Application, monitoring, and control of vibrations induced by underground rock blasting using a near-field methodology

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Abstract

This paper investigates how to manage and model the vibrations caused by rock blasting in a Brazilian underground mine. Considering the frequent detonations and the previous lack of effective vibration control, understanding, and reducing the impact of these seismic waves is critical. We emphasize the use of the near field model technique, which considers the varied physical properties of different rocks, optimizes blasting plans, and minimizes damage to the rock mass.

We detail a case study that demonstrates a comprehensive approach to vibration control. The discussion includes the creation of a monitoring plan, the methodology used, results and the specific challenges and solutions found during the blasting process. This study provides a practical guide for similar future projects.

Finally, we present a predictive model based on the collected data, offering insights into the vibrations caused by blasting. This model helps decision-makers minimize the risk of displacing rock blocks in the blasting area, improving safety and operational efficiency.

Introduction

Underground mining is a highly complex operation that relies significantly on efficient rock fragmentation through detonation for its progression. The process generates vibrations that, if correctly interpreted through monitoring tools like velocity sensors and geophones, can provide comprehensive insights into the detonation process. This information is invaluable in quantifying particle velocity levels, assessing the efficiency of explosive charges, analyzing charge interactions, and comprehending their overall impact on the rock mass. In essence, vibration monitoring serves as a diagnostic tool, capable of identifying issues such as incorrect sequencing, delay dispersion, poor charge detonation, and damages instigated by neighboring charges.

Despite the crucial role that rock blasting plays within the mining cycle, it is often an overlooked component, with industry practices heavily leaning on empirical approaches. Recognizing this gap, the presented study proposes an innovative methodology for optimizing and controlling rock blasting practices. This is achieved through near-field analysis and seed wave characterization. By measuring vibrations in the near field using engineering seismographs and sacrificial geophones, a more accurate evaluation and modeling of the generated vibrations and wave propagation is possible. This facilitates a deeper understanding of their behavior, further enhancing the predictability and control of blast outcomes.

Comprehending the vibrations induced by detonation and their interplay with the geomechanical properties of the rock mass forms a crucial aspect of this study. These vibrations, particularly those of high intensity, can lead to the creation of new fractures or reopening of existing discontinuities. These disruptions can inflict potential damages to the overlying rock layers and even the surface structures. Hence, it is crucial to establish accurate control and damage criteria, such as the critical and minimum peak particle velocity, for the safe execution of blasting operations.

The primary objectives of this study center around the investigation and comprehensive analysis of the rock blasting process in underground mining. This includes establishing quality control criteria, characterizing the geomechanical properties of the rock mass, developing accurate vibration models, and defining robust damage criteria. By accomplishing these goals, the study aims to substantially improve drilling, blasting, and vibration control practices within the mining sector.

In conclusion, the proposed methodology holds significant potential to enhance the efficiency, safety, and sustainability of underground mining operations. By adopting a data-driven approach to rock blasting, the study offers a method of transforming this often-overlooked area into a meticulously managed, predictable, and optimized component of the mining cycle. Through a blend of innovative techniques and in-depth analysis, the research seeks to redefine the way we perceive and handle rock blasting in underground mining.

Literature Review

Vibrational studies are conducted to control detonation processes both in proximity and in surrounding areas. They are of vital importance to determine the vibration threshold generated in the far field and the influence area generated in the surrounding rock mass, referring to the near-field studies.

The near-field vibrational study allows the assessment of the damages inflicted on the surrounding rock mass because of blasting and their variations according to distances and the amount of explosive used. From this study, parameters are obtained which inform decisions aimed at reducing excessive damages, which result in less stability in the exploitation method, due to increased dilution, increased over excavation, escalated fortification costs, and rework.

It is for this reason that continuous improvement is sought in all operational processes where damage to the rock mass, its quality, and characterization are variables that must be internalized in the drilling, blasting, and geomechanics process. Therefore, this research aims to provide a structured and comprehensive framework for understanding and controlling the effects of blasting in underground mining, ultimately improving the safety, efficiency, and sustainability of these operations.

