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Review

Development of Rockburst Research: A Comprehensive Review

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Abstract: Rockburst is a difficult problem in underground resource development and infrastructure construction. With scientific and technological progress, more research technologies and methods to prevent rockburst have been proposed and applied. Research content has become more comprehensive, and positive progress and achievements have been made. However, due to the complexity of rockburst control factors and the sudden occurrence of rockburst, the occurrence mechanism and accurate prediction of occurrence intensity and time are still difficult worldwide problems. In this paper, the research development and achievements of rockburst are reviewed. Firstly, various definitions and types of rockburst are briefly summarized. Then, research progress and achievements in four aspects are comprehensively reviewed, including methods and techniques of rockburst research (theoretical research, numerical simulation, physical model tests and in situ monitoring), mechanism of rockburst, classification and prediction of rockburst (empirical criteria, in situ monitoring, mathematical model approaches and rockburst chart) and prevention and control of rockburst. Of particular significance is that the classification and prediction with prevention and control are summarized in detail. Finally, limitations, deficiencies and some promising directions for future research are listed.

Keywords: rockburst mechanism; rockburst classification; rockburst prediction; rockburst prevention

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1. Introduction

Rockburst is a sudden rock failure characterized by the breaking up and expulsion of rock from its surroundings, accompanied by a violent release of energy, which can pose a severe threat to engineering and people [1]. Due to the fact that rockburst in underground coal mining is very different from that in tunnelling projects and other mines in the aspects of mechanism, classification, risk assessment, monitoring and early warning, prevention and control, it is not reviewed in this article.

The rockburst at the Altenberg tin mine in Germany (1640) may be the earliest catastrophic rockburst, which led to the shutdown of the mine for many years. In Canada, rockburst has occurred in many mines, including the Brunswick lead–zinc mine at Bathurst, the Lake Shore mine, the Teck-Hughes mine, the Wright-Hargreaves mine, the Falconbridge nickel mine and the Macassa gold mines at Kirkland Lake [2]. From 1996 to 2003, rockburst was the second leading cause of fatal accidents in South Africa [3]. The Kolar gold mine in India, the East Rand Proprietary Mines (ERPM) in South Africa, the Idaho lead–zinc–silver mine in the USA, the Kan-Etsu highway tunnel in Japan, the Heggura highway tunnel in Norway, the diversion tunnel of the Vietas hydropower station in Sweden, the Hongtoushan copper mine, the Linglong gold mine, the Yuzixi I hydropower station, the Tianshengqiao II hydropower station, the Taipingyi hydropower station, the Jinping II hydropower station, the Erlangshan tunnel of Sichuan-Tibet highway, the Qinling railway tunnel and the Jiulongxia hydropower station have also suffered rockburst [4]. Figure 1 shows the distribution of typical mines prone to rockburst in the world.

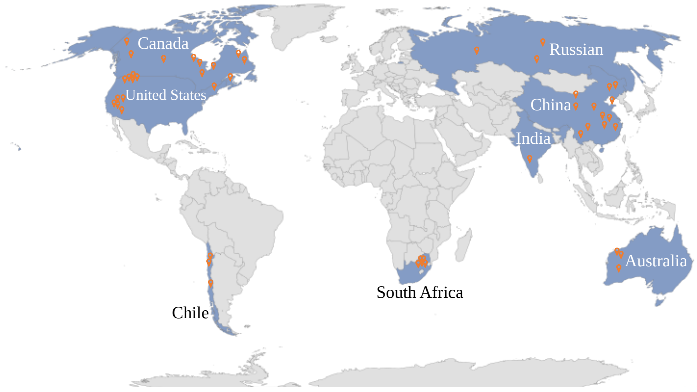

Figure 1. Distribution of typical mines prone to rockburst in the world.

Rockburst often brings great threats to people, property and engineering stability. Therefore, the mechanism and control of rockburst have received much attention.

South Africa was one of the first countries to systematically carry out rockburst research. As early as the 1960s, the Rockburst Committee was established, and then research institutes, laboratories and management institutions were established to carry out rockburst research. In 1977, the International Society of Rock Mechanics established a special committee on rockburst. In 1984, Canada launched two 10-year deep mine rockburst-related research programs and introduced the geophysical method of seismic monitoring into prediction of rockburst. Rockburst research institutions have also been established in the USA, India, Poland and China. In 1995, China launched the "Ninth Five Year Plan" for tackling key scientific and technological problems, "Research on comprehensive technology for 3-million-ton intensive mining of kilometer deep mines", and began research on rockburst mechanism and prediction. Figure 2 demonstrates the main scientific research institution of rockburst since the 21st century (data source: Web of Science, keywords: rockburst, rock burst). The sizes represent the rankings of the number of published papers. The number of papers published by Chinese academic circles ranks first.

Figure 2. Institution cooperation network for rockburst research.

At present, the research object of studying rockburst has developed from the state where rockburst occurs to the mechanism, monitoring and early warning; from the focus on supporting design to the optimization of excavation technology, stress release optimization and optimization of combined support with energy absorption. However, due to the complexity of the rockburst control factors, the current research results have not been able to explain the mechanism of rockburst in detail, and reasonably, and it is difficult to establish a set of universal mechanical theories about rockburst. On the other hand, the key part of rockburst warning/prediction of occurrence time is still an unsolved problem. At the same time, as more and more mines enter the stage of deep and ultradeep mining, the requirements for rockburst prevention technology will become higher.

The remainder of this paper consists of the following parts: Section 2 presents an overview of rockburst definition and type; Section 3 introduces the technologies and methods of rockburst research; Section 4 presents research progress into the rockburst mechanism in recent years; Section 5 presents progress of rockburst classification and prediction from empirical criteria for in situ monitoring methods, mathematical model approaches and rockburst charts; Section 6 presents rockburst prevention and control measures in the project site, and rockburst support is especially introduced; Sections 7 and 8 point out limitations of the research achievements and suggest future research directions.

2. Rockburst Definition and Types

2.1. Rockburst Definition

Many journal papers and government publications have defined rockburst. Table 1 provides a timeline of rockburst definitions based on the literature review. There were controversies in early academic circles, mainly including the following three points:

- Whether rockburst occurs only in hard brittle rock mass.
- Whether static failure, such as spalling and splicing, is rockburst.
- Whether pressure bump can be attributed to rockburst.

With the accumulation of engineering data and the deepening of research, the above three controversies have basically reached a consensus:

- Rockburst failure is a dynamic instability phenomenon, which is essentially different from static failure. Simple static failure does not belong to rockburst, but the precursory phenomenon of rockburst may be static failure.
- Pressure bump has the characteristics of high intensity, long lag time and large influence range, but its essence is the same as rockburst and thus it can be generalized as rockburst.

Table 1. Rockburst definitions.

Researchers (Year)	Rockburst Definition and Its Description
Cook (1965) [5]	• Rockburst is an uncontrolled disruption of rock associated with a violent release of energy.
Blake (1972) [1]	• Rockburst is a sudden rock failure characterized by the breaking up and expulsion of rock from its surroundings, accompanied by a violent release of energy.
Zhang (1991) [6]	• Rockburst is a phenomenon that occurs when a hard and complete rock mass that has accumulated a large amount of strain energy has been excavated, the initial stress of the rock mass exceeds the elastic limit of the rock mass and the accumulated strain energy is suddenly released, accompanied by loud noises and lenticular rock fragments flying out.
Ortlepp et al. (1994) [7]	• Rockburst is a sudden and violent expulsion of rock from the surrounding rock mass.
Kaiser et al. (1996) [8]	• Rockburst is a seismic event that is associated with damage to a mine opening.
Singh et al. (1999) [9]	• Rockburst is a violent failure in hard (brittle) and massive rock masses of Class II * (* uniaxial compressive strength (UCS) test on Class II type) when subjected to high stress.
Blake et al. (2003) [10]	• Rockburst can be regarded as a large seismic event or a small seismic event.
He et al. (2007) [11]	• Rockburst is the phenomenon of nonlinear dynamics with the instantaneous release of energy along the free surface of rock excavation.

Table 1. *Cont.*

Researchers (Year)	Rockburst Definition and Its Description
Solak (2009) [12]	• Rockburst is a sudden and violent failure of rock mass, caused by highly stressed brittle rocks and the rapid release of accumulated strain energy.
Li (2014) [13]	• Deep rock is under in situ stress and maintains in elastic range and the stored elastic energy is high enough to break the rock. If triggered by a certain degree of perturbation, the stored elastic energy is likely to release and break the rock mass and energy required to break the rock mass is greater than that carried by the perturbation, then we say rockburst occurs.
Zhou et al. (2017) [14]	• The local stress concentration is caused by deep engineering excavation and the storage of large elastic strain energy in surrounding rock mass; thus, brittle rock failure may occur under the action of the external dynamic disturbance loading, causing the release of internal storage energy of the rock mass. Most of the released storage energy results in the destruction of the rock and the extra part of the energy results in the broken rock blocks ejected, which induces rockburst.
Dietz et al. (2018) [15]	• Rockburst is a sudden and violent movement and collapse of rock in underground caves which occurs under high stress conditions.
Feng et al. (2019) [16]	• Rockburst is a dynamic phenomenon when the elastic deformation potential energy accumulated in underground engineering rock mass suddenly releases under excavation or another external disturbance, leading to the burst and ejection of surrounding rock.
Zhao et al. (2020) [17]	• Rockburst is defined as damage to an excavation that occurs in a sudden or violent manner.
Farhadian (2021) [18]	• Rockburst is defined as a phenomenon with immediate dynamic instability under excavation unloading conditions of deep or high geostress areas.

At present, although there is no internationally recognized definition of rockburst, the definition is basically the same in terms of failure phenomenon and failure mechanism.

2.2. Rockburst Types

Both statistics of on-site rockburst data and physical model tests of rockburst are carried out based on rockburst type. Therefore, reasonable classification of rockburst type is of great significance. Table 2 presents the main rockburst types of classification schemes.

Hoek divided rockburst into strain type and fracture type according to the slip of fracture surface and the degree of rock fracture [19]. Kaiser et al. divided rockburst into three types: bulking, ejection and seismically induced fall of ground via a rockburst damage mechanism (See Figure 3a). He et al. divided rockburst into three types: (a) instant rockburst, (b) standard rockburst and (c) delayed rockburst, according to the length of time from unloading to rockburst occurrence, along with two other types: (a) strainburst and (b) impact-induced rockburst.

Table 2. Types of rockburst.

