Blasting Parameters Optimization in Tunnel Engineering: A Survey

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Abstract

This survey provides a comprehensive analysis of blasting parameters optimization in tunnel engineering, emphasizing the critical role of controlled explosive methods in achieving efficient rock fragmentation. It explores key variables such as explosive type, charge size, and detonation timing, essential for optimizing blasting operations. The survey reviews both traditional and modern blasting techniques, evaluating their advantages and contributions to tunnel excavation efficiency and safety. A significant focus is placed on blasting effect evaluation, highlighting the use of technologies like UAVs, machine learning, and numerical simulations to enhance accuracy. The analysis of rock fragmentation discusses factors affecting fragmentation and the importance of achieving optimal fragment size for efficient excavation. The survey concludes with a summary of key points and future research directions, emphasizing the importance of optimizing blasting parameters and evaluating blasting effects for successful tunnel engineering projects.

1 Introduction

1.1 Structure of the Survey

This survey provides a detailed examination of blasting parameters optimization in tunnel engineering. The underscores the significance of controlled explosive techniques in achieving efficient and safe rock fragmentation during tunnel construction, highlighting that effective blasting optimizes rock fragment size and distribution while minimizing damage to surrounding rock mass. Key concepts discussed include the formation of tension cracks, blast pattern design, and methodologies for assessing explosive performance, which are essential for desired fragmentation outcomes and structural integrity in tunneling operations [1, 2, 3, 4]. Additionally, it identifies critical variables such as explosive type, charge size, and detonation timing.

The survey progresses to the **Background and Core Concepts**, providing an overview of fundamental concepts related to blasting parameters optimization and their significance in tunnel engineering. This section addresses tunnel construction techniques, engineering challenges, and the pivotal role of rock fragmentation.

Central to the survey is the section on **Blasting Parameters Optimization**, which investigates various parameters involved in blasting operations and explores methods and technologies for their optimization, ensuring desired fragmentation while mitigating environmental impacts.

The survey further examines **Blasting Techniques in Tunnel Engineering**, reviewing both traditional and modern methods, assessing their advantages and disadvantages, and their contributions to tunnel excavation efficiency and safety.

A vital component is the **Blasting Effect Evaluation**, which analyzes methods and tools for assessing blasting impacts on rock fragmentation and the surrounding environment. This section highlights the role of technologies such as UAVs, machine learning, and numerical simulations in enhancing evaluation accuracy.

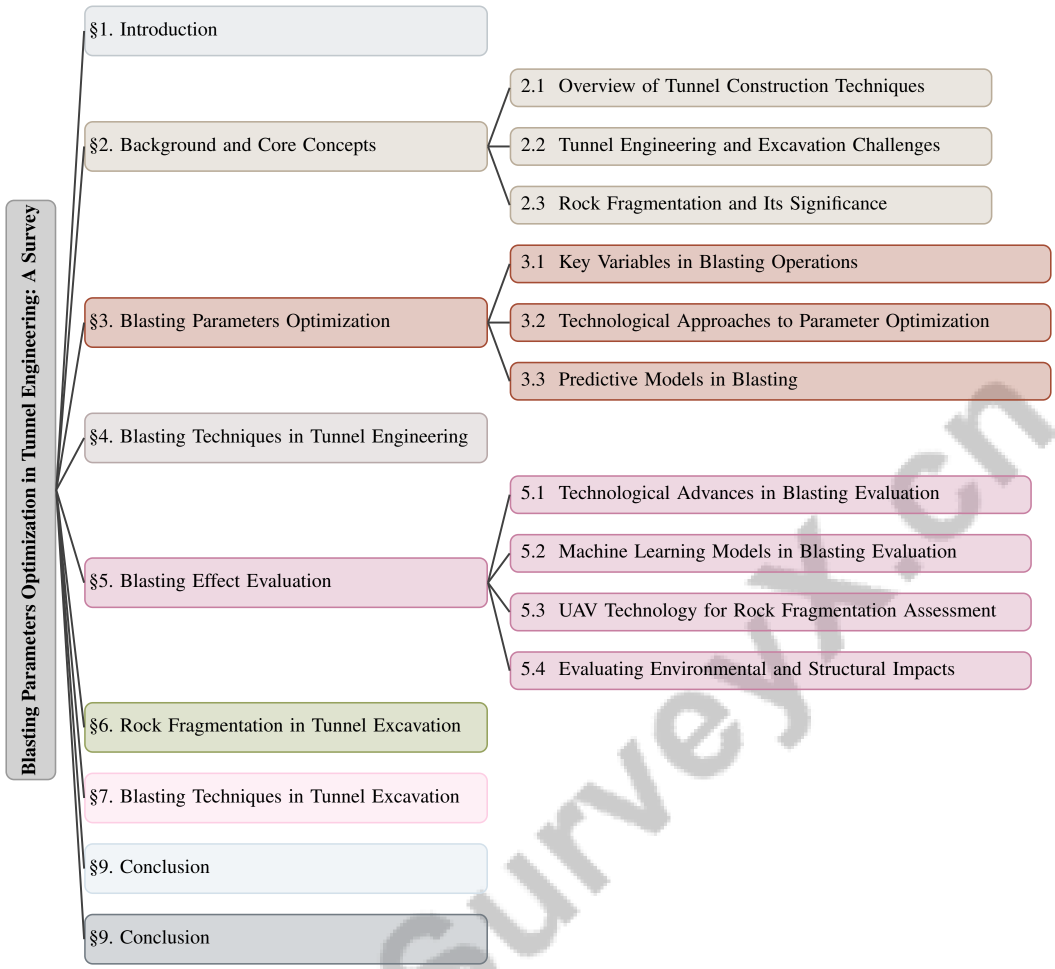

Figure 1: chapter structure

The analysis of discusses factors influencing fragmentation, including impact loading rates and rock properties, emphasizing the importance of achieving optimal fragment size to enhance excavation efficiency and subsequent mining processes. It illustrates how precise measurement techniques, particularly UAV technology, can improve rock size distribution assessments, leading to better blast design and operational efficiency in tunneling and mining [5, 6, 7].

The survey concludes with a summary of key findings and recommendations for future research directions in the **Conclusion** section, stressing the importance of optimizing blasting parameters and evaluating blasting effects for successful tunnel engineering projects.The following sections are organized as shown in Figure 1.