Seismic Vibrations

"Vibration" refers to mechanical waves that, once generated, propagate through a specific medium carrying energy. When these waves propagate through the ground (soil and/or rock), they are termed "seismic vibrations." These vibrations, generated from the source detonation, can lead to structural damage in the rock mass. The detonation process, described by Dowding (1985), involves a fast, high-temperature exothermic chemical reaction causing these vibrations.

The primary parameters of seismic vibrations include displacement (the distance a rock or soil particle moves), velocity (the rate of this movement), acceleration (the change rate in particle velocity), and frequency (the oscillation rate of the ground due to seismic energy from detonation). Understanding these parameters is crucial for the safe and efficient execution of blasting operations.

Emitter Source: Detonation Using Explosives

Understanding each explosive's distinct characteristics is vital to ensure its proper usage, especially in light of the rock's geostructural and geomechanical properties. Seismic vibrations in underground mining are often primarily generated by explosive detonations. The produced seismic waves' amplitude hinges on the energy released during detonation, tied to the employed Blast Design. Multiple factors can lead to excessive detonation-induced vibrations, including improper or oversized Blast Design, low-quality delay accessories usage, drilling, the distance of detonation, water presence, and the local geological conditions.

One critical parameter in the detonation process is the Detonation Velocity (VoD). VoD represents the velocity at which the explosive's chemical reaction propagates. Influenced by factors like the explosive's composition, drilling diameter, explosive density, confinement degree, and initiation, VoD is a key determinant of the explosive's rock-breaking power. As per Garrido (2007), hard rocks require fast explosives for effective fracturing, while softer rocks can be managed with lower detonation velocity explosives to reopen pre-existing discontinuities.

Seismic wave propagation induced by rock blasting

Moments after explosive detonation-induced vibrations, seismic waves propagate through the rock mass, reaching potential receptors like nearby excavations or geotechnical structures. This seismic activity disturbs the rock mass, causing constituent particles to oscillate and transfer energy successively. As energy is lost in each transmission, the wave intensity diminishes as it moves away from the source, and particles gradually return to their rest state.

Seismic wave propagation characteristics change in a heterogeneous medium, introducing a main aspect of seismic wave propagation: spherical spreading. In a theoretical scenario with a homogeneous and isotropic terrain, seismic energy would undergo attenuation solely due to the wave's spherical spreading. This dispersion leads to a rarefication of the initially concentrated energy. Even though the energy remains constant, the expanding propagation area naturally attenuates the wave amplitude, making seismic vibration levels reduce as we move away from the source (Bullen and Bolt, 1985).

Analyses of particle vibration velocities focus on the peak particle velocity, obtained by summing the orthogonal components of particle vibration velocity over a time interval. This sum is known as the Peak Vector Sum (PVS), a measure of maximum vibrational velocity/acceleration. These calculations are important because they provide an understanding of how the rock mass moves elliptically in three dimensions during a detonation, with the peaks of the three perpendicular components (transversal, perpendicular, and vertical) occurring at different times and frequencies. PVS is calculated as the square root of the sum of the squares of these peaks (Dowding, 1985).

$$\mathrm{PVS} = \sqrt{(\mathrm{L}^2 + \mathrm{V}^2 + \mathrm{T}^2)} \qquad \text{Equation 1}$$

The propagation velocity of compressional waves (P-waves), considered primary due to their higher amplitude compared to S-waves, is directly related to the density of the propagation medium (γ), the modulus of elasticity (E), and the bulk modulus (K), which is the ratio between stress and volumetric strain. The velocity of propagation (VP) is also influenced by the rock mass's conditions, including its quality, presence of faults, mass alterations, presence of water, and excavation depth. Each of these factors can affect the wave's natural attenuation (Barton, 2006, 2007).

Rock mass attributes

In reality, seismic wave propagation is influenced by the rock mass's heterogeneous and anisotropic composition, alongside the seismic attenuation effect due to spherical scattering. Direct impacts on seismic behavior emerge from the interaction of geological aspects, ranging from the structural to the geomechanical quality of the mass. Knowledge of rock mass structures is vital, significantly impacting the performance of detonation.

