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An Alternative Approach to Burden Estimation Based on Targeted Mean Fragment Size Using Rock Fragmentation Models

Kaya Parçalanma Modellerini Kullanarak Hedeflenen Ortalama Parça Boyutuna Dayalı Yük Tahminine Alternatif Bir Yaklaşım

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Abstract

In the mining industry, bench blasting efficiency is determined by rock fragmentation. Therefore, it is crucial to predict the result of rock fragmentation before blasting. It is widely accepted that empirical fragmentation models like Kuz-Ram and Chung and Katsabanis (C&K) are the most reliable tools for predicting the size distribution of rock fragments following blasting. The main aim of this study is to provide an approach to estimating the optimal burden according to the intended mean fragment size using rock fragmentation models. It is necessary to determine or know the rock factor used in the mentioned models in attempting to apply the method proposed in this study. Initially, studies were conducted to determine the most appropriate burden according to the intended mean fragment for a quarry where the rock factor is known. After this, simplified equations were derived for the optimal burden depending on the rock factor, the intended mean fragment size, the bench height and the density of the explosive.

Keywords: Burden, fragmentation size, kuz-ram model, rock factor.

Öz

Madencilik sektöründe, basamak patlatmalarının verimliliği kaya parçalanma derecesine göre belirlenmektedir. Bu nedenle, patlatma öncesinde kaya parçalanma derecesinin tahmin edilmesi oldukça önem taşımaktadır. Kuz-Ram ve Chung ve Katsabanis (C&K) gibi görgül parçalanma modellerinin, patlatma sonrasındaki kaya parçalarının boyut dağılımının tahmin edilmesinde en güvenilir yöntemler olduğu yaygın olarak kabul edilmektedir. Bu çalışmanın temel amacı, kaya parçalanma modellerini kullanarak istenilen ortalama parça boyutuna göre en uygun yük mesafesinin tahmin edilmesine yönelik bir yaklaşım sağlamaktır. Bu çalışmada önerilen yöntemin uygulanabilmesi için söz konusu modellerde kullanılan kaya faktörünün belirlenmesi veya bilinmesi gerekmektedir. İlk olarak, kaya faktörünün bilindiği bir ocak için istenilen ortalama parça boyutuna göre en uygun yük mesafesinin belirlenmesine yönelik çalışmalar yapılmıştır. Bundan sonra ise, kaya faktörüne, amaçlanan ortalama parça boyutuna, basamak yüksekliğine ve patlayıcının yoğunluğuna bağlı olarak en uygun yük mesafesinin belirlenmesine yönelik basitleştirilmiş denklemler türetilmiştir.

Anahtar Kelimeler: Yük mesafesi, parçalanma boyutu, kuz-ram modeli, kaya faktörü.

1. Introduction

The use of explosives is probably the most common and cost-effective method of excavating rock on mining, quarrying, and construction sites (Hu et al. 2020, Li et al. 2021). Several reasons may have contributed to this, including efficiency, economy, and the ability to break even the hardest rocks. Explosive energy is used in blast design to break rock masses into smaller, more manageable sizes and shapes that are easier to excavate, load, transport, crush and grind in the future (Ouchterlony 2003, Sanchidrian and Ouchterlony 2017). The first step in size reduction in quarries is blasting, followed by crushing and grinding. One of the most important parameters for determining yield is the fragment size distribution of blasted rock fed to the crusher, since oversize blocks cannot be loaded into the crusher bins (Cunningham 2005). During loading and transportation, smaller or finer fragments cause ore loss, while larger or coarser fragments require further processing, thereby increasing production

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costs. Therefore, bench blasting effectiveness is measured by rock fragmentation in the mining industry. Prediction of rock fragmentation is therefore essential before blasting (Li et al. 2021, Cho et al. 2003).

The size distribution resulting from a particular blast design has been predicted by different models over the years (Ouchterlony 2003). Indirect and direct methods are used to measure fragmented rock's size distribution after blasting. Despite its accuracy, the sieving analysis method, a typical technique in the direct method, is not practical due to time and cost constraints. To address these limitations, indirect methods have emerged, including observational, empirical, and digital methods (Esen and Bilgin 2000). In practice, the empirical models are the ones that are used for daily blast designs.

