Scientific Research Publishing

Journal of Geoscience and Environment Protection, 2024, 12, 333-347
https://www.scirp.org/journal/gep
ISSN Online: 2327-4344
ISSN Print: 2327-4336

Environmental Protection of a Natural Upland Lake through an Innovative Approach for Determining the Critical Peak Particle Velocity of Surrounding Detonations in Large-Scale Iron Mining

Vidal Félix Navarro Torres[1], Juan Manuel Girao Sotomayor[1], Fabiano Veloso Ferreira[1], Leonardo Chaves[2]

[1]Vale Institute of Technology, Belo Horizonte, Brazil
[2]Vale SA, Canaã dos Carajás, Brazil
Email: vidal.torres@itv.org, juan.sotomayor@itv.org, fabiano.v.ferreira@itv.org, leonardo.s.chaves@vale.com

How to cite this paper: Torres, V. F. N., Sotomayor, J. M. G., Ferreira, F. V., & Chaves, L. (2024). Environmental Protection of a Natural Upland Lake through an Innovative Approach for Determining the Critical Peak Particle Velocity of Surrounding Detonations in Large-Scale Iron Mining. *Journal of Geoscience and Environment Protection, 12,* 333-347.
https://doi.org/10.4236/gep.2024.1212020

Received: November 6, 2024
Accepted: December 27, 2024
Published: December 30, 2024

Copyright © 2024 by author(s) and Scientific Research Publishing Inc.
This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).
http://creativecommons.org/licenses/by/4.0/
Open Access

Abstract

This study presented an innovative approach to determining the acceptable peak particle velocity (PPV) required to ensure the stability of Lagoa do Violão, an upland lake near the mining operations of the S11D project. By combining analysis of the vibrations caused by rock blasting with advanced three-dimensional (3D) geotechnical modeling, the induced accelerations contributing to pseudo-static models were calculated. This methodology enabled the establishment of safe PPV limits, which were crucial for maintaining the structural integrity of the lagoon and its surrounding ecosystem. The findings highlighted the importance of carefully managed blasting practices to maintain geotechnical stability, as the safety factor was significantly influenced by both frequency and PPV. The analysis confirmed that a PPV threshold of 4 mm/s was generally safe near the lake. Accordingly, two specific operational approaches for conducting blasting operations were proposed, considering different drilling diameters, and ensuring compatibility with activities within 500 meters of the lagoon. This research contributed to the practice of sustainable mining by offering evidence-based guidelines for blasting operations near sensitive ecosystems, thereby ensuring both structural safety and environmental conservation.

Keywords

Rock Blasting, Vibrations, Geotechnical Stability, Lake Protection

1. Introduction

Rock blasting using explosives is the most employed method in open-pit mining to release in situ materials. Despite the existence of alternatives (Zhou, Xie, & Feng, 2018), explosive rock blasting has the best cost-benefit ratio. However, the energy efficiency of this technique is low. It is estimated that only 40% of the energy provided by explosives can be effectively used for rock fragmentation (Barros, 2008). The remaining energy causes adverse effects, such as shock waves and ground vibrations (Lawal et al., 2021). Rock blasting with explosives can permanently damage natural and anthropogenic structures. Therefore, quantifying these vibrations can ensure that mining activities are performed within safe operational limits, allowing for the preservation of structures in areas affected by rock blasting (Aladejare, Lawal, & Onifade, 2022).

According to Aladejare, Lawal and Onifade (2022), the most used methods for analyzing ground-induced vibrations are based on obtaining the peak particle velocity (PPV; mm/s) through attenuation characteristics. According to Santos Júnior (2017) and Kalayci & Ozer (2016), the effects on rock masses are difficult to predict, requiring methodological development for each region studied.

Considering the importance of approaches tailored to each region in the monitoring and evaluation of vibrations, the analysis of PPV can be complemented with other analyses that address the behavior of the rock mass. For instance, slope stability analysis is a commonly used tool for evaluating the geotechnical stability of a structure or terrain under various loading conditions (Nilsen, 2000). There are several methods, including static, pseudo-static, dynamic, deterministic, and probabilistic approaches. When considering seismic loading, analytical and numerical pseudo-static methods are commonly employed (Jlilati & Masri, 2022).

The largest mining complex in Brazil, the S11D project by Vale S/A, has various important geological structures within its exploration area, among which Lagoa do Violão is noteworthy. This perennial upland lake is important to the local fauna, whose preservation is mandatory according to the decree of the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA). Thus, the goal is to suggest the maximum permissible vibration for the region of this lagoon through the analysis of vibrations and geotechnical modeling, correlating it with the explosive charge used in rock blasting and ensuring the preservation and geotechnical stability of this structure within a radius of 500 m.

2. Theoretical Framework

During the detonation of an explosive charge for rock blasting, the shock waves generated upon reaching the free face of the bench ruptures the rock due to tension, and the pressure of the gases displaces the dislodged mass (Zhang, 2016). However, a significant portion of the energy from these waves continues to propagate through the surrounding rock mass (Aloui et al., 2016).

The behavior of seismic waves surrounding the detonation point depends on the detonated explosive charge and is conditioned by the lithological, geomechanical, and topographical characteristics of the terrain, with a three-dimensional correlation that is characteristic of each location (Trabi & Bleibinhaus, 2023).

2.1. Peak Particle Velocity

The PPV is the maximum speed a particle can reach during a vibration. This value is measured in millimeters per second (mm/s) and is used to assess the risk of damage induced by ground vibrations. Different standards are set for the peak particle vibration velocity above which ground vibration-induced damage may occur. These limits vary according to the frequency range (Silva, 2012).

