International Journal of Engineering Research and Technology. ISSN 0974-3154, Volume 14, Number 2 (2021), pp. 144-150

Drilling Mesh Design based on Holmberg's Mathematical Model to Decrease Mineral Fragmentation of Blasting Processes at Underground Mines in Peru

Dy Vasquez[1] and Luis Arauzo[2]

[1]*Ingenieria de Gestion Minera, Universidad Peruana de Ciencias Aplicadas, Peru*

[2]*Ingenieria de Gestion Minera, Universidad Peruana de Ciencias Aplicadas, Peru*

Abstract

Over the years, blasting engineering in Peruvian mining is a process that has evolved. However, there are currently still diverse fragmentation results, which are obtained and compared to those expected and cause a lack of efficiency in the extraction processes of economic minerals. The implementation of a new mesh design based on Holmberg's mathematical model is proposed based on the explosive energy of a new explosive. When the model is applied, the results demonstrate a fragmentation reduction regarding the generated history. To summarize, the proposed model produced adequate fragmentation using rock blasting.

Keywords - Blast Design, Detonation Velocity, Explosive Emulsion, Explosive Energy, Fragmentation.

I. INTRODUCTION

Currently, drilling and blasting are used in 95% of the world's mining operations on a daily basis [1]. Mineral fragmentation is the direct result produced by these processes, and it can be explained as a determinant of the effectiveness of the operations executed as per the variables applied. Several studies have sought, over time, to produce efficient blasting processes, based on parameters that affect drilling designs as well as examining the relationship between the rock mass and explosive energy [1] [2] [3] [4] [5]. They sought to describe whether the full potential of the energy produced by explosives was used [6] [7] [8].

An existing problem is the inefficient fragmentation that directly affects processes produced after the blast was executed [9]. The problem's primary causes are attributed to an inadequate analysis of detonation properties of explosives, the unchangeable aspects of rock masses, and blast design parameters [7] [9]. The production of efficient fragmentation allows for improvements to be proposed to develop excavation operations [10], work stability and production costs [4]. Hence, an important factor to achieve optimal fragmentation results is determining an appropriate blast design based on rock mass conditions. Several studies confirm that, evaluating parameters such as diameters of relief drills, the energy power for explosive weight, detonation speeds, and drilling lengths, benefit mineral fragmentation [4] [7] [11].

For improvement and innovation process, underground mining added new alternatives, such as bulk emulsions, because of their considerable detonation speed, density variability and optimal reactions in areas with water [12]. However, aspects such as the explosive energy are not being considered as part of the parameters set for perforation meshes. Hence, this study aims to determine a drilling mesh considering the energy required for the explosive regarding the properties of the rock mass for the task and evaluating the corresponding diameter required to free the face of underground mining. Hence, formulas proposed as part of the mathematical model by Holmberg will be used to determine the quantity of relief holes required to start the blast, considering the actual hole drilling and the section area [8], and the energy required for rock fracturing would be evaluated based on an impedance relationship between the emulsion explosive and the rock mass where the task is performed.

II. STATE OF THE ART

II.I. Drilling Mesh Design Used for Underground Mining

The preparation of the drilling and blasting designs directly influences the time, expense, and production efficiencies of underground mining operations [2] [4] [8]. The most commonly used mathematical models for designing underground mining drilling meshes are developed using wedge cutting, burnt cutting and by combining them with empirical methods, based on the division of the section into zones that are known as cutting, outline and supports [1] [2] [4] [8]. To conduct an appropriate suitable blast, the most efficient approach is to guarantee that the detonation starts and to produce a free face with sufficient dimensions to prevent the freezing of holes loaded with supports and profiles [8]. Throughout the years, these designs have been applied all over the world. Nevertheless, when comparing them to technological innovations for new explosives, these methods curtail the manufacturing of drilling meshes, which are based on load factors, and do not consider properties such as explosive energies that particular rock masses are required to produce their fragmentation [1] [8] [13].