Engineering fragmentation models can be defined as equations which define the position and shape of the fragment size distribution and how these properties are influenced by factors such as explosive strength, blasting geometry, and rock properties, as well as the amount of explosives used (Ouchterlony and Sanchidrian 2019). Several fragmentation models have been developed in response to the need to provide engineering solutions to full scale blasting problems such as optimisation of run of mine fragmentation (Ouchterlony 2003, Cunningham, 2005, Chung and Katsabanis 2000, Gheibie et al. 2009) Based on Kuznetsov's mean fragment size equation as well as Rosin-Rammler's fragment size distribution equations, Cunningham introduced a model for estimating fragmentation in the early 1980's called the Kuz-Ram model (Cunningham 1983, Cunningham 1987). For predicting rock fragmentation size distribution after blasting, the Kuz-Ram model is the most commonly used model in the industry (Gheibie et al. 2009). Due to the ease of parameterizing the model for blast layout spreadsheets, it has become widely used, but has not been seriously updated since 1987 (Cunningham 2005). After that, in the early 2000's, Chung and Katsabanis (2000) verified the accuracy of the Kuz-Ram model by using other researchers' data. They proposed that the RR function describes fragment size distribution data well enough used (Ouchterlony and Sanchidrian 2019). Chung and Katsabanis (C&K) model (2000) is a modification of original Kuz-Ram model.

This study includes studies on estimating the optimal burden according to the intended mean fragment size using empirical fragmentation models such as Kuz-Ram and Chung and Katsabanis models. It is necessary to determine or know the rock factor used in the mentioned models in attempting to apply the method proposed in this study. This rock factor is in fact the most crucial parameter for fragmentation models to function correctly.

Despite the fact that this method might seem complicated at first glance to calculate the burden, it should be remembered that it is based on fragmentation theories. Nevertheless, this study derived simplified equations from the complex relations, resulting in practical solutions for the researchers. Finally, generalized equations were derived for the optimal burden depending on the rock factor, the intended mean fragment size, the bench height and the density of the explosive.

2. Kuz-Ram Model

The estimation of fragmentation before blasting has been the subject of some modelling research from past to present. It is often the first target of a blast fragmentation model to predict the mean fragment size (50% passing size). An empirical fragmentation model, Kuz-Ram fragmentation model, is presented by Cunningham (1983). The Kuznetsov equation, which forms the basis of the Kuz-Ram fragmentation model, was first introduced in an article published by Kuznetsov in 1973. Kuznetsov (1973) developed an empirical equation to predict, as a function of rock type, the mean fragment size and blast energy applied per unit volume. Based on the mass percentage passing through versus fragment size, the model predicts fragmentation from blasting. The equation of Kuznetsov is

$$X_m = A\left(\frac{V_0}{Q_e}\right)^{0,8} Q_e^{1/6} \tag{1}$$

where X_m is the mean fragment size (cm), Q_e is the mass of explosive per blasthole (kg), V_0 is the rock volume broken per blasthole (m^3) and A is the rock factor (Kuznetsov 1973). The rock factor here represents the blastability of the rock mass. This equation was originally been prepared according to TNT. Since the strength of TNT compared to ANFO (ANFO=100) is 115, Cunningham (1983) rearranged this equation based upon ANFO instead of TNT. The adapted Kuznetsov equation is

$$X_m = A\left(\frac{V_0}{Q_e}\right)^{0,8} Q_e^{1/6} \left(\frac{Sanfo}{115}\right)^{-19/30} \tag{2}$$

where all symbols are as given before and S_{anfo} is the relative weight strength of the explosive to ANFO (ANFO = 100). Since

$$\frac{V_0}{Q_e} = \frac{1}{K} \tag{3}$$

where K is the powder factor (kg/m^3), Equation (2) can be rewritten as

$$X_m = A(K)^{-0.8} Q_e^{1/6}\left(\frac{115}{Sanfo}\right)^{19/30} \tag{4}$$

The fragment size distribution is then predicted using the Rosin-Rammler equation. According to this model, fragmentation in blasted rocks can be reasonably described. The equation is as follows (Rosin and Rammler 1933).

