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## COMPARATIVE ANALYSIS OF FRAGMENTATION MODELS FOR UNDEGROUND BLASTING

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**Abstract:** This work was carried out in the context of an internship at the company O-Pitblast, as part of creating and developing UG software. During the work, topics such as the prediction of rock mass fragmentation in a tunnel were addressed moving on to explaining the functioning of the different models, along with the entire workflow and the formulas used by each of them are addressed. The Kuz-Ram and Swebrec models were studied to predict tunnel blast fragmentation, in which case study of a Finish mine (Kittila) was used, and the modelled curves were compared with the actual curve taken from a blast.

**Keywords:** blasting, underground, tunneling, fragmentation

### 1 INTRODUCTION

The detonation procedure is relatively simple: the drilled holes are filled with explosive that is detonated. The resulting detonation and gaseous products induce pressure on the rock that results in its fragmentation and prominence. The fire plane is a process that includes the selection of the appropriate explosive, design of the distribution and sizing of the holes to be loaded and definition of the initiation sequence. Poorly sized and executed drilling and detonation practices are characterized by excessive over-break<sup>1</sup>, dilution, unwanted size fragmentation, restricted access, and increased structural reinforcement requirements. They thus contribute to the increase in mining cycle times and costs and can have a negative effect on the efficiency of mining activities.

The blasts in tunnels and galleries are characteristic of the absence, at least at the beginning of the dismantling, of a free face. The method used for its execution is to carry out a burn cut with wide holes and loaded holes that first detonate making room for the dismantling process to occur at the origin of the dismantling of this section. The creation of fragmentation models serves to make an approximate estimation of the granulometry

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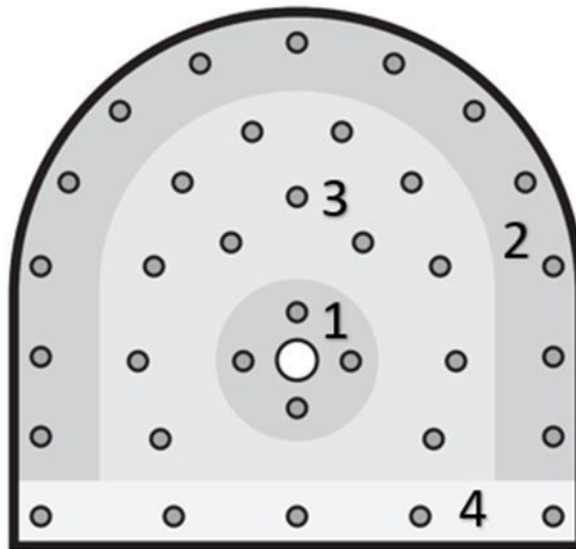
after a dismantling, however there are no exact methods for predicting the granulometric curve.

There are 3 groups of parameters that influence the desired fragmentation. The type of rock that is worked as well as its structural characteristics are the main parameter in the study of the fragmentation models that will influence the choice of the explosive and its quantity as well as the geometry of the blast plan.

## 2 TUNNEL DESIGN

For the study to be carried out, 4 sections will be studied in the tunnel dismantling: lift holes, burn cut, production holes and contour holes (as presented on figure 1).

- Burn cut.
- Contour holes.
- Production holes.
- Lift holes.



**Figure 1** Expression diagram of tunnel sections

There are two types of tunnels that can be sized, the smooth tunnel in which the blast plan will have a smaller load because it is responsible for advancing in the rocky massif to the zone of the mineral mass to be extracted; and one of different characteristics that arises when to drill the mineral mass zone it is necessary to proceed to a conventional

dismantling that reaches higher load values as well as will have an increase in the value of the specific drilling.

In both the burn cut section consists of one or more wide holes that are holes with a diameter larger than any other hole in the tunnel design. Around the wide holes, holes with diameters similar to those of the following sections are made, but with much shorter spacings. This section will be the first to be detonated allowing the creation of a free front of the tunnel. Due to its large specific load and drilling specifies the granulometry obtained because of the detonation of the burn cut section will lead to the creation of a large Crush Zone obtaining crushed material and consequently a large percentage of fine material (less than 1.18mm).

The contour hole has a smaller diameter that allows to break the material of the massif without it being severely damaged thus avoiding unnecessary costs in the support of the mineral massif. They'll be the last in the firing sequence to be detonated.

