Vibration-Safe Blasting: A Study on Parameter Optimization: A Meta-Analytic Review

Rajeev Kumar Sahu[1], Dr. Ram Chandra Chaurasia[2]

M.Tech Scholar, Department of Mining Engineering, LNCT, Jabalpur[1]
Associate Professor, Department of Mining Engineering, LNCT, Jabalpur[2]

Abstract

Ground vibrations induced by blasting operations in mining, quarrying, and construction pose significant risks to nearby structures, ecosystems, and community well-being, while also attracting stringent regulatory scrutiny. Optimizing blast design parameters offers the most direct engineering control over vibration propagation. This paper synthesizes past research through a comprehensive meta-analysis focused on identifying and quantifying the influence of key blast design parameters on peak particle velocity (PPV), the primary vibration metric. Analysis of aggregated data from numerous field studies reveals that scaled distance (SD), incorporating both maximum instantaneous charge (MIC) per delay and distance, remains the paramount predictor, following the power-law relationship PPV = K (SD)^-β, though site-specific K and β values exhibit considerable variability. Beyond SD, precise delay timing, particularly inter-hole and inter-row delays, emerges as critical for vibration reduction through effective fragmentation and wave superposition/cancellation. Hole geometry (diameter, depth, inclination), stemming pattern (burden, spacing, stiffness ratio), and decking strategies significantly influence energy distribution and confinement, thereby impacting vibration generation. Initiation sequence and directionality also play measurable roles. While empirical scaled distance laws dominate prediction, recent trends integrate advanced monitoring, numerical modeling (FEM, DEM), and machine learning for enhanced understanding and site-specific optimization. This review underscores that effective vibration minimization requires a holistic approach, moving beyond simplistic SD reliance to meticulously control charge distribution, timing, and blast geometry, tailored to local geomechanical conditions and regulatory limits.

Keywords: Blast-induced ground vibration, Peak Particle Velocity (PPV), Scaled Distance (SD), Maximum Instantaneous Charge (MIC), Delay Timing, Blast Design Optimization, Vibration Control.

1. Introduction

1.1 The Ubiquity and Impact of Blast-Induced Ground Vibrations:

Blasting remains the most efficient and economical method for rock fragmentation in mining, quarrying, and large-scale civil engineering projects. However, the detonation of explosives generates significant energy, a portion of which propagates through the ground as seismic waves, manifesting as ground vibrations. These vibrations are characterized by measurable parameters, primarily Peak Particle Velocity (PPV), Peak Particle Acceleration (PPA), frequency content, and duration. PPV is the most widely used metric for regulatory compliance and structural response assessment due to its direct correlation with potential damage thresholds. Excessive ground vibrations can lead to cosmetic or structural damage to nearby buildings, infrastructure (pipelines, tunnels), and historical sites. Beyond structural concerns, they cause environmental disturbances (noise, dust, flyrock), contribute to slope instability risks, and significantly impact community relations through annoyance and perceived risk, often leading to operational restrictions and project delays.

1.2 Regulatory Frameworks and the Imperative for Control:

Recognizing the potential adverse effects, regulatory bodies worldwide impose strict limits on allowable ground vibration levels (typically PPV) and airblast overpressure near sensitive receptors. These limits are often defined based on structural type, frequency content, and established damage criteria standards (e.g., USBM RI 8507, DIN 4150, AS 2187.2). Non-compliance can result in severe penalties, operational shutdowns, costly litigation, and irreparable reputational damage. Consequently, minimizing blast-induced vibrations is not merely an engineering challenge but a critical operational, environmental, and social responsibility for any blasting operation.

1.3 Optimization as the Primary Control Strategy: Scope and Objectives:

While vibration propagation can be influenced by geological conditions and topography, blast design parameters represent the most controllable factors within the engineer's purview. Optimization involves systematically adjusting these parameters to achieve the desired fragmentation while keeping vibration levels below regulatory thresholds and as low as reasonably achievable (ALARA principle). This review paper focuses explicitly on synthesizing past research, particularly meta-analyses, concerning the optimization of blast design parameters for ground vibration minimization. Its core objectives are: (1) To identify and rank the relative influence of key blast design parameters on PPV based on aggregated field data; (2) To critically evaluate established and emerging methodologies for vibration prediction and control; (3) To highlight gaps, limitations, and future research directions in blast vibration optimization.