$$R_x = e^{-(X/X_c)^n} \tag{5}$$

where R_x is the mass fraction retained on screen opening X (%), X is the fragment size (cm), X_c is the characteristic size (cm) and n is the index of uniformity. The characteristic size X_c is one through which 63.2% of the particles pass. A typical fragmentation curve can be plotted if the characteristic size X_c and the index of uniformity n are known. Rearranging Equation (5) yields the following expression for characteristic size:

$$X_c = \frac{X}{\sqrt[n]{-In\ R_x}} \tag{6}$$

According to the Kuznetsov formula, 50% of material passes through a screen size X_m. Therefore, substituting X = X_m and R = 0.5 into Equation (6) yields

$$X_C = \frac{X_m}{\sqrt[n]{0.693}} \tag{7}$$

(-ln 0.5=0.693). Calculating the index of uniformity is the most important step in this equation. The value of n determines the shape of the Rosin–Rammler curve. Uniform sizing is indicated by high values. Conversely, low values suggest a wide range of sizes, including both oversize and fines (Gheibie et al. 2009). By considering the effects of blast geometry, hole diameter, burden, spacing, hole length and drilling accuracy, Cunningham (1987) established the applicability of index of uniformity. The index of uniformity, n, is estimated by

$$n = \left(2.2 - 14\frac{B}{D}\right)\left(\frac{1}{2} + \frac{S}{2B}\right)^{0,5}\left(1 - \frac{W}{B}\right)\left(\frac{L}{H}\right) \tag{8}$$

where B is the burden (m), S is the spacing (m), D is the borehole diameter (mm), W is the standard deviation of drilling accuracy (m), L is the total charge length (m) and H is the bench height (m). When there is more than one explosive in the hole (bottom charge and column charge), Equation (8) is modified as follows:

$$n = \left(2.2 - 14\frac{B}{D}\right)\left(1 - \frac{W}{B}\right)\left(\frac{1}{2} + \frac{S}{2B}\right)^{0,5} \left(0.1 + abs\left(\frac{BCL - CCL}{L}\right)\right)^{0,1}\left(\frac{L}{H}\right) \tag{9}$$

where BCL is the bottom charge length (m) and CCL is the column charge length (m). It is necessary to multiply this equation by 1.1 if you are using a staggered pattern. Besides, Gustafsson (1973) suggested the following relation for standard deviation of drilling accuracy.

$$W = 0.1 + (0.03 \times H) \tag{10}$$

where all symbols are as given before in meters. It has been referred to as the Kuz-Ram fragmentation model after combining the Kuznetsov and Rosin-Rammler equations. Using the Kuznetsov and Rosin-Rammler equations and an algorithm, it derives the exponent of uniformity in the Rosin-Rammler equation from blasting parameters.

3. Chung and Katsabanis (C&K) Model

A number of papers were published on rock blasting by the US Bureau of Mines (USBM) until the mid-1990s (Ouchterlony and Sanchidrian 2019). Using data from the literature, Chung and Katsabanis (2000) introduced new relations that can be interpreted as a modification of the Kuz-Ram model.

The Kuz-Ram model calculates the mean fragment size for a given rock type and explosive, using the specific charge and the amount of explosive per blasthole. Chung and Katsabanis (2000) suggested that delay time and distribution of explosive in rock mass should be considered when calculating the mean fragment size. However, they later concluded that delay time has a critical effect but after a certain point there is no remarkable change in the fragmentation. Therefore they removed the delay time parameters from the model. They presented the following equations with the Kuz-Ram a value as an improvement:

$$X_{50} = AQ_e^{-1.193} B^{2.461} (S/B)^{1.254} H^{1.266} \tag{11}$$

$$X_{80} = 3AQ_e^{-1.073} B^{2.43} (S/B)^{1.013} H^{1.111} \tag{12}$$

$$n = 0.842(\ln x_{80} - \ln x_{50}) \tag{13}$$

where all symbols are as given before and X_{50} and X_{80} are the 50% and 80% passing size respectively. As the definition of specific charge is $q = Q_e / (BSH)$, Equation (11) may be rewritten as

$$X_{50} = A\,(B^{0.005} S^{0.009} H^{0.003})\, Q_e^{0.07}\, q^{-1.263} \tag{14}$$

