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A practical method of bench blasting design for desired fragmentation based on digital image processing technique and Kuz-Ram model

I.C. Engin

Afyon Kocatepe University, Iscehisar Vocational School, Iscehisar, Afyonkarahisar, Turkey

ABSTRACT: Blasting is the most productive excavation method in hard rock mining. In quarries, to remove the mother rock from in-situ and crush into the desired size is realized by bench blasting method. Bench height, hole diameter, spacing, burden, hole length, bottom charge, column charge, stemming, specific hole length and specific charge are the design parameters in bench production blasting. In addition, rock factor has to be known for estimating the rock fragmentation. In determination of the design factors, the most economic solution which provides required fragmentation is selected in the view of engineering aspect. This research was carried out as a practical method to determine the design parameters giving desired fragmentation and cost in a limestone quarry. In this research, rock factor was calculated indirectly by using bench blasting design parameters which has already been applied and resultant fragment size instead of the geological data. Fragmentation characteristics such as mean fragment size, uniformity index and characteristic size were calculated by using digital images in an image analysis system called SplitDesktop® software. Rock factor value of this part of the quarry was calculated by Kuz-Ram model by means of design parameters and fragment size. After that, different bench blasting design parameters were selected by optimization according to Langefors and other suggested equations. Optimum drill hole diameter was observed as 89 mm and bench design parameters such as spacing 2.5 m, burden 2 m, specific charge 0.97 kg/m³ were proposed according to this value. These parameters provide desired fragmentation and less cost at the same time for given quarry conditions.

1 INTRODUCTION

In open pit mining where blasting is employed for excavation, the overall cost—effectiveness of the production operations is compatible with optimization of drilling and blasting. Loading, hauling and crushing costs decrease with increasing rock fragmentation while drilling and blasting costs increase with increasing rock fragmentation. Rock fragmentation is considered as the most important matter in quarrying because of its direct effects on the efficiency and cost of drilling and blasting, and subsequent loading, hauling and finally crushing operations. Rock fragmentation depends on two groups of variables: rock mass properties which cannot be controlled and blasting parameters that can be controlled and optimized.

Total cost of aggregate production in a quarry has a minimum value at an optimum fragmentation size (Mackenzie 1967; Morin & Ficarazzo 2005). Prediction of the optimum fragmentation size will help the quarry owners in selecting blasting parameters to produce required material size at a known cost and also in selecting other crushers

and conveyor systems. Optimum fragmentation size may not be the required size but knowing the size distribution for particular blast and rock mass conditions, the contractor can adapt the blasting if possible (Morin & Ficarazzo 2005).

For prediction of the fragmentation size after blasting the Kuz-Ram model is generally used. The Kuz-Ram model is an empirical fragmentation model based on the Kuznetsov (1973) and Rosin & Rammler equations modified by Cunningham (1983, 1987), which derives the coefficient of uniformity in the Rosin & Rammler equation from blasting parameters. Rock properties, explosive properties, and design variables are combined in this modern version of the Kuz-Ram fragmentation model.

1.1 The Kuznetsov equation

The amount of breakage that occurs with a known amount of explosive energy can be estimated using Kuznetsov's equation. The original equation, developed by Kuznetsov (1973), was modified by Cunningham (1987) for ANFO based explosives.

$$X_m = AK^{-0.8} Q_e^{0.167} (115/S_{ANFO})^{0.633} \quad (1)$$

where X_m is the mean fragment size (cm), A the rock factor (or blastability index), K the powder factor or specific charge (kg of explosives/m³ of rock), Q_e the mass of explosive being used (kg), S_{ANFO} the relative weight strength of the explosive relative to ANFO.

The blastability index (or rock factor) is calculated from an equation originally developed by Lilly (1986). It is used to modify the average fragmentation based on the rock type and blast direction.

$$A = 0.06(RMD + JF + RDI + HF) \quad (2)$$

where A is the blastability index, RMD the rock mass description, JF the joint factor, RDI the rock density index, HF the hardness factor. These factors are calculated from geological data such as; in situ block size, joint spacing, joint orientation, rock specific gravity, Young's modulus, unconfined compressive strength and etc.

