BD2 over BD1 for the Kofi C Pit would be economically beneficial to KGM if the fragmentation of BD2 is equivalent to, or better than that of, BD1. The question that arises is whether the fragmentation of BD2 could be improved at acceptable cost to achieve higher productivity by adjusting the blast design parameters? The answer is provided by Cremenose *et al*. (2016) who note that when rock excavation is carried out by drilling and blasting, one can manage the performance and the expenditure of the whole fragmentation process by adjusting drilling and blasting parameters.

Taking cognisance of the fact that the drilling and blasting cost of BD2 is significantly lower than that of BD1, the approach adopted in this study entailed the improvement of the fragmentation of BD2 by increasing the explosive per unit volume of rock at additional marginal cost such that the total drilling and blasting cost would not exceed that of BD1. The strategy that worked was to modify the blast design parameters of BD2 to arrive at a third Blast Design, (BD3) with increased powder factor of 0.79 kg/m^3, achieved by increasing the hole diameter to 127 mm, increasing burden and spacing to 3.6 m and 4.1 m respectively and reducing the stemming length to 3.1 m.

When the fragmentation of BD3 was estimated and compared with that of BD1 and BD2, the fragmentation modelling showed insignificant difference between the fragmentation of BD1 and that of BD3 (Table 3). The differences in fragmentation are 0.7 cm at 50% passing and 1.0 cm difference at 80% passing, which are considered insignificant.

Table 1 Blast Design Parameters

Blast Geometry	BD1	BD2	BD3
Hole Diameter (mm)	115	115	127
Stemming Length (m)	2.2	3.2	3.1
Column Length (m)	3.3	7.6	7.7
Hole Depth (m)	5.5	10.8	10.8
Bench Height (m)	5.0	10	10
Sub-Drill (m)	0.5	0.8	0.8
Burden (m)	3.2	3.5	3.6
Spacing (m)	3.8	4.0	4.1
Powder Factor (kg/m^3)	0.68	0.68	0.79

Table 2 Explosive Properties, Timing Delays and Rock Mass Data

Explosive Properties	
Bulk Emulsion	HEF100
Average In-hole Density (g/cm^3)	1.2
Relative Weight Strength (RWS)	87
Relative Bulk Strength (RBS)	130.5
Timing Delays	
Spacing Delay (ms)	17
Burden Delay (ms)	65
Down Hole Delay (ms)	500
Rock Mass Property	
Rock type	Sandstone
Density (t/m^3)	2.74
Uniaxial Compressive Strength (MPa)	217
Poison Ratio	0.2
Youngs Modulus (GPa)	40
Rock Mass Description	Massive

1	NEW KUZ-RAM MODEL			
2	GEOMETRY	BD1	BD2	BD3
3	Height m	5.00	10.00	10.00
4	Diameter	115	115	127
5	Hole L, m	5.50	10.80	10.80
6	Stemming m	2.20	3.20	3.10
7	Spacing	3.80	4.00	4.10
8	Burden	3.20	3.50	3.60
9	Stag?	y	y	y
10	SD drilling m	0.15	0.15	0.15
11	S/B ratio	1.19	1.14	1.14
12	Red. Pat. m	3.49	3.74	3.84
13	Sub drill	0.50	0.80	0.80
14	Ch length m	3.30	7.60	7.70
15	PF kg/m3	0.677	0.677	0.793
16	RE/hole	87.0	87.0	87.0
17	Rock kg/hole	166,592	383,600	404,424
18	Rock tons/kg	4.05	4.05	3.45
19	TIMING	BD1	BD2	BD3
20	ED?	n	n	n
21	dt spacing ms	17	17	17
22	Target dt ms	12	14	14
23	DH Delay ms	500	500	500
24	CoV%	1.5	1.5	1.5
25	Range	45	45	45
26	Scatter ratio	2.65	2.65	2.65
27	n scat	0.87	0.87	0.87
28	ms/m bdn.	5.3	4.9	4.7
29	[illegible]	[illegible]	[illegible]	[illegible]