The PPV can be measured in three orthogonal directions: the longitudinal, transverse, and vertical directions. The vector sum of these components is called the peak vector sum (PVS), and it corresponds to the maximum vibration at the monitoring point.

2.2. Attenuation Characteristics

The attenuation characteristics describe the mechanism by which the intensity of seismic waves decreases as they propagate through a medium. In the context of blasting, seismic waves are generated by the detonation of an explosive and propagate through the surrounding medium. The intensity of these waves decreases as they move from the detonation point due to the absorption and dispersion of energy by the medium. The magnitude of attenuation depends on several factors, including the distance from the detonation point, the explosive charge used, the lithology of the medium, and the geomechanical characteristics of the terrain. Equation (1) is the most used empirical model according to Aladejare, Lawal, & Onifade (2022).

$$\mathrm{PPV} = a \times \left(\frac{D}{\sqrt{Q}} \right)^{b} \tag{1}$$

where D is the distance from the detonation point to the monitoring point, Q is the maximum explosive charge per delay (the charge detonated simultaneously), and the parameters a and b are coefficients that depend on the propagation medium and are generally determined for each region of interest. The term ($D/\sqrt{Q}$) is referred to as the scaled distance (SD). For this work, a similar model was adopted, without conditioning on the charge per delay (Navarro Torres et al., 2018):

$$\mathrm{PPV} = a \times Q^{b} \times D^{c} \tag{2}$$

where a, b and c are the local conditions determined by multiple linear regression from field data.

2.3. Geotechnical Stability

The geotechnical stability of a structure can be evaluated using the factor of safety (FoS) (Das & Sobhan, 2016). With respect to computational modeling, two methods are widely used to obtain the FoS under various loading conditions: the static method, when there is no seismic influence, and the pseudo-static method, in which seismic effects are represented by an equivalent static force. The magnitude of this force is the product of a seismic coefficient, k, and the weight of a potential sliding mass (Baker et al., 2006). For both methods, the parameters that define the shear strength of the soil, specifically the friction coefficient and cohesion, and the tensile strength of the material are progressively reduced until structural failure is induced.

3. Study Area

Lagoa do Violão is a perennial upland lake, and its preservation is mandatory according to the Brazilian Institute of Environment and Renewable Natural Resources. This lake is on the southern plateau of the Serra dos Carajás, with a surface area of approximately 0.3 km^2, a maximum length from NW to SE of 1.1 km, and a maximum width from NE to SW of 0.46 km.

Bathymetry reveals a water volume of 1.8 million m^3, and water level records from 2012 to 2020 indicate a minimal altitude variation from 724.80 m to 730.0 m. The average depth is 7.4 m, with a cumulative frequency of 35% concentrated between 9 and 10.5 m. Other important information about the morphology, hydrology, geology, and sedimentology of the lake has been described previously (Souza-Filho et al., 2016).

In the studied area, predominant faults occur in the NE-SW and NW-SE directions, forming large blocks of volcanic and iron-rich rocks that influence the position and shape of the lake (**Figure 1**).

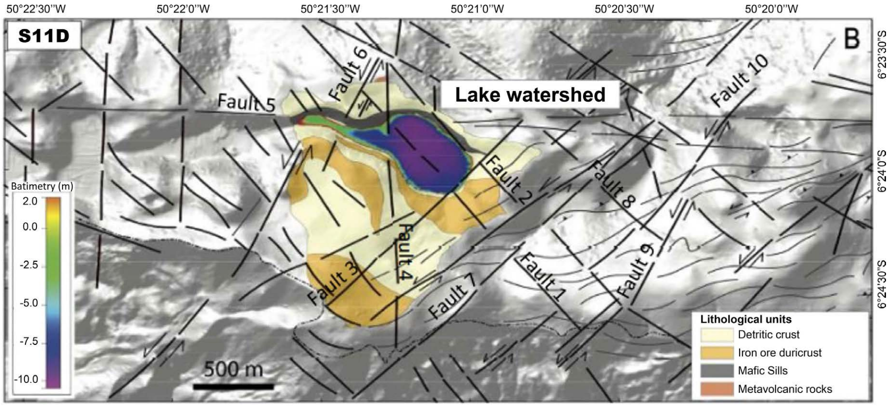

Figure 1. Lithology and tectonics in the region of Lagoa do Violão (Souza-Filho et al., 2016).

The faults are sets of conjugate oblique normal sinistral faults, dipping approximately 60° to 80° toward the SE at the NE border and toward the NE at the SE border. These faults, along with iron formations (hematite, canga, and jaspillite), mafic dikes, and sills, strongly influence the current geometry of the lake.

The basin of Lagoa do Violão features collapse faults, submerged faults, and emerging faults predominantly in the NW direction and on the north and south cliffs of the lagoon, with a NE-NW orientation. Furthermore, collapse faults and vertical fracture faults are predominant in the NE direction on all lateral cliffs of the lake.

4. Methods

The monitoring of vibrations induced by rock blasting in the study area was conducted using three-component seismographs. A total of 165 events were recorded. For each event, the diameters of the drill holes, the explosive charges (kg/delay), the shortest distance to the lake (m), the PVSs (mm/s), the PPVs (mm/s), the frequencies (Hz), the accelerations (g), and the displacements (mm) caused by each event were noted. The flowchart of the methodology used is presented in **Figure 2**.