Powder factor or specific charge is the mass of explosive being used (kg) to break a cubic metre volume of rock.

$$K = Q_e/V_0 \quad (3)$$

where Q_e is the mass of explosive being used (kg), V_0 the rock volume (m³) broken per blasthole = burden (B) \times spacing (S) \times bench height (H).

1.2 The Rosin & Rammler equation

The size distribution of the materials is calculated from the Rosin & Rammler equation especially in mineral processing area (Rosin & Rammler 1933).

$$y = 100(1 - e^{-(X/X_c)^n}) \quad (4)$$

where y is the percentage of material less than the size X (%), X the diameter of fragment (cm), X_c the characteristic size (cm), n the Rosin & Rammler exponent (uniformity coefficient), and e the base of natural logarithms.

Since the Kuznetsov formula gives the screen size X_m for which 50% of the material would pass, the characteristic size is calculated from the average size for use in the Rosin & Rammler equation by substituting $X = X_m$ and $y = 0.5$ into Equation 4 one finds that

$$X_c = \left(\frac{X_m}{0.693^n} \right) \quad (5)$$

Average particle size of the materials obtained from a blasting operation is not enough information explaining the efficiency of the operation. There could be two broken rock piles having the same average particle size but they could have different particle size distributions. Very coarse and fine particles can give acceptable average particle size but can cause problems in subsequent operations. Uniform particle size distribution is an important parameter that has to be considered.

The uniformity coefficient is calculated from an equation developed by Cunningham (1987). Cunningham established the applicable uniformity coefficient through several investigations, taking into consideration the impact of such factors as: blast geometry, hole diameter, burden, spacing, hole lengths and drilling accuracy. The exponent n for the Rosin & Rammler equation is estimated as follows:

$$n = \left(2.2 - 14 \frac{B}{D} \right) \left[\frac{1 + \frac{S}{B}}{2} \right]^{0.5} \left(1 - \frac{W}{B} \right) \left(\frac{L}{H} \right) \quad (6)$$

where B is the blasting burden (m), S the blasthole spacing (m), D the blasthole diameter (mm), W the standard deviation of drilling accuracy (m), L the total charge length (m), and H the bench height (m). Cunningham (1987) notes that the uniformity coefficient n usually varies between 0.8 and 1.5.

1.3 The bench blasting parameters

Bench blasting can be defined as drilling of vertical or angled holes in one or several rows from a free surface, which then are blasted again a second free surface.

The bench blasting operations are classified according to their purpose (Jimeno et al. 1995):

- Conventional bench blasting; the pursuit of maximum fragmentation and swelling of the rock.
- Rip-rap blasting; obtaining large fragments of rock.
- Cast blasting; using explosives to not only fragment the rock, but to also project a large quantity of it to a predetermined place.
- Road and railway blasting; conditioned by the terrain and road plan.
- Trench and ramp blasting; lineal operations due to the shape and narrowness of the excavations the confinement of explosives is high.
- Ground leveling and foundation blasting; usually over a small area and quite shallow.
- Preblasting; increasing the natural fractures in the rock mass with as little displacement as possible.

Bench blasting can also be classified by the diameter of the blast hole:

- Small diameter blasting: from 65 to 165 mm
- Large diameter blasting: from 180 to 450 mm

The subject of this research is conventional small diameter blasting because it is performed in a quarry to obtain a desired fragmentation with minimum cost.

Many formulae and methods for calculating geometric parameters such as burden, spacing, and subdrilling have been around since the early 1950's, and use one or more of the following parameters: hole diameter, characteristics of explosives, compressive rock strength, and many more. In small diameter blasting Swedish method developed by Langefors & Kihlström (1976) is used (Jimeno et al. 1995).

Bench blasting design parameters are given in Figure 1 are; D is the blasthole diameter (m), K the bench height (m), B the burden (m), E the blasthole spacing (m), U the blasthole subdrilling (m), S (h_0) the blasthole stemming length (m), H the blasthole length (m), h_p the length of column charge (m), h_b the length of bottom charge (m). Other parameters considered in bench blasting calculations are; I_p the concentration of column charge (kg/m), I_b the concentration of bottom charge (kg/m), Q_p the weight of column charge (kg), Q_b the weight of bottom charge (kg), Q_e is the total weight of explosive being used in a hole (kg), q the powder factor or specific charge (kg of explosives/m³ of rock), g the specific drilling (drilled meters/m³ of rock). Blasthole pattern, delay timing and initiation sequence are also very important parameters in bench blasting operations.

