Jr. of Industrial Pollution Control 33(1)(2017) pp 931-936
www.icontrolpollution.com
Review

DRILLING AND BLASTING DESIGN BASED ON INVARIABLE MINING PARAMETERS

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(Received 06 May, 2017; accepted 08 May, 2017)

Key words: Drilling and blasting parameters, Energy distribution, Particle size distribution, Blast fragmentation, Determination method

ABSTRACT

The article summarizes scientific and industrial research of blast fragmentation patterns in different mining and geological conditions. Particle size distribution in a bulk is one of the most important parameters for ore mining as it significantly affects further production process and profit return. Efforts to estimate effective blast design principles that could be applied in any geological and technical conditions are made. Three invariants are suggested as basis to determine drilling and blasting parameters for expected fragmentation results. Experimental blasts results are described and analysed to study the influence of charge parameters on particle size distribution. Obtained results could be used to design blasts on open pits to get pre-defined particle size distribution.

INTRODUCTION

Rock fragmentation quality differently affects the economy and performance of core mining enterprise processes. For example, expectancy decrease of characteristic rock fragment size affects escalation of drilling and blasting cost but leads to reduction of loading and hauling cost. Mining experience worldwide clearly shows that the maximum profit corresponds to exact blast fragmentation distribution (Sanchidrián, *et al.*, 2014). This variation of blast fragmentation particle size impact on economic parameters actualizes the search of the optimum blast design to minimize overall rock production cost. So, a sustainable method of blast design parameters (e.g., burden, borehole diameter, etc.) estimation is needed. Blast fragmentation models are supposed to be based on invariants: uniform input data, some constants, laws or equations that do not change after rock properties, loading time or size scale.

GENERATION OF THE DATA

Based The first fragmentation invariant can be stated. Total blast and mechanical fragmentation and the native rock block size have a lognormal distribution and its variance is a structural invariant.

Three general assumptions about rock fragmentation are limiting laws of linear size, surface or weight distribution:

- lognormal, in case the size of a piece does not affect its fragmenting probability (Kolmogorov model) (Gorokhovski and Saveliev, 2003);

- gamma distribution, in case fragmenting probability shows a positive growth proportionally to any positive degree of the piece size (Kolmogorov-Filippov model) (Ghorbel and Huillet, 2007);

- no limiting law when fragmenting increases proportionally to a negative degree of the piece size.

Overall distribution of particle size varying from tens and hundreds of meters to millimeters and less obviously can be approximated by all of the described models in some intervals. However, economic performance of mining is highly dependent on quantity of rocks of a size which has the most influence on loading and hauling productivity. In this regard, the methods of particle size estimation at mining enterprises are oriented on grades between 0.1 m to 2 m. And within this range the lognormal distribution (Kolmogorov model) could be used, as

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mechanical properties are unlikely to vary from one particle size to another.

Experimental results analysis (Lu, 1997) has shown that particle size distribution of destroyed rock mass can be approximated by a lognormal function even in a wide range of blasting design parameters in similar rock mass conditions and with a constant variance. Meantime, we have established (Vinogradov and Tumasheva, 1975) that even in considerably different mining conditions high fluctuation of particle size expectation (e.g. x50) is not followed by significant variance fluctuation. This is considered as a result of averaging of elemental destruction events (molecular bond breaking). Also, it explains almost identical results of rock mass centuries-long loading and blast fragmentation. Fig. 1 shows similar particle size distribution in conditions of "Kuznechnoe" open-pit mine.

Conformity of logarithmic variance (~1.0) between drilling chips, blasted rock and natural block size shows that statistical analysis characterizes stochastic process of elemental destruction events causing molecular bond breaking. The experimental data confirms that logarithmic variance of lognormal distribution function is a structural fragmentation invariant on the level of statistical ensemble of rock blocks and pieces.

According to the above, the problem of regular or more uniform fragmentation by change of rock mass blast destruction parameters is almost unsolvable. Short range and random nature of logarithmic variance change for rock mass fragmentation allows getting more or less fragmentation ratio in terms of mean fragment particle size. However, more fragmentation uniformity usually leads to decrease of coarse particles content but increase in fine parts which doesn't affect much loading and hauling.