2 Background and Core Concepts

2.1 Overview of Tunnel Construction Techniques

Tunnel construction employs a multifaceted approach prioritizing structural stability and efficiency, with drilling and blasting as predominant methods due to their efficacy in rock fragmentation across diverse geological conditions. Conventional drilling techniques, often combined with blasting, facilitate penetration through various rock types, establishing a foundation for subsequent explosive operations [8]. Innovations like deep-hole cumulative blasting have become crucial in contexts with high gas content and low permeability, enhancing permeability and gas extraction, thereby optimizing tunnel excavation efficiency and safety [9]. Construction techniques are selected based on geological and environmental characteristics, allowing engineers to integrate traditional and

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modern methodologies to maximize benefits while minimizing drawbacks. This adaptability is vital for executing tunnel projects in complex environments where precision and control over ground characteristics, excavation techniques, and external loads, including explosions, are essential for maintaining structural integrity and safety [10, 11, 12, 13, 14].

2.2 Tunnel Engineering and Excavation Challenges

Tunnel engineering faces challenges requiring a comprehensive understanding of geological, mechanical, and technological factors. Predicting rock behavior, particularly in hydro-mechanical interactions within saturated rock masses, complicates tunneling due to seepage affecting stability, necessitating advanced modeling techniques for safe excavation [14]. Blasting operations add complexity, as induced tension cracks can destabilize surrounding rock masses, affecting support structures' load-bearing capacity [4]. Understanding dynamic fragmentation, such as in granite under high ejection velocities, is crucial for optimizing blasting parameters to enhance safety and efficiency [15]. Tunnel failure characteristics under multiple explosive loads further complicate design and evaluation processes in protective engineering [10]. Addressing these challenges requires advanced predictive models and thorough evaluations of rock mass quality to improve tunneling safety and efficiency [16]. Managing ground conditions, ensuring safety, and integrating new technologies into traditional tunneling methods remain significant hurdles [11]. Accurate predictions of flyrock distance, a critical safety concern in blasting, require precise modeling [17]. The complexity of rock fragmentation processes, influenced by joint patterns, rock resistance, and impact dynamics, adds further challenges [18]. Simulating hydro-mechanical processes in fractured rock presents significant difficulties [19]. Inadequate modeling of rockfall fragmentation can lead to inaccuracies in predicting trajectories and impacts, complicating safety and operational planning [20]. Optimizing drilling and blasting practices is crucial for enhancing operational efficiency [21]. Predicting air-overpressure from blasting remains challenging due to empirical method limitations [22]. Environmental impacts of blasting pose risks to safety, equipment integrity, and environmental health, necessitating improved prediction and management strategies [23]. A rigorous theoretical framework linking microscopic particle-based models to macroscopic mean field theories is essential for accurate predictions and simulations, contributing to successful tunnel engineering [24]. Innovative monitoring approaches are needed to detect and classify complex ground deformation signals from satellite InSAR data, particularly in urban settings during tunnel excavation [25].

2.3 Rock Fragmentation and Its Significance

Rock fragmentation is crucial in tunnel excavation, directly affecting project efficiency and success. The size distribution of rock fragments from blasting influences subsequent operations such as digging, hauling, crushing, and grinding [2]. Effective fragmentation is vital for material removal and transport and optimizing comminution processes, enhancing overall productivity [7]. Controlled fragmentation minimizes excessive vibrations and flyrock, safeguarding surrounding structures and personnel. The Discrete Element Method (DEM) effectively simulates rock fragmentation under impact conditions, providing insights into fragmentation intensity and size distribution influenced by impact loading rates [6]. These simulations are invaluable for optimizing blasting parameters to achieve desired fragmentation while mitigating environmental impacts. Technological advancements have improved the accuracy of measuring and evaluating fragmentation outcomes. Integrating deep learning techniques enhances detection accuracy and facilitates efficient processing of large datasets, offering a comprehensive understanding of fragmentation patterns [25]. This progress is essential for refining blasting strategies and ensuring that rock fragmentation positively contributes to tunnel excavation success.

In the context of tunnel engineering, the optimization of blasting parameters is critical for enhancing both efficiency and safety. As illustrated in Figure 2, this figure provides a comprehensive overview of the hierarchical categorization of blasting parameters optimization. It emphasizes key variables, technological approaches, and predictive models that are integral to the optimization process. Notably, the figure highlights the relationships and contributions of each category, focusing on essential aspects such as energy distribution, environmental impact, and operational efficiency. This visual representation not only complements the textual analysis but also serves to clarify the complex interdependencies among the various elements involved in blasting optimization.

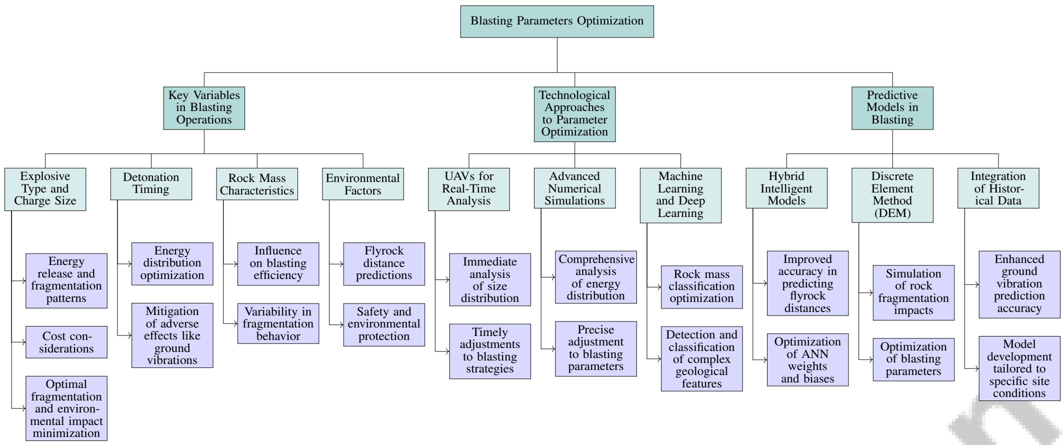

Figure 2: This figure illustrates the hierarchical categorization of blasting parameters optimization in tunnel engineering, emphasizing key variables, technological approaches, and predictive models. It highlights the relationships and contributions of each category to the overall optimization process, focusing on energy distribution, environmental impact, and operational efficiency.

