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A deep dive into tunnel blasting studies between 2000 and 2023—A systematic review

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ABSTRACT

Tunnel blasting is a common practice used to excavate rock formations. Many academic research articles have emerged and burgeoned in the field of tunnel blasting. These articles are dedicated to investigating objectives such as blasting vibration, rock damage, and vibration energy individually. However, no systematic analysis is conducted to consolidate and analyze the findings from the literature related to tunnel blasting. This study addresses this by offering a systematic review to explore the state of tunnel blasting research. A science mapping approach using bibliometric analysis is employed to examine 144 peer-reviewed journal articles. The review identified the most influential journals, institutions, researchers, and articles on tunnel blasting research, and it also summarizes the research hotspots of tunnel blasting according to the cluster analysis of research keywords. Findings in this review revealed the contribution of two leading journals, three leading institutions, and three leading researchers on the research of tunnel blasting. Moreover, four research keywords, i.e., blasting vibration, numerical simulation, rock damage, and overbreak, were identified as the research hotspots in 2018–2023. Finally, this review also speculated the future research directions/avenues of tunnel blasting, aiming to bring to light the deficiencies in the currently existing research and provide paths for future research.

1. Introduction

Drilling and blasting is a common rock excavation method used in the construction of tunnels and underground structures. The process involves the controlled use of explosives to break up the rock mass and create the desired excavation profile. The success of tunnel rock blasting depends on a range of factors, including the design of the blast, the selection of explosives and initiation systems, and the properties of the rock mass. In recent years, research in the area of tunnel blasting has focused on various aspects, such as the design of blasting patterns, optimization of blast parameters, and other potential environmental impacts (Jiang et al., 2021; Yilmaz and Unlu, 2014). Many studies have investigated the effects of blasting on the stability of surrounding rock formations, the potential for overbreak, and the generation of ground vibrations and noise (He et al., 2023; Jang and Topal, 2013; Mottahedi et al., 2018). Various techniques such as field monitoring and numerical simulation have been applied to investigate these topics (Jiang and Zhou, 2012).

While there have been many individual studies on tunnel blasting, few studies have provided an overall pattern of tunnel blasting. Individual research efforts, while valuable, often lack a holistic view that synthesizes these disparate findings into a coherent framework. Thus, there is a need for a systematic review that can consolidate and analyze the findings from multiple sources that are relevant to tunnel blasting. A systematic review is a rigorous and transparent method for identifying, selecting, and appraising relevant studies on a particular topic. By providing an unbiased and comprehensive analysis of the existing knowledge, a systematic review can inform future research and practice and identify gaps in the literature (Harris et al., 2014; Wright et al., 2007). Furthermore, the application of science mapping within the systematic review process offers a powerful means to navigate the expansive landscape of tunnel blasting research. Given that a complete

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picture of what has been done and what needs to be done in tunnel blasting is yet to emerge, this study attempts to synthesize relevant research to explore the patterns and praxis in the existing body of knowledge on tunnel blasting.

Science mapping is a useful tool for conducting a systematic review, as it can help researchers identify relevant literature and visualize the connections between different literature (Börner et al., 2003). A science mapping study typically applies a bibliometric or a scientometric analysis method (Hosseini et al., 2018). It primarily comprises several specific phases: data collection analysis, science mapping tools selection, modeling, visualization, and communication of findings (Jin et al., 2019; Liang et al., 2023; Tarekegn Gurmu et al., 2022). Thus, this study uses the bibliometric analysis approach to provide insights into research collaboration networks and research clusters of tunnel blasting. The review work is conducted on 144 peer-reviewed journal articles published from 2000 to 2023. The purposes of this review are to: (1) summarize research on tunnel blasting; (2) highlight the contributed researchers, collaboration networks, and preferred outlets; (3) identify research hotspots through cluster analysis and highlight research gaps; (4) speculate future research directions/avenues. The insights gained from this study of previous literature on tunnel blasting could assist researchers in bridging existing theories and exploring other directions in the near future.

This study is structured with the following sections. Section 2 introduces the approach to conducting this systematic review, as well as the detailed steps in performing the bibliometric analysis. Section 3 first presents the descriptive results of the reviewed articles and then identifies the research hotspots through cluster analysis of research keywords. Section 4 summarizes the main findings of this review and proposes the potential future research directions/avenues of tunnel blasting. Section 5 reports the main conclusions of this review.

2. Research methodology

To synthesize the existing research related to tunnel blasting in scientific literature, this study performed a systematic review to provide a thorough and valuable examination. The systematic review includes five phases:

1) The first phase is to conduct a preliminary search according to the drafted keywords.
2) The second phase is to filter out the irrelevant terms/publications to refine the search results.
3) The third phase is to further manually select the terms/publications that highly conform to the topic, i.e., tunnel blasting.
4) The fourth phase is to use the bibliometric tool VOSviewer to analyze the underlying relationship between the obtained results (publications).
5) The fifth phase is to conduct a discussion on the publications that were reviewed by the bibliometric analysis.

Fig. 1 illustrates the process of systematic review in this study.

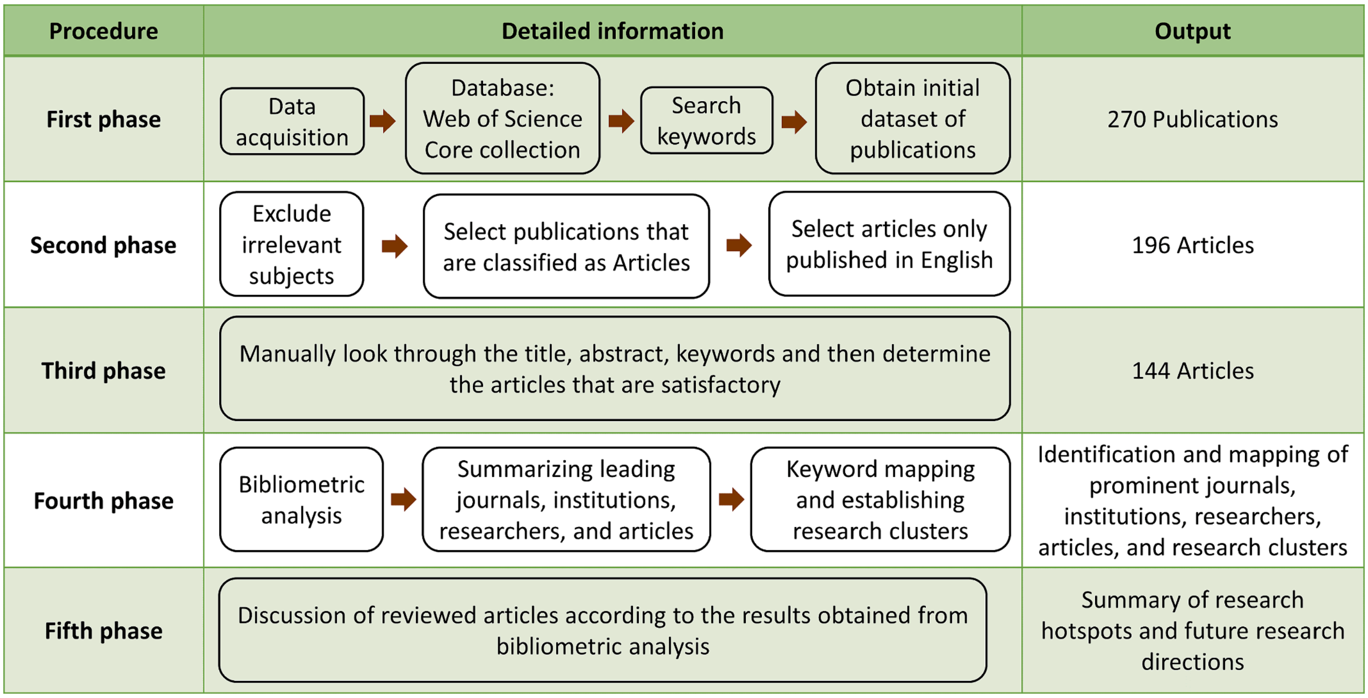
2.1. Publication selection process and criteria

We retrieved the publications tied to tunnel blasting from Web of Science. The publications covered the period 2000–2023 and the database is the Web of Science Core Collection. The process of publication searching is based on guidelines of the preferred reporting items for systematic reviews and *meta*-analysis protocols (PRISMA-P) (Moher et al., 2015; Shamseer et al., 2015). The preliminary search is according to some tailored keywords/strings listed as follows; meanwhile, Boolean operators in Web of Science such as “OR” and “NOT” are used to filter relevant literature.

- The inclusive keywords/strings are: “tunnel blast*” OR “underground blast*” OR “underground rock blast*” OR “underground rock fragment*” OR “rock tunnel excavation”.
- Necessarily, we also set the exclusion criteria: “surface blast*” OR “quarry” OR “pit” OR “mine*” OR “mining” OR “pile”, to avoid gathering some irrelevant literature.

These keywords/strings are judged by the search engine (SE) in Web of Science in the title, abstract, and keywords of publications. As a result, the preliminary search identified 270 results (the first phase).