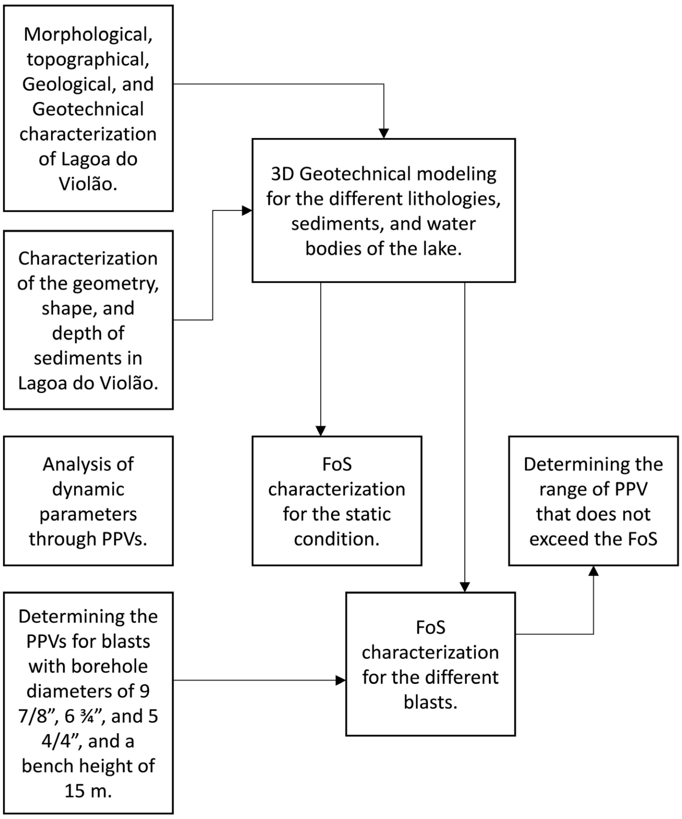

Figure 2. Flowchart of the methodology adopted to determine the permissible critical vibration 500 m from the edge of Lagoa do Violão.

By analyzing the vibration monitoring data, it was possible to determine the PPVs generated by blasting for different drill hole diameters of 9.7/8", 6.3/4", and 5.3/4" and to characterize the PPVs and frequency limits that occur near the Lagoa do Violão.

Using the data from geological, topographic, and bathymetric surveys, three-dimensional (3D) geotechnical modeling was performed, including the lake, its water, and sediments and the lithologies of friable hematite (HF), structural canga (CE), chemical canga (CQ), jaspillite (JP), weathered mafic (MD), and semi-weathered mafic (MSD). With this model, we characterized the FoS under static conditions.

A value of 1.5 was adopted as the minimum acceptable value (ABNT NBR 11682, 2009). Subsequently, we characterized the FoS values under pseudo-static conditions. Herein, we used the determined PPVs to calculate the induced accelerations (Equation (7)). Thus, it was possible to determine the range of PPV within the safety limits of FoS.

4.1. Analysis of the Dynamic Parameters

The PPV was adopted as the dynamic parameter to assess possible damage to the rock mass. The PVS, as a result, had a greater amplitude, and thus, using it could increase the admissibility for individual PPVs, thereby increasing the risk of instability.

a) The trend curve of the PVS with the SD for the 165 events resulted in a coefficient $R^2 = 0.6935$.

b) After adopting a conservative approach, events that showed low PVSs at short distances were removed. Thus, with 145 events and an adjustment $R^2 = 0.8067$ it was obtained the following equation:

$$\mathrm{PPV} = 688.44 \times Q^{0.893} \times D^{-1.785} \tag{3}$$

c) Subsequently, we generated a trend curve that included 95% of the data (**Figure 3**):

$$\mathrm{PPV} = 1744.2 \times Q^{0.866} \times D^{-1.731} \tag{4}$$

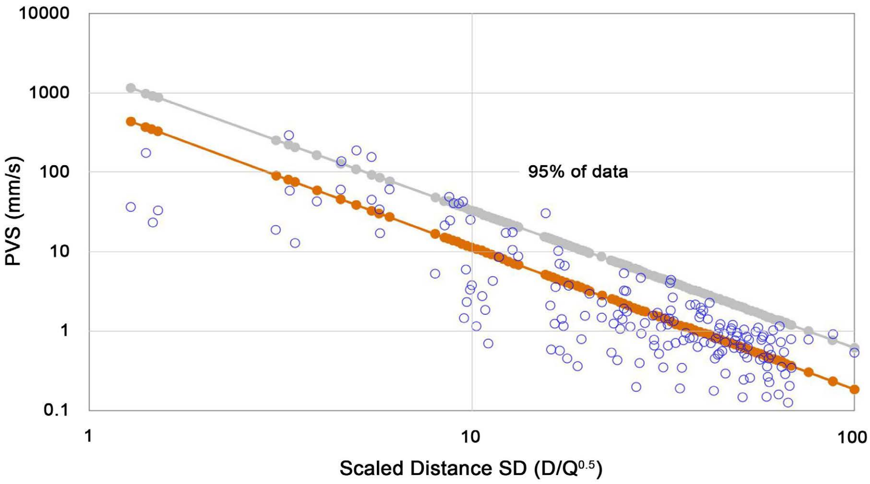

Figure 3. Correlation between the PVS and scaled distance, with $R^2 = 0.81$ and a representativeness of 95%.

d) Correlating the PVS with the PPV, it is observed that, as expected, the PPVl contributes the most to the PVS. Thus, considering a representativeness of 95% of the events and an adjustment, we have $R^2 = 0.9574$, it was obtained:

$$\mathrm{PPVl} = 1415.42 \times Q^{0.866} \times D^{-1.731} - 0.462 \qquad (5)$$

e) From the correlation of the frequencies with the PVS frequencies, it is observed that the frequencies vary from 1.5 to 38.6 Hz (**Figure 4**).

