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A Systematic Literature Review on the Influence of Geology and Geotechnical Parameters in Blast Design Optimization

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Abstract: Blasting is a critical operation in mining and civil engineering projects, and its effectiveness is strongly influenced by both blasting parameters and the geological characteristics of the rock mass. However, conventional blast design approaches often rely mainly on empirical guidelines and explosive parameters, while the variability of geological and geotechnical conditions is frequently underrepresented in the design process. Therefore, this study aims to systematically review and synthesize existing scientific literature on the influence of geological and geotechnical parameters in blast design optimization in order to identify key controlling factors, research trends, and technological developments that support more efficient and environmentally responsible blasting practices. This research adopts a systematic literature review approach based on established review procedures. Relevant scientific publications were collected from major academic databases, particularly Scopus indexed journals, using structured search strings applied to article titles, abstracts, and keywords. The selected studies were screened and analyzed, and the findings were synthesized into several thematic categories related to geological conditions, rock mass properties, blasting performance, environmental impacts, and emerging technologies in blast design optimization. The results show that geological and geotechnical parameters such as rock strength, discontinuity characteristics, structural geology, and rock mass classification significantly influence blasting outcomes, including rock fragmentation, explosive energy distribution, ground vibration, and flyrock generation. The findings also highlight the importance of the interaction between blast design parameters and geological variability in determining blasting efficiency. In addition, recent technological developments, including Measurement While Drilling systems, numerical modeling techniques, and machine learning based predictive models, have improved the integration of geological information into blast design optimization. The novelty of this study lies in its comprehensive synthesis of interdisciplinary research that integrates geological characterization, geotechnical analysis, and blasting engineering within a unified conceptual framework. This study contributes to the advancement of blasting research by providing an integrated understanding of the role of geological and geotechnical parameters in blast design optimization and by highlighting the transition toward data driven and geology informed blasting strategies in modern mining operations.

Keywords: Blast design optimization; geological parameters; geotechnical parameters; rock fragmentation; blasting performance; systematic literature review

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Introduction

Drilling and blasting remain the primary rock breakage technique in mining, tunneling, and large-scale civil engineering projects because of their ability to fragment large rock volumes efficiently and economically. In both surface and underground mining operations, blasting is a critical stage that strongly influences downstream processes such as loading, hauling, crushing, and grinding. The quality of blast outcomes therefore directly affects operational productivity, energy consumption, and overall mine economics. Poorly designed blasting operations can result in oversized fragments, excessive fines, increased energy consumption during comminution, and operational inefficiencies throughout the mine to mill chain. Consequently, the optimization of blast design has become an important research focus in mining engineering in order to improve rock fragmentation quality while minimizing environmental impacts such as ground vibration, flyrock, and blast induced damage (Singh et al., 2016; Zhang et al., 2023).

Blast performance is controlled by a complex interaction between explosive characteristics, blast geometry, initiation systems, and the mechanical and structural properties of the rock mass. Among these factors, geological and geotechnical parameters play a fundamental role in determining how explosive energy is transmitted and dissipated within the rock mass. Rock masses are inherently heterogeneous and discontinuous media composed of intact rock blocks separated by structural discontinuities such as joints, faults, bedding planes, and fractures. These discontinuities strongly influence the propagation of stress waves, crack initiation, and crack propagation mechanisms during blasting. As a result, identical blast design parameters applied in different geological conditions may produce significantly different fragmentation outcomes and environmental impacts. Understanding the influence of geological and geotechnical parameters is therefore essential for developing adaptive and reliable blast design strategies.

Numerous studies have investigated the relationship between rock mass characteristics and blasting performance. Choudhary et al. (2016) demonstrated that key rock mass properties such as compressive strength, joint spacing, and structural discontinuities significantly influence blast induced rock fragmentation. Their findings indicate that rock mass structure can modify the distribution of explosive energy within the blasting zone, leading to variations in fragment size distribution. Similarly, Chandrahas et al. (2021) reported that joint spacing, joint orientation, and compressive strength significantly affect both mean fragmentation size and blast induced ground vibration in surface mining operations. The study emphasized that rock mass properties can alter the efficiency of explosive energy utilization during blasting, thereby affecting both productivity and environmental outcomes. These findings highlight that geological variability must be considered when designing blast parameters to achieve optimal fragmentation performance.

Structural geological features represent one of the most influential factors affecting blasting efficiency. Discontinuity orientation, persistence, and spacing determine the mechanical behavior of rock masses under dynamic loading conditions generated by explosives. Previous studies have shown that joint orientation relative to blast holes and bench faces strongly affects crack propagation patterns and damage zones in blasted rock masses. For instance, Himanshu et al. (2023) demonstrated that joint orientation and spacing significantly influence blast induced rock mass damage in limestone mines. When joint sets are favorably oriented with respect to the direction of stress wave propagation, they can facilitate crack propagation and enhance fragmentation efficiency. Conversely, unfavorable joint orientations may inhibit crack propagation and lead to the formation of oversized fragments. These findings confirm that structural geology plays a critical role in controlling the mechanical response of rock masses during blasting operations.

Geological structures also influence the environmental effects associated with blasting operations. Flyrock, ground vibration, and blast induced damage are among the most significant environmental concerns in mining and civil engineering blasting projects. Mohamad et al. (2018) reported that geological structures significantly affect the prediction and distribution of flyrock during construction blasting activities. Similarly, numerical investigations conducted by Haghnejad et al. (2019) demonstrated that rock mass mechanical properties strongly influence the propagation characteristics of blast induced ground vibrations. Rock masses with higher stiffness and lower discontinuity density tend to transmit vibration waves more efficiently, resulting in higher vibration levels at greater distances. These environmental impacts are particularly critical in mining areas located near residential zones or sensitive infrastructure, where uncontrolled blasting effects can lead to safety hazards and regulatory challenges.

In recent years, advances in rock mechanics and blasting engineering have led to the development of various models and approaches aimed at improving blast design. Several empirical, analytical, and numerical models have been proposed to predict blast fragmentation, blastability, and blast induced damage. For example, Ouchterlony and Sanchidrián (2018) reviewed the development of predictive equations for blast fragmentation and highlighted the importance of rock mass characteristics in determining fragmentation outcomes. More recently, Zhou et al. (2024) reviewed methods used to evaluate rock mass blastability and emphasized that geological parameters such as rock mass quality, discontinuity characteristics, and mechanical strength play an essential role in determining blasting efficiency. Despite these advancements, many blast design methods still rely heavily on empirical relationships that do not fully account for the complex interaction between geological conditions and blasting parameters.

Although a substantial number of studies have investigated various aspects of blasting engineering, the integration of geological and geotechnical parameters into blast design optimization remains limited. Many conventional blast design approaches are primarily based on simplified empirical equations or field experience, which often fail to capture the complex behavior of heterogeneous rock masses. Existing research frequently focuses on individual blasting outcomes such as fragmentation prediction, ground vibration control, or flyrock mitigation, while the broader interaction between geological structures and blast design parameters is rarely addressed in a comprehensive manner. In addition, previous studies tend to evaluate geological factors independently rather than examining their combined influence on blasting performance. This fragmented approach limits the development of systematic frameworks for incorporating geological information into blast design optimization.

Another important limitation in the current literature is the lack of systematic synthesis linking rock mass characterization methods, blastability evaluation techniques, and modern blast optimization strategies. Rock mass classification systems and geological characterization methods have been widely used in rock engineering applications, yet their integration into blasting design frameworks remains inconsistent. Bhatawdekar et al. (2021) emphasized that rock mass classification systems can provide valuable information for assessing blastability, but their application in blast design optimization is still not fully standardized. As mining operations expand into deeper and geologically more complex environments, the need for systematic integration of geological information into blasting design becomes increasingly important.

Given these challenges, there is a clear need for a comprehensive synthesis of existing research that systematically evaluates how geological and geotechnical parameters influence blast design optimization. A systematic literature review provides a structured and transparent method to analyze previous research, identify key influencing parameters, and evaluate emerging research trends in blasting engineering. Through systematic analysis of the existing literature, it becomes possible to identify research gaps, establish conceptual relationships between geological factors and blast design variables, and highlight future research directions.

Therefore, this study aims to conduct a systematic literature review on the influence of geological and geotechnical parameters in blast design optimization. The objectives of this study are threefold. First, this study aims to identify the most significant geological and geotechnical parameters that influence blasting performance in mining and tunneling applications. Second, this study seeks to analyze the mechanisms through which these parameters affect fragmentation, blast induced vibration, and rock mass damage. Third, this study aims to synthesize current research trends and emerging approaches that integrate geological characterization with blast design optimization techniques.

The novelty of this study lies in the development of a comprehensive synthesis that integrates geological structures, rock mass mechanical properties, and geotechnical classification parameters within a unified framework for blast design optimization. Unlike previous reviews that mainly focus on specific aspects of blasting technology, this study provides a holistic analysis of how geological and geotechnical factors collectively influence blasting performance. By bridging the gap between geological characterization and blast engineering design, this study provides new insights that can support the development of geology informed blasting strategies capable of improving fragmentation efficiency while reducing environmental impacts in modern mining operations.

