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ASSESSMENT OF BLASTING-INDUCED GROUND VIBRATIONS AND INFLUENCING FACTORS IN SURFACE MINING OPERATIONS

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ABSTRACT

Blasting operations in surface mining are essential for rock fragmentation but are also associated with ground vibrations that can cause structural damage, disturb communities, and impact the environment. This review paper presents a comprehensive analysis of the factors influencing blast-induced ground vibrations, with a specific focus on parameters related to explosive design and blast geometry. The study synthesizes literature findings on variables such as charge weight, charge type, charge diameter, charge length, burden, decking, free space, and velocity of detonation (VOD). Among these, charge weight per delay and burden are often identified as the most critical parameters directly affecting Peak Particle Velocity (PPV), the standard metric for assessing vibration levels. The review also evaluates the impact of decking and free face conditions on energy dissipation and ground response. Empirical models such as the scaled distance approach and advanced vibration prediction techniques are discussed in relation to these influencing factors. The paper highlights the importance of site-specific investigations and integrated monitoring to manage blast vibrations effectively. It serves as a consolidated reference for mining professionals aiming to design optimized blasts that ensure safety, regulatory compliance, and minimal environmental disruption in surface mining operations.

Keywords: Ground Vibrations; Velocity of Detonation (VOD); Peak Particle Velocity (PPV); Surface Mining

1. INTRODUCTION

Blasting is a common technique used in mining and construction to break up rock using controlled explosives. The goal is to safely and effectively create rock fragments that can be used or removed for different purposes like collecting raw materials or digging tunnels. However, blasting often causes ground vibrations, which can affect nearby structures and the environment. Because of this, the mining and construction industries are closely watched to make sure their blasting activities are done carefully and responsibly, with as little impact as possible.1The challenge with blasting in areas near towns or cities is finding the right balance. While the main goal of blasting is to break as much rock as possible for production, the process also creates ground vibrations. These vibrations can negatively affect nearby buildings and disturb people living close by. Even though we now understand rock blasting better and have made progress with new technology, not all of the explosive energy actually goes into breaking the rock. A significant part of it is wasted as ground vibrations, flying debris (back breaks), air pressure waves (air blasts), and other side effects.2 Ground vibrations can come from many different human activities and can impact nearby buildings and people. However, when we talk about ground vibration in this context, we usually mean vibrations caused by man-made sources not natural events like earthquakes. This definition also doesn't include effects like seismic wave amplification caused by the shape of the land, such as hills, ridges, or valleys.3As a result, ground vibration includes a broad spectrum of vibrations caused by activities such as construction work and traffic movement. The impact of these vibrations can vary greatly because of the complex factors involved in how seismic waves are created and how they travel through the ground. Ground vibrations caused by traffic especially from railways are among the most thoroughly researched. The challenge in studying railway vibrations lies in the complexity of modelling moving sources, like a series of axle loads, which interact with intricate structures such as the railway track and its foundation.4 In road transportation, the movement of heavy vehicles over uneven or damaged road surfaces can also produce considerable ground vibrations due to dynamic interactions.5 Vibrations in the environment caused by vibratory and impact pile driving can produce either short-term (transient) or repeating (cyclic) waves, with their

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energy linked to the vertical movement of the pile. The characteristics of these waves differ significantly between areas close to the source (near-field) and those farther away (far-field). The demolition of structures can also induce significant soil movements. The extent of these effects largely depends on the type of excitation involved for example, whether the loading is transient or continuous loading It has been observed that the vibrations produced during pavement breaking depend on both the duration of each impact and the sequence of impacts, particularly when using a multi-head pavement breaker. Explosive blasting, commonly used in the construction and mining sectors, is increasingly worrisome due to the ground vibrations it creates, which can travel over long distances. Production blasts typically involve multiple blastholes filled with explosives, and the resulting wave movement is influenced by many different factors. It is clear that ground vibration is influenced by the type of source excitation and the attenuation properties.