Then, we excluded the articles from subjects such as molecular & cell biology, herbicides, telecommunications, optical electronics &



Procedure	Detailed information	Output
First phase	Data acquisition → Database: Web of Science Core collection → Search keywords → Obtain initial dataset of publications	270 Publications
Second phase	Exclude irrelevant subjects → Select publications that are classified as Articles → Select articles only published in English	196 Articles
Third phase	Manually look through the title, abstract, keywords and then determine the articles that are satisfactory	144 Articles
Fourth phase	Bibliometric analysis → Summarizing leading journals, institutions, researchers, and articles → Keyword mapping and establishing research clusters	Identification and mapping of prominent journals, institutions, researchers, articles, and research clusters
Fifth phase	Discussion of reviewed articles according to the results obtained from bibliometric analysis	Summary of research hotspots and future research directions

Fig. 1. Flowchart of the systematic review.

engineering, management, social reform, asphalt, ocean dynamics, sensors & tomography, as these subjects are irrelevant to the context of this review. We also excluded publications published in proceeding papers, early access, editorial material, review article, and only reserved publications in academic journals. The reason for only considering academic journals is because articles published in peer-reviewed academic journals represent the research works that are most reputable, influential, and rigorous (Santos et al., 2017). Additionally, only articles published in English were considered. As a result, the refined search identified 196 results (the second phase).

Further, we manually check the title, abstract, and keywords of articles to determine which of them conform to the topic of this systematic review. For example, Wu and Hao (2005) developed a numerical model to simulate the transmission of stress waves induced by the explosion in an underground chamber and assessed the blast ground motion effect on structures. Although the mentioned article covered the keyword such as “underground blast”, it cannot be measured as an outcome of studying tunnel blasting. Some other articles that have similar situations to the article of Wu and Hao also have been excluded. In this way, this study ultimately obtained 144 articles for conducting the systematic review work (the third phase).

2.2. Bibliometric analysis

This review performed bibliometric analysis to map and visualize the bibliographic information and systematic flow of the selected 144 journal articles. Bibliometric analysis has been widely adopted in systematic review studies to analyze the chronological pattern of publications, journal sources, and key research hotspots (Darko et al., 2020; Lang et al., 2021; Li et al., 2022; Ma et al., 2022). This review adopted the bibliometric analysis tool VOSviewer 1.6.18 to produce prominent journal outlets, prominent institutions, author collaboration networks, keywords mapping, and research clusters. VOSviewer is a software program specifically designed for visualizing bibliometric data. It describes a type of visualization that helps researchers better understand the publication networks in their field of study. Also, it provides various features for analyzing the structure of these types of networks, including the ability to calculate centrality measures, perform clustering analysis, and mine text features (Eck and Waltman, 2016; van Eck and Waltman, 2010).

3. Analysis and results

3.1. Descriptive results

3.1.1. The trend of research on tunnel blasting

The research output on tunnel blasting has shown a gradual growth trend in Fig. 2. No articles were published in 2000–2002, 2005, and 2007. Few articles (less than 10) were published in 2008–2017. From 2018 to 2023, the number of published articles related to tunnel blasting has grown significantly, and it reached a peak in 2023, which has 33 published articles. Regarding the total citation, we can observe four peaks of total citations from 2000 to 2023. The first peak is in 2004, and one article published by Wu et al. (2004) received 79 citations. The article’s research topic is the development of a numerical model to predict the dynamic response of rock mass subjected to large-scale underground explosion. The second peak is in 2009, one article published by Kwon et al. (2009) received 132 citations. The article’s research topic is the investigation of characteristics of excavation damaged zones during tunnel blasting excavation. The third peak is in 2013, and one article published by (Xia et al., 2013) received 92 citations. The article’s research topic is the investigation of effects of tunnel blasting excavation on the surrounding rock mass and the lining systems of adjacent tunnels. The fourth peak is in 2018, and one article published by (Zhou et al., 2018) received 64 citations. The article’s research topic is the investigation of effects of loading rates on crack propagation velocity and rock fracture toughness when subjected to blasting loads.

Fig. 3 shows the number of published articles in each country. Notably, a considerable number of published articles in this review are from China, compared with countries such as South Korea and Australia, while other countries contributed less than five articles related to tunnel blasting.

3.1.2. Journal outlets leading research on tunnel blasting

The bibliometric analysis used the function of Citation analysis in VOSviewer to identify the leading journals. Setting the minimum number of articles of a journal source as 1, 68 journals meet the thresholds. By sorting out the number of articles published in a journal from large to small, Table 1 resultantly listed the top 10 contributing journals in the research field of tunnel blasting in 2000–2023. The maximum number of articles (24 articles) on tunnel blasting appeared in *Tunnelling and Underground Space Technology*, followed by *Shock and Vibration* (12 articles). As for another 8 journals, all published less than 10 articles. The published papers in each journal covered some primary topics such as rock damage pattern, blast-induced vibration, and blasting design, while topics such as overbreak control, toxic fumes, waveform characteristics, and safety assessment have received less attention.

3.1.3. Institutions leading research on tunnel blasting

The bibliometric analysis used the function of Co-authorship analysis in VOSviewer to identify the leading institutions. Setting the minimum number of articles of an institution as 3, 26 institutions meet the thresholds. By sorting out the number of articles published in an institution from large to small, Table 2 resultantly listed the top 10

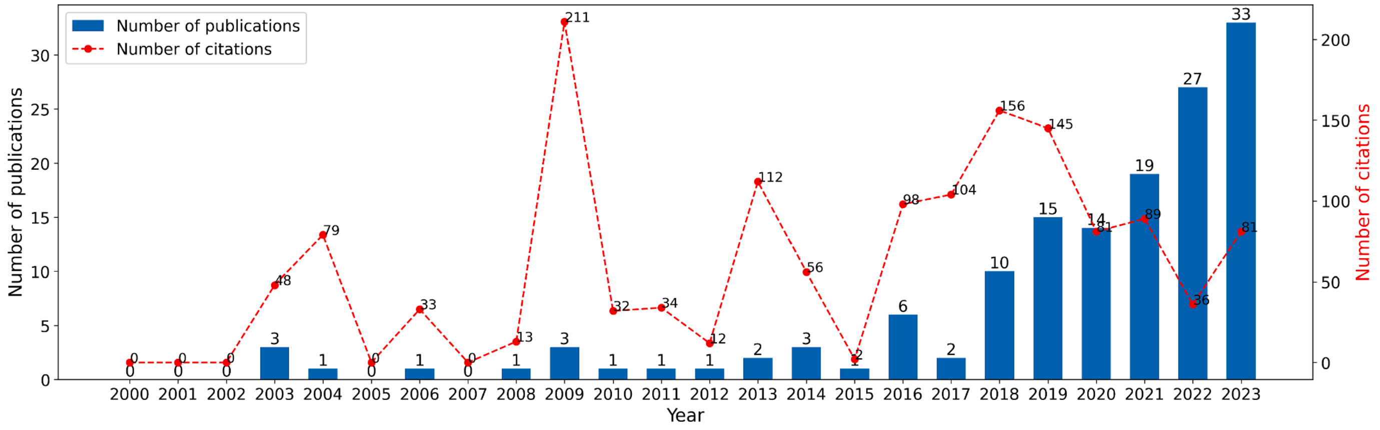


Fig. 2. Publications and citations of articles in 2000–2023.

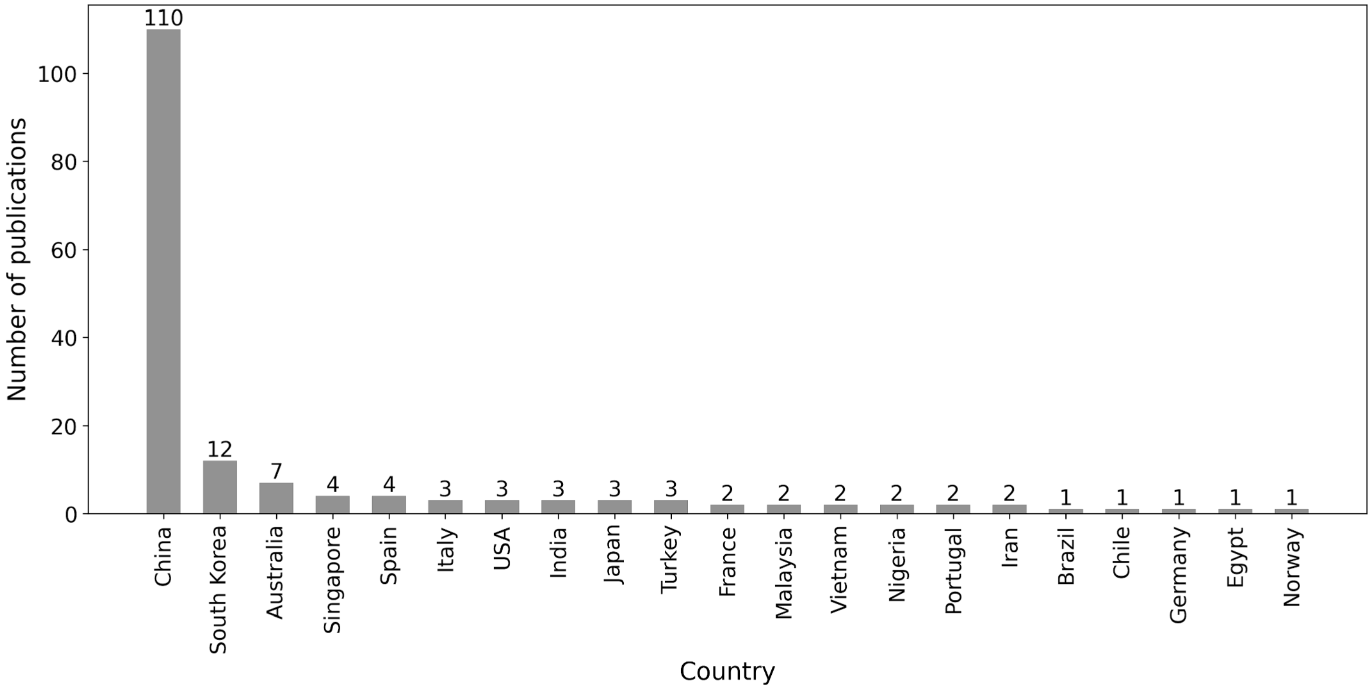


Fig. 3. The number of published articles in different countries.