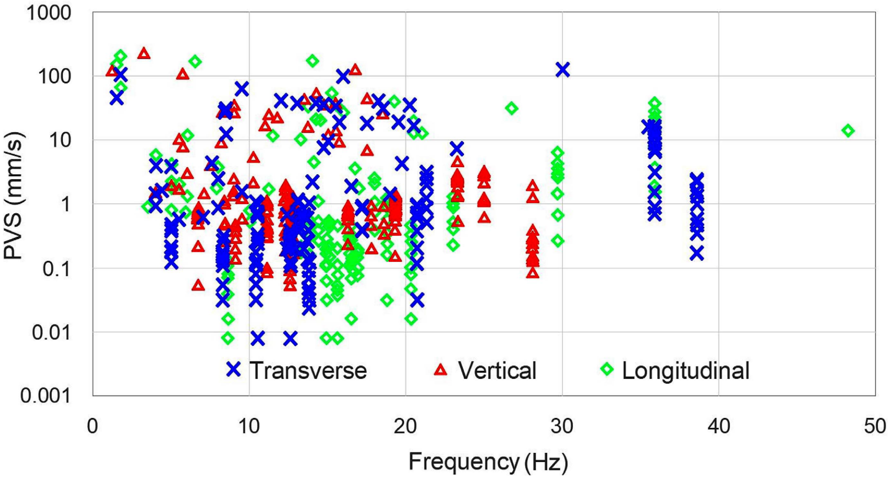

Figure 4. Correlation of PVS's with frequencies for the 165 recorded events.

4.2. Geotechnical 3D Model

To assess the level of risk in Lagoa do Violão due to induced vibrations, a 3D geotechnical model was constructed that incorporated lithologies, faults, sediments, mechanical strength parameters and elastic parameters (**Figure 5**).

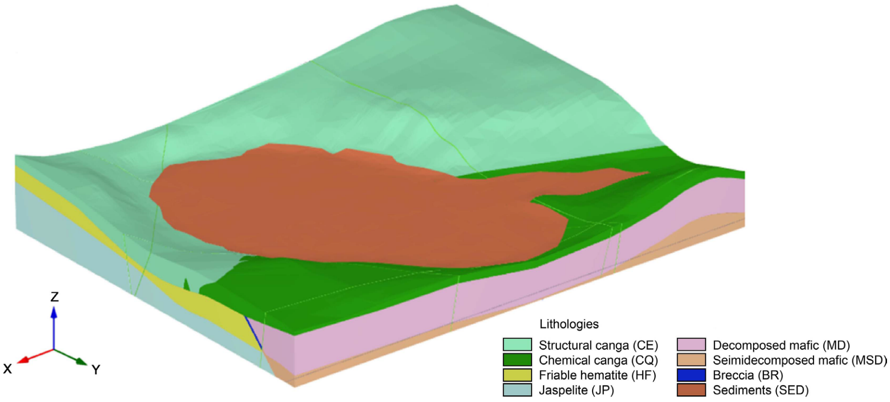

Figure 5. 3D Geological model.

In Plaxis3D, the finite element mesh was created (**Figure 6**), geotechnical properties were assigned, and the water level was inserted. Stability and stress-strain analyses were conducted to evaluate the model under various conditions, and the results were validated to ensure accuracy before considering the model valid and finalizing the development process.

The geotechnical parameters of the sediments, lithologies, and discontinuities are presented in **Table 1**.

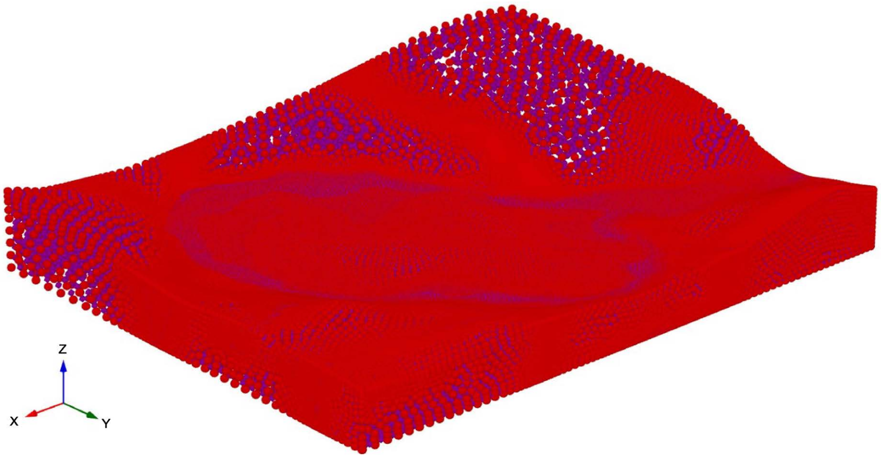

Figure 6. 3D finite element mesh.

Table 1. Geotechnical parameters.

