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Blast-induced vibration assessment in the Rouina open-pit mine: Impacts and measurements for the Ouled Mellouk Dam

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Abstract

Purpose. This paper aims to investigate the characteristics of blast-induced vibrations in Algeria's Rouina open-pit mine and their potential impact on nearby infrastructure, specifically the Ouled Mellouk Dam, located downstream. The research seeks to understand the propagation patterns of these vibrations and assess their environmental and structural consequences, with a focus on risk mitigation strategies for infrastructure protection.

Methods. The research was carried out through experimental explosion tests at Rouina mine. Advanced tools such as ETNA-type accelerographs and seismographs with highly sensitive triaxial LE-3Dlite sensors and a K2 digitizer were utilized to measure the induced vibrations. Various parameters related to the fragmentation process were adjusted to analyze their effect on vibration characteristics. The damping coefficient of the rock mass was calculated using Chapot's law, and potential impacts on water discharge were also examined.

Findings. The results indicate that the blast-induced vibrations have significant effects on vibration propagation, posing potential risks to nearby infrastructure. The research has also determined the rock mass's damping coefficient, which serves to explain the behavior of vibration damping. The findings show that the implementation of optimized blasting plans can effectively control vibration levels and mitigate risks to structures such as the Ouled Mellouk Dam.

Originality. This research provides new insights into the behavior of blast-induced vibrations in open-pit mining, especially when in proximity to critical infrastructure. The innovative use of advanced instrumentation and the application of Chapot's law for vibration analysis emphasize the originality of the research.

Practical implications. The research offers practical recommendations for managing blast-induced vibrations in mining operations near sensitive infrastructure, facilitating the development of improved safety protocols and environmental management strategies.

Keywords: *vibration propagation, discharge rate design, Chapot's Law Analysis, damping coefficient, structural impacts, environmental effect*

1. Introduction

Mining activities pose significant environmental threats, impacting air quality, water resources, soil integrity, and biodiversity [1]. Despite these concerns, the mining sector is essential for providing energy and raw materials critical to various industries [2]. The increasing global demand for blasts, driven by mining and construction needs, underscores their economic importance [3].

Blasting operations in open-pit mining facilitate efficient mineral extraction but generate significant ground vibrations, affecting nearby infrastructure and ecosystems [4]. These vibrations can damage critical infrastructure like dams, buildings, and transportation networks, posing safety risks [5]. Traditionally, rock blasting operations relied on empirical knowledge aimed at efficient rock fragmentation [6]. However, the complex dynamics of blast-induced vibrations were often neglected, leading to potential environmental and infrastructural risks.

The growth of human settlements near mining sites and stricter environmental regulations necessitate scientific methods to mitigate blast-induced vibrations [7]. Extensive research has emerged, focusing on the environmental impacts of mining, particularly vibrations from blasting operations [8]. Studies have examined factors influencing vibration propagation and damping, such as geological conditions and charge characteristics, to develop strategies for minimizing adverse effects [9].

Assessing blast-induced vibrations is crucial in industries like mining, construction, and infrastructure development, involving parameters such as Peak Particle Velocity (PPV), peak vector sum, and frequency. Frequency is vital in understanding the impact of vibrations on structural integrity [10]. Human sensitivity to vibrations also depends on factors like PPV, vibration frequency, event duration, and frequency, influencing discomfort levels [11].

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Ground vibrations result from the combined effects of compression waves (P-wave), shear waves (S-wave), and Rayleigh waves (R-wave), each propagating at different velocities [12]. Researchers have explored methodologies to mitigate these effects, including multivariate analysis, empirical laws, and artificial neural networks [13], [14]. Advanced modelling techniques like fuzzy logic have shown robust predictive potential for PPV [15].

Empirical models have been developed to predict blast-induced vibrations, considering factors like geological conditions and structural attributes [16]. Despite advancements, predicting ground vibration levels remains complex, requiring computational expertise, especially in large-scale mining operations near human settlements [17].

Constructing iso-value maps for visualizing shock wave propagation through ground and air has received limited academic attention due to logistical challenges [18]. Geosonics Inc. [19] introduced "iso-seismic mapping" using multiple seismographs to understand geological factors contributing to structural damage and human discomfort. Iso-seismic maps are created using interpolation techniques like kriging to predict and visualize contour maps from seismograph data points [20].

In regions with extensive open-pit mining, such as the Quadrilátero Ferrífero in Brazil, blast-induced vibrations are a recurrent issue [21]. This study aims to minimize these vibrations and presents a robust methodology for their assessment and control, focusing on an iron ore mine near a populated community. This research highlights the benefits of blockometric distributions for delineating and understanding fracture patterns in fissured rock formations [22]. Blockometric analysis quantifies discrete rock blocks defined by discontinuities, offering insights into the mechanical behavior and stability of rock masses [23].