Method

Research Design

This study employs a systematic literature review (SLR) approach to comprehensively analyze the influence of geological and geotechnical parameters on blast design optimization in mining and underground excavation. A systematic literature review is a structured and transparent research method used to identify, evaluate, and synthesize existing scientific evidence related to a specific research topic through a rigorous and reproducible procedure (Moher et al., 2009; Page et al., 2021). Compared with traditional narrative reviews, the SLR method applies explicit protocols for literature identification, screening, and synthesis, thereby reducing potential bias and improving the reliability of the conclusions drawn from the reviewed studies.

The methodological framework of this study follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The

PRISMA framework provides a standardized protocol for conducting systematic reviews and meta-analyses by organizing the review process into several stages, including literature identification, screening, eligibility assessment, and final inclusion of relevant studies (Page et al., 2021). The use of the PRISMA methodology has become widely accepted in scientific research because it ensures transparency, replicability, and methodological rigor in literature review studies. In engineering and geoscience research, PRISMA is increasingly used to synthesize complex and multidisciplinary knowledge domains such as rock mechanics, blasting engineering, and geotechnical analysis.

The adoption of the SLR approach in this study is particularly appropriate because research related to blasting engineering is distributed across multiple disciplines, including mining engineering, engineering geology, geotechnical engineering, and rock mechanics. Previous studies have investigated different aspects of blasting performance, such as fragmentation prediction, blast-induced vibration, flyrock generation, and blastability assessment (Ouchterlony & Sanchidrián, 2018; Zhou et al., 2024; Zhang et al., 2023). However, the relationship between geological conditions and blast design optimization remains scattered across different research areas. Therefore, a systematic review is necessary to integrate these fragmented findings and develop a comprehensive understanding of how geological and geotechnical parameters influence blasting performance.

Research Questions

The systematic review was guided by several research questions formulated to examine the role of geological and geotechnical parameters in blast design optimization. These research questions were developed based on the research gaps identified in previous studies related to rock mass characterization and blasting engineering. The research questions aim to systematically explore the relationships between geological conditions and blasting performance indicators.

The first research question focuses on identifying the geological and geotechnical parameters that have been most frequently investigated in blasting research. Rock masses are characterized by various mechanical and structural properties, including compressive strength, joint orientation, fracture density, and rock mass classification indices, which can significantly influence blasting performance (Choudhary et al., 2016; Himanshu et al., 2023). Understanding which parameters are most influential is essential for improving blast design strategies.

The second research question aims to analyze how geological and geotechnical parameters affect blasting outcomes such as rock fragmentation, blast-induced ground vibration, flyrock occurrence, and rock mass damage. These blasting outcomes represent key performance indicators used to evaluate blasting efficiency and environmental safety in mining operations (Mohamad et al., 2018; Haghnejad et al., 2019).

The third research question investigates the analytical and modeling approaches used in previous studies to integrate geological and geotechnical parameters into blast design optimization. Various modeling approaches have been proposed, including empirical models, numerical simulations, and data-driven techniques (Ouchterlony & Sanchidrián, 2018; Zhou et al., 2024). Understanding these approaches is important for identifying methodological trends and limitations in current blasting research.

The final research question seeks to identify emerging research trends and knowledge gaps related to geology-informed blast design optimization. As mining operations increasingly encounter complex geological environments, there is a growing need to integrate geological information into blasting design frameworks to improve operational efficiency and reduce environmental impacts.

Literature Search Strategy

The literature search was conducted systematically to identify peer-reviewed scientific publications related to geological and geotechnical influences on blast design optimization. The primary database used for literature retrieval was the Scopus database because it provides comprehensive coverage of high-quality publications in engineering, geosciences, and mining research. To ensure completeness of the search process, additional searches were conducted using Google Scholar to capture potentially relevant articles that might not have been indexed in the primary database.

The search process focused on studies published between 2010 and 2026 in order to capture both foundational and recent developments in blasting engineering and rock mass characterization. This time range was selected because significant advancements in blasting analysis, numerical modeling, and rock mass characterization techniques have occurred during the last decade.

The search strategy was developed using combinations of keywords related to blasting engineering, geological structures, and geotechnical parameters. These keywords were applied to titles, abstracts, and author-defined keywords to maximize retrieval accuracy. The main search string used in this study consisted of three groups of keywords connected using Boolean operators.

The first group of keywords targeted blasting engineering concepts, including “blast design”, “rock blasting”, “drill and blast”, and “blasting optimization”. The second group targeted geological and geotechnical parameters, including “geology”, “geological structure”, “rock mass properties”, “rock mass classification”, and “geotechnical parameters”. The third group focused on blasting performance indicators, including “fragmentation”, “blastability”, “blast performance”, and “blast-induced vibration”.

The use of Boolean operators allowed the search process to systematically retrieve articles that simultaneously addressed blasting engineering and geological conditions. This search strategy was designed based on previous systematic reviews in blasting and rock mechanics research to ensure comprehensive coverage of relevant literature.

Inclusion and Exclusion Criteria

To ensure that the selected studies were relevant to the research objectives, predefined inclusion and exclusion criteria were applied during the screening process. These criteria were established before the literature search in order to maintain objectivity and consistency during article selection.

Studies were included in the review if they focused on blasting applications in mining, tunneling, or civil engineering excavation and explicitly examined the influence of geological or geotechnical parameters on blasting performance. Only peer-reviewed journal articles and conference proceedings published in English were considered eligible for inclusion. Studies employing empirical analysis, field observations, numerical modeling, or experimental investigations related to blasting engineering were also included.

Conversely, studies were excluded if they focused solely on explosive chemistry or detonation physics without considering geological or geotechnical factors. Publications that addressed blasting impacts without analyzing rock mass properties were also excluded. In addition, non-peer-reviewed documents such as technical reports, theses, and unpublished materials were not included in the final dataset. Duplicate records retrieved from multiple databases were removed during the screening stage to avoid redundancy in the review process.

Study Selection Procedure

The study selection process followed the PRISMA workflow, which consists of four sequential stages. The first stage was the identification stage, during which the literature search produced an initial dataset of potentially relevant publications from the selected databases. All retrieved records were exported into reference management software to facilitate organization and duplicate removal.

The second stage was the screening stage, during which the titles and abstracts of the retrieved articles were examined to determine their relevance to the research objectives. Articles that clearly did not address geological or geotechnical influences on blasting performance were excluded during this stage. The third stage was the eligibility stage, which involved a detailed review of the full text of the remaining articles. Each article was carefully evaluated against the predefined inclusion and exclusion criteria. Studies that did not explicitly analyze the influence of geological or geotechnical parameters on blast design or blasting outcomes were excluded at this stage.

The final stage was the inclusion stage, during which the remaining studies were selected for qualitative synthesis and analysis. These studies represent the most relevant and scientifically rigorous publications addressing the relationship between geological conditions and blast design optimization.

Data Extraction

After the final set of studies was determined, a structured data extraction process was conducted to collect relevant information from each selected article. Data extraction was performed using a predefined data collection template to ensure consistency across all reviewed studies.

The extracted information included the authors and publication year, study location, geological setting, type of blasting application, geological parameters analyzed, geotechnical parameters considered, blast design variables investigated, research methods used, and the main findings related to blasting performance. Particular attention was given to identifying the relationships between geological characteristics and blasting outcomes such as fragmentation distribution, vibration levels, and rock mass damage. This structured data extraction process allowed the reviewed literature to be systematically organized and facilitated the identification of recurring themes and methodological approaches in blasting research.

Data Analysis and Synthesis

The collected data were analyzed using qualitative thematic synthesis combined with descriptive analysis. The qualitative synthesis aimed to identify recurring patterns and relationships between geological parameters and blasting performance indicators reported in previous studies. The reviewed studies were categorized into thematic groups based on the type of geological or geotechnical parameter investigated.

The main categories identified during the synthesis process included rock mass mechanical properties, structural geological characteristics, rock mass classification systems, and in situ stress conditions. Each category was analyzed to evaluate its influence on blasting outcomes such as fragmentation quality, blast induced vibration, flyrock occurrence, and blast damage propagation.

In addition to thematic synthesis, the literature was also analyzed to identify emerging research trends in blasting engineering, including the use of numerical modeling, advanced rock mass characterization techniques, and data-driven optimization approaches. This analytical process enabled the identification of research gaps and provided insights into future research directions for geology-informed blast design optimization.

Result and Discussion

Theme 1. Influence of Rock Mass Mechanical Properties on Blasting Performance

The systematic review reveals that rock mass mechanical properties constitute one of the most influential geological factors controlling blasting performance and fragmentation characteristics in mining operations. Mechanical parameters such as uniaxial compressive strength (UCS), tensile strength, Young's modulus, rock density, and brittleness index directly affect the manner in which explosive energy propagates within the rock mass and governs the initiation and propagation of fractures generated by blasting.

