

u e n g t r t c e

## Definition and classification of rockburst

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### ABSTRACT

The rockburst is a violent failure in rock during mining and tunneling operations. Since tunnel constructions for hydropower and transportation purposes and mining operations in deep rock masses have been increasing recently, more frequent rockburst cases have been reported. This paper proposes a new definition for rockburst, considering the main components of the rockburst along with triggering mechanisms and reasons. For this purpose, the historical definitions of rockburst and its related classifications have been reviewed. In terms of triggering mechanisms, a rockburst must be induced by excavation resulting from three effects arising from the transition of stress state from 3- to 1-dimension, such as the transient radial stress loss, the time-dependent tangential stress increase, and the peak strength drop, which are explained by examining the stress transition in the *shear stress vs normal stress* space and energy transition in the *stress-strain* space. Based on the understanding of the three effects of excavation, a new definition of rockburst is proposed: "A rockburst is a sudden failure of rock mass surrounding the excavations caused by the rapid release of stored energy when induced stresses exceed the rock strength". Additionally, rockbursts are classified according to transitions in the static and dynamic stress fields, with further subclassifications into instantaneous and delayed bursts based on the timing of occurrences relative to radial stress drop and tangential stress increase. Rockburst management strategies are also proposed to address stress and energy transitions in excavations.

### 1. Introduction

A rockburst is usually characterized by a sudden release of accumulated energy within rock masses during mining and tunnelling operations. The violent failure of rock leads to substantial and often unpredictable damage to the surrounding rock and equipment, posing a serious threat to personnel safety. Extensive studies have been carried out in the context of underground mining for mineral resources. Hard and brittle rock properties and high-stress conditions are widely recognized as key factors to a rockburst. Since the rise of tunnelling for hydropower and transportation projects, and as underground mines go deeper, more case histories have revealed that dynamic disturbances also contribute to the occurrence of rockbursts. Thus, understanding the historical occurrences of rockbursts is essential for exploring the mechanisms and

developing effective management strategies for subsurface excavations.

The first recorded rockburst in mining is documented in a tin mine in Altenberg, Germany, in the 1640s. Other rockburst cases recognize that it is a specific type of rock failure around excavations that is uncontrollable and usually accompanied by rock ejection, bulking and/or shakedown such as the rockburst cases recorded in a gold mine in Kolar Goldfields (India), a gold mine in ERPM (North Africa), a lead-zinc-silver ore in Idaho (the U.S.), etc. The first recorded rockburst in China is found in the Shengli coal mine. Although coal and typical rock differ in composition, coal can be classified as a type of sedimentary rock rich in organic materials. The bursting mechanism of coal can be treated as a rockburst. With the increase of tunnelling in hydropower and transportation projects and mines going deeper, more cases of rockbursts are documented. For example, hundreds of rockburst cases are encountered during the

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construction of the Jinping II hydropower station, where the overburden is as deep as 2000 m (Feng et al., 2015) and in underground mines such as Creighton Mine in Canada that is over 3000 m deep. Observations have shown that thin and sharp-edged fragments are separated from the main body during the minor rockburst. The rock fragments could eject with a velocity of up to 6 m/s, while some small flakes could move at a speed of 8–50 m/s (He et al., 2023; He et al., 2012b) during strainbursts. Other parameters, such as noise and depth of notches, are also recorded. These observations show that a rockburst can be distinguished from brittle failure based on the failure phenomena.

More explorations to define rockburst have been carried out based on energy release and energy conversion. The stored energy in a highly-stressed rock mass is analyzed to determine rockburst potential. Attention has been given to the strain energy changes arising from the way in which a new excavation surface is generated (Brady and Brown, 2006). Conceptual models have shown that the magnitude of the burst is mainly determined by the strain energy released from the ejected rock in a strain burst event, but it is more associated with the energy released from surrounding rock mass in a large-scale burst event (Li et al., 2022). The presence of geological structures, such as faults, shear zones, and dykes near excavation boundaries, may result in more released kinetic energy (Manouchehrian and Cai, 2017).

As shown in Fig. 1, rockburst may not be a universal problem. It usually occurs in locations of high magnitude in situ stresses where excavation activities are continuing at depth. A large number of rockburst cases have been reported in countries rich in mineral resources, such as South Africa, Austria, Australia, the U.S., China, Norway, Canada, and Germany. There is a common problem that rockburst usually occurs suddenly, and critical parameters, such as time of occurrence, location, and intensity, are unpredictable.

In this paper, the definitions of a rockburst and the related classifications are first reviewed. Specified stress paths are introduced based on the stress transitions observed during rockburst events in tunnel engineering. The energy sources and energy conversion are explained in relation to the stress evolution during the establishment of an excavation. Finally, a new definition and classification of rockburst are proposed for tunnel engineering. It should be noted that this paper is produced as part of the first focused workshop on the definition of rockburst. Further discussions will be conducted to refine the current definition and classification of rockburst.

## 2. Definition and classification of a rockburst

A rockburst has been defined from two points of view: the sudden failure phenomenon and the violent energy-release process. This study reviewed hundreds of rockburst definitions found in the literature. We

selected 80 descriptions from the past 80 years, listed in Table 1 in chronological order. In 1946, Terzaghi defined rockburst by emphasizing the suddenness and ejection phenomenon in brittle and hard rock. In 1965, Cook defined a rockburst as an uncontrolled disruption of rock associated with a violent release of energy, highlighting violent energy release of energy as a key phrase. The stored energy in a highly stressed rock mass was analyzed to indicate the rockburst potential. Since then, the three words “energy”, “sudden”, and “violent” have become the most frequently used to describe rockburst (see Fig. 2). In 1999, Mitri et al. proposed a widely accepted definition of strain bursts in deep underground hard rock mines, describing them as a sudden release of energy in a highly stressed rock volume, often leading to localized, violent failure of the rock mass surrounding the opening. Along with these, other keywords, such as, “dynamic or seismic”, “excavation”, “ejection”, and “brittle or hard rock” appear in Table 1 more than ten times. In the following sections, we will explore the three most frequently occurring words and their related classification in conjunction with these keywords.

### 2.1. Dynamic and seismic event

Rockburst was recognized as a seismic event as early as 1967 by Obert and Duvall, who described the featured vibration. After the 1980s, dynamic phenomena were emphasized as a result of force or stresses changes during rock failure. During the last five years, “dynamic” has been used more frequently. In general, both dynamic and seismic events involve the generation and propagation of vibrations. Seismicity could be seen as a fracturing process in rockbursts. By examining the correlation between rockburst intensity and seismicity, Ortlepp and Stacey (1994) classified the rockburst into five categories, namely, strain bursting, buckling, face crush, shear rupture, and fault-slip, indicating the varying magnitudes of micro-seismicity may be generated. Regarding whether the location and source of damage are consistent, the five categories could be divided into two classes, as listed in Table 2. Class 1 occurs in the area where the energy is stored, while class 2 includes the sub-classes of rockburst induced by shear rupture and fault-slip. The energy source may come from the area far from the location that has potential rockburst damage.

Seismic source characteristics are characterized in recent studies as the magnitudes are not always determined consistently (Cai and Kaiser, 2018). Violent ejections of rock fragments are also evaluated, as well as the shape and size of the fragments. The kinetic energy is calculated based on the mass and ejection velocity. Thereafter, the severity in terms of displaced volume of rock is presented (Kaiser et al., 1996), i.e., minor, moderate and major, with consideration of the corresponding mechanisms (see Table 3). The temporal and spatial characteristics of

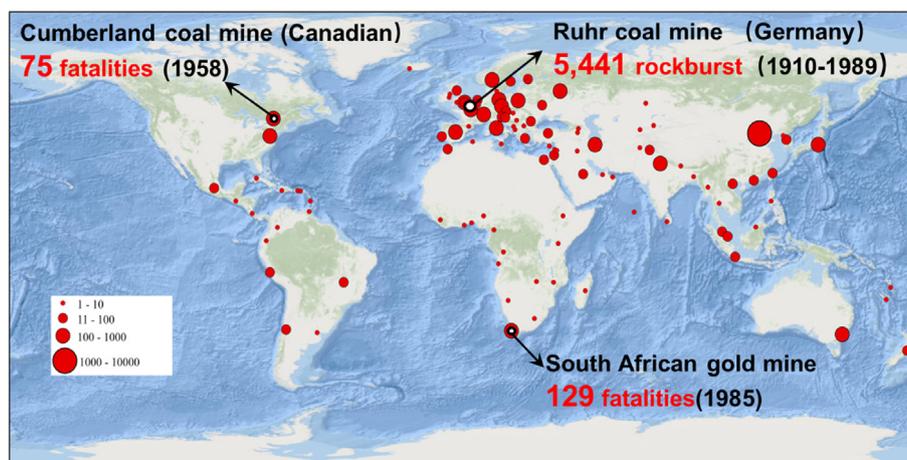


Fig. 1. Worldwide records of rockburst cases in literature from the WOS database (till the date of Sep. 2023).