2. Study area

The Rouina iron deposit covers 436 hectares between 394300 to 390900 E Longitude and 4005400 to 4007700 N latitudes (UTM 31N WGS 84), situated along national road RN4 and 3 km from the railway line (Fig. 1). The region has rugged mountain ranges forming the autochthonous Wadi Chelif structural zone, with valleys and watercourses inclu-ding Wadi Chelif and Rouina. The climate is sub-Mediterranean, with mild, rainy winters and arid summers, temperatures ranging from 7°C in January to 36°C in summer. Nearby settlements include Rouina city (3 km), Ain Defla (17 km), Khemis Miliana (43 km), and Chlef (46 km), where agriculture and livestock farming are primary industries. Local carbonate outcrops are used for producing construction materials.

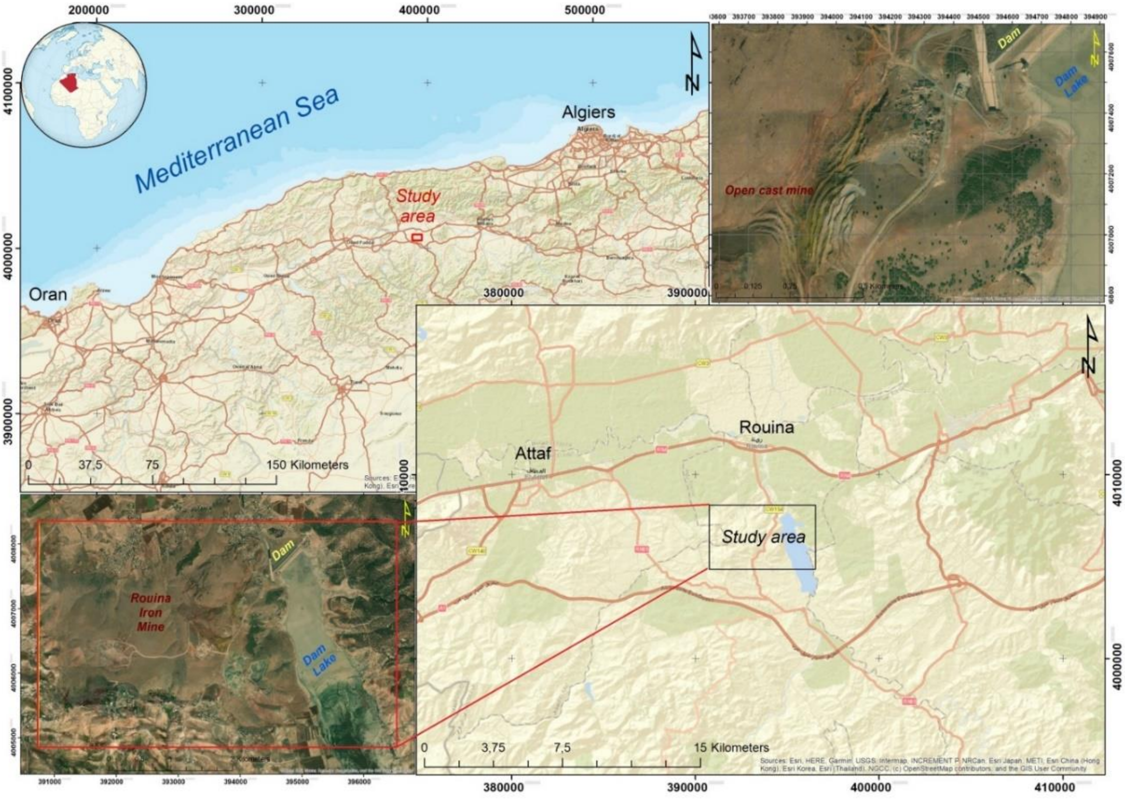


Figure 1. Geographic location of the Rouina iron mine

Geologically, the deposit is part of the Rouina rocky mass, formed after the Alpine orogeny at the borders of a mega-geosyncline. The mass is presented as a 30-40° NE-trending anticline among the Chelif valley's alluvial deposits [24] (Fig. 2). The flanks are composed of Mesozoic carbonate terrains, with the core containing Paleozoic formations. The Rouina mass includes schist-sandstone and conglomerate series of the Paleozoic, Jurassic carbonate beds, Lower Cretaceous marls, and basal conglomerate, indicating a unique geological history without Triassic formations. The iron mineralization originated during the Triassic and Middle Jurassic (Lias) periods as a result of a hydrosomatic process. The Ouled Mellouk Dam on the Rouina river controls a watershed of approximately 876 km², with an average elevation of 480 m and a highest point of 1786 m at the top of Jebel Meddad.