II.II. Drilling Mesh Design Used in Parallel for Underground Mining

Related to burnt cut blasting, one of the most commonly used cuts is the burnt cut with four initial sections of parallel holes

International Journal of Engineering Research and Technology. ISSN 0974-3154, Volume 14, Number 2 (2021), pp. 144-150

because they distribute the explosive energy of the entire section in a better manner [3] [5]. One of the most commonly applied mathematical models was proposed by Langefors and Kilhsftrom (1963), subsequently revised by Holmberg (1982) and updated by Persson et al. (2001) in which the face is divided into five sections as this enables the existence of an expansion space using detonation intervals [2] [3] [14]. The model connects geomechanical characteristics of rock masses, explosive mixtures, blasting parameters and principally the load (charge) and spacing (which is the distance between drilled holes). The last two items were proposed to produce an interaction between the relief drill (with vacuum) and the explosive-charged drill. The aim is to create an actual effective free face [5] [14]. However, four-section stripping exerts a significant impact on mineral fragmentation efficiency [5]. Nevertheless, the estimation of the number of drills applied must be carefully reviewed because if there is a large number, the drilling and blasting processes will take longer. However, if there are a smaller number of holes, rock fragmentation will be inefficient [1] [14].

II.III. Influence of the Hole Diameter in the Drilling Mesh Design

For efficient blasting, certain design parameters must be evaluated. The following factors must be determined with sufficient certainty to achieve fragmentation effectiveness: the diameter of the relief holes, the distances between holes, the effective hole lengths, and the detonation delays applied [3] [12] [15]. Several studies demonstrate that production and relief diameters are closely related to the performance of the explosive applied. This is because the velocity of detonation (VOD) is impacted by the dimensions and locations of the holes used to create free faces [15] [16]. Thus, each explosive has a critical diameter, i.e., the smallest permissible diameter for the explosive to detonate. This indicates that when diameter increases, VOD increases, which repeatedly occurs until reaching the upper limit, also known as the maximum diameter [16]. However, it is feasible that several explosives may not produce their maximum VOD even if the charge diameters are considerably greater than the critical diameters. Therefore, it is very important, when designing the blasting parameters, to specify the appropriate explosive depending on geological work conditions and after identifying its maximum VOD [12] [16].

II.IV. Mathematical Model for the Perforation Mesh Design

To increase excavation development efficiencies, one of the trends is the enhancement of drilling and blasting operations. The reliability degree of calculated parameters for drilling and blasting operations can affect the technical and economic results of excavation development [4] [13]. To achieve successful blasts, the use of the energy produced by explosives must be considered because only a small portion of that energy is used to fragment rock masses, and the rest is released as heat. When the depth of the initial explosion is quite small, the pressure wave of the explosion extends after it traverses the primary shear zone, producing low energy usage and concentration [4] [9]. For these purposes, calculations to design the blasting parameters using models that consider initial designs as one of their principal factors are required.

III. CONTRIBUTION

III.I. Rationale

The drilling mesh design is developed using Holmberg's mathematical model as its foundation. This model was specifically created for underground mining, tunnel construction, cuts, and facades using cuts with perforations in parallel. Similarly, the front face is split into five sections, which are individually calculated: cuts, drags or elevators, one profile and two gables (with one at each side of cuts). The design relies on the hole lengths and diameters, the geological characteristics of rock masses, the concentration of explosive linear charges, and the type of explosive applied [2]. The model with parallel holes depends on empty holes to produce a free face. Nevertheless, if the matching diameter is not correctly specified, the starter holes may not work [8]. This model is primarily applied to areas with small to medium sections because they demonstrated the capability to produce deep advances, and they contribute to dilute minerals and provide increased rock fragmentation [8].

III.II. General Contribution

As a depth of 5 m, the mathematical model is based on a 95% progress length. In actual conditions, this depth is not quite successful because of overbreaks, dilution, and the degrees of fragmentation that need to be considered [2]. Thus, the constraint on the drilling depth for relief holes regarding actual sections areas is included as a good rule of thumb. Similarly, to create a more accurate design, the impedance relationship between explosives and rocks must be estimated because this model is applied and improved based on trial and error due to the load factors of explosives. For this purpose, the intention is to calculate the VOD because such models use average values from conventional explosives (i.e., ANFO and dynamite), which affect the accuracy of estimations of burdens and spacing [10]. In this study, a bulk emulsion blasting agent is applied; a practice not common in Peruvian underground mines. The aim is to more accurately define the design of a drilling mesh, considering VOD calculations, and exploiting the explosive energy of blasting agents, which had not been considered as part of parameters for drilling mesh.

III.III. Details of the Contribution

III.III.I Determination of the Section Area Using Integrals

The area sections were determined by calculating the integral area (the area under the curve). This is based on the fact that multiple estimations consider upper front profiles with specific circumference radius values.

$$A(s) = A1 + A2 \tag{1}$$

$$A1 = b \times h \quad (2)$$

$$A2 = \int f(x)dx \quad (3)$$

where

A(s) = Area of the section

b = Base of section

h = Height of area 1

A2 = Integral value to calculate the area under the curve (in the upper part of the section).