The rock rupture mechanism involves a detonation pressure associated with the shock wave, exceeding the rock's compressive resistance, and leading to a crushing or pulverizing effect. The transferred wave generates tangential forces, creating radial fractures originating from the drilling. The wave propagates and reflects, creating a traction wave that eventually returns to the rock, inducing the formation of initial fissures due to tensile stress.

The concept of Critical Peak Particle Velocity (PPVcrit) is crucial in establishing reference vibration values through geomechanical parameters. This measure helps predict potential damage, linking the PPV of particles to the generation of new fractures via the relationship between particle velocities and dynamic deformation. According to Hooke's Law, the PPVcrit that the rock can endure before a traction failure occurs can be calculated for P Wave using a specific equation.

$$\mathrm{PPV}_{\mathrm{crit}} = \frac{\sigma_{\mathrm{T}} \times \mathrm{V_p}}{\mathrm{E}} \qquad \text{Equation 2}$$

Where,
PPV_{crit} = Vibration capable of generating new fractures (mm/s).
σ_T = Tensile Strength (MPa).
Vp = Propagation Velocity of Rock (m/s)
E = Young's Modulus (GPa)

Following the determination of PPV_crit, it is possible to establish damage criteria that consider the effects on the rock mass. This approach, supported by various studies and prominent researchers in the field, applies PPV-based Damage Criteria. Table 1 below provides a comprehensive overview of the damage criteria selected, defined according to their specific impact on the rock mass.

Table 1 - Damage criteria defined according to the effects on the rock mass

PPV	Influência	Zona
¼ PPVc	Fracture Extension	4
PPVc	Development of New Fractures	3
4 PPVc	Intense Fracturing	2
8 PPVc	Pulverization	1

Methodology

This chapter delineates the methodology deployed to conduct seismographic measurements within an underground polymetallic mine located in Brazil. The central aim of this research was to establish the near-field attenuation curve, a vital tool in understanding seismic activities and their impact within the mine.

To capture accurate and representative data, sacrificial geophones were used as primary data collection tools. These are short-term deployment devices designed to convert ground motion, or velocity, into an electrical signal, or voltage. These geophones were systematically interconnected to an engineering seismograph via a connector box, a setup specifically designed to facilitate the precise measurement of seismic-induced ground movements.

In a bid to gather diverse data, the seismographs and geophones were installed at two distinct sites within the mine. These sites were carefully selected based on their unique geological features and seismic activity levels, which made them perfect for seismic data acquisition. The installation adhered to a standardized protocol, ensuring the reliability and consistency of the data. Of particular note was the positioning of the geophones, a factor considered critical to the accuracy of the data.

Following installation, a series of measurements were conducted to validate the setup's efficiency and precision. These readings, capturing data such as amplitude, frequency, and duration of seismic waves, were meticulously documented and digitally processed in preparation for in-depth analysis.

In summary, the methodology adopted involves the utilization of sacrificial geophones and engineering seismographs in two distinct locations within an underground polymetallic mine in Brazil. The collected data was subsequently analyzed and employed to define the near-field attenuation curve, offering a detailed insight into the ground's response to seismic activities in the area.

Results

Near-Field Vibration Modeling

This chapter delves into the development of a predictive vibration model, centered around data collected from specific blasting sites and the theoretical foundations proposed by Holmberg & Persson (1978). This model's primary function is to simulate vibration propagation behavior close to the blast, influenced by several variables including explosive charge distance, linear concentration, charge geometry, and rock mass characteristics.

Statistical adjustments were made to the gathered data, offering an understanding that 50% of the data falls below and 50% above the modeled curve. However, to ensure practicality, especially for vibration control projects, the attenuation curve was adjusted to a 90% confidence level. This adjustment made the model more reliable and safer for estimating vibrations.

Utilizing data from the entire blasting campaign, which encompassed a total of 73 data points, attenuation curves were drawn considering the maximum charges per delay and distances from the monitored points to the blasting sites. The resultant model provided a good fit to the recorded particle velocities at the mine site, with a correlation coefficient (r^2) of 0.69.

The model's predictive capacity was further enhanced by identifying and removing outlier points. The revised model showed an improved correlation coefficient (r^2) of 0.80, achieved by using 63 data points (Figure 1).