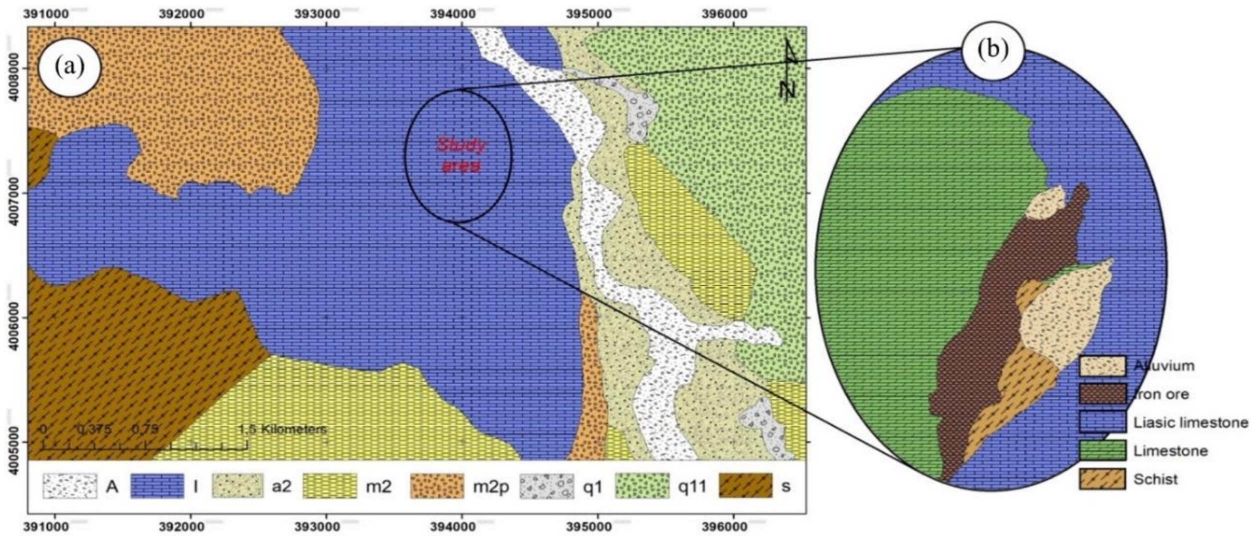


Figure 2. small scale lithologic map (1/50000) of the study area digitized from geologic map of El Abadia (Carnot N° 83) (a); large scale facies map (1/2000) of the mine (b)

The average annual precipitation is 461 mm/year, with an annual liquid input of 45 million m³ and a runoff depth of 51 mm. The solid input reservoir is estimated at 1150 m³/year/km², resulting in a dead volume of about 40% of its total capacity. Evaporation loss is estimated at 1325 mm/year [25] (Fig. 3).

Figure 3. Panoramic view of the Ouled Mellouk Dam

3. Materials and methods

To calculate the damping coefficient (ξ) of the rock mass relative to vibrations, the Chapot's law is used, which is expressed by the Equation (1):

$$(\xi)=\left[\frac{V}{Q_i \cdot D}\right], \tag{1}$$

where:

V – the weighted maximum speed, mm/s;

D – the distance between the explosive shot and the sensor location in meters, m;

Q_i – the instantaneous explosive charge, kg.

This analytical approach enabled us to gain valuable insights into the rock mass behavior in response to induced vibrations and their potential impact on nearby structures [26], [27].

The study utilized ETNA-type accelerographs and K2 seismographs equipped with highly sensitive triaxial LE-3Dlite sensors and a K2 digitizer, which were chosen for their advanced digital capabilities, eliminating the need for preliminary data processing [28]. Both devices have the same specifications, including a natural frequency of 0.1 Hz, critical damping of 0.707, and 64 MB of memory for data storage. Sensors were calibrated for STA/LTA triggering to prevent saturation and aligned with the directions of blast events (Fig. 4).

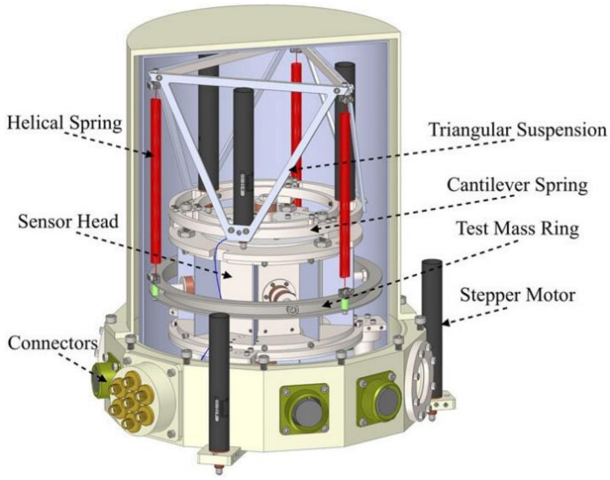


Figure 4. Seismometer sensor head, architecture [29]

ETNA accelerometers, calibrated to detect a minimum trigger threshold of 1/1000th of gravitational acceleration (g), were strategically oriented for accurate data capture. The digital recording format enhanced data usability. K2 seismographs, with high-precision triaxial sensors, measured ground motion in three orthogonal directions at a sampling rate of 1024 samples per second, ensuring a wide frequency bandwidth and capturing high-frequency components. With a dynamic range of 130 dB, they accurately measured low- and high-amplitude vibrations. Data processing involved advanced signal analysis techniques like Fourier transforms and time-frequency analysis.

Combining data from ETNA accelerographs and K2 seismographs allowed for a comprehensive analysis of blast-induced vibrations. This integrated approach provided insights into peak particle velocities, dominant frequencies, and patterns of damping across various distances from the blast sites. These findings were compared with established mining and blasting guidelines to assess potential impacts on nearby structures and infrastructure.