In this manner, the overbreak and mineral dilution is constrained to the crown part of such section (Figure 1).

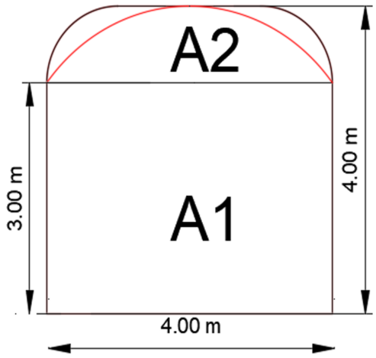

Figure 1. Area Calculated Using Integrals.

If the section is limited using integrals, a profile similar to the one proposed in the front division design by Holmberg is created. Furthermore, the model proposes the generation of a free face using empty holes and creating an equivalent diameter to extend from the empty hole to the first quadrant of holes charged with explosives. The principal factor for determining the depth of the equivalent diameter is the empty hole diameter and its length.

The equivalent diameter produced by relief holes is calculated as follows:

$$\emptyset e = \emptyset a \times \sqrt{n} \quad (4)$$

where

$\emptyset$e= Equivalent hole diameter

$\emptyset$a= Relief hole diameter

n= Number of holes.

The depth of the hole with an equivalent diameter is calculated as follows:

$$H = 0.15 + 34.1 * \emptyset_e - 39.4 * \emptyset_e{}^2 \quad (5)$$

where

H= Depth of the hole

$\emptyset$e= Equivalent hole diameter

The Holmberg proposal relies on a progress length of 95% with regards to a depth of 5 m. Nevertheless, it is not an actual advancement in the application because of constraints such as effective drilling of equipment, dilution factors, overbreaks, drilling deviations, socket deviations, and stability [2]. Thus, as a good rule of thumb, the constraint on the drilling depth for relief holes regarding actual sections areas is included.

$$H \leq \sqrt{As} \quad (6)$$

where

H: Equivalent diameter of the hole depth.

As: Area of the section. This constraint considers geological characteristics of the area, such as density, hardness, and the existence of water.

III.III.II. Impedance Ratio

To continue specifying design parameters of perforation meshes, the relative power by weight of explosives to be applied regarding standard explosives must be estimated. In this case, the ANFO was used. This must be performed because the mathematical model is applied to conventional explosives (such as ANFO and dynamite) [8]. Similarly, to identify if the selected explosive has the characteristics required to produce an efficient blast, the explosive impedance ratio regarding the rock is calculated. The impedance ratio corresponds to the ratio of seismic velocity and rock density to VOD and explosive density.

$$Z = \left(\frac{\rho_e \, x \, VOD_e}{\rho_{r\,x} \, VOP}\right) \quad (7)$$

where

Z = Impedance ratio,

ρ_e = Density of the explosive (gr/cm³),

VOD_e = Explosive velocity of detonation (m/s),

ρ_r = Rock density (gr/cm³), and

VOP = P wave velocity (m/s)

The P wave velocity is the longitudinal speed based on which energy is transferred. The calculation is the following one:

$$VOP = (1000 \, x \, LogQ) + 3500 \quad (8)$$

where

Q= Barton's Q

Barton's Q is estimated after the RMR of Bieniawski (1979) is converted.

$$RMR = (9LnQ) + 44 \quad (9)$$

In general, the VOD of an explosive must be greater than the P wave velocity to produce an efficient blast. This indicates that if the P wave velocity is greater, explosives with a higher VOD will be required.

III.III.III. Calculation of the VOD

The VOD is calculated using the formula proposed by Mertuszka and Kramarczyk (2018). They examined the influence of the hole diameter and the explosive charge density on the VOD produced after blasting occurs. The formula used is as follows:

$$VODe = (4.8\ x\ \rho_e + 1926) x\ \emptyset p^{0.014\sqrt[3]{\rho_e}} \quad (10)$$

where

$\emptyset p$ = diameter of production hole in m;

ρ_e = density of the explosive in kg/m3;

VOD_e = explosive VOD in m/s.