Researchers (Year)	Classification Basis	Types of Classification
Hoek (1980) [19]	Sliding of fracture surface and degree of rock fracture	(a) strain rockburst (b) fracture rockburst
Ryder (1988) [20]	Mechanical characteristics and seismic signatures of rockburst	(a) rockburst caused by crushing of highly stressed rocks (b) rockburst associated with slip or rupture along planes of weakness
Tan (1991) [21]	In situ stress action pattern	(a) horizontal stress type (b) vertical stress type (c) mixed stress type
Ortlepp et al.(1994) [7]	Characteristics of mine rockburst and focal mechanism	(a) strain rockburst (b) bending failure rockburst (c) pillar failure rockburst (d) shear failure rockburst (e) fault slip rockburst
Kaiser et al. (1996) [8]	Triggering mechanism	(a) remotely triggered (b) self-initiated
	Damage mechanism	(a) bulking (b) ejection (c) seismically induced fall of ground
Tang (2000) [22]	Rockburst mechanism	(a) strainburst (b) fault-slip burst (c) combined mechanisms
Blake et al. (2003) [10]	Potential causes of rockburst	(a) strain rockburst (b) pillar failure rockburst (c) fault-slip rockburst
He et al. (2012) [23]	Time from unloading to rockburst	(a) instant rockburst (b) standard rockburst (c) delayed rockburst
	Characteristics of mine rockburst	(a) strainburst (b) impact-induced rockburst
Feng et al. (2012) [24,25]	Time of rockburst occurrence	(a) immediate rockburst (b) time-delayed rockburst
	Development mechanism	(a) strain rockburst (b) strain structural plane sliding rockburst (c) fracture slip rockburst
Wu et al. (2013) [26]	Control factors of surrounding rock failure	(a) strain rockburst (b) discontinuity rockburst
Qian (2014) [27]	Stress release mode of rockburst	(a) pillar strain rockburst (b) enclosing rock strain rockburst (c) fault-slip rockburst
Li et al. (2017) [28]	Geomechanical characteristics of rockburst	(a) tensile cracking and spalling (b) tensile cracking and toppling (c) tensile cracking and sliding (d) tensile shearing and bursting (e) buckling and breaking (f) arc shearing and bursting
Deng et al. (2018) [29]	In accordance with the magnitude of stimulation force	(a) induced rockburst (b) triggered rockburst (c) inherent rockburst

Based on in situ monitoring of rockburst in the Jinping II hydropower station, Feng et al. divided rockburst into two types: (a) immediate rockburst and (b) time-delayed rockburst, according to occurrence time of rockburst. Immediate rockburst generally occurs during or after an excavation unloading effect, from a few hours to 1 to 3 days. Time-delayed rockburst generally occurs outside the excavation stress disturbance range of the tunnel face, 80% of which occurs 6–30 days after excavation in this area [24,25]. Li et al. divided rockburst into six basic geomechanical types with unique development characteristics based on geomechanical analyses of a rockburst event which occurred in China (See Figure 3b) [28].

According to the above classification scheme, when it is necessary to classify rockburst type, whether structural surface plays a major role should be judged first, and then rockburst can be preliminarily divided into strain type and structural surface type. Furthermore, type of strain rockburst can be divided into type of surrounding rock strain and type of rock pillar strain via the occurrence location of rockburst.

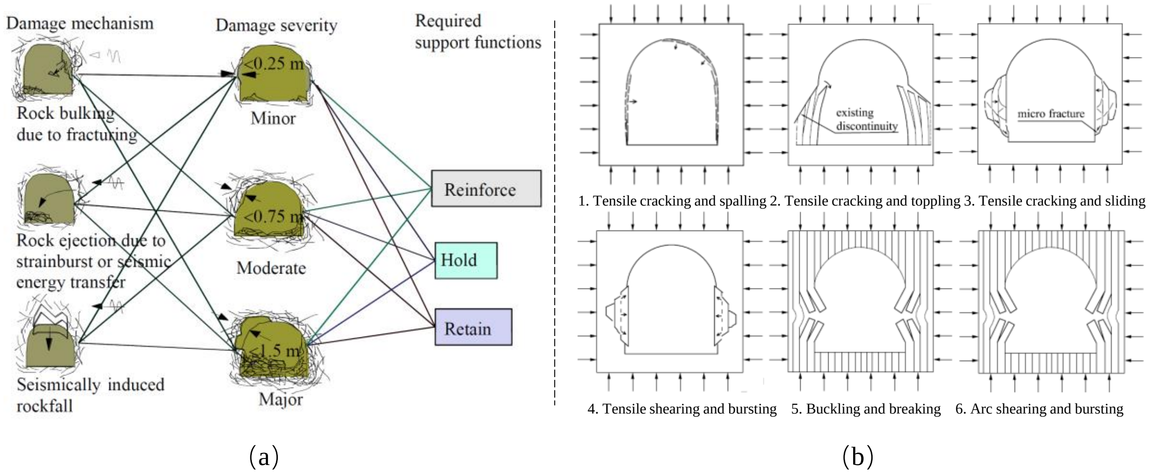

Figure 3. Rockburst types of classification: (**a**) rockburst damage mechanism, damage severity and required support functions (from [30]); (**b**) six geomechanical types of rockburst adapted from [28].

3. Technologies and Methods for Rockburst Research

Currently, technologies and methods for rockburst can be basically divided into four aspects: theoretical research study, numerical simulation, physical model tests and in situ monitoring.

3.1. Theoretical Research

At the moment, theoretical research refers to analyzing the mechanisms and categories of rockburst via different aspects, such as the strength theory, the stiffness theory, the energy theory, the inclusion theory, the fractal theory, the defect theory, the energy disturbance theory, the blasting reliability theory, the instability theory, the catastrophe theory, the bifurcation theory, the dissipative structure theory and the theory of chaos [31–36], which are used to study the deformation and stability of rock mechanics systems and the rockburst mechanism. Among them, research based on the strength theory, the energy theory and the stiffness theory is dominant.

The strength theory is based on the concept of material strength in traditional mechanics, which only provides the necessary conditions for rockburst; it does not point out under what conditions rockburst will occur.

The energy theory explains the failure mechanism of rockburst from an energy point of view, but it does not explain the failure conditions of an equilibrium state.

According to the stiffness theory, the necessary condition for rockburst is the stiffness of the mine structure (ore body) being greater than that of the mine load (surrounding rock). However, it does not give a clear concept of the division and stiffness of the mine structure and mine load systems.

Since rockburst is a process of rock mass moving from static equilibrium to dynamic instability, it is hard to comprehensively explain the mechanism and severity of rockburst through a single theory. Therefore, the existing technologies and methods examining rockburst mostly focus on numerical simulation, physical model tests and in situ monitoring.

3.2. Numerical Simulation Techniques

The theoretical basis of the numerical simulation of rockburst mainly includes: the finite element method (FEM) [37], the extended finite element method (XFEM) [38], the boundary element method (BEM) [39], the finite difference method (FDM) [40], the discrete element method (DEM) [41], general particle dynamics (GPD) [42], discontinuous deformation analysis (DDA) [43], the numerical manifold method (NMM) [44] and the particle manifold method (PMM) [45]. NMM is a coupling method of FEM and DDA, which is used to solve the problems of continuous deformation and discontinuous deformation. PMM is another coupling method proposed by introducing the concept of particles into NMM. For instance, a realistic full 3D finite element model was used to evaluate the distribution and accumulation of strain energy in kimberlite to predict potential rockburst induced by mining [46]. The mechanical behavior of rock samples was simulated by DEM to observe the basic mechanism of rock deformation and failure [47]. The Johnson–Holmquist–Beissel (JHB) model was introduced into particle-based numerical manifold method (PNMM) to capture more mechanical responses on the micro scale [48]. Since DEM can obviously reflect a continuous nonlinear stress–strain relationship, yield strength and process of post peak strain softening or hardening, it is strongly applicable to studying mechanical properties of heterogeneous materials of rock mass.

Numerical simulation can also be used to dynamically evaluate rockburst risk. The focus is to establish a quantitative mapping relationship with rockburst characteristic parameters with evaluation indicators. The commonly used evaluation indices can be divided into numerical indicators based on the strength theory or the energy theory (See Table 3).

Table 3. Common numerical calculation indicators.

Type	Evaluating Indicator	Characteristics of Indicator
Indicators based on the strength theory	Excess shear stress (ESS)	• Possibility of rockburst controlled by rock mass structural stress can be obtained [20].
	Failure approach index (FAI)	• Failure depth, section distribution and position of rock mass can be obtained [49].
Indicators based on the energy theory	Energy release rate (ERR)	• Energy released from rock mass under different excavation sequences and sizes can be obtained [31].
	Energy storage rate (ESR)	• Energy evolution process before and after rock failure can be characterized [50].
	Burst potential index (BPI)	• Possibility of rockburst when energy storage rate reaches the maximum energy storage limit can be presented [51].
	Local energy release density (LERD)	• Effective kinetic energy released from surrounding rock system before and after pillar failure can be characterized [52].
	Modelled Ground Work (MGW)	• Energy change of rock mass before and after failure can be characterized [53].
	Local energy release rate (LERR)	• Energy release value and evolution law on the section before and after rock mass excavation can be obtained [54].
	Relative energy release index (RERI)	• Energy evolution of the instability process can be tracked, and influence of deformation characteristics on failure is implicitly considered [55].

Numerical simulation can reflect actual situation to a certain extent, which is a good auxiliary research method. However, it is not simple to establish a realistic model and set reasonable initial conditions and parameters to make simulation results more realistic.

3.3. Physical Model Tests

Since rockburst is sudden, dynamic and instantaneous, physical model tests of rockburst have special requirements for similar materials, similar theories, instruments and equipment (for loading, excavation, support, monitoring and measurement). Hence, there are not many physical model tests on rockburst.

Similar materials are the basis of rockburst physical model tests, which are mainly composed of aggregate materials (sand, slag, barite, etc.), cementitious materials (gypsum, cement, epoxy resin, etc.) and additives to improve performance (water reducer, retarder, rosin alcohol solution, etc.) [56–58]. Although it is impossible to achieve the same violent ejection as an in situ phenomenon with similar materials, there should be ejection phenomenon with a low initial velocity. Therefore, the strength of the rockburst of the similar materials should not be too low so that some of the energy can be accumulated. In addition to meeting similarity conditions of basic mechanical parameters, the most critical point should meet a brittle similarity relationship. According to current test phenomena, there is almost no difference from general static failure, only slag falling, spalling, block falling and no dynamic instability process of surrounding rock from energy accumulation to sudden burst ejection. Consequently, it is necessary to explore more suitable similar materials, study the similarity of hard structural surfaces between original rock and similar materials and prepare structural planes with different geometric forms and mechanical properties in the specimens.

In terms of loading devices, to facilitate observation, a simple two-dimensional loading mode was adopted in most tests (plane strain or plane stress [59–61]), and loading capacity was also weak. However, rockburst mostly occurs in deep buried high-stress rock mass, so a loading device needs to have a strong loading capacity.

Occurrence of rockburst is not only affected by lithology and stress state, but also induced by blasting disturbance. If loading devices can provide static load (original rock stress) and dynamic load with frequency and amplitude (simulating an explosion stress wave), the action mechanism of the stress wave on rockburst may be revealed. However, how to quantify "dynamic similarity" between an in situ explosion stress wave and a simulated stress wave is a theoretical problem to be solved.

Model excavation is also an important link. There are four main schemes:

- A cylinder core is preinserted into a test specimen and then pulled out after the test specimen dries to complete the tunnel specimen. The effect of tunnel formation is good, but it does not well simulate the process of tunnel excavation and the characteristics of stress redistribution.
- A cylinder core consisting of several small sections (the mechanical properties, such as elastic modulus, should be as consistent with the test specimen as possible) is preinserted into a test specimen and then pushed out in sequence (simulating sectional excavation) after the test specimen dries and is loaded to initial stress. The difficulty is that it is necessary to make the deformation of small sections consistent with the test specimen and small sections are difficult to be pushed out under high stress.
- After the test specimen dries and is loaded to the initial stress, the specimen is manually excavated to create a tunnel by a drilling rig or small excavation machine. However, when the tunnel is long and there is concealed excavation, it is difficult to excavate manually in a narrow space.
- The advantage is high efficiency, but there is still a great difference between a simple mechanical rock breaking mechanism and an in situ machine, which makes the accuracy of the test result low. Therefore, the interaction mechanism of the TBM excavation rate, cutter head thrust, torque, shoe pressure, shield pressure to rockburst, reasonable

selection of explosive, similarity index of the blasting effect evaluation for drilling and blasting method are the keys to increasing the accuracy of the test result.