Following a comprehensive assessment of instrument functionality, we conducted a series of blast experiments in two phases at the Rouina iron mine. Each phase involved a total explosive charge of 250 kg, with an instantaneous charge of 20 kg. All recorded events at designated stations for both phases were thoroughly documented, excluding stations 4 and 5. Station 3 was excluded from the recording process during Phase 2.

Accurate vibration measurements were conducted at critical locations, including nearby residential areas and fragile structures, during two shooting sessions at the study site. To capture the vibration data, five ETNA digital triaxial acelerographs and two K2 digital seismographs were installed at seven carefully selected stations (Fig. 5).

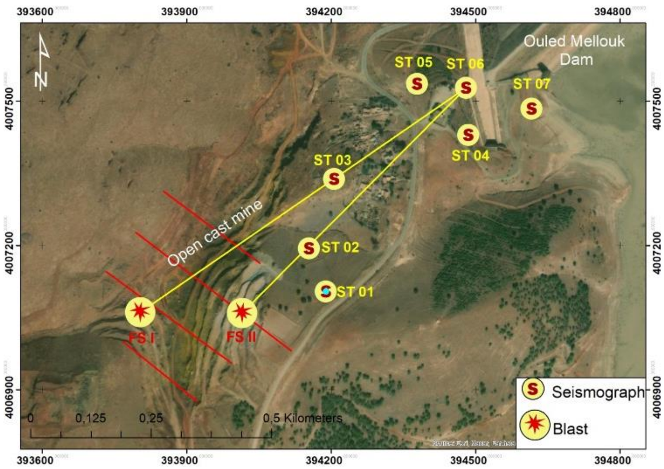


Figure 5. Position of shot sources and acquisition devices in the field

The comprehensive analysis of blast-induced vibrations, using advanced instrumentation, provided valuable insights into the dynamics of ground vibrations during mining operations. The strategic orientation and sensitivity of the acelerographs and seismographs ensured accurate data capture, allowing for a detailed assessment of vibration characteristics. The use of Chapot's law to calculate the damping coefficient has contributed to understanding of how vibrations propagate through geological formations, which is crucial for assessing the potential impact of blasting operations on nearby structures and environment. These findings have significant implications for mining operations near human settlements and critical infrastructure, emphasizing the need for effective mitigation measures to ensure environmental and structural safety.

This study represents a significant advancement in the scientific exploration of blast-induced vibrations in mining operations. The advanced instrumentation and analytical methods employed provide a solid foundation for further research in this field, with the ultimate goal of minimizing the adverse effects of mining-induced vibrations on both the environment and human infrastructure. The initiation sequences play a crucial role in managing in managing wave propagation from blasting and excavation activities. Proper initiation system design, including the positioning of micro-delays, significantly impacts the direction of blast lines. High-quality fragmentation and effective control of wave dissipation are directly related to successful blasting results, as measured values below 2 mm/s support the mine expansion project.

The use of Chapot's law has certain limitations and assumptions, such as uniform vibration energy attenuation, constant damping over distances, linear behavior of the rock mass, and exclusion of energy lost to air or structure transmission. Accurate particle velocity and blast energy measurements are crucial for reliable results, and the law may not be valid for very large or small-scale blasts. The results are applicable only to the specific rock mass studied, and damping tends to be overestimated for near-field measurements and underestimated for far-field measurements.

Timing of detonations is crucial to reduce vibrations and enable the successive release of blast rows. Fine-tuning delays with electronic detonators is hindered by uncertainty in dynamic fragmentation mechanisms. The scientific community is divided on the merits of controlling delay times to the millisecond level, and the experience of the blasting supervisor often takes precedence over theoretical knowledge. Recommended delay time between successive rows in a blast pattern should be within the range of 1.5 to 3.0 Tmin, with Tmin being the minimum delay time. The delay between holes within the same row should be around Tmin or slightly lower.

The control of drilling, rock face geometry, and geostructural conditions play a decisive role in the successful outcome of the blasting operation. This reinforces the importance of systematic instrumentation and monitoring of the blasting process, which is a legal requirement in certain jurisdictions. The recommended delay time ranges optimize rock mass fragmentation and displacement while minimizing vibration-related issues, although the scientific consensus on the precise benefits of these settings remains unclear.

The accelerometers were carefully calibrated to detect a minimum trigger threshold. The LE-3Dlite sensors have a sensitivity of 400 V/g, allowing for accurate measurement of minute ground vibrations, which is crucial for capturing the nuances of blast fragmentation.

The K2 digitizer employed in the instrumentation setup provided a high sampling rate of 200 samples per second, ensuring temporal resolution sufficient to analyze the dynamic behavior of rock fragmentation. Additionally, the 16-bit resolution of the digitizer enabled capturing a wide range of signal amplitudes, from the smallest vibrations to the most intense ground motion. We conducted two test shots, varying a few key parameters to investigate the impact on the blast fragmentation process. The experimental approach was aimed at bridging the gap between theoretical models and practical applications, providing valuable insights for optimizing mining rock fragmentation techniques.