4. Determination of Rock Factor A

The rock factor represents the blastability of the rock mass, which quantifies the compound effect of the geological and geotechnical site factors on fragmentation (Salmi and Sellers 2021). It is therefore essential to correctly determine the rock factor A so that the Kuz-Ram model can be used effectively. Due to the complex parameters involved, determining this factor that defines the rock is difficult. Cunningham (1987) adapted Lilly's (1986) Blastability Index for Kuznetsov's model in an attempt to better quantify the selection of rock factor A, which made determining rock factor A easier. Cunningham (1987) stated that every assessment of rock for blasting should at least take into account the density, mechanical strength, elastic properties and fractures. A single rock factor A can be calculated by addressing some of the key issues despite the difficulty of estimating individual geological effects:

$$A = 0.006\,(RMD + JF + RDI + HF) \tag{15}$$

where RMD is the rock mass description, JF is the joint factor, RDI is the rock density influence and HF is the hardness factor. Generally rock factor is 7 for medium hard rocks, 10 for hard highly fissured Rocks, 13 for hard, weakly fissured rocks (Cunningham 2005). The description of the rock factor parameters and rates are given in Table 1.

As can be seen in Table 1, rock factor A, which represents the structural geology of rock mass, is influenced by several factors including joint factors such as vertical joint plane spacing, joint plane angle and joint condition, rock density, and hardness factor, which is determined by the young's modulus or the uniaxial compressive strength of intact rock.

The vertical joint plane spacing depends partly on the absolute joint spacing, and partly on the spacing to drilling pattern ratio. In addition vertical joint plane angle is related to dip, which is steeper than 30 degrees (Cunningham 2005).

5. Estimation of Burden Based on Mean Fragment Size

If the rock factor A in the Kuz-Ram and C&K models is known or predefined, it can be used to determine the most appropriate blast pattern for future blasts. The Kuz-Ram and C&K models will be used to calculate the burden according to the intended mean fragment size in this part of the study.

In the Kuz-Ram model, the mean fragment size is obtained as a function of the explosive charge in each blasthole and the rock volume broken per blasthole. The rock volume broken per blasthole (V_0) can calculated as

$$V_0 = BSH \tag{16}$$

where B is the burden (m), S is the spacing (m) and H is the bench height (m). Spacing is the distance between adjacent blastholes and is measured perpendicular to the burden. According to Swedish researchers (Gustafsson 1973, Olofsson 1988) the relation between burden and spacing is

$$S = 1.25\,B \tag{17}$$

Substituting the values S = 1.25 B into Equation (16) and rearranging to yield the following expression for the burden gives

Table 1. Rock factor parameters and rates (Ouchterlony 2003).

RMD	Rock Mass Description
Powdery/friable	10
Vertically jointed	JF
Massive	50
JF	**Joint Factor**
	JF = (JCF JPS)+ JPA
JPS	**Joint Plane Spacing**
<0.1 m	10
0.1–0.3 m 0.3 m–95% of P	20 80
> P	50
JPA	**Joint Plane Angle**
Horizontal	10
Dip into face	20
Strike out of face	30
Dip out of face	40
JCF	**Joint Condition Factor**
Tight joints Relaxed joints Gouge-filled joints	1 1.5 2
RDI	**Rock Density Influence**
	RDI =(0.025 RD –50)
HF	**Hardness Factor (GPa)**
Young's modulus (E)<50 GPa	HF = E/ 3
E>50 GPa	HF = UCS/5
P = $\sqrt{Burden.Spacing}$ RD: Rock Density (kg/m^3) UCS = Uniaxial Compressive Strength (MPa)	

$$B = \sqrt{\frac{V_0}{1.25\,H}} \tag{18}$$

For the Kuz-Ram model, Equation (2) can be rearranged to yield the following expression for the rock volume broken per blasthole (m^3).