Second fragmentation invariant is related to blast energy distribution and can be stated. Energy absorbing capacity of rock mass volume is a variable and it depends on correlation between specific energy input and burden.

Available methods of blasting parameters estimation to get the predetermined particle size distribution are based on correlations between certain drilling and blasting parameters and fragmentation characteristics. But, pair correlation requires determining quantity related association between certain drilling and blasting parameters and characteristics of blast fragmentation quality. The reasons for such association are possibly connected with blasting energy redistribution, which is inadequately described.

Estimation of blasting parameters to get certain particle size distribution should consider study of pattern of energy distribution among main technological blast works (fragmentation and mass movement). Prediction of such distribution for different blasting parameters, first of all, must concern drilling pattern and specific charge.

The main objectives of the research are:

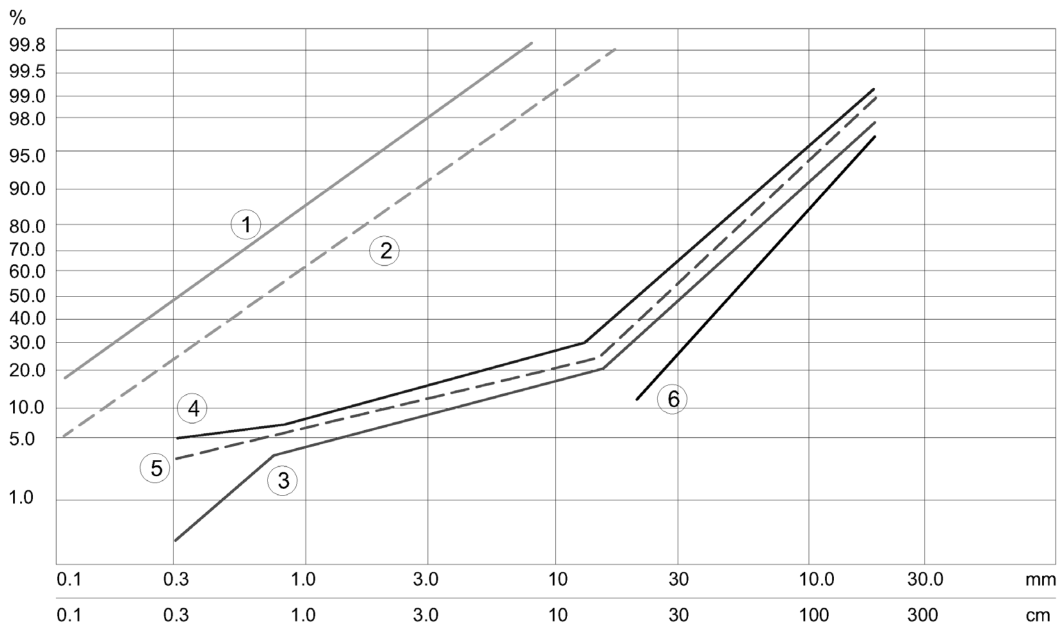

Fig. 1 Particle size distribution for Kuznechnoe granite deposit: 1, 2-drilling chips for two roller-bit drilling rigs (X-axis in mm); 3, 4, 5-fragmentation for three near-by ballast quarries, 6-natural block size.

1. Study of quantity related association between rock mass blast fragmentation, movement, seismic vibrations and burden/charge weight proportion.

2. Study of energy input needed for fragmentation and mass movement depending on specific charge and drilling pattern.

The third fragmentation invariant considers charge diameter. Specific charge/rock contact surface (charge surface/weight ratio) determines quantity of energy spent on fragmentation or blast efficiency.

RESULTS

The first bigger part of experiments was set at Olenegorsk quarry. Further experiments were conducted at Maleevsky mine and granite quarries near Saint-Petersburg. Each experiment was a single borehole blast varying depth, specific charge weight and charge surface. The parameters measured are the volume of blast crater, particle size distribution, average velocity of rock and rock mass acceleration. Working assumption to determine energy spent on fragmentation is probabilistic-statistic hypothesis of rock destruction (Shams, *et al.*, 2015).