contributing institutions in the research field of tunnel blasting in 2000–2023. Notably, the *China University of Geosciences* stands out as the most influential institution in the research field of tunnel blasting, followed by *Central South University*. We also find that nine research institutions are from China and the remaining one is from South Korea. Additionally, it seems that articles published by institutions such as *Nanchang University* and *Chinese Academy of Sciences* have a prominent influence. For example, *Nanchang University* published 5 articles that collectively have received 91 citations, and *Chinese Academy of Sciences* published 5 articles that collectively have received 115 citations.

3.1.4. Researchers leading research on tunnel blasting

The bibliometric analysis used the function of Co-authorship analysis in VOSviewer to identify the leading researchers. Setting the minimum number of articles of a researcher as 3, 26 researchers meet the thresholds. By sorting out the number of articles published by a researcher from large to small, Table 3 resultantly listed the top 10 contributing researchers in the research field of tunnel blasting in 2000–2023. Jiang Nan has published the most articles and received the most citations, followed by Zhou Chuanbo. Other researchers have also contributed articles in the research field of tunnel blasting.

This review also identified the co-authorships between the researchers. Fig. 4 illustrates some major collaborative clusters between the researchers. For example, the red cluster includes nine cooperative researchers: Zhou Chuanbo, Jiang Nan, Li Haibo, Luo Xuedong, Xia Yuqing, Sun Jinshan, Yao Yingkang, Cai Zhongwei, and Zhu Bin. Some of their cooperative studies mainly focus on the effects of underground blasting on the safety and dynamic behaviors of adjacent buried pipelines, tunnels, or buildings (Jiang et al., 2019; Liu et al., 2020; Shi et al., 2023; Xia et al., 2021; Zhu et al., 2022). The green cluster includes five cooperative researchers: Castedo R., Lopez L. M., Navarro J., Sanchidrian J. A., and Segarra P.. Some of their cooperative studies mainly focus on utilizing the measure while drilling (MWD) system to monitor the quality of blast hole drilling (Navarro et al., 2019); to predict potential overbreak and underbreak zones induced by blasting operations (Navarro et al., 2018a); to optimize the parameters that govern the drilling operations (Navarro et al., 2018b). The blue cluster includes four cooperative researchers: Fu Hongxian, Guan Xiaoming, Zhang Liang, and Yang Ning. Some of their cooperative studies mainly focus on investigating the effects of tunnel blasting on the adjacent pipelines, such as the dynamic response, damage mechanism, and safety assessment of pipelines when subjected to tunnel blasting loads (Guan et al., 2023, 2020a, 2020b). The cyan cluster includes two cooperative researchers: Yang Jianhua and Yao Chi. Some of their cooperative studies mainly focus on exploring the differences between blasting vibration on the tunnel surface and that inside surrounding rock or on the tunnel entrance slope face, in terms of the dynamic response of rock mass (Wang et al., 2021; Yang et al., 2019). The yellow cluster includes three cooperative researchers: Zhao Yan, Shan Renliang, and Wang Hailong. Some of their cooperative studies mainly focus on analyzing the effect of blasting parameters on vibration distribution from the perspective of energy transfer (Zhao et al., 2021), or investigating the blasting vibration response and safety control of tunnel blasting (Shan et al., 2023). The purple cluster includes three cooperative researchers: Lei Mingfeng, Yang Weichao, and Deng E. Some of their cooperative studies mainly focus on the influence of weak interlayer within rock on the propagation velocity and stress peak of the stress wave induced by blasting (Lei et al., 2022).

3.1.5. Articles leading research on tunnel blasting

According to the citations that the published articles received, this review summarized the top most-cited articles in Table 4. Noteworthily, this review herein only considered the articles that received at least 40 citations, and resultantly, seven articles were identified. Among these articles, three were published in *Tunnelling and Underground Space Technology*. Others were from journals such as *International Journal for Numerical and Analytical Methods in Geomechanics, International Journal of Rock Mechanics and Mining Sciences, Soil Dynamics and Earthquake Engineering,* and *Rock Mechanics and Rock Engineering.*

Regarding the topics of these articles, most of them focused on the damage/fragmentation characteristics of rock mass, wave propagation behavior with rock mass, and dynamic response of rock mass when subjected to blasting loads. Their research methods primarily included categories such as numerical simulation and in-situ experiments or monitoring. For example, Kwon et al. (2009) reported that an EDZ (Excavation Damaged Zone) can be defined as a rock zone where the

Table 1
Top 10 contributing journals in Web of Science (2000–2023).

Journal	Number of publications	Total citations	Impact fact	Main topics covered
Tunnelling and Underground Space Technology	24	525	6.407	Rock damage pattern, blast-induced vibration, blasting design, drilling control, overbreak control, vibration stress response, toxic fumes, dilution ventilation
Shock and Vibration	12	20	1.616	Rock damage pattern, blast-induced vibration, vibration stress response, blasting design, safety assessment, waveform characteristics
Applied Sciences-Basel	9	15	2.838	Rock damage pattern, blasting design, blast-induced vibration, energy response, smooth blasting
Frontiers in Earth Science	5	2	3.661	Rock damage pattern, blast-induced vibration, vibration control, waveform characteristics
International Journal of Rock Mechanics and Mining Sciences	4	94	6.849	Rock damage pattern, blast-induced vibration, blasting design, crack propagation, hydrocodes
Advances in Civil Engineering	4	25	1.843	Safety assessment, blast-induced vibration, vibration stress response
Geotechnical and Geological Engineering	4	20	1.7	Rock damage pattern, vibration stress response, tunnel stability, overbreak control
Engineering Failure Analysis	4	18	4.0	Vibration stress response, damage mechanism, safety assessment
Rock Mechanics and Rock Engineering	3	47	6.518	Rock damage pattern, blast-induced vibration, blasting pattern
Geomechanics and Engineering	3	27	3.2	Blast-induced vibration, blasting design, crack propagation

rock properties and conditions have been changed due to the blasting excavation. The disturbance of blasting excavation could influence some characteristics of an EDZ, such as the mechanical stability, hydraulic behavior, thermal behavior, and chemical behavior of underground space. They investigated the characteristics of the EDZ developed during the tunnel's excavation using in-situ tests, laboratory rock core testing, computer simulations, and empirical equations. Taking the Damaoshan highway tunnel as a case study, Xia et al. (2013) comprehensively investigated the effects of tunnel blasting excavation on the surrounding rock mass and the lining systems of adjacent existing tunnels. Blast vibration monitoring was conducted in the Damaoshan highway tunnel project to examine the characteristics of blast vibrations in the existing tunnels when subjected to blasting in the adjacent new tunnel. The results indicated that the safety of an existing tunnel is often affected by blasting vibrations from adjacent tunnel excavation. By considering the threshold peak particle velocity (PPV), they proposed a damage control method to predict the safety of the existing tunnels. Wu et al. (2004) proposed a numerical model to predict the dynamic response of rock mass subjected to large-scale underground explosion. The numerical model involves the Hugoniot equation of state, a piecewise linear Drucker–Prager strength criterion taking into account the strain rate effect, and a double scalar damage model accounting for both compression and tension at a material point during the blasting process. The predicted dynamic response of the rock mass included the PPV, peak particle acceleration (PPA) attenuation laws, damage zone, and time histories and frequency of the particle velocity. After calibrating the numerical model against data obtained from large-scale field tests, the results showed that the numerical model was in reasonable agreement with the field test data. Further, the numerical model was applied to examine the effects of the charge chamber geometry and charge weight on the stress-wave propagation in the rock mass. The results showed that the charge loading density showed a primary impact on the stress wave intensity, while the charge weight and charge chamber geometry showed a relatively slight impact on the stress wave intensity compared with the charge loading density. Zhou et al. (2018) investigated the effect of loading rates on crack propagation velocity and rock fracture toughness using a newly proposed cracked tunnel specimen and drop weight impact experiments. They used crack propagation gauges to

Table 2
Top 10 contributing institutions in Web of Science (2000–2023).

Institution/affiliation	Country	Number of publications	Total citations
China University of Geosciences	China	10	62
Central South University	China	9	32
Qingdao University of Technology	China	8	35
Southwest Jiaotong university	China	7	24
China University of Mining & Technology Bejing	China	7	19
Beijing Jiaotong University	China	6	25
Changan University	China	6	23
Jianghan University	South Korea	6	7
Chinese Academy of Sciences	China	5	115
Nanchang University	China	5	91

Table 3
Top 10 contributing authors in Web of Science (2000–2023).

