Use of RocFall Software for Flyrock Simulation in Open-Pit Mining

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ABSTRACT

In open-pit mining, a flyrock corresponds to the projection of a fragment because of the energy released in a blast, which increases the risk to personnel, equipment, and infrastructure. In recent decades, several models have been generated that attempt to predict the velocity and maximum projection distance to define safety zones. However, there is no generalized vision on how to approach this phenomenon, nor is there a widespread approach to its analysis using software. Under the assumption that an analogy can be assumed between the flyrock phenomenon and the rockfall considering an initial acceleration, the use of RocFall software is proposed to simulate this phenomenon. For this purpose, a case study was generated considering a conventional blasting with 10-meter high benches and an initial velocity based on existing empirical models. The three scenarios studied were: (i) a base case without considering the restitution coefficient, (ii) a case considering the restitution coefficient, and (iii) a three-dimensional model. A total of 100 possible trajectories were simulated, measuring the range of each and the distribution of impacts along the study profile. The importance of considering the coefficient of restitution in the analysis is evident because many existing models only consider the distance reached by the initial impact of the fragment and not what happens to the fragment after the impact. Finally, it was concluded that RocFall can be used as a visual tool for the study of projections, and different lines for future applications are proposed.

KEYWORDS: *flyrock, blasting, open-pit mining, RocFall.*

1 INTRODUCTION

The use of explosives in mining and civil engineering is the most commonly used means for the fragmentation of rock masses where mechanical means are inefficient [1, 2]. Blasting is a fast and inexpensive technique; however, it has some limitations and risks.

Flyrock is one of the most important undesirable effects that can be generated by blasting, as it has great potential to cause damage to workers and nearby infrastructure. Despite the occurrence of this phenomenon, it is often not documented, because it does not

generate personal injuries, so many of these incidents are poorly documented worldwide [3]. However, it is possible to find compilations of these by the Mine Safety and Health Administration (MSHA). [3-5], which reported 168 blasting-related injuries (including open-pit and subway mining) between 1994 and 2005. On the other hand, Kecojevic and Radomsky [6] report that the lack of a safety area and the occurrence of flyrock were responsible for 281 accidents during 1978 to 1998. In recent years, blasting fatalities have decreased; however, this phenomenon continues to attract the attention of mining professionals worldwide.

Currently, there are different methods for predicting flyrock, focusing on avoiding its generation or mitigating its consequences. Some of the most commonly applied models are traditional, empirical, and semi-empirical. In the last few years, novel models based on the use of artificial intelligence algorithms have been developed. Despite the existence of different methods, there is no commercial software that allows flyrock trajectory prediction and visualization.

This study aims to show the application and potential of the RocFall software in conjunction with empirical formulas to be used as a visual tool for flyrock simulation in mining. In addition, the use of the coefficient of restitution in the analysis is introduced. Owing to its simplicity, this program is proposed as a new method for flyrock prediction and analysis.

2 THEORETICAL FRAMEWORK

Drilling and blasting operations correspond to the first stage of the crushing process. These activities have the greatest impact on the efficiency of a mining operation because of their repercussions on all downstream operations and processes [7]. This is reflected in both the shape of the material pile and the distribution of fragment yields and costs of downstream processes [8]. In addition, blasting is more energy efficient than crushing and milling processes, reducing the energy per ton produced during the whole process, being, in addition, beneficial at an environmental level if it is considered that energy consumption in mineral comminution is 2-3% worldwide [9].

The main objective of blasting is to achieve an adequate fragmentation. However, approximately 20% of the explosive energy is used to achieve this objective, and approximately 80% of the explosive energy is dissipated as other forms of energy [10]. The rest of the energy is lost in undesirable transient effects such as vibrations, pressure waves, and flyrock [11]. Sanchidrián et al. [12] reported that 26% of the total energy measured in a single blasthole, 2-6% is used for fragmentation, 1-3% for seismic energy and 3-21% for kinetic energy.