Experiments show the correlation between blast fragmentation efficiency (η/σ) and equivalent burden ($W/\sqrt[3]{Q}$) using the fundamental equation of probabilistic-statistic hypothesis of rock destruction (Fig. 2):

$$\frac{\eta}{\sigma} = \frac{1}{q_0} \ln \frac{W}{d} \tag{1}$$

Where η is blast potential energy, output spent on fragmentation (hereafter blasting efficiency or b.e.); σ is strength of the rock, kg/m^2; q_0 is specific energy cost, kgm/m^3; W is burden, m; d is statistical expectation of the particle size, m.

The diagrams for all cases (different blast series at Olenegorsk and Maleevsky mines) on interval including min and max b.e. can be approximated:

$$\eta_i = \eta_0 \left(\frac{K_i}{K_0}\right)^2, \text{ or } \eta_1 = \eta_0 \left(\frac{W_i}{W_0}\right)^2 \cdot \left(\frac{Q_0}{Q_i}\right)^{2/3} \tag{2}$$

Where η_i is b.e. for specific K value; η_0 is the same but for K_0.

The shown K value interval is the most suitable for mining blasts while K ≥ 1.1 describes confined blasts.

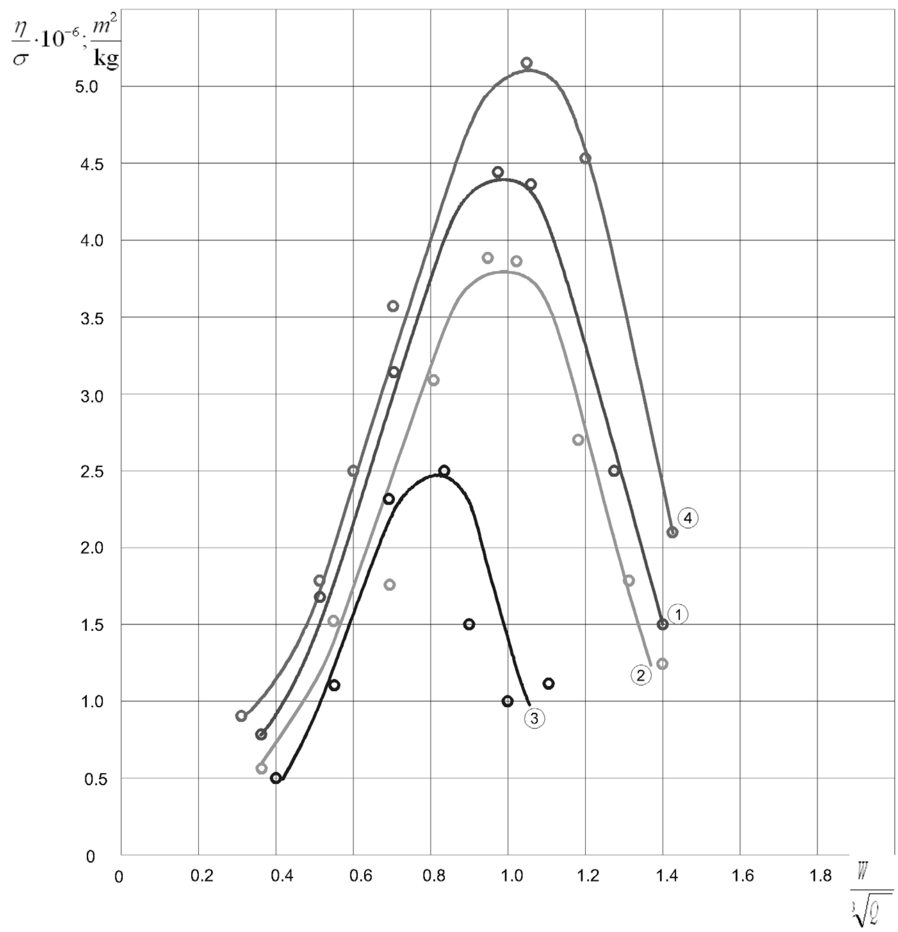

Fig. 2 Correlation between blast fragmentation efficiency and burden/charge weight ratio. 1. f = 14÷16; 2. f = 12÷14; 3. f = 10÷12; 4. f = 16÷18.