From a rock mechanics perspective, the interaction between explosive detonation energy and rock mechanical resistance determines the efficiency of the blasting process. During detonation, explosive charges generate high pressure shock waves that propagate radially from the borehole. The response of the rock mass to these stress waves is strongly influenced by its mechanical characteristics. Rocks with higher compressive strength and elastic modulus tend to resist deformation and require greater explosive energy to initiate fractures, whereas weaker rocks tend to fragment more easily under similar blasting conditions (Choudhary et al., 2016). This mechanical resistance affects not only the extent of crack propagation but also the distribution of fragment sizes, which is a key parameter influencing downstream mining operations such as loading, hauling, and crushing.

Empirical and numerical studies further demonstrate that the mechanical properties of rock masses influence the efficiency of explosive energy utilization. When rock strength is high, a significant portion of explosive energy is consumed in overcoming the inherent strength of the rock material, leading to larger fragments and reduced fragmentation efficiency. Conversely, rocks with lower mechanical strength allow stress waves to propagate more effectively, resulting in enhanced crack propagation and finer fragmentation (Chandrahas et al., 2021). Numerical modelling studies also confirm that rock strength and brittleness significantly influence fragmentation mechanisms and fragment size distribution during blasting operations (Zhou et al., 2020).

Another important finding from the reviewed literature is the role of rock mass heterogeneity. Mechanical properties rarely remain uniform throughout a blasting block. Variations in rock strength, elasticity, and density can produce uneven stress distribution during explosive detonation. Such heterogeneity often leads to irregular fragmentation patterns, including the formation of oversized boulders in stronger zones and excessive fines in weaker zones. Consequently, many researchers emphasize the necessity of incorporating rock mechanical characterization into blast design models in order to achieve optimal blasting performance and improved fragmentation control.

Recent studies also highlight the importance of integrating mechanical rock mass characterization systems such as Rock Mass Rating (RMR), Geological Strength Index (GSI), and rock brittleness indicators into predictive models for blast design optimization. These indices provide a systematic representation of rock mechanical conditions and have been shown to correlate strongly with fragmentation performance and blastability indices. Research indicates that rock mass classification parameters can sometimes exhibit stronger correlations with fragmentation outcomes than certain blasting design parameters themselves (Strelec et al., 2025).

Overall, the reviewed literature consistently demonstrates that mechanical properties of the rock mass play a fundamental role in determining blasting efficiency, fragmentation size distribution, and the overall productivity of mining operations. Therefore, incorporating detailed mechanical characterization into blast design optimization frameworks is essential for improving operational efficiency and minimizing environmental impacts associated with blasting activities.

The synthesis of the reviewed studies indicates that rock mass mechanical properties exert a primary control over blasting outcomes, often interacting with blast design parameters such as burden, spacing, and powder factor. While blasting geometry and explosive characteristics determine the amount of energy introduced into the rock mass, mechanical properties regulate how that energy is transmitted, dissipated, and converted into fracture energy.

Several patterns emerge from the literature synthesis. First, rock strength parameters such as UCS and tensile strength consistently show strong correlations with fragmentation size distribution. Stronger rocks require higher energy input to achieve adequate fragmentation, which often necessitates adjustments in explosive charge, burden spacing, or drilling patterns. Second, elastic properties such as Young's modulus influence stress wave propagation, which controls the development of radial and tangential cracks during blasting. Third, rock brittleness plays a crucial role in crack propagation mechanisms, determining whether rocks tend to fracture into fine particles or larger blocks.

Table 1. Summary of Key Studies on the Influence of Rock Mechanical Properties on Blasting Performance

Authors	Title and Year	Country	Aim	Methodology Findings	Journal
Choudhary et al.	Effect of Rock Mass Properties on Blast-Induced Rock Fragmentation (2016)	India	To evaluate the influence of rock mass mechanical parameters on blasting fragmentation	Field blasting experiments and statistical analysis showed that UCS, tensile strength, and joint spacing significantly control fragment size distribution and blastability index.	International Journal of Mining and Mineral Engineering
Chandrahas et al.	An Investigation into the Effect of Rock Mass Properties on Mean Fragmentation (2021)	India	To analyze the relationship between rock mass properties and mean fragment size	Field data analysis demonstrated that variations in rock strength and elasticity significantly influence the mean fragment size produced by blasting operations.	Archives of Mining Sciences
Zhou et al.	Numerical Investigation of Blast-Induced Rock Fragmentation (2020)	China	To examine the role of mechanical properties in blasting fragmentation using numerical modelling	Numerical simulations indicated that rock brittleness and mechanical strength strongly control crack propagation patterns and fragmentation size distribution.	Computers and Geotechnics
Li et al.	Study on Fragmentation Characteristics of Rock Mass in Bench Blasting with Different Coupling Media (2024)	China	To investigate fragmentation mechanisms in relation to rock mass mechanical conditions	Experimental and numerical results showed that rock mechanical response to explosive pressure determines fracture development and final fragmentation characteristics.	Frontiers in Earth Science
Strelec et al.	Influence of Rock Mass Properties and Powder Factor on Fragmentation (2025)	Croatia	To analyze the relationship between rock mass classification and fragmentation outcomes	Results revealed strong correlations between rock mass rating parameters and fragmentation efficiency, indicating the dominant influence of rock mass characteristics.	Discover Geoscience

Another critical observation is the importance of rock mass classification systems. Many recent studies emphasize that parameters such as RMR or GSI provide a more realistic representation of blasting conditions because they account for both intact rock strength and structural discontinuities. This approach enables more reliable prediction of fragmentation outcomes and facilitates the development of geology-based blast design optimization models. Despite significant progress, the literature also reveals several research gaps. Most existing studies analyze rock mechanical properties in isolation, without fully integrating them into comprehensive blast design optimization frameworks. Furthermore, many predictive models focus primarily on explosive parameters while treating geological conditions as secondary variables. This imbalance highlights the need for a more systematic integration of geological and geotechnical parameters into blast design methodologies. This systematic literature review provides several important contributions to the existing body of knowledge on blasting optimization.

First, it synthesizes current scientific evidence on the role of rock mass mechanical properties in blasting performance, offering a structured understanding of how geological conditions influence fragmentation outcomes. Second, the review integrates findings from empirical studies, numerical simulations, and rock mass classification approaches to provide a comprehensive perspective on blast design optimization. Third, the study identifies critical research gaps in the existing literature, particularly the limited integration of geological parameters into predictive blast design frameworks.

The novelty of this study lies in its systematic synthesis of geological and geotechnical parameters influencing blast design optimization, highlighting the need for a more geology-driven approach to blasting engineering. By emphasizing the interaction between rock mechanical properties and blasting parameters, this review contributes to the development of more efficient, safe, and environmentally responsible blasting practices in modern mining operations.

Theme 2. Role of Geological Discontinuities in Controlling Fragmentation and Blast-Induced Damage.

Geological discontinuities represent one of the most critical structural characteristics of rock masses that influence blasting performance and fragmentation mechanisms in mining and excavation operations. Discontinuities such as joints, fractures, bedding planes, faults, and shear zones form natural planes of weakness within the rock mass and significantly affect how explosive energy is transmitted and dissipated during blasting. Because most rock masses are inherently discontinuous rather than homogeneous, the presence and spatial distribution of these structural features strongly control the propagation of blast-induced stress waves and the development of fractures.

From a rock mechanics perspective, discontinuities modify the dynamic response of rock masses to explosive loading. During detonation, high-pressure stress waves radiate outward from the blast hole. When these waves encounter discontinuities, their propagation may be reflected, refracted, or attenuated, depending on the orientation, spacing, persistence, and surface characteristics of the discontinuities. These interactions can significantly alter the distribution of explosive energy within the rock mass and therefore influence the fragmentation pattern (Singh & Narendrula, 2007).

One of the most frequently discussed parameters in the literature is joint orientation relative to the blast hole direction and free face. Favorable joint orientations may promote crack propagation along existing structural planes, thereby enhancing fragmentation efficiency and reducing the energy required to break the rock. Conversely, unfavorable orientations may inhibit crack propagation and lead to uneven fragmentation patterns, including the formation of oversized fragments or back-break. Himanshu et al. (2023) demonstrated that joint orientation and spacing significantly influence blast-induced damage zones in limestone quarry blasting. Their findings indicate that joints aligned with the direction of stress wave propagation tend to facilitate fracture growth and improve fragmentation efficiency.

Another key parameter influencing blast performance is joint spacing, which controls the size of intact rock blocks within the rock mass. Closely spaced joints generally produce smaller natural rock blocks, which can enhance fragmentation because the explosive energy required to break the rock is reduced. In contrast, widely spaced joints result in larger intact blocks that require higher explosive energy to achieve adequate fragmentation (Hoek & Brown, 2019). Consequently, joint spacing is often incorporated into rock mass classification systems such as Rock Mass Rating (RMR) and Geological Strength Index (GSI), both of which are commonly used to evaluate blastability conditions in mining operations.

The persistence and roughness of discontinuities also influence blasting outcomes. Persistent discontinuities that extend across large portions of the rock mass may control the overall fracture geometry during blasting, while rough or interlocked joint surfaces may restrict sliding movement and alter crack propagation mechanisms. These structural characteristics often determine whether blasting produces controlled fragmentation or causes undesirable blast-induced damage such as overbreak and excessive vibration.