Flyrock, or rock projections, correspond to the random and excessive launching of a rock fragment due to detonation, which can compromise the integrity of people, structures, and equipment [13], understanding "excessive" as beyond a preset zone or an expected range [14]. Other authors distinguish between flyrock and wild flyrock, that is, those generated but driven within a previously established zone and those that exceed this safety distance [15,16].

Among these undesired effects, flyrock is the most prone to generate serious accidents [17]. Although most fragments travel up to a few meters, there are circumstances that can cause them to reach up to 1,000 m [15,18], which implies not only an impact inside the mine but also in its surrounding areas. Furthermore, compared to vibrations, flyrock is a much less known and studied phenomenon; therefore, it is of fundamental importance to study its causes, origin mechanisms, and existing predictive models [15].

The main causes for the generation of these projections are associated with local anomalies of the rock mass, blasting design configuration, and explosive loading [13]. In mining, three mechanisms can be distinguished according to the origin of the phenomenon: (i) Face Bursting, which occurs due to high gas pressure and condition of the distance from the blasthole to the free face; (ii) Cratering, which occurs due to the presence of weak rock in the collar, or if the blasthole height-diameter ratio is too small; and (iii) Rifling or Gun-barreling, which occurs due to the presence of an insufficient, weak, or non-existent stemming [14, 19, 20] (Fig. 1).

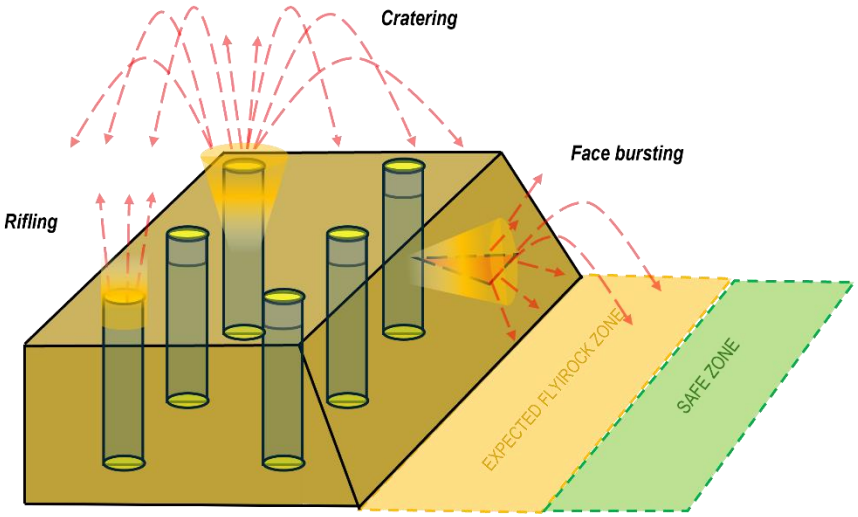

Fig 1. Types of flyrock generation mechanisms in mining.

The factors that influence the generation of these mechanisms have been classified as controllable, which include design variables and explosive parameters, and uncontrollable, which includes rock mass characteristics, fragment properties, wind conditions, and various environmental constraints [16]. Several studies have focused on understanding the influence of these parameters. Armaghani et al. [21] noted that the most influential parameters are blasthole length, spacing, powder factor and maximum detonated charge per delay. Supandi [22] reported that the parameters affecting the flyrock distance are burden, stemming, blasthole length, powder factor, and average load per blasthole.

Zhou et al. [23] compiled and developed models to predict and mitigate these projections, including mathematical models, empirical methods, probabilistic approaches, fragment velocity and range approaches (semi-empirical), and artificial intelligence (AI) approaches (Fig. 2).