The section of the production holes is the most important because they occupy the largest area of the entire design and where the spacing and distance forward as well as the specific load will interfere more markedly in the fragmentation curve.

### **3 FRAGMENTATION**

A well-designed drilling pattern as well as the choice of explosive type and quantity can lead to optimal fragmentation or unwanted fragmentation.

When the fragmentation obtained in the dismantling is not desired, it will force the movement of heavy machinery to perform a mechanical fragmentation. The consequence of the lack of planning raises the costs of the operation and the time for the removal of the disassembled material. The entire cycle of loading and transportation cycle is affected, reflecting higher costs and lower productivity.

Therefore, it is necessary to predict a possible fragmentation through the geometric parameters of the mesh, type of explosives and their parameters, and the geotechnical and geomechanical characteristics of the rock.

As the advance takes place in the tunnel it is necessary to identify what geological and geotechnical characteristics we will face, to make the necessary adjustments in the drilling network and explosive load, to obtain the desired fragmentation.

To predict fragmentation there are several mathematical models that take into account all the parameters of the plane of fire. From this forecast we can change the fire plane so that we get different sizes according to the need of the operation.

### 3.1 Model KUZ-RAM

The Kuz-Ram model was developed for open-air detonation, so different results should be expected in the case of underground detonation (Ouchterlony, 2005).

Although the fragmentation of debris in tunnel detonation is not as important a factor as in open-air dismantling, whenever possible, it is interesting to evaluate the feasibility of the Kuz-Ram model for underground detonation.

The Kuz-Ram model does not cover all aspects of detonation and has never been developed to do so. It is a deterministic model not considering the delay time between holes, which has an influence on rock fragmentation and does not even can predict the amount of thin in the stack.

The properties of the rocks, the properties of the explosives, and the geometric variables of the plane of fire are combined using five equations that make up the Kuz-Ram fragmentation model.

#### 3.1.1 Kuznetsov equation

A correlation between the average fragment size and the detonation energy applied per rock volume unit (load ratio) was developed by Kuznetsov (1973) as a function of the rock type. This equation was modified by Cunningham (1983) and is given by:

$$X_{50} = A \cdot K^{-0,8} \cdot Q_{6}^{\frac{1}{6}} \cdot \left( \frac{115}{RWS} \right)^{\frac{19}{30}} \quad (1)$$

where:

- $X_{50}$  - the average particle size (cm),
- $A$  - the rock factor.
- $K$  - the load ratio ( $\text{kg}/\text{m}^3$ ).
- $Q_{and}$  - the mass of the explosive used (kg),
- $RWS$  - he mass relative energy (RWS) of the explosive compared to THE ANFO (ANFO=100).

#### 3.1.2 Equation of Rosin-Rammler

With the following equation it is possible to define a particle curve that allows you to visualize the size of the particles of the disassemble.

$$R(x) = 100 \cdot \left[ 1 - e^{-0,693 \cdot \left( \frac{x}{X_{50}} \right)^n} \right] \quad (2)$$

where:

- $X$  - the mash size of sieve,
- $X_{50}$  - the average particle size, n is the uniformity index,
- $R(X)$  - the percentage of passing material in the x-size sieve.

### 3.1.3 Uniformity Index Equation

This expression was developed through field tests by Cunningham (1987). It correlates all the geometric parameters of the plane of fire, as follows:

$$n = \left[ 2,2 - 14 \cdot \left( \frac{B}{D} \right) \right] \cdot \left[ \frac{1 + \frac{S}{B}}{2} \right]^{0,5} \cdot \left( 1 - \frac{W}{B} \right) \cdot \left( \frac{|L_B - L_c|}{L} + 0,1 \right)^{0,1} \cdot \frac{L}{H} \quad (3)$$

where:

- B - the burden (m),
- S - the spacing (m),
- D - the diameter of the hole (mm),
- W - the deviation of the perforation (m),
- L - the total load length (m),
- H - the height of the seat (m).

## 3.2 KCO Model

Ouchterlony (2005) stated that the Kuz-Ram model was not enough to define fine and coarse granulometric fractions. The weak capacity of the model proposed by Cunningham to describe fines was one of the main reasons why the Two-Component-Model (1999) and the Crush Zone Model (1999) were developed. Both combine two Rosin-Rammler distributions or components, one for the rough part of the curve and the other mainly for the thin ones.