$$V_0 = Q_e\left(X_m / \left(A Q_e^{1/6} (S_{anfo}/115)^{-19/30}\right)\right)^{1.25} \tag{19}$$

Equation (18) and Equation (19) can be combined to give the burden (B) as follows:

$$B = \sqrt{\frac{Q_e(X_m/(AQ_e^{1/6}(S_{anfo}/115)^{-19/30}))^{1.25}}{1.25H}} \text{ for Kuz-Ram model} \tag{20}$$

As far as the C&K model is concerned, Equation (11) can be directly rearranged to yield the following expression for burden (B) by substituting the values S/B = 1.25:

$$B = \left(\frac{X_{50}}{AQ_e^{-1.193}\,1.25^{1.254}H^{1.266}}\right)^{\frac{1}{2.461}} \text{for C\&K model} \tag{21}$$

Thus, the burden can be estimated by using Equation 20 or Equation 21 depending on the intended mean fragment size and bench height for a certain site whose rock factor has been determined beforehand. The mass of explosive in the hole here can be calculated depending on the blasthole diameter, the charge height and the density of the explosive used. The unloaded part of the blasthole is defined as the stemming. There are different approaches in the literature to calculate the stemming according to the burden or blasthole diameter. In accordance with Swedish researchers the stemming is equal to the burden $H_s = B$ (Langefors and Kihlsröm 1963, Olofsson 1988). Konya and Walter (1990), on the other hand, suggested the stemming as a function of blasthole diameter as H_s =0.7d. These approaches will give a constant value for the stemming height according to the varying bench height. However, it is a very common practice in quarrying to leave 1/3 of the blasthole height as the stemming length in general. Therefore, it would be more accurate to calculate the stemming height as a function of the bench height to calculate the specific charge density. In this study, the ratio S/B =1.25 which was observed to give the best results in terms of fragmentation was used.

6. Simplified Equations

In first part of this section, since the mass of explosive per blasthole (Q_e) varies according to the density of the explosive (ρ_e), multiple regression analyses were performed using Equation (20) and Equation (21) for a certain type of explosive. In this context, ANFO with a density of 800 kg/m^3 was taken as a reference explosive. In other words, the linear charge concentration of the referenced explosive is 5 kg/m in the blasthole for a blasthole diameter of 89 mm. It is also critical to note that the mass of explosive per blasthole changes as a function of the bench height, as previously discussed.

In the work done here, regression analysis is not used to estimate the relationship between the dependent variable and independent variables. Instead it is used to reduce the number of independent variables given in Equation (20) and Equation (21) rearrange the equation. In the regression analyses using Equation (20) and Equation (21), a burden value (B) was obtained by randomly assigning different values for the rock factor (A), the mean fragment size (X_m) and the bench height (H). In the regression analyses, B is the dependent variable, while A, X_m and H are independent. For those analyses values from 0.8 to 22 were assigned for the rock factor, values of 30, 40, 50, 60, 80 and 100 cm were assigned for the mean fragment size, and values ranging from 5 to 30 m were assigned for the bench height (H). A total of 1800 calculations were made for each equation. If the results obtained by Equation (20) and Equation (21) are rearranged by regression analysis, it can be re-written as follows according to the rock factor, the mean fragment size and the bench height as

$$B = 1.36\left(\frac{X_m}{A}\right)^{5/8} H^{-0.104} \text{ for Kuz-Ram model using ANFO} \tag{22}$$

$$B = 1.60\left(\frac{X_c}{A}\right)^{2/5} H^{-0.030} \text{ for C\&K model using ANFO} \tag{23}$$

where all the symbols and units are as given before. With this equation, the burden can be calculated according to the intended mean fragment size for different sites by using standard ANFO for 89 mm blasthole.