Institution/affiliation	Number of publications	Total citations	Institution Affiliation in the Web of Science
Jiang, Nan	10	58	China University of Geosciences, China
Zhou, Chuanbo	9	48	China University of Geosciences, China
Guan, Xiaoming	8	35	Qingdao University of Technology, China
Fu, Hongxian	6	25	Beijing Jiaotong University, China
Yang, Jianhua	4	37	Nanchang University, China
Castedo, R.	3	42	Universidad Politécnica de Madrid, Spain
Lopez, L. M.	3	42	Universidad Politécnica de Madrid, Spain
Navarro, J.	3	42	Universidad Politécnica de Madrid, Spain
Sanchidrian, J. A.	3	42	Universidad Politécnica de Madrid, Spain
Segarra, P.	3	42	Universidad Politécnica de Madrid, Spain

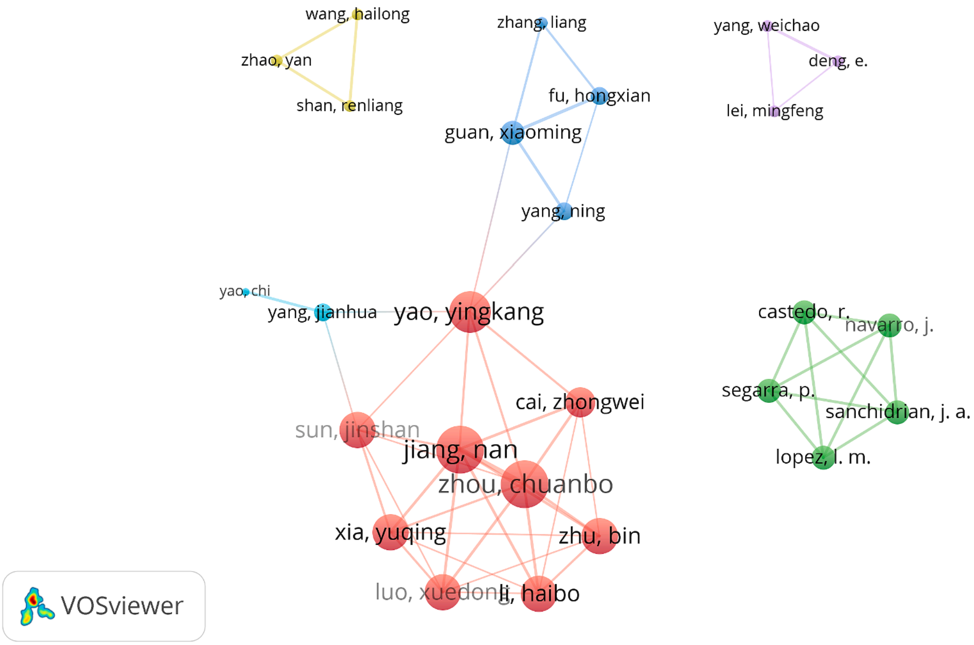


Fig. 4. Co-authorships between researchers in the field of tunnel blasting.

Table 4
Most cited papers relevant to tunnel blasting in Web of Science (2000–2023).

Reference	Citations	Journal	Main topic	Method	Major findings
Kwon et al., 2009	132	Tunnelling and Underground Space Technology	Underground excavation risks, characteristics of the EDZ after blasting, rock mass behavior after blasting	Empirical prediction models, laboratory rock core testing, in-situ tests, computer simulations, sensitivity analysis	RQD, deformation modulus, elastic modulus, and P wave velocity decreased due to blasting excavation; in-situ stress ratio, Young’s modulus, and EDZ size primarily influence the mechanical behavior of the excavated tunnel.
Xia et al., 2013	92	Tunnelling and Underground Space Technology	Damage control of rock mass, threshold PPV, rock damage characteristics, the safety of tunnels under blasting excavation	Field tests of blasting vibration, numerical simulation of blasting in adjacent tunnels	Rock damage extent around the excavation zone linearly increased with the increase of PPV; the safe PPV threshold should be less than 0.3 m/s; a feasible PPV-based damage control method was proposed.
Wu et al., 2004	79	International Journal for Numerical and Analytical Methods in Geomechanics	Wave propagation, dynamic response of rock mass under blasting load, predicting PPV and PPA	Numerical analysis of blast-induced stress wave, in-situ tests	The charge loading density significantly affects the stress wave propagation; the charge weight under a given loading density shows an insignificant impact on PPV.
Zhou et al., 2018	64	International Journal of Rock Mechanics and Mining Sciences	Crack propagation behavior, rock fracture toughness criteria, dynamic stress intensity of rock mass	Split Hopkinson pressure bars (SHPB) impact test systems, numerical analysis of crack propagation	Crack propagation speed increases with the increase of loading rates and finally tends to a stable value; delayed fracture time and crack arrest period both decrease with the increase of loading rates and finally tend to a stable value.
Yang et al., 2017	60	Tunnelling and Underground Space Technology	Rock discontinuities and EDZ formation, risks associated with exceeding PPV thresholds, mitigation strategies for underground blasting	Numerical simulation of rock damage	Dynamic stress redistribution could cause the formation of EDZ; factors affecting the in-situ stress in tunnels should be considered as the blasting vibration standards and damage criteria.
Wang et al., 2009	49	Soil Dynamics and Earthquake Engineering	Wave propagation in the fractured rock mass, effects of fault parameters on rock failure	Coupled finite element and discrete element simulation of blast loading	The existing fault in rock mass significantly affects the pattern of rock fragmentation.
Yang et al., 2019	40	Rock Mechanics and Rock Engineering	Surface reflection and surface waves of blast-induced vibrations, mitigation strategies for blast-related structural damage to nearby structures, effects of geological and technological conditions on blast-induced vibrations	In-situ experiments and monitoring, dynamic finite element method	Surface waves significantly dominate the tunnel surface vibration in the far field; high-frequency body waves significantly dominate the vibration transmission in the near field; rock vibration on tunnel surfaces has greater amplitude and lower frequency compared with rock vibration inside surrounding rocks.

measure crack propagation velocity and crack initiation time, which were applied in the determination of initiation toughness. Also, they established finite difference numerical models to validate the effectiveness of the cracked tunnel specimens and predict test results. The results showed that crack propagation speeds and initiation toughness increase with loading rates, but tend towards stable values beyond a certain point. Yang et al. (2017) investigated the combined effects of in-situ stress redistribution and blast loading on rock damage, with a focus on the dynamic process of stress redistribution. They used a 2D finite element simulation to model a circular tunnel excavation using full-face millisecond delay blasting. The key findings included that dynamic stress redistribution generated larger EDZ than quasi-static conditions and that the critical PPV for blast damage initiation increased and then decreased with an increase in in-situ stress. Wang et al. (2009) coupled UDEC and LS-DYNA to simulate underground blasting and its dynamic effects in a rock mass containing a fault. The proposed method can simulate the blast-induced crack evolution and failure zone distribution, and can disclose the relationship between rock failure and fault parameters (dip, stiffness, and friction). The results showed that the effect of a single fault on wave propagation was asymmetrical, with maximum tension increasing due to the reflection of the fault surface; the fault-induced tensile failure around the borehole was strongly dependent on the fault dip; the magnitude of the failed zone significantly reduced with the increase of fault stiffness and friction angle. Yang et al. (2019) comprehensively studied the tunnel blast-induced vibration on tunnel surfaces and inside surrounding rock through in-situ experiments and numerical simulations. The authors discussed the mechanisms of differences between these two types of vibrations when assessing the dynamic stability of tunnels under blasting vibrations. They also provided empirical relations for PPV attenuation and dominant frequency change based on data collected from field vibration monitoring during blasting excavation.

3.2. Research hotspots in recent years (from 2018 to 2023)

As stated by van Eck and Waltman, 2022, a well-networked mapping of author keywords can deepen the understanding of the relationships, trends, and intellectual organization of the research hotspots. Consequently, this review creates a co-occurrence network of author keywords to identify the core contents and range of previous research on tunnel blasting. Since the number of articles in 2018–2023 is 118, accounting for 81.94 % of the entire number of articles, we conducted the co-occurrence analysis based on these 118 articles, which can embody the research hotspots in recent years.

In VOSviewer, the function “Co-occurrence keywords” can compute the frequency with which a given keyword occurs across diverse articles, thereby enabling an assessment of the keyword’s prominence. In short, keywords with high frequency signify the more concern that the researchers pay attention to, and vice versa. Setting the minimum number of occurrences of a keyword as 2, 32 keywords meet the thresholds. Since some generic terms such as “tunnel”, “subway tunnel”, “blasting”, “excavation”, “blasting excavation”, “underground”, “underground blasting”, “tunnel blasting”, “tunnel engineering”, “surrounding rock”, “model analysis”, “rock mass rating”, “geological condition”, and “tunnel construction” could affect the generation of keywords mapping network, we omitted them and only reserved other effective author keywords. Meanwhile, we merged the semantically repetitive author keywords. For example, author keywords “numerical model” and “field measurement” were replaced by “numerical simulation” and “field monitoring”, respectively; author keywords “vibration energy”, “vibration response”, and “peak particle velocity” were replaced by “blasting vibration”. Ultimately, the co-occurrence mapping network has 13 items with 4 clusters connected through 122 links, as shown in Fig. 5. The subsequent subsection will discuss each cluster to identify the research hotspots in recent years (from 2018 to 2023).