III.III.IV. Calculation of Burden and Hole Spacing

There are several methods used to estimate the burden and front spacing. A large number of units make these estimations empirically and adapt improvements after multiple trials and error in underground mining operations. Nevertheless, they do not consider correlated variables in such process. This produces inefficient final products, i.e., the fragmentation of valuable mineral ore [14]. Holmberg's mathematical model estimates the calculated front areas that would break around explosive charges initiated by a starter with a relief drill and quadrants. Moreover, they consider geological conditions of the exploitation zone, as well as drilling errors, and relative powers by weight, in the calculation of parameters [14]. The following formula is used to calculate burdens and hole spacings for optimal starter blasting.

$$B_e max. = \frac{\pi x \emptyset_e}{2} \quad (11)$$

where

B_e max= maximum burden

$\emptyset_e$= diameter of the equivalent hole

To calculate this more accurately, a drilling error factor was included, as mentioned. For drilling deviations of >1%, the following formula is used to calculate the practical burden:

$$B_p = B_e max. - \Psi \quad (12)$$

where

B_p= practical burden

Ψ = drilling error

This is the formula for calculating drilling errors:

$$\Psi = B_e max(0.1 \pm 0.03 L_e) \quad (13)$$

where

L_e= Effective length of the hole

The calculation of the linear load concentration is presented for the starter hole by considering the relative potency by weight regarding ANFO. Thus, a change was made as required for using emulsions as explosives. The calculation is as follows:

$$Dc.a = \frac{55\ x\ \emptyset_p\ x\ \left[\frac{B_{max}}{\emptyset_e}\right]^{\frac{3}{2}}\ x\ \left[B_{max} - \frac{\emptyset_e}{2}\right]\ x\ \frac{C}{0.4}}{PRP\ de\ ANFO} \quad (14)$$

where

Dc.a= Density of the linear load (kg/m)

PRP_{ANFO}= Relative potency of ANFO.

The change comprises the relative potency of the modern explosive regarding the one of the conventional explosives applied in the following formula:

$$PRP = \left[\frac{\rho_{Emulsión}\ x\ V^2}{\rho_{ANFO}\ x\ {V_0}^2}\right]^{1/3} \quad (15)$$

where

$\rho_{Emulsión}$ = density of the explosive emulsion (g/cm³),

ρ_{ANFO} = density of the ANFO explosive (g/cm³),

$V =$ volume of gas released by emulsions (l/kg), and

V_0 = volume of gas released by ANFO (l/kg)

By replacing the relative potency variable by weight, the linear charge density would then be calculated when emulsion is used as a blasting agent. To calculate parameters corresponding to the following sections, Holmberg's mathematical model is applied.

IV. Indicators

Specific factors affect fragmentation results, such as the inefficiency of technical blasting parameters, an unsuitable combination of explosive components, and the response of the explosive to rock mass conditions [7]. Because the latter conditions cannot be changed, several solutions center on improving explosive features when facing diverse conditions of operations as well as on the optimization of existing technical parameters. Therefore, this study aims to create a suitable fragmentation with the application of a mathematical model and the evaluation of a novel explosive application. The size of rock fragments after blasts will be used as indicators to assess the achievements. Such tests were conducted at a mining unit in the Department of Huaral, Peru. For these purposes, Split will be used to determine the fragment sizes generated by blasts based on qualitative analysis.

Table 1. Indicator of Achievement of Goals.

Name	Degree of Fragmentation
Objective	To measure the fragment size of detonated minerals.
Software	Split
Indicator	Granulometric curve of P (80)
Reference	Historical results at the mining unit