2. Literature Survey

Research into blast-induced vibrations spans decades, driven by the dual needs of efficient rock breakage and environmental protection. Early work (e.g., Duvall and Petkof, 1959; Edwards and Northwood, 1960) established the fundamental concept of scaled distance (SD = D / √Q, where D is distance and Q is charge weight) as the dominant factor controlling PPV, formalized in the power-law equation PPV = K (SD)^-β. This empirical relationship became the cornerstone of vibration prediction and regulatory frameworks. Countless site-specific studies confirmed its general applicability but also revealed significant scatter, attributed primarily to variations in geology (rock type, stiffness, jointing, attenuation characteristics), explosive properties, and blast design details beyond just total charge and distance.

The recognition that not all explosive energy contributes equally to vibrations led to the crucial distinction of Maximum Instantaneous Charge (MIC), the largest amount of explosive detonated within a time window (typically 8 ms) sufficient for vibration waves to constructively interfere. Optimizing MIC per delay became a primary control strategy. However, meta-analyses synthesizing data from diverse sites (e.g., Mesec et al., 2010; Raina et al., 2014) demonstrated that while SD based on MIC is the strongest predictor, the constants K (site characteristic) and β (attenuation rate) exhibit substantial variability, emphasizing the need for site-specific calibration. Beyond scaled distance, extensive research has focused on the critical role of delay timing. Precise millisecond delays between holes and rows are paramount. Meta-analytic reviews (e.g., Siskind et al., 1980; Yang & Scovira, 2010) consistently show that:

- Insufficient inter-hole delay can lead to constructive interference, amplifying vibrations.
- Optimal inter-hole delays (typically 3-9 ms/m of burden/spacing) promote effective rock movement and fragmentation, often coinciding with reduced PPV compared to simultaneous or poorly timed detonations.
- Inter-row delays significantly larger than inter-hole delays (e.g., ≥ 1.5-2 times) are generally beneficial for vibration reduction, allowing the vibration wave from one row to partially decay before initiation of the next. Timing accuracy and consistency are vital; scatter in actual detonation times versus design can negate benefits and increase vibration scatter.

Hole geometry and stemming significantly influence confinement and energy release. Larger diameter holes generally require higher charge weights per hole, potentially increasing MIC unless compensated by more holes per delay or precise timing. Deeper holes can lead to greater confinement and energy retention before release, potentially increasing vibrations near the blast but altering attenuation with distance. Inclined holes often yield better fragmentation near the toe and can influence directivity, sometimes reducing vibrations in specific directions compared to vertical holes. Adequate stemming length and material (crushed aggregate preferred) are crucial to prevent premature venting of gases, which wastes energy and can increase airblast without improving fragmentation, potentially leading to attempts to compensate with higher charges, indirectly affecting vibrations. Decking, dividing the hole charge into separate decks separated by inert material, reduces the charge mass detonating instantaneously at any point within the hole, effectively lowering MIC for that hole. Meta-analyses confirm decking as a viable strategy for vibration reduction, particularly in shallow blasts or near sensitive areas.

Stemming pattern geometry– burden (B), spacing (S), and their ratio (S/B) – governs the stiffness of the rock mass being blasted and the efficiency of energy utilization. Insufficient burden leads to excessive flyrock and airblast but may reduce ground vibrations due to less confinement. Excessive burden causes poor fragmentation, toe problems, and potentially higher vibrations due to greater confinement and inefficient energy use. An optimal S/B ratio (typically 1.0 to 1.5 for production blasts) ensures good breakage and movement. Studies aggregated in reviews show that patterns with high stiffness ratio (low B/diameter) often correlate with lower PPV for a given scaled distance, as energy is used more efficiently for breakage rather than generating vibrations. Pattern geometry also interacts strongly with delay timing.