Table 1 Frequency and particle motion ranges, is provided by the International Organization for Standardization (ISO) in standard ISO 4866(6)

Vibration Source	Frequency Range (Hz)	Particle Velocity Range (mm/s)	Particle Acceleration Range (m/s²)
Traffic (road/rail)	1–100	0.2–50	0.02–1
Blasting	1–300	0.2–100	0.02–50
Pile Driving	1–100	0.2–100	0.02–2
Outside Machinery	1–100	0.2–100	0.02–1

Table 1 highlights that blasting activities produce vibrations with both higher intensity and frequency compared to other artificial vibration sources. This makes blasts particularly important to study, especially regarding their dynamic impacts on urban environments. To effectively predict vibrations resulting from production blasts, it is crucial to accurately characterize the vibration source the production blast itself. This paper provides a comprehensive review of the latest methods for modelling and characterizing blasting-induced excitation, summarizes the blasting process, and discusses the various factors that influence blasting effectiveness and the resulting ground vibrations.

2. OVERVIEW OF THE BLASTING PROCESS

Breaking up rock in open-pit mines and quarries involves drilling a planned pattern of blastholes into the rock. After the explosives are loaded and positioned in these holes, they are triggered in a precisely timed sequence to break apart the rock. Once the blast is complete, the shattered rock is collected and moved away from the site for further processing or transport. The explosive forces generated during blasting come from the detonation of chemicals confined in the blastholes, where exothermic reactions rapidly convert the explosives into gases and release a large amount of energy. A detonation involves the creation of a supersonic combustion wave that causes a rapid rise in thermodynamic properties. This type of reaction is typical in rock blasting. Because the wave moves faster than the speed of sound, the materials in front of the detonation are unaffected until the wave reaches them, so they stay in their original state. The detonation front moves through the explosive at its Velocity of Detonation (VoD), which for most high explosives ranges from about 1,500 to 9,000 meters per second (Aimone 1992). The explosion can produce extremely high pressures, often between 1 GPa and more than 14 GPa. The detonation process results in two main effects: first, it creates a shock wave from the rapid explosion of the explosives; second, it forces high-pressure gases into existing or newly formed cracks. The shock wave, which is a powerful pressure pulse, moves through the material at supersonic speeds and plays a key role in breaking the rock apart. The pressure or stress waves produced last only a few milliseconds and radiate outward into the surrounding ground, driven by the swift expansion and contraction of the blasthole. These waves

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move in multiple directions, bouncing off and bending at internal boundaries within the material, such as joints, fractures, and bedding planes. When these waves, having travelled along different paths, reach a specific point away from the blast, they combine and overlap. Various factors then affect the final amplitude and shape of the resulting vibration waveform at that location. Kutter and Fairhurst (1971) were among the first to propose that three separate zones surround a blasthole: (1) a strong-shock hydrodynamic or crushed zone, (2) a transitional nonlinear cracking zone, and (3) an elastic zone. While this three-zone model has been widely accepted, it has also faced criticism. Two key concerns have been raised, suggesting that this concept should be approached cautiously. First, the idea of clearly defined zones is based on simplified and static rock mechanics, which tends to overstate the role of tensile stresses and neglects the unique radiation patterns of various stress wave types. Second, rather than being sharply divided, the crushed zone is more accurately described as an area with a dense concentration of sheared or cracked material that gradually becomes less fractured farther from the blasthole. When examining ground vibrations caused by blasting, attention is typically focused on two main regions: the near-field and the far-field zones.

2.1 Near Field Region

The near-field region refers to the area directly around the blasthole and is the most complex zone. Here, the explosives' chemical reaction generates extremely high temperatures and pressures on the blasthole wall. As the detonation shock wave moves outward, the surrounding rock is exposed to very high strain, resulting in inelastic effects like fracturing, breaking, and shearing. Although the actual fracture process is intricate and depends on the rock's inelastic behaviour, it is often simplified in practice by using numerical or analytical models that assume a cylindrical, elastic region around the blasthole.

Experimental data on strain waves or pressures at the blasthole wall for fully coupled explosives is limited in the literature, mainly because most sensors cannot survive the extremely high pressures and temperatures involved (Fleetwood 2010). Recently, however, new systems have been developed to measure detonation pressures and temperatures during production blasts given the challenges in directly measuring the rock mass response in this zone, researchers often rely on mathematical models or scaled-down blast tests instead. Several empirical methods also exist to estimate the size of the crushed zone, using factors like explosive characteristics, blasthole radius, and rock properties. More recently, some researchers have started measuring and analysing vibrations in the near field although this area still needs much more study.