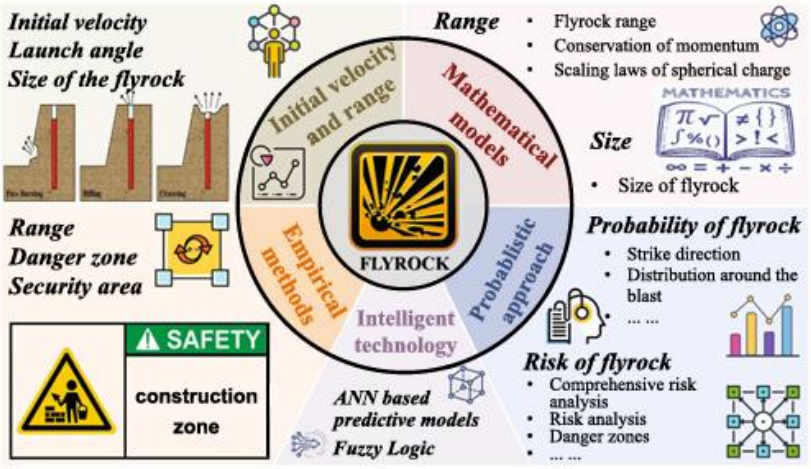

Fig 2. Main methods for flyrock prediction [23].

In the literature, there are many empirical and semi-empirical methods that attempt to describe different factors of projections, such as range [24-26], velocity [27], and safety distances [17].

Szendrei and Tose [14] noted that maximum reach models are often based on design parameters, explosive loading, and rock mass properties to a lesser extent. On the other hand, Murlidhar et al. [28] indicated that rock mass parameters (GSI, WI, and RQD) also have a significant effect on the distance reached by the flyrock, whereas velocity models tend not to consider aerodynamic drag, and safety distance models are based on risk and the consequences they may have [13].

It is possible to find different formulations that focus only on predicting the initial velocity of the rock projection, which depends on the design parameters, rock or explosive characteristics, or integration of these three factors (Table 1).

Table 1. Initial flyrock velocity velocity formulas.

Author	Formulas	Application
Lundborg [29] modified by McKenzie [30]	$v_o = K_v \left(\frac{d}{0.0254\ x_f}\right)\left(\frac{2{,}6}{\rho_r}\right)$	Crater blasting: $K_v = 10$ Bench blasting: $K_v = 0.65$ Heavily confined: $K_v = 0.11$
Roth [27]	$v_o = (2E)^{0.5} f$	Bench blasting
Moore & Richard [19]	$v_o = k\left(\frac{m^{0,5}}{SH\ o\ B}\right)^{1.3}$	Crater blasting: S.H Face bursting: B
Stajodinovic et al. [31]	$v_o = C_f \frac{3\ \rho_{exp}\ {V_d}^2\ \Delta t}{32 x_f\ \rho_r}$	Face bursting
Cánovas et al. [32]	$v_o = \left(\frac{K}{2}\right)\left(\frac{E_{exp}}{2}\right)^{0.5}\left(\frac{\rho_{exp}}{\rho_r}\right)^{0.5}\left(\frac{d}{B}\right)^{1.5}\left(\frac{L_c}{B}\right)^{0.5}$	Face bursting

d is the diameter of the blasthole (m), x_f is the fragment size (m), is the density of the rock (t/m^3), $(2E)^{0.5}$ is Gurney's constant, which is related to the detonation velocity of the type of explosive, f is a function that depends on the geometry of the system, k is a constant that varies from 15 to 37, m is the charge per meter (kg), C_f is a correction factor, V_d is the detonation velocity (m/s), Δt is the impulse time (s), SH is the length of the

stemming (m), B is the burden (m), L_c is the length of the explosive column (m), K is the correction factor that varies between 16-18; E_{exp} is the energy of the explosive (J/kg).

Currently, several techniques have been developed that seek to predict the occurrence of flyrock using artificial intelligence [23, 28, 33-35]. It is important to highlight the emergence of models using this approach, which is currently the most used when developing a predictive model. According to van der Walt & Spiteri [36], from a review of articles from 2010 to 2020, 53% employed artificial intelligence techniques, followed by empirical techniques with 23%, ballistic approaches with 12%, and the rest corresponding to statistical analysis and rock engineering systems (RES). Similarly, it is possible to identify other more sophisticated models based on ballistics [31] and analogous to hydrodynamic models [32].