Initiation sequence and directionality influence the vector sum of vibration waves at a monitoring point. Initiating towards or away from a receptor, or using specific sequencing patterns (e.g., V-cut, echelon), can leverage wave superposition principles to achieve some cancellation in specific directions, though the effect is often modest and highly dependent on geology and topography. Meta-analyses suggest directionality effects are secondary to SD and timing but can be exploited for marginal gains in specific scenarios.

Advanced Techniques: The limitations of purely empirical SD laws led to the development of **numerical modeling** (Finite Element Method - FEM, Discrete Element Method - DEM, Hybrid approaches). Meta-reviews of modeling applications (e.g., Jiang & Zhou, 2012; Singh & Singh, 2018) highlight their value in understanding wave propagation mechanisms, stress distribution, and parametric sensitivity studies under controlled conditions. However, computational cost, complexity in accurately characterizing heterogeneous rock masses, and the need for extensive calibration limit their routine predictive use for every blast. Machine learning (ML) and Artificial Intelligence (AI) are emerging as powerful tools. Meta-analyses of recent literature (e.g., Nguyen et al., 2021; Zhang et al., 2022) indicate promising results using techniques like ANNs, SVMs, and Random Forests to predict PPV by incorporating a wider range of parameters (blast design, geology, monitoring data) than traditional SD laws. ML models can potentially capture complex non-linear interactions and offer site-specific predictive accuracy superior to generalized SD equations, representing a significant future direction.

3. Methodology

This review employs a systematic meta-analytic approach to synthesize findings from existing primary research studies, review articles, and crucially, past meta-analyses focused on blast design parameters and ground vibration minimization. The core methodology involves:

1. Literature Identification and Screening: Comprehensive searches were conducted across major scientific databases (Scopus, Web of Science, Google Scholar, OneMine) using keywords related to "blast-induced vibration," "ground vibration," "peak particle velocity," "scaled distance," "blast design," "optimization," "delay timing," "maximum instantaneous charge," "vibration control," and "meta-analysis." The search was initially broad but focused on identifying studies that either conducted quantitative meta-analysis or provided extensive qualitative synthesis of experimental/field data linking specific blast parameters to PPV. Inclusion criteria prioritized peer-reviewed journal articles, conference proceedings, and authoritative technical reports, particularly those presenting aggregated data analysis, statistical evaluation of parameter influence, or comparative reviews of control strategies. Studies solely focused on airblast, fragmentation without vibration correlation, or purely theoretical/numerical without field validation were excluded.

2. Data Extraction and Synthesis Framework: Relevant data and findings were systematically extracted from the selected literature. Key extracted elements included: (a) Primary blast design parameters investigated (e.g., MIC, delay timing types and values, hole diameter/depth/inclination, burden/spacing/stiffness ratio, stemming/decking details, initiation sequence); (b) Reported quantitative influence on PPV (e.g., correlation coefficients, regression slopes, percentage reduction estimates, comparative statistics); (c) Site characteristics (geology, rock type); (d) Methodologies used in the original studies (monitoring standards, prediction models); (e) Strengths and limitations identified within the reviewed meta-analyses and major reviews. Synthesis involved grouping findings by parameter category (e.g., charge-related, timing-related, geometry-related). The relative impact and consistency of findings across different studies and meta-analyses were evaluated, noting areas of consensus, significant variability, and contradictions. Trends over time in research focus and methodology were also identified.

3. Critical Evaluation and Trend Identification: The aggregated findings were critically evaluated to assess the robustness of conclusions regarding parameter optimization. This involved examining the methodological rigor of the underlying studies included in past meta-analyses, the representativeness of the aggregated data across diverse geological settings, and the handling of confounding factors. The evolution of understanding – from reliance on simple scaled distance to the recognition of complex interactions and the role of advanced techniques like modeling and ML – was charted. Gaps and limitations inherent in the existing body of meta-analytical work were identified, paving the way for discussing future research needs.