**Table 1**  
Summary of rockburst definitions in chronological order (date range:1946–2024).

References	Regions	Definitions and descriptions
Terzaghi (1946)	Austria	<b>A sudden separation or falling off of the rock from the tunnel wall due to excessive stress on brittle and hard rocks.</b>
Cook (1965)	South Africa	<b>An uncontrolled disruption of rock is associated with a violent release of energy; many rockbursts can result from the release of more than <math>5 \times 10^4</math> ft. lb of energy.</b>
Obert and Duvall (1967)	the U.S.	Any sudden and violent expulsion of rock from its surroundings, the phenomenon resulting from the static stress exceeding the static strength of the rock as a result of a seismic event or directly associated with a seismic event, and the result being of sufficient magnitude to create an engineering problem. There are no constraints on the magnitude or type of seismic event. It only needs to produce enough energy to cause damage in the tunnel.
U.S. Bureau of Mines and Thrush (1968)	the U.S.	Phenomena occur when a volume of rock is strained beyond the elastic limit, and the accompanying failure is of such a nature that accumulated energy is released instantaneously.
Blake (1971)	the U.S.	A rockburst is generally defined as a sudden rock failure characterized by the breaking up and expulsion of rock from its surroundings accompanied by the violent release of energy.
Russenes (1974)	Norway	As long as there are sounds, phenomena such as wall caving, spalling, and even ejection and new fracture face, these phenomena can be called rockbursts.
Luo (1975)	China	The rockburst mostly occurs on the excavated section. First, the sound of rock tearing is emitted, and at the same time, the smell of smelly Century egg is emitted. Then, the sound is similar to that of a single detonator explosion, and then the rock fragments are ejected with the sound.
Lippmann (1978)	Canada	An instability phenomenon in the sense of limiting static equilibrium of elastic-plastic rock material.
Pan (1979)	China	A rockburst is a sudden failure of rock layers characterized by the detachment and protrusion of rocks from the rock mass, accompanied by intense energy release.
Larocque (1980)	Canada	Violent failures of geologic members in the immediate excavation area cause mine damage.
Heunis (1980)	South Africa	A seismic event radiating sufficiently intense shock waves to cause visible damage to an excavation.
Curtis (1981)	Australia	A rockburst is a sudden and violent natural phenomenon that occurs accompanied by impact or vibration.
Zhu (1982)	China	During excavation, elastic energy is released, forming a rockburst accompanied by sound and vibration, and sharp rock fragments fly out.
Ontario Ministry of Labour (1983)	Canada	An instantaneous failure of rock causes an expulsion of material at the surface of an opening or a seismic disturbance to a surface or underground mine.
Zubelewicz and Mroz (1983)	Poland	The phenomenon of rockburst occurs when static stability conditions of rock mass are violated, and the uncontrollable dynamic failure process proceeds starting from the equilibrium state.
MSHA (1984)	the U.S.	A sudden and violent failure of a large volume of overstressed rock resulting in the instantaneous release of large amounts of accumulated energy.
Vardoulakis (1984)	the U.S.	Mining cavities often intersect horizontal soft-rock or coal strata, which then tend to move suddenly into the cavity. Catastrophic events of this kind are called rockbursts or bumps. A surface instability phenomenon.
Chen (1987)	China	A rockburst must be caused by the delayed damage of unstable rocks and coal seams, and it can generate catastrophic high-intensity shock waves in the air.
Singh (1988)	Canada	A rockburst is a sudden manifestation of the release of strain energy stored in the rock mass.
Bardet (1989)	the U.S.	The term rockburst is used to designate a violent failure of rock, which is periodically experienced in deep underground excavations. It involves a rapid convergence and oscillation of the excavation walls, followed by slabbing and failure of the rock immediately adjacent to the excavation.
Tan (1991)	China	Only when ejection or throwing damage occurs can it be called a rockburst; the rupture of the non-dynamic ejection phenomenon should be attributed to brittle failure under static conditions.
Zou (1990)	China	A rockburst is an engineering geological phenomenon in which the elastic strain energy accumulated inside the surrounding rock of an underground cavern is suddenly released, causing a sudden explosion or splitting towards the free face direction, accompanied by sound.
Muller (1991)	Germany	Rockbursts or "bumps" in coal mines are characterized by the spontaneous release of elastic energy, which is largely transformed into kinetic energy, thus leading to abrupt lateral displacements of the coal seam.
Hedley (1992)	Canada	A seismic event which causes injury to persons or damage to underground workings. The general and essential feature of rockbursts is their sudden, violent nature.
Lenhardt (1992)	South Africa	A general term relating to seismic events generated in a mining environment, especially in connotation with violent rock failure.
Gill et al. (1993)	Canada	A sudden rock failure is characterized by the breaking up and expulsion of rock from its surroundings, accompanied by a violent release of energy.
Pan et al. (1994)	China	A rockburst is caused by sudden damage to a large area of rock mass, throwing it into the cavity space, releasing a large amount of energy from the surrounding rock, causing instantaneous damage to the cavity from a few meters to several hundred meters, and causing casualties.
Hoek et al. (1995)	Canada	In extreme cases, the spalling may be severe enough to be classed as a rockburst. Rockbursts are explosive failures of rock mass around an underground opening, which occur when very high stress concentrations are induced around underground openings.
Maleki (1995)	the U.S.	A rockburst is considered to be a violent expulsion of highly stressed rock into a mine opening.
Kaiser et al. (1996)	Canada	A rockburst is defined as damage to an excavation that occurs in a sudden or violent manner and is associated with a seismic event.
Sun (1996)	China	A rockburst is a local instability phenomenon caused by brittle failure of the surrounding rock in a relatively short period of time after excavation in high stress areas. The elastic strain energy originally stored in the rock mass is suddenly and suddenly released, leading to high-speed collapse or even ejection.
Scott et al. (1997)	the U.S.	A rockburst is defined as the sudden and sometimes violent release of accumulated energy when a volume of rock is strained beyond its elastic limit.
Bennett and McLaughlin (1997)		Any type of stress-release phenomenon which has been induced by mining activity and which results in the emission of seismic signals.
Ortlepp (1997)	South Africa	A seismic event which causes violent and significant damage to the tunnel or the excavations of a mine.
Li and Feng (1998)	China	A rockburst is a special manifestation of mining pressure, which is the sudden failure of the rock mass around the underground excavation space (or its deep surrounding rock), accompanied by a rapid release of rock strain energy.
Mitri et al. (1999)	Canada	<b>Strain burst (strain-type rockburst) phenomena in deep underground hard rock mines are generally characterized by a sudden release of energy in a volume of highly stressed rock, which, more often than not, causes local violent failure of the rock mass around the opening.</b>

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Table 1 (continued)