3 Blasting Parameters Optimization

3.1 Key Variables in Blasting Operations

Optimizing blasting operations in tunnel engineering hinges on understanding key variables such as explosive type, charge size, detonation timing, rock mass characteristics, and environmental conditions, each of which significantly impacts rock fragmentation and excavation efficiency. Figure 3 illustrates these key variables, environmental factors, and advanced methodologies in optimizing blasting operations, highlighting the importance of explosive type, charge size, detonation timing, flyrock distance predictions, and the use of advanced technologies like machine learning and hybrid models. The choice of explosive type and charge size dictates energy release and fragmentation patterns, while precise detonation timing is crucial for managing tension crack formation and effective rock displacement. Knowledge of rock mass characteristics and environmental factors informs blast pattern design, essential for achieving desired outcomes in drilling and blasting activities [21, 3, 4].

Selecting explosives, particularly emulsions, depends on rock hardness and fragmentation objectives, with cost considerations being crucial due to the high expenses of drilling and blasting [3]. Charge size must be accurately calculated to ensure optimal fragmentation while minimizing excessive flyrock and environmental impacts [1].

Meticulous control of detonation timing optimizes energy distribution and mitigates adverse effects like ground vibrations. Advanced predictive models using machine learning algorithms enhance the classification of Measurement While Drilling (MWD) data into Q-classes and Q-values, vital for assessing rock mass stability and refining detonation strategies [26].

Rock mass characteristics, including permeability and mechanical properties, critically influence blasting efficiency. Variability in fragmentation behavior due to impact loading rates, rock properties, and environmental conditions necessitates innovative modeling approaches to comprehensively account for these influences [6]. Tailored explosive selection and charge distribution are required to address variability in rock hardness and achieve optimal fragmentation.

Environmental factors, particularly flyrock distance predictions, are pivotal for minimizing adverse impacts on surrounding structures and ecosystems. Current fragment size estimation models often lack solid theoretical foundations, limiting their reliability [23]. Hybrid models have been developed to improve flyrock distance predictions, enhancing safety and environmental protection [24].

Innovative methodologies, such as integrating laboratory impact tests with the coupled finite-discrete element method (FDEM), provide a comprehensive understanding of the fragmentation process, allowing for the refinement of blasting parameters [13]. The discrete fracture-matrix approach, coupled with robust iterative splitting, offers a sophisticated means of managing complex mechanical interactions, surpassing traditional methods in effectiveness [27].

The optimization of blasting operations involves a multifaceted evaluation of key variables like rock fragmentation quality, explosive performance, and environmental impacts, all influencing safety, equipment integrity, and operational efficiency [23, 28, 3]. Leveraging advanced technologies and predictive models enhances efficiency, safety, and environmental stewardship in tunnel engineering projects.

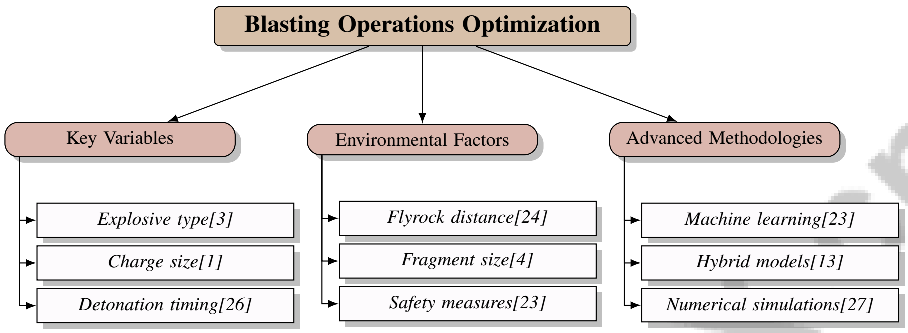

Figure 3: This figure illustrates the key variables, environmental factors, and advanced methodologies in optimizing blasting operations, highlighting the importance of explosive type, charge size, detonation timing, flyrock distance predictions, and the use of advanced technologies like machine learning and hybrid models.

3.2 Technological Approaches to Parameter Optimization

Optimizing blasting parameters in tunnel engineering has been significantly advanced through technological methods that enhance precision and effectiveness. Unmanned Aerial Vehicles (UAVs) for real-time rock fragmentation analysis (UAV-RFA) capture images of rock fragments, facilitating immediate analysis of size distribution and timely adjustments to blasting strategies [7].

Advanced numerical simulations, particularly three-dimensional models, provide comprehensive analyses of blasting operations, offering insights into energy distribution and fragmentation characteristics, enabling precise adjustments to blasting parameters [27]. The BCM method simplifies complex tunnel geometries for analysis using linear systems, improving the accuracy and efficiency of blasting parameter optimization [13].

In machine learning, the Ensemble Learning for Rock Mass Classification (ELRMC) method integrates various algorithms to optimize rock mass quality classification from MWD data, enhancing rock mass assessments and enabling informed decisions regarding explosive selection and charge distribution [26].

Evaluating explosive performance is crucial for blasting parameter optimization. A methodology assessing the performance index of explosives based on energy and detonation characteristics provides a robust framework for selecting suitable explosives for specific geological conditions [3]. This approach, combined with detailed categorization of explosives based on chemical properties and application methods, ensures alignment with desired fragmentation outcomes [8].

Deep learning techniques have improved accuracy in detecting and analyzing rock fragmentation patterns. Enhancement methods, such as spatial interpolation with modified matrix completion and synthetic training datasets, have advanced the detection and classification of complex geological features in tunnel excavation environments [25].

Integrating advanced technological approaches, including machine learning and optimization algorithms, represents a significant advancement in refining blasting parameters in tunnel engineering. These innovations enhance rock fragmentation precision and address critical environmental concerns associated with blasting operations, such as air overpressure, ground vibration, and dust generation. By systematically analyzing factors contributing to the environmental effects of blasting (EEB), researchers develop effective predictive and preventive strategies, facilitating the design of optimized

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blasting patterns that minimize damage to surrounding rock masses and improve operational safety [23, 4].