Ouchterlony suggested a new approach parallel to TCM and CZM, calling its model KCO. In this model, the average fragment size and uniformity index are calculated by the equation proposed by Cunningham (1987). The function that was previously presented by Rosin-Ramler to define the particle size distribution is now replaced by Swebrec.

### 3.2.1 Equation SWERBEC

Like the Rosin-Rammler equation, it uses the value of 50% of past X50 as the center parameter but adds a maximum limit value for the Xmax.

The third parameter b is a calculated parameter that defines the ripple of the curve (Ouchterlony, 2005).

$$P(x) = \frac{1}{1 + \left( \frac{\ln \left( \frac{x_{max}}{x} \right)}{\ln \left( \frac{x_{max}}{x_{50}} \right)} \right)^b} \quad (4)$$

where:

- $P(x)$  - the percentage of passing material in the x-size sieve (%),
- $X$  - mesh size corresponds to sieve (mm),
- $X_{50}$  - opening of the sieve where 50% of the fragmented material is passing (mm),
- $b$  - ripple parameter,
- $X_{max}$  - maximum value of the block that will be generated. It is usually mín.  $\left(S, B \text{ ou } \frac{S+B}{2}\right)$  the (mm).

The material size with 50% of passers-by is calculated by the following equation:

$$X_{50} = \left[ \frac{g(n) \cdot A \cdot Q^{\frac{1}{6}} \cdot \left(\frac{115}{S_{ANFO}}\right)}{q^{0,8}} \right] \quad (5)$$

Parameter b, called the ripple exponent or sometimes the exponent of natural breaking characteristic (Ouchterlony, 2009).

$$b = \left[ 2 \ln 2 \cdot \ln \left( \frac{X_{max}}{X_{50}} \right) \right] \cdot n \quad (6)$$

For the equation that allows the fragmentation curve to be solved, it is necessary to obtain the n (uniformity index) by the following equation:

$$n = \frac{(2,2 - 0,014B)}{\phi_n} \cdot \left( \frac{1 - SD}{B} \right) \cdot \sqrt{\left[ \frac{\left(1 + \frac{S}{B}\right)}{2} \right]} \cdot \left[ \frac{|L_b - L_c|}{L_{tot} + 0,1} \right]^{0,1} \cdot \left( \frac{L_{tot}}{H} \right) \quad (7)$$

The new Swebrec model has three large parameters and allows for a good to excellent fit for different types of fragmentation data with correlation coefficients of at least 0.997 or better ( $r^2 > 0.995$ ) for a variety of fragment sizes of two to three orders of magnitude. This model has the ability to achieve a prediction of the size of the fines very effectively (Ouchterlony & Sanchidrián, 2019).

### 3.3 KUZ-RAM vs KCO

For the study of tunnel fragmentation models, a real case of the Kittila mine in Finland was used, which is owned by Agnico-Eagle Mines Limited and is dedicated to gold mining.

The tunnel section has an area of 27.7m<sup>2</sup> volcanic rock and we can find in table10 all the parameters used in the execution of the fire plane and in table 9 the parameters that affect the different sections of the tunnel.

## 4 CASE STUDY KITILLA MINE IN FINLAND

### 4.1 Local geological information

The region around the Kittila mine is underlies volcanic and sedimentary rocks from the Kittila Greenstone Belt which has a trend from north to north-northeast and are almost vertical. This Kittila Greenstone Belt is similar to those hosting Canadian deposits in Quebec's Abitibi and Nunavut region.

The contact between an iron-rich zone and a magnesium-rich volcanic sedimentary zone consists of a transition zone (the "Porkonen Formation") ranging from 50 to 200 m thick. This area is severely fractured, characterized by an intense hydrothermal alteration and mineralization of gold, characteristics consistent with the main fragile deformation zones. The area is part of a large north-northeast oriented area (the "Suurikuusikko Trend"). The Porkonen Formation houses the Kittila gold deposit, which contains multiple mineralized zones extending over a length of more than 25 km.

### 4.2 Blasting plan

The parameters of blasting holes is presented in table 1. In table 2 the tunnel blasting plan is presented.