The most critical and important dimension in blasting is that of the burden B as it represents

the rock mass to be fragmented by the explosive column, and is calculated as follows:

$$B_{\max} = \frac{D45}{1000} \left(\frac{0.4}{c} \right)^{\frac{1}{2}} \left(\frac{PS}{1.25} \right)^{\frac{1}{2}} \left(\frac{1}{f} \right)^{\frac{1}{2}} \quad (7)$$

where B_{\max} is the maximum burden (m), D the blasthole diameter (mm), c the rock constant, P the degree of packing of the explosive, S the relative weight strength of the explosive, f the fixation of the hole.

Subdrilling is calculated by the formula given below:

$$U = 0.3B_{\max} \quad (8)$$

Total length of the blasthole is:

$$H = (K + U)k \quad (9)$$

Practical burden distance is calculated as follows:

$$B = B_{\max} - (D/1000 + 0.03H) \quad (10)$$

Spacing (E) is the distance in meters between adjacent blastholes and is measured perpendicular to the burden. The relation between burden and spacing is:

$$E = 1.25B \quad (11)$$

Stemming (S) is the inert material filled between the explosive charge and the collar of the blast-hole to confine the explosion gases. The stemming material could be water, drill cutting, sand, mud or crushed rock. Stemming distance is taken as equal to the burden.

$$h_0 = B \quad (12)$$

To obtain a satisfactorily breakage in the bottom part, the required height of the bottom charge should be equal to:

$$h_b = 1.3B \quad (13)$$

Total quantity of bottom charge is given as:

$$Q_b = h_b I_b \quad (14)$$

Bottom charge concentration is:

$$I_b = (D^2/1000)(P/1.25) \quad (15)$$

The required height of the column charge should be equal to:

$$h_p = H - h_b - h_0 \quad (16)$$

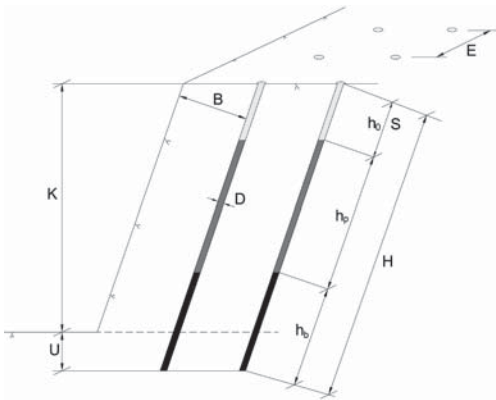


Figure 1. Parameters considered in bench blasting operations.

Total quantity of column charge is given as:

$$Q_p = h_p I_p \quad (17)$$

Column charge concentration is:

$$I_p = \%40\text{--}\%50 \text{ of } I_b \quad (18)$$

Total weight of explosive being used in a hole (kg) is given as:

$$Q_c = Q_p + Q_b \quad (19)$$

In addition to Langefor's approach there are several other approaches for determining the bench blasting parameters.

Wyllie & Mah (2005) describe some procedures for calculating the parameters involved in designing production blasts according to also Ash (1963) and Konya & Walter (1990).

The relationship between the bench height K and the burden B is expressed in terms of the "stiffness ratio, K/B ". To reduce the effects of the blasting such as backbreak, airblast, flyrock and vibration, the burden distance B is calculated from:

$$B = 0.33K \text{ to } 0.25K \quad (20)$$

Once the burden B (m) has been set to provide an appropriate stiffness ratio (Equation 20), the diameter of the explosive d is given by,

$$d = \left(\frac{B}{8(RBS/\gamma_r)^{0.33}} \right) \quad (21)$$

where RBS is the relative bulk strength compared to ANFO (100), γ_r is the unit weight of the rock.