When it comes to ground vibrations, the near-field region is defined as the area where vibration attenuation behaves nonlinearly. As commercial blasting mainly aims to break up rock masses, the explosive fracturing process caused by production blasts has been extensively studied. Seismic waves from blasting decay quickly until the compressive stress they create drops below the rock's compressive failure limit; beyond this, the rock's response becomes elastoplastic.

2.2 Far Field Region

The far-field region is where the energy of the blast-induced waves has decreased enough that it no longer causes permanent changes to the rock. In this zone, the ground behaves elastically, meaning it returns to its original state after the seismic waves pass. Wave propagation in the far-field occurs at a constant speed.

3. BLAST INDUCES GROUND VIBRATION

Ground vibrations in this area are particularly important because they have the potential to affect or damage buildings and other infrastructure. This zone is much larger than the near-field region and, in theory, has no defined boundary. They are three-dimensional in nature, and their reduction in intensity depends on factors such as geometry, geological characteristics, distance, as well as irregularities like fractures, faults, and cavities. This section outlines the three main types of waves produced during a production blast and discusses the kinds and possible causes of structural damage that can result from blast-induced ground vibrations.

3.1 Waves Generated Due To Blasting

Explosive blasting generates various types of seismic waves. The first kind, known as body waves, travel through the interior of the ground. Body waves consist of compressional P-waves, which involve particle movement in the same direction as the wave travels, and transverse S-waves, where particles move perpendicular to the direction of wave propagation. The second kind are surface waves, like Love waves (Q-waves) and Rayleigh waves (R-waves), which occur when there is a free surface present. Surface waves move more slowly along the surface compared to body waves. In uniform materials, Rayleigh waves are formed when shear waves reflect off the free surface, and they feature elliptical, retrograde particle movement close to the surface in the direction the wave is traveling. The strength of these surface waves decreases quickly with depth. Rayleigh waves can form whenever there is a free surface, while Love waves happen specifically when a soft upper layer covers a harder substrate. Love waves arise from the interference of multiple S-waves trapped within the soft layer and involve side-to-side particle movement.

Three principal types of seismic waves generated by blasting—excluding the Q-wave—with a focus on their propagation velocities and the proportion of energy they transmit. Their findings indicate that for a point source, the compressional P-wave is the fastest but carries only about 7% of the total input energy. The shear S-wave travels at a velocity between that of the P-wave and the Rayleigh (R) wave and typically accounts for approximately 26% of the transmitted energy. In contrast, the Rayleigh wave, despite being the slowest of the three, conveys the majority of the energy, transmitting around 67% of the source input.

The propagation velocities of the P-wave (CP) and S-wave (CS) can be expressed mathematically in terms of the bulk modulus (k), shear modulus (l), and the density of the medium (q) as follows:

$$\text{P-wave (CP)} = \sqrt{\frac{(k+21)}{q}} \qquad (1)$$

$$\text{S-wave (CS)} = \sqrt{\frac{1}{q}} \qquad (2)$$

For the R-wave, only approximate formulas exist to estimate its velocity based on the elastic properties of a homogeneous half-space. However, when dealing with layered media, the situation becomes much more complex because of the various reflections, refractions, and conversions that occur at the boundaries between layers. While each individual layer can be characterized by body waves, surface waves in these layered environments are dispersive. This means the phase velocities of different vibration modes vary with frequency and are influenced by both the arrangement and thickness of the layers.

3.2 Structural Damage Due to Blast-Induced Vibrations

When blasting operations are planned near urban areas, it is advisable to conduct preliminary test blasts before starting full-scale production. It is the site engineer's responsibility to gather as much detailed information as possible from these tests to determine the most effective blasting parameters. Regulations exist that set limits on blasting activity, which are based on the distance between nearby structures and the blast location. These regulations specify the maximum permissible ground vibration level, commonly measured as peak particle velocity (PPV)—the highest amplitude of ground motion recorded. PPV is determined by measuring particle velocity in three directions (vertical, transverse, and longitudinal), and the reported value is the largest vector sum of these components. Additionally, the dominant frequency of the ground vibration is measured and recorded from the spectrum of the measured vibration.