In the aspect of support, a plastic push rod, brass rod or enameled wire is used to simulate bolts, and aluminum wire or fine copper wire is used to simulate anchor cables. However, the bolts or cables are mostly embedded in the designated position before the test, and simulated support equipment played a role in the specimen before excavation, which is different from the actual process of strengthening surrounding rock.

In terms of monitoring, most attention is paid to monitoring deformation and the stress of the model surrounding rock [62]. However, monitoring should focus on the surrounding rock fracture and its evolution law, supplemented by deformation and stress. Therefore, developing a high-precision comprehensive information monitoring system that can adapt to the typical deformation and failure characteristics of hard rock dominated by cracking is crucial for physical model tests of rockburst.

3.4. In Situ Monitoring

The most significant advantage of in situ monitoring is that it can obtain relevant parameters directly and in real time, truly reflecting the development mechanism and evolution law of rockburst, to timely evaluate and predict the risk of rockburst. In situ monitoring methods mainly include microseismic (MS) monitoring [63], microgravity [64], infrared thermal imaging [65], electromagnetic radiation [66], acoustic emission (AE) [67] and the photoelastic method [68]. Compared with other methods, acoustic emission and microseismic monitoring technology can be used to detect the occurrence of failure in early stages, before complete failure and destructive deformation of structure, which is more suitable for the process of rockburst.

Microseismic monitoring is a record of the temporal and spatial characteristics of microseismic events. Microseismic events are low-energy seismic events related to sudden inelastic deformation, which radiates detectable seismic waves. Both AE and MS can detect seismic waves. The main difference between the two signals is that the seismic motion frequency of the AE signal is higher than that of the MS signal, which is shown in Figure 4a. However, the acoustic emission signal is usually very weak, so it is difficult to collect accurate data in the noisy environment of the project site [67]. Moreover, due to the existence of high-frequency components, an acoustic emission signal attenuates very fast, so an acoustic emission sensor can only cover a small volume of rock. Microseismic monitoring is more suitable for rockburst microseismic event monitoring on account of its advantages of real-time monitoring, large regional detection range, large data scale and no destructive impact on production. A typical mine microseismic monitoring system is shown in Figure 4b.

At present, microseismic monitoring technology is mainly used for rockburst early warning. Through analysis of micro fracture signals, the occurrence time and location of microseismic events are obtained, and then microsource characteristic parameters, such as number of microseismic events, microseismic energy, apparent volume and apparent stress, are obtained, which can be used for rockburst prediction.

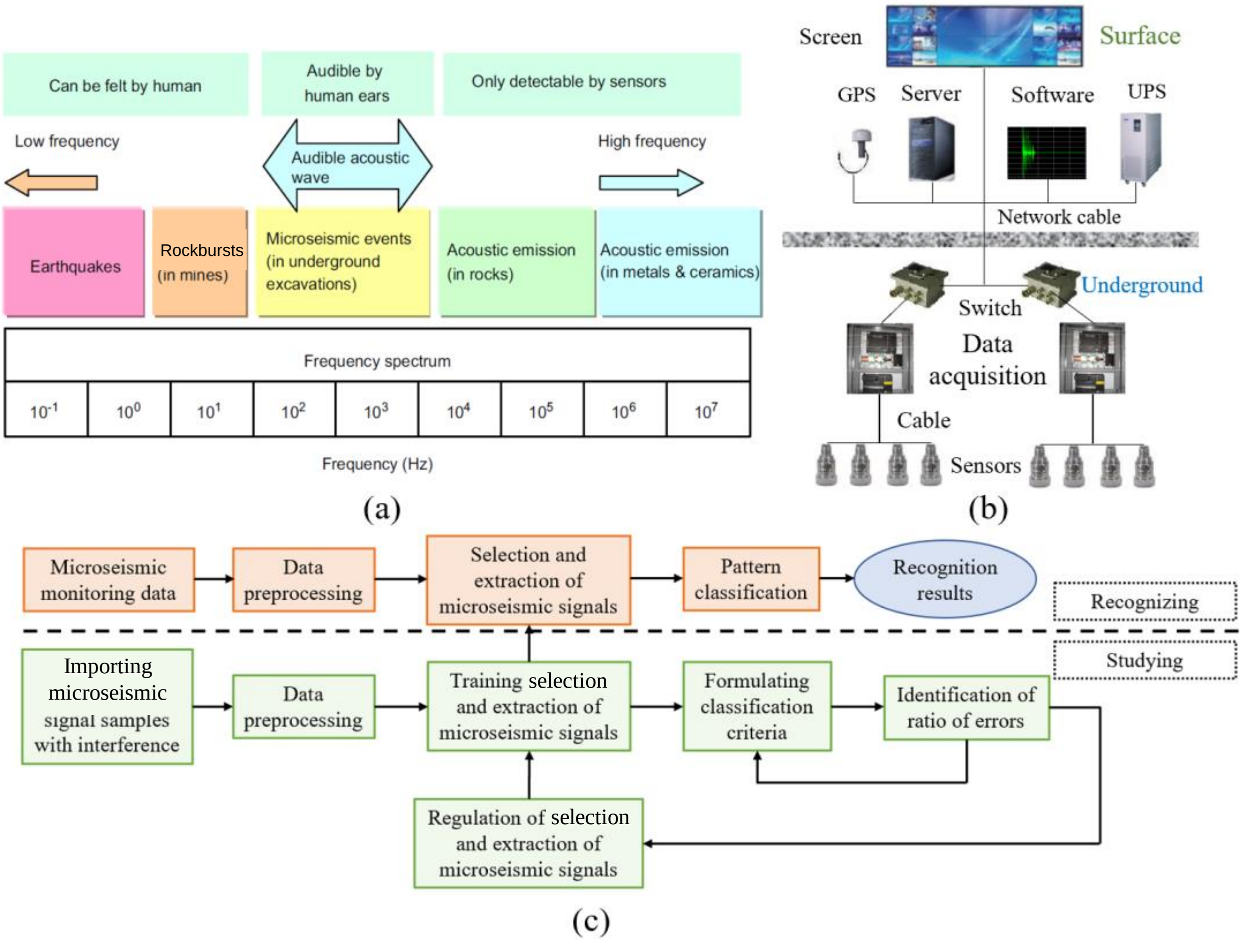

Figure 4. In situ monitoring for rockburst: (**a**) seismic motion wave frequency spectrum and field of application of AE/MS techniques (from [67]), (**b**) structure of a microseismic monitoring system in a mine (modified from [69]), (**c**) pattern recognition for microseismic signals (from [70]).

The accuracy of the microseismic source location will affect the application effect of microseismic monitoring [69]. The key factors for the accuracy of the microseismic source location are sensor arrangements [71], noise reduction in microseismic waveform [72,73], identification and classification of microseismic waveform [74,75], arrival time picking of microseismic waveform [76], the wave velocity model [77,78] and the source location method [79,80]. The flow chart of microseismic signal recognition is shown in Figure 4c.

The accuracy of microseismic positioning can basically meet the requirements of mines. The problem needed to be solved urgently in microseismic monitoring is how to obtain useful laws from large amounts of data.

4. Rockburst Mechanism

Although the main factors affecting the occurrence and severity of rockburst have been roughly clear, it is obviously difficult to reveal and unify the mechanisms of rockburst under different geological environments and excavation disturbances. Researchers try to explain formation conditions and development processes of rockburst from different angles by studying different engineering examples and physical model tests. Kaiser and Cai summarized the main factors influencing rockburst damage and its severity (See Figure 5) [30].

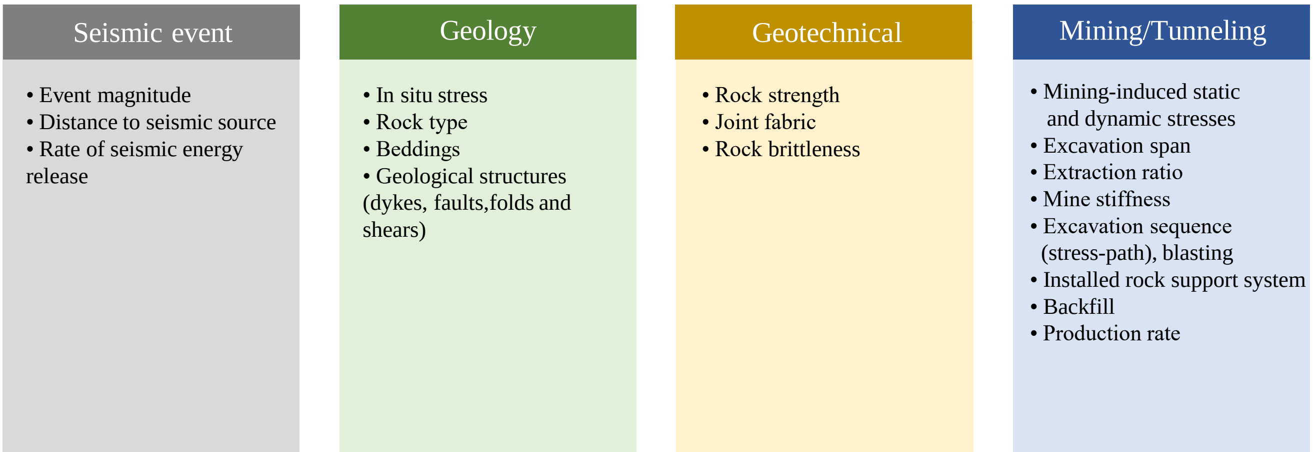

Figure 5. The main factors influencing rockburst damage and its severity (from [30]).

Li et al. used a digital borehole camera, cross hole acoustic meter and sliding micrometer to monitor the tunnel excavation process of the Jinping II hydropower station and then summarized the rockburst precursory characteristics and four stages of rockburst development [81]. Zhao et al. used the general particle dynamics (GPD) program and Holmquist–Johnson–Cook damage model (HJC) to simulate rockburst phenomena caused by fracture evolution, which revealed the two-dimensional and three-dimensional crack propagation processes in the surrounding rock [82]. Keneti et al. used scanning electron microscopy (SEM) to analyze the failure/fracture propagation mode of rockburst fragments and proposed that it was helpful to reveal the true source mechanism of microseismic events (if its original source is known) [83].

Meng et al. studied the influencing factors of slip rockburst caused by a structural plane through physical model tests. The results showed that the normal stress level had a great impact on the failure mode of joints, which is consistent with the analysis results of in situ microseismic monitoring [57,84]. Li et al. put forward a new theory of static–dynamic coupling and developed the corresponding true triaxial test device. The results showed that internal pre-static stress was the dominant factor of rock failure and external dynamic disturbance stress was an important inducement [85]. Gong et al. studied the causes of rockburst induced by collapse via a true triaxial test system, which is mainly reflected in promoting large buckling deformation (providing energy for rockburst) and weakening rock strength (creating conditions for a sudden release of energy) [86]. Deng et al. regarded rockburst as a buckling (instability) phenomenon of a structure. By establishing a rigorous mathematical model, the parametric resonance in induced and triggered rockburst was revealed, the quantitative relationship between blasting parameters and rockburst was established and the critical static load conditions of an inherent rockburst were obtained [29].