References	Regions	Definitions and descriptions
Singh and Goel (1999)	Netherlands	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.
Nussbaumer (2000)	the U.S.	The term "rockburst" is commonly used to describe a wide range of rock failures which occur in tunnels, shafts, caverns and mines. A rockburst is a sudden form of rock failure characterized by the breaking up and expulsion of rock from its surroundings accompanied by a violent release of energy.
Aydan et al., 2001	Japan	A rockburst phenomenon, usually causing injury to workers, damage to equipment and even substantial economic losses and delays, is one of the common dynamic instability modes in underground mining and excavating in hard, brittle and relatively unfractured surrounding rock strata.
Österreichische Gesellschaft für Geomechanik (2001)	Austria	Sudden and violent failure of the rock mass, caused by highly stressed brittle rocks and the rapid release of accumulated strain energy.
Van Der Merwe and Madden (2002)	South Africa	A rockburst is a seismic event that causes damage to underground workings.
Tang et al. (2002)	China	A rockburst is a dynamic failure phenomenon caused by the sudden release of elastic strain energy stored in rocks, manifested by the outward ejection of damaged rock blocks at a certain speed.
Zhou et al. (2003)	China	A rockburst is a common dynamic failure phenomenon in deep buried underground engineering construction. It is caused by the accumulation of strain energy in rocks that exceeds the energy consumed by rock failure. The excess energy leads to the detachment and collapse of rock fragments from the rock mass.
Larsson (2004)	Sweden	A rockburst is a mining-induced seismic event that affects and causes destruction to excavations in the rock.
He et al., 2005	China	<b>A rockburst is a nonlinear dynamic phenomenon in which energy is instantly released from a rock mass along an excavation face. The definition points out the four elements of rockburst, including energy rock mass, excavation face, instantaneous release of energy, and the complexity of dynamic processes.</b>
Ortlepp (2005)	South Africa	A seismic event is considered to be the "... transient energy released by a sudden fracture or failure in the rock mass which results in the emission of a seismic vibration transmitted through the rock". A rockburst "... is the significant damage caused to underground excavations by a seismic event".
Wang et al. (2006)	China	Rockbursts are sudden, explosion-like events that occur deep underground, posing a hazard to the safety of underground miners and causing damage to mine structures.
Sharan (2007)	Canada	A rockburst is a sudden and violent expulsion of rock from the surrounding rock mass.
Hirata et al. (2007)	Japan	A rockburst is a phenomenon in which a mass of rock collapses explosively.
Wang et al. (2008)	China	A rockburst is an engineering disaster phenomenon in underground rock excavation, which is the dynamic form of damage caused by the release and conversion of stored elastic energy into kinetic energy when the rock structure is damaged.
Wang et al. (2009)	China	A rockburst is a dynamic instability phenomenon caused by the sudden release of strain energy accumulated in the surrounding rock of underground spaces in high stress environments. It often manifests as rock flaking, severe fragmentation, rock collapse, and rock ejection and is sometimes accompanied by sound.
He et al. (2010)	China	As a typical failure phenomenon, rockburst often occurs in a sudden or violent way in the excavation surface of underground rock masses. Such a failure process of rocks is usually characterized by crack initiation, propagation, and coalescence with associated damage and evolution.
Jiang et al. (2010)	China	When excavation for a deep underground tunnel or chamber is undertaken in strong, brittle rock, the change in stress results in dynamic damage to the adjacent rock, referred to as a rockburst.
Tang (2011)	China	A rockburst is a phenomenon of severe failure of rock structures accompanied by the violent release of elastic energy.
Zhou et al. (2011)	China	A rockburst is a kind of geological hazard which is characterized by dynamic failure.
Gong et al. (2012)	China	A rockburst is a sudden rupture and explosion of rock on the surface of a tunnel and is associated with a violent release of energy.
Adoko et al. (2013)	China	... be referred to as a deadly phenomenon initiated in high geostress and brittle rock conditions with extremely complex mechanical features. This results in a violent expulsion of rock from the surrounding rock mass. Usually, rockburst occurs with a sudden release of elastic strain energy and some other phenomena, such as slabbing, spalling, ejecting or throwing.
Cai (2013)	Canada	As mining and underground constructions migrate to deep grounds, stress-induced rock fracturing and failure are inevitable, and in some cases, rocks can fail violently, releasing a large amount of seismic energy and causing damage in the form of rockburst. A rockburst is defined as damage to an excavation that occurs in a sudden or violent manner and is associated with a seismic event.
Zhao et al. (2014)	China	A rockburst is a sudden and violent failure of rocks, and it often occurs in hard rocks on highly stressed ground.
Mazaira and Konicek (2015)	Czech Republic	A rockburst always involves a violent energy release with large rock deformation and rock ejection that can cause severe damage to openings, equipment, and facilities and may result in fatalities.
Cai (2016)	China	<b>A rockburst is a kind of artificial earthquake induced by human activities, such as mining excavations. Rockburst is one of the dynamic hazards induced by mining excavation, a process of accumulation, evolving and sudden release of energy.</b>
Su et al. (2017)	China	A rockburst is a typical geological disaster that occurs during deep underground excavations and is frequently accompanied by rock fragment ejection at high speed.
Feng (2017)	China	Rockbursts are a dynamic hazard induced by tunnelling. A rockburst is a combination of the seismic event and the behaviour of the rock mass and discontinuities. Rockburst is related to rock mechanics and geophysics. Rockburst is the result of the induced seismicity. It should be clear enough, though, that the induced seismicity in mines is not equal to a rockburst hazard.
Chen et al. (2018)	China	A rockburst is a sudden and often violent breaking of a mass of rock from the walls of a tunnel, mine, or deep quarry. It is caused by the failure of highly stressed rock and the rapid or instantaneous release of accumulated strain energy.
Zhou et al. (2018)	China	From the perspective of keywords like a violent failure, highly stressed, brittle rock, and strain energy, these definitions include everything from the popping off from the face of a few small pieces of rock to seismic events that displace large volumes of rock underground and are felt on the surface, similar to a local earthquake.
Keneti and Sainsbury (2018)	Australia	The term "rockburst" is applied to the damage that occurs as a result of, or which is directly associated with, a seismic event that generates sufficient energy to cause violent failure of the rock mass.
Akdag et al. (2018)	Australia	A rockburst is a typical unstable rock failure associated with the violent ejections of rock fragments from the free face/sidewall/roof of an underground excavation.
Dietz et al. (2018)	Germany	A rockburst is a sudden and violent movement and collapse of rock in underground caves which occurs under high stress conditions.
Hu et al. (2019)	China	A rockburst is an unstable or violent failure leading to sudden or rapid damage to excavation with an explosive release of elastic strain energy and fragments ejection.
Feng et al. (2019)	China	<b>A rockburst is a dynamic phenomenon in which the elastic deformation potential energy accumulated in the underground engineering rock mass is suddenly released during excavation or other external disturbances, leading to burst and ejection of rock.</b>

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Table 1 (continued)

References	Regions	Definitions and descriptions
Si and Gong (2020)	China	A rockburst is a type of dynamic failure phenomenon often encountered in deep rock engineering (deep underground mines, tunnels for transportation systems, and hydroelectric projects), and it releases a large amount of kinetic energy, thereby seriously threatening the safety of construction personnel and mechanical equipment.
Farhadian (2021)	Iran	A rockburst is defined as a phenomenon with immediate dynamic instability under excavation unloading conditions of deep or high geostress areas.
Wei et al. (2022)	Australia	A rockburst is a term used to characterize rock dynamic failure associated with a large amount of energy released in a sudden and violent manner.
Askaripour et al. (2022)	Canada	Rockbursts consist of violent wall rock failures associated with high energy rock projections in response to the instantaneous stress release in rock mass under high strain conditions. All the previous definitions of rockburst seem to be based on the fact that the rock's elastic energy is suddenly released due to perturbation of the magnitude of in situ stresses during the excavation.
He et al. (2023)	China	A rockburst is a sudden and violent rock failure with the ejection of rock fragments and rapid release of energy, always associated with seismic events and causing serious damage to underground engineering. Three basic features that distinguish rockburst from other rock failures are summarized, including: (1) suddenness; (2) dynamic rock rupture and ejection; and (3) rapid release of energy.
Gong et al. (2023)	China	A rockburst is a dynamic failure phenomenon characterized by the bursting, ejection or throwing of hard rocks on the excavation surfaces of deep tunnels, as well as deep metal or non-metallic mine roadways, ore pillars, and heading faces, often accompanied by varying levels of sounds.
Zhou et al. (2024)	China	A rockburst is a significant and hazardous phenomenon that can occur during underground projects involving hard and brittle rock. It is characterized by its destructiveness, suddenness, and complexity.

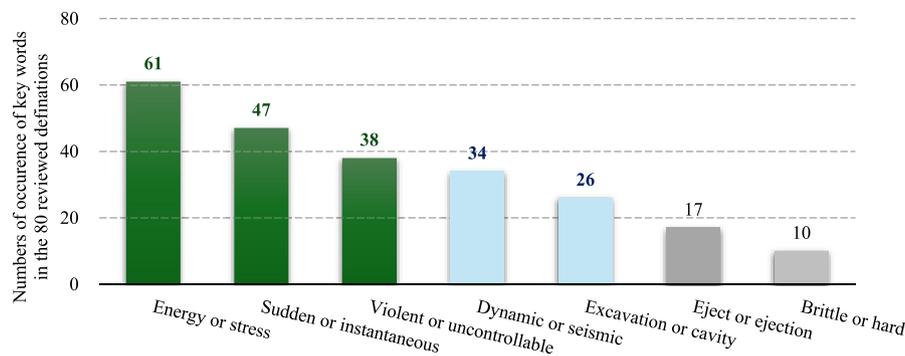


Fig. 2. Statistical analysis of the keywords in from the definitions of rockbursts given in Table 1.

microseismic (MS) events and rockbursts are jointly analyzed to understand the formation mechanisms of rockbursts (Duan et al., 2024). It should be noted that many velocity magnifiers resulting from momentum transfer and failure mechanisms may be involved, and ejection velocity estimates are, therefore, in general, poor measures of the damage severity (Cai and Kaiser, 2018). Fracture mechanics is used to explain the crack development and quantify the rockburst intensity (Li et al., 2017; Zhang

et al., 2017). The dynamic impact of fault-slip makes the situation more complex (Manouchehrian and Cai, 2017). The amount of seismic energy is significantly high if the rockburst is triggered by a fault slip (Li et al., 2022). As a result, finer rock fragments could be generated (Li, 2021). It is a non-trivial exercise to integrate, numerically, the products of energy over the surface of an excavation. In such a way, the scales of released energy could be classified together with the phenomena.

Table 2

Classification of rockburst according to the seismicity (Ortlepp and Stacey, 1994).

Classes	Postulated Source Mechanism	First motion from seismic Records	Richter Magnitude, $M_L$
Class 1	Strain-bursting	Superficial spalling with violent ejection of fragments	Usually undetected; could be implosive
	Buckling	Outward expulsion of pre-existing larger slabs parallel to the opening	Implosive
	Face crush	Violent expulsion of rock from tunnel face	Implosive
Class 2	Shear rupture	Violent propagation of shear fracture through intact rock mass	Double-couple shear
	Fault-slip	Violent renewed movement on existing fault	Double-couple shear

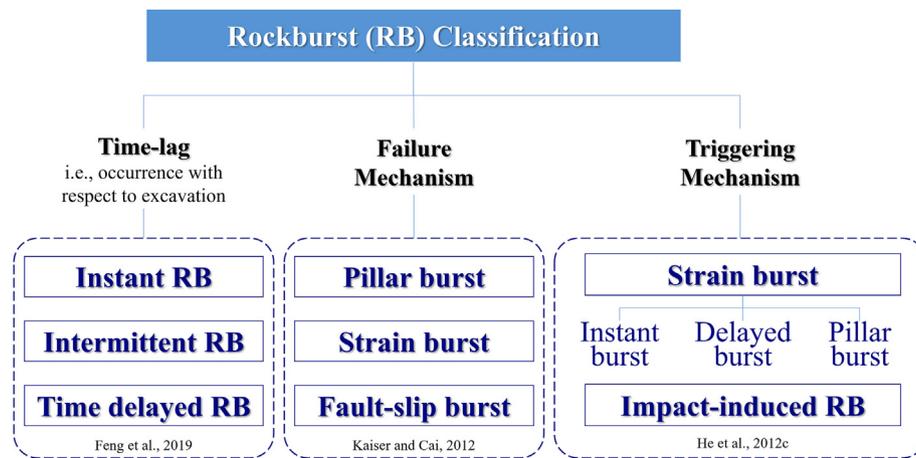
### 2.2. Excavation

Attention has been focused on the contribution of excavation to the rockburst since 1975. Luo (1975) stated that the rockbursts mostly occurs in the excavated section, particularly at the arch corner or sidewall, where stress concentration may develop after excavations. As shown in Fig. 2, nearly 1/3 of the description includes excavation or similar expressions when defining a rockburst. Excavation provides the space for energy release. Based on the difference in occurrence time relative to the excavation, rockburst can be classified into instantaneous rockburst and delayed rockburst (see Fig. 3). Both types of rockburst are driven by the energy stored in the rock mass system, and the evolution of this energy is closely linked to their specific failure modes. Delayed rockburst is characterized by a significant time delay after excavation. For instance, delayed rockburst histories in Jinping II hydropower station have shown that most of the cases occurred 2–5 h after excavation (Feng et al., 2012b). However, cases after 6–30 days later were also recorded (Chen et al., 2012). Instantaneous burst cases also occurs at the advanced face immediately after establishing and excavation (Feng et al., 2019). Typical features between the two types of rockburst are listed in Table 4. Due to the uncertain time-dependent behavior of rocks and the evolution

**Table 3**  
Rockburst damage mechanisms and nature of the anticipated damage (Kaiser et al., 1996).

Damage mechanism	Damage severity	Cause of rockburst damage	Thickness (m)	Weight (kN/m <sup>2</sup> )	Closure* (mm)	v <sub>e</sub> (m/s)	Energy (kJ/m <sup>2</sup> )
Bulking without ejecting	Minor	Highly stressed rock with little excess stored strain energy	<0.25	<7	15	<1.5	Not critical
	Moderate		<0.75	<20	30	<1.5	
	Major		<1.50	<50	60	<1.5	
Bulking causing ejecting	Minor	Highly stressed rock with significant excess strain energy	<0.25	<7	50	1.5 to 3	Not critical
	Moderate		<0.75	<20	150	1.5 to 3	
	Major		<1.50	<50	300	1.5 to 3	
Ejection by remote seismic event	Minor	Seismic energy transfer to jointed or broken rock	<0.25	<7	<150	>3	3 to 10
	Moderate		<0.75	<20	<300	>3	
	Major		<1.50	<50	>300	>3	
Rockfall	Minor	Inadequate strength, forces increased by seismic acceleration	<0.25	<7g/(a + g)	N.A.	N.A.	N.A.
	Moderate		<0.75	<20g/(a + g)	N.A.	N.A.	
	Major		<1.50	<50g/(a + g)	N.A.	N.A.	

Note: v<sub>e</sub> is the velocity of displaced or ejected rock; a and g are seismic and gravitational accelerations, respectively, and \* means closure expected with an effective support system.



**Fig. 3.** Classification of rockburst based on the time difference from excavation (RB is short for rockburst, modified after He et al., 2023; Feng et al., 2019; Kaiser and Cai, 2012; He et al., 2012c).

of stress, rockbursts are difficult to predict precisely in terms of both timing and location with current knowledge and technology.

### 2.3. Hard and brittle rock

Initially, a rockburst is recognized as a special failure mode in brittle and hard rock, as defined by Terzaghi in 1946 (see Table 1). As a result, the inherent properties of rock, such as strength and brittleness, are used to assess the likelihood of rockburst occurrence. The brittleness of rock can be defined as the ratio of rock strength (Qian and Zhou, 2011) to that

**Table 4**  
Features of rockburst based on the time between excavation and rockburst (modified after Feng et al., 2012a).

Classes	Fracture features	Micro-seismicity features
Instantaneous burst	Tensile cracks with few shearing cracks	Micro-seismic energy index increases at the beginning, decreases and then increases again before the occurrence of the rockburst.
Delayed burst	Alternately of tensile cracks, shear cracks and mixed cracks	Initial micro-seismicity is active, but there is a quiet period of several days to several tens of days before the occurrence of the rockburst.

of strain energy capacity (He et al., 2023; Luo et al., 2023; Tang et al., 2002b). Some later observations have demonstrated that strain bursts might also occur in non-brittle rocks (Chen et al., 2015), such as limestone, potash and shale. Experimental results show that the brittle behavior of rock is associated with energy evolution, confinement loss, and rate of excavation. Therefore, the brittle-ductile characteristics of some rocks controlled by energy evolution and confinement, and excavation rate should be further examined.

As discussed above, the rockburst could exhibit three basic features: (1) a sudden/violent energy release, (2) a seismic/dynamic event, and (3) occurring at an excavation. As shown in Fig. 4, some definitions emphasize these features in different ways (He et al., 2014; Cai, 2016; Feng et al., 2019). Additional information, such as fracture mechanism, energy and stress evolution, and location, is needed to classify rockbursts. It is evident that all these phenomena are associated with the excavation. Therefore, understanding the fundamentals of excavation is crucial for defining a rockburst in tunnel engineering.

### 3. Fundamental interaction between excavation and rockburst

The excavation causes stress redistribution, creates space for rock displacement (bulking), and exposes the surrounding rock mass to potential damage. These combined effects provide the conditions under which a seismic event may be classified as a rockburst.

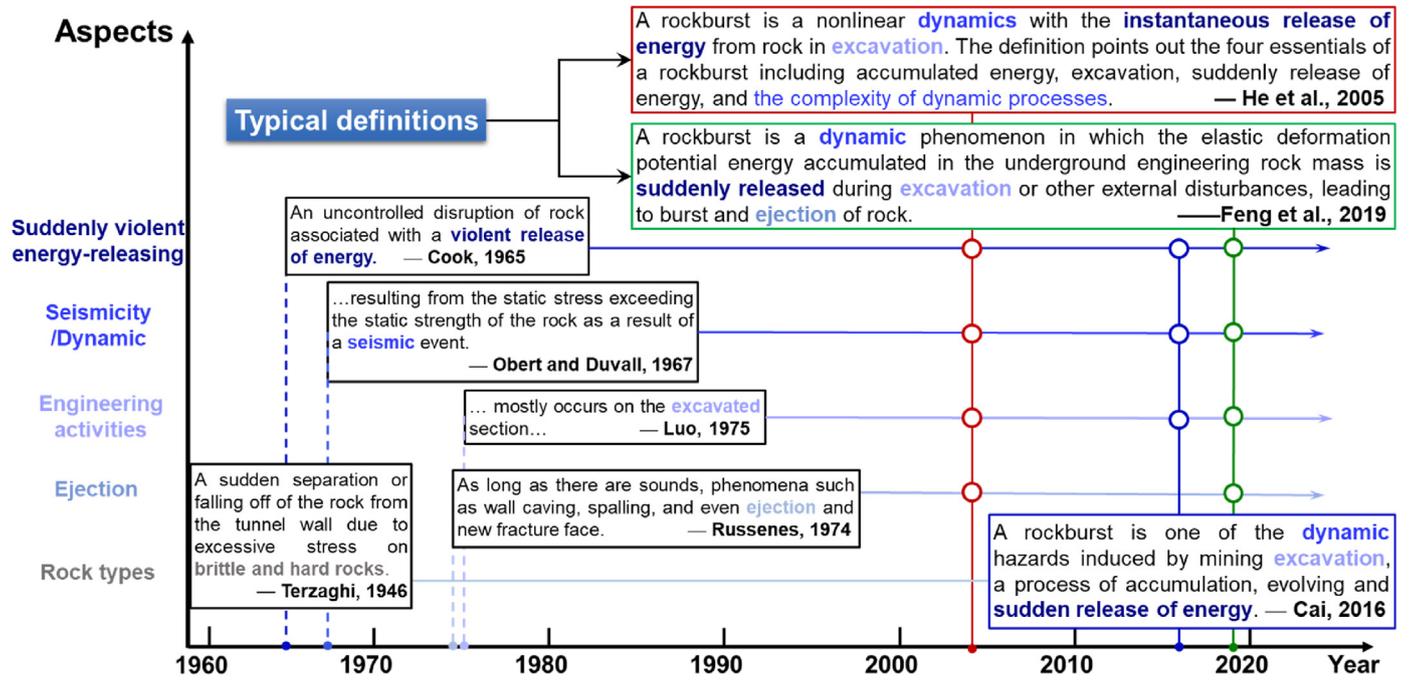


Fig. 4. Illustrations of the history of rockburst definitions

3.1. Loading path

In terms of triggering mechanisms, a rockburst may occur during or after excavation under high in-situ stress conditions. Additionally, external disturbances (e.g., blasting, karst caves, activities in adjacent tunnels, and fault movement) may also trigger rockbursts. In the context of underground construction, Fig. 5 illustrates the determination of loading paths based on the stress evolution of rock surrounding the excavation. Initially, the rock mass is in equilibrium (i.e., under 3-dimensional compression) when the tunnel is not excavated. After excavation, a free face is created, changing the stress state from 3-dimensional to 2-dimensional compression in the rock surrounding the excavation. In some cases, two or more free faces might be created by excavation, leading to the transition of stress state from 3- to 2-dimensional, or even

to 1-dimension in extreme cases. By denoting the above two kinds of stress evolution as the first stress path (SP1), the kinetic energy for the burst is mainly converted from the strain energy accumulated in the static state, resulting in strain burst. This means that a strain burst occurs in rock when the relative stress transitions from 3- to 1-dimensional in the static stress field.

The rock on the periphery of the excavation might be stabilized after excavation. However, due to the propagation of vibrations from the far field, a rockburst might occur at the excavation site. Sources of these vibrations can include blasting, further excavation, roof collapse, fault slip, and other possible seismic events. It should be noted that the stress wave not only provides additional stresses but also induces vibrations in the rock mass. As a result, the second stress path 2 (SP2) is determined (Fig. 5), which relates to the sudden transition of energy from dynamic vibrations.

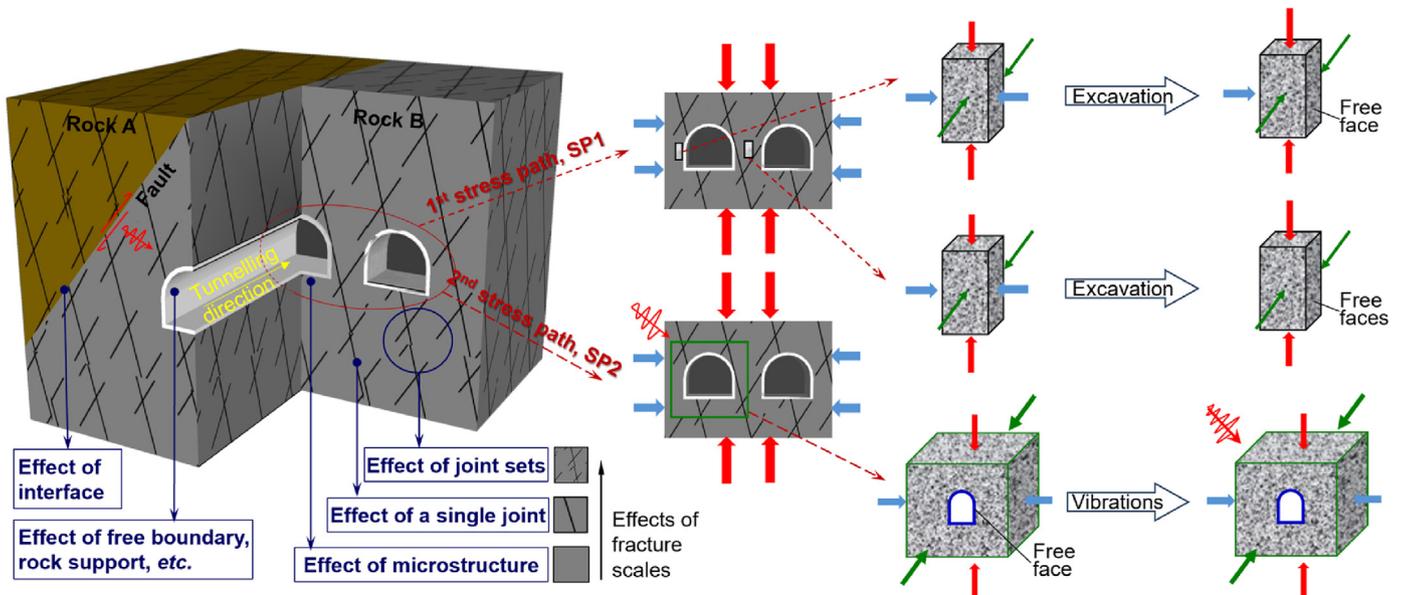


Fig. 5. Illustrations of two kinds of stress paths during the rockbursts

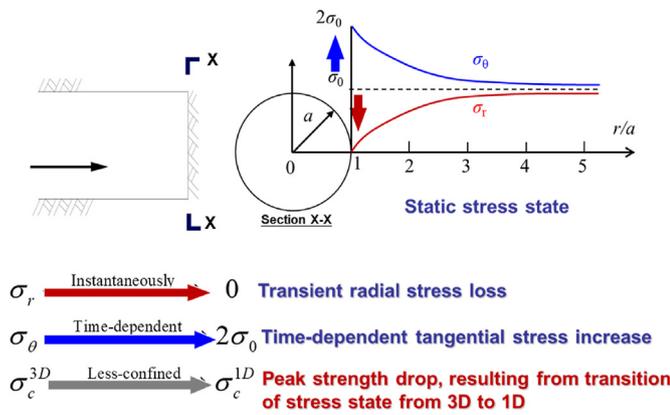


Fig. 6. Idealized illustration of the three effects of excavation

Fig. 6 presents a diametral section of a circular tunnel (of radius  $a$ ) in a hydrostatic stress field (of magnitude  $\sigma_0$ ). Right after excavation, the following mechanical perturbations are imposed in the rock medium. The radial stress is removed instantaneously, while the tangential stress is increasing progressively. The ideal stress concentration factor  $\sigma_\theta/\sigma_0$  at the boundary of the tunnel in elastic rock is 2, where  $\sigma_\theta$  and  $\sigma_0$  are the tangential stresses after and before excavation, respectively. The induced stresses acting through the excavation surface movements result in an increase in the strain energy stored locally in the rock under stress concentration. Moreover, the peak strength of the rock on the periphery of the excavation drops during the removal of the confining medium. The strength and deformation properties of rock must be reconsidered in the lower dimensional compression (i.e., dual- or single-dimension). These three effects of excavation, such as the transit radial stress loss, the time-dependent tangential stress increase, and the peak strength drop, are significant in assessing the rockburst potential. In the following, the three effects of excavation will be discussed in  $\tau$ - $\sigma$  and  $\sigma$ - $\epsilon$  spaces by analyzing the transitions of stress and energy fields, respectively.

### 3.2. Evolutions of energy/stress in loading paths

#### 3.2.1. Transitions of stress in the $\tau$ - $\sigma$ space

The Mohr circle and Mohr-Coulomb failure envelope are used to analyze the stress transition due to excavation in the  $\tau$ - $\sigma$  space. The initial stress state of rock mass, denoted as  $(\sigma_1, \sigma_2, \text{ and } \sigma_3)$ , is represented by half-circles shown by dark solid lines. In the deep rock mass, the initial stress is in equilibrium under a higher major principal stress (see Fig. 7a). However, the introduction of excavation, i.e. confinement loss, causes an energy imbalance in the rockmass, resulting in a transient stress state different from the static equilibrium stresses. Fig. 7a shows radial stress ( $\sigma_3$ ) drops to zero resulting in a new stress state denoted by the blue dashed line. This new stress state also violates the strength envelope of the rock indicating an instant rock failure or instantaneous rockburst. A relatively shallow depths, the initial stress is not high enough (see

Fig. 7b) to initiate a similar stress environment. Even after the excavation, the local static stress may not be sufficient to cause immediate stress failure. However, the stress concentration and superposition of the dynamic stresses may be sufficient to induce an adverse mechanical response in the medium (Fig. 7b). For example,  $\sigma_1$  may increase significantly within time due to stress concentration, leading to the new stress state exceeding the strength envelope of the rock (represented by the red dashed line in Fig. 7b), resulting in a delayed rockburst.

#### 3.2.2. Transitions of energy in $\sigma$ - $\epsilon$ space

Fig. 8 illustrates a simplified transition of energy due to excavation in the  $\sigma_1$ - $\epsilon_1$  space. It shows the stress-strain curve of the triaxial compressive strength ( $\sigma_{1,3D}$ ) test. Under the influence of confinement stresses in an enclosed rock mass environment, more strain energy will be accumulated in the rock. Once the excavation occurs, the excess strain energy, denoted by  $\Delta E$ , is readily released. The excess energy could be calculated as  $\Delta E = E' - E(\sigma_{c,1D})$ , where  $E'$  is the accumulated strain energy in the rock under triaxial stress state and  $E(\sigma_{c,1D})$  is the strain energy required for failure under uniaxial stress state.

For a non-dissipative system, the excess energy is assumed to be equal in magnitude to the released energy, ensuring energy conservation. As the strain energy accumulates in 3-dimensional compression is much larger than that of in 1-dimensional (i.e.,  $\Delta E > 0$ ), the stored energy will be transferred to the kinetic energy, leading to rock fragmentation and ejection. In some cases, the stored excess energy may not be high enough to induce violent failure. Instead, incremental accumulation of strain energy within time may occur in the areas of stress concentration that might cause rockbursts. The sudden reduction of strength occurs at the excavation surface due to confinement loss following little or no plastic deformation. Additional energy might be imposed on the stressed rock from the surrounding rock and seismic events from the far field. Assessing rock behavior under sudden changes of stress or energy from 3-dimensional to 1-dimensional compression in an excavation is crucial.

## 4. A new definition of rockburst in tunnel engineering

A rockburst is a sudden failure of rock mass surrounding the excavations caused by the rapid release of stored energy when induced stresses exceed the rock strength.

This definition contains three essential components.

- (1)**Excavation (Confinement loss):** The rockburst only occurs with and/or after the excavation in the surrounding rock. The three effects of excavations arise from the generation and displacement of the excavation surface due to the transition of the stress state from 3D to 1D, such as the transit radial stress loss, the time-dependent tangential stress increase, and the peak strength drop. This implies the locations for energy release for the potential rockburst.
- (2)**Abruptness:** Energy transmission is related to the manner of energy absorption in rock. The excess energy mobilized locally by a sudden reduction of surface forces may propagate to its surroundings

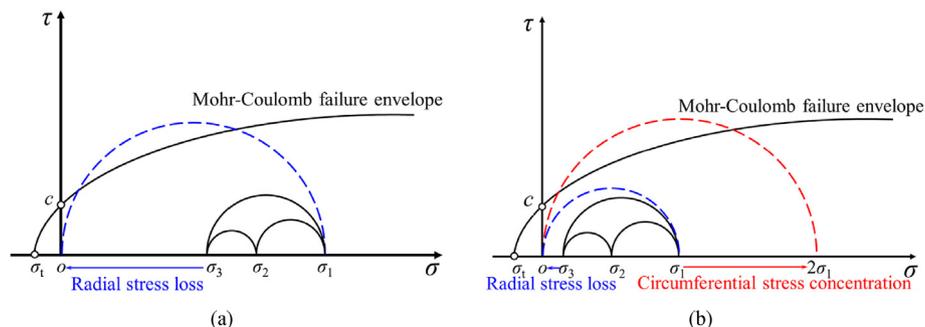


Fig. 7. Illustrations of stress transitions in cases of (a) instantaneous burst and (b) delayed burst in the  $\tau$ - $\sigma$  space under hydrostatic stress conditions

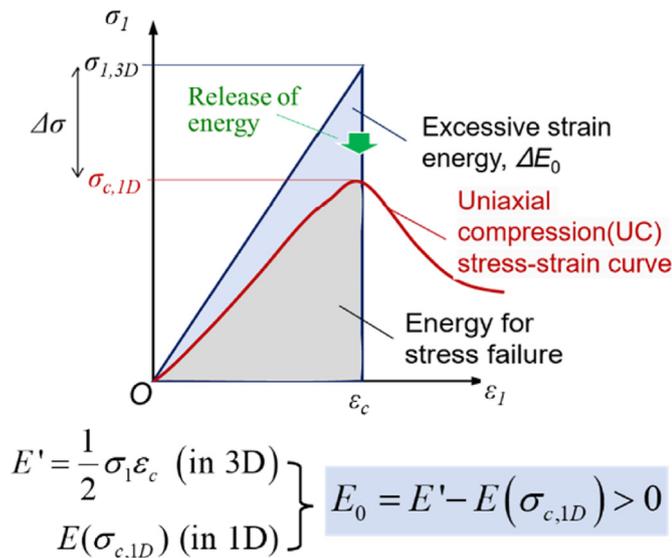


Fig. 8. Illustration of energy transition from 3D to 1D at excavation surface in the  $\sigma_1-\epsilon_1$  space (modified after He et al., 2014)

to establish local equilibrium. Remarkable developments in monitoring seismicity for the management of rockbursts have been carried out. It has been superseded by controlling the application of support. (3) **Overstressed rock:** The difference between transient stress from the equilibrium static stress is proportional to the volume increment of excavation, acting as the source of excess energy at the excavation periphery. The peak strength increases with increasing confining pressure in rock materials. However, the post-peak drop in stress reduces at a low value of confinement (i.e., radial stress becomes zero), leading to the transition from ductile to brittle behaviour. In this case, it is not always necessary to say that the rockburst commonly arise in areas characterized by high in-site stress and brittle and hard rock formation. That is the reason the phase of “induced stresses exceed the rock strength” is adopted.

Considering the timing of rockburst occurrence with respect to the excavation, a rockburst could be classified into two types: one related to transitions of stress in a static state and the other related to transitions of stress in a dynamic state (see Fig. 9). The rockburst related to static stress is primarily related to the transitions of energy of rock accumulated in strain energy during excavation. With the instantaneous drop of radial stress and progressive increase of tangential stress in the surrounding rock, a rockburst could be further classified as an instantaneous rockburst and delayed rockburst, respectively. The rockburst related to dynamic stress occurs when the excavation is fully completed where rock strength has been degraded due to excavation. Possible vibrations from the far-

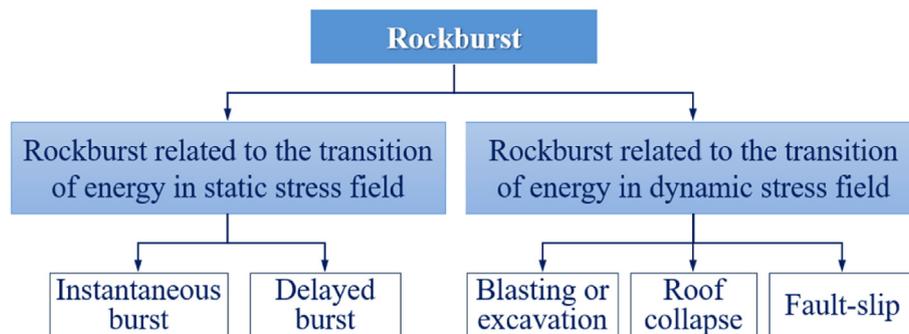


Fig. 9. A classification of rockburst based on the source of excess energy (modified after He et al., 2012a)

field provide excess energy, which can contribute to the violent energy released at the rockburst.

### 5. Potential management of rockburst

Considering the transitions of the stress field illustrated in Fig. 7, the following discussion addresses the compensatory approaches for the transient radial stress loss and the progressively tangential stress increments, referred to as compensatory approach 1 and compensatory approach 2, respectively. As shown in Fig. 10, compensatory approach 1 involves active support that imposes a predetermined load on the excavation surface prior to excavation. This approach can reduce the radial stress loss, thereby mitigating the potential for instantaneous bursts. Compensatory approach 2 involves passive support to sustain parts of the concentrated stress in the rock. Both approaches aim to reduce the difference between transient stress and equilibrium static stress.

Timely installation of supports is required for the above-mentioned compensatory approaches. Nevertheless, the reduction of peak strength due to the conversion from 3- to 1-dimensional compression should be carefully considered. A strength degradation curve (SDC) is proposed in the rock-support interaction diagram to understand the stiffness, the bearing capacity, and the time of installation of the support element on the rockburst control. As shown in Fig. 11a, the pre-excavation state of stress is assumed to be hydrostatic and of magnitude  $p_0$ . When the face is advanced, the support pressure is progressively reduced to zero due to the loss of confinement by the proximity of the face. The radial support pressure is required at a point to limit the boundary convergency after a certain time of relaxation. Traditionally, support could be installed close to the face. Interacting with the rock, it is assumed the support shows linear stress behavior. Equilibrium between the rock and the support could be achieved to restrict the displacement. At this time, the relative peak strength of the rock is significantly decreased as indicated by SDC. It means, that traditional support allows the yielding of rock first and provides support later.

For effective rockburst management, the support should provide essential pre-loadings at the very beginning, as indicated by compensatory

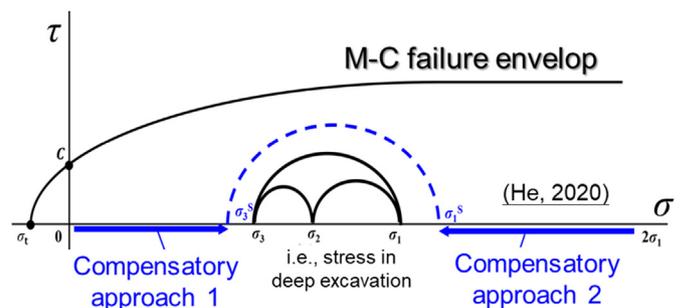


Fig. 10. Illustration of the compensatory approaches (modified after He, 2020)

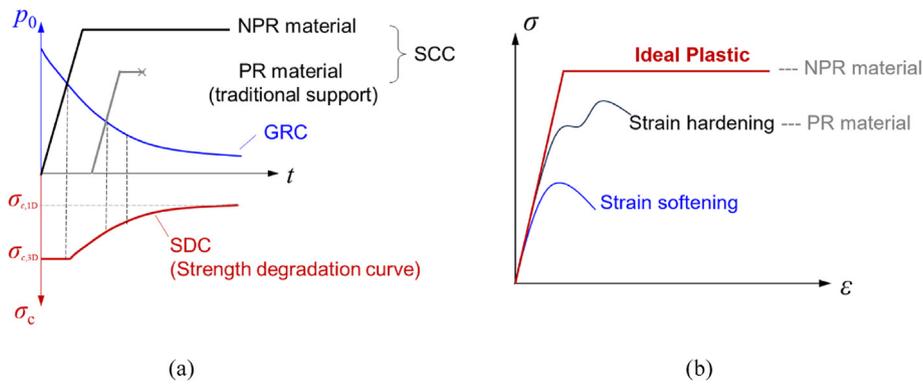


Fig. 11. Illustration of (a) the influences of support capacity and its installation time and (b) the mechanical behavior of NPR material

approach 1. Additionally, it should also have sufficient deformability to absorb energy caused by stress concentration. The rock-support interaction diagram is like that of traditional support, but the support provides loading at the very beginning when the mechanical properties of the rock at the periphery of excavation are not significantly degraded. With sufficient bearing capacity, equilibrium is achieved between the rock and support, with yielding occurring at a high support pressure. The large deformability of the ideal support allows the support to absorb excess energy from other resources. Therefore, support for rockburst management that behaves in an ideal elasto-plastic manner is preferred. A notable example of such support is made of NPR (negative Poisson's ratio) material developed by He et al. (2014). In contrast, the traditional support is termed as PR (positive Poisson's ratio) material. The mechanical behaviours of the NPR and PR materials are compared in Fig. 11b.

6. Conclusion

In this paper, more than 80 definitions of a rockburst in the literature during the past 80 years were reviewed in chronological order. The top three basic features defining a rockburst are summarized as (1) a sudden/violent energy release, (2) a seismic/dynamic event, and (3) an excavation that can be interpreted as confinement loss. All the phenomena are associated with the excavation.

The understanding of essences of excavation is discussed by analyzing the stress paths of a rockburst. Three effects of excavation are identified: the transit radial stress loss, the time-dependent tangential stress increase, and the peak strength drop. These three effects of excavation are explained in the shear stress vs normal stress space using Mohr circles, showing that a sudden transition of the stress state due to excavation leads to the violent release of excess energy.

Based on these three effects of excavation, a new definition of a rockburst is proposed, emphasizing the importance of "excavation", "abruptness", and "overstressed rock". Rockburst are further classified into those related to the transition of static stress and those related to the transition of dynamic stress. Corresponding compensatory approaches for rockburst management are discussed accordingly. The behavior of NPR (negative Poisson's ratio) material, which exhibits ideally elasto-plastic characteristics, is highlighted as beneficial for risk management.

CRediT authorship contribution statement

**Manchao He:** Supervision, Methodology, Investigation, Conceptualization. **Ismet Canbulat:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Fidelis T. Suorineni:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Murat Karakus:** Writing – review & editing, Supervision, Investigation. **Wen Nie:** Writing – original draft, Supervision, Investigation, Conceptualization. **Dongqiao Liu:** Writing – original draft, Methodology, Investigation, Data curation. **Chengguo Zhang:** Validation, Resources, Investigation, Data curation. **Alexey Nagibin:** Resources, Data curation. **Bauyrzhan Rustembek:** Resources, Data curation.

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. Manchao He is the Editor-in-Chief for Rock Mechanics Bulletin and was not involved in the editorial review or the decision to publish the article.



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## References

- Adoko, A.C., Gokceoglu, C., Wu, L., Zuo, Q.J., 2013. Knowledge-based and data-driven fuzzy modeling for rockburst prediction. *Int. J. Rock Mech. Min. Sci.* 61, 86–95.
- Akdag, S., Karakus, M., Taheri, A., Nguyen, G., He, M.C., 2018. Effects of thermal damage on strain burst mechanism for brittle rocks under true-triaxial loading conditions. *Rock Mech. Rock Eng.* 51 (6), 1657–1682.
- Askaripour, M., Saeidi, A., Rouleau, A., Mercier-Langevin, P., 2022. Rockburst in underground excavations: A review of mechanism, classification, and prediction methods. *Undergr. Space* 7 (4), 577–607. <https://doi.org/10.1016/j.undsp.2021.11.008>.
- Aydan, Ö., Geniş, M., Akagi, T., 2001. Assessment of susceptibility of rock bursting in tunnelling in hard rocks. In: Adachi, T., Tateyama, K., Kimura, M. (Eds.), *Modern Tunnelling Science and Technology*. Routledge, London.
- Bardet, J.P., 1989. Finite element analysis of rockburst as surface instability. *Comput. Geotech.* 8 (3), 177–193.
- Bennett, T.J., McLaughlin, K.L., 1997. *Seismic Characteristics and Mechanisms of Rockbursts for Use in Seismic Discrimination*. RaSiM4 Krakow, Poland, pp. 61–66.
- Blake, W., 1971. *Rock Burst Mechanics*. PhD Thesis. Colorado School of Mines, Golden, USA.
- Brady, B.H.G., Brown, E.T., 2006. *Rock Mechanics for Underground Mining*. Springer, The Netherlands.
- Cai, M., 2013. Principles of rock support in burst-prone ground. *Tunn. Undergr. Sp. Tech.* 36, 46–56.
- Cai, M.F., 2016. Prediction and prevention of rockburst in metal mines—A case study of Sanshandao gold mine. *J. Rock Mech. Geotech. Eng.* 8 (2), 204–211.
- Cai, M., Kaiser, P.K., 2018. *Rockburst support reference book, Volume 1: rockburst phenomenon and support characteristics*. MIRARCO – Mining Innovation. Laurentian University, Sudbury, Ontario, Canada.
- Chen, Z.J., 1987. Engineering realities, theory and control of rockbursts. *J. Rock Mech. Geotech. Eng.* 1, 1–18. (in Chinese).
- Chen, B.R., Feng, X.T., Ming, H.J., Zhou, H., Zeng, X.H., Feng, G.L., Xiao, Y.X., 2012. Evolution law and mechanism of rockburst in deep tunnel: time delayed rockburst. *Chin. J. Rock Mech. Eng.* 31, 561–569 (in Chinese).
- Chen, B.R., Feng, X.T., Li, Q.P., Luo, R.Z., Li, S., 2015. Rock burst intensity classification based on the radiated energy with damage intensity at Jinping II hydropower station. *Chin. J. Rock Mech. Eng.* 48, 289–303.
- Chen, G.Q., He, M.C., Fan, F.S., 2018. Rock burst analysis using DDA numerical simulation. *Int. J. GeoMech.* 18 (3), 04018001. [https://doi.org/10.1061/\(ASCE\)GM.1943-5622.0001055](https://doi.org/10.1061/(ASCE)GM.1943-5622.0001055).
- Cook, N.G.W., 1965. A note on rockburst considered as a problem of stability. *J. S. Afr. Inst. Min. Metall.* 65 (8), 437–446.
- Curtis, J.F., 1981. Rockburst phenomena in the gold mines of Witwatersrand: a review. *Trans. Inst. Min. Metall.* 90, 163–176.
- Dietz, M., Oremek, G.M., Gronenberg, D.A., Bendels, M.H.K., 2018. What is a rock burst? *Zentralbl. Arbeitsmed. Arbeitsschutz Ergon.* 68 (1), 45–49.
- Duan, W.S., Tang, C.A., Zhang, S.C., Tang, L.X., Ma, T.H., Gong, B., Wang, Y.C., Xie, P., 2024. Formation mechanism of micro-seismicity difference between rockbursts in deep-seated parallel tunnels. *Eng. Geol.* 335, 107544.
- Farhadian, H., 2021. A new empirical chart for rockburst analysis in tunnelling: tunnel rockburst classification (TRC). *Int. J. Min. Sci. Technol.* 31 (4), 603–610.
- Feng, X.T., 2017. *Rockburst: Mechanism, Monitoring, Warning, and Mitigation*. Elsevier-Health Sciences Division, Oxford, UK.
- Feng, X., Chen, B., Li, S., Zhang, C., Xiao, Y., Feng, G., Zhou, H., Qiu, S., Zhao, Z., Yu, Y., Chen, D., Ming, H., 2012a. Studies on the evolution process of rockbursts in deep tunnels. *J. Rock Mech. Geotech. Eng.* 4, 289–295. <https://doi.org/10.3724/SP.J.1235.2012.00289>.
- Feng, X.T., Chen, B.R., Ming, H.J., Wu, S.Y., Xiao, Y.X., Feng, G.L., Zhou, H., Qiu, S.L., 2012b. Evolution law and mechanism of rockbursts in deep tunnels: immediate rockburst. *Chin. J. Rock Mech. Eng.* 31, 434–444 (in Chinese).
- Feng, G.L., Feng, X.T., Chen, B.R., Xiao, Y.X., 2015. Microseismic sequences associated with rockbursts in the tunnels of the Jinping II hydropower station. *Int. J. Rock Mech. Min. Sci.* 80, 89–100.
- Feng, X.T., Xiao, Y.X., Feng, G.L., Yao, Z.B., Chen, B.R., Yang, C.X., Su, G.S., 2019. Study on the development process of rockbursts. *Chin. J. Rock Mech. Eng.* 38, 649–673 (in Chinese).
- Gill, D.E., Aubertin, M., Simon, R., 1993. A practical engineering approach to the evaluation of rockburst potential. In: Young (Ed.), *Proceedings of the 3rd International Symposium on Rockbursts and Seismicity in Mines*. A.A. Balkema, Rotterdam, Netherlands. Rotterdam, pp. 63–68.
- Gong, Q.M., Yin, L.J., Wu, S.Y., Zhao, J., Ting, Y., 2012. Rock burst and slabbing failure and its influence on TBM excavation at headrace tunnels in Jinping II hydropower station. *Eng. Geol.* 124 (4), 98–108.
- Gong, F.Q., Dai, J.H., Xu, L., 2023. A strength-stress coupling criterion for rockburst: inspirations from 1114 rockburst cases in 197 underground rock projects. *Tunn. Undergr. Sp. Tech.* 142, 105396.
- He, M.C., 2020. *Rockburst Mechanism—The Experimental Investigation*. Science Press, Beijing.
- He, M.C., Cheng, T., Qiao, Y.F., Li, H.R., 2023. A review of rockburst: experiments, theories, and simulations. *J. Rock Mech. Geotech. Eng.* 15 (5), 1312–1353. <https://doi.org/10.1016/j.jrmge.2022.07.014>.
- He, M.C., Gong, W.L., Wang, J., Qi, P., Tao, Z.G., Du, S., Peng, Y.Y., 2014. Development of a novel energy-absorbing bolt with extraordinarily large elongation and constant resistance. *Int. J. Rock Mech. Min. Sci.* 67, 29–42.
- He, M.C., Miao, J.L., Feng, J.L., 2010. Rockburst process of limestone and its acoustic emission characteristics under true-triaxial unloading conditions. *Int. J. Rock Mech. Min. Sci.* 47 (2), 286–298.
- He, M.C., Nie, W., Zhao, Z.Y., Guo, W., 2012b. Experimental investigation of bedding plane orientation on the rockburst behavior of sandstone. *Rock Mech. Rock Eng.* 45, 311–326. <https://doi.org/10.1007/s00603-011-0213-y>.
- He, M.C., Xia, H., Jia, X., Gong, W., Zhao, F., Liang, K., 2012a. Studies on classification, criteria and control of rockbursts. *J. Rock Mech. Geotech. Eng.* 4, 97–114. <https://doi.org/10.3724/SP.J.1235.2012.00097>.
- He, M.C., Xia, H.M., Jia, X.N., Gong, W.L., Zhao, F., Liang, K.Y., 2012c. Studies on classification, criteria and control of rockbursts. *J. Rock Mech. Geotech. Eng.* 4 (2), 97e114.
- He, M.C., Xie, H.P., Peng, S.P., Jiang, Y.D., 2005. Study on rock mechanics in deep mining engineering. *Chin. J. Rock Mech. Eng.* 24 (16), 2803.
- Hedley, D.G.F., 1992. *Rockburst Handbook for Ontario Hardrock Mines*. Communication Group, Ottawa, Canada. CANMET Special Report SP92-1E.
- Heunis, P., 1980. The development of rock-burst control strategies for South-African-gold mines. *J. S. Afr. Inst. Min. Metall.* 80 (4), 139–150.
- Hirata, A., Kameoka, Y., Hirano, T., 2007. Safety management based on detection of possible rock bursts by A.E. monitoring during tunnel excavation. *Rock Mech. Rock Eng.* 40 (6), 563–576.
- Hoek, E., Kaiser, P.K., Bawden, W.F., 1995. *Support of Underground Excavations in Hard Rock*. A.A. Balkema Publishers, Rotterdam, Netherlands.
- Hu, X.C., Su, G.S., Chen, G.Y., Mei, S.M., Feng, X.T., Mei, G.X., Huang, X.H., 2019. Experiment on rockburst process of borehole and its acoustic emission characteristics. *Rock Mech. Rock Eng.* 52 (3), 783–802.
- Jiang, Q., Feng, X.T., Xiang, T.B., Su, G.S., 2010. Rockburst characteristics and numerical simulation based on a new energy index: a case study of a tunnel at 2500 m depth. *Bull. Eng. Geol. Environ.* 69 (3), 381–388.
- Kaiser, P.K., Cai, M., 2012. Design of rock support system under rockburst condition. *J. Rock Mech. Geotech. Eng.* 4 (3), 215e227.
- Kaiser, P.K., Tannant, D.D., McCreath, D.R., 1996. *Canadian Rockburst Support Handbook*. Geomechanics Research Centre. Laurentian University, Sudbury, Ontario, p. 314.
- Keneti, A., Sainsbury, B.A., 2018. Review of published rockburst events and their contributing factors. *Eng. Geol.* 246, 361–373.
- Larocque, G., 1980. *Review of Rockburst Phenomena*. Canada Centre for Mineral and Energy Technology, Canmet, Mining Research Lab., Report ERP-MRL, pp. 80–94.
- Larsson, K., 2004. *Mining Induced Seismicity in Sweden*. Luleå University of Technology, Luleå. Master's Thesis.
- Lenhardt, W.A., 1992. Seismicity associated with deep level mining at western deep levels limited. *J. S. Afr. Inst. Min. Metall.* 92 (5), 113–120.
- Li, C.C., 2021. Principles and methods of rock support for rockburst control. *J. Rock Mech. Geotech. Eng.* 13, 46–59.
- Li, S.L., Feng, X.T., 1998. Multi-indicator adaptive modeling of rockburst susceptibility in deep hard rock. *Min. Res. Dev.* 6, 3–5 (in Chinese).
- Li, T., Ma, C., Zhu, M., Meng, L., Chen, G., 2017. Geomechanical types and mechanical analyses of rockbursts. *Eng. Geol.* 222, 72–83.
- Li, C.C., Zhao, T., Zhang, Y., Wan, W., 2022. A study on the energy sources and the role of the surrounding rock mass in strain burst. *Int. J. Rock Mech. Min. Sci.* 154, 105114.
- Lippmann, H., 1978. The mechanics of translatory rock bursting. *Advances in Analysis of Geotechnical Instabilities* 13, 25–63. Univ. Waterloo, S.M. Study No.
- Luo, Y.L., 1975. *The reality and general treatment of rock explosion phenomenon in tunnel construction*. Railroad Standard Design Newsletter 3, 8+17 (in Chinese).
- Luo, S., Gong, F., Peng, K., Liu, Z., 2023. Influence of water on rockburst proneness of sandstone: insights from relative and absolute energy storage. *Eng. Geol.* 323, 107172.
- Maleki, H.N., 1995. *Proceedings: Mechanics and Mitigation of Violent Failure in Coal and Hard-Rock Mines*. Bureau of Mines, United States.
- Manouchérian, A., Cai, M., 2017. Analysis of rockburst in tunnels subjected to static and dynamic loads. *J. Rock Mech. Geotech. Eng.* 9, 1031–1040.
- Mazaira, A., Konicek, P., 2015. Intense rockburst impacts in deep underground construction and their prevention. *Can. Geotech. J.* 52 (10), 1426–1439.
- Mine Safety and Health Administration, 1984. *Hearing on Proposed Standards for Ground Control Metal/Nonmetal Mines*. Spokane, WA, June 19.
- Mitri, H.S., Tang, B., Simon, R., 1999. FE modelling of mining-induced energy release and storage rates. *J. S. Afr. Inst. Min. Metall.* 99 (2), 103–110.
- Muller, W., 1991. Numerical simulation of rock bursts. *Min. Sci. Technol.* 12 (1), 27–42.
- Nussbaumer, M.M., 2000. *A Comprehensive Review on Rock Burst*. Massachusetts Institute of Technology, Master Thesis.
- Obert, L., Duvall, W.I., 1967. *Rock Mechanics and Design of Structures in Rock*. Wiley, New York.
- Ontario Ministry of Labour, 1983. *Occupational health and safety act and regulations for mines and mining plants*. Reg 694 (34a), 48.
- Ortlepp, W.D., 1997. *Rock Fracture and Rockbursts, an Illustrative Study*. Johannesburg.

- Ortlepp, W.D., 2005. RaSiM comes of age—a review of the contribution to the understanding and control of mine rockbursts. In: Potvin, Y., Hudyma, M. (Eds.), *RaSiM6: Proceedings of the Sixth International Symposium on Rockburst and Seismicity in Mines Proceedings*, Australian Centre for Geomechanics, Perth, pp. 3–20.
- Ortlepp, W.D., Stacey, T.R., 1994. Rockburst mechanisms in tunnels and shafts. *Tunn. Undergr. Sp. Tech.* 9, 59–65. [https://doi.org/10.1016/0886-7798\(94\)90010-8](https://doi.org/10.1016/0886-7798(94)90010-8).
- Österreichische Gesellschaft für Geomechanik, 2001. Richtlinie für Geomechanische Planung von Untertagebauarbeiten mit Zyklischem Vortrieb. Salzburg