3.2.1. Research cluster 1: Blasting vibration, numerical simulation, field monitoring, dynamic response, and buried pipeline

Research cluster 1 consists of five keywords: blasting vibration, numerical simulation, field monitoring, dynamic response, and buried pipeline.

Blasting vibration refers to the mechanical vibration that is generated as a result of detonating explosives during tunnel blasting (Zhang et al., 2023). It propagates through the surrounding rock mass and induces ground vibrations that may impact adjacent structures. The impact of blasting vibration on the safety and stability of surrounding rock or adjacent structures is a common concern for geotechnical engineers. Monitoring factors such as peak particle velocity (PPV), frequency, and duration can provide data for understanding the characteristics of blasting vibration and their effects on surrounding rock or adjacent structures. For example, Zhao et al. (2022) established a mathematical relationship that used the frequency to estimate the PPV, and then they used PPV to evaluate the safety threshold of blasting vibrations. Commonly, The higher the PPV, the stronger the vibrations and the more potential for damage to nearby structures (Yang et al., 2019). PPV is a direct measure of the strength of the blasting vibrations, which is used to quantify the magnitude of the vibrations (Jiang et al., 2019). It is typically measured and analyzed to assess the potential impacts of blasting on nearby structures, such as buildings, buried pipelines, and infrastructure (Dang et al., 2018; Hou et al., 2022). Research on PPV in tunnel blasting involves investigating the relationship between the resulting PPV values and blasting parameters such as blast design, explosive properties, and distance from the blast (Yang et al., 2019). For example, some researchers indicated that the maximum segmental explosive charge, instead of the total charge among excavation steps, has a significant impact on PPV (Dang et al., 2018; Qin and Zhang, 2020). Some research also proposed the development of guidelines, regulations, and best practices for managing PPV during tunnel blasting operations to ensure compliance with safety and environmental standards (Ji et al., 2021b). A common way is to optimize blasting design parameters to minimize PPV levels and reduce potential impacts on the surrounding environment and structures (Zhou et al.,

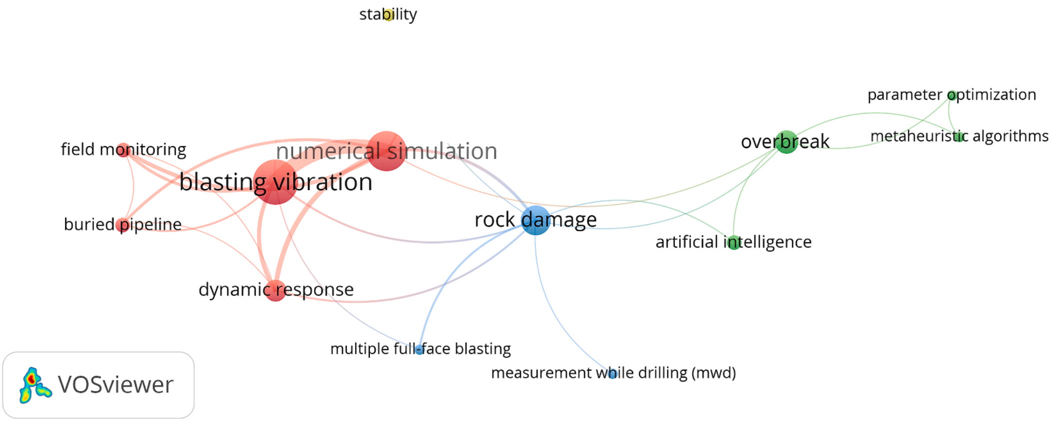


Fig. 5. Co-occurrence mapping network of research hotspots tied to tunnel blasting.

2022). Additionally, some research contributes to developing prediction models, risk assessment tools, and monitoring techniques for controlling PPV (Paneiro et al., 2020; Peng et al., 2021).

Another contribution of studying blasting vibration in tunnel blasting is the development of mitigation measures to reduce or control the impact of blasting-induced vibrations. Mitigation measures include techniques such as vibration energy monitoring and blast design optimization (Kim and Lee, 2021; Wu et al., 2021). Vibration energy monitoring is commonly used as a safety evaluation index of the magnitude and distribution of vibrations generated by blasting operations. It serves to evaluate the seismic wave intensity, thereby reflecting the impact of tunnel blasting on structures (Peng et al., 2021). Also, it can serve to measure the cumulative failure and damage of structures when subjected to tunnel blasting loads (Hou et al., 2022). The monitoring of vibration energy can help in understanding the extent and severity of vibrations, which is essential for assessing potential impacts and designing effective mitigation measures. This information can be used to optimize blast design to minimize potential damage to adjacent structures (Zhao et al., 2021). For example, optimizing blast design parameters, such as blast hole layout, hole diameter, hole spacing, explosive properties, and charge weight per delay, can minimize the generation of vibrations and mitigate their harmful impacts on adjacent structures (Li et al., 2022). Then, refined blasting tests or field trials can be conducted to validate the effectiveness of different mitigation measures.

Numerical simulation plays a crucial role in tunnel blasting research by providing a powerful tool for analyzing and predicting the behavior of rock masses during blasting operations. This method involves the use of mathematical models and computational techniques to simulate the complex and dynamic processes involved in tunnel blasting. Since conducting field/physical experiments to study tunnel blasting can be expensive and time-consuming, researchers tend to favor numerical methods—relatively cheap, flexible, and fast. Numerical simulations allow researchers to study various blasting scenarios that may not be feasible with field/physical experiments. One of the main advantages of numerical simulation in tunnel blasting research is the ability to conduct controlled experiments in a virtual environment. This allows researchers to manipulate various parameters, such as blast design, explosive properties, rock mass characteristics, and vibration characteristics, to assess their effects on blasting outcomes (Kim et al., 2022; Liu et al., 2022; Luo et al., 2019; Ma et al., 2022; Zhao et al., 2022). In this way, researchers can gain insights into the fundamental mechanisms and dynamics of tunnel blasting. For example, by simulating the propagation of stress waves and ground vibrations, researchers can predict the amplitude, frequency, and direction of vibrations at different locations, and assess their potential effects on the environment and structures (Duan et al., 2022; Wang et al., 2021). This information can be used to develop guidelines, regulations, and best practices for managing ground vibrations in tunnel blasting operations. Furthermore, numerical simulation can facilitate the analysis of complex and heterogeneous rock masses, accounting for their inherent variability and anisotropy (Bao et al., 2022). By incorporating realistic rock mass properties such as strength, stiffness, and joint characteristics into the simulation models, researchers can accurately capture the response of the rock mass to blasting loads and evaluate its stability.

Finite element method (FEM) is a classical and powerful numerical method that is commonly used to study blasting vibration in tunneling because of its ability to model complex geometries and material properties. It enables researchers/engineers to simulate the effects of blasts on tunnel structures and to design appropriate measures to minimize damage and ensure the safety of the surrounding environment. The commonly used FEM dynamic hydrocodes include ANSYS/LS-DYNA (Jiang et al., 2019; Liu et al., 2020; Qin and Zhang, 2020) and ABAQUS (Dang et al., 2018). Additionally, finite difference method (FDM)-based hydrocode such as FLAC3D is also prevalent (Yang et al., 2018).

FEM is often used to model the behavior of structures subject to tunnel blasting vibration. By creating a numerical model of the structure, researchers can simulate the effect of different blasting scenarios and predict the resulting vibration levels. This can be used to assess the potential for damage to nearby structures and to optimize blasting operations to minimize harmful impacts. Yang et al. (2019) investigated the differences between the blasting vibrations on tunnel surfaces and those inside surrounding rock by field testing and numerical modeling. The results showed that monitoring the blasting vibrations both propagating on tunnel surfaces and inside surrounding rock is essential for assessing the overall stability of adjacent structures. They also pointed out that the dynamic FEM can effectively embody the attenuation law of blasting vibrations when propagating inside the surrounding rock with discontinuities or fragmentations. However, one limitation is that FEM is usually based on some simplifications when modeling tunnel blasting, e.g., the simplified equivalent explosive loading, charge structure, physical behavior of rock materials, and the equivalent loading boundary (Yang et al., 2018). These simplifications in FEM would inevitably cause a loss of accuracy.

Similar to numerical simulation, field monitoring also plays a critical role in tunnel blasting research. Field monitoring can provide invaluable data for the research objects such as vibration energy, vibration response, dimensional analysis, and so on. It involves the collection and analysis of data from sensors placed in and around the blast site, which quantify the actual impacts of blasting on the surrounding environment. One key aspect of field monitoring in tunnel blasting research is the measurement and analysis of blast-induced vibrations. Blast-induced vibrations can cause potential damage to adjacent structures, utilities, and the environment. Understanding their characteristics and effects is essential for ensuring the safety and sustainability of tunneling operations (Liu et al., 2020; Wang et al., 2019). Field monitoring allows for the direct measurement of blast-induced vibrations, including parameters such as PPV, frequency, and duration (Peng et al., 2021). This data can be used to analyze the intensity, propagation, and attenuation of vibrations, as well as to develop predictive models and guidelines for blast design optimization (Peng et al., 2019; Zhao et al., 2021).