3.3 Predictive Models in Blasting

Predictive models are crucial for optimizing blasting parameters, offering sophisticated tools for understanding and controlling interactions between explosives and rock masses. These models leverage deep learning techniques to forecast critical outcomes in blasting operations, such as rock fragmentation size distributions, flyrock distances, and ground vibrations. Utilizing comprehensive datasets and sophisticated algorithms, these models enhance understanding of blast-induced effects, enabling informed decisions that optimize blast design, improve operational efficiency, and mitigate environmental risks [23, 2].

Hybrid intelligent models combining Artificial Neural Networks (ANN) with evolutionary algorithms like Particle Swarm Optimization (PSO) and Joint Simulation Algorithm (JSA) show improved accuracy in predicting flyrock distances compared to traditional methods [29]. By optimizing ANN weights and biases, these models effectively enhance prediction accuracy, addressing limitations of conventional techniques.

The Discrete Element Method (DEM) simulates rock fragmentation impacts, providing insights into the fragmentation process under various loading conditions and aiding in optimizing blasting parameters for desired outcomes [6]. Such simulations are crucial for refining blasting strategies and ensuring effective rock breakage while minimizing environmental impacts.

Integrating historical blasting data into predictive models enhances ground vibration prediction accuracy, leading to improved safety and efficiency in blasting operations [29]. This approach allows for model development tailored to specific site conditions, ensuring optimized blasting parameters for unique project site characteristics.

The advent of deep learning techniques has revolutionized rock fragmentation measurement. Deep neural networks (DNNs) predict characteristic sizes of rock fragments from two-dimensional images of muckpiles, utilizing image analysis for rapid and precise fragmentation assessments, enhancing blasting operation efficiency [6].

4 Blasting Techniques in Tunnel Engineering

Category	Feature	Method
Traditional Blasting Techniques	Simulation Techniques	BCM[13]
Modern Blasting Techniques	Simulation Techniques	TCEM[4], ODB[28]
Innovative Blasting Techniques	Simulation-Based Insights	DEM[6], DL-GDD[25]

Table 1: This table provides a comprehensive summary of various blasting techniques employed in tunnel engineering, categorized into traditional, modern, and innovative methods. Each category is associated with specific simulation techniques and methodologies, highlighting the evolution and integration of advanced modeling approaches in blasting practices. The referenced studies underscore the ongoing advancements in enhancing blasting efficiency, safety, and environmental sustainability.

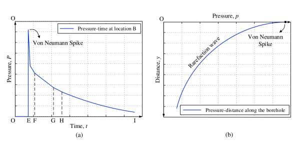
Blasting techniques are pivotal in tunnel engineering, influencing both excavation efficiency and safety. Traditional methods, which rely on explosives and careful planning, have established the foundation for advancements in this field. Table 1 presents a detailed categorization of blasting techniques in tunnel engineering, illustrating the progression from traditional to modern and innovative methods and their respective simulation techniques. Additionally, Table 2 offers a comprehensive comparison of blasting techniques in tunnel engineering, detailing the transition from traditional to modern and innovative methods and their respective technological and environmental characteristics. The subsequent subsection delves into these techniques, focusing on their mechanisms, benefits, and continued relevance in current practices.

4.1 Traditional Blasting Techniques

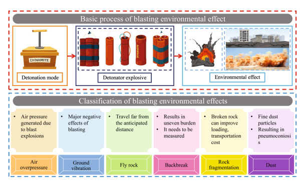
Traditional blasting techniques form the cornerstone of rock excavation in tunnel engineering, utilizing established practices to achieve effective rock fragmentation. This involves drilling boreholes filled with explosives that, upon detonation, generate pressure waves causing tension cracks in the rock. Key factors in optimizing fragmentation include blasting pattern design, explosive selection, borehole placement, and initiation sequence. Research has aimed to enhance these parameters through advanced modeling approaches—analytical, numerical, and experimental—designed to estimate explosion-induced damage and improve blasting operations [1, 4].

A critical component of traditional blasting is the precise calculation of charge size and placement to achieve desired fragmentation while minimizing adverse effects such as excessive vibrations and flyrock. Computational methods, like the bidirectional conformal mapping proposed by Lin et al., streamline the process by using only a pair of linear systems for accurate results, thereby enhancing the effectiveness of traditional techniques [13].

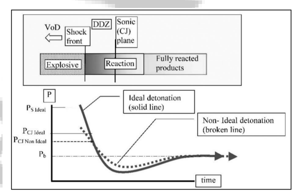
Despite technological advancements, traditional methods remain prevalent due to their adaptability to diverse geological conditions and proven efficacy. The integration of advanced computational techniques and predictive models, including hydro-mechanical modeling and machine learning algorithms, significantly enhances the efficiency and safety of traditional excavation methods. Techniques such as the smoothed excavation method in finite element software and persistent homology-based machine learning for tunnel failure analysis under explosive loads address common numerical challenges and improve predictive capabilities regarding ground vibrations and structural stability, ensuring traditional methods' continued relevance in modern tunneling projects [12, 10, 14].



(a) The rock mass response to explosion wave in the form of (a) p-t and (b) p-y graphs.[1]



(b) Basic process of blasting environmental effect[23]



(c) Detonation Process in a Explosive System[4]

Figure 4: Examples of Traditional Blasting Techniques

As shown in Figure 4, traditional blasting techniques are essential for efficient tunnel excavation. The first image illustrates the rock mass response to explosion waves via pressure-time (p-t) and pressure-displacement (p-y) graphs, demonstrating how pressure varies as the explosion wave interacts with the rock. The second image outlines the basic blasting process and its environmental effects, from dynamite depiction to the ensuing explosion and its ecological impact. The third image details the detonation process within an explosive system, emphasizing the shock wave propagation, known as the Von Karman detonation (VoD). Together, these visuals elucidate the mechanics and consequences of traditional blasting techniques, underscoring their significance in tunnel engineering [1, 23, 4].