Therefore, knowing the values of η_0, W_0, Q_0, the equation allows determining b.e. for any blast for the similar rocks and varying burden and charge weight.

The influence of explosives characteristics on blast fragmentation efficiency can be estimated after (Golovko, *et al.*, 1874). Published results of single-charge blasts experiments allowed deducing the efficiency of blast fragmentation for different explosives. Comparing these with results obtained at Olenegorsk quarry for ANFO-type explosive showed perfect analogy.

For bulk blasts after United States Bureau of Mines (Siskind and Fumanti, 1974; Atchison and Tourney, 1959) the composition of distance between rows and holes in a row can be used as W_2. This is characteristic value of an adequate accuracy for a mean burden of a blast hole pattern. Hence, the function (2) considering specific charge is:

$$\eta_i = \eta_0 \left(\frac{q_0}{q_i} \cdot \frac{W_i}{W_o} \right)^{2/3} \quad (3)$$

where W_0 is reference value of a blast hole pattern, m; q_0 is reference specific energy cost, kgm/m^3; Q_i is new blast hole pattern value, m; q_i is new specific energy cost, kgm/m^3.

The analysis of bulk blasts using (3) showed that even drastic change of energy costs (up to two times) and hole pattern (up to 1.5 times) kept good convergence of measured and expected blast results. The important point of the analysis is the flexibility of the function introduced for certain conditions (Olenegorsk quarry, ferruginous quartzite) and used for different mining conditions show a good convergence with real blasts. This allows considering it as invariant to rock mechanical properties.

The charge diameter is one of the most important parameters of blasting which significantly influences both fragmentation quality and drilling-and-blasting performance indicators.

According to similarity principle, the charge diameter influences the quantitative characterization of particle size distribution in a bulk and is determined by equal stress-and-strain parameters of rock mass with equal specific fragmentation energy costs. However, a number of researches (Cirel, 2005; Isheyskiy and Yakubovskiy, 2016) show that for constant specific energy of explosive fragmentation ratio is a linear function of charge diameter. It demonstrates that similar distribution of explosion energy does not provide similar rock mass fragmentation, and the total specific blast-formed surface of particles is more when charge diameter is less. This explains the increase of explosives specific consumption with big diameters comparing with small diameters of blast holes.

The contradiction between the similarity principle, according to which distance of equal actions of tension waves is pro rata to the charge linear sizes, and improvement of fragmentation with reduction of a charge diameter can be explained as change of the energy quantity transferred by a charge to the rock mass.

To clear this statement a number of experimental blasts was taken under the following conditions:

– constant volume and mechanical properties of rock mass, charge potential energy and height, density and type of explosive, as well as charge volume by varying diameter and construction;

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The first series of experiments were set in conditions of Olenegorsk quarry with single charge blasts. Blasting results for different depth of charge are described by volume of blasting wedge and particle size distribution. Also, kinematic parameters of rock mass movement in strain wave were measured in charge vicinity.

Charge diameter in different blasts was 76, 105 mm and 132 mm and charge height, energy and explosive type (ANFO) remained constant. Charge weight was 1.6 kg. Charge height is kept constant by disposition of a concrete kernel in the center.

DISCUSSION

The main result of the experiment is correlation between rock mass velocity and acceleration and charge surface changes. These values were measured on same distances from the center of the charge, and normalized to real radius they describe the velocity and acceleration for solid charge. In this case increase of specific surface (and radius) of a charge with a constant weight and inert material in the center results in increase of blast seismic influence zone proportional to relative increase of specific charge volume.

Related b.e. values predicted using (2) for three sets of blasts (Fig. 3) are proportional to charge diameter to the power 4/3:

$$\frac{\eta_i}{\eta_j} = \left(\frac{D_i}{D_j} \right)^{4/3}$$

However, experimental conditions are taken to determine not the charge diameter influence but charge surface/weight ratio. So (2) can be transformed to:

$$\eta_i = \eta_0 \left(\frac{D_0 \cdot \rho_0}{D_i \cdot \rho_i} \right)^{4/3} \quad (4)$$

Where D_i is new charge diameter, ρ_i is new charge density.