Regarding the keywords “dynamic response” and “buried pipeline”, the research mainly centres on the dynamic response behavior of buried pipelines subjected to dynamic loads generated by tunnel blasting. When a tunnel is excavated close to a buried pipeline, the blasting shock waves can induce ground vibrations that propagate to the surrounding soil and affect the buried pipeline. The dynamic response of the buried pipeline is characterized by the induced strains, stresses, and deformation in the pipeline structure, which can cause damage, leaks, or failure.

The safety of pipelines near the tunnel is a main concern when implementing the blasting construction operations. Tunnel blasting construction could cause adverse effects on nearby pipelines. For example, the shockwaves generated by tunnel blasting can cause ground vibrations that could damage the adjacent pipelines; the movement of the ground during tunnel blasting can cause the pipelines to shift or even break; the rapid expansion of gases during blasting can create a pressure wave in the air that could damage the pipelines and associated equipment (Li et al., 2023). Therefore, precautions such as monitoring and assessing the dynamic response of buried pipelines are essential.

The common way, to explore the dynamic response of buried pipelines under the effect of blasting loads, is by combining the field measurement/experiment and numerical simulation (Guan et al., 2020a; Wang et al., 2019; Xia et al., 2021). Guan et al. (2020b) investigated the effect of tunnel blasting excavation on the vibration velocity and stress response of reinforced concrete water pipelines with different shapes (circular, square, and horseshoe-shaped). The results showed that water pipelines with three different shapes emerged with different dynamic responses to the blasting vibration. For example, the circular water pipeline produced the greatest peak vibration velocity and tensile stress, followed by the square water pipeline, and the horseshoe-shaped water pipeline produced the smallest peak vibration velocity and tensile stress. Additionally, they observed that the increased magnitude of tensile stress is more significant than that of peak vibration velocity. Xia et al. (2021) investigated the influence of tunnel blasting loads on the joints of buried reinforced concrete pipelines. The results showed that the failure of the buried reinforced concrete pipeline had two forms: cracked segments due to tensile stress induced by blasting and crushed bell-and-spigot joints induced by the rotation of joints. Compared with the segments, the bell-and-spigot joints are more vulnerable when subjected to tunnel blasting loads. Therefore, they suggested using high-strength materials for the joint to enforce its ability to resist deformation and blasting vibration. Zhu et al. (2022) studied the dynamic response between buried gas pipelines with different working pressures and clay layers. They found that the direction of vibration velocity transmitting in both buried gas pipelines and clay layers is vertical, and the deformation of buried gas pipelines is axial tensile strain. When the buried gas pipeline is under working pressure at 0–1.6 MPa, its dynamic peak effective stress experiences three phases: initial stress, peak stress, and residual stress. The working pressure has an inessential impact on the vibration velocity of buried gas pipelines, but it has a significant impact on the dynamic stress—high working pressure could incur large dynamic stress. Shi et al. (2023) investigated the dynamic response and failure mechanism of deep-buried tunnels close to each other when subjected to blasting loads. Through numerical simulation using ANSYS/LS-DYNA, they identified the attenuation law of blasting seismic and the dynamic response of the tunnel lining. The results revealed that the vibration propagated from the arch foot along the tunnel lining towards the vault, and the vibration velocity researched maximum at the arch foot, followed by the vault.

Some researchers also proposed the control criteria for assessing whether the tunnel blasting load will harm the stability of buried pipelines. For example, Shi et al. (2019) proposed the control criteria for determining the PPV for buried pipelines subjected to tunnel blasting loads. The control criteria were established according to the von Mises yield criterion of the materials of the buried pipeline, mainly combining the acceleration time-history function with a dynamic and static analysis of the pipeline. Zhao et al. (2022) studied the dynamic response characteristics of buried gas pipelines subjected to blasting loads, aiming to determine the safety criteria of buried gas pipelines according to the connection modes. The results showed that the peak strain (mainly axial tensile strain) of gas pipelines increased when the distance from the blasting source decreased. The pipelines with bolted flange joints are more prone to failure damage when subjected to tunnel blasting loads. They suggested considering the deflection angle of bolted flange joints as the failure criterion.

3.2.2. Research cluster 2: overbreak, metaheuristic algorithms, parameter optimization, and artificial intelligence

Research cluster 2 consists of four keywords: overbreak, metaheuristic algorithms, parameter optimization, and artificial intelligence.

Overbreak is one of the primary challenges to tunnel engineering when drilling and blasting methods are applied to excavate rock mass. Geological and blasting factors have a significant impact on the overbreak phenomenon in tunnel blasting (Hong et al., 2023). For example, Jang et al. (2019) reported that blast-induced overbreak is highly sensitive to geological factors such as the angle between discontinuities and tunnel contours and uniaxial compressive strength. Mohammadi and Azad (2020) emphasized that the Tunneling Rock Quality Index (Barton's Q-value (Barton et al., 1974)) can be used to assess the problematic overbreak. Li et al. (2022) pointed out that the weak interlayer within rock mass could cause severely excessive overbreak. This is because the blasting gas formed air wedges, dramatically expanding the crack within the rock mass. On the other hand, blasting factors such as the design of perimeter spacing-to-burden (S/B) dramatically dominate the generation of overbreak and the quality of tunnel excavation contour (Kang and Jang, 2020). An appropriate burden by the actual blast damage zone radius of the buffer hole is essential for controlling overbreak. Kang and Jang (2020) investigated the reasonable design values of the S/B ratio to control the generation of potential overbreak. The results showed that the excessive overbreak can be mitigated when the S/B ratio is set to 1.0. In this way, the fractures in the area between the buffer and perimeter row of holes were significantly reduced. Himanshu et al. (2022) conducted a blasting numerical simulation to explore the improved design of relief holes, aiming to mitigate the hazardous overbreak. They found that arranging multiple numbers of small diameter relief holes could better control the rock deformation, thereby reducing the amount of generated overbreak.

Since overbreak can incur unstable tunnel profiles and increase the risk of collapses, minimizing overbreak is paramount for ensuring the structural integrity of tunnels (Liu and Liu, 2017). Research on this topic mainly focuses on utilizing metaheuristic algorithms to optimize the blasting parameters. Metaheuristic algorithms have emerged as powerful tools for tackling complex optimization problems. These algorithms, known for their flexibility and efficiency, excel in finding near-optimal solutions to problems that are otherwise difficult to solve using traditional methods. In the context of overbreak minimization, metaheuristic algorithms are used to optimize blasting parameters to achieve desired blasting outcomes with minimal rock excavation. For example, Liu et al. (2023 and 2024) employed four metaheuristic algorithms, which are particle swarm optimization (PSO), whale optimization algorithm (WOA), sparrow search algorithm (SSA), and archimedean optimization algorithm (AOA), to determine the optimal blasting parameters to minimize overbreak. The optimized blasting parameters include uniaxial compressive strength, surrounding rock grade, jointing degree, buried depth, the number of blast holes, spacing, burden, total explosive charge, explosive charge of perimeter holes, and maximum charge per single cut hole. The optimization process begins with the definition of an objective function that quantifies overbreak with blasting parameters. Subsequently, PSO, WOA, SSA, and AOA iteratively search for the blasting parameters that minimize overbreak and adaptively refine their strategies to converge toward the most effective blasting parameter configurations.

Research of artificial intelligence on tunnel blasting mainly focused on establishing prediction models of blast-induced environment issues such as air overpressure, ground vibration, and overbreak. For example, Lawal et al. (2021a) developed an optimized artificial neural network (ANN) model based on swarm intelligence to predict air overpressure caused by tunnel blasting. The dataset used for modeling has 56 samples and consists of variables such as charge per delay, number of holes, distance, rock mass rating, and air overpressure. The results showed that the model—ANN optimized by particle swarm optimization algorithm—had the best prediction ability, and the variable (i.e., distance) had a significant influence on determining the air overpressure. Lawal et al. (2021b) also developed an optimized ANN model and a gene expression programming model to predict the peak particle velocity (PPV). The dataset used for modeling had 56 samples and consisted of variables such as hole length, charge per delay, number of holes, total charge, distance, rock mass rating, and PPV. The results showed that the model—ANN optimized by moth-flame optimization algorithm—performed the best prediction ability, and variables such as charge per delay and number of holes have a significant influence on determining the PPV. He et al. (2023) developed a hybrid random forest (RF) to predict the blast-induced overbreak. A dataset with 523 overbreak events was used to establish the RF model; three swarm-based optimization algorithms were used to capture the optimal hyperparameters of the RF model. Factors used for overbreak prediction included the number of holes, hole depth, total charge, advance length, rock mass rating, tunnel cross-sectional area, and powder factor. The results showed that the RF model demonstrated high performance in predicting overbreak, achieving a coefficient of determination (R^2) greater than 0.93. In addition, sensitivity analysis revealed that factors such as total charge and powder factor have a significant impact on the generation of overbreak during blasting operations.