In situ microseismic monitoring shows that most of the monitored rockbursts have microseismic precursors [87]. When rockburst occurs, accumulated energy and the number of microseismic events reach the maximum [88]. Using the energy rate, moment tensor analysis and the P-wave development method based on actual microseismic information, supplemented by in situ macro failure characteristics of rockburst and identification of rock fracture modes (tension, mixing and shear), is a promising way to interpret rockburst mechanism [89]. Zhang et al. revealed the time characteristics of rockburst through microseismic monitoring results of a time-delayed rockburst and uniaxial dead load test. The time behavior of rockburst is the time behavior of crack propagation under high stress. When the internal damage of rock mass accumulates to a critical stage, even if there is no obvious excavation disturbance, rock mass may still be unstable [90]. Based on the thin plate theory, Yang et al. studied the occurrence mechanism of rockburst during mining of an irregular working face through microseismic monitoring, theoretical analysis, numerical simulation and working resistance of support of field measurement. The results showed that the combined dynamic and static load was the main factor inducing rockburst [91].

Although much research has been conducted on the rockburst mechanism, there is not a unified theory yet. The complex and diverse influencing factors and unclear nonlinear relationship make it difficult for the existing research conclusions to explain the formation mechanisms of rockburst in different environments, and it is arduous to establish a universal mechanical theory for rockburst.

5. Rockburst Intensity Classification and Prediction

5.1. Empirical Criteria for Rockburst Intensity Classification and Prediction

In the early stage of the construction, the empirical method is usually used to determine the rock mass quality and evaluate the risk of rockburst to provide empirical guidance for design and support. The empirical criterion is an index or criterion for judging the occurrence and strength of rockburst based on the summary of rockburst physical tests and engineering cases, which is divided into a single index criterion and comprehensive index criterion.

The single index empirical criterion method is mainly based on stress/strength, brittleness, energy and depth, including the Turchaninov criterion [92], the Peng criterion [93], the Russense criterion [94], the Hoek criterion [95], the elastic energy index [96], the Tao criterion [97], the Erlangshan criterion [98], the potential stress failure index [99] and the peak energy impact index [100].

The index criteria proposed in recent years are shown in Table 4. The single index criterion is one-sided, which does not consider the influence of other factors on rockburst.

Table 4. Rockburst criteria and valuation of qualitative indices of rockburst classification (modified from [101]).

Researchers (Year)	Index and/or Equations	No Rockburst	Light Rockburst	Medium Rockburst	Heavy Rockburst	Serious Rockburst
Qiu et al. (2011) [102]	RVI = $FsFrFmFg$	\	\	\	\	\
Tarasov et al. (2011) [103]	Brittleness index $B_4 = (E_u - M)/M$	\	\	\	\	\
Castro et al. (2012) [104]	BSR = $(\sigma 1 - \sigma 3)/\sigma c$	0.35–0.45	0.45–0.6	0.6–0.7	0.7	\
Shang et al. (2013) [105]	$P_{rb} = (Kv\sigma_\theta)/\sigma_t$	1.7	1.7–3.3	0.3.3–9.7	9.7	\
Zhang et al. (2013) [106]	$S = tanh\{[0.1648(\sigma_\theta/\sigma_c)^{3.064}(\sigma_c/\sigma_t)^{-0.4625}(W_{et})2.672]^{(1/3.6)}\}$	0.25	0.25–0.50	0.50–0.75	0.75	\
Qiu et al. (2014) [55]	$RERI = [(U_{imax} - U_{imin})/U_{imax}]/[U_{max}(p)/(U_{max}(p) - U_{res}(p))]$	\	\	\	\	\
He et al. (2015) [107]	$IRB = H/\sigma_{RB}$	\	0.6	0.6–1.2	1.2–2.0	2.0
Yang et al. (2015) [108]	URLERI = $[(U_i - U_{i+1})/U_i]/\mathrm{dt}/f(p)$	\	\	\	\	\
Guo et al. (2015) [109]	$R_i = A^*(2E_0U^e/\sigma^2{}_t)$	3	3–10	10–110	110	\
Gong et al. (2018) [100]	$A'_{\mathrm{CF}} = U^e/U^a$	\	\	\	\	\
Ma et al. (2018) [110]	$RPI = \sigma'_{rm}/\sigma_{max}, \sigma'_{rm} = \sigma'_3 + \sigma_{ci}[m_b(\sigma'_3/\sigma_{ci}) + s]^\alpha$	7	4–7	2–4	1–2	
Zhang et al. (2020) [111]	$U \geq U_h + U_d$ $\sigma_x \geq R_x \in [s,l\text{-}s]$	\	\	\	\	\

The comprehensive index criterion considers the important control factors of rockburst and then establishes the corresponding mathematical model or system to evaluate rockburst. The excavation vulnerability potential (EVP), considering stress condition, ground support, portal span and geological structure, which was calibrated by using eighty case histories and 250 individual incidences of rockburst damage from underground hard rock metalliferous mines in Australia and Canada, is used for a vulnerability assessment of underground excavation for rockburst damage [112].

The rockburst vulnerability index (RVI), consisting of four control factors (stress Fs, rock mass Fr, rock mass system stiffness Fm and geological structure Fg), was proposed to determine the risk level of rockburst via analyzing 62 rockburst cases in the chamber group of the Jinping II hydropower station. The RVI index can be used when rockburst case data, in situ stress conditions, engineering geological conditions, rock mechanical properties, rock mass structure and construction design are sufficient [102].

Shang et al. found that the three variables maximum tangential stress of tunnel wall σ_θ, tensile strength σ_t, and rock mass integrity coefficient K_v are relatively independent through an in situ geological survey, and then the authors proposed a comprehensive risk criterion of strain rockburst named rockburst potential P_{rb}, which is based on experimental data [105].

Ma et al. proposed a criterion named the rockburst proneness index (RPI) in combination with rock strength, the brittleness coefficient, the geological strength index (GSI), TBM excavation disturbance and in situ stress [110]. Considering a roadway's buried depth and rock hardness, Zhang et al. proposed a rockburst occurrence criterion based on stress and energy [111].

The comprehensive index criterion is mainly combined with in situ stress, inherent rock properties and geological information of surrounding rock. Compared with single index criterions, they have obvious advantages. However, they are not universal and need to be used according to the details of specific projects.

5.2. *Microseismic Monitoring Technology for Rockburst Prediction*

Rockburst is a complex process of rock fracture. Data of microseismic monitoring contain the information of stress and fracture development trends in rock, which are used to establish a microseismic early warning system in engineering. Table 5 lists the commonly used microseismic indicators for rockburst prediction.

Liu et al. proposed a microseismic multiparameter prediction method based on apparent volume, energy, spatial correlation length, fractal dimension and b value to predict large deformation and rockburst [4]. Feng et al. used real-time microseismic data and a rockburst early warning formula in the rockburst risk of the Jinping II hydropower station deep tunnel during excavation, which focused on a rockburst database, with a selection of typical rockburst cases [113].

Ma et al. summarized the characteristics, mechanisms and roles of geological structures of rockburst according to the rockburst events counted in engineering cases and then used microseismic monitoring technology to reveal the relationship between the temporal and spatial evolution of microseismic activity and rockburst [70].

When rockburst is about to occur, the energy of microseismic events presents a temporary fractal behavior. The aggregation and spatial distribution self-similarity of microseismic events can be used to warn the of location of a potential rockburst, and the temporary distribution of measured energy and the number of microseismic events can be used to warn of the severity of rockburst [89,113,114].

Based on in situ microseismic monitoring and acoustic emission test data of laboratory rock samples, Cai et al. established a fuzzy comprehensive evaluation model to predict the occurrence of rockburst [115]. Dou et al. established a multiparameter microseismic index system of coal dynamic failure, including bursting strain energy (BSE) index, time–space–magnitude independent information (TSMII) indices and time–space–magnitude compound information (TSMCI) indices, and then quantitatively analyzed prewarning rockburst risk in the Hujiahe Coal Mine (China) via introducing the R-value scoring method to calculate the weights of each index [116].

Table 5. Summary of the commonly used MS indices for the forecasting of rockburst (from [115]).

Name	Basic Equations	MS Aspects	Key References	Common Features
b value	$\log N(M) = a - bM$ $N(M)$ is the cumulative number of MS events having magnitude larger than M and a and b are constants. It has been shown in laboratory studies, field observations and numerical simulations that the slope of this distribution curve depends on stress conditions.	Magnitude	Gutenberg et al. (1944) [117]; Li et al. (2017) [118]; Cao et al. (2018) [119]	Statistical feature indices.
Lack of shock b_L	$b_L = \log_e/(M_{mean} - M_{min})$ M_{mean} is the mean magnitude and M_{min} is the minimum magnitude of given MS events.	Magnitude	Aki (1965) [120]	
Fractal dimension	$D = \lim\limits_{r\to 0} \frac{lgC(r)}{lgr}$	Spatial	Xie et al. (1993) [36]	
	$C(r)$ is the correlation integral of the energy or number of MS events and r is the energy or spatial radio scale.	Magnitude	Feng et al. (2016) [114]	
Moment tensor	Percentage of the shear component of moment tensor.	Magnitude	Gibowicz et al. (1994) [121]; Xiao et al. (2016) [122]	Source mechanism parameters.
Energy ratio	Ratio of the S-wave and P-wave energies (E_S/E_P).	Magnitude	Gibowicz et al. (1994) [121]	
Seismic diffusivity	$d_s = (\overline{X})^2/\overline{t}$ $\overline{X}$ is the mean distance between consecutive events and t is the mean time between events.	Temporal and spatial	Mendecki 1996 [123]	
Apparent stress/volume	$\sigma_A = \mu EA/M_0,\ V_A = M_0^2/\mu E_A$ μ is the shear rigidity modulus, EA is the MS energy and M_0 is the MS moment.	Magnitude	Mendecki 1996; [123] Tang et al.(2010) [124]	
Energy index	$EI = E_A/\overline{E}(M_0)$ $\overline{E}(M_0)$ is the average energy released by events of the same MS moment.	Magnitude	Mendecki 1996; [123] Tang et al.(2010) [124] Xu et al. (2011) [125]	
Number of events ΣN	Total number of MS events in a given time window.	Temporal	Srinivasan et al. (1997) [126]	
Amount of energy ΣE	Total amount of MS energy in a given time window.	Magnitude		
Source concentration degree	$S_d = \sqrt[3]{\sqrt{\lambda_1 \bullet \lambda_2 \bullet \lambda_3}}$ λ_1, λ_2 and λ_3 are standard orthogonal eigenvectors of the covariance matrix of MS hypocentre parameters x, y, z.	Spatial	Cai et al. (2014) [127]	
Fault total area	$A(t) = \sum_{k=k_0}^{k=1} N(k) \bullet 4.5^{k-k_0}$ k_0 is the lower limit of the statistical MS energy level and k is the energy level of each event. $N(k)$ is the event count of MS energy level k.	Magnitude	Lu et al. (2015) [128]	

5.3. Mathematical Model Approaches for Rockburst Classification and Prediction

Influencing factors of rockburst are partly determined and quantitative, while the others are random, qualitative and fuzzy. Hence, it is reliable to establish an appropriate mathematical model based on empirical criteria and use previous engineering cases for data-driven prediction, which can be broadly categorized into uncertainty theory algorithms and machine learning.

5.3.1. Uncertainty Theory Techniques

Due to some influencing factors of rockburst being random and fuzzy, some uncertainty theories have been introduced to rockburst research, including the unascertained mathematical theory [129], the fuzzy mathematics theory [130], the catastrophe theory [131], the grey system theory [132], the cloud model [133,134], the rough set theory [135], the extension theory [136], the attribute mathematics theory [137], the interval number theory [138] and the set pair analysis [139], shown in Figure 6. They are often used in combination, or operations research algorithms and heuristic algorithms are introduced.