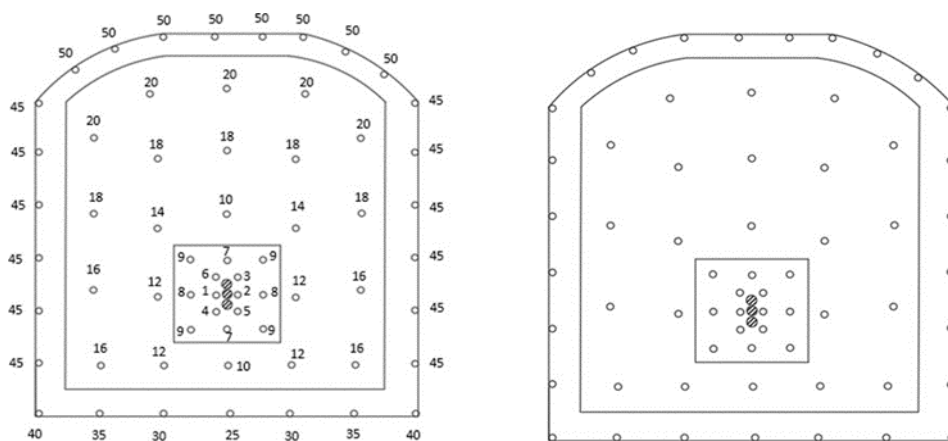
**Table 1** Fire plan for the four sections of the tunnel

	Parameters	Mine Finland
Burn cut	number of holes	14
	explosive volume, cm <sup>3</sup>	7204
	kg/hole	7.6
	density, kg/m <sup>3</sup>	1.05
Lifter	number of holes	7
	explosive volume, cm <sup>3</sup>	5757
	kg/hole	6.08
	density, kg/m <sup>3</sup>	1.05
Production	number of holes	22
	explosive volume, cm <sup>3</sup>	5033
	kg/hole	5.3
	density, kg/m <sup>3</sup>	1.05
Contour	number of holes	21
	explosive volume, cm <sup>3</sup>	4490
	kg/hole	4.8
	density, kg/m <sup>3</sup>	1.05

**Table 2** Tunnel fire plan

Description	Parameters	Mine Finland
Drawing	width, m	5.3
	height, m	4.5
	arrow, m	1
	drilling diameter, mm	48
	empty diameter, mm	140
	long. drilling, m	5
	steaming, m	1.9
Explosive	density, g/cm <sup>3</sup>	1.9
	explosion heat, MJ/kg	3.19
Drawing	area, m <sup>2</sup>	27.7
	loaded holes	64
	empty holes	3
	advance, m	4.8
Explosive	kg of explosive	370.5
	booster, 150g kg/m <sup>3</sup>	9.45
	total, kg	379.95
General	volume, m <sup>3</sup>	139
	meters drilled, m/m <sup>3</sup>	315
	perf. specifics, m/m <sup>3</sup>	2.3
	specific load, kg/m <sup>3</sup>	2.73

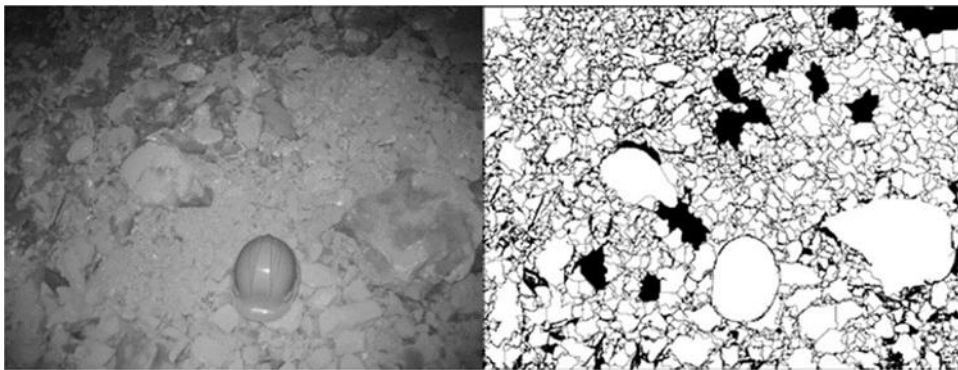
In the following figure (figure 2) the drilling plan executed in the dismantling of the tunnel was elaborated.