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4. BLASTING FACTORS AND THEIR INFLUENCE ON GROUND VIBRATION

The complexity of blasting operations means that both the effectiveness of a production blast and the ground vibrations produced are influenced by many different factors as shown in figure 1. Before attempting to model blasting-induced vibrations, it is important to assess and understand these various aspects that can impact the blasting process. This section outlines the key factors affecting blasting performance. It is essential for a blasting engineer to be well-informed about these variables to achieve the right balance between efficient rock breakage and minimizing ground vibrations.

4.1 Charge Weight

The amount of explosive used is the most common variable considered in blast vibration studies, and it depends on factors like the arrangement of the charge, blasthole design, and loading methods. For monitoring structures in the far field, the main focus is usually on the peak vibration level. The standard approach relies on a charge weight scaling law, which assumes that increasing the charge weight will always lead to higher peak vibrations. However, this assumption is actually challenged by axisymmetric radiation models for blastholes in an infinite medium, which suggest otherwise. Additionally, the existence of multiple versions of the scaling law highlights ongoing debates about how charge weight truly affects peak vibration levels. A large set of peak vibration measurements from both surface and underground sites, involving numerous single blastholes and production blasts, was analysed. The findings showed that peak vibration levels underground are not significantly affected by changes in charge weight, whereas, for surface blasts, considering the charge weight leads to more accurate predictions of peak vibrations.

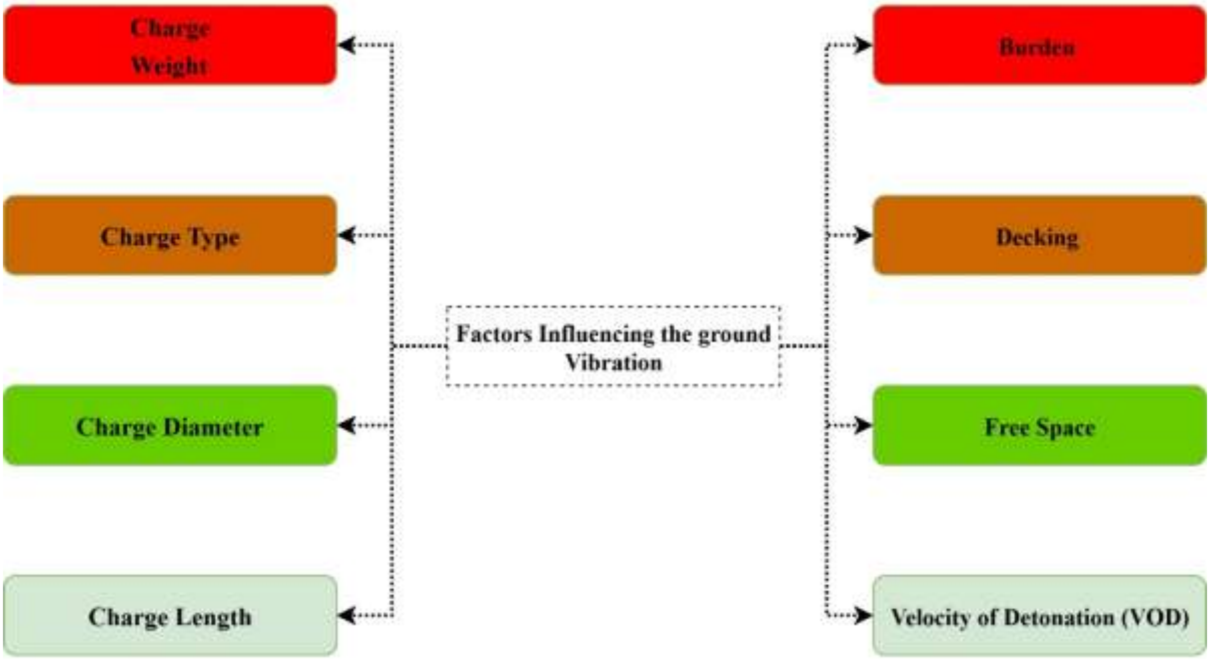

Figure 1 Different Ground Vibration Influencing Factors

4.2 Charge Type

The type of explosive charge, determined by its chemical composition, affects the amount of energy, pressure, velocity of detonation (VoD), and gases produced during blasting. While there are several explosives available for rock blasting, ammonium nitrate and fuel oil (ANFO) are the most widely used due to its low cost compared to other options. When blasting must take place in wet environments, it is important to consider the water resistance of the chosen explosive to avoid

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significant reductions in performance. Gelled explosives, such as gelatine dynamite, typically have strong water resistance, whereas non-gelatine types can differ greatly in this respect. For instance, ANFO does not perform well in wet conditions and should only be used in dry blastholes. If an explosive lacks adequate water resistance, it often releases brown nitrogen oxide fumes during detonation a clear sign of compromised performance.