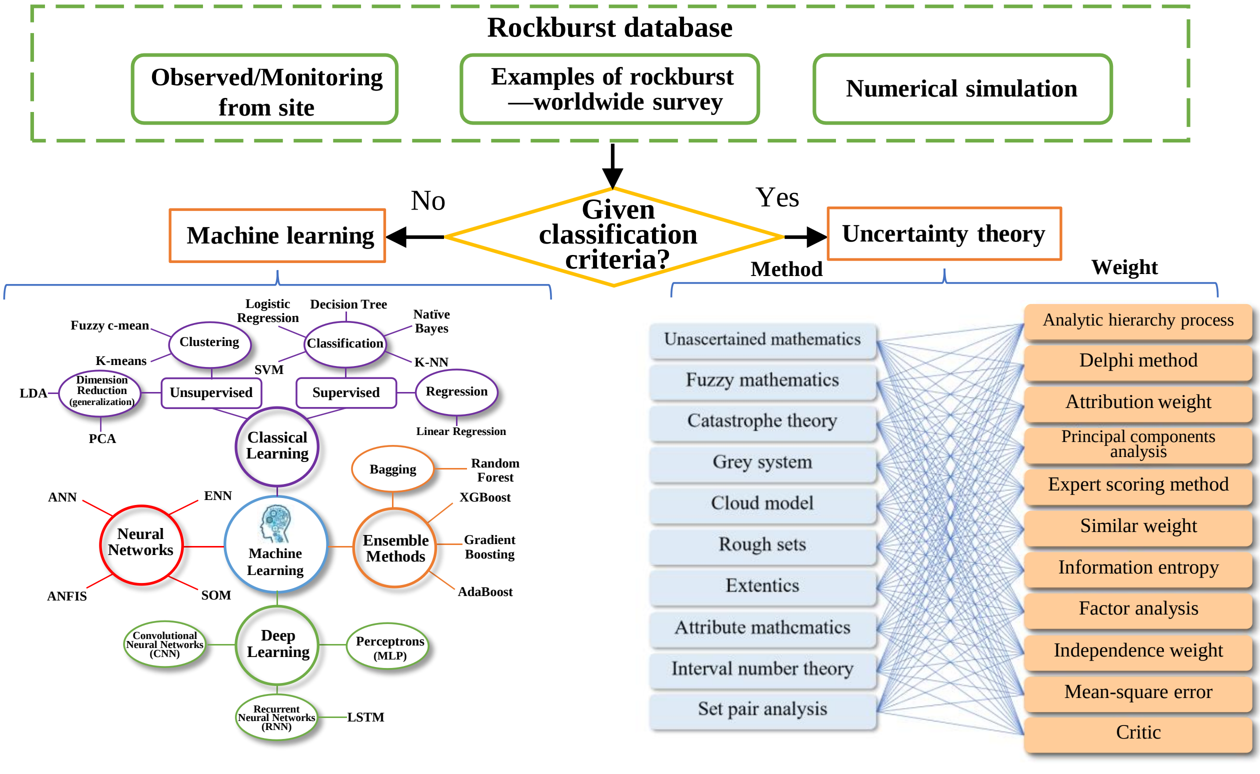

Figure 6. Mathematical model approaches of rockburst classification and prediction.

For instance, Liu et al. proposed a rockburst classification model via a rough set and cloud model, which was verified through five groups of rockburst samples [133]. A multidimensional connection cloud model based on set pair analysis and cloud model theory for rockburst strength prediction was proposed [134], which is simpler and more convenient for practical application than a one-dimensional cloud model.

An extended multiattribute boundary approximate area comparison method (MABAC) based on a triangular fuzzy number was used to evaluate the rockburst tendency in four key areas of the Kaiyang Phosphate Mine [140].

Three distance-based multicriteria decision making methods combining hesitant fuzzy sets were used to evaluate the rockburst risk of the Xincheng Gold Mine; the results were consistent with the measured results [141].

Xue et al. established a two-step comprehensive evaluation model via the rough set theory and technique for order preference by similarity to an ideal solution based on five empirical criteria (the elastic energy index criterion, the Russenes criterion, the Tao criterion, the rock brittleness coefficient criterion and the rock mass integrity coefficient criterion), and 20 rockburst samples were collected to evaluate the effectiveness of the two-step model. The results showed that compared to the existing artificial intelligence methods, the minimum error rate of the two-step model was significantly reduced [142].

5.3.2. Machine Learning

Mathematical models of rockburst classification and prediction based on empirical criteria have great limitations in considering the nonlinearity of influencing factors. In view of this, some researchers tried to use machine learning methods. The merit is that machine learning does not need any prior knowledge about the relationship between input/output variables and reduces the intervention of human factors. Machine learning can be categorized into four categories: classical machine learning, reinforcement learning, ensemble learning and artificial neural network (ANN), as shown in Figure 6.

Classical machine learning is often used in situations with less data and clear characteristics. At present, with the amount of in situ monitoring and physical model tests data about rockburst we are more inclined to choose classical machine learning methods for classification and prediction. Support vector machines (SVMs) [143], the logistic regression classifier [144], decision trees (DT) [145], Bayesian networks [146], naive Bayes [147] and the k-nearest neighbor (KNN) [148] are all invoked for rockburst classification and prediction.

An artificial neural network is often used to deal with complex nonlinear relationships, which can model and extract unknown features and relationships. Feng et al. used an ANN model to predict the rockburst risk of a deep gold mine in South Africa [149]. Sousa et al. predicted the type of rockburst via ANN according to the geological and construction characteristics of the mine [150].

Self-organizing mapping (SOM) clustering technology was invoked to divide rockburst data into four groups, which can accurately identify rockburst [151]. Zhou et al. used a firefly algorithm (FA) and ANN to establish a complex relationship model between rockburst risk and influencing factors in deep mines and tunnels for predicting the severity of rockburst [152]. An extreme learning machine (ELM) algorithm with particle swarm optimization (PSO) was invoked to predict fifteen typical rockburst examples of Jiangbian hydropower station in China, which achieved good results [153]. Compared with traditional machine learning algorithms, neural networks usually require more data, and the computational cost will be more expensive.

Since the advent of deep learning (developed from ANN) in 2012, great achievements have been made in the fields of speech recognition and computer vision. Compared with classical machine learning technology, deep learning provides a more powerful prediction model and faster learning mechanism and is more adaptable to changes of environment. Deep learning needs a lot of data to improve the generalization ability of models; thus, deep learning is almost always applied in microseismic monitoring technology.

Perol et al. used a convolutional neural network (CNN) model (ConvNetQuake, Figure 7) to cluster microseismic events into six regions according to the three-component waveform received by the station, which realized the preliminary location of microseismic events and completed preliminary exploration of a deep learning algorithm for microseismic source location [80].

CNN was also invoked to identify the Time Delay of Arrival (TDOA) and the source location of seismic waves in underground mines. The data of field blasting tests and simulation tests show that compared with several existing typical methods, the proposed approach can identify noise waveforms recorded in an in situ blasting test more accurately [154], which gave more accurate microseismic source identifications.

Tang et al. proposed a lightweight network architecture named ResSCA based on CNN for complex signal recognition and classification in microseismic monitoring. While it improves the network performance, it does not produce additional computational overhead [155].

The fracture-induced electromagnetic radiation (FEMR) signal recognition model based on bidirectional long short-term memory recurrent neural networks (bi-directional LSTM RNN) had a good response to the occurrence of rockburst and can capture rockburst information in advance in order to realize the automatic/intelligent discrimination of rockburst precursory [156].

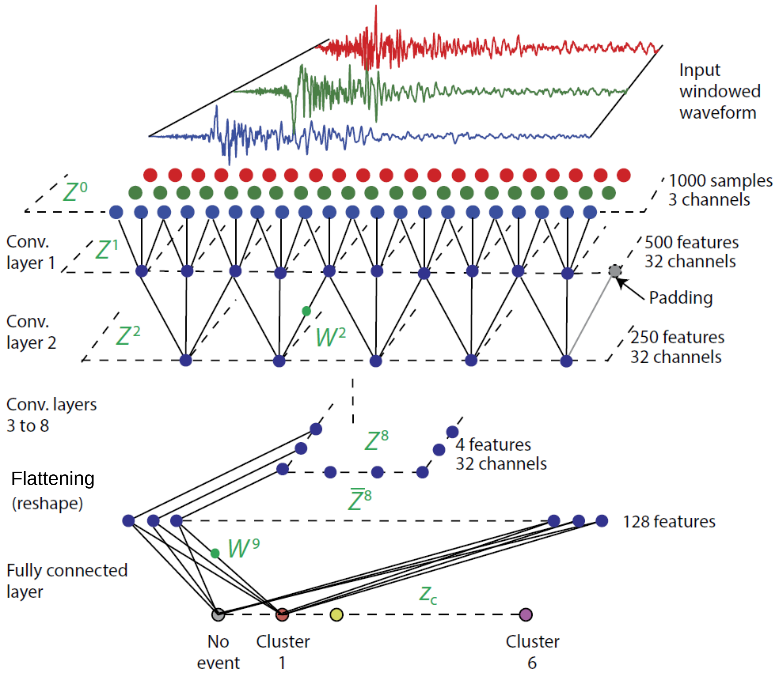

Figure 7. Network structure of ConvNetQuake model (from [80]).

Ensemble learning is a method which can improve the learning effect via gathering several weak classifiers of machine learning. The strong classifier of ensemble learning can overcome the defects of each weak classifier (such as the difference of algorithm and the application scope of classifier), divide a large problem into thousands of small problems and then train the corresponding weak classifier to break these small problems one by one.

Zhang et al. integrated seven classifiers (BP neural network, SVM, DT, KNN, logistic regression, multiple linear regression and naive Bayes) and combined them with nine data interpolation methods to classify rockburst severity. Compared with the single classifier, which had the best classification effect, the accuracy was improved by 15.4% [157].

Based on the tunnel microseismic data of the Jinping II hydropower station, Liang et al. used six microseismic monitoring indicators as training sets and test sets via five ensemble learning methods (random forest RF, adaptive boosting, gradient boosting decision tree GBDT, extreme gradient boosting and light gradient boosting machine) to predict the short-term rockburst risk. The results showed that RF and GBDT had better comprehensive prediction performance [158].

By the stacking technique of ensemble learning, based on KNN, SVM, deep neural network (DNN) and RNN, four ensemble learning models KNN–RNN, SVM–RNN, DNN–RNN and KNN–SVM–DNN–RNN were built to predict the occurrence of rockburst. The results showed that the stacking technique of ensemble learning had unique superiority when using unbalanced data for rockburst prediction [159].

Five ensemble classifiers based on logistic regression, naive Bayes, Gaussian process (GP), multilayer perceptron (MLP), SVM and DT were used to estimate the occurrence probability of each risk level for short-term rockburst prediction. The results showed that the comprehensive performance of ensemble classifiers was better than each basic classifier individually [160].

Due to the characteristics of the reinforcement learning algorithm and rockburst, there is no research on rockburst classification and prediction using reinforcement learning.

Many machine learning methods have been used to study classification and prediction of rockburst, but there are still some problems in engineering application, such as insufficient data, inability to provide a simple model and computational overhead.

5.4. Rockburst Chart

A rockburst chart is a method to directly reflect the relationship between rockburst influencing factors and rockburst severity with one chart. Based on the data of physical tests, in situ monitoring and cases, a classification boundary line was marked to emphasize the centralization and visualization of rockburst information.

A rockburst chart was first proposed by Russenes (1974) [94] and used the boundary line of maximum tangential stress of the tunnel and point load strength of the surrounding rock to divide potential risk level of rockburst. Afterwards, many researchers studied rockburst charts based on different influencing factors, as shown in Table 6.