**Figure 2** Tunnel drilling geometry under study

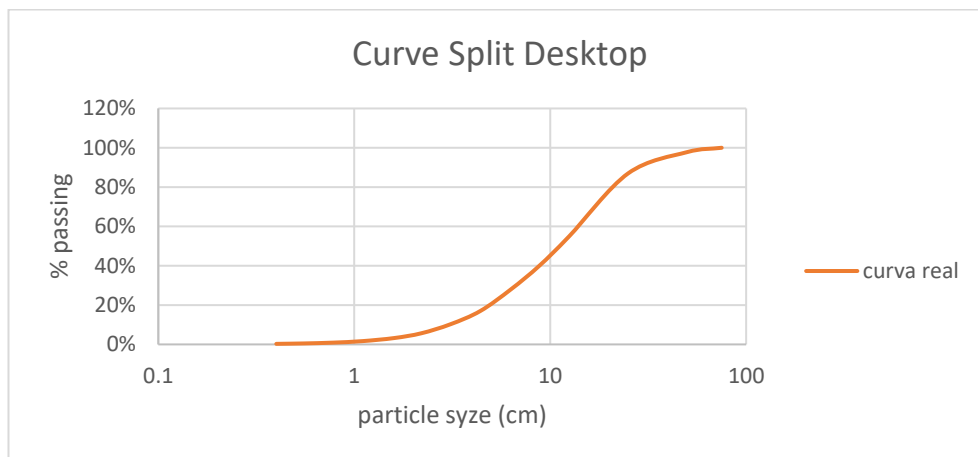


In this case study, the measurement of the fragmentation of the stack was performed with the *Split desktop tool* that analyzes from a photo of the stack after dismantled to measure the fragmented particles (figure 3) and generate a particle curve (figure 4).

A comparison was made between the Kuz-Ram model and Swebrec to evaluate which of the models can produce a curve closer to the curve obtained by the photos collected and worked in the field. The rock factor can be calibrated by collecting photos for the construction of the particle size curve. Calibration will allow models to be more efficient and generate more real-looking curves in future blasts.



**Figure 3** Photos used in Split Desktop



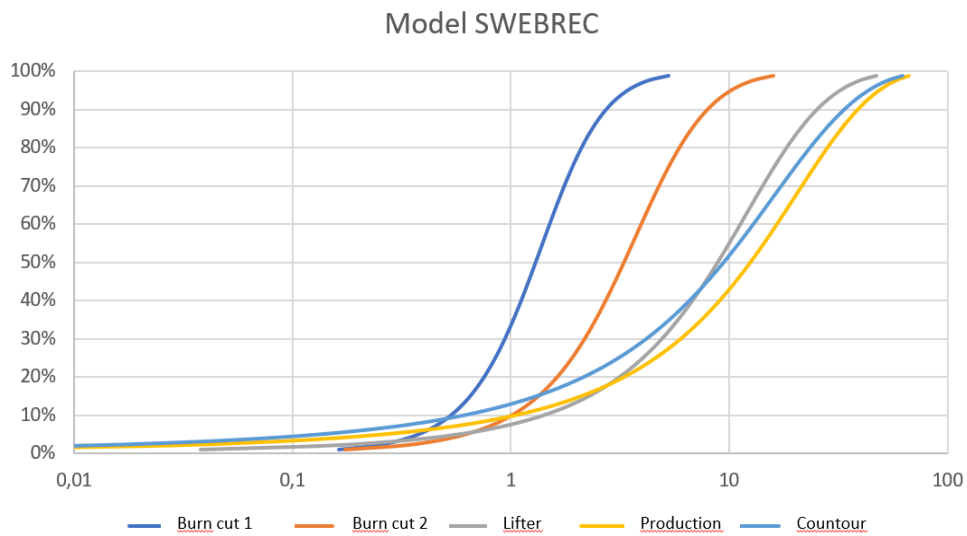
**Figure 4** Actual dismount curve using in Split Desktop

To use the Kuz-Ram model and the Swebrec model in underground mining was divided into 4 sections: burn cut, lifter, contour and production. Each of these sections has a different specific load which will lead to a dismount with different characteristics. A granulometric curve was calculated for the different sections.

After modeling the particle size curve for each section, a weighted average was executed with the amount of volume obtained from each disassembled section to obtain a resulting particle size curve that will represent the complete dismantling.

#### 4.3 Curves of the different sections under study with SWERBEC model

Figure 5. presents the results of the different sections with Swerbec model.