The sampling interval (Δt) was established at 0.004 seconds, enabling a high-frequency capture rate of 250 recordings per second, facilitating the acquisition of high-frequency components induced by blast events. The longitudinal accelerometer was precisely aligned with the longitudinal direction of the blast event, the transverse accelerometer with the transverse direction, and a vertical accelerometer was employed to capture the full three-dimensional vibration response.

A series of blast experiments were conducted in two phases, each involving a total explosive charge of 250 kg with an instantaneous charge of 20 kg. Recorded events were thoroughly documented at the seven designated stations, except for stations 4 and 5, with station 3 being excluded during Phase 2. Vibration measurements were obtained at strategically selected critical points, including nearby residential areas and fragile structures, using five ETNA digital triaxial accelerographs and two K2 digital seismographs installed at seven stations.

4. Results and discussion

4.1. Ground vibration measurements

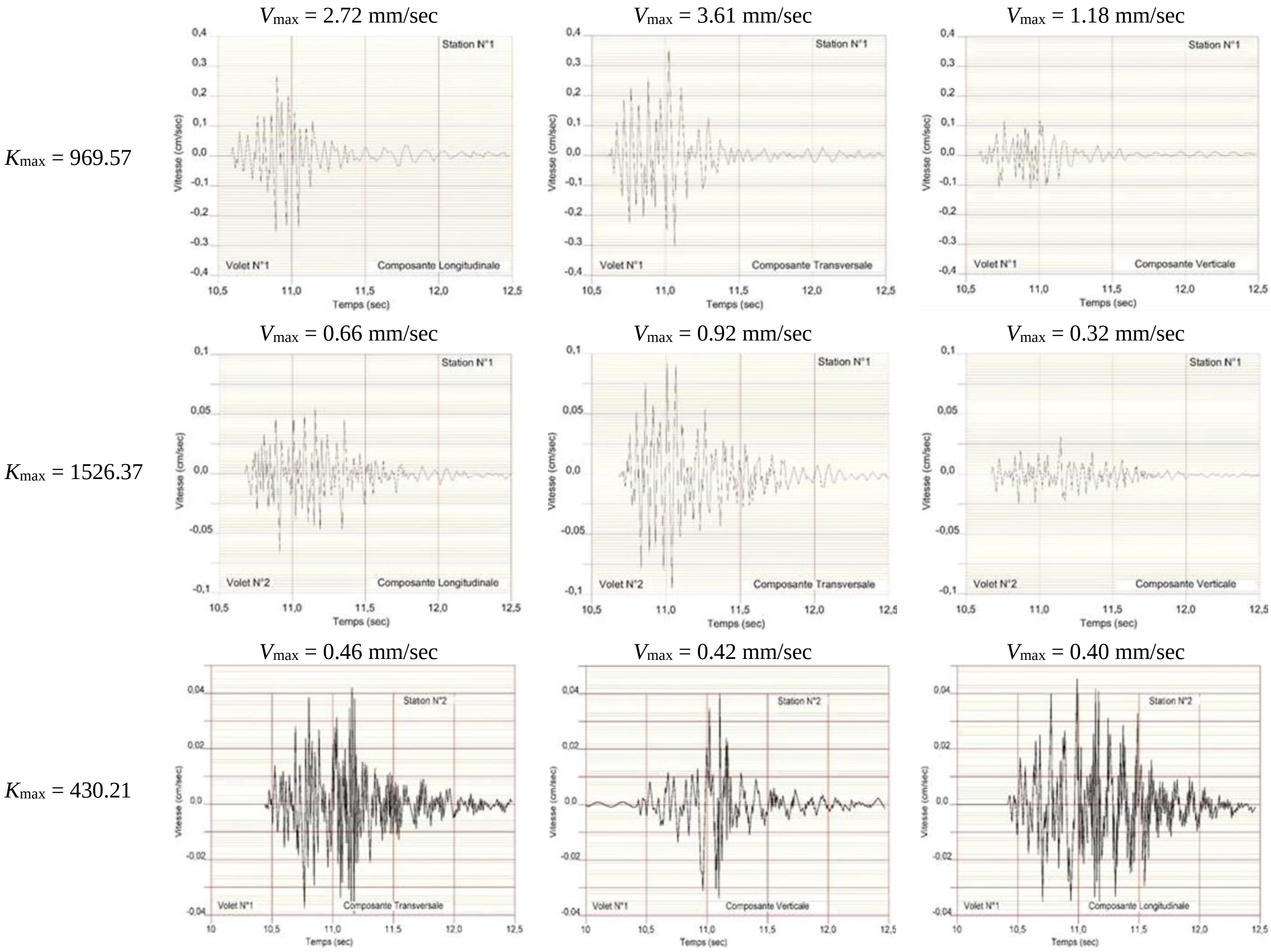
The records of ground vibration measurements obtained during blasting operations conducted at seven stations for two different firing shutter configurations are presented in Table 1. It allows the analysis of the vibration intensity (V_{max}) observed at different distances (D) from the blast source, as well as the corresponding explosive charge (Q_i) used in each configuration (Fig. 6).

The V_{max} values represent the maximum recorded particle velocity (in mm/s) at each measurement station. These values indicate the intensity of the ground vibrations generated by the blasting activities at the respective locations. As expected, the V_{max} values generally decrease as the distance (D) from the blast source increases, reflecting the vibration energy attenuation with increasing distance.