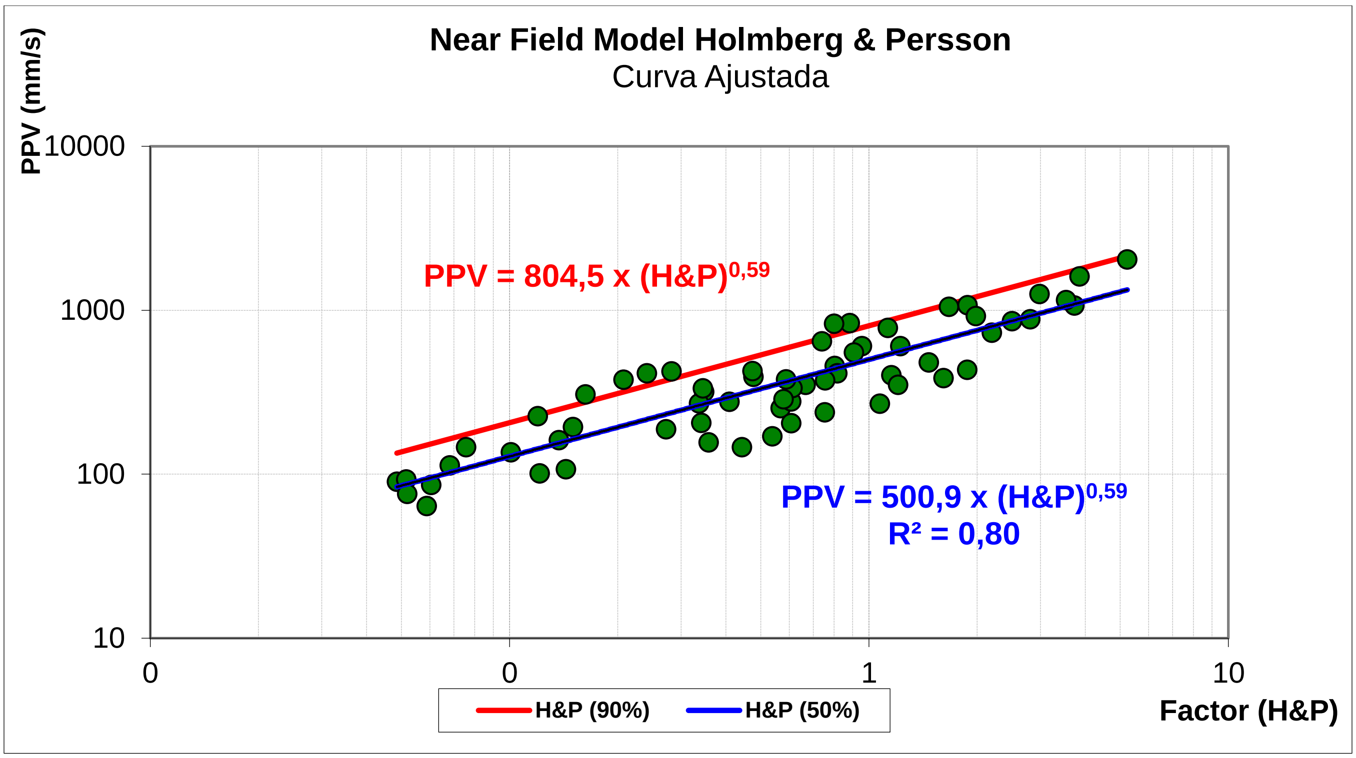

Figure 1 - Adjusted Curve for Near-Field H&P Model.

The adjusted model provides a more reliable and accurate tool for predicting and controlling vibrations generated by blasting operations. It must be noted, however, that continued monitoring is recommended to populate the curve with more data and enhance the reliability of the analysis.

The developed model is a valuable resource for controlling and predicting vibrations from blasting operations. Nevertheless, continual monitoring and model updating are essential to ensure ongoing reliability and applicability.

Velocity of Propagation (VP) Results

Table 2 displays the data related to the identification times of the pulses and the distance between the installed geophones.