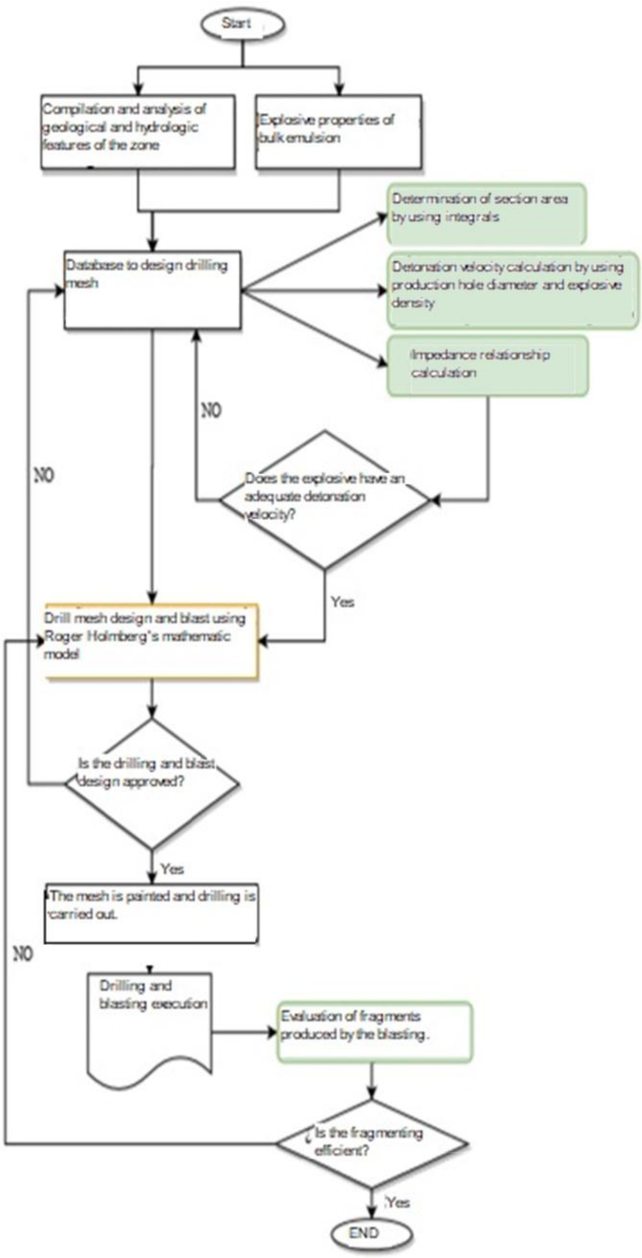

Figure 2. Flowchart of the process to calculate the drilling mesh design based on Holmberg's mathematical model

The indicator is used to analyze and compare the efficiency of mesh designs based on the parameters calculated by applying the mathematical model. For these purposes, Split can compile historical data, set a statistical baseline, and track any changes that occur during the study. One of its tools is used to determine the position of materials before they are fragmented. These position values are then stored in a database.

If the size of detonated rock fragments is reduced, the aim of this study would be met. Otherwise, if mineral reduction is not achieved, the parameters that determine the blast efficiency would require to be reassessed.

V. VALIDATION

V.I. Validation Scenario

The mining unit is in Huaral, a district in the province of Huaral, Department of Lima, Perú. It is part of the coastal region of the country, and it is located 7 km west of Huaral in the Jecuán area. This mine forms part of the VMS-type ore belt of the Cretaceous volcanic-plutonic arc in the central coast area of Perú [15]. It is 2 km long and has mineralized bodies in the shape of irregular lenses. Their arrangements denote blocks because of impacts from faults. The primary mineralization has fine and medium-grained sphalerite, galena, and barite, as well as chalcopyrite, arsenopyrite, and pyrite traits. For this study, a geomechanical analysis was conducted to supply information on rock quality. An RMR between 50 and 70 was determined; therefore, its quality is from medium to regular.

V.II. Validation Design

Based on the high-resolution images that were obtained, Split calculated dimensions of fragmented minerals by relying on qualitative analysis. Based on historical fragmentation, a P (80) of 6.69 in (17 cm) in mineral ore was calculated. After a blasting process with bulk emulsion, at five fronts, an average of 6.18 in (15.7 cm) was calculated for a section of 4 × 4 m and 6.65 in (16.9 cm) for a section of 4.5 ×4.5 m. To show an approximate scale, a measuring tape was used in the images that were obtained. This contributes to identifying fragment dimensions through polygons.

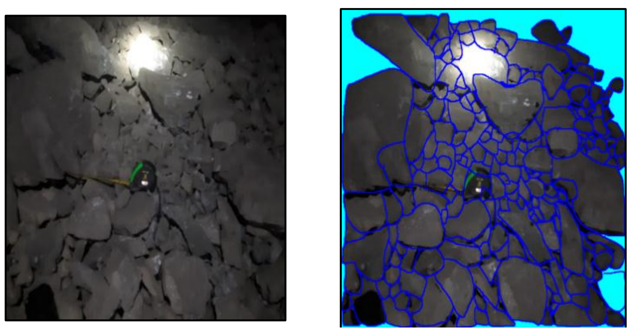

Figure 5. Digitization of Fragmented Ore for a 4 m x 4 m section for an eight-inch scale.