In addition to the above mentioned equations, in the second part of the study different explosive densities were also considered in a more general form. The mass of explosive in the blasthole Q_e, which is the independent variable in Equation (20) and Equation (21), is actually a variable depending on the blasthole diameter, the charge length and the density of the explosive. In order to generalize the obtained relations for any field, regression analyses were performed by taking the explosive density as an independent variable. Rearranging the results obtained by Equation (20) and Equation (21) by regression analysis, it is possible to write it according to the density of the explosive as

$$B = 0.097\left(\frac{X_m}{A}\right)^{5/8} H^{-0.104} \rho_e^{79/200} \text{ for Kuz-Ram model} \qquad (24)$$

$$B = 0.114\left(\frac{X_c}{A}\right)^{2/5} H^{-0.030} \rho_e^{79/200} \text{ for C\&K model} \qquad (25)$$

where ρ_e is the density of the explosive (kg/m^3). Thus, using Equation (24) and Equation (25), the burden B (m) can be determined depending on the rock constant A, the intended mean fragment size X_m (cm), the bench height H (m) and the density of the explosive ρ_e (kg/m^3).

7. Results and Discussion

As a result of the variety of factors involved in blasting operations as well as the unpredictable response of rock masses to excavation, correlations between blasting quality parameters and rock mass quality have not always been clear (Costamagna et al. 2021). Inevitably, blasting loads have some negative effects, such as damage and vibration. To reduce and minimise these problems, blasting design has incorporated a variety of control techniques. By controlling blasting, rocks beyond the contour of the excavation are minimized from being damaged (over-broken) (Cardu et al. 2022). This study focused on calculating the burden according to rock fragmentation size distribution after production blasting in quarries. Since slopes or blasted surfaces are beyond the scope of this study, only fragmentation of rock is addressed. Keeping open pit excavation damage to a minimum can also provide satisfactory results in terms of stability conditions and control over block size distribution in quarry aggregates.

As much as both models are concerned separately, Figure 1 shows the relationship between the burden and the bench height for the reference explosive ANFO according to considered four different mean fragment sizes (30, 50, 80 and 100) using Equation 22 and Equation 23. Three different rock factor values were considered here: 7 for medium hard rock, 10 for hard, highly fissured rocks and 13 for very hard, weakly fissured rock. As can be seen from Figure 1, unlike the Kuz-Ram model, which varies significantly with bench height, the C&K model is not significantly affected. Besides, according to the C&K model, burden varies within a narrow range when the rock factor changes, but in the Kuz-Ram model, burden varies quite a bit when the rock factor changes.

With respect to three different rock factor values (A= 7, 10 and 13), Figure 2 illustrates the relationship between the burden and the density of the explosive for both models taken into consideration using Equation 24 and Equation 25. For better understanding, in this figure, bench height