Table 2 – Measurement data from VP

ID geophone	Dist. between geophones (m)	Time (s)			Velocity (m/s)
		A Geo 1	A Geo 2	Delta Tempo (ms)	
F1	5,68	0,30450	0,30536	0,00086	**6604**
F2	5,51	0,32672	0,32758	0,00086	**6406**

The velocity of propagation of the wave within the rock mass is the relationship between the time taken by a wave to travel a certain distance within the mass. Using the exact time when the wave passed through two points in the mass and the distance between them, it's possible to calculate the VP for that point in the mass.

Critical Particle Velocity (PPV_crit) Results

Geotechnical information of the lithological units that make up the ZHDT (Hydrothermal Zone) such as mechanical strength, Young's modulus, and P-wave velocity were provided by the Geomechanics team of the mine and are summarized in Table 3 below.

Table 3 - Geomechanical Parameters of ZHDT Lithology

Front	Lithology	Density (Ton/M³)	Q Barton	Depth (m)	UCS (Mpa)	Indirect Tension (MPa)	Young's Modulus (GPa)
AR1_3.3_DA	ZHDT Silica	2,74	2,76	81,72	49	16,9	63
AR2_2.1_BS3_LE1	ZHDT Tremolita	3	3,1	78,1	55	10	47
AR3_2.2_BS1_LE1	ZHDT Sericita	2,79	4,8	102,41	140	13,5	47

Thus, using the H&P damage criterion, Table 4 shows the reference values for each influence range of the damage area.

Table 4 - Damage Criteria Based on Rock Mass Effects

Lithology	PPV	Influence	Zone	PPVc (mm/s)
ZHDT Silica	¼ PPVc	Extension of Fractures	4	436
	PPVc	Development of new Fractures	3	1745
	4 PPVc	Intense Fracturing	2	6980
	8 PPVc	Pulverization	1	13960
ZHDT Tremolita	¼ PPVc	Extension of Fractures	4	346
	PPVc	Development of new Fractures	3	1384
	4 PPVc	Intense Fracturing	2	5536
	8 PPVc	Pulverization	1	11072
ZHDT Sericita	¼ PPVc	Extension of Fractures	4	467
	PPVc	Development of new Fractures	3	1868

	4 PPVc	Intense Fracturing	2	7472
	8 PPVc	Pulverization	1	14944

Abacus Obtained by Iterations through the H&P Model

Based on the measurements made, the adjusted model, and the calculated critical particle velocity restrictions, vibration levels can be estimated based on any combination of explosive charge and distance.

In the case of interest, the ZHDT Silica lithology at the Arex mine were considered, where drill holes are up to 25 meters long and are mined with fan blasting. Curves corresponding to the larger, average, and smaller normal charges of the conducted production drillings were constructed. This abacus can assist in planning projects by demonstrating the relationship between vibration, explosive charge, and the distance of the blasting.