Material	Specific weight (kN/m³)	Cohesion (kN/m²)	Friction angle (°)	σ tension (MPa)	E (GPa)	ν
Sediments (SED)	18	30	10	0	0.005	0.40
Chemical canga (CQ)	26	50	30	2.5	22	0.35
Structural canga (CE)	33	94	37	10	20	0.35
Friable Hematite (HF)	37	60	36	5	15	0.28
Weathered Mafic (MD)	25	78	31	2	15	0.30
Semi-weathered Mafic (MSD)	26	240	32	2.5	17	0.22
Breccia (BR)	37	3750	48	15	60	0.21
Jaspilite (JP)	37	3750	48	15	60	0.21
Faults (F)	19	9	18	0	0.32	0.35

Source: Das and Sobhan (2016).

4.3. Pseudo-Static Method

To determine the acceleration induced by blasting for different frequencies and to assess the geotechnical stability of Lagoa do Violão through the pseudo-static method, we used the recorded particle accelerations:

$$\mathrm{APP} = d \times f \times \mathrm{PPV} \tag{6}$$

where APP is the peak particle acceleration (g), f is the frequency of the seismic wave (Hz), and PPV is the peak particle velocity (mm/s). The parameter d is determined by linear regression from the data recorded on the accelerometers. For our study, we obtained the following equation:

$$\mathrm{APP} = 6.41 \times 10^{-4} \times f \times \mathrm{PPV} \tag{7}$$

5. Results and Discussions

5.1. Geotechnical Safety Factor under Static Conditions

To assess the influence of vibrations, i.e., the accelerations induced by blasting, the criterion was adopted to analyze the FoS under static conditions and to verify the mechanism by which the action of vibrations near the lake reduces this factor through comparison. Without considering the blasting operations, the location with the lowest static stability was found on the west slope (**Figure 7**).

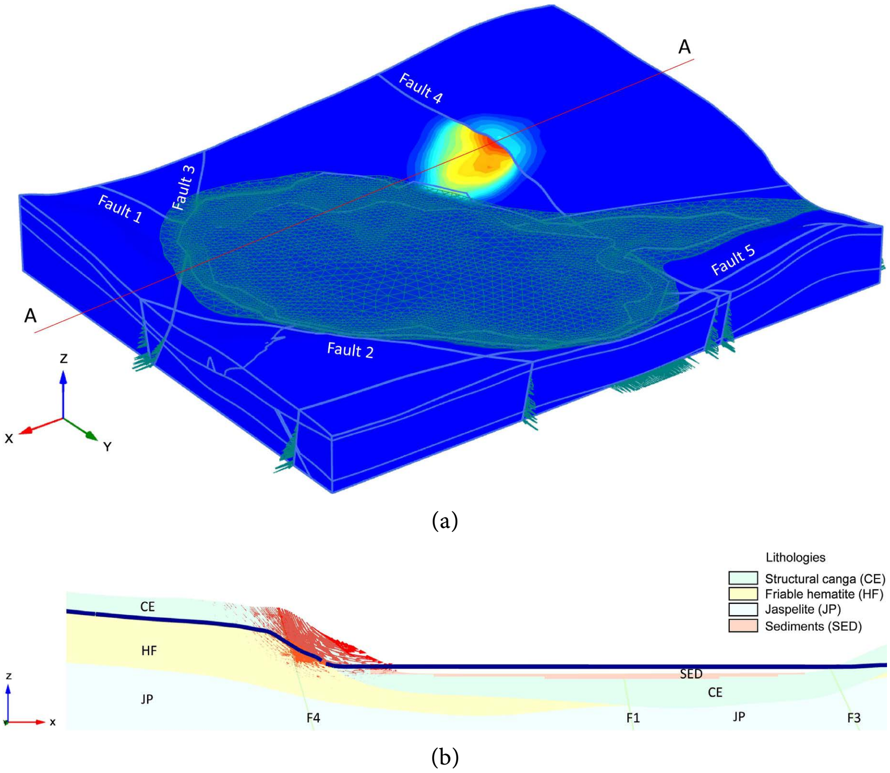

Figure 7. Analysis under static conditions. Minimum registered FoS of 1.877.

This zone of low static stability presented a minimum safety factor of 1.877. This low factor was related to the characteristics of the structural canga, contact with friable hematite, steep geometry of the slope, and presence of geological faults.

5.2. Safety Factor Influenced by Vibrations

To evaluate the influence of vibrations induced by rock blasting, it was assumed that the vibrations at the edge of the lake acted with the same amplitude throughout the basin. Importantly, this criterion corresponded to the poorest conditions for the seismic action of blasts.

The pseudo-static coefficient related to the peak particle accelerations at frequencies of 1.5 and 38.6 Hz was used. For the minimum frequency of 1.5 Hz and a PPV of 1.6 mm/s, an APP of 0.0015 g was calculated. Under these conditions, the minimum observed factor of safety was 1.869, indicating an acceptable margin of stability according to civil engineering and geotechnical criteria. Conversely, by increasing the PPV to 9 mm/s (maintaining a frequency of 1.5 Hz), corresponding to an APP of 0.0087 g, a marginal decrease in the FoS to 1.848 was observed. This result suggested that the FoS was sensitive to increases in PPV, even if the frequency remained constant. For the maximum frequency of 38.6 Hz, with a PPV of 1.6 mm/s (0.0396 g), the obtained FoS was 1.75, showing a reduction in structural stability with increasing frequency. Significantly, with a PPV of 9 mm/s (0.2227 g at the same maximum frequency), the FoS decreased to 1.293, demonstrating a marked negative correlation between vibrational frequency and stability, expressed through the factor of safety.

5.3. Operationalization of Blasting

5.3.1. Recent Blasting

With the relationship described by Equation (5), simulations were performed to predict the behaviors of vibrations in the region of Lagoa do Violão if the same parameters for the blasts conducted in other areas of the mine were used.