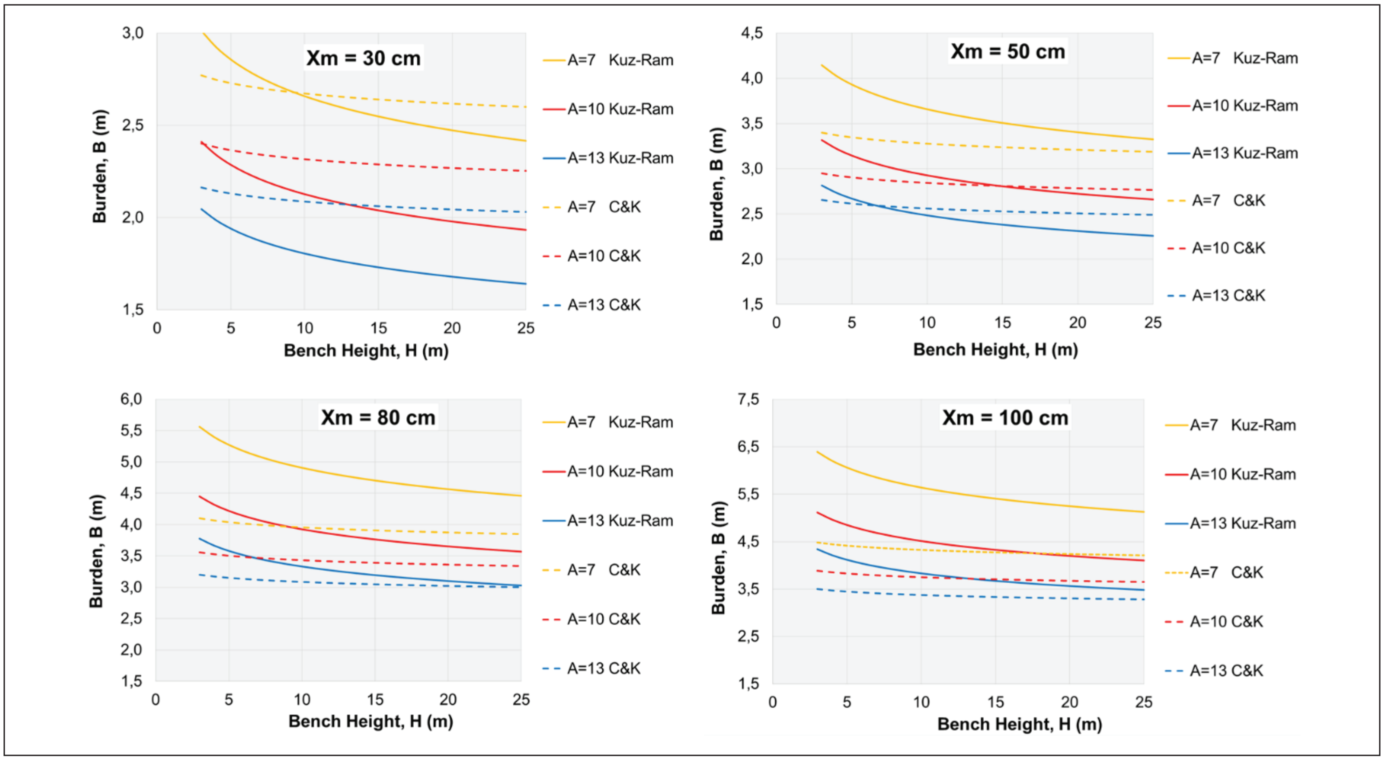

Figure 1. The relationship between the burden and the bench height for the reference explosive ANFO according to four different mean fragment sizes for both models.

was chosen as 15 m and the mean fragment size was chosen as 80 cm. As shown in Figure 2, for both models, the burden increases in direct proportion to explosive density as expected. It is important to note here that the Kuz-Ram model gives wider burden values than the C&K model. While this chart demonstrates the consistency of the proposed equations, it also shows how practical they can be for calculating the burden for a given site.

For three different explosive densities (800, 1200 and 1800 kg/cm^3), Figure 3 shows the relationship between burden and rock factor representing the blastability of the rock mass is given separately for two fragmentation models considered using Equation 24 and Equation 25. Similar to Figure 2, in this Figure 3 bench height was chosen as 10 m and the mean fragment size was chosen as 50 cm. As can be seen from Figure 3, for the rock factor between 10 and 20, which represents hard rocks, the burden varies between 2 and 3 m, which is what is commonly used in practice.

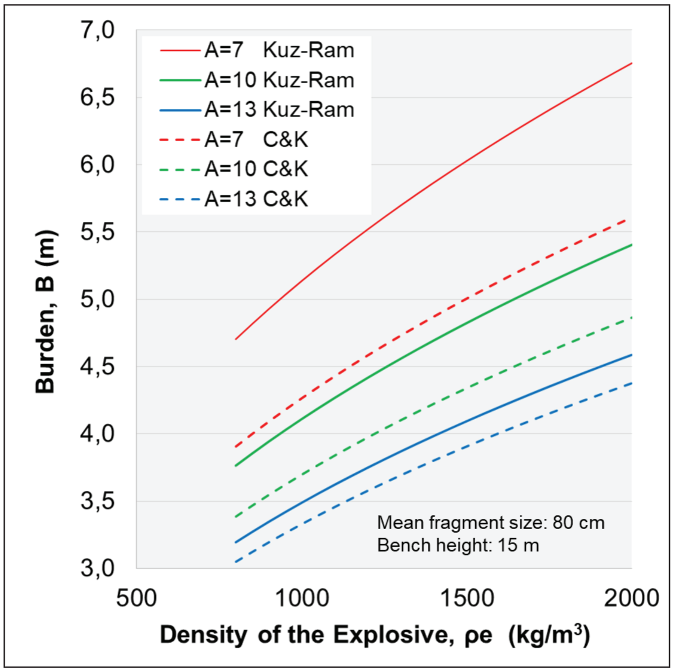

Figure 2. The relationship between the burden and the density of the explosive for both fragmentation models.