Some of the most common applications of artificial intelligence use machine learning techniques, such as artificial neural networks (ANN) [37-40], support vector machines (SVMs) [35, 41, 42], and genetic algorithm-based methods [34, 43], which have been used to predict the maximum range distance and define safety zones. A further compilation of machine learning techniques can be found in Zhou et al. [22].

Regarding various existing models, van der Walt & Spiteri [44] reported certain limitations, such as empirical and statistical approaches that only produce models specific to the location where they are fitted. In addition, they pointed out that artificial intelligence models, despite their advantages, are highly dependent on the input parameters. All these models have the purpose of adjusting the proper configuration of the wells, that is, defining design parameters (such as burden and stemming) and blast configuration explosive parameters. Despite the existence of different methodologies, there is no consensus on how to approach flyrock study or commercial software for its specific use.

The following section discusses the methodology used together with the parameters of the designed cases, then the results and main analyses are presented, and finally, the conclusions are obtained.

3 METHODOLOGY

The methodology is divided into four stages:

1. Definition of initial parameters.
2. Obtaining the initial velocity of the fragment.
3. Construction and execution of the cases
4. Analysis of the results.

In the first instance, the blasting parameters are defined, such as the burden, length of the explosive column, and explosive used, which conditions the energetic properties.

Subsequently, a bibliographic search of the main equations presented in the literature was conducted, from which one was selected for testing in the software as an example. The selection criteria for these equations are based on the following: (i) they must allow the expression of the velocity in its horizontal and vertical components, (ii) it must be a simple and replicable model, and (iii) the conditions of use of the equation must be clearly stipulated, that is, it must indicate what type of flyrock generation mechanism was used for its development (Table 1). From these, the minimum and maximum initial velocities that a fragment may present at the moment of being projected are obtained as a function of controllable parameters, which serve as input parameters for the design. Then, a base case

study is constructed using RocFall, considering the design limits, bench height, location of the flyrock origin (seed), and mass of the projected fragment, among other parameters.

RocFall is a software designed to assess the risk of rockfall on slopes by determining the energy envelopes, velocities, positions, and rebound heights of the rocks [45]. The rationale for using this program, which was not created for flyrock, was based on the similarity between the characteristics of both events. A flyrock can resemble the launching of a rock fragment, but considering a high initial velocity owing to the energy transmitted by the detonation. There are two versions of this software, RocFall2 and RocFall3, which allow analysis in two and three dimensions, respectively.

In this study, three cases are considered: 1) the base case, only considering the initial impact of the fragment; 2) the case considering the restitution coefficient, that is, contemplating what happens to the fragment after the impact (rebound and change of trajectory); and 3) a three-dimensional case, considered only to see the potential that the program can have when modeling more complex cases. Finally, the results are compared and the advantages of using the two versions of the program are indicated.

3.1 Case studies

The blasting parameters used in the velocity calculation, together with the geometrical parameters of the site, are given below. These elements were common in all three cases. For the blasting parameters, the blasting scheme and the corresponding properties of the explosives used were defined (Table 2). In addition, for the geometric parameters, bench height, bench width, and maximum extension of the model were considered (Table 2). The latter was generated by considering an extension that did not limit the fragment projection.

Table 2. Blasting design parameters and explosive properties.

Nomenclature	Parameters	Value	Unit
B	Burden	8	m
d	Blasthole diameter	12½	’’
L_c	Explosive column length	7	m
V_d	Detonation velocity	3,000	m/s
E_{exp}	Explosive energy	3,818	kJ/kg
ρ_{exp}	Explosive density	0.8	t/m^3
H_b	Bench height	10	m
A_b	Berm width	24	m
E_m	Model extension	500	m

In addition, the following terrain characteristics were considered for each case, considering the coefficient of restitution (normal and tangential) and angle of friction (Table 3). It should be noted that, in order to simplify the study, the rotational velocity of the fragment was not considered in the analysis.