4.3 Charge Dimeter

It is well recognized in the blasting field that the diameter of the blasthole plays a crucial role in the effectiveness of the explosives used. In practice, companies often have access to only one or two drill bit sizes and typically do not vary the blasthole diameter during operations. Standard blasthole diameters generally range from 0.05 to 0.32 meters. Research has produced several equations linking blasthole diameter to the extent of rock fracturing, indicating that, depending on the type of explosive and the geological conditions, rock can fracture anywhere from three up to fifty-five times the radius of the blasthole. For example, larger blasthole diameters have been associated with an increased area of damage and a wider fracture zone, particularly when large diameter charges are used. Analytical models developed for cylindrical explosive columns show that the diameter of the charge significantly affects the magnitude of the vibrations produced during blasting. Studies comparing different explosives, such as ANFO and EM120D, found that as the blasthole diameter increases, the velocity of detonation (VoD) for the explosive also rises. This relationship between blasthole diameter, fracture extent, and explosive performance highlights the importance of considering hole size in blast design for optimal fragmentation and vibration control.

4.4 Charge Length

The charge length refers to how much of the blasthole is filled with explosive, and this length typically remains the same unless there are specific operational reasons to change it. In open-pit mining, charge lengths are usually between 5 and 15 meters, though they can be much longer in some cases—for example, blastholes in opencast coal mines may reach up to 70 meters. Research has shown that, generally, longer blastholes tend to produce higher peak vibration levels. Analytical modelling studies have found that, in a uniform viscoelastic medium, the far-field peak vibration levels are not affected by charge lengths greater than 0.01 meters, and similar observations have been made in the near-field in certain circumstances. However, in the "medium field," it was noted that peak vibration levels do increase as the charge length becomes longer.

4.5 Burden

Refers to the arrangement pattern of drilled blastholes and specifically denotes the shortest distance from a blasthole to the exposed bench face but does not take into account the type or condition of the rock. It is commonly believed in the blasting industry that vibration levels increase as the burden increases; however, there is currently no definitive research to confirm this relationship.

For example, conducted multiple blasting experiments and used pressure gauges to measure the resulting vibrations. Although their data did not show any connection between burden and vibration levels, they still assumed such a dependency and controversially included burden in a nine-parameter model. Similarly, other researchers measured vibrations from single blastholes with two different burden sizes (3 meters and 6 meters) and found no clear correlation between burden size and vibration levels. Despite experimental results failing to demonstrate any significant relationship, some studies have still incorporated burden into their predictive models, even if the data do not support its inclusion.

A small-scale study was conducted to examine the impact of burden width (ranging from 3 to 14 meters) using vibration data collected from two different mining sites. The findings suggested a slight trend where increasing the burden width seemed to result in lower peak vibration levels; however, the results varied significantly, making it difficult to definitively attribute this effect to the burden width itself. Across all studies reviewed, there has not been any clear or conclusive

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evidence demonstrating that burden width directly affects blast vibration. One proposed approach to better understand this potential relationship is to utilize an experimental procedure in which the rock mass is assessed with a non-invasive seismology test prior to each production blast. After these initial assessments, several blasts can be conducted and the resulting vibration levels measured and compared to determine if burden width truly influences blast vibrations.

4.6 Decking

Decking of charges involves using an inert material to separate explosive charges within the same blasthole. Air-decking, specifically, replaces a portion of the explosive charge with air, which decreases the amount of explosive needed and is believed to enhance fragmentation. Most research on decking has focused on how it affects fragmentation efficiency. Although it is commonly assumed that decking can help lower ground vibration levels by reducing the total amount of explosive in the blasthole, some studies have argued that this is not always the case. This is because superposition effects meaning the constructive or destructive interference of waves can occur, as observed in some field trials comparing decked and non-decked single blasthole detonations.