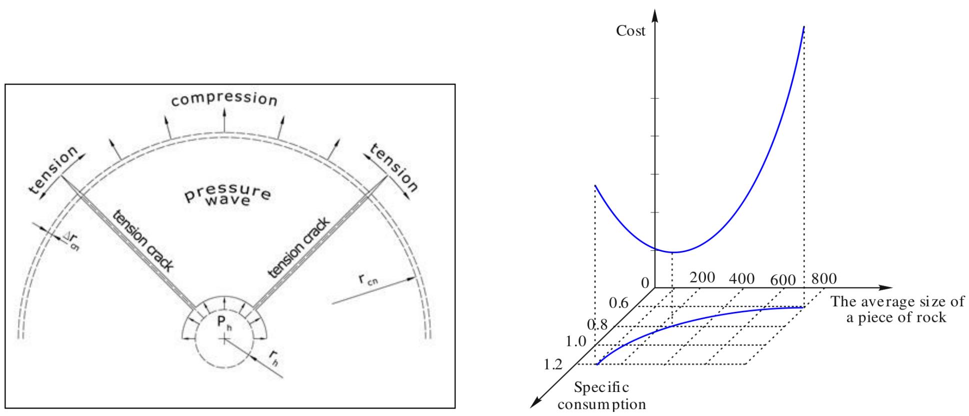
4.2 Modern Blasting Techniques

Recent advancements in blasting techniques have substantially enhanced the efficiency, safety, and precision of tunnel excavation. The Discrete Element Method (DEM) has emerged as a significant development, effectively simulating rock fragmentation dynamics under varying loading rates and surpassing previous models in accurately representing explosive forces' interactions with rock masses [6].

Technological integration into blasting operations has introduced digital blasting systems, featuring electronic detonators capable of achieving microsecond delays between explosions. This precision optimizes rock fragmentation while reducing adverse environmental impacts, such as ground vibrations and flyrock, enhancing safety for personnel and equipment and addressing environmental challenges like air overpressure and dust generation [23, 3].

Real-time monitoring and feedback systems, utilizing Unmanned Aerial Vehicles (UAVs), have also transformed blasting operations. These systems automate the collection of high-resolution rock fragmentation data, improving post-blast analysis accuracy and allowing immediate adjustments in blast strategies, thus reducing manual labor and mitigating environmental impacts [5, 23, 3, 7].

Advancements in explosive formulations have further evolved modern blasting techniques, providing higher energy output with lower environmental impact. These explosives enhance fragmentation while minimizing flyrock and ground vibrations, facilitating more effective rock fragmentation through optimized blast design, including tailored explosive selection and strategic borehole placement. Such innovations enhance safety and productivity in tunnel excavation projects by minimizing damage to surrounding rock masses and improving operational efficiency [5, 7, 9, 3, 4].



(a) Pressure Wave and Tension Crack in a Circular Structure[4]

(b) Cost vs. Specific Consumption of Product[28]

Figure 5: Examples of Modern Blasting Techniques

As depicted in Figure 5, modern blasting techniques enhance precision and efficiency. The first image illustrates the dynamics of a pressure wave and tension crack within a circular structure, highlighting the interaction of pressure and tension forces on structural integrity during blasting. This understanding is vital for optimizing blast designs to minimize damage. The second image presents a graph examining the economic implications of blasting, particularly the relationship between product cost and specific consumption, allowing engineers to balance economic efficiency with operational effectiveness. Together, these examples underscore the importance of integrating physical and economic considerations in modern blasting techniques in tunnel engineering [4, 28].

4.3 Innovative Blasting Techniques

Innovative blasting techniques in tunnel engineering signify major advancements, improving precision, safety, and environmental sustainability. Hybrid blasting techniques, merging traditional methods with modern technologies like electronic detonators and real-time monitoring systems, enable precise control over detonation timing and energy distribution, resulting in enhanced fragmentation and reduced environmental impacts [6].

The integration of machine learning and artificial intelligence into blasting operations is another groundbreaking innovation. By analyzing extensive datasets from prior blasting operations, these technologies can predict optimal blasting parameters, improving rock fragmentation patterns and blasting strategies [25].

Advanced simulation models, such as the Discrete Element Method (DEM), offer detailed insights into fragmentation processes under varying conditions, allowing engineers to simulate different blasting scenarios and refine parameters for more effective strategies tailored to specific geological contexts [6].

The development of environmentally friendly explosives and blasting agents marks a significant advancement, designed to minimize ecological impacts associated with tunnel excavation. These innovations address traditional blasting's ecological concerns by delivering high energy output with minimal harmful byproducts, promoting the sustainability of blasting operations while enhancing efficiency and safety through optimized rock fragmentation and reduced emissions [9, 23, 12, 3, 4].

Feature	Traditional Blasting Techniques	Modern Blasting Techniques	Innovative Blasting Techniques
Fragmentation Technique	Explosive Detonation	Electronic Detonators	Hybrid Methods
Technological Integration	Computational Modeling	Real-time Monitoring	Machine Learning
Environmental Impact	High Vibrations	Reduced Vibrations	Eco-friendly Explosives

Table 2: This table provides a comparative analysis of traditional, modern, and innovative blasting techniques used in tunnel engineering. It highlights key features such as fragmentation techniques, technological integration, and environmental impact, illustrating the evolution and advancements in blasting methods. The comparison underscores the progression towards more efficient, precise, and environmentally friendly blasting practices.

5 Blasting Effect Evaluation

5.1 Technological Advances in Blasting Evaluation

Technological advancements have significantly enhanced the evaluation of blasting effects, improving accuracy in assessing rock behavior and environmental impacts. The SE method is noted for its computational efficiency and convergence, proving to be a reliable tool in engineering practices [14]. Machine learning techniques, particularly persistent homology-based methods, have advanced the understanding of tunnel failure characteristics under explosive loads, offering insights beyond traditional approaches [10]. Hybrid models like PSO-ANN demonstrate superior predictive accuracy, effectively reducing the environmental impacts of blasting operations [30]. Performance metrics such as balanced accuracy, precision, recall, and F1-score underscore the field's advancements [16].

UAV-based methods have become crucial in blasting evaluation, providing rapid data collection and real-time analysis, reducing operational disruption. These methods achieve approximately 20% time savings compared to conventional techniques while maintaining accuracy in rock size distribution predictions. The point-cloud-based approach further enhances precision and safety by eliminating the need for placing scale objects [31]. In predictive modeling, the EO-ELM model surpasses PSO-ANN and PSO-ELM in predicting flyrock distance, showcasing superior accuracy and convergence [17]. Neuro-based models have outperformed traditional empirical methods in predicting PPV, proving their applicability in civil and mining engineering [12]. These technological advancements significantly improve the evaluation of blasting effects, fostering enhanced safety and environmental outcomes [23].