Table 3. Geometric characteristics of the Base case.

	Normal coefficient of restitution	Tangential coefficient of restitution	Friction angle (°)
Case 1	0	0	30
Case 2	0.35	0.85	30

Case 3	0	0	30

Finally, the characteristics of each case were introduced, and the point of generation of the flyrock was selected as the first bench of the case study at approximately 2/3 of the bench height (Fig. 3). In addition, the mass and density of the fragments were taken into account for the analyses; therefore, spherical fragments of 11.3 kg with a density of 2.7 t/m^3 were defined.

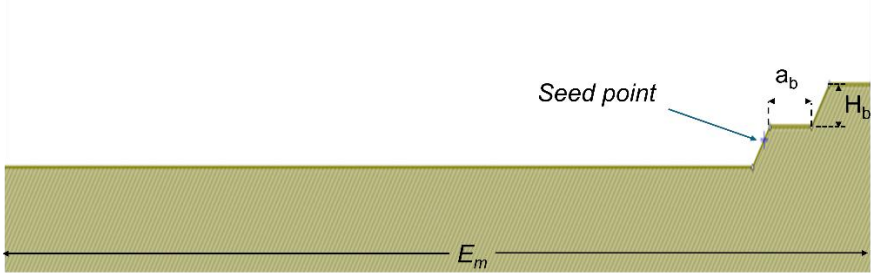

Fig 3. Geometric characteristics of the Base case.

4 RESULTS AND DISCUSSION

A bibliographic search was made of the main formulations found in the literature focused only on launching velocity (Table 1), from which the different velocities were obtained for each of the models, using the constants provided in the original publications, if necessary (Table 4).

Table 4. Initial velocities for each model.

Author	Velocity (m/s)
Lundborg [29] modified by McKenzie [30]	39.1
Roth [27]	19.1
Moore & Richard [19]	95.0
Stajodinovic et al. [31]	36.0
Cánovas et al. [32]	50.1

As an example, the equation proposed by Stajovidinovic et al. [31] was used because it is one of the most current and simple semi-empirical equations. The initial velocity of the fragment was defined using the previously defined parameters and the selected equation. To consider the possible launch angles that may occur, a triangular distribution is defined for the velocity, where the maximum value is given by the value obtained from the formulations, with the minimum value corresponding to zero and the mean value corresponding to vo/2, in both the vertical and horizontal directions. Subsequently, the input parameters were entered into the software to generate each case.

For the first case (Base case), 100 possible trajectories were simulated for the rock fragment, resulting in the following visualization (Fig. 4). The maximum range of the trajectories corresponds to a distance of 186.5 m from the toe of the first bench.

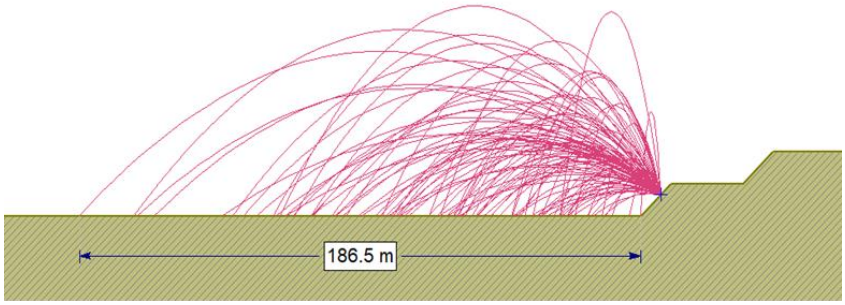

Fig 4. Visualization of the projection trajectory for the Base case.