Fig. 2 Inputs of Blast Design Parameters in Modified Kuz-Ram Software

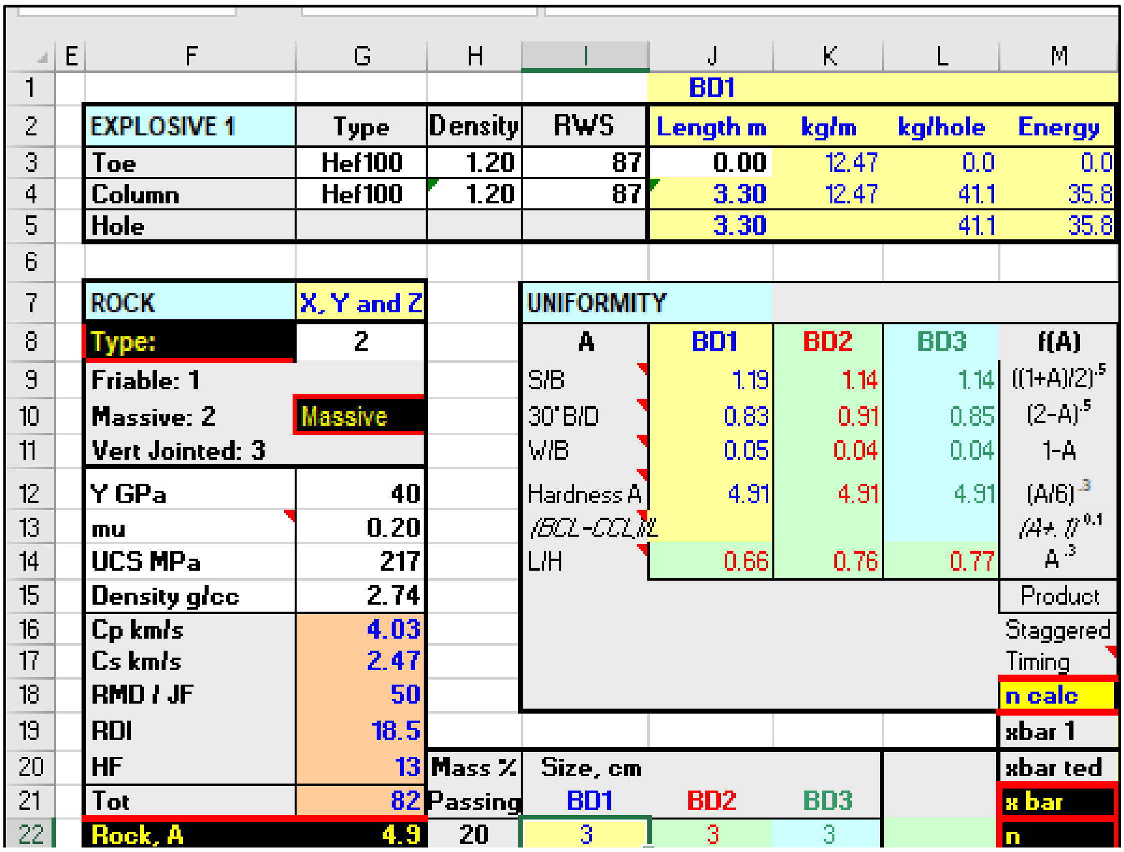

Fig. 3 Inputs of Rock Mass and Explosive Data in Modified Kuz-Ram Software

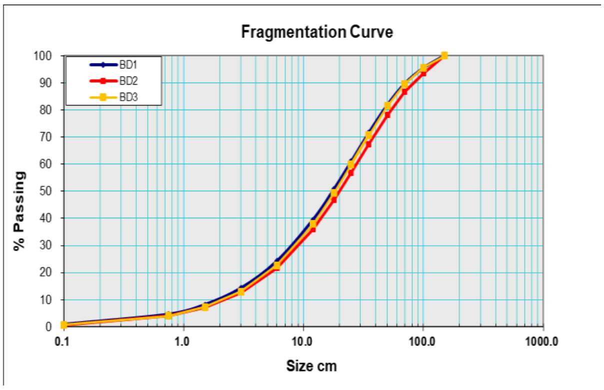

Fig. 4 Fragmentation Curves of DB1, DB2 and DB3

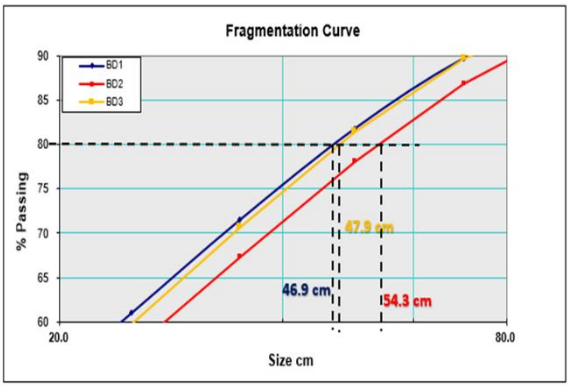

Fig. 6 Zoom View of 80% Passing Section of Fragmentation Curves

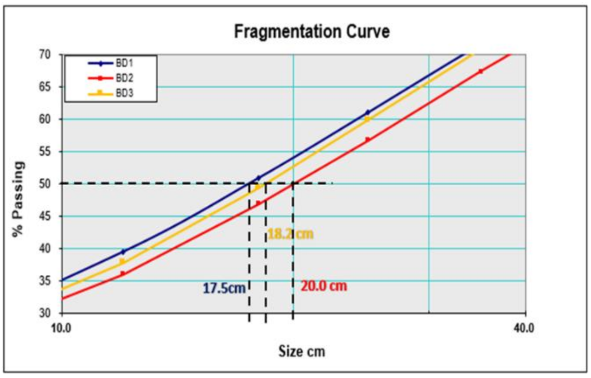

Fig. 5 Zoom View of 50% Passing Section of Fragmentation Curves

Table 3 Summary of 50% and 80% Passing Fragmentations

Blast Design	50% Passing (cm)	80% Passing (cm)
DB1	17.5	46.9
DB2	20.0	54.3
DB3	18.2	47.9
Difference Between DB1 and DB3	0.7	1.0

3.2 Results of Cost Analysis

The drilling and blasting cost estimates are shown in Table 4. The estimates show that the drilling and blasting cost per BCM of BD1 would be $1.21 and that of BD2 would be $ 1.04.