Table 6. Rockburst prediction classification charts.

Chart Type	Reference	Factor Index	Rockburst Intensity
1D	Palmström (1995) [161]	Cg	3 level: mild, heavy and very heavy
	Peng et al. (1996) [93]	σ_c/σ_t	4 level: no rockburst, light rockburst, moderate rockburst and heavy rockburst
	Barton et al. (1974) [162] Russenes (1974) [94] Hou et al.(1992) [163]	σ_1/σ_c	4 level: no rockburst, weak rockburst, medium rockburst and strong rockburst
2D	Hou et al. (1992) [163]	W_{qx}, σ_θ/σ_t	4 level: no rockburst, low rockburst, medium rockburst and high rockburst
	Diederichs (2007) [164]	UCS, m_i	4 level: low rockburst, medium rockburst, high rockburst and very high rockburst
	Farhadian (2021) [18]	W_{et}, σ_θ/σ_c	7 level: no rockburst, moderate low rockburst, low rockburst, moderate medium rockburst, medium rockburst, moderate high rockburst and high rockburst
Multidime-nsional	Lee et al. (2004) [165]	PES, B_3, σ_c	4 level: no rockburst, low rockburst, medium rockburst and high rockburst
	Shang et al. (2010) [166]	σ_θ, σ_{max}, σ_c/σ_{max}, σ_θ/σ_c, $(\sigma_\theta + \sigma_L)/\sigma_c$	4 level: no rockburst, weak rockburst, medium rockburst and strong rockburst
	Zhang et al. (2011) [167]	σ_c/σ_t, K_V, σ_θ/σ_c, σ_1/σ_c, W_{et}	4 level: no rockburst, low rockburst, medium rockburst and high rockburst
	Russo (2014) [168]	δ_0, r_p/r_0, σ_θ, σ_{cm}, RMR	2 level: no rockburst and rockburst

According to the rockburst influencing factors invoked in the rockburst chart, the rockburst chart can be categorized into three categories: (a) one-dimensional rockburst chart, (b) two-dimensional rockburst chart and (c) multidimensional rockburst chart, as shown in Figure 8.

The classification results of the chart method can be used to quickly identify high-risk areas and select targeted supports during construction in the early stage of design and planning. Its shortcomings are similar to those of the comprehensive index criterion, which is not being universal in engineering application and needing to be used according to details of specific engineering.

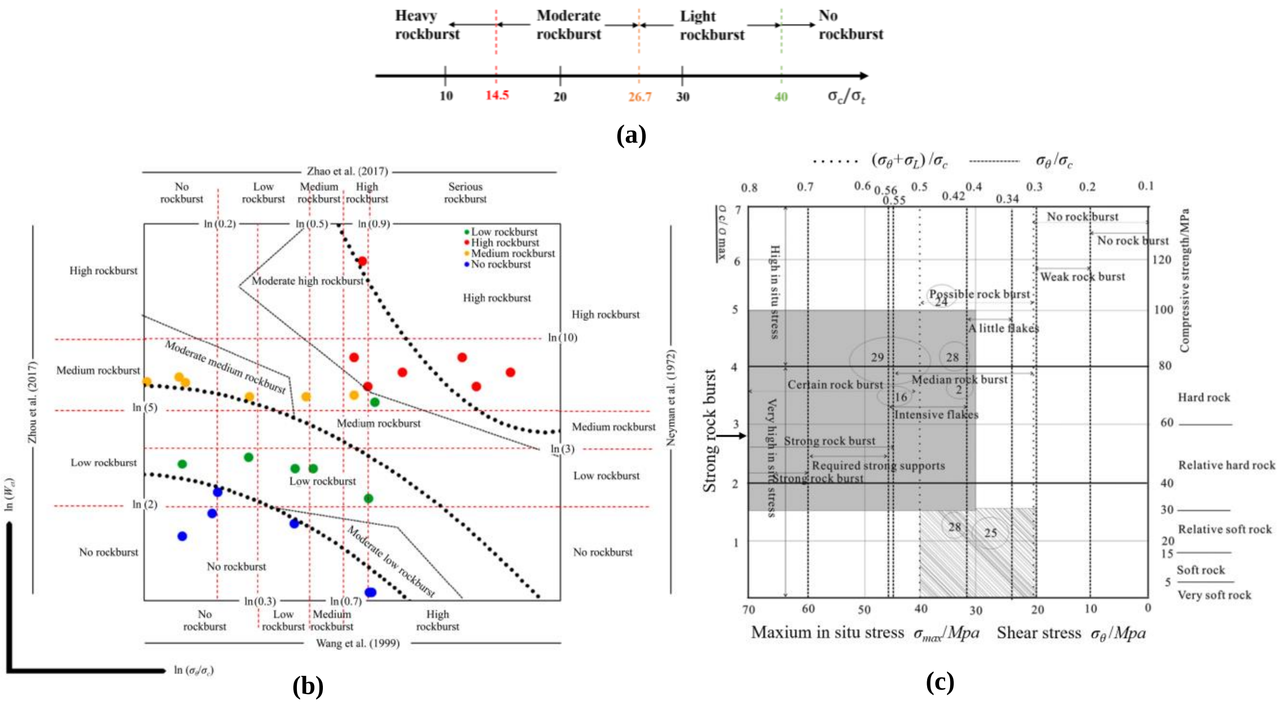

Figure 8. Rockburst charts: (**a**) one-dimensional rockburst chart: the rockburst intensity diagram represented by σ_c/σ_t (from [93]); (**b**) two-dimensional rockburst chart: performance of the TRC chart and the empirical formulas used to determine the rockburst intensity as compared to the observed values (from [18]); (**c**) diagrammatic explanation of limit values for prediction of rockburst and squeezing from different aspects (from [166]).

6. Rockburst Prevention and Control

Due to the seriousness of rockburst accidents, prevention and control methods of rockburst have always been the research focus of engineers and researchers. It is undoubtedly the most direct means to explore and summarize the prevention and control methods of rockburst from project sites.

Whyatt et al. summarized the experience and lessons of the Coeur d'Alene district on rockburst accidents in the past 60 years, focusing on the practical measures successfully taken to reduce hazards [169]. Yan et al. summarized the rockburst prevention measures of the Jinping II hydropower station, which effectively controlled rockburst via reducing surrounding rock stress and weakening excavation disturbance [170].

Yang et al. deemed that the combined dynamic and static load is the main cause of rockburst in an irregular working face. Based on this, a cooperative control technology was proposed to weaken the dynamic load through hard roof directional hydraulic fracture and enhance the surrounding rock by a supporting system (See Figure 9) [91].

Simser presented some methods used in Canada to reduce risk of rockburst in deep mines and proposed that with a continuous increase in mine depth, a pervasive installation of a support system with dynamic load bearing capacity may become necessary [171].

Li et al. summarized pretreatment methods for rockburst, mainly including blasting, decompression drilling and hydraulic fracturing, and introduced the experience of rockburst support in Australia, Canada and South Africa [172].

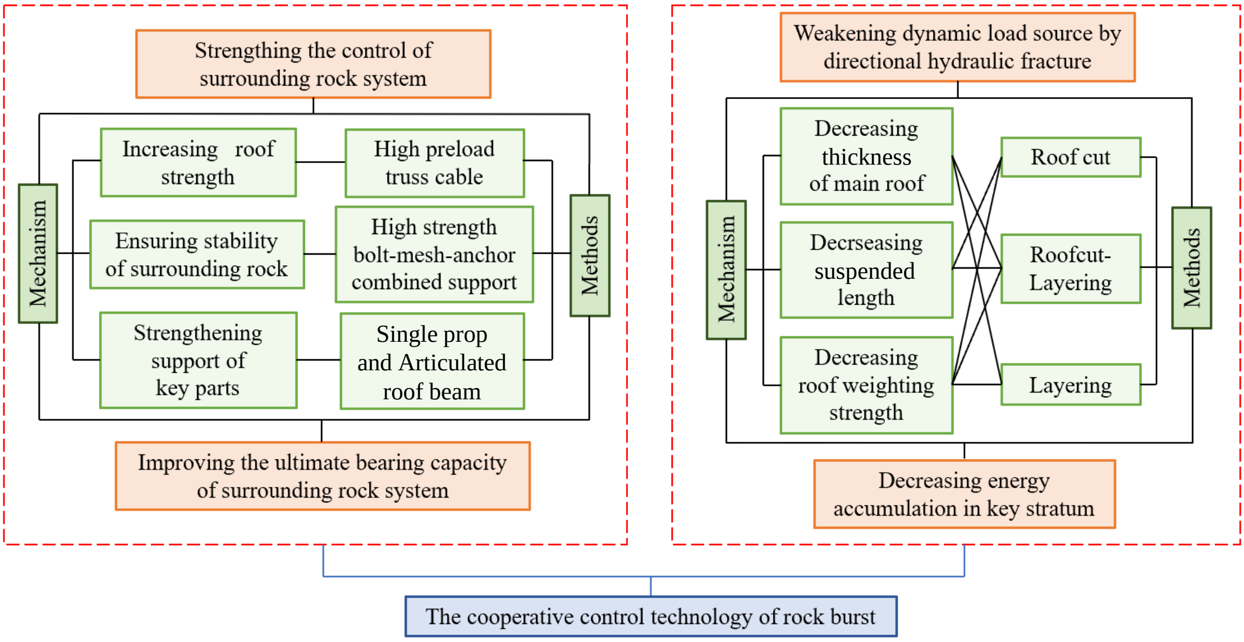

Figure 9. Cooperative control technology of rockburst in irregular working face (from [91]).

The main prevention and control measures for rockburst in some mines and tunnels are listed in Table 7 and summarized in Figure 10.

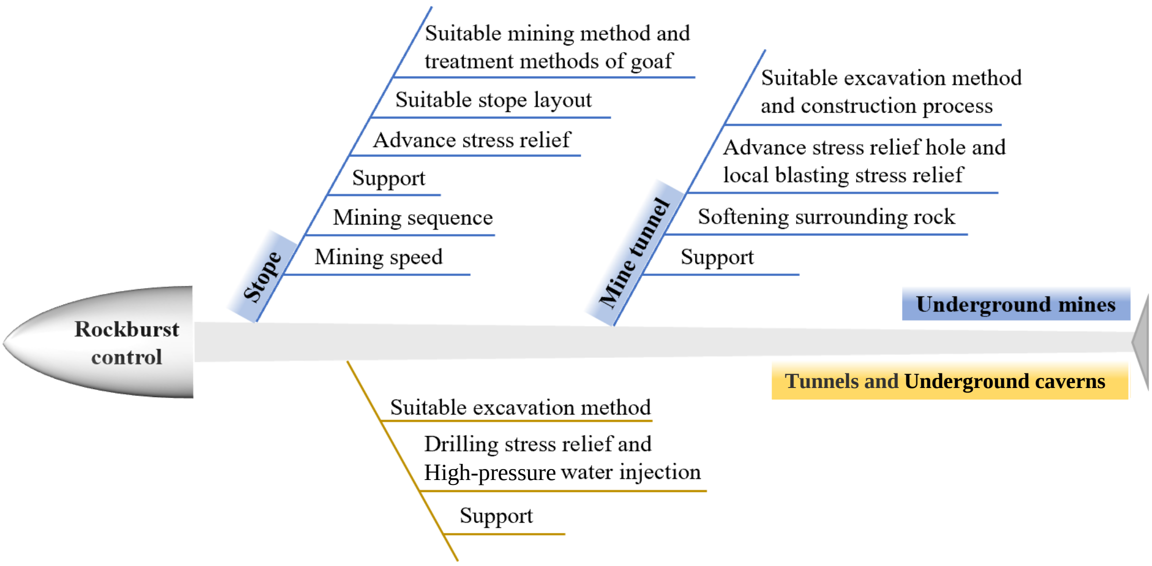

Figure 10. Control measures of rockburst.