Fig. 5 shows the distribution of the range of the different fragment trajectories, visualizing a bimodal distribution with the largest distributions near coordinates 375 m and 405 m with respect to the origin of the system, equivalent to distances from the toe of the slope of 57 m and 27 m, respectively, becoming zero at distances greater than 187 m.

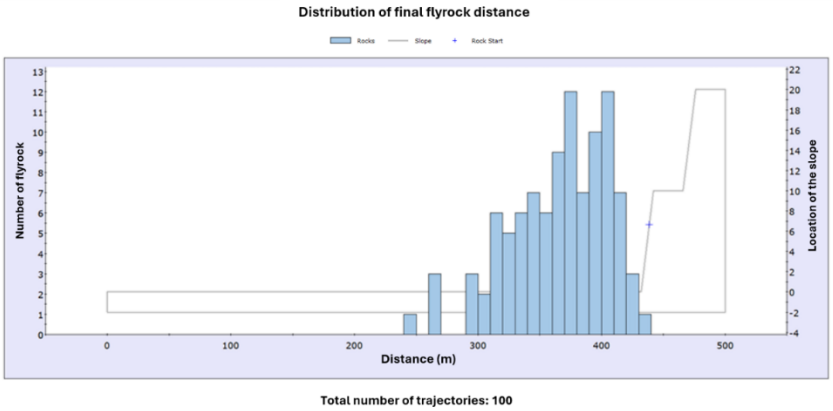

Fig 5. Distribution of the pattern of fragment reaches Case 1.

For Case 2, the trajectories were obtained by considering the previously defined coefficient of restitution. The maximum reach increased compared to the first case (Fig. 6), reaching a maximum distance of 228.4 m with respect to the toe of the slope.

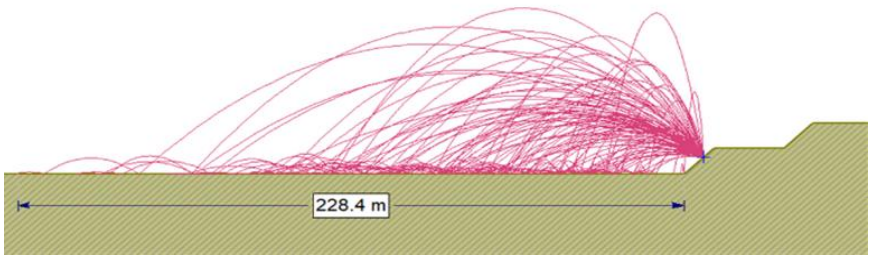

Fig 6. Visualization of the projection trajectory for Case 2: with coefficient of restitution.

When comparing the results, it can be observed that the use of the coefficient of restitution has a significant impact on the maximum reach of the flyrock, presenting an increase of 22.1% with respect to the maximum reach obtained for the first case. In addition,

it was observed that the largest distribution was found at coordinate 360, that is, 72 m from the toe of the slope (Fig. 7).

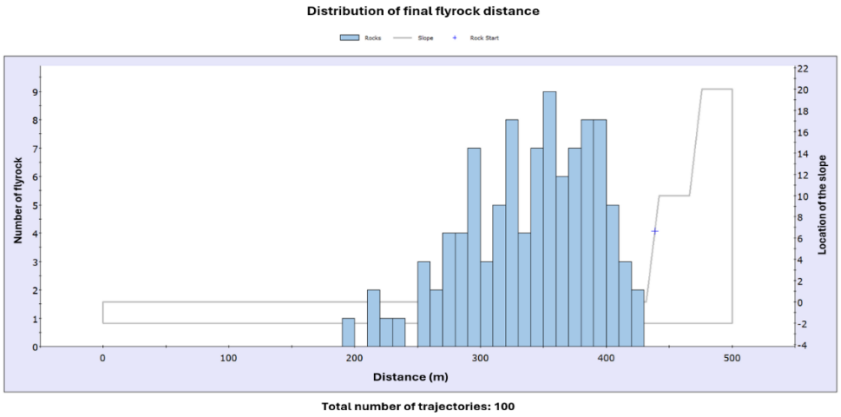

Fig 7. Distribution of the pattern of fragment reaches Case 2: with coefficient of restitution.