5.2 Machine Learning Models in Blasting Evaluation

Machine learning (ML) models have transformed blasting effect evaluations, enhancing precision and reliability in predictions of rock fragmentation, flyrock distance, and environmental impacts. By employing extensive datasets and sophisticated algorithms, these models surpass traditional empirical methods. They integrate ML and optimization techniques to accurately assess factors like rock fragmentation, air overpressure, and ground vibration, significantly improving safety and efficiency in mining activities [23, 2]. The Joint Simulation Algorithm-Artificial Neural Network (JSA-ANN) exemplifies advanced ML applications, achieving high R^2 values and lower RMSE than traditional models [29]. This accuracy underscores the potential of ML models in enhancing blasting operations' safety and efficiency.

Deep neural networks (DNNs) offer robust alternatives for rock fragmentation evaluations, demonstrating capacity for accurate assessments through mean percent error calculations [2]. These models enable rapid processing of large datasets, allowing real-time adjustments to blasting strategies. In predicting environmental impacts, ML models forecast air-overpressure (AOp) values, a critical concern in blasting operations, evaluated using metrics like RMSE, MAPE, and correlation coefficient (R) [22]. Comparative analyses of ML and orthogonal array methods in predicting explosive energy balance (EEB) emphasize ML's advantages, proving invaluable for optimizing blasting operations [23]. Integrating ML models into blasting evaluation processes marks a significant advancement in tunnel engineering, enhancing accuracy in EEB predictions and providing critical operational insights [23, 3].

5.3 UAV Technology for Rock Fragmentation Assessment

The integration of UAV technology into rock fragmentation assessment has revolutionized data collection and analysis efficiency in tunnel engineering. UAVs equipped with advanced imaging technologies capture high-resolution images of rock fragments, enabling real-time analysis and immediate feedback on blasting performance, reducing analysis time by approximately 80% compared to conventional methods [5]. UAVs operate effectively in low-light conditions, aided by artificial lighting, ensuring consistent image quality [32]. Point-cloud-based methods automate data collection, enhancing image data quality for real-time analysis [7]. This approach increases efficiency and precision through detailed 3D representations of rock fragments [31]. UAV technology significantly improves data collection efficiency, accuracy, and safety, facilitating precise optimization of blasting operations and contributing to the success and cost-effectiveness of tunnel excavation projects [2, 5, 7, 32, 31].

5.4 Evaluating Environmental and Structural Impacts

Assessing the environmental and structural impacts of blasting operations is crucial in tunnel engineering, requiring advanced methodologies. This evaluation includes environmental effects like air overpressure, ground vibrations, and dust generation, posing risks to safety and equipment integrity. Machine learning and optimization algorithms enhance the prediction and prevention of these adverse effects. Understanding rock fracturing mechanisms and explosive performance informs blasting pattern design, improving safety and efficiency [23, 10, 3, 4]. A major concern is air-overpressure (AOp) generation, potentially causing structural damage. Sophisticated predictive models, such as EO-ELM, outperform traditional methods in predicting flyrock distances, enhancing precision [17].

Advanced simulation techniques like the Finite-Discrete Element Method (FDEM) effectively evaluate fragmentation processes and damage evolution during blasting, offering insights into environmental and structural impacts [15]. The weathering index (WI) in predictive models provides nuanced insights into weathering's influence on blasting outcomes [17]. The Rockfall Fragmentation Fractal Model (RFFM) improves hazard assessment and risk management by enhancing predictions related to rock fragmentation during rockfall events [18]. UAV technology has revolutionized rock fragmentation assessment, improving accuracy in low-light conditions and ensuring reliable data collection [32]. Innovative methodologies, including ML and optimization algorithms, advance the assessment and management of blasting's environmental effects, enabling comprehensive evaluations of factors like rock fragmentation and air overpressure. These advancements improve blasting parameters' accuracy, contributing to safer and more efficient practices, enhancing operational safety and environmental stewardship [23, 9, 3].

6 Rock Fragmentation in Tunnel Excavation

6.1 Factors Affecting Rock Fragmentation

Rock fragmentation plays a pivotal role in tunnel excavation, influencing project efficiency and success through its impact on rock fragment size distribution, which affects downstream processes such as digging, hauling, crushing, and grinding. Advancements like UAVs for real-time analysis have improved data collection, enhancing prediction accuracy and optimizing blast designs, thereby facilitating effective excavation management and reducing costs [5, 32, 2, 7]. The fragmentation process, particularly through blasting, directly determines fragment sizes, making effective fragmentation crucial for efficient material transport and comminution.

The dynamic nature of fragmentation, significantly influenced by impact velocities, is a key factor. Research shows increased fragmentation intensity with higher impact velocities in hard rock, highlighting the need for optimized blasting parameters for efficiency and safety [15]. The Discrete Element Method (DEM) is a powerful tool for simulating rock fragmentation under impact conditions, providing insights into how fragmentation intensity and size distribution are affected by impact loading rates [6].

Variability in rock mass characteristics, including permeability and mechanical strength, is another critical factor. Accurate classification of rock mass quality is essential for predicting stability and selecting appropriate explosives and charge distributions [16]. Advanced predictive models, such as the Joint Simulation Algorithm-Artificial Neural Network (JSA-ANN), have improved the accuracy of predicting outcomes like flyrock distances, which are vital for safe and efficient blasting operations [29].

Environmental factors, including flyrock distance predictions, are crucial for minimizing adverse impacts on surrounding structures and ecosystems. The introduction of the weathering index (WI) in predictive models has enhanced the ability to forecast environmental impacts, providing a comprehensive assessment of potential blasting risks [23]. Additionally, integrating deep learning techniques has improved the detection and analysis of rock fragmentation patterns, offering a more nuanced understanding of fragmentation dynamics [25].

6.2 Technological Advancements in Fragmentation Analysis

Technological advancements have significantly enhanced rock fragmentation analysis, a vital component for optimizing tunnel excavation projects. The integration of computational methods like the Discrete Element Method (DEM) has deepened insights into rock fragmentation mechanics under varying impact loading conditions, aiding in understanding how rock properties and explosive characteristics influence fragmentation patterns [6].