There is no doubt that support of excavation has always been the key research object of scholars and engineers in rockburst prevention measures. In 1996, the Rock Mechanics Research Center of Laurentian University conducted a five-year support design study for rockburst control. Based on this work, the Canadian Rockburst Support Handbook was published to summarize the characteristics and causes of rockburst failure and provide design methods of the rockburst support system [8]. Cai et al. put forward seven simple principles on rockburst support according to field experience, shown in Figure 11, for a design guide of rockburst support [30,173].

Table 7. Worldwide survey of rockburst prevention and control.

Country	Location	Buried Depth of Main Rockburst Sites/m	Rock Types	Main Prevention and Control Measures
China	Jinchuan No.2 Mine [174]	470~800	Marble, Granite, Migmatite	Strengthen support, in situ monitoring, stress relief
	Dongguashan Copper Mine [175]	800~1150	Skarn	Optimize mining method, sequence and parameters; monitoring, flexible support
	Erdaogou Gold Mine [176]	1050	Diorite	Improve mining technology and methods, optimize mining sequence and support
	Ling Long Gold Mine [177]	650~1100	Granite	Optimize mining sequence, filling mining, improve support, blasting methods, in situ monitoring
	Dahongshan Iron Mine [178]	807~1301	Marble, Schist Gabbro diabase, Metasodic lava,	Controlled blasting, watering and softening, optimize and strengthen support
	Changba Lead–Zinc mine [179]	700~1082	Quartz schist, Marble	Change mining methods, fill goaf and stope
	Jiguanzui Gold Mine [180]	1024	Quartz monzonite, Long porphyrite	Improve excavation process sequence, strengthen support
	Erlang mountain Tunnel of Sichuan-Tibet highway [181]	770	Mudstone, Siltstone, Marlstone, Sandstone	Surrounding rock monitoring, high-pressure watering, optimization of excavation scheme, combined support
	Qinling Zhongnanshan Tunnel [182]	1640	Migmatitic gneiss, Granite	Stress relief by drilling, excavation of small sections, select the best support time
	Cangling Mountain Tunnel [183]		Tuff, Granite	Improve excavation methods, advance bolt reinforcement, high-pressure watering
	Jinping II Hydropower Station, Diversion Tunnel [184]	2525	Sandstone, Slate, Limestone, Marble	Improve stress state of surrounding rock, combined support and construction methods
	Yebatan Hydropower Station, Tailrace Tunnel [185]	709	Quartzite, Granite	Optimize excavation method, advance stress relief, strengthen support
Canada	Kirkland Lake Gold Mine [186]	630~2520	Porphyry, Alkaline Syenite	Central stress relief by blasting, change mining technology, strengthen shaft support
	Creighton Mine [186]	700~2400	Granite, Gabbro Norite	Stress relief by blasting, optimize mining sequence, filling mining, improve support methods, strengthen rock mechanics research, microseismic monitoring
	New Brunswick Lead–Zinc Mine [186]	892	Sulfide ore	Change mining technology and support methods, stress relief, real-time monitoring of surrounding rock stress
America	Star Lead–Zinc Mine Burke, Idaho [2]	1120~2440	Quartzite	Advance stress relief by blasting, microseismic monitoring
	Sunshine Siderite Mine Kellogg, Idaho [2]	2100	Quartzite, Pelitic siltstone	Limit the number of stopes, single shift operation, microseismic monitoring, diversification of support methods
	Galena Silver Mine Wallace, Idaho [2]	2400~3000	Quartzite	Improve mining methods and technology, optimize mining sequence, stress relief by blasting, monitoring of surrounding rock stress
	Lucky Friday Silver-Lead Mine, Mullan, Idaho [2]	1808	Quartzite	Change mining geometry and monitoring of surrounding rock stress
	Brunswick Mine Bathust, New Brunswick [2]	725~1000	Tuff	Change of mining method, modified cone bolts, real-time quantitative seismic system
	Strathcona Mine Onaping, Ontario [2]	2300~2500	Breccia, Granite gneiss	Microseismic system, shotcrete, support system
	Creighton Mine Sudbury, Ontario [2]	1200~2000	Granites, Gabbros, Quartz diorite	Change of mining method, improved microseismic and seismic systems
Chile	El Teniente Copper Mine [187]		Diorite, Andesite	Strengthen support, change mining methods
Australia	Mount Charlotte Gold Mine [188]	1200	Dolerite	Improve and strengthen support, strengthen monitoring
Poland	Lubin Copper Mine [189]	600~1000	Sandstone, Dolomite, Shale	Stress relief by blasting, filling mining, control of structural parameters
Norway	Diversion Tunnel of Sima Hydropower Station [190]	700	Granite	Optimize support, adjust geometry of underground cavern section

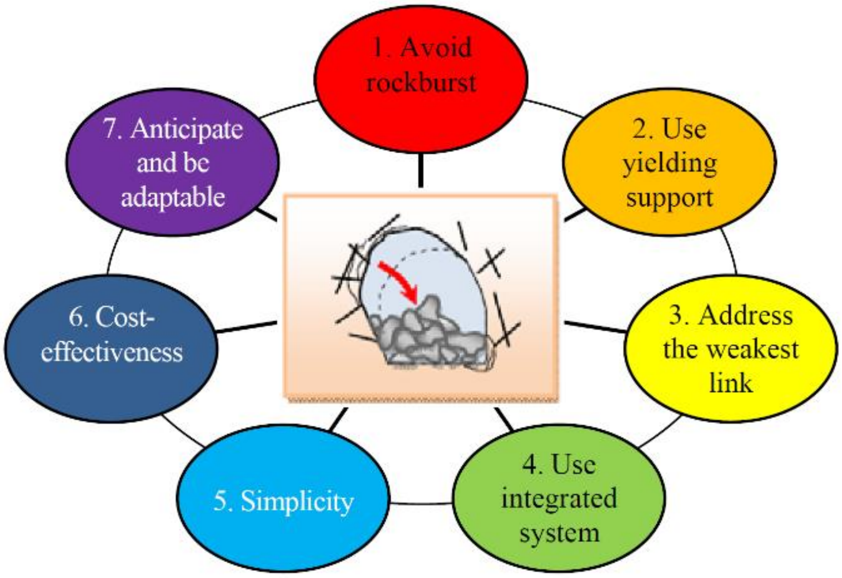

Figure 11. Seven rockburst support design principles (from [30]).

Kaiser et al. summarized four functions required to provide a reliable support system for burst-prone conditions, shown in Figure 12, pointing out that support selection in burst-prone areas is a repeated process, which needs to be verified and modified based on field observation [191].

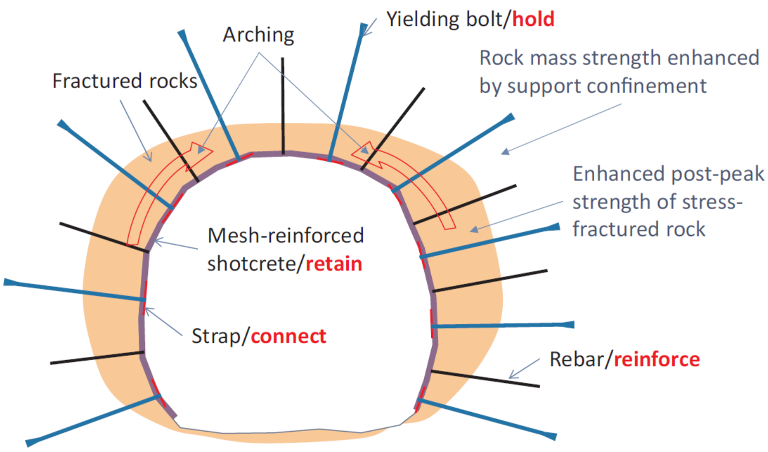

Figure 12. Required support functions in burst-prone ground (from [191]).

In terms of design of rockburst support for shallow-dipping tabular excavations in South Africa, due to the small width of stope and effect of shallow-dipping tabular geometric structure, the length of bolts is limited (usually 0.9 m) and may be less than settlement height. Steel mesh is easily damaged by the impact of blasting and cleaning operations, so it is difficult to design a stronger and permanent regional support system with large coverage, while it will also lead to the failure of regional support and single yield support to form an integrated system. Malan et al. deemed that a possible solution is the use of reef boring techniques, where the reef is drilled out by boring machines from predeveloped access drives while removing miners from the hazardous stope faces [192].

Morissette et al. used the seismic events and rockburst events of three deep mines in the Sudbury basin of Canada to establish a comprehensive database and proposed a database-based support design strategy to determine the mine location for enhanced support, the time for dynamic support installation and selection of the appropriate surrounding rock support system [193].

A new design method for deep hard rock foundation support was proposed by Rahimia et al. [194], shown in Figure 13, including estimation of depth failure, calculation of the static and/or dynamic demand on ground support capacity, selection of support surface and reinforcement unit, which was carried out in several deep underground mines in Western Australia.

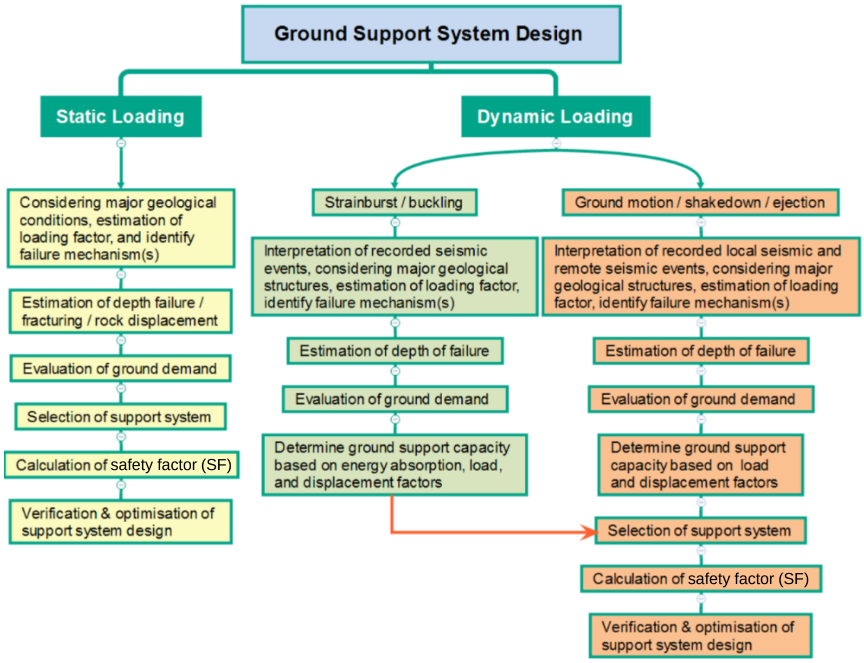

Figure 13. Ground support design in deep underground mines (from [194]).