The distance (D) parameter is a key factor in understanding the spatial distribution and damping of the ground vibrations. The data shows that the vibration intensity, as represented by V_{max}, decreases with increasing distance from the blast, following the well-established principle of geometric damping of vibrations in the propagation of waveforms through the earth's medium.

Table 1. Ground vibration measurements obtained during the blasting operations

	Firing Shutter (FS I)						
	St 01	St 02	St 03	St 04	St 05	St 06	St 07
V_{max}	3.61	0.46	0.30	–	–	0.09	0.05
D	100	200	350	540	630	540	700
Q_i	20	20	20	–	–	20	20
K	969.57	430.21	768.28	–	–	503.07	445.88
	Firing Shutter (FS II)						
V_{max}	0.92	0.30	–	–	–	0.05	0.02
D	275	360	460	650	760	650	840
Q_i	20	20	–	–	–	20	20
K	1526.37	808.24	–	–	–	390.20	247.63



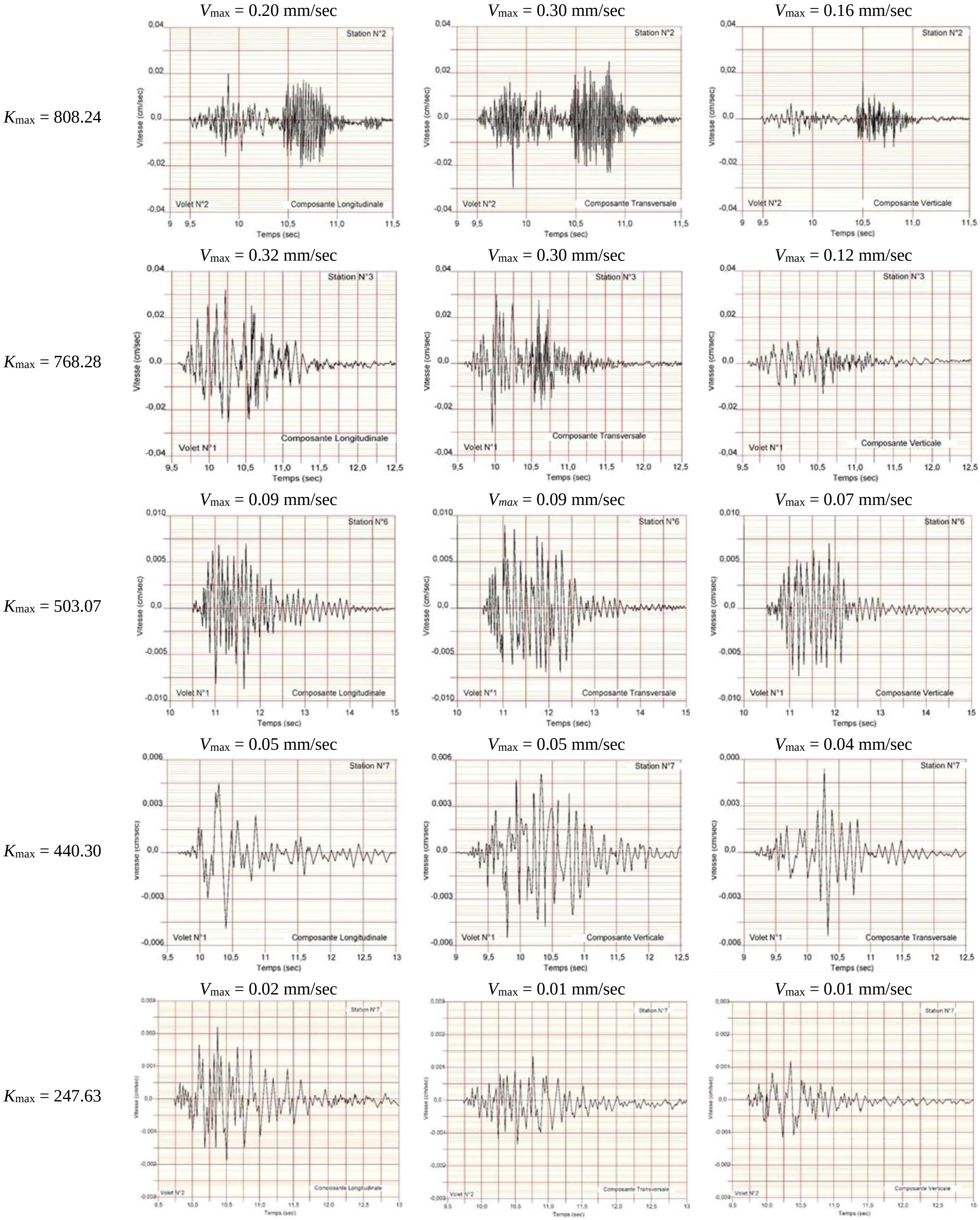


Figure 6. The vibration intensity observed at different distances from the blast source, and the calculated "K_{max}" coefficient

The Q_i column specifies the instantaneous explosive charge (in kg) used in each configuration at the respective stations. This information is essential for correlating the applied blast energy with the resulting ground vibrations. By considering the Q_i values, researchers can investigate the relationship between the charge mass and the vibration intensity, which is fundamental to understanding the blast-induced ground motion and its implications.