Park and colleagues suggested placing an air-deck at the bottom of a blasthole to minimize blast vibrations in the tunnelling direction. Their research found that increasing the air-deck ratio (the ratio of explosive length to air gap, from 0.1 to 0.5) led to lower vibration levels in the direction of the tunnel. However, it was also noted that, in some cases, decked charges could actually produce higher vibrations compared to a continuous column of explosive. Ultimately, the vibration outcome depends on several factors, including the properties of the rock, the explosive's velocity of detonation, the length of the decks, the delay time between detonations, and the spacing between decks

4.7 Free Face

A free face refers to an exposed section of rock where fragmented material can be displaced. During a production blast with a free surface, the explosive-generated waves move toward this boundary, and the reflection of plane waves at such a surface is well understood and explained by the Toeplitz equations. However, the waves produced by explosives within a blasthole are not planar, making it challenging to accurately predict how they will reflect off the free face.

Research by Blair and others showed that accounting for free faces is important to prevent overestimating the vibration levels resulting from a blast. By developing an analytical model that considers non-planar wave radiation, they demonstrated that free faces significantly impact the body waves produced by blasting. The angle at which these waves strike the free surface, known as the incidence angle, greatly influences whether the amplitude of body waves (P and S waves) is increased or decreased upon reflection. S-waves show even more complex behaviour, as they can reflect at angles beyond the critical angle, complicating the prediction of their amplification.

4.8 The Velocity of Detonation

The velocity of detonation (VoD) describes how quickly the detonation shock wave travels through an explosive charge. VoD values can be provided for either confined or unconfined explosives and generally fall between 2,500 and 7,000 meters per second. Devices for measuring VoD are becoming more commonly used in the blasting and mining industries.

VoD is recognized as one of the most critical characteristics of an explosive, as the detonation pressure is directly proportional to VoD, making it a strong indicator of an explosive’s strength and overall performance. Conversely, a lower-than-expected VoD can signal that an explosive has not performed as intended used a numerical model to study the effects of VoD and found that higher VoD values increase the peak vibration levels detected in the far-field. Notably, in the near-field, peak vibration levels are highly sensitive to VoD, rising with increasing VoD up to a point, and then decreasing if VoD increases further. Analytical modelling has also shown that VoD does not significantly affect peak vibrations if the charge length is less than 0.45 times the charge diameter.

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Failing to properly account for VoD, or ignoring it entirely, can lead to a major overestimation of vibration levels. Some researchers have even assumed an infinite VoD in their calculations, but this approach has been proven inaccurate. Over time, numerous numerical models have been created to calculate the VoD, but these methods are often resource-intensive compared to empirical formulas, which can usually be solved manually. Most empirical methods rely on statistical analysis of the performance of known explosives and require specific physical and chemical properties as input variables.

5. CONCLUSIONS

This review has consolidated and critically analysed the key parameters influencing blast-induced ground vibrations in surface mining environments. Based on the literature and illustrated factors—charge weight, charge type, charge diameter, charge length, burden, decking, free space, and velocity of detonation (VOD)—it is evident that ground vibrations are a function of both the energy released during detonation and the efficiency of energy transmission through rock and air media.

The charge weight per delay is the most influential factor affecting vibration intensity. Larger charge weights lead to higher energy release and, consequently, higher Peak Particle Velocity (PPV) values. The charge type and VOD determine the rate and pattern of energy release, significantly affecting the frequency content of vibrations. Charge geometry, including diameter and length, influences the distribution of energy within the blast hole and the degree of confinement.

On the geometric side, burden and decking play crucial roles in controlling the confinement and the breakout path of the explosive force. Improper burden can result in overbreak or poor fragmentation, both contributing to elevated ground vibrations. Decking—the separation of charges in a single hole—has shown potential for reducing vibration by minimizing explosive coupling. The presence of free space or a proper free face allows energy to dissipate more effectively, reducing reflected shock waves and ground motion.

The review underscores the importance of integrated vibration control through optimal blast design, site-specific calibration of predictive models, and real-time vibration monitoring. No single factor operates in isolation; rather, a combined and holistic approach is required to minimize the adverse impacts of ground vibrations.

In conclusion, a detailed understanding of the influencing parameters can significantly aid in designing safer and more controlled blasting operations. The mining industry must continually adapt blast practices based on evolving site conditions, regulatory limits, and technological advancements to ensure sustainable and socially responsible mining.

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