Machine learning (ML) and artificial intelligence (AI) techniques have revolutionized fragmentation analysis. Deep learning models achieve high accuracy in detecting fragmentation patterns, particularly in complex geological settings, enabling rapid processing of large datasets for real-time adjustments to blasting strategies [25].

Innovative methodologies, such as point-cloud-based approaches, have improved fragmentation analysis accuracy. Utilizing UAV technology for automated data collection provides high-resolution imagery, enhancing fragmentation assessments and reducing operational disruption [7]. The UAV-RFA method exemplifies this, offering real-time analysis capabilities that yield faster, more accurate insights into size distribution compared to conventional methods.

Hybrid models that combine traditional empirical methods with advanced computational techniques, including deep learning and UAV-based analysis, have significantly improved the accuracy and efficiency of predicting rock fragmentation outcomes. These models, which leverage the strengths of various algorithms, outperform conventional methods in accuracy and reliability, thus optimizing blasting operations [23, 5, 2, 31].

6.3 Modeling and Simulation Techniques

Modeling and simulation techniques are essential for understanding rock fragmentation during tunnel excavation, enabling precise predictions and optimizations of blasting outcomes. These advanced methods clarify the intricate interactions between explosives and rock masses, allowing for the optimization of blasting parameters to achieve desired fragmentation while minimizing damage to surrounding structures. Techniques such as deep learning for real-time analysis and UAV technology for high-resolution imaging enhance the accuracy of fragment size predictions and improve blasting pattern designs, contributing to more efficient mining operations [2, 5, 7, 3, 4].

The Discrete Element Method (DEM) is particularly effective for analyzing rock fragmentation, modeling mechanical interactions between individual rock particles to yield a detailed understanding of the fragmentation process under various impact loading conditions. This method is crucial for optimizing blasting parameters by simulating different explosive characteristics and their effects on rock breakage [6].

Advancements in computational capabilities have enabled the development of three-dimensional numerical simulations, offering a more comprehensive analysis of blasting operations than traditional two-dimensional approaches. These simulations provide deeper insights into energy distribution and fragmentation dynamics, allowing for precise adjustments to blasting parameters [27].

Integrating machine learning with simulation techniques enhances understanding of rock fragmentation. By leveraging extensive datasets from previous blasting operations, machine learning models can predict optimal blasting parameters and fragmentation patterns with high accuracy. Models employing deep neural networks facilitate real-time adjustments to blasting strategies, improving both efficiency and safety in tunnel excavation projects [25].

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Moreover, hybrid models that combine traditional empirical methods with advanced computational techniques have led to improved predictions of fragmentation outcomes. These models, integrating various algorithms' strengths, demonstrate superior accuracy and reliability compared to conventional methods, making them invaluable for optimizing blasting operations [29].

6.4 Measurement and Evaluation of Fragmentation Outcomes

Accurate measurement and assessment of rock fragmentation outcomes are vital for enhancing tunnel excavation processes, directly impacting the efficiency of downstream operations, including transportation and comminution. Advanced technologies, such as UAVs for real-time image analysis, significantly improve data quality and collection speed, facilitating better predictions of rock size distribution and optimizing blast designs. This advancement reduces reliance on manual data collection, which often suffers from low temporal and spatial resolution, thus ensuring that rock size distribution aligns with operational requirements [5, 7].

One effective method for evaluating rock fragmentation is the point-cloud-based approach, which utilizes advanced imaging technologies to create detailed models of rock fragments. This method's effectiveness stems from its ability to generate comprehensive, high-resolution representations of fragmentation patterns, enabling precise analysis and optimization of blasting strategies [31].

The use of UAVs equipped with real-time data acquisition systems has transformed rock fragmentation analysis. The UAV method allows rapid data collection and real-time analysis of rock fragments, enhancing measurement reliability and enabling immediate adjustments to blasting designs, which is crucial for optimizing blast performance and minimizing adverse environmental impacts [7].

Furthermore, integrating artificial lighting with aerial imaging improves fragmentation analysis accuracy, allowing for high-quality image capture in low-light conditions typical of underground tunnel environments, thus enhancing the reliability of fragmentation assessments [32].

Additionally, deep learning techniques have revolutionized the evaluation of rock fragmentation outcomes. Deep neural networks (DNNs) can predict rock fragment size distribution with a percent error for coarse size predictions within ± 25%, significantly improving fragmentation assessment precision [2]. These models process large volumes of data rapidly, providing real-time insights essential for optimizing blasting designs.

The development and application of advanced methods for measuring and evaluating rock fragmentation outcomes have greatly enhanced the precision and reliability of blasting operations. By employing technologies such as UAVs, point-cloud-based analysis, and machine learning algorithms, engineers can significantly improve their understanding of fragmentation dynamics. This approach automates data collection, enhancing both temporal and spatial resolution, and enables accurate measurement of rock fragmentation without the need for scale objects. Ultimately, these advancements lead to more efficient tunnel excavation projects by optimizing blast design and improving rock size distribution, which is crucial for downstream mining and comminution processes [5, 31]. These improvements enhance blasting operation efficiency and safety, supporting sustainable development in tunnel engineering projects.

7 Blasting Techniques in Tunnel Excavation

7.1 Categorization of Blasting Techniques

Blasting techniques in tunnel excavation are divided into conventional and advanced methods, tailored to geological conditions and project needs. Conventional methods, such as the Kuz-Ram and Modified Kuz-Ram models, depend on established parameters and scale objects for rock fragmentation analysis. Advanced methods, including point-cloud-based analysis with UAV technology, enhance measurement accuracy without scale objects, improving safety and efficiency [9, 21, 31].

Conventional techniques involve borehole drilling, explosive insertion, and detonation to achieve effective rock fragmentation for material removal. The efficiency of these techniques relies on precise calculation and placement of explosive charges to optimize fragmentation and minimize adverse effects like vibrations and flyrock [13].