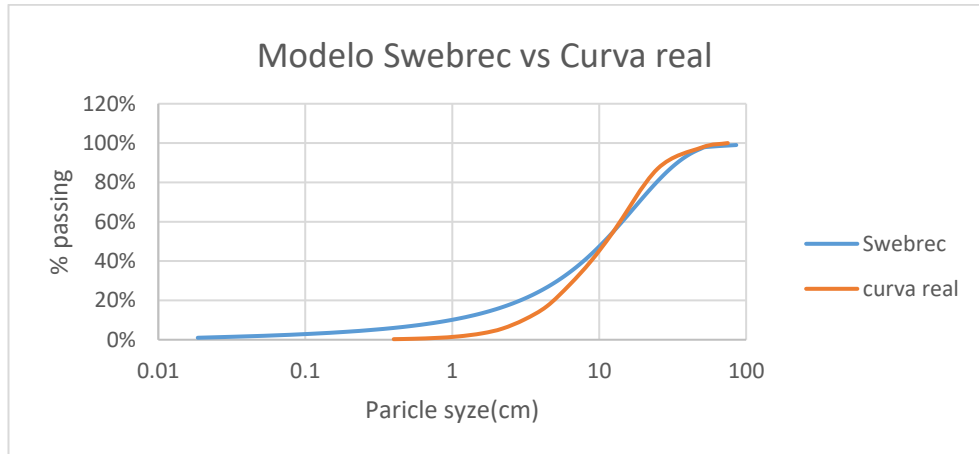


**Figure 5** Results of the different sections with Swebrec model

According to Figure 5, the section of the burn cut is the one that produces more quantity of fines due to its specific high load, but as also the section occupies little volume will have little influence on the final curve, the curve (production) is the curve that will most influence the modeling of the total curve, due to its large busy volume.

The joined curve of the sections is obtained from a correlation between the sizes and their percentages with the occupied volume of each section. The volume is obtained by multiplying the area of the tunnel section with the advance (Figure 6).

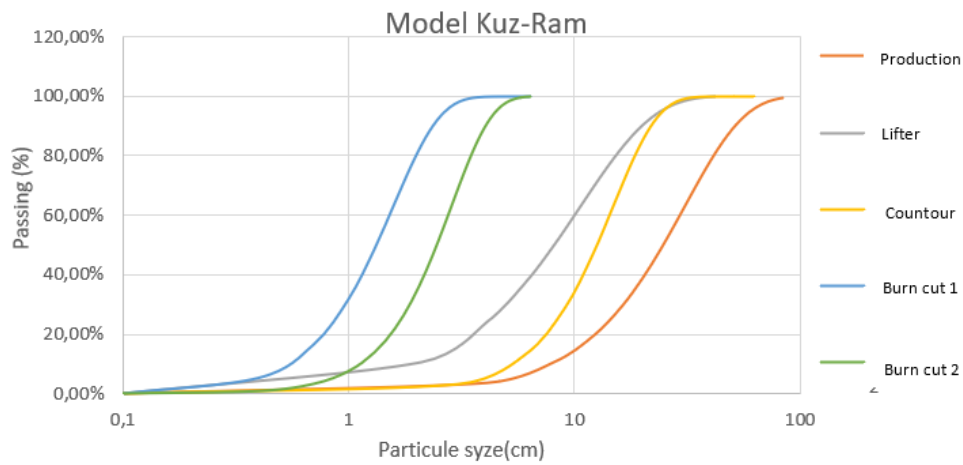
In the Swebrec model, according to tests conducted by (Ouchterlony & Sanchidrián, 2019) the modeling of fines is more effective than the modeling of fines of the Kuz-Ram model.



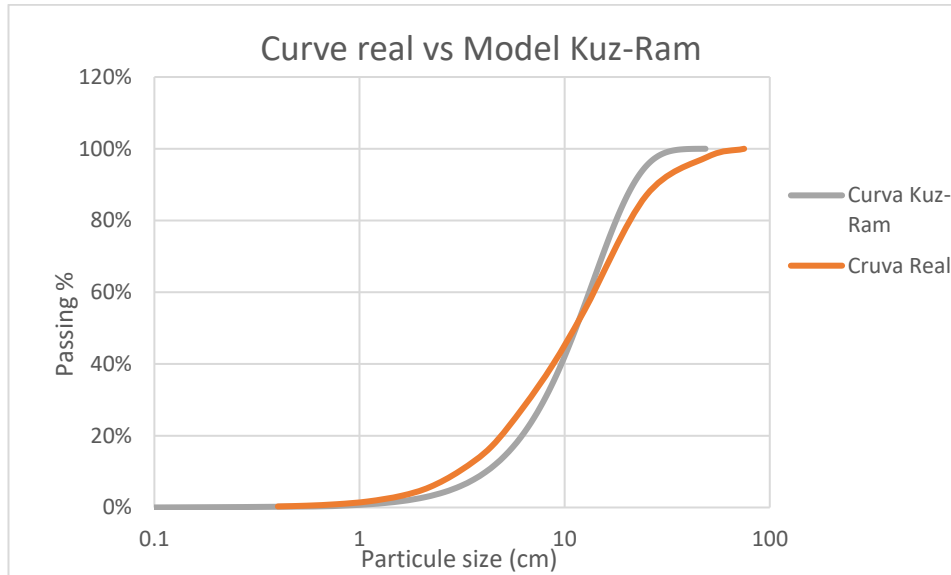
**Figure 6** Prediction of Swebrec vs Real granulometric curves