The experimental blast series results showed that blast fragmentation efficiency was determined by outer part of explosive charge and the increment of the charge surface.

The second experimental blasts series was set on a granite-gneiss quarry. The series included three sets of single-charge blasts of 1.2 kg of ANFO at 1.2 m depth and varying charge diameter of 64, 89 and 102 mm. Charge depth was equivalent to 1 m burden, which showed maximum values of rock mass velocity and acceleration. Kinematic parameters of mass movement were measured using piezoelectric accelerometers placed 1 meter from the charge, or for 64 mm charge, 30 radii length (30xR). Four blasts were made for each charge diameter. Mean rock mass velocity for each set is described at Fig. 4. Seismic effect of the explosion, i.e., particle velocity in seismo-blast wave is a function of contact surface of charge and rock. Blast fragmentation efficiency can be determined using (4).

Comparison between results for granite-gneiss and ferruginous quartzite demonstrates that dependences between rock mass movement parameters and specific charge surface are similar for charges of constant and varying height.

CONCLUSION

The analysis of bulk explosions results justifies the dependence (4) received experimentally for rocks with various mechanical properties.

The offered method of drilling and blasting parameters estimation on the set particle size distribution is based on above the specified invariants and represents the solution of the following equations system:

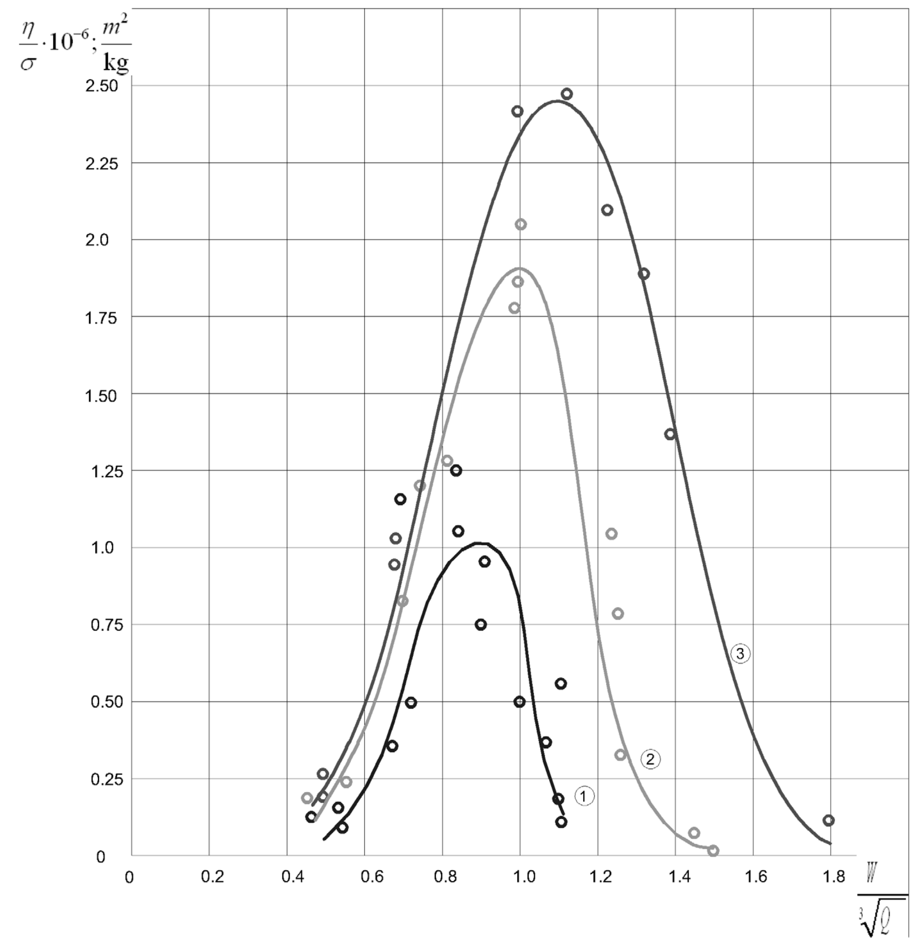

Fig. 3 Correlation between blast fragmentation efficiency and burden/charge weight ratio for charges of different diameter and equal potential energy and volume: 1-diameter 76 mm; 2-diameter 105 mm; 3-diameter 132 mm.