3.2.3. Research cluster 3: Rock damage, measurement while drilling (MWD), and multiple full-face blasting

Research cluster 3 consists of three keywords: rock damage, measurement while drilling (MWD), and multiple full-face blasting.

Rock damage during tunnel blasting is a critical concern that encompasses both the failure mechanisms and cumulative damage effects inherent to the blasting process. The failure mechanism of rock during tunnel blasting is primarily governed by the interaction of mechanical, thermal, and chemical forces exerted by the explosive charges. This interaction induces stress waves and gas pressure expansion, leading to fracture initiation, propagation, and the eventual fragmentation of the rock mass (Yu et al., 2021). Beyond the immediate impact of blasting, the cumulative damage effect plays a significant role in the long-term stability and integrity of the tunnel structure. Repeated blasting operations can induce micro-cracks and weaken the rock mass surrounding the tunnel. This cumulative effect can significantly alter the rock's mechanical properties, reducing its strength and enhancing permeability, which may compromise the safety and durability of the tunnel.

Studies on failure mechanism include the damage characteristics of rock mass, tunnel lining structure, and the temporary supporting structure. For example, Chen et al. (2021) investigated the failure mechanism and progressive damage of hard-brittle sandstone under the action of tunnel excavation. They conducted experimental tests such as cyclic loading–unloading, loading–unloading, uniaxial, conventional, and unloading triaxial compression tests. The results showed that increasing confining pressure improves mechanical parameters but reduces brittle failure features, while the unloading state causes more remarkable stress drop and unstable failure characteristics. Zhou et al. (2022) investigated the failure mechanism of tunnel lining structure when subjected to blasting loads from the blasting excavation of an adjacent subway station. They used commercial software LS-DYNA to implement the modeling and found that the lining structure experienced tensile failure when the blasting tensile stress significantly surpassed the tensile strength of the lining structure. Guan et al. (2022) studied the failure mechanism of a temporary middle wall when using tunnel excavation methods such as the center diaphragm method or the center cross diaphragm method. The results showed that the main reasons causing the damage to the temporary middle wall included two aspects. The first one is the inappropriate charge design of the blast holes that are closest to the temporary middle wall, resulting in the temporary middle wall encountering excessive blasting loads. Another one is the inappropriate design of the number of blast holes, resulting in generating the unwanted free face by blasting, which could disturb the blasting impact effect. The reason why the failure occurred is due to the excess high peak tension and compression stress propelling the deformation of the temporary middle wall.

Studies on the cumulative damage effect focus on controlling the seismic vibration and assessing the long-term stability of tunnels (Chu et al., 2018). It primarily involves the evolution of stress, strain, and deformation in rock mass. For example, Chen et al. (2021) conducted several mechanical compression tests to investigate the cumulative damage process of sandstone. They found that the cumulative damage of sandstone can be classified into four phases, i.e., (1) initial compression phase, (2) energy hardening phase, (3) energy softening phase, and (4) post-peak phase. Ji et al. (Ji et al., 2021b) analyzed the cumulative damage effects of surrounding rock subjected to multiple full-face blasting. They found that the detonation sequence has a significant impact on the cumulative damage of surrounding rock. The initial detonation could induce large damage within the surrounding rock, while the subsequent detonation would cause less damage within the surrounding rock.

Regarding the keyword: measurement while drilling (MWD), it is a monitoring system when drilling blast holes in tunnels (Williamson, 2000). It can collect operational data when drilling operations are conducted at predetermined length intervals along the blast hole. In tunnel blasting, MWD is used for several aspects: constructing the relations between the drilling parameters and rock mass properties, analyzing the mutual relations between the frilling parameters, or evaluating the quality of blast hole drilling. For example, Navarro et al. (2018a) developed an engineering model, based on MWD parameters, to predict the potential overbreak and underbreak zones. Such a predictive model can serve as a drill or rock index that could be used to identify the zones with high geotechnical risk. The result showed that the geotechnical condition of the rock mass has a significant impact on the generation of overbreak and underbreak. Different geotechnical conditions correspond to different MWD parameters. If the MWD parameters such as normalized penetration rate, hammer pressure, rotation pressure, and the lookout distance have high values, it indicates that the properties of the rock are hard and unaltered. Such rock conditions could encounter low-level overbreak and underbreak after blasting. If the MWD parameters such as normalized rotation speed and water flow have high values, it indicates that the properties of rock are soft and fractured. Such rock condition could encounter high-level overbreak and underbreak after blasting. Navarro et al. (2018b) investigated the mutual relations between the MWD parameters stemming from the drilling control operational system. They applied two statistical tools, i.e., auto-correlation and cross-correlation, to determine the master parameters that most significantly embody the variations in the rock mass. The result showed that parameters, such as hammer pressure, feed pressure, penetration rate, rotation pressure, and damp pressure, have significant mutual correlations. Among these, feed pressure can drive the adjustment of other parameters to optimize the drilling. Additionally, the authors suggested that the feed pressure could be a potential MWD parameter for characterizing the rock mass. Navarro et al. (2019) quantified the drilling quality of blast holes by comparing the data from the MWD system with data from the actual end position of the blast hole logged. The results indicated that the quality of blast hole drilling is significantly influenced by the rock structure, particularly in the presence of disturbance zones within the rock mass, leading to deviation from the intended borehole trajectory.

Regarding the keyword: multiple full-face blasting, it is a technique used in tunnel blasting where several blast holes are detonated simultaneously across the full face of the tunnel excavation. By detonating multiple blast holes simultaneously, a large section of the tunnel face can be excavated in a single blast, reducing the need for sequential drilling and blasting. Multiple full-face blasting produces unique blasting effects on the surrounding rock mass compared with other blasting techniques. The simultaneous detonation of multiple blast holes can result in different fragmentation patterns, vibration characteristics, and damage mechanisms. For example, Ji et al. (2021b) proposed a blast-induced damage model that integrates the tensile damage model with the Drucker-Prager yield condition, which is used to simulate the cumulative damage of surrounding rock under multiple full-face blasting. The results showed that the maximum damage depth and the maximum PPV occurred in the middle of the tunnel invert, and the maximum damage depth of surrounding rock hinged on the blasting quality of the outermost excavated cross-section. Ji et al. (2021a) compared the cumulative damage effects of single and multiple full-face blasting on surrounding rock. They found that the maximum damage depth of surrounding rock caused by multiple full-face blasting is slightly larger than that caused by single full-face blasting. Compared with the numerical results of single full-face blasting, the PPV measured from the numerical simulation of multiple full-face blasting is more consistent with the PPV measured from the field test.

3.2.4. Research cluster 4: Stability

Research cluster 4 consists of only one keyword: stability. The stability problems induced by tunnel blasting mainly include the stability of the surrounding rock, especially the rock mass of the tunnel roof and the adjacent geological formations such as the slope. Deng et al. (2018) conducted a numerical simulation to explore the influence of thin bedrock roofs on the stability of tunnel surrounding rock after blasting.

The modeling results show that the thickness of the bedrock roof is a major factor affecting the stability of the tunnel surrounding rock. For example, when blasting work operated with a 5 m thick bedrock roof, the surrounding rocks are stable, but when blasting work operated with a 2 m thick (or even below) bedrock roof, the surrounding rocks are prone to collapse. Fu et al. (2018) conducted a series of blasting trials and measured the PPV on the roof of a tunnel to propose the safety criterion for how calculating the maximum charge per delay in a blasting operation. Sun et al. (2019) investigated the influence of tunnel blasting on the stability of the adjacent slopes. Through field monitoring, geological survey, and numerical simulation, they found that the slope toe was prone to be unstable due to the significant disturbance effect incurred by tunnel blasting. The slope failure mainly consisted of two modes: a vertical falling of rock mass and a landslide.

4. Summary of review findings and future research directions

The bibliometric analysis of the research on tunnel blasting helped in developing a comprehensive understanding of the existing research. The findings of this review could contribute to sorting out the pivotal information on tunnel blasting research, such as the leading journals, institutions, researchers, and articles, as well as the research hotspots. Fig. 6 presents a summary of the main findings. The citation analysis identified two prominent journals that possess the most articles on tunnel blasting research. Particularly, the journal, *Tunnelling and Underground Space Technology*, published the predominant articles on tunnel blasting research. The co-authorship analysis illustrated that the existing research on tunnel blasting has been undertaken predominantly in China as all research institutions are from China. Additionally, the co-authorship analysis identified three leading researchers in this research area and also indicated that they have a good cooperative relationship with each other. The co-occurrence of keywords analysis classified the research keywords into four clusters and identified four high-frequency keywords from the retrieved articles.

To figure out current research hotspots on tunnel blasting, we summarized the temporal evolution and occurrence frequency of each keyword from 2018 to 2023 in Table 5, which aims to identify the most concerned research methods and topics of tunnel blasting. For example, numerical simulation is regarded as the most time- and cost-effective way of researching tunnel blasting, and field monitoring is commonly used to calibrate the results of numerical simulation. The current remarkable research topics of tunnel blasting include the characteristics of blasting vibration and rock damage, the dynamic response of buried pipelines when subjected to blasting loads, and the way of overbreak prediction and control. Additionally, taking research keywords such as “buried pipeline”, “overbreak”, “dynamic response”, “artificial intelligence”, “metaheuristic algorithms” and “parameter optimization” as examples, the summarized results show that they are emerging in recent years. While for research keywords such as “stability” and “measurement while drilling (MWD)”, the relevant research has gradually decreased in recent years.