The "K" is a coefficient related to the vibration data, such as a site-specific damping factor or a scaled distance metric.

The data presented in this study provide insights into the ground vibration characteristics induced by two different firing shutter configurations. The key parameters analyzed include the maximum particle velocity (V_{max}), the distance (D) from the blast source to the measurement stations, and the explosive charge (Q_i) used.

For the firing shutter 01 configuration, the highest vibration intensity was observed at station St01, which recorded a V_{max} of 3.61 mm/s. This indicates that the ground vibrations were strongest at this location, closest to the blast source. Stations St03, St06, and St07, located further from the source at distances ranging from 100 to 540 m, recorded lower but still measurable V_{max} values of 0.3, 0.09 and 0.05 mm/s, respectively. The explosive charge used at these stations was 20 kg. The parameter "K" is introduced in the data, but its meaning and units are not clearly defined, which limits the interpretation of its significance.

In the Volet II configuration, a similar trend is observed, with the highest V_{max} of 0.92 mm/s recorded at station St01, which was located 275 m from the blast source. Stations St03, St06, and St07, located at distances ranging from 375 to 650 m, registered lower vibration intensities of 0.3, 0.05 and 0.02 mm/s, respectively. The explosive charge used in this configuration was also 20 kg for the stations with available data (St01, St02, St06, and St07). As in the previous configuration, the meaning and units of the "K" parameter remain unclear.

The results demonstrate the expected inverse relationship between the distance from the blast source and vibration intensity, as stations located closer to the source generally had higher V_{max} values. This is a well-established principle in blast-induced vibration studies, where the damping of ground vibrations with increasing distance is a fundamental characteristic.

However, the absence of distance data for stations St04 and St05 in both configurations limits the ability to fully evaluate the distance-vibration relationship for the entire dataset. Additionally, the lack of Q_i data for some stations (St03, St04, and St05 in Volet II) prevents a comprehensive assessment of the influence of explosive charge on the observed vibration levels.

4.2. Vibration monitoring implications

The vibrations generated by blasting at Rouina Mine do not pose a threat for neighboring residential areas or the Ouled Mallouk Dam. Measurements revealed vibration values below the recommended minimum velocity of 0.2 mm/s, with actual values less than 0.1 mm/s. This indicates no significant vibration-related concerns for the mine expansion project.

Further measurements could assess the effects of existing faults and local geological facies on vibration damping, providing a more comprehensive understanding of vibration propagation. Initiation sequences play a crucial role in controlling blast-induced wave propagation. Proper placement of millisecond delays can qualitatively influence the direction of blasted rock movement, while poorly designed plans can negatively impact the quality of blasting operations.

Overall, the current blasting practices at Rouina Mine are effectively managing vibration levels. Additional research into local geological features could further optimize blasting design and initiation sequencing.

4.3. Optimization of borehole diameter and blast pattern geometry in blasting operations

Drilling with a reduced borehole diameter enhances the distribution of blast energy within the rock mass, which helps address technical difficulties posed by closely spaced discontinuity networks. However, this approach increases drilling costs [30], [31]. Blast holes are arranged in multiple rows based on a theoretically defined geometry influenced by the borehole diameter. The rock thickness between rows, known as the bench height, must be proportional to the borehole diameter. Key parameters include stemming height (*Hb*), subdrilling depth (*Psf*), and hole spacing (*S*). Recommended stemming height is approximately equal to the bench height, subdrilling depth is generally $B/3$, and the spacing-to-bench height ratio (S/B) typically varies between 1 and 2. While a reduced borehole diameter improves energy distribution and manages rock discontinuities, it requires more boreholes to cover the same area compared to larger diameters. The use of different delay times for detonations reduces vibrations and allows for the successive release of blast rows. However, uncertainties in the dynamic fragmentation mechanisms hinder fine-tuning of these delays with electronic detonators. The benefits of millisecond precision in delay times and specific initiation sequences remain debated within the scientific community, often relying on the blasting supervisor's practical experience (Fig. 7).

Successful blasting operations depend on controlling drilling parameters, geometric variations of rock faces, and geostructural conditions of the benches. Systematic instrumentation and monitoring of the blasting process are crucial, and in some jurisdictions, legally required [32].