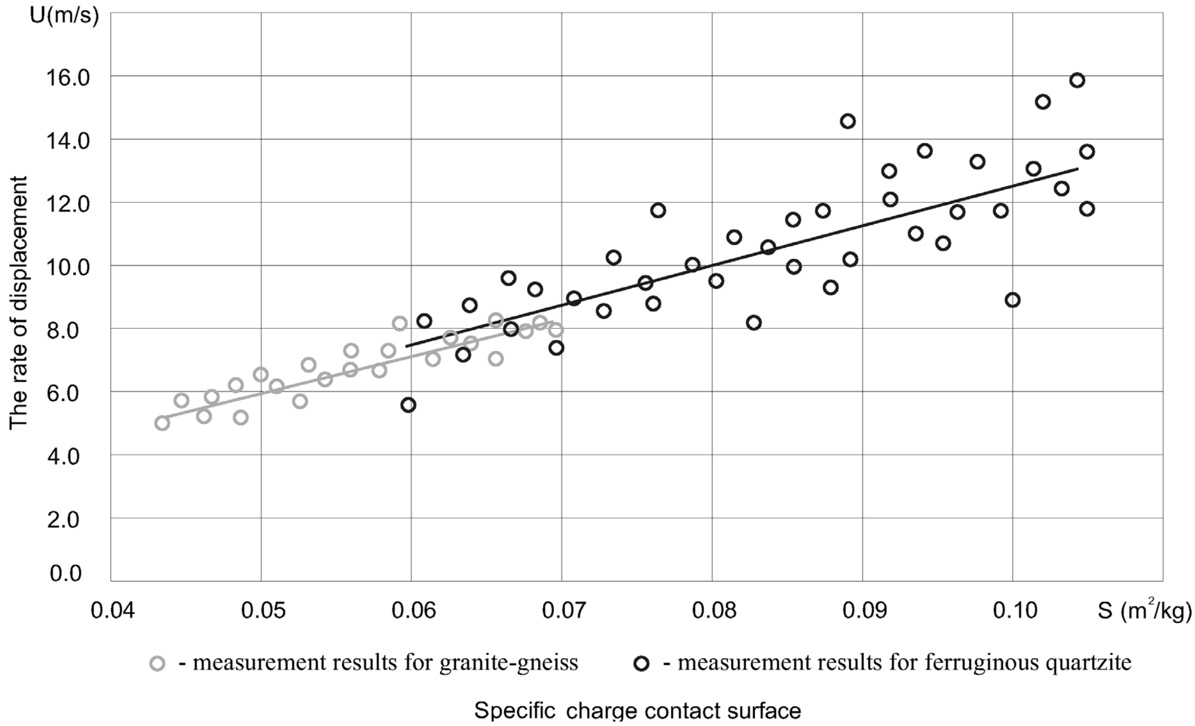

Fig. 4 Correlation between rock mass velocity and specific surface of a charge.

$$d_i = W_i \cdot \exp\left[-\eta/\sigma \left(\frac{W_i q_0}{W_0 q_i}\right)^{2/3} \cdot q_i\right]$$

Which is substitution of (3) to (1).

$$\eta_i = \eta_0 \cdot \left(\frac{D_0 \rho_0}{D_i \rho_i}\right)^{4/3}, \quad q_i = \frac{\pi D^2}{4} \cdot \frac{l\rho}{W_i L^2}$$

Where d_i is particle size expectation, m; W_0 is drill pattern parameter, m; g_0 is specific consumption of explosives, kg/m^3; η_0 is blast efficiency; D_0 is used blast hole diameter, m; W_i, g_i is new design parameters of drill pattern and explosives specific consumption for D_i diameter; l is charge height, m; L is bench height, m.

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