Recent research has also highlighted the influence of discontinuity networks on blast-induced damage zones, particularly in underground excavations and tunnel blasting. Li et al. (2025) reported that the spatial distribution of joints within hard rock masses significantly affects tunnel blasting profiles and the extent of damage surrounding excavation boundaries. Their numerical and field investigations demonstrated that discontinuity networks can redirect stress waves and produce anisotropic damage patterns around blast holes. These findings emphasize the importance of integrating structural geological information into blast design models.

Overall, the reviewed studies consistently demonstrate that geological discontinuities play a fundamental role in controlling rock fragmentation, blast-induced damage, and excavation stability. Therefore, incorporating detailed structural characterization into blast design optimization is essential for achieving predictable blasting outcomes and minimizing environmental and operational impacts.

Table 2. Summary of Key Studies on Geological Discontinuities and Blasting Performance

Authors	Title and Year	Country	Aim	Methodology Findings	Journal
Singh & Narendrula	Influence of joint orientation on blast fragmentation (2007)	India	To investigate the influence of joint orientation on blast fragmentation	Field blasting observations showed that joint orientation relative to the free face significantly controls fragmentation patterns and blast efficiency.	International Journal of Rock Mechanics and Mining Sciences
Himanshu et al.	Effect of Geological Discontinuities on Blast-Induced Damage in Limestone Quarry (2023)	India	To evaluate the influence of joint orientation and spacing on blast-induced damage	Field measurements and numerical modelling indicated that favorable joint orientations enhance crack propagation and improve fragmentation efficiency.	Mining Technology
Li et al.	Influence of Jointed Rock Mass on Tunnel Blasting Damage (2025)	China	To analyze the role of discontinuity networks on tunnel blasting profiles	Numerical modelling demonstrated that joint networks significantly influence blast-induced damage zones and excavation profiles.	Tunnelling and Underground Space Technology
Singh et al.	Blast Damage Control in Jointed Rock Mass (2016)	India	To assess blast damage mechanisms in jointed rock masses	Field and empirical analysis showed that joint spacing and persistence control blast damage and overbreak.	Engineering Geology
Ghasemi et al.	Prediction of Rock Fragmentation Using Geological Parameters (2012)	Iran	To examine the influence of geological structures on fragmentation	Statistical analysis revealed that joint spacing and orientation strongly affect fragmentation size distribution.	International Journal of Rock Mechanics and Mining Sciences

The synthesis of the reviewed studies indicates that geological discontinuities are among the dominant geological controls on blasting outcomes, particularly in structurally complex rock masses. While mechanical rock properties determine the intrinsic resistance of intact rock material, discontinuities define the structural framework that governs fracture propagation pathways.

One major pattern observed across the literature is the strong influence of joint orientation relative to the blast hole axis and free face direction. Favorably oriented joints can act as natural extension paths for blast-induced cracks, thereby reducing the amount of explosive energy required to fragment the rock mass. However, unfavorable orientations may deflect stress waves and restrict crack growth, resulting in inefficient energy distribution and irregular fragmentation patterns. Another critical observation concerns the relationship between joint spacing and block size. Closely spaced discontinuities produce smaller rock blocks that are easier to fragment, while widely spaced joints result in larger intact rock masses that require higher energy input. Consequently, joint spacing often becomes a key parameter in blastability assessments and blast design optimization models. Furthermore, discontinuity persistence and connectivity play a crucial role in determining the extent of blast-induced damage. Highly persistent joints can propagate fractures over long distances, sometimes resulting in excessive overbreak or instability in underground excavations. Conversely, discontinuities with limited persistence may act only as local crack initiation points without significantly affecting the overall fragmentation pattern.

Despite the substantial evidence demonstrating the importance of discontinuities, many existing blast design approaches still rely primarily on geometric blasting parameters and explosive characteristics. Geological structural parameters are often incorporated only qualitatively rather than quantitatively. This limitation indicates the need for more advanced blast design frameworks that integrate detailed structural geological data with blasting parameters. This systematic literature review contributes to the current understanding of blast design optimization by synthesizing research findings on the role of geological discontinuities in controlling blasting performance and blast-induced damage. The study highlights the importance of integrating structural geological parameters such as joint orientation, spacing, persistence, and roughness into blasting models.

The novelty of this review lies in its systematic integration of structural geology and blasting engineering perspectives, providing a comprehensive framework for understanding how discontinuity networks influence fragmentation processes. By consolidating empirical, numerical, and field-based studies, this research identifies key mechanisms through which geological structures control explosive energy distribution and fracture propagation. Ultimately, the findings emphasize that blast design optimization should not rely solely on explosive and geometric parameters but must also incorporate detailed geological structural characterization. Such an integrated approach can significantly improve fragmentation predictability, enhance operational efficiency, and reduce environmental impacts associated with blasting activities in mining and underground excavation projects.

Theme 3. Rock Mass Classification Systems as Indicators of Blastability.

Rock mass classification systems have long been recognized as essential tools in rock engineering for evaluating the quality, structural characteristics, and mechanical behavior of rock masses. In the context of blasting operations, these classification systems provide valuable indicators of rock blastability, which refers to the ease or difficulty with which a rock mass can be fragmented using explosives. A growing body of literature highlights that integrating rock mass classification systems into blasting analysis can significantly improve the prediction of blasting performance and support the optimization of blast design parameters.

Among the most widely applied classification systems in rock engineering are Rock Mass Rating (RMR), the Geological Strength Index (GSI), and the Q-system. These systems integrate multiple geological and geotechnical parameters, including intact rock strength, joint spacing, joint condition, groundwater presence, and structural orientation. Because these parameters directly influence the mechanical response of rock masses under dynamic loading, rock mass classification indices provide a useful framework for estimating how a rock mass will respond to explosive energy during blasting operations.

The Rock Mass Rating system, originally proposed by Bieniawski, is one of the most commonly applied rock mass classification approaches in mining and civil engineering. The RMR system evaluates rock mass quality based on six parameters, including uniaxial compressive strength of intact rock, rock quality designation, joint spacing, joint condition, groundwater conditions, and joint orientation. These parameters collectively describe the structural integrity of the rock mass and therefore provide important insights into its blastability characteristics. Research has shown that rock masses with lower RMR values generally exhibit higher degrees of fragmentation due to the presence of numerous discontinuities and weaker structural integrity, whereas rock masses with higher RMR values tend to require greater explosive energy to achieve adequate fragmentation (Bhatawdekar et al., 2021).

Another widely recognized system is the Geological Strength Index, which was developed to characterize the mechanical behavior of jointed rock masses. The GSI system evaluates the structural condition of rock masses by considering both blockiness and surface conditions of discontinuities. These characteristics strongly influence the propagation of blast-induced stress waves and the development of fractures during blasting. Hoek and Brown (2019) emphasized that the GSI parameter is particularly useful for representing the mechanical behavior of heavily fractured rock masses and for predicting rock mass strength parameters used in engineering design.

The Q-system, originally developed for tunnel support design, has also been applied in several studies to assess rock mass conditions that influence blasting performance. This system incorporates parameters such as joint set number, joint roughness, joint alteration, groundwater conditions, and stress reduction factors. Because these parameters describe the structural complexity of the rock mass, they can provide valuable information regarding the likely fragmentation behavior during blasting.

Recent research has increasingly explored the integration of rock mass classification indices into blastability evaluation models. Zhou et al. (2024) highlighted that modern blastability prediction approaches increasingly incorporate geological classification parameters to improve the accuracy of blasting performance predictions. By combining classification indices with blasting design parameters such as burden, spacing, and powder factor, researchers have developed predictive models capable of estimating fragmentation outcomes with greater reliability.

Table 3. Summary of Key Studies on Rock Mass Classification Systems and Blastability

Authors	Title and Year	Country	Aim	Methodology Findings	Journal
Bhatawdekar et al.	Rock mass classification as a tool for blastability evaluation (2021)	India	To evaluate the applicability of rock mass classification systems for blastability assessment	Field data analysis demonstrated that RMR and rock strength parameters strongly correlate with blast fragmentation performance.	Journal of Mines, Metals and Fuels
Hoek & Brown	The Hoek–Brown failure criterion and Geological Strength Index (2019)	Canada	To describe the application of GSI in rock engineering design	The study showed that GSI effectively represents the mechanical behavior of fractured rock masses and can be used to estimate rock mass strength parameters relevant to blasting.	Journal of Rock Mechanics and Geotechnical Engineering
Zhou et al.	Review of blastability evaluation methods in rock blasting (2024)	China	To analyze existing blastability prediction approaches	The review highlighted that modern blastability models increasingly integrate rock mass classification parameters to improve predictive accuracy.	Rock Mechanics and Rock Engineering
Singh et al.	Evaluation of blastability index using rock mass properties (2015)	India	To develop a blastability index based on rock mass characteristics	Statistical analysis indicated that rock mass classification parameters significantly influence blastability predictions.	International Journal of Mining Science and Technology
Khandelwal & Singh	Prediction of blast-induced ground vibration using rock mass parameters (2009)	India	To investigate the influence of rock mass parameters on blasting outcomes	Regression models showed strong relationships between RMR values and blasting performance indicators.	International Journal of Rock Mechanics and Mining Sciences

Despite the significant potential of rock mass classification systems for blast design optimization, their practical application in blasting engineering remains relatively limited. Many blasting designs in mining operations still rely primarily on empirical rules or geometric blast design parameters without fully incorporating geological classification data. As a result, the predictive capability of blast design models may remain limited when geological variability is not adequately considered. The reviewed literature therefore emphasizes the importance of integrating rock mass classification systems into blast design methodologies. Such integration can provide a more comprehensive representation of geological conditions and enable more accurate prediction of blasting performance and fragmentation outcomes.