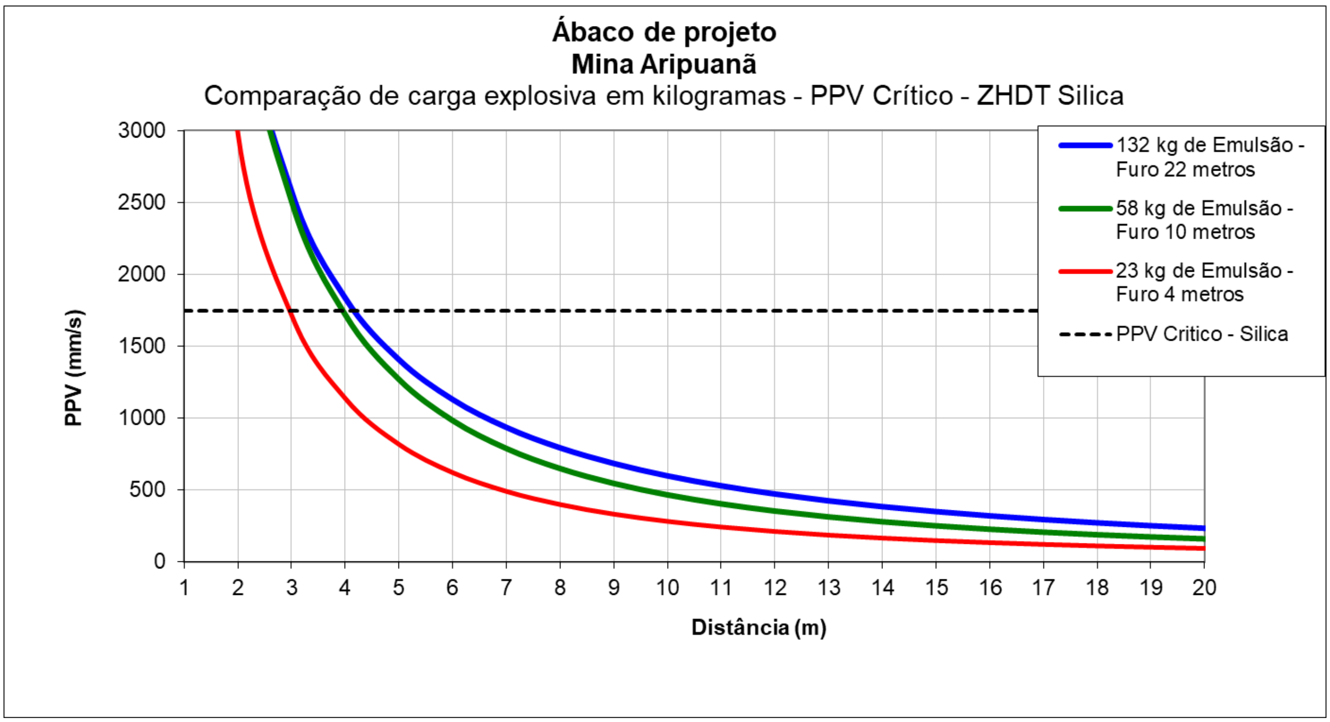

Figure 2 - Abacus of comparison of usual explosive charges with damage limit of the PPVcrit Silica

In the graph of Figure 2 above, it can be observed that the intersection of the PPVcrit curve (Dotted black line, parallel to the abscissa axis) and the blue curve, which corresponds to the linear concentration of the explosive used in the detonation (132 kg / 22 meters), gives us a development of new fractures (1xPPVc) close to 4.1 meters (1745 [mm/s]). This indicates that at distances less than 4.1 meters from the blasted hole, new fractures open in the massif. When compared to smaller holes (23 kg / 04 meters) which are usually closer to the HW, we have a development of new fractures close to 3 meters.