According to the research findings summarized previously, future research efforts could be directed toward exploring the relevant content according to the retrieved research keywords. For example, the blasting vibration is a significant concern in tunnel blasting due to its potential to cause damage to nearby structures and affect the safety of construction workers (Huo et al., 2022; Navarro Torres et al., 2018). While there has been significant research on the effects of blasting vibration on nearby structures, further investigation is needed to understand the relationship between blasting parameters (e.g., charge weight, distance from the source) and PPV (Qiu et al., 2022). Improved understanding in this area could lead to more accurate PPV predictions and better management of blasting-induced vibrations. Regarding numerical simulation, it represents a highly promising and rapidly evolving field of research for the study of tunnel blasting. In recent years, advances in computational methods and modeling techniques have greatly expanded the scope and accuracy of numerical simulations, enabling researchers to generate highly detailed and accurate predictions of the behavior of rock mass during blasting (Li et al., 2023). The continued development of numerical simulations is expected to play an increasingly important role in the study of tunnel blasting, enabling researchers to gain deeper insights into the complex physics of blasting and to design safer and more efficient blasting plans. Furthermore, the increasing availability of high-performance computing resources and sophisticated simulation tools is expected to drive further innovation in this field, opening up new avenues for research and enabling more advanced and comprehensive simulations of blasting processes. Regarding the rock damage and overbreak, they are the common issues in tunnel blasting, which can lead to safety concerns and increased costs. Further research could explore new blasting techniques to reduce overbreak and improve the stability of surrounding rock mass. This could involve the use of different explosives or initiation sequences, as well as improved numerical modeling to optimize blasting design.

Another fertile and promising avenue for further research is to explore the application of machine learning (ML) on tunnel blasting. Recent developments in ML have the potential to significantly enhance the understanding and management of tunnel blasting-induced vibrations. One potential application is the development of predictive models for PPV based on blasting parameters and geological characteristics of the surrounding rock mass. These models could improve the accuracy of PPV predictions and help optimize blasting design to reduce potential risks to nearby structures. Similarly, ML techniques could be applied to the problem of overbreak, which is a significant concern in tunnel blasting. By analyzing large datasets of blasting events and geological

Prominent journal outlets	Co-authorship analysis	Research clusters	Frequency of keywords analysis
1. Tunnelling and Underground Space Technology 2. Shock and Vibration	❑ *Leading institutions* 1. China University of Geosciences 2. Central South University 3. Qingdao University of Technology ❑ *Leading researchers* 1. Jiang, Nan 2. Zhou, Chuanbo 3. Guan, Xiaoming	1. Blasting vibration, numerical simulation, dynamic response, buried pipeline, field monitoring 2. Overbreak, artificial intelligence, metaheuristic algorithms, parameter optimization 3. Rock damage, measurement while drilling (MWD), multiple full-face blasting 4. Stability	1. Blasting vibration 2. Numerical simulation 3. Rock damage 4. Overbreak

Fig. 6. Summary of the main findings.

Table 5
Frequency of research keywords on tunnel blasting in recent years (2018–2023).

Research keyword	Frequency	Year					
		2018	2019	2020	2021	2022	2023
Blasting vibration	37	×××××××	××××××	××××××	××××××××	×××××××	×××
Numerical simulation	29	××××	×××××	×××××××	××××××	×××××	××
Rock damage	16	××	××××	×××	×××	×××	×
Overbreak	10	×	×	××	××	××	××
Dynamic response	9	×		××	×××	××	×
Artificial intelligence	4			×	××		×
Buried pipeline	4			×	×	××	
Field monitoring	4		×	×	×	×	
Stability	3	××	×				
Measurement while drilling (MWD)	2	××					
Metaheuristic algorithms	2						××
Multiple full-face blasting	2					××	
Parameter optimization	2						××

Note: "×" denotes the occurrence (one time) of keywords in a certain year.

characteristics, ML models could identify patterns and predict areas of high overbreak risk. This information could be used to optimize blasting design and improve the stability of the surrounding rock mass. However, there are also challenges associated with integrating ML techniques into tunnel blasting research. One key challenge is the availability of high-quality data, as well as the need to ensure data privacy and security (He et al., 2024). Additionally, the development of accurate predictive models and algorithms requires significant computational resources and expertise.

In summary, the integration of ML techniques has the potential to significantly enhance tunnel blasting research, particularly in areas related to PPV prediction and overbreak formation. However, further research is needed to address challenges related to data availability, privacy, high-accuracy models, and computational resources.

Apart from that, recently the environmental issues induced by tunnel blasting are also becoming the researchers' concerns (Liu et al., 2023; Luo et al., 2022; Sun et al., 2023). Tunnel blasting will generate vast fumes containing high mass concentrations. The high fume concentration can extremely pollute the air environmental pollution and harm the workers' health. The tunnel blast-induced fumes mainly involve two harmful ingredients: dust and gases. Regarding dust, Shi et al. (2022) investigated the variation of dust concentration and the distribution of dust particles at different tunnel locations after tunnel blasting (during 1200 s). They designed dust reduction measures to accelerate the dilution and dissipation of dust. Regarding the gases, especially toxic gases: carbon monoxide (CO) and nitrogen oxides (NO_x) (Chen et al., 2021). Feng et al. (2022) investigated the diffusion law of CO after tunnel blasting at high altitudes. They identified the functional relationship between CO concentration and parameters such as ventilation time, distance from the working face, and altitude. The proposed functional relationship is effectively applied for predicting the CO concentration. Torno and Toraño (2020) utilized computational fluid dynamics (CFD) technology and experimental measurements to analyze the gas dilution behavior of CO and NO_2. They deduced the reasonable re-entry time after blasting according to different tunnel cross-sectional areas. To address the problem of blast-induced fumes or toxic gases, future research may focus on further developing and refining ventilation systems to improve their effectiveness, as well as exploring the use of new technologies, such as advanced sensors and real-time monitoring, to better understand the generation and dispersion of toxic gases during tunnel blasting. Additionally, there may be a greater emphasis on developing and implementing regulations and guidelines to ensure that tunnel blasting is conducted in a safe and environmentally responsible manner.

5. Conclusions

This review conducted a bibliometric analysis of research on tunnel blasting. The analysis involved 144 English peer-reviewed articles indexed in the Web of Science Core Collection from 2000 to 2023. This review revealed the prominent journal outlets, leading institutions, researchers, and articles through the bibliometric analysis. Also, it summarized the research hotspots in 2018–2023 and speculated the future research directions of tunnel blasting. The following conclusions can be extracted from this review.

i. Research articles on tunnel blasting burgeoned in 2018 and showed an upward trend in recent years (after 2018). Regarding the publications, China contributed the most articles related to tunnel blasting research, followed by South Korea. In addition, the top two journals that published the most articles on tunnel blasting are *Tunnelling and Underground Space Technology* and *Shock and Vibration*. The top three institutions that contributed the most articles on tunnel blasting are *China University of Geosciences*, *Central South University*, and *Qingdao University of Technology*. The top three researchers who contributed the most articles on tunnel blasting are Jiang Nan, Zhou Chuanbo, and Guan Xiaoming.
ii. High-frequency research hotspots in 2018–2023 included blasting vibration, numerical simulation, rock damage, and overbreak. They are the noteworthy research objectives of tunnel blasting, such as the investigation of characteristics of blasting vibration, dynamic response of rock damage when subjected to blasting loads, and overbreak prediction and controlling.
iii. Future research directions of tunnel blasting could focus on developing high-performance computational techniques/approaches to tunnel blasting, exploiting effective ML models to embody the dynamic characteristics of tunnel blasting, and establishing feasible measures for addressing environmental issues induced by tunnel blasting. Further research and development in these directions will undoubtedly continue to shape the future of tunnel blasting research and practice.

Despite the significant contributions of this review, it is also necessary to highlight some limitations of the work presented in this review. First, the analysis was based on a dataset extracted from the Web of Science Core Collection, so an inevitable limitation is the limited coverage of publications; on the other hand, the academic publications were searched through specific keywords, which may cause losing sight of some other relevant keywords. Another potential limitation is the possibility of language bias, as the review has only included studies published in English, and may have missed important studies published in other languages. This could result in a limited scope of the research included in this review and may limit the applicability of the findings.

Although the review has these unavoidable limitations, we believe it can provide helpful and valuable guidance for researchers who focus on the field of tunnel blasting. This is because the longitudinal study method on articles and the bibliometric analysis technique offer support for validating the results and removing the subjective elements.

CRediT authorship contribution statement

Biao He: Conceptualization, Formal analysis, Methodology, Validation, Writing – original draft, Writing – review & editing. **Danial Jahed Armaghani:** Conceptualization, Supervision, Validation, Writing – original draft, Writing – review & editing. **Sai Hin Lai:** Conceptualization, Supervision, Writing – original draft, Writing – review & editing. **Xuzhen He:** Conceptualization, Validation, Writing – original draft, Writing – review & editing. **Panagiotis G. Asteris:** Conceptualization, Supervision, Validation, Writing – original draft, Writing – review & editing. **Daichao Sheng:** Conceptualization, Supervision, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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