According to information from the drilling and blasting area of S11D, the blasting plans for 9.7/8" holes varied depending on the lithology, with an average explosive charge of 495 kg/hole for friable hematites, 690 kg/hole for structural canga, and 768 kg/hole for jaspillites. The 6.3/4" and 5.3/4" holes presented average charges of 462 kg/hole and 260 kg/hole, respectively, for all lithologies.

According to the hypothesis of blasting with 9.7/8" holes with normal charges, PPVl values between 6.0 and 9.0 mm/s were estimated at distances of 500 m from the lake (**Figure 8**), exceeding the safety limit presented in **Table 2**. At 100 m, the behavior was very critical, with PPVls between 105 and 154 mm/s.

Table 2. Safety factors obtained for induced accelerations (L-W direction).

PPV (mm/s)	Frequency (Hz)	Acceleration (g)	FoS	Frequency (Hz)	Acceleration (g)	FoS
1.6	1.5	0.0015	1.869	38.6	0.0396	1.751
2		0.001	1.871		0.0495	1.725
3		0.0029	1.870		0.0742	1.653
4		0.0038	1.86		0.0990	1.579
5		0.0048	1.866		0.1237	1.515
6		0.005	1.866		0.1485	1.451
7		0.0067	1.859		0.1732	1.389
8		0.0077	1.856		0.1979	1.354
9		0.0087	1.848		0.2227	1.293

When using an air deck and/or gasbag, with the explosive charge reduced by half, PPVls between 3.1 and 4.7 mm/s were estimated to 500 m. At 100 m, PPVls between 57 and 84 mm/s could be estimated.

Other hypotheses analyzed were for the 6.3/4" and 5.3/4" holes, the normal charge and the reduced charge (with the use of an air deck and/or gasbag) without variation due to lithology (**Figure 8**).

For 6.3/4" holes, PPVls were estimated between 2.9 and 5.7 mm/s at 500 m and between 54 and 99 mm/s at 100 m. For 5.3/4" holes, the estimate at 500 m was that

PPVls would be between 1.6 and 3.3 mm/s (**Figure 9**). At a distance of 100 m, PPVls would be between 33 and 60 mm/s.

These results highlighted the sensitivity of vibrations as a function of the distance to the detonation point. Furthermore, the findings reinforced the importance of this work for the practice of sustainable mining, showing that the application of usual blasting techniques surrounding Lagoa do Violão generated unsafe conditions for environmental preservation.

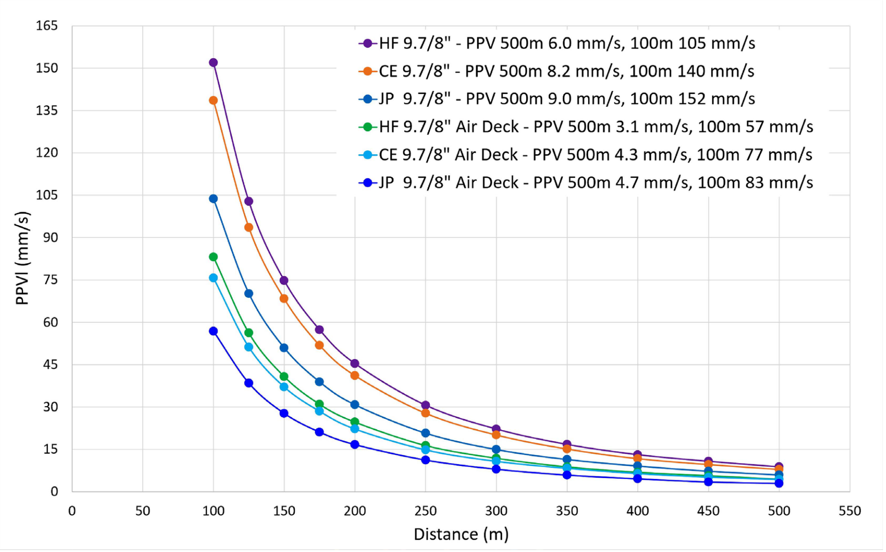

Figure 8. Estimation of PPVs for 9.7/8" boreholes with normal and reduced charge for distances between 100 and 500 m.

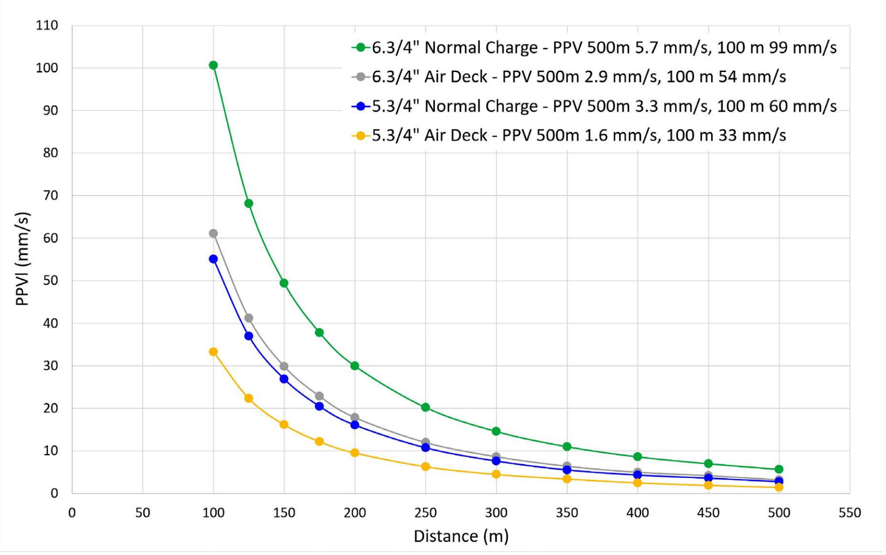

Figure 9. Estimation of PPVs for 6.3/4" and 5.3/4" boreholes with normal and reduced charge for distances between 100 m and 500 m.