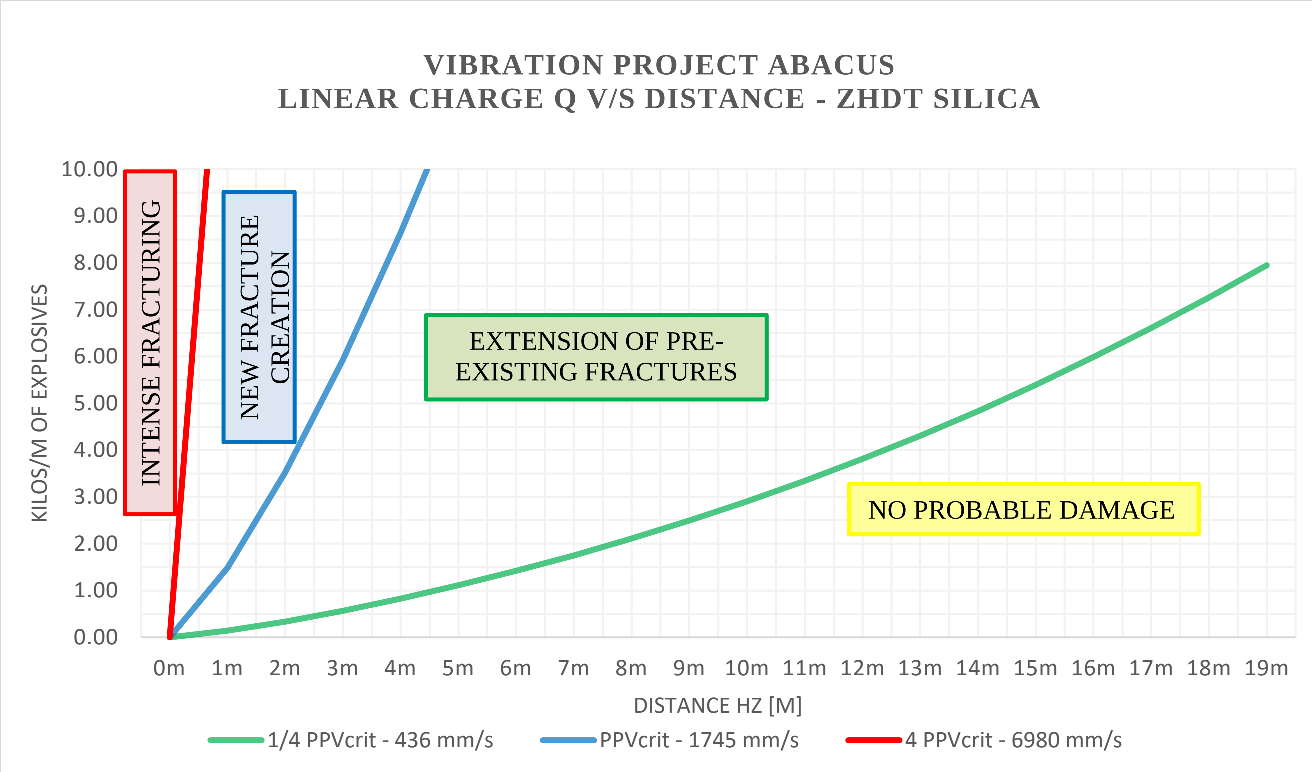

Figure 3 - Abacus of comparison damage limit of the PPV_crit Silica with linear charges

In addition to the distance versus PPV abacus, it is also possible to generate the distance versus linear charge ratio abacus as shown in Figure 3 above. Through this analysis, we can understand the probable damage, according to the critical PPV criterion defined for the ZHDT Silica lithology, considering the amount of explosives per linear meter of drilling and the horizontal distance of this probable damage.

These figures and abacuses offer crucial insights into understanding how varying the explosive charge and its distance impacts the vibration levels and potential damage. They also highlight how these factors are directly linked to the development of new fractures in the rock mass. Using this data, it is possible to make informed decisions when planning and carrying out blasting operations to minimize damage to the rock mass and optimize extraction processes.

Conclusion and Future Work

This comprehensive study focused on the production blasting at the mine. It concentrated on the potential damage to the host rock due to blasting vibrations and the resultant implications for recovery and dilution. Key sectors, namely AR3 N2.2 BS1 LE1 and AR2 N2.1 BS3 LE, offered crucial insights underpinning the analysis.

The research revealed that vibration models effectively predict the level of damage to the surrounding massif associated with specific blasting projects. Laboratory tests and geomechanical data analysis of intact rock allowed the establishment of a theoretical critical particle velocity (PPVcrit) connected with a lithology, thus forming a damage criterion. The use of PPV_crit allows for the classification of damage intensity to the surrounding rock mass. During data processing, certain constants such as wave attenuation and explosive constants are obtained. These values reflect the lithology type of the monitored area, giving insights into the rock mass quality, as well as changes, structures, and overall characterization of the sector.

Recommendations based on the study propose enhancing the Geomechanical information base and its analysis, including structural mapping, massif quality, vibration model, and adjustments. A suggested database should incorporate different designs that vary based on rock type, encompassing specific projects, explosives, plugs, uncoupled charges, etc. It is also advised to focus on the objective evaluation of results to allow for the permanent calibration of blasting projects.

For continuous improvement, incorporating an evaluation of the Drilling and Blasting process is proposed, to establish a permanent correction. This will aim to calibrate operating projects, enhance execution quality, or both. These practices will seek to boost results and ensure tolerances are not exceeded. Finally, these initiatives will enable the assimilation of best practices, customized for the Mine, and guarantee the attainment of expected outcomes in terms of minimizing dilution and damage induced by detonation.

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We sincerely hope that our work contributes to the knowledge base and enhances the practical application of blasting vibration control in underground mining operations.

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