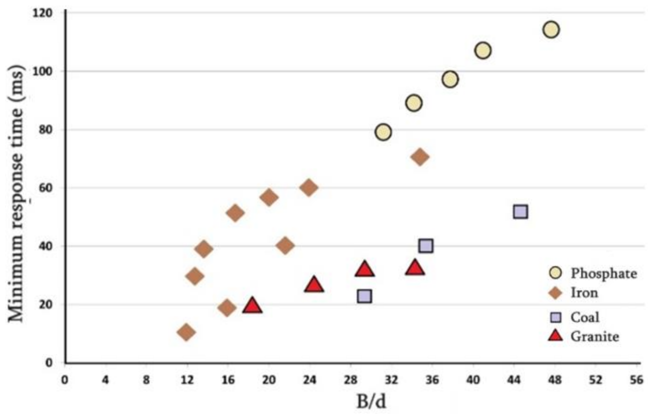


Figure 7. Minimum response time for different rocks and bench/hole diameter ratios (B/d) [33]

Based on these results and their analysis, several recommendations can be made for mining operations in sensitive regions. First, optimizing the initiation sequence by refining micro-delay positioning is critical for better managing blast wave propagation and improving operational outcomes. High-quality fragmentation should also be prioritized, as it plays a key role in controlling wave dissipation and minimizing the impact on surrounding areas. Furthermore, continued research is needed to enhance our understanding of blast-induced vibrations and to develop more precise predictive models. It is essential to conduct comprehensive environmental impact assessments that account for the effects of vibrations on both infrastructure and ecosystems.

Future research should also aim to overcome the limitations of current models, explore the non-linear behavior of fractured rock masses, and assess the impact of different rock types and blast scales on the vibration dynamics. As mining technologies advance, the dual focus on environmental sustainability and structural safety will remain paramount. Innovations in monitoring systems, predictive modelling, and mitigation strategies will be vital to minimize the blasting impact on the environment and infrastructure.

5. Conclusions

This research provides a detailed examination of blast-induced vibrations in the Rouina iron mine, utilizing advanced tools like ETNA accelerographs and K2 seismographs equipped with triaxial sensors. Through careful calibration and comprehensive data collection during blast experiments, valuable insights were obtained regarding vibration characteristics. A key outcome was the successful application of Chapot's law to calculate the damping coefficient of the rock mass, offering a deeper understanding of how vibrations propagate and their potential effects on nearby structures, such as the Ouled Mellouk Dam, and the surrounding environment.

The study highlights the importance of recognizing the limitations and assumptions of Chapot's law, such as uniform vibration energy attenuation and constant damping when interpreting the results. These considerations are essential for ensuring the accuracy of vibration impact assessments.

The research has significant implications for mining operations near populated areas and critical infrastructure, emphasizing the need to develop effective mitigation measures to protect human settlements and the environment. By enhancing our understanding of blast-induced vibrations, this research provides a foundation for future work aimed at reducing the negative impacts of mining activities on ecosystems and infrastructure. This research contributes to improving operational safety and supports sustainable mining practices in sensitive regions.

Author contributions

Conceptualization: HS, SB, RH; Data curation: HS, SB; Formal analysis: HS, RH; Funding acquisition: HS; Investigation: HS; Methodology: SB, RH; Project administration: SB, RH; Software: HS, RH; Supervision: SB; Validation: RH; Visualization: SB; Writing – original draft: HS; Writing – review & editing: RH. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Оцінка коливань, спричинених вибухом у відкритому кар'єрі Руїна: вплив та вимірювання для дамби Улед Меллук

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Мета. Дослідження характеристики коливань, спричинених вибухом, в алжирському кар'єрі Руїна та їхній потенційний вплив на прилеглу інфраструктуру, зокрема дамбу Улед Меллук, розташовану нижче за течією річки. Дослідження спрямоване на розуміння закономірності поширення коливань та оцінку їх екологічних і структурних наслідків, з акцентом на стратегіях зменшення ризиків для захисту інфраструктури.

Методика. Дослідження проводилося шляхом експериментальних випробувань вибухів на шахті Руїна. Для вимірювання індукованих коливань були використані сучасні інструменти, такі як акселерографи типу ETNA, сейсмографи з високочутливими тривісними датчиками LE-3Dlite і дигітайзером K2. Різні параметри, пов'язані з процесом фрагментації, були скориговані для аналізу їх впливу на вібраційні характеристики. Коефіцієнт демпфування гірської маси був розрахований з використанням закону Чапо, а також було досліджено потенційний вплив на водовідведення.

Результати. Встановлено, що коливання, спричинені вибухом, мають значний вплив на поширення вібрацій, створюючи потенційні ризики для прилеглої інфраструктури. Визначено коефіцієнт демпфування гірничої маси, який пояснює поведінку демпфування коливань. Доведено, що впровадження оптимізованих планів вибухових робіт може ефективно контролювати рівень коливань та зменшити ризики для таких споруд, як дамба Улед Меллук.

Наукова новизна. Це дослідження дає нове розуміння поведінки коливань, спричинених вибухом, при видобутку корисних копалин у відкритих кар'єрах, особливо в безпосередній близькості до об'єктів критичної інфраструктури. Інноваційне використання передових методів вимірювання та застосування закону Чапо для аналізу коливань підкреслюють оригінальність дослідження.

Практична значимість. Дослідження пропонує практичні рекомендації щодо управління коливань, спричинених вибухом, під час видобутку корисних копалин поблизу чутливих об'єктів інфраструктури, сприяючи розробці вдосконалених протоколів безпеки та стратегій управління навколишнім середовищем.

Ключові слова: *розповсюдження коливань, розрахунок швидкості розряду, аналіз закону Чапо, коефіцієнт демпфування, структурні впливи, вплив на навколишнє середовище*

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