Recent advancements have led to sophisticated blasting techniques that improve precision, safety, and environmental sustainability. Digital blasting systems, employing electronic detonators, provide precise control over detonation timing and sequence, optimizing energy distribution and improving fragmentation while reducing environmental impact [6]. The Discrete Element Method (DEM) simulates rock fragmentation dynamics under varying loading rates, offering accurate insights into explosive forces and rock mass interactions, allowing for refined blasting parameters and enhanced excavation effectiveness [6].

Integrating real-time monitoring and feedback systems, such as UAV technology for post-blast analysis, has significantly improved tunnel excavation efficiency and safety. These systems automate data collection, providing high-resolution, real-time insights into rock size distribution, enabling precise blast design that optimizes downstream processes and minimizes environmental impacts [5, 9, 7, 23, 3]. Utilizing sensors and data analytics, they deliver immediate feedback on blast performance, allowing real-time adjustments to the blasting process, reducing human error, and enhancing risk management, contributing to safer working environments and increased productivity.

8 Conclusion

8.1 Impact of Blasting Techniques on Fragmentation

Blasting techniques critically influence rock fragmentation in tunnel excavation, affecting efficiency, safety, and environmental outcomes. Traditional methods, notably the drill-and-blast approach, are widely used for their adaptability across diverse geological conditions, utilizing strategic explosive placement to facilitate rock removal [13]. However, these methods often result in excessive vibrations and flyrock, posing risks to structural integrity and safety. The pursuit of enhanced fragmentation and reduced environmental impacts has led to the adoption of advanced techniques, incorporating machine learning and optimization algorithms to refine blasting processes, thereby boosting efficiency and reducing safety hazards [9, 23, 21, 3, 4].

Modern technologies like the Discrete Element Method (DEM) provide precise simulations of rock fragmentation, enabling engineers to optimize parameters for desired outcomes while minimizing environmental effects [6]. Digital blasting systems with electronic detonators enhance precision by allowing microsecond delays, optimizing energy distribution, and reducing ground vibrations and flyrock, thus improving safety and efficiency [6]. Hybrid techniques, combining traditional methods with advanced technologies such as electronic detonators and real-time monitoring, offer superior control over fragmentation tailored to specific geological contexts [25]. Moreover, environmentally friendly explosives have been developed to deliver higher energy outputs with reduced environmental impact, promoting sustainability in tunnel excavation [8].

8.2 Criteria for Technique Selection

Selecting suitable blasting techniques for tunnel excavation requires evaluating various criteria to optimize efficiency, safety, and environmental sustainability. Key factors include geological conditions, project requirements, environmental impacts, and economic viability, crucial for effective drilling and blasting operations [11, 9, 23, 8, 3]. Geological factors such as rock type and joint patterns significantly influence technique choice, necessitating tailored explosive selection and charge distribution. Advanced simulation models like DEM provide insights for optimizing blasting parameters according to geological conditions [6].

Environmental considerations are vital in technique selection, focusing on mitigating adverse effects like air overpressure, ground vibration, and dust emissions. Employing machine learning and optimization algorithms aids in predicting and preventing negative environmental impacts during blasting [23, 3]. Hybrid models such as PSO-ANN and EO-ELM demonstrate superior predictive accuracy for estimating flyrock distances and air-overpressure values, guiding the selection of environmentally considerate techniques.

Economic factors, including the costs of explosives and operations, also influence technique selection. The choice of explosives, particularly emulsion types, is driven by desired fragmentation outcomes and cost considerations [3]. The performance index of explosives, evaluating energy and detonation characteristics, serves as a tool for selecting cost-effective explosives for specific geological contexts [8]. Integrating real-time monitoring systems enhances selection by providing immediate insights into blast performance, enabling data-driven decisions that optimize fragmentation while minimizing environmental impacts [23, 21, 2, 3].

8.3 Comparative Analysis of Blasting Techniques

Choosing the appropriate blasting technique for tunnel excavation requires understanding each method's advantages and disadvantages. Traditional techniques, such as the drill-and-blast method, are favored for simplicity, cost-effectiveness, and adaptability to various geological conditions, strategically placing explosives to achieve effective fragmentation [13]. In contrast, modern techniques offer significant advancements in precision and control. The Discrete Element Method (DEM) provides sophisticated simulations, enabling detailed energy distribution analysis and optimized blasting parameters to improve outcomes and reduce environmental impacts [6].

Digital blasting systems enhance modern techniques by incorporating electronic detonators for precise detonation timing, optimizing energy distribution, and minimizing adverse effects like ground vibrations and flyrock, thus improving safety and efficiency [6]. Innovative hybrid methods integrate traditional practices with modern technologies, utilizing real-time monitoring to provide immediate insights into blast performance, allowing adjustments that enhance project success [25]. Additionally, environmentally friendly explosives have been developed to reduce the environmental footprint of blasting operations, delivering high energy output while minimizing harmful byproducts, thereby enhancing sustainability [8].

9 Conclusion

The optimization of blasting parameters and the evaluation of blasting effects remain pivotal for the advancement of tunnel engineering projects. This survey highlights the importance of diverse blasting techniques—ranging from traditional to cutting-edge approaches—in ensuring effective and safe rock fragmentation during tunnel construction. Critical elements such as explosive type, charge size, detonation timing, and the intrinsic properties of rock masses significantly influence the success of blasting operations.

Technological innovations have significantly enhanced parameter optimization processes. The application of machine learning models, notably the Joint Simulation Algorithm-Artificial Neural Network (JSA-ANN), has shown exceptional precision in predicting outcomes such as flyrock distances, thereby improving safety and operational efficacy. The use of Unmanned Aerial Vehicles (UAVs) for real-time rock fragmentation analysis has revolutionized data acquisition and interpretation, enabling more strategic optimization of blasting methods.

Nonetheless, challenges remain, particularly in the accurate representation of complex interactions between explosives and geological formations. Future research should focus on strengthening predictive models by integrating hybrid intelligent systems that merge machine learning with conventional techniques. Additionally, expanding the use of advanced simulation methods, like the Discrete Element Method (DEM), to a broader spectrum of geological settings and real-world applications is essential.

Moreover, the development of environmentally sustainable explosives and refined methods for assessing environmental impacts, such as the weathering index (WI), is crucial for future investigations. These advancements will facilitate the sustainable evolution of tunnel engineering endeavors by minimizing the ecological impact of blasting activities.

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