Experience has shown that a subdrill depth of 0.2–0.5 times the burden is usually adequate for effective digging to grade:

$$U = 0.2B \text{ to } 0.5B \quad (22)$$

The common stemming length is about 0.7 times the burden, which is adequate to keep material from ejecting prematurely from the hole.

$$h_0 = 0.7B \quad (23)$$

For a series of delayed holes, the spacing E can be calculated from the following equation for a stiffness ratio K/B between 1 and 4:

$$E = \left(\frac{K + 7B}{8} \right) \quad (24)$$

In this research these two approaches are used in optimization of the quarry bench blasting parameters.

2 METHODOLOGY

Bench blasting design parameters which give the desired fragmentation were determined for a distinct limestone quarry by a practical method. Rock mass properties and blasting parameters control the efficiency of a blasting operation. But all the blasting design parameters cannot be arranged. Bench height is related to the working capability of loaders and is limited to 6 m for the quarry that we work in.

First, blasting design parameters already used were determined in the quarry. Then several blasting operations were performed and after each, scaled digital photographs of the broken rock pile were taken. Fragmentation characteristics such as mean fragment size, uniformity index and characteristic size were calculated by using digital images in an image analysis system called SplitDesktop® software. The rock factor value for the quarry was calculated by the Kuz-Ram model by means of design parameters and fragment size indirectly. By using this rock factor value and the Swedish method new blasting design parameters were determined by optimization including target mean fragmentation size and minimum cost were performed using the Microsoft® Excel Solver tool. Research methodology is given in Figure 2 as a worksheet.

2.1 Information about the quarry

The quarry was established in 1975 in the south-eastern province of Afyonkarahisar in Turkey to provide crushed marl aggregate to the cement industry. The quarry runs benches that are approximately 6 m high. The mine performed percussion drilling with bits that are sized at 4.5 inches

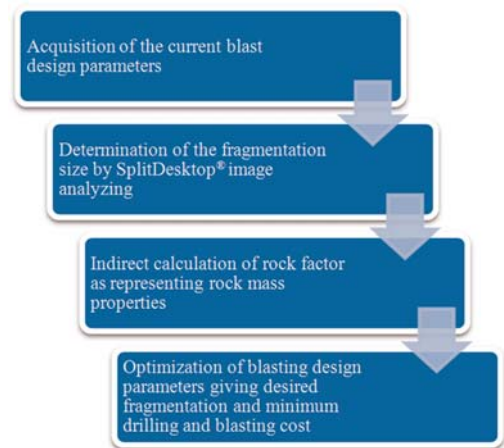


Figure 2. General layout of the research worksheet.

(approx 115 mm) when the research was started. Production has been observed at the rate of 2,000 tons per day in 3,000 square meters of the working area. Blasting design parameters were selected firstly as given in Table 1.

Blasting was done via the use of a non-electrical shock tube system. Each hole is loaded with a 1 kg booster, and approximately 40 kg of ANFO per hole for a total of 41 kg of explosives per hole. Blasthole pattern were arranged as staggered three rows. 500 millisecond delays are used to ensure that all the holes are burning before the first hole row detonates. A view of the quarry is given in Figure 3.

After the blast, fragmentation was investigated using the SplitDesktop® image analysis software. The investigation procedure is given in Figure 4 as working scheme.

Fragmentation sizes of the broken rock piles were investigated in this way and mean fragmentation size was calculated as 29.1 cm. By using the formula given in Equation 1 and parameters given in Table 1 blastability index (rock factor) of the quarry rock was calculated as 6.65.

Table 1. Quarry blasting design parameters.

Parameter	Value
Rock type	Limestone
Bench height	6 m
Blasthole length	7 m
Blasthole spacing	4.5 m
Burden	4 m
Blasthole diameter	115 mm
Rock volume broken per blasthole	$6 \times 4.5 \times 4 = 108 \text{ m}^3$
Blasthole pattern	staggered
Length of ANFO charge	5 m
Weight of ANFO charge	40 kg
Weight of booster at each hole	1 kg
Detonators in a blasthole	1 non-electric shock tube



Figure 3. General view of the bench blasthole pattern.

2.2 Optimization of the blasting parameters

The plan was to change the mean fragmentation size to approximately 15 cm for subsequent operation units. In this research, bench blasting design parameters were optimized to give the desired mean fragmentation size and minimum cost.