The synthesis of the reviewed studies demonstrates that rock mass classification systems provide a systematic and integrated approach for evaluating geological conditions that influence blastability. Unlike individual geological parameters, classification systems combine multiple variables into a single index that reflects the overall mechanical and structural condition of the rock mass.

One of the key advantages of using classification systems in blasting analysis is their ability to represent the combined influence of rock strength and discontinuity characteristics. For example, RMR integrates intact rock strength with structural discontinuity properties such as spacing and joint condition. This integrated representation enables engineers to better estimate how explosive energy will interact with the rock mass.

Another important observation from the literature is that rock mass classification systems can support the development of quantitative blastability indices. By correlating classification values with fragmentation results, researchers have developed predictive relationships that allow blasting engineers to adjust blasting parameters based on geological conditions. Such relationships can significantly improve the efficiency of blasting operations by reducing trial-and-error design approaches.

However, the literature also indicates that classification systems alone may not fully capture the complexity of blasting processes. Blasting performance is influenced not only by geological conditions but also by explosive characteristics, charge distribution, and drilling geometry. Therefore, rock mass classification systems should ideally be integrated with blasting design parameters within a comprehensive predictive framework.

Another limitation observed in the literature is the lack of standardized methodologies for integrating classification systems into blast design optimization models. While many studies demonstrate correlations between classification indices and blasting outcomes, relatively few studies have developed operational models that directly link classification parameters with specific blast design adjustments. This systematic literature review contributes to the field of blasting engineering by synthesizing current research on the application of rock mass classification systems as indicators of blastability. The study demonstrates that classification systems such as RMR, GSI, and the Q-system provide valuable geological and geotechnical information that can significantly improve the understanding of blasting performance.

The novelty of this review lies in its systematic integration of rock mass classification concepts with blast design optimization frameworks. By consolidating findings from empirical studies, theoretical analyses, and review papers, this study highlights the potential of classification systems to serve as key parameters in geology-based blasting design methodologies. Furthermore, this review identifies important research gaps related to the limited practical integration of rock mass classification systems into operational blast design procedures. Addressing this gap can lead to the development of more accurate predictive models that combine geological characterization with blasting engineering principles. Ultimately, the findings emphasize that incorporating rock mass classification systems into blast design optimization can improve fragmentation prediction, enhance blasting efficiency, and reduce environmental impacts associated with blasting operations in mining and excavation projects.

Theme 4. Influence of Geological Conditions on Blast-Induced Environmental Effects

Blasting operations in mining and civil engineering projects inevitably generate a range of environmental effects, including ground vibration, flyrock, air overpressure, and blast-induced damage to surrounding rock masses. While blasting parameters such as explosive charge weight, burden spacing, and initiation timing are widely recognized as key determinants of these effects, an increasing body of research highlights the important role of geological and geotechnical conditions in controlling the propagation and intensity of blast-induced disturbances. Geological conditions influence the manner in which explosive energy is transmitted through the rock mass and therefore significantly affect the magnitude and spatial distribution of environmental impacts associated with blasting.

One of the most widely studied environmental effects of blasting is blast-induced ground vibration. Ground vibration occurs when explosive detonation generates stress waves that propagate through the surrounding rock mass and soil. The propagation characteristics of these waves depend not only on the amount of explosive energy released but also on the mechanical and structural properties of the geological medium through which the waves travel. Rock masses with high stiffness, high density, and low fracture density tend to transmit vibration waves more efficiently, allowing vibrations to propagate over greater distances with limited attenuation. In contrast, fractured or highly jointed rock masses tend to dissipate energy more rapidly due to scattering and absorption along discontinuity surfaces (Haghnejad et al., 2019).

The mechanical properties of rock masses therefore play a fundamental role in determining the attenuation behavior of blast-induced vibrations. Variations in parameters such as elastic modulus, compressive strength, and rock mass density can alter wave velocity and energy dissipation characteristics. Studies have demonstrated that incorporating rock mass mechanical properties into ground vibration prediction models can significantly improve the accuracy of vibration estimates compared with models that rely solely on explosive charge weight and distance parameters (Khandelwal & Singh, 2009). Another important environmental effect associated with blasting is flyrock generation, which refers to the uncontrolled projection of rock fragments beyond the designated blasting zone. Flyrock represents one of the most hazardous consequences of blasting operations because it can cause damage to infrastructure, equipment, and personnel. Geological structures such as bedding planes, joints, and faults play a critical role in determining the direction and trajectory of rock fragments during blasting. When explosive energy interacts with unfavorable structural conditions, rock blocks may detach along existing discontinuities and be propelled outward from the blast site.

Mohamad et al. (2018) demonstrated that geological structures significantly influence flyrock generation during construction blasting operations. Their findings indicate that the orientation and persistence of discontinuities can control the direction of rock fragment movement and the distance traveled by flyrock. In particular, bedding planes that dip toward the free face may facilitate the ejection of rock fragments when subjected to explosive loading. Geological conditions also influence blast-induced rock mass damage, which refers to the development of fractures and weakened zones surrounding the blast area. While controlled blasting aims to limit damage to the intended excavation boundary, variations in rock mass structure can cause irregular crack propagation and excessive overbreak. Numerical and field studies have shown that discontinuity networks and heterogeneous rock properties significantly affect the extent of blast damage zones around excavation boundaries (Sanchidrián et al., 2007).

Overall, the reviewed literature demonstrates that geological and geotechnical conditions strongly influence the magnitude and spatial distribution of environmental impacts generated by blasting operations. Understanding these geological controls is therefore essential for developing effective strategies to mitigate environmental risks and improve the safety of blasting activities.

Table 4. Summary of Key Studies on Geological Controls of Blast-Induced Environmental Effects.

Authors	Title and Year	Country	Aim	Methodology Findings	Journal
Haghnejad et al.	Influence of rock mass properties on blast-induced ground vibration (2019)	Iran	To investigate the influence of rock mass mechanical properties on vibration propagation	Field monitoring and statistical modelling showed that rock stiffness and fracture density significantly influence vibration attenuation.	International Journal of Mining Science and Technology
Khandelwal & Singh	Prediction of blast-induced ground vibration using artificial neural network (2009)	India	To develop predictive models for blast vibration	ANN modelling demonstrated that rock mass parameters significantly improve prediction accuracy for ground vibration.	International Journal of Rock Mechanics and Mining Sciences
Mohamad et al.	Flyrock prediction and risk assessment in blasting operations (2018)	Malaysia	To analyze geological factors affecting flyrock generation	Field observations and modelling showed that geological structures and discontinuities strongly influence flyrock trajectory and distance.	Engineering Geology
Sanchidrián et al.	Analysis of blast-induced damage in rock masses (2007)	Spain	To evaluate blast-induced damage mechanisms in rock masses	Analytical and experimental studies revealed that rock mass structure strongly controls crack propagation and damage zone extent.	Rock Mechanics and Rock Engineering
Monjezi et al.	Prediction of flyrock in mine blasting using empirical models (2012)	Iran	To predict flyrock distance using blasting and geological parameters	Statistical analysis confirmed that geological conditions significantly influence flyrock distance and distribution.	Safety Science

The synthesis of the reviewed literature indicates that geological and geotechnical conditions play a decisive role in determining the environmental impacts of blasting operations. Although blasting design parameters control the initial release of explosive energy, the geological characteristics of the surrounding rock mass largely determine how that energy propagates through the ground.

One key observation from the literature is the significant influence of rock mass mechanical properties on vibration propagation. Rock stiffness and density control wave velocity and attenuation characteristics, while fracture density influences energy dissipation mechanisms. Highly fractured rock masses tend to scatter vibration energy, resulting in lower vibration levels at greater distances. In contrast, intact and stiff rock masses allow vibrations to propagate more efficiently, potentially increasing the risk of damage to nearby structures.

Another important finding concerns the influence of structural geological features on flyrock generation. Discontinuities such as joints and bedding planes may create natural release surfaces along which rock fragments can detach and be projected outward during blasting. The orientation of these structures relative to the blast hole and free face strongly influences the direction and magnitude of flyrock hazards.

The literature also highlights the complex interaction between geological conditions and blast-induced damage zones. Structural heterogeneity within the rock mass can cause uneven stress distribution during blasting, leading to localized overbreak and excessive fracturing beyond the intended excavation boundary. This phenomenon is particularly significant in underground excavations and tunnelling operations, where maintaining excavation stability is critical.