Despite its finer fragmentation, BD1 cannot be selected over BD2 because its higher drilling and blasting cost and lower drilling and blasting productivity could lead to a higher overall mining cost. BD2 cannot also be selected over BD1 despite its lower drilling and blasting cost and higher drilling and blasting productivity since its poorer fragmentation could adversely affect the productivity and cost of downstream mining operations such as loading, hauling and crushing and hence the overall mining operation.

The drilling and blasting cost of BD3 was estimated and compared with that of BD1 and BD2. The estimates showed that the drilling and blasting cost of BD3 would be the same as that of BD1 (Table 4).

4 Conclusions and Recommendations

4.1 Conclusions

After assessing the performance of proposed blast designs for the Kofi C Pit of KGM, the following conclusions are made:

The fragmentation of BD1 in the Kofi C Pit would be better than that of BD2 but the drilling and blasting cost for BD2 would be lower than that of BD1.

(i) BD2 would have a higher drilling and blasting productivity than BD1 as a result of higher bench height.

(ii) Modification of BD2 to the alternative Blast Design (BD3) by increasing the powder factor by 16.18% to 0.79 kg/m^3 would produce the same fragmentation as BD1 with the same drilling and blasting cost per BCM.

(iii) BD3 would have a higher drilling and blasting productivity than BD1. Thus, for a given blasting area, BD3 would yield more BCM of broken rock per blast than BD1 at the same fragmentation and drilling and blasting cost.

Table 4 Estimated Drilling and Blasting Costs

Parameters	**DB1**	**DB2**	**DB3**	**Notes**
Burden (m)	3.2	3.5	3.6	B
Spacing (m)	3.8	4.0	4.1	S
Hole Diameter (mm)	115	115	127	ϕ
Bench Height (m)	5	10	10	H
Sub Drill (m)	0.5	0.8	0.8	U
Stemming (m)	2.2	3.2	3.1	T
Drilling Cost per Metre ($)	7.14	7.14	8.85	D_M
Emulsion Density (g/cm3)	1.20	1.20	1.20	ρ
Emulsion Cost per Kilogramme ($)	0.63	0.63	0.63	E_c
Booster Cost per Hole ($)	2.26	3.45	3.45	B_c
Cost of In-hole Detonator Unit ($)	3.21	3.51	3.51	D_c
Cost of Surface Connector Unit ($)	2.49	2.49	2.49	S_c
BCM per Hole (m3)	60.8	140.0	147.6	B.S.H
Mass of Emulsion per Metre (kg)	12.47	12.47	15.20	$M_m=(\pi d^2/4)\rho$
Mass of Emulsion per Hole (kg)	41.15	94.77	117.04	$M_h=(H+U-T)M_m$
Emulsion Cost per Hole ($)	25.93	59.71	73.74	$E_h=M_h \times E_c$
Initiation Cost per Hole ($)	7.96	9.45	9.45	$I_c=B_c+D_c+S_c$
Drilling Cost per Hole ($)	39.27	77.11	95.58	$D_C=D_M(H+U)$
Drilling Cost per BCM ($)	0.65	0.55	0.65	$D_{BCM}=D_C/BSH$
Emulsion Cost per BCM ($)	0.43	0.43	0.50	$E_{BCM}=E_h/BSH$
Initiation Cost per BCM ($)	0.13	0.07	0.06	$I_{BCM}=I_c/BSH$
Explosive Cost per BCM ($)	0.56	0.49	0.56	$X_{BCM}=E_{BCM}+I_{BCM}$
Drilling and Blast Cost per BCM ($)	**1.21**	**1.04**	**1.21**	$\mathbf{D_{BCM}+X_{BCM}}$

4.2 Recommendations

The following recommendations are made:

(i) BD3 should be selected ahead of BD1 and BD2 for ore blasting in the Kofi C Pit as it has highest productivity and also cost effective.

(ii) BD2 could be considered for waste drilling and blasting since its lower fragmentation, which is not good enough when the rock is ore, is acceptable when the rock is waste.

(iii) BD1 could be used for ore blasting in the Kofi C Pit when operation expediencies require blasting to be done over 5 m bench height.

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