4. Critical Analysis of Past Work

Despite the substantial body of work synthesized through meta-analyses, significant limitations and challenges persist in optimizing blast design for vibration control:

Over-reliance on Scaled Distance and Site Variability: The pervasive use of site-specific scaled distance laws, while practical, often masks the underlying physics and complex interactions. Meta-analyses consistently show large variations in the attenuation constant (β) and site factor (K), even for similar rock types. This variability stems from the inability of simple SD to capture crucial factors like complex wave propagation paths, anisotropic rock mass properties (jointing, bedding planes), varying degrees of saturation, topographic amplification effects, and explosive-rock coupling efficiency. Consequently, SD predictions for new sites or significantly altered blast designs on existing sites can be unreliable without extensive calibration blasts, which are costly and disruptive. Past meta-analyses often struggle to quantitatively disentangle the pure parameter effect from overwhelming site-specific geological influences using aggregated field data.

Inconsistent Definitions, Measurement, and Reporting: A major hurdle for robust meta-analysis is the lack of standardization across primary studies. Key terms like "Maximum Instantaneous Charge" (MIC) lack a universally applied temporal window definition (8ms is common but not universal). Delay timing accuracy and actual achieved delays versus design are frequently not reported or measured with sufficient precision. Vibration monitoring practices (sensor type, orientation, coupling, location selection relative to geology/topography) vary, impacting data quality and comparability. Descriptions of blast design parameters (e.g., precise stemming length/material, exact initiation sequence) and geological conditions are often inadequate. This inconsistency introduces significant noise and bias into aggregated datasets, making it difficult for meta-analyses to draw precise quantitative conclusions about parameter effects independent of measurement artefacts.

Limited Exploration of Complex Interactions: Blast design parameters do not act in isolation. Meta-analyses often focus on correlating individual parameters with PPV, but the reality involves complex, non-linear interactions. For instance:

- The optimal delay time depends on burden and spacing (stiffness).
- The effectiveness of decking interacts with hole diameter, depth, and rock stiffness.
- Pattern geometry influences confinement, which affects how MIC and timing translate to vibration energy.
- Geological structure can drastically alter how timing sequences influence wave superposition at a point. Most meta-analyses, constrained by the data available in primary studies, lack the granularity to systematically explore and quantify these higher-order interactions across diverse sites.

Focus on PPV and Neglect of Frequency/Duration: Regulatory focus and measurement practicality have led to PPV being the dominant metric in meta-analyses. However, the potential for structural damage and human annoyance is also strongly influenced by vibration frequency content and duration. Low-frequency vibrations travel farther and can resonate with large structures, while high frequencies attenuate faster but may cause rattling. Longer durations increase perceived annoyance. Blast design parameters (e.g., timing, charge distribution) significantly influence frequency spectra and duration. Past meta-analyses have largely neglected the synthesis of findings related to frequency control through parameter optimization, representing a significant knowledge gap.

Challenges in Isolating Control Strategy Efficacy: Evaluating the true effectiveness of specific vibration control strategies (e.g., precise electronic delays vs. pyrotechnic, specific decking schemes) is difficult in meta-analyses. Confounding factors abound: controlled experiments isolating single changes are rare in large-scale production blasting; adopting advanced techniques often coincides with overall improved blast design practices; geological variability between sites implementing different strategies muddies comparison. Consequently, meta-analyses often report associations rather than causally proven efficacy for specific techniques.

Underutilization of Advanced Data: While the potential of numerical modeling and ML is acknowledged in recent meta-reviews, the integration of findings from these advanced methods into comprehensive optimization frameworks synthesized by meta-analysis remains limited. Results from sophisticated 3D models or complex ML algorithms are often site-specific case studies, making broad quantitative synthesis challenging. Furthermore, the "black box" nature of some ML models hinders the extraction of generalizable physical insights about parameter influence.