5.3.2. Suggestions for Blasting in the Lagoa do Violão Area

Assuming a maximum PPVl between 4 and 5 mm/s, we calculated the maximum charge per delay (Equation (5)):

$$Q_{\max} = 0.0016 \times D^{1.9988}, \text{ for PPVl} = 4 \text{ mm/s} \tag{8}$$

$$Q_{\max} = 0.0013 \times D^{1.9988}, \text{ for PPVl} = 5 \text{ mm/s} \tag{9}$$

Based on Equations (8) and (9) and considering distances greater than 500 m from the edge of the lake, we suggested two alternatives:

a) For the distances indicated in **Table 3**, drilling and blasting performed with hole diameters of 9.7/8" and bench heights of 15 m. Fractionated charges with an air deck at distances close to 500 m with 248 kg for HF, 345 kg for CE, and 384 kg for JP. Normal charges of 495 kg for HF, 690 kg for CE, and 768 kg for JP for greater distances.

b) For the distances indicated in **Table 4**, normal charge of 260 kg for HF, CE, and JP in 5.3/4" diameter holes at distances approaching 500 m. For 6.3/4" diameter holes, normal charges of 462 kg for CE and JP. For 9.7/8" diameter holes, normal charges of 495 kg for HF, 690 kg for CE, and 768 kg for JP at great distances from the lake.

In our analyses, we considered distances measured on the surface, which represent minimum values. The values tended to increase as open-pit mining operations near Lagoa do Violão expanded. We used pseudo-static models considering that the vibrations at the edge of the lake acted uniformly across its entire length. Although this approach did not consider the attenuation of vibrations along the lake, we adopted a conservative principle in our analysis. Thus, the proposed recommendations ensured that the induced vibrations remained within a range considered safe for the complete preservation of Lagoa do Violão.

Table 3. Suggestion for blasting with a hole diameter of 9.7/8" and a bench height of 15 m at distances greater than 500 m and PPVls of 4 and 5 mm/s.

D (m)	HF		CE		JP	
	4 mm/s	5 mm/s	4 mm/s	5 mm/s	4 mm/s	5 mm/s
	Q (kg/delay)		Q (kg/delay)		Q (kg/delay)	
500	321	405	321	405	321	405
525	354	447	354	447	354	447
550	388	490	388	490	388	490
552.5	392	495	392	495	392	495
575	424	536	424	536	424	536
600	462	583	462	583	462	583
621	495	625	495	625	495	625
625	501	633	501	633	501	633
650	542	685	542	685	542	685
652.5	546	690	546	690	546	690
674	583	736	583	736	583	736

Continued

689	609	769	609	769	609	769
700	629	794	629	794	629	794
725	674	852	674	852	674	852
733.5	690	872	690	872	690	872
750	722	911	722	911	722	911
774	768	971	768	971	768	971
775	770	973	770	973	770	973
800	821	1037	821	1037	821	1037

🟨 Fractional charge with an air deck; 🟩 Normal charge.

Table 4. Suggestion for blasting with normal charges, for holes with diameters of 9.7/8", 6.3/4", and 5.3/4" and bench heights of 15 m at distances greater than 500 m and PPVls of 4 and 5 mm/s.

D (m)	HF		CE		JP	
	4 mm/s	5 mm/s	4 mm/s	5 mm/s	4 mm/s	5 mm/s
	Q (kg/delay)		Q (kg/delay)		Q (kg/delay)	
500	321	405	321	405	321	405
525	354	447	354	447	354	447
534	366	462	366	462	366	462
550	388	490	388	490	388	490
552.5	392	495	392	495	392	495
575	424	536	424	536	424	536
600	462	583	462	583	462	583
621	495	625	495	625	495	625
625	501	633	501	633	501	633
650	542	685	542	685	542	685
652.5	546	690	546	690	546	690
674	583	736	583	736	583	736
688.5	608	768	608	768	608	768
700	629	794	629	794	629	794
725	674	852	674	852	674	852
733.5	690	872	690	872	690	872
750	722	911	722	911	722	911
774	768	971	768	971	768	971
775	770	973	770	973	770	973
800	821	1037	821	1037	821	1037

🟦 Normal charge for 5.3/4"; 🟨 Normal charge for 6.3/4"; 🟩 Normal charge for 9.7/8".

6. Conclusion

This study provided insights into the safety limits of the PPV necessary to maintain the geotechnical stability of Lagoa do Violão. Through the application of 3D geotechnical modeling and detailed vibration analyses, it was established that a PPV reaching 4 mm/s was considered safe for all analyzed lithologies, minimizing the risk of harmful displacements and preserving the structure of the lake and its ecosystem. Furthermore, this work proposed operational methodologies to execute blasting, considering different drilling diameters and distances in relation to the lake, to mitigate adverse impacts.

The results of this study highlighted the importance of monitoring PPVs and adapting blasting practices in accordance with the specific characteristics of each region to protect sensitive structures. The sensitivity of the FoS to variations in the PPV and frequency values of induced vibrations reinforced the need for a careful and well-founded approach for conducting blasting operations near these structures.