#### 4.4 Curve KUZ-RAM sections

As in the Swebrec model, the method used to be able to gather the curves in a resulting particle size curve was the use of the weighted mean of the areas of influence of each section.



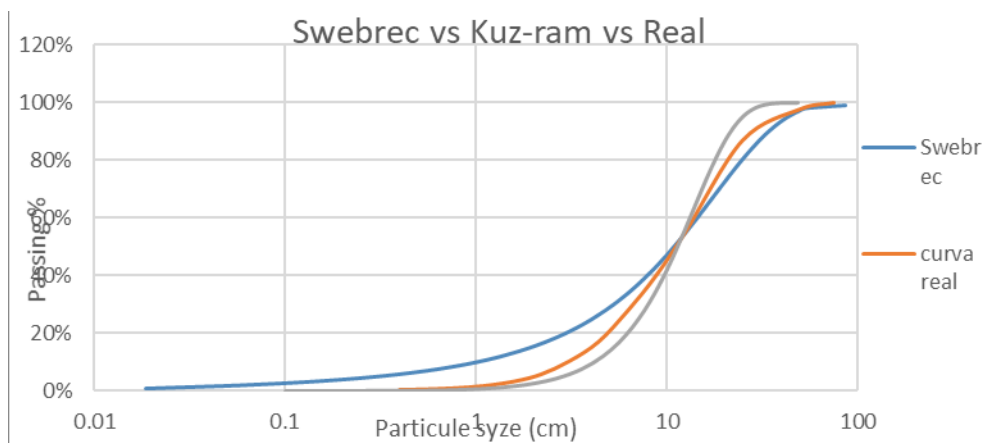
**Figure 7** Results of the different sections with Kuz-Ram model



**Figure 8** Prediction of Kuz-Ram vs Real granulometric curves

#### 4.5 Comparison of the two curves

The two models are completed: by comparing the results of the two with the actual curve, the Kuz-Ram model better models the thin curve while the Swebrec model better models the upper thick zone X50, however the actual curve was defined from photogrammetry that fails to make a complete prediction of the zone of the fines, because this models particle to particle and is sometimes unable to identify particles with a smaller size.



**Figure 9** Comparison of the results obtained from the models with actual curve

## 5 CONCLUSION

Works with Wipfrag and Splitdesktop should be performed in all blasts, to compare the results obtained in reality with the results modeled for fragmentation, in order to correct values of the parameters used as input, such as the value of the rock factor, allowing critical thought with the results determining all the possibilities that can lead to the difference of the granulometric curve modeled and obtained in reality. An example of this would be the realization of low-quality photos that can lead to gross fragmentation errors and occurrence of misfires in the disassemble. The use of a tool such as Wipfrag or Splitdesktop has the limitation inherent in the fact that they are not fully correct in measuring fine material. When taken the photograph to measure the size of the particles, it is not possible to conclude the size of the particles at the bottom of the pile and the amount of dust that is formed and not recorded in the photograph.

The models studied for tunnel opening are models used and developed for use in open skies with free front. However, the results obtained were not far from expected.

We can then conclude that the use of the Swebrec model is the most indicated to predict fragmentation in the tunneling and be applied in the software. Once compared to the actual curve with the modeled curve, the values above X50 of the curves reach high precision values. However, the modeling is not so similar in the zone of the fines (lower values of the X50), but as already mentioned the modeling of the actual curve from photogrammetry does not allow to measure exactly the amount of thinner material, where in swebrec modeling the uniformity of particles is smaller extending the zone of fine material more than in the actual curve. In the software itself will be allowed to choose between the use of the two models allowing the user to choose which model to use.

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