Quarry drilling and blasting operation involves cost (in Turkish Liras, TL) of the main explosive mostly ANFO, booster, detonator and drilling itself as shown in Tables 2–3.

Total drilling-blasting cost can be defined as:

$$C_T = C_A + C_B + C_D + C_{DR} \quad (25)$$

$$C_T = 0.92Q_A + 3.73Q_B + 2.4Q_D + 2.05L_{DR} \quad (26)$$

Cost components of the percussive dry type drilling unit are defined as:

$$C_{DR} = C_{YD} + C_F + C_P + C_M \quad (27)$$

In this part of the research, blasthole diameter D (m), burden B (m), blasthole spacing E (m), sub-drilling U (m), blasthole stemming length S (m), blasthole pattern (staggered or rectangular) and explosive properties were selected according to

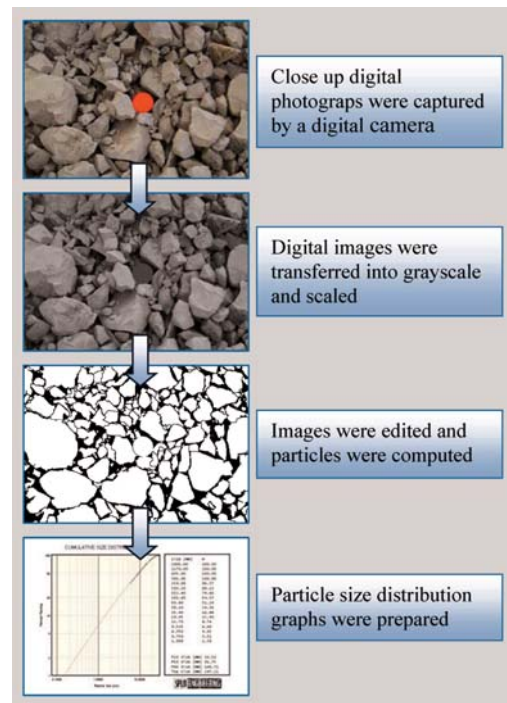


Figure 4. Procedure for the determination of particle size distribution by using SplitDesktop® digital image analysis software.

Table 2. Quarry drilling-blasting cost components.

Cost components	Symbol	Quantity	Unit	Unit cost
ANFO	C_A	Q_A	kg	0.92 TL/kg
Booster	C_B	Q_B	kg	3.73 TL/kg
Detonator	C_D	Q_C	item	2.40 TL/it.
Drilling	C_{DR}	L_{DR}	m	2.05 TL/m

Table 3. Quarry drilling cost components.

Drilling cost components	Symbol	Unit cost (TL/m)
Yield of depreciation	C_{YD}	0.792
Fuel cost	C_F	0.994
Personnel expenses	C_P	0.173
Cost of maintenance	C_M	0.087
Total drilling cost	C_{DR}	2.047

the desired fragmentation size and minimum total drilling and blasting cost.

Optimization criteria were desired fragmentation size and minimum drilling-blasting cost, bench height was considered as constant 6 m, explosive was selected as ANFO. Optimization process can be defined as:

- Optimization function:
Minimize $C_T = C_A + C_B + C_D + C_{DR}$
- Constraints:
Rock factor, $A = 6.65$
Bench height, $K = 6$ m
Mean fragment size, $X_m \leq 15$ cm
Uniformity coefficient, $n \geq 1.5$

Using Langefor's approach and minimization with the Microsoft® Excel Solver tool produced results in Table 4.

An increase in the blasthole diameter increases the mean fragment size and decreases the total drilling and blasting cost according to Langefors approach as shown in Figure 5.

Optimization of the blasting parameters using Ash (1963) and Konya & Walter (1990) approach produced the results in Table 5.

In the quarry the parameters given in Table 6 were selected. After the blasting operations fragmentation was investigated with the SplitDesktop® image analysis software, and the mean fragment size was obtained as 15.33 cm, top fragment size was obtained as 54.67 cm.

The results from the two different optimization processes were very different to each other. Although the optimization criteria and the main constraints were the same, the approaches used were quite different. The relations between blasthole diameter D (m), burden B (m), blasthole spacing

Table 4. Quarry blasting design parameters according to Langefors approach.