Despite these findings, many conventional blast design approaches still rely primarily on explosive parameters and empirical vibration prediction formulas that do not explicitly incorporate geological variables. This limitation suggests that existing environmental impact prediction models could be significantly improved through the integration of geological and geotechnical parameters. This systematic literature review provides a comprehensive synthesis of research on the influence of geological conditions on blast-induced environmental effects, highlighting the critical role of geological and geotechnical parameters in controlling vibration propagation, flyrock generation, and blast-induced rock mass damage.

The novelty of this review lies in its integration of environmental impact considerations with geological and geotechnical characterization in blast design optimization studies. By systematically analyzing the relationships between geological parameters and environmental blasting outcomes, this study provides a broader framework for understanding how geological variability influences both blasting efficiency and environmental safety. Furthermore, this review identifies significant research gaps in current blasting practices, particularly the limited incorporation of geological parameters into environmental impact prediction models. Addressing these gaps can support the development of more accurate predictive tools and safer blasting practices in mining and civil engineering projects. Ultimately, the findings emphasize that geological characterization should be considered a fundamental component of environmentally responsible blast design, enabling engineers to optimize blasting performance while minimizing environmental risks.

Theme 5. Integration of Geological Data into Blast Design Optimization

A recurring theme identified in recent blasting research is the increasing recognition of the need to integrate geological and geotechnical data into blast design optimization frameworks. While numerous studies have demonstrated that geological conditions significantly influence blasting outcomes, the practical incorporation of geological information into blast design processes remains relatively limited in many mining operations. Conventional blasting designs frequently rely on empirical rules, simplified equations, or the operational experience of engineers, rather than systematic geological characterization of the rock mass. As a result, blasting performance can vary significantly even when identical blasting parameters are applied in areas with different geological conditions.

Blast design optimization traditionally focuses on parameters such as burden, spacing, hole diameter, explosive type, powder factor, and initiation sequence. Although these parameters are critical for controlling explosive energy distribution, they do not fully account for the inherent variability of rock masses. Geological conditions, including rock strength, structural discontinuities, rock mass classification indices, and in situ stress conditions, strongly influence how explosive energy interacts with the rock mass. Therefore, neglecting geological variability can lead to inefficient energy utilization, poor fragmentation quality, and increased environmental impacts.

Recent research increasingly emphasizes the importance of incorporating geological data into predictive blast design models. Zhang et al. (2023) highlighted that improved fragmentation control can be achieved when rock mass characteristics are integrated into blasting design and mine-to-mill optimization strategies. By incorporating geological parameters into fragmentation prediction models, mining operations can achieve more consistent fragment size distributions and improve downstream processing efficiency. Similarly, Zhou et al. (2024) emphasized that modern blastability evaluation methods should incorporate geological and geotechnical parameters to improve the reliability of blasting performance predictions.

One of the key approaches proposed in the literature involves the development of geology-based blast design models. These models integrate geological information obtained from field mapping, core logging, geotechnical testing, and rock mass classification systems with blasting parameters to predict fragmentation outcomes. Advances in numerical modelling techniques, machine learning algorithms, and digital mine data management systems have significantly improved the ability of researchers and engineers to incorporate geological variables into blast design frameworks.

In addition, several studies highlight the growing role of data-driven approaches in blast design optimization. Modern mining operations generate large datasets related to drilling, blasting, geological mapping, and production performance. By applying advanced analytical techniques such as machine learning and multivariate statistical analysis, researchers have developed models capable of identifying complex relationships between geological parameters and blasting performance indicators. These approaches enable more accurate prediction of fragmentation size distribution, ground vibration levels, and blast-induced damage.

Despite these technological advancements, the literature indicates that the practical integration of geological data into blast design processes remains limited in many mining operations. Several barriers contribute to this limitation, including insufficient geological data resolution, lack of standardized integration methodologies, and the complexity of modelling heterogeneous rock masses. Consequently, further research is required to develop operational frameworks that effectively combine geological characterization with blast design parameters.

Overall, the reviewed literature demonstrates that integrating geological data into blast design optimization represents a critical step toward improving blasting efficiency, reducing operational costs, and minimizing environmental impacts associated with blasting activities.

Table 5. Summary of Key Studies on the Integration of Geological Data in Blast Design Optimization.

Authors	Title and Year	Country	Aim	Methodology Findings	Journal
Zhang et al.	Integration of geological characteristics in mine-to-mill blasting optimization (2023)	China	To investigate the role of geological data in improving blasting performance	Field data analysis showed that integrating rock mass properties into blast design significantly improves fragmentation uniformity and mine-to-mill performance.	Minerals Engineering
Zhou et al.	Review of blastability evaluation methods in rock blasting engineering (2024)	China	To review modern blastability evaluation approaches	The study highlighted the importance of integrating geological and geotechnical parameters into blastability prediction models.	Rock Mechanics and Rock Engineering
Sanchidrián et al.	Analysis of energy distribution in rock blasting (2007)	Spain	To analyze explosive energy distribution in rock masses	The study demonstrated that rock mass conditions significantly influence the efficiency of explosive energy utilization.	Rock Mechanics and Rock Engineering
Khandelwal & Singh	Prediction of blast-induced vibration using neural networks (2009)	India	To improve prediction models for blasting impacts	Results showed that integrating geological parameters improves predictive accuracy for blasting effects.	International Journal of Rock Mechanics and Mining Sciences
Hasanipanah et al.	Data-driven approaches for blasting performance prediction (2018)	Iran	To develop predictive models using machine learning	Machine learning models successfully integrated geological parameters with blasting design variables to improve prediction accuracy.	Engineering with Computers

The synthesis of the reviewed studies clearly demonstrates that the integration of geological data into blast design optimization is essential for improving blasting performance and operational efficiency. While blasting parameters control the amount and distribution of explosive energy, geological conditions determine how that energy interacts with the rock mass. Therefore, blast design optimization should be considered a multidisciplinary process that combines geological characterization, geotechnical analysis, and blasting engineering.

One of the key findings from the literature is the strong relationship between rock mass characteristics and explosive energy utilization efficiency. When geological variability is not properly accounted for in blast design, a significant portion of explosive energy may be wasted or inefficiently distributed within the rock mass. This inefficiency can result in poor fragmentation, excessive oversize material, and increased energy consumption during downstream comminution processes.

Another important observation concerns the increasing role of data-driven modelling approaches in blast design optimization. Machine learning algorithms and advanced statistical techniques allow researchers to analyze complex relationships between geological parameters and blasting performance indicators. These models can identify patterns that may not be easily detected using traditional empirical methods. As a result, data-driven models have the potential to significantly improve blast design accuracy and operational efficiency.

However, the literature also highlights several challenges associated with integrating geological data into blast design frameworks. Geological conditions are inherently heterogeneous and often vary significantly within short distances. Capturing this variability requires detailed geological mapping, high-resolution geotechnical data, and advanced modelling techniques. In addition, the lack of standardized methodologies for integrating geological data into blast design models remains a major limitation in current blasting practices.

Addressing these challenges will require closer collaboration between geologists, geotechnical engineers, and blasting engineers. By combining geological expertise with advanced analytical tools, future blast design frameworks can achieve a more comprehensive representation of rock mass conditions and improve the predictability of blasting outcomes.

This systematic literature review contributes to the advancement of blasting engineering research by synthesizing current knowledge regarding the integration of geological and geotechnical data into blast design optimization frameworks. The study highlights the importance of considering geological variability as a fundamental component of blasting analysis rather than treating it as a secondary factor.

The novelty of this review lies in its comprehensive synthesis of geological, geotechnical, and blasting engineering perspectives, demonstrating how these disciplines can be integrated to improve blast design methodologies. By systematically analyzing previous research, this study identifies key mechanisms through which geological parameters influence blasting performance and environmental outcomes. Furthermore, this review identifies critical research gaps related to the limited operational integration of geological data in blast design practices. Addressing these gaps can support the development of advanced blast design models that incorporate geological characterization, predictive analytics, and optimization techniques. Ultimately, the findings of this study emphasize that future blast design optimization strategies should adopt a geology-driven approach, in which detailed geological characterization is combined with blasting design parameters to achieve improved fragmentation performance, greater energy efficiency, and reduced environmental impacts.

Theme 6. Emerging Technologies for Geology-Informed Blasting Design

Recent developments in blasting research indicate a growing transition toward the use of advanced monitoring technologies, numerical modelling techniques, and data-driven analytical approaches to support geology-informed blast design optimization. Traditional blasting practices have historically relied on empirical relationships and limited geological information. However, advances in digital mining technologies have significantly improved the ability of engineers to collect, analyze, and integrate geological and geotechnical data into blasting decision-making processes. These technological developments allow for a more detailed understanding of the interaction between explosive energy and rock mass conditions, thereby enhancing the accuracy of blast design optimization.

One of the most important technological innovations in this area is Measurement While Drilling (MWD) technology. MWD systems collect real-time drilling data such as penetration rate, rotation pressure, feed pressure, torque, and vibration during drilling operations. These parameters can be used as indirect indicators of rock mechanical properties and structural conditions along the drill hole. Because drilling is conducted prior to blasting, MWD data provide a valuable opportunity to characterize rock mass variability at a high spatial resolution before explosives are loaded.