This work contributed significantly to the practice of responsible and sustainable mining, providing evidence-based guidelines for the safety of rock blasting activities. The recommendations presented could ensure that mining operations complied with regulatory requirements and with the commitments to environmental preservation and the protection of natural heritage.

Finally, we recognized the need for future research to explore the behavior of Lagoa do Violão at distances shorter than 500 m from blasting operations, expanding the mining activities in the region. Other monitoring methodologies and data processing methods, including dynamic analyses that could provide increasingly precise responses to the presented conditions, could be explored. The continuation of studies in this area would allow for the continuous improvement in mining practices, aiming for a balance between resource exploitation and environmental conservation.

Acknowledgements

The authors would like to thank the Vale Institute of Technology for supporting this research. The authors would also like to acknowledge Vale S.A. for providing the necessary data.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

ABNT NBR 11682 (2009). *Estabilidade de encostas. Norma brasileira de procedimento* (33 p.).

Aladejare, A. E., Lawal, A. I., & Onifade, M. (2022). Predicting the Peak Particle Velocity from Rock Blasting Operations Using Bayesian Approach. *Acta Geophysica, 70,* 581-591. https://doi.org/10.1007/s11600-022-00727-5

Aloui, M., Bleuzen, Y., Essefi, E., & Abbes, C. (2016). Ground Vibrations and Air Blast Effects Induced by Blasting in Open Pit Mines: Case of Metlaoui Mining Basin, Southwestern Tunisia. *Journal of Geology & Geophysics, 5,* 8. https://doi.org/10.4172/2381-8719.1000247

Baker, R., Shukha, R., Operstein, V., & Frydman, S. (2006). Stability Charts for Pseudo-Static Slope Stability Analysis. *Soil Dynamics and Earthquake Engineering, 26,* 813-823. https://doi.org/10.1016/j.soildyn.2006.01.023

Barros, M. L. (2008). *Modelo de aferição da velocidade de partículas através de parâmetro energético*. Ph.D. Thesis, Universidad Federal de Pernambuco. https://repositorio.ufpe.br/handle/123456789/5046>

Das, B. M., & Sobhan, K. (2016). *Principles of Geotechnical Engineering* (9th ed.). Cengage Learning.

Jlilati, M. N., & Masri, H. (2022). Slope Stability Analysis under Seismic Loads (Comparative between Numerical and Traditional Pseudo-Static Methods). *Proceedings of International Structural Engineering and Construction, 9,* GFE-02-1. https://doi.org/10.14455/isec.2022.9(1).gfe-02

Kalayci, U., & Ozer, U. (2016). Selection of Site Specific Vibration Equation by Using Analytic Hierarchy Process in a Quarry. *Environmental Impact Assessment Review, 56,* 50-59. https://doi.org/10.1016/j.eiar.2015.09.004

Lawal, A. I., Olajuyi, S. I., Kwon, S., Aladejare, A. E., & Edo, T. M. (2021). Prediction of Blast-Induced Ground Vibration Using GPR and Blast-Design Parameters Optimization Based on Novel Grey-Wolf Optimization Algorithm. *Acta Geophysica, 69,* 1313-1324. https://doi.org/10.1007/s11600-021-00607-4

Navarro Torres, V. F., Silveira, L. G. C., Lopes, P. F. T., & de Lima, H. M. (2018). Assessing and Controlling of Bench Blasting-Induced Vibrations to Minimize Impacts to a Neighboring Community. *Journal of Cleaner Production, 187,* 514-524. https://doi.org/10.1016/j.jclepro.2018.03.210

Nilsen, B. (2000). New Trends in Rock Slope Stability Analyses. *Bulletin of Engineering Geology and the Environment, 58,* 173-178. https://doi.org/10.1007/s100640050072

Santos Júnior, E. J. (2017). *Modelagem estocástica aplicada na estimativa do raio de proteção de cavidades naturais subterrâneas*. M.Sc. Thesis, Universidade Federal de Ouro Preto. https://www.repositorio.ufop.br/items/b38fda52-9409-4116-afe8-1f90f311822e

Silva, T. (2012). *Avaliação da carga máxima por espera através de lei de atenuação visando à minimização de danos decorrentes das operações de desmonte de rochas nas escavações da Arena Pernambuco*. MSc. Thesis, Universidade Federal de Pernambuco. https://repositorio.ufpe.br/handle/123456789/5206

Souza-Filho, P. W. M., Guimarães, J. T. F., Silva, M. S., Costa, F. R., Sahoo, P. K., Maurity, C. W. et al. (2016). Basin Morphology, Sedimentology and Seismic Stratigraphy of an Upland Lake from Serra Dos Carajás, Southeastern Amazon, Brazil. *Boletim do Museu Paraense Emílio Goeldi—Ciências Naturais, 11,* 71-83. https://doi.org/10.46357/bcnaturais.v11i1.461

Trabi, B., & Bleibinhaus, F. (2023). Blast Vibration Prediction. *Geophysical Prospecting, 71,* 1312-1324. https://doi.org/10.1111/1365-2478.13361

Zhang, Z. (2016). *Rock Fracture and Blasting: Theory and Applications*. Butterworth-Heinemann. https://doi.org/10.1016/C2014-0-01408-6

Zhou, H., Xie, X., & Feng, Y. (2018). Rock Breaking Methods to Replace Blasting. *IOP Conference Series: Materials Science and Engineering, 322,* Article ID: 022014. https://doi.org/10.1088/1757-899x/322/2/022014