5. Discussion

This meta-analytic review consolidates a clear hierarchy of influence among blast design parameters for vibration minimization. Scaled Distance (SD), defined using Maximum Instantaneous Charge (MIC), remains the undisputed primary factor, underpinning all regulatory frameworks and serving as the essential first step in prediction and control. However, the substantial site-specific variability in the SD law constants (K, β) underscores its limitation as a sole optimization tool and highlights the profound impact of uncontrollable geological factors. This necessitates site-specific vibration monitoring and model calibration as a fundamental practice. Beyond SD, the optimization landscape requires meticulous attention to delay timing precision and sequencing. Meta-analysis conclusively demonstrates that millisecond delays are not merely for fragmentation; they are a powerful vibration control lever. Achieving optimal inter-hole delays (typically 3-9 ms/m of burden/spacing) and sufficiently long inter-row delays (often ≥ 1.5-2 times inter-hole delay) is critical to promote wave superposition effects that reduce PPV compared to poorly timed or simultaneous detonations. The move towards high-precision electronic initiation systems is strongly supported by aggregated findings, enabling the reliable execution of complex timing designs crucial for vibration control.

Blast geometry (hole diameter, depth, inclination, burden, spacing, stiffness ratio) and charge distribution (stemming, decking) form the next critical layer. While their influence is sometimes partially captured indirectly in SD (via MIC), meta-analysis shows that optimizing these parameters directly impacts confinement, energy efficiency, and the vector nature of vibration generation. Patterns designed for good fragmentation (appropriate B, S, S/B ratio) generally correlate with lower vibrations for a given MIC. Decking is a validated strategy for reducing MIC per hole source, particularly beneficial near sensitive areas. Adequate stemming prevents energy waste and indirect vibration increases. The discussion reveals that effective vibration minimization is not achieved by tweaking a single parameter but requires a holistic, integrated design approach. Parameters interact: optimal timing depends on geometry; decking effectiveness depends on confinement (geometry and geology). Future optimization strategies must explicitly account for these interactions. This is where advanced techniques show promise. While traditional meta-analysis struggles with interactions, numerical modeling offers a platform to explore parameter sensitivity and interaction effects in silico, providing deeper physical insight to complement field data. Machine Learning, particularly when fed high-quality, standardized field data encompassing design, geology, and vibration results (PPV and frequency), holds immense potential to develop next-generation predictive models that capture the complex non-linear relationships and interactions identified as limitations in past work. These models can move beyond simple SD extrapolation to offer truly site-adaptive, optimized blast designs. The persistent challenge of standardization in measurement, terminology, and reporting must be addressed to improve the quality of future primary research and, consequently, the robustness of future meta-analyses. Furthermore, expanding the focus beyond PPV to include frequency spectra and duration in both monitoring and optimization efforts is crucial for comprehensive vibration management addressing both damage potential and community annoyance.

6. Conclusion

This meta-analytic review unequivocally confirms that optimizing blast design parameters is fundamental for minimizing blast-induced ground vibrations. Scaled Distance, based on Maximum Instantaneous Charge (MIC) and distance, remains the strongest empirical predictor of Peak Particle Velocity (PPV), but its site-specific nature, reflected in highly variable K and β constants, necessitates local calibration and highlights the significant role of uncontrollable geological factors. Moving beyond scaled distance, precise control of millisecond delay timing, particularly optimal inter-hole and inter-row delays, emerges as the most critical active design parameter for vibration reduction through wave interaction management. Blast geometry (hole dimensions, pattern stiffness) and charge distribution control (effective stemming, strategic decking) significantly influence confinement and energy release efficiency, directly impacting vibration generation magnitude. Initiation sequence offers secondary directional control potential. Critically, the review identifies major limitations in past meta-analyses: over-reliance on often inadequately calibrated SD models; inconsistent definitions and reporting hindering data comparability; insufficient exploration of complex parameter interactions; and a predominant focus on PPV neglecting frequency and duration. Future advancements hinge on adopting standardized monitoring and reporting practices, explicitly researching parameter interactions, incorporating frequency control objectives, and leveraging advanced numerical modeling and machine learning. These techniques offer pathways to develop holistic, site-adaptive optimization models that transcend simplistic scaled distance reliance. Ultimately, minimizing ground vibrations requires a comprehensive, integrated blast design philosophy that meticulously controls charge distribution, timing precision, and geometric configuration, informed by robust site characterization and continuous performance monitoring.

7. References

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