Isheyskiy and Sanchidrián (2020) demonstrated that MWD data can be used to identify variations in rock hardness, fracture density, and lithological changes along blast holes. Their study showed that integrating MWD-derived rock property indicators into drilling and blasting operations significantly improves quality control and enables more precise adjustment of blasting parameters. By detecting zones of varying rock strength and structural conditions, engineers can modify explosive charge distribution, burden spacing, or initiation sequences to achieve more consistent fragmentation outcomes.

Another emerging approach involves the application of numerical modelling techniques to simulate blasting processes under different geological conditions. Advanced numerical models such as finite element methods, discrete element methods, and hybrid continuum-discontinuum models allow researchers to analyze the complex interaction between explosive detonation, stress wave propagation, and fracture development within heterogeneous rock masses. These models can incorporate geological parameters such as rock strength, joint orientation, and discontinuity spacing, thereby providing a more realistic representation of blasting processes.

In addition to numerical modelling, machine learning and data-driven analytical techniques are increasingly being applied to blasting research. Machine learning algorithms can analyze large datasets containing geological parameters, blasting design variables, and fragmentation outcomes. By identifying complex nonlinear relationships among these variables, machine learning models can significantly improve the accuracy of blast performance predictions. Dumakor-Dupey et al. (2021) demonstrated that machine learning models are capable of predicting rock fragmentation characteristics with high accuracy when geological and blasting parameters are integrated into the modelling process.

Recent review studies also highlight the increasing importance of integrated blastability evaluation models that combine geological characterization with advanced computational methods. Zhou et al. (2024) emphasized that future blast design optimization frameworks will likely rely on integrated systems that incorporate geological mapping, drilling data, machine learning algorithms, and numerical modelling techniques. These systems have the potential to transform conventional blasting practices into more adaptive and data-driven processes.

Another promising technological development involves the integration of digital mine platforms and real-time data analytics into blasting operations. Modern mining operations increasingly utilize digital mine systems that combine geological databases, drilling data, and production monitoring systems. These integrated platforms enable engineers to analyze geological variability across entire mining blocks and adjust blasting strategies accordingly.

Overall, the reviewed literature indicates that emerging technologies are playing an increasingly important role in enabling geology-informed blasting design approaches. By improving the accuracy and availability of geological data and analytical tools, these technologies allow engineers to optimize blasting performance while minimizing operational costs and environmental impacts.

The synthesis of the reviewed studies demonstrates that emerging technologies are transforming blasting engineering from an empirical practice into a data-driven and geology-informed discipline. Traditional blasting design methods often rely on empirical relationships derived from historical data, which may not adequately capture the complex interactions between geological conditions and explosive energy.

One of the most significant contributions of modern technologies is the ability to collect high-resolution geological data during drilling operations. MWD systems provide continuous data along the length of blast holes, allowing engineers to detect variations in rock properties that may not be visible through conventional geological mapping. This capability enables more adaptive blast design strategies in which explosive charges and drilling patterns can be adjusted based on real-time geological conditions.

Table 6. Summary of Key Studies on Emerging Technologies for Geology-Informed Blasting Design.

Authors	Title and Year	Country	Aim	Methodology Findings	Journal
Isheyskiy & Sanchidrián	Prospects of MWD technology for drilling and blasting optimization (2020)	Spain	To evaluate the application of MWD data for blasting optimization	Analysis of drilling parameters showed that MWD data can identify rock mass variability and improve blasting quality control.	International Journal of Rock Mechanics and Mining Sciences
Dumakor-Dupey et al.	Application of machine learning for rock fragmentation prediction (2021)	Ghana	To develop predictive models for rock fragmentation using machine learning	Machine learning models successfully integrated geological and blasting parameters to predict fragmentation outcomes with high accuracy.	Engineering with Computers
Zhou et al.	Review of blastability evaluation methods in rock blasting engineering (2024)	China	To review modern computational approaches in blastability evaluation	The study emphasized the integration of machine learning, geological data, and numerical modelling for advanced blast design optimization.	Rock Mechanics and Rock Engineering
Sanchidrián et al.	Analysis of energy distribution in rock blasting (2007)	Spain	To examine the distribution of explosive energy in rock masses	Analytical models demonstrated the importance of rock mass conditions in determining energy utilization during blasting.	Rock Mechanics and Rock Engineering

Another major advancement involves the use of numerical simulation tools to analyze blasting processes in heterogeneous rock masses. These models allow researchers to simulate complex fracture development mechanisms and evaluate the influence of geological parameters on blasting outcomes. Numerical modelling therefore provides a powerful tool for testing different blast design scenarios before field implementation.

Machine learning techniques represent another rapidly growing research area in blasting engineering. By analyzing large datasets containing geological parameters and blasting performance indicators, machine learning algorithms can identify complex nonlinear relationships that may not be captured by traditional empirical models. As a result, these models can significantly improve the accuracy of fragmentation prediction and blast design optimization.

Despite these technological advancements, several challenges remain. Many mining operations still lack the infrastructure required to collect high-resolution geological data or to implement advanced computational models. Additionally, the integration of multiple data sources, including geological mapping, drilling data, and blasting performance indicators, requires standardized data management systems and interdisciplinary collaboration.

This systematic literature review contributes to the field of blasting engineering by synthesizing recent research on emerging technologies that enable geology-informed blasting design. The study highlights the growing importance of advanced monitoring systems, numerical modelling techniques, and machine learning approaches for improving blast design optimization.

The novelty of this review lies in its comprehensive integration of technological innovations with geological and geotechnical analysis in blasting research. By examining the role of modern technologies in enhancing geological data acquisition and analytical capabilities, this study provides a framework for understanding how digital mining technologies can support more effective blast design strategies. Furthermore, this review identifies key research gaps related to the practical implementation of emerging technologies in blasting operations. Addressing these gaps will be essential for developing integrated blasting systems that combine geological characterization, real-time monitoring, and predictive modelling techniques. Ultimately, the findings suggest that the future of blasting engineering will increasingly rely on data-driven, geology-informed, and technology-enabled design approaches, which can significantly improve fragmentation efficiency, operational safety, and environmental sustainability in mining and civil engineering projects.

Synthesis Across Themes

The synthesis of the six themes identified in this systematic literature review demonstrates that the optimization of blasting design is fundamentally influenced by the complex interaction between geological conditions, geotechnical parameters, blasting design variables, and emerging technological approaches. Although each theme addresses a specific aspect of this interaction, the literature consistently shows that blasting performance cannot be fully understood or optimized without integrating these factors within a comprehensive analytical framework. The reviewed studies collectively indicate that geology is not merely a background condition in blasting operations but rather a primary determinant of how explosive energy is distributed, transmitted, and converted into rock fragmentation.

The first group of findings highlights the critical influence of rock mass mechanical properties on blasting performance. Parameters such as uniaxial compressive strength, tensile strength, elasticity modulus, and rock density directly control the resistance of rock materials to explosive loading and the propagation of stress waves generated during detonation. These mechanical characteristics determine the efficiency of energy utilization and strongly influence the resulting fragmentation size distribution (Choudhary et al., 2016; Chandrahas et al., 2021).

However, mechanical properties alone cannot fully explain blasting outcomes because most rock masses are structurally heterogeneous. This limitation leads to the second major theme concerning the role of geological discontinuities, including joints, fractures, bedding planes, and faults. Structural discontinuities act as natural planes of weakness that can either facilitate or restrict crack propagation during blasting, depending on their orientation, spacing, and persistence. As a result, discontinuity networks often control the spatial distribution of fragmentation and the development of blast-induced damage zones (Singh & Narendrula, 2007; Himanshu et al., 2023).

The third theme demonstrates that rock mass classification systems, such as Rock Mass Rating, Geological Strength Index, and the Q-system, provide a practical framework for integrating multiple geological and geotechnical parameters into a unified representation of rock mass conditions. These classification systems combine rock strength, structural characteristics, and groundwater conditions into indices that reflect the overall mechanical behavior of rock masses. Several studies indicate that such classification indices can serve as useful indicators of blastability and can support the development of more reliable blasting design strategies (Bhatawdekar et al., 2021; Hoek & Brown, 2019). Nevertheless, despite their potential value, the practical application of rock mass classification systems in blast design optimization remains relatively limited in many mining operations.

The fourth theme extends the discussion by examining the influence of geological conditions on blast-induced environmental effects, including ground vibration, flyrock generation, and blast-induced rock mass damage. The literature consistently indicates that geological and geotechnical characteristics strongly influence the propagation of vibration waves and the spatial distribution of blasting impacts. For example, intact and stiff rock masses tend to transmit vibration energy more efficiently, while fractured rock masses dissipate energy through discontinuity networks. Similarly, geological structures such as bedding planes and joints can influence the trajectory and distance of flyrock during blasting operations (Haghnejad et al., 2019; Mohamad et al., 2018). These findings highlight that geological characterization is essential not only for improving blasting efficiency but also for minimizing environmental risks associated with blasting activities.