Parameter	Symbol	Value
Blasthole diameter (inch)	D	1.25
Blasthole diameter (mm)	D	39
Blasthole length	H	6.41
Burden (m)	B	1.12
Blasthole spacing (m)	E	1.40
Stemming length (m)	$h_0(S)$	1.12
Length of ANFO charge (m)	L	5.28
Weight of ANFO charge (kg)	Q_c	5.42
Specific charge (kg/m ³)	q	0.57
Specific drilling (m/m ³)	I	0.68
Mean fragment size (cm)	X_{av}	15.00
Uniformity coefficient	n	1.80
Total drilling-blasting cost (TL/m ³)	Mt	2.54

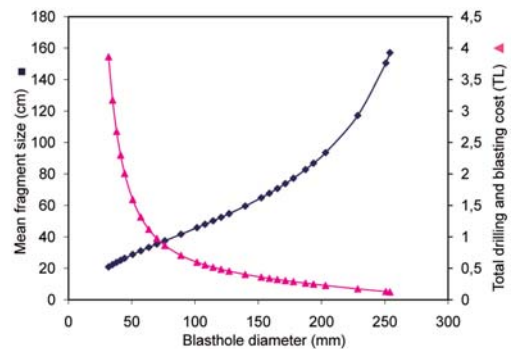


Figure 5. The relations between blasthole diameter, mean fragment size and total drilling—blasting cost according to the Langefors formulas.

Table 5. Quarry blasting design parameters according to suggested formulas (Wyllie & Mah 2005).

Parameter	Symbol	Value
Blasthole diameter (inch)	D	3.5
Blasthole diameter (mm)	D	89
Blasthole length	H	6.92
Burden (m)	B	2.00
Blasthole spacing (m)	E	2.50
Stemming length (m)	$h_0(S)$	1.40
Length of ANFO charge (m)	L	5.52
Weight of ANFO charge (kg)	Q_c	29.12
Specific charge (kg/m ³)	q	0.97
Specific drilling (m/m ³)	I	0.23
Mean Fragmentation size (cm)	X_{av}	13.07
Uniformity coefficient	n	2.00
Total cost (TL/m ³)	Mt	1.56

Table 6. Quarry blasting design parameters selected by the owner.

Parameter	Value
Blasthole diameter (inch)	3.5
Blasthole diameter (mm)	88.9
Blasthole length	7.00
Burden (m)	2.00
Blasthole spacing (m)	2.50
Stemming length (m)	2.10
Length of ANFO charge (m)	4.90
Weight of ANFO charge (kg)	25.91
Specific charge (kg/m ³)	0.86
Specific drilling (m/m ³)	0.23
Mean Fragmentation size (cm)	15.33
Uniformity coefficient	1.77
Total drilling-blasting cost (TL/m ³)	1.47

$E(m)$, subdrilling $U(m)$, blasthole stemming length $S(m)$ and etc. were also taken into consideration as constraints for the optimization process. Blasthole sizes were also restricted to the drill bit diameters that were already used in drilling operations.

3 RESULTS AND DISCUSSION

In this study, rock factor representing the rock mass properties of a quarry was determined indirectly by the resultant fragmentation of the blasting operation carried out by using the specified blast design parameters. Rock factor was calculated by Kuz-Ram model by means of design parameters and fragment size investigated by SplitDesktop® image analysis software.

Optimum blast design parameters were determined by optimization of the drilling and blasting costs and also fragmentation. The first optimization study used the Langefors & Kihlström (1976) approach which predicted the required fragment size and other targets but predicted relatively high total drilling and blasting costs.

In the second optimization process optimum blast design parameters were determined by using suggested formulae used in the bench blasting operations. The desired fragment size as well as minimum drilling and blasting costs were predicted. Similar parameters were then used by the

quarry owner for the actual blasts and similar results such as mean fragment size, uniformity coefficient, specific charge, and total drilling and blasting cost were observed with a cost reduction of around 50%.

The results show that this procedure can be applied in quarry blasting operations, but fragmentation determination by image analysis and selected constraints used in optimization controls the performance and validity of the operation. The optimization process has to be repeated for other bench blasting design approaches to produce the best results.

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