A support system for rockburst control comprises, in general, three support layers, including a layer of fully covered surface retaining devices (mesh, mesh strap and shotcrete), a layer of systematic energy absorbing rockbolts and a layer of energy absorbing cable bolts (optional) [195]. A bolt is an indispensable and important piece of equipment in a support system. Under the condition of high stress, a traditional bolt is hard to provide satisfactory rock reinforcement effect. An energy absorbing bolt with sufficient strength and good energy absorption capacity has become an internationally recognized momentous support component for underground engineering. An energy absorbing bolt dissipates energy by the stretching of the bolt body or the sliding of the inner anchor in the borehole. Compared with a traditional bolt, an energy absorbing bolt not only has a greater deformation capacity but also has higher bearing capacity, so it can absorb a large amount of energy released by rock dynamic failure [196]. Some typical energy absorbing bolts and their energy absorbing characteristic curves are shown in Figures 14 and 15.

In an early stage of support design, it is significant to select the appropriate bolt. An ideal rockburst support system should be a combination of a high-strength energy absorbing bolts and high-strength fully covered surface support components [197]. Masoudi et al. used a large-scale dynamic testbed to give the application scope of various energy absorbing bolts and classified the appropriate bolt types with different surrounding rock energy demands and deformation capacity ranges, which provided clear guidance for the initial design of the support system [198].

On the other hand, Moganedi et al. evaluated the potential value of various rockburst support systems in deep tunnels and mines, providing guidance for the selection of support systems from an economic level [199].

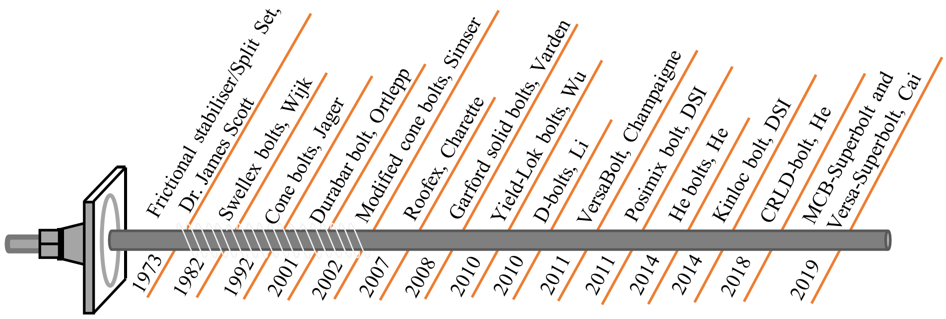

Figure 14. Typical energy-absorbing bolts [60,191,200–206].

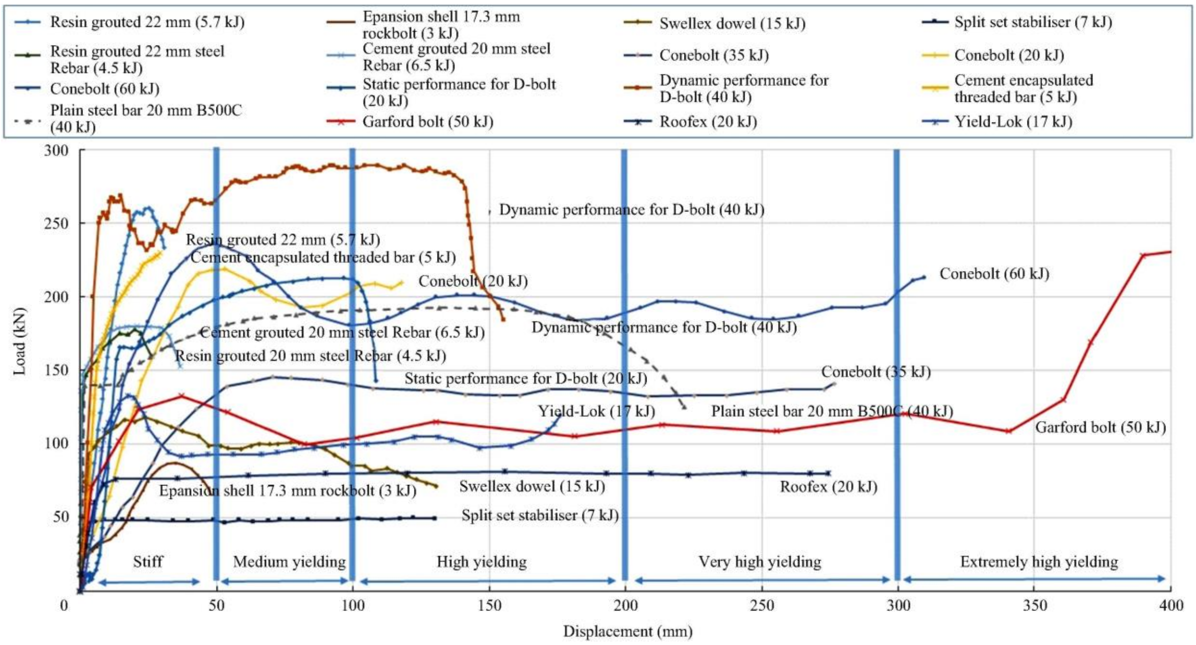

Figure 15. Load-displacement behavior of different types of rockbolts [198].

7. Discussions

As a worldwide scientific problem, rockburst has always been a key research object of scholars and engineers. The developing trend of rockburst research can be divided into two stages. The research work in the first stage mainly focused on the failure and fracture characteristics of rocks and the mechanism of rockburst. At this stage, the study of the rockburst mechanism mostly stayed at the level of qualitative interpretation. The research work in the latter stage is more comprehensive, due to the gradual enrichment of research means. At this stage, new theories and research means make the research on the mechanism of rockburst more in-depth. Whilst classification, prediction and prevention methods of rockburst have gradually become a research hotspot and a large number of research results have been obtained, the following deficiencies are worth discussing:

- Regarding numerical simulations, most numerical simulation studies of rockburst adopt a continuous media mechanics model, which has the deficiency of being unable to simulate the large deformation mechanical behavior of discontinuous media in rockburst development. DEM can make up for this deficiency, but the shortcoming of DEM is also obvious. The three elements, namely, motion, force and deformation, need artificial assumptions, resulting in more input parameters and calibration. Complex data structure, grid retrieval, determination of adjacent blocks and detection of generation or cancellation for block contact will consume a large computational cost.

- Regarding the physical model tests, due to loading conditions and the similarity relationship that needs to be met, the strength of similar materials is usually lower than that of the original rock with rockburst, so it is difficult to accumulate high energy. Coupled with an unclear brittle similarity relationship, whether the structure surface of similar materials can truly reflect the influence of the structure surface on rockburst is worthy of further discussion. On the other hand, owing to the complexity of the simulated excavation operation and the lack of dynamic similarity theory, it is also debatable whether it can truly reflect the influence of excavation dynamic disturbance on rockburst.
- Regarding the empirical criteria, although some influencing factors of rockburst have been considered in the comprehensive criteria, there are many influencing factors in practical engineering, not only the static stress of surrounding rock but also other unpredictable dynamic disturbance. Moreover, the occurrence of rockburst is sudden and random, and the existing criteria are still difficult to accurately evaluate and predict rockburst. In addition, some empirical criteria are not unified, which causes trouble for researchers.
- Regarding the mathematical model approaches for rockburst classification and prediction, whether using uncertainty algorithm models or machine learning, the crux for the accuracy of classification and prediction results is the amount and availability of data for rockburst. In actuality, the amount of existing rockburst data makes it difficult to ensure the high accuracy of model. The imbalance of training samples (such as "rockburst occurrence" records being far fewer in number than "no rockburst" records), leads to poor generalization capability of the model. On the other hand, there are few selected index factors in uncertainty algorithm models and input indices (rockburst influencing factors) in machine learning. Whether it can represent the most important influencing factors of rockburst is still worth discussing.
- Regarding microseismic monitoring, due to the unpredictable distribution of underground strata, anisotropy of medium and the sudden change of wave velocity between two various rock formations, it is difficult to ensure the accuracy of microseismic source location results. On the other hand, with deep learning as a black box model, the mapping relationship between data and results is hard to explain; in addition, modeling is complex and the computational cost is high, which is not realistic to be applied in engineering.
- Regarding rockburst support, the existing evaluation methods of support demand have great uncertainty, and the evaluation and test methods of support systems cannot fully simulate the actual situation of surrounding rock; hence, it is difficult to have a quantitative evaluation of support effect.

8. Conclusions

Considering the existing research results and trends, future research may focus on the following points:

- It is necessary to develop a new type of similar material with "low strength and high brittleness" and also to explore and summarize the brittleness similarity criterion especially suitable for rockburst and quantify the brittleness similarity of materials. In addition, to improve the excavation efficiency and accuracy of the test results, it is necessary to develop a set of TBM excavation machines with a simple structure, which can accurately simulate the breaking process of a cutterhead and comprehensively consider the complex rock–machine interaction. Further, for the test of drilling and blasting excavation, how to reasonably determine the blasting scheme and appropriate parameters to evaluate the blasting effect is also a crux.
- It is necessary to develop and establish a rockburst database system including a microseismic waveform database, rockburst case database and a microseismic event sequence database. An upload portal is provided to collect accurate historical rockburst data from engineering cases around the world, which is convenient for researchers

and engineers to use rockburst data more conveniently, economically and efficiently. More data are conducive to improve the generalization capacity of the mathematical models of rockburst classification and prediction and further lay a data foundation for the application of deep learning in the future.

- It is necessary to introduce information-fusion technology into microseismic source location based on multimethod combinations and establish a scientific evaluation model for a reasonable data-fusion algorithm. In addition, an anomaly detection method based on machine learning may be used for in situ signal monitoring. The abnormal changes of all monitoring signal type near rockburst can used to establish the model relationship between the abnormal signal and the occurrence of rockburst, further predicting the occurrence time of rockburst.
- It is necessary to develop high stress utilization technology. High stress is one of the main factors causing rockburst, which may be used for high-efficiency rock breaking with superposition of a stress wave to transfer most of the energy and prevent rockburst.
- It is necessary to develop a high damping energy absorbing bolt with small strain, high energy absorption and antirepeated impact with high damping rubber material for rockburst support of deep hard rock.

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Nomenclature

σ_θ	Maximum tangential stress of surrounding rock, MPa	U_{imin}	Valley elastic strain energy density
σ_1	Axial stress of surrounding rock, MPa	E_0	Initial elastic modulus
σ_L	Axial stress of tunnel, MPa	σ'_{rm}	Triaxial rockmass strength based on the Hoek–Brown strength criterion
σ_c	Uniaxial compressive strength of rock, MPa	σ'_3	Minimum principal stress at failure, MPa
σ_{RB}	Rockburst maximum stress, MPa	U_h	Energy dissipated to overcome frictional and support resistance during rockburst, kJ·m^{-3}
H	is the buried depth of rock sample, m	U_d	Energy dissipated by failing the rock mass during rock burst, kJ·m^{-3}
K_v	Rock mass intact coefficient	σ_{max}	Maximum tangential stress on the boundary of acircular opening (or σ_θ), MPa
W_{et}	Elastic energy index, kJ·m^{-3}	RERI	Relative energy release index
U^e	Peak elastic energy density	RVI	Rockburst vulnerability index
U^a	Failure energy density of post peak	S	Stress index
U_{imax}	Peak elastic strain energy density	RPI	Rockburst proneness index
C_g	is the competency factor	UCS	Unconfined compressive strength, MPa
σ_c/σ_t	Rock brittleness coefficient	RMR	Rock mass rating
δ_0	Radial displacement, m	PES	Elastic strain energy, kJ·m^{-3}
m_i	Intact rock parameter (Hoek–Brown constant)	σ_t	Tensile strength of rock mass, MPa
σ_{cm}	Rock mass strength	B_3	Rock brittleness coefficient (σ_c/σ_t)
r_p	Plastic radius, m	W_{qx}	Rockburst energy tendency index
		r_0	Cavity radius, m

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