Finally, to demonstrate the potential of the software to model more complex scenarios, a three-dimensional case was developed (Fig. 8). To simplify the scenario, no coefficient of restitution, Y-axis velocities, or rotational velocities were considered. However, these factors should be considered for a more detailed analysis.

In this analysis, it was determined that the maximum reach is 168.2 m from the toe of the slope, which is less than that in Case 1. This is because the velocities generated in the simulations, despite following the same distribution, were not necessarily equal.

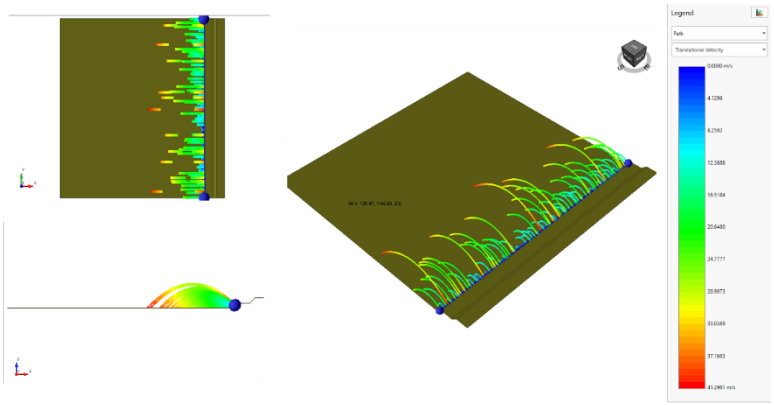

Fig 8. Visualization of the projections in the three-dimensional analysis.

From the study presented, some advantages of using RocFall software can be observed, which can be summarized as follows:

- The input of parameters is simple, and only the model describing the initial velocity modulus must be known.
- This allows the creation of different study cases, from simple to more complex scenarios.
- It has great simulation capacity, allowing the simulation of a large number of trajectories in a short time.

- It can contemplate the study of a flyrock with different origin positions, allowing the study of three possible generation mechanisms (face burst, cratering, and rifting). - It considers the change in trajectory after the first impact of the rock; that is, it considers the real range that the fragment can have, and not only the theoretical maximum range. This was achieved through the coefficient of restitution.
- The analysis can be expanded by considering three-dimensional designs, through the implementation of RocFall3. This version allows importing models and adapting them directly to the RocFall2.
- It is useful for mines or quarries that already have the software for the analysis of rock falls on slopes. In other words, it can be put to a second use without the need for additional programs.

5 CONCLUSIONS

In mining, blasting is the most commonly used method for rock fragmentation. Thus, there are associated desired and undesired effects. Among the latter, flyrock is one of the most important because of its risks to personnel, equipment, and nearby structures. Several approaches have been developed to address the flyrock phenomenon, ranging from the use of simple formulas based on field experience to more advanced techniques involving the use of artificial intelligence. However, the use of software for its analysis has not been observed, so having a visual and easy-to-handle tool can be fundamental for its study.

In this paper, the use of the RocFall software in conjunction with semi-empirical formulas for flyrock analysis was presented. It was shown that although RocFall was not created with the purpose of being used in flyrock, it is a useful tool for the visualization and analysis of flyrock, allowing the recreation of the different mechanisms of origin in a simple way. In addition, several advantages of using this program were described, the main one being the use of the coefficient of restitution.

Finally, the use of the coefficient of restitution is recommended to improve the flyrock analysis to consider possible rebounds of these projections, which has not been widely studied so far. The authors leave a future line of study to expand the implementation in RocFall3, considering the restitution coefficient, angular velocity, different design schemes, fragment geometries, and different flyrock velocity models.

6 CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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