7. Conclusions

The objective of this study is to recommend alternative approaches to design quarry blast rounds according to intended fragmentation size. The interrelated Kuz-Ram and C&K fragmentation models that are widely used in the literature were considered in this context. Kuznetsov's model is derived from geomechanical and geometrical parameters as well as explosive properties. Therefore, in order to apply this proposed method correctly, the rock factor reflecting the geomechanical properties of blasted rock masses needs to be well defined.

In this study, the approach of calculating the burden according to the intended mean fragment size based on the aforementioned fragmentation models was introduced. Based on this, the Equation 20 and Equation 21 were first obtained mathematically using Kuz-Ram and C&K fragmentation models, then four simplified equations were proposed based on these equations. Two of these are in their simplest form for ANFO (Equation 22 and Equation 23), while the other two include explosive density in a more general form (Equation 24 and Equation 25). Afterwards, charts that provide guidance in practical applications were

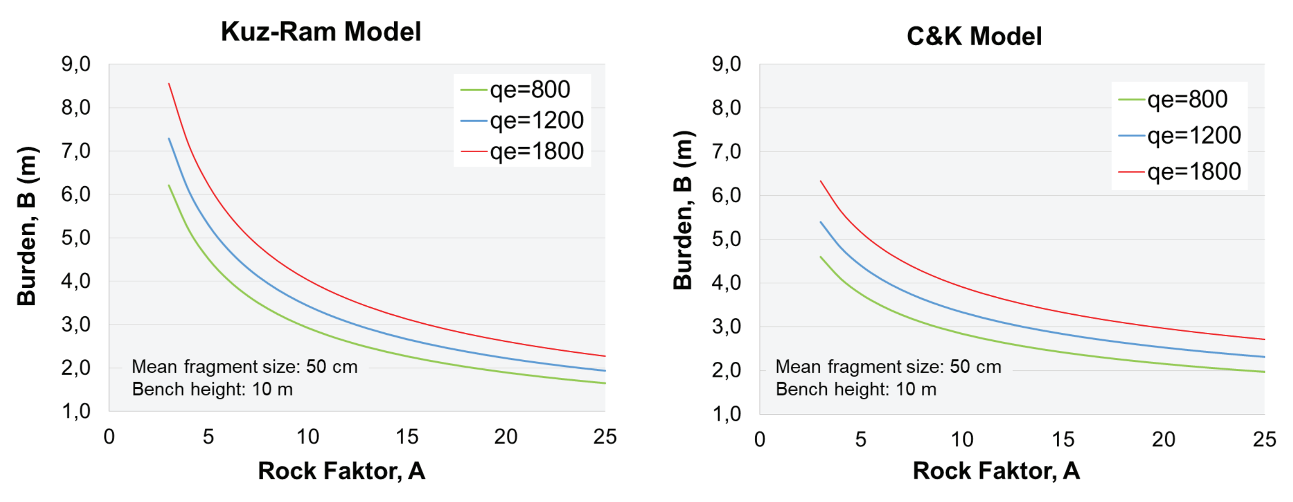

Figure 3. The relationship between the burden and the rock factor according to three different explosive densities.

created using Equations 22-25 for certain conditions. These site-specific diagrams demonstrate not only the consistency of the proposed equations, but also show how practical they can be for calculating the burden for a given site. Hereby, each quarry can prepare practical charts according to its own conditions and design blasting accordingly. As a result, the proposed method for calculating the burden yields results consistent with the intended mean fragment size.

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