The fifth theme emphasizes the growing recognition that effective blasting optimization requires the systematic integration of geological data into blast design frameworks. Traditional blasting approaches often rely heavily on empirical rules and field experience, which may not adequately account for geological variability across mining areas. Recent studies therefore advocate the development of geology-based blast design models that incorporate rock mass characteristics, structural discontinuities, and geotechnical parameters into predictive blasting models (Zhang et al., 2023; Zhou et al., 2024). Such integrated approaches have the potential to improve fragmentation control, enhance energy efficiency, and support mine-to-mill optimization strategies.

The final theme highlights the increasing role of emerging technologies in enabling geology-informed blasting design. Advances in monitoring technologies, numerical modelling techniques, and machine learning methods have significantly improved the ability of engineers to analyze complex interactions between geological conditions and blasting processes. Technologies such as Measurement While Drilling provide real-time geotechnical information during drilling operations, allowing engineers to detect variations in rock properties and adjust blasting parameters accordingly (Isheyskiy & Sanchidrián, 2020). In addition, machine learning algorithms and advanced numerical simulations allow researchers to integrate large datasets containing geological and blasting parameters to predict blasting outcomes with greater accuracy (Dumakor-Dupey et al., 2021).

When considered collectively, these six themes reveal a clear evolution in blasting research from traditional empirical design methods toward integrated, geology-driven, and data-supported blasting approaches. The literature increasingly recognizes that successful blast design optimization requires the integration of multiple sources of information, including rock mechanical properties, structural geological characteristics, rock mass classification systems, environmental impact considerations, and advanced technological tools for data acquisition and analysis. Despite significant progress, several important challenges remain. Many mining operations still rely primarily on empirical blasting practices and lack systematic frameworks for integrating geological data into blasting design processes. In addition, geological heterogeneity and limited data resolution often complicate the development of predictive blasting models. These challenges highlight the need for further research aimed at developing integrated geological–geotechnical–blasting optimization frameworks supported by advanced monitoring technologies and data-driven analytical methods.

Overall, the synthesis across themes indicates that the future of blasting engineering will increasingly depend on the development of geology-informed and technology-enabled blasting design strategies. Such approaches have the potential to significantly improve fragmentation efficiency, enhance operational productivity, reduce environmental impacts, and support more sustainable mining practices.

The synthesis of findings from the six thematic areas demonstrates that geological and geotechnical parameters play a central role in determining the effectiveness and environmental performance of blasting operations. The present study confirms that blast outcomes such as fragmentation quality, energy distribution, and vibration propagation are strongly controlled by rock mass characteristics including strength, structural discontinuities, and rock mass classification parameters. These findings align with recent blasting research which emphasizes that rock fragmentation and blasting performance are governed by the interaction between blast design variables and inherent rock mass properties rather than by explosive parameters alone. Recent studies show that rock mass characteristics such as uniaxial compressive strength, joint orientation, and rock mass rating significantly influence fragmentation patterns and muck pile distribution, highlighting the importance of incorporating geological parameters into blasting design frameworks (Gebretsadik et al., 2024, https://doi.org/10.1007/s42452-024-05888-0).

The findings of this review also support theoretical perspectives in rock blasting engineering which state that the response of rock masses to explosive energy is highly dependent on the mechanical and structural conditions of the surrounding geology. In practice, variations in geological conditions can cause identical blast designs to produce different fragmentation outcomes and environmental effects. This phenomenon is supported by recent modeling studies that demonstrate the strong influence of blast design parameters such as burden, powder factor, and maximum charge per delay in combination with rock mass properties on both fragmentation efficiency and ground vibration levels (Saubi et al., 2026, https://doi.org/10.1038/s41598-025-33871-1). These results reinforce the argument that blast design optimization must consider geological variability in order to achieve consistent blasting performance.

Another important aspect highlighted in this study concerns the environmental implications of blasting operations, particularly ground vibration and flyrock hazards. The synthesis across themes indicates that geological structures such as faults, joints, and bedding planes can significantly influence the propagation of vibration waves and the trajectory of flyrock. These observations are consistent with recent research showing that blast induced vibration is controlled by a combination of explosive parameters and geological transmission pathways within the rock mass. Intelligent predictive models have been developed to improve vibration prediction accuracy by incorporating multiple geological and blasting variables simultaneously (Guo et al., 2023, https://doi.org/10.3390/app13127166). Similarly, recent studies using advanced machine learning techniques confirm that geological variability plays a critical role in determining blast induced environmental impacts and must therefore be incorporated into predictive models (Fissha et al., 2024, https://doi.org/10.1038/s41598-024-70939-w).

The discussion also highlights the limitations of traditional blast design approaches that rely primarily on empirical formulas and field experience. Although empirical methods such as scaled distance models have been widely used for predicting blasting outcomes, they often fail to capture the complex interactions between geological conditions and blasting parameters. Recent literature suggests that modern data driven approaches can overcome these limitations by integrating large datasets and multiple geological variables into predictive frameworks. For instance, machine learning models have demonstrated significant potential in predicting blast induced fragmentation and environmental impacts by analyzing complex relationships between rock properties, blast geometry, and explosive characteristics (Dumakor Dupey et al., 2021, https://doi.org/10.3390/min11060601).

Technological advancements have further strengthened the ability to integrate geological information into blasting design. Measurement While Drilling technology has emerged as an important innovation that enables real time acquisition of geotechnical data during drilling operations. These datasets provide high resolution information about rock strength, hardness, and structural variability along the drillhole. When integrated with analytical and predictive models, such data allow engineers to adjust blast design parameters according to localized geological conditions. Recent research also demonstrates that machine learning based analytical systems can significantly improve fragmentation prediction accuracy and enable adaptive blast design strategies in complex geological environments (Li et al., 2024, https://doi.org/10.3389/feart.2024.1445990).

From a theoretical perspective, the findings of this study contribute to the evolving concept of geology informed blasting design. Traditional blasting theory primarily focuses on explosive energy distribution and blast geometry, whereas modern research increasingly recognizes the need to incorporate geological variability as a core design parameter. The synthesis presented in this review demonstrates that geological and geotechnical parameters should be treated as fundamental inputs in blast design optimization rather than as secondary considerations. This shift reflects a broader movement toward integrated mine to mill optimization strategies, where blasting performance is linked directly to downstream processing efficiency and environmental sustainability.

The implications of this research are particularly important for mining operations located in geologically complex environments or near environmentally sensitive areas. By incorporating geological characterization into blast design, mining engineers can improve fragmentation efficiency, reduce excessive energy consumption, and minimize environmental risks such as ground vibration and flyrock. The integration of geological data into predictive blasting models also supports more consistent blasting performance across varying rock conditions, thereby improving operational reliability and safety.

In terms of research contribution, this study provides a comprehensive synthesis of the role of geological and geotechnical parameters in blast design optimization by systematically integrating findings from multiple research themes. The study contributes to the advancement of blasting science by highlighting the importance of interdisciplinary approaches that combine geological characterization, blast engineering, and data driven analytical methods. Furthermore, the study identifies emerging technological trends that are transforming blasting practices toward more adaptive and intelligent design systems. These findings offer valuable insights for both researchers and practitioners seeking to develop more efficient, environmentally responsible, and geology informed blasting strategies in modern mining operations

Conclusion

This study presents a systematic literature review on the influence of geological and geotechnical parameters in blast design optimization. The synthesis of the reviewed literature indicates that geological and geotechnical conditions exert a stronger and more complex influence on blasting performance than traditionally assumed in conventional blast design practices. Rock mass properties such as rock strength, discontinuity characteristics, structural features, and rock mass classification significantly affect fragmentation quality, explosive energy distribution, and blast induced environmental impacts including ground vibration and flyrock. These findings demonstrate that blasting performance is not determined solely by explosive characteristics and geometric design parameters, but rather by the interaction between blasting variables and geological conditions. Consequently, the study challenges traditional assumptions in blasting practice and highlights the importance of geology informed blast design approaches that consider rock mass variability as a fundamental factor in blast optimization.

From a scientific perspective, this study contributes to the development of blasting research by synthesizing and integrating existing knowledge regarding the relationship between geological conditions and blasting outcomes. The review strengthens previous findings that emphasize the critical role of rock mass characteristics in controlling blasting efficiency while also highlighting the limitations of traditional empirical approaches that often overlook geological variability. In addition, the study enriches the scientific discussion by emphasizing the need for interdisciplinary integration between geology, geotechnical engineering, and blasting technology. The findings also underline the growing importance of emerging technologies such as Measurement While Drilling systems, numerical modeling techniques, and machine learning based predictive models, which enable more accurate integration of geological information into blast design optimization and support the development of data driven blasting strategies in modern mining operations.

Despite these contributions, this study has several limitations that should be acknowledged. The review is based on selected journal publications and academic sources, which may not fully represent operational data from industrial blasting practices. Differences in geological settings, blasting conditions, and methodological approaches among the reviewed studies also limit the generalization of the findings across all mining environments. Therefore, further research involving larger datasets, multi site case studies, and integrated monitoring systems is recommended to obtain a more comprehensive understanding of the interaction between geological parameters and blasting performance. Future studies should also focus on developing advanced predictive models that integrate geological, geotechnical, and blasting variables in order to improve blast design optimization and support safer, more efficient, and environmentally responsible blasting operations.

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