In Figure 5, the fragmentation and digitization of the mineral

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is presented for a section of 4 × 4 m by calculating the polygons. In a similar manner as the one used for the 4.5 × 4.5 m section, Split was used for digitization. It generates a particle size curve after digitized fragments are analyzed. In Figure 6, the percentage is shown for a through element of 80 compared against the fragment sizes in inches for a 4 × 4 m transept.

In Table 2, a comparison is presented for averages of a through element of 80 for studied areas. Compared to the ANFO, A difference pf P (80) averages was calculated for the emulsion. Nevertheless, the degrees of fragmentation for the work identified as Gal-17-151S are quite similar to historical results.

Table 2. Representative table of averages of P(80) calculated from analysis made using Split.

Work areas	Mean of historic P(80) with ANFO (inches)	Mean of historic P(80) with ANFO (cm)	Mean of P(80) with emulsion (inches)	Mean of P(80) with emulsion (cm)
SN-15-158N	6.7	16.99	5.8	14.83
Cx-17-57W	6.7	16.99	6.6	16.69
Gal-17-151S	6.7	16.99	6.7	16.97
General meams	6.7	17.0	6.4	16.2

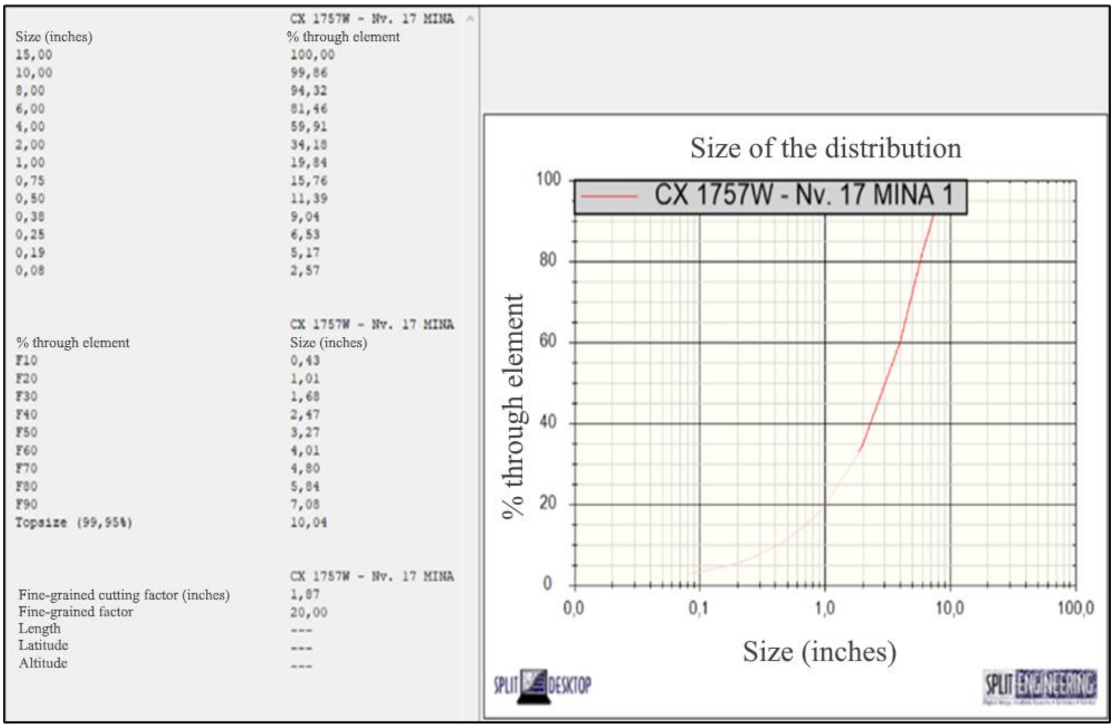

Figure 6. Granulometric Distribution Graph for an area of 4 m x 4 m.

VI. CONCLUSIONS

Holmberg's mathematical model improved mineral fragmentation results from the ones obtained in historical results. For geological circumstances of work zones, an average P(80) of 6.13 in was obtained. This corresponds to a 4% decrease compared to historical results.

The impedance relationship of rock mass properties were analyzed along with the features of gasified emulsions. Then, it can be stated that the specified explosive created a VOD as required to fragment minerals in such work areas.

The drilling mesh applied considers the relative energy of the emulsion explosive to estimate the design parameters; it brings about better results than the ones produced by using standard meshes at mining units.

ACKNOWLEDGEMENTS

The author would like to sincerely thank engineer Giancarlo Rivera Montalván because he provided the study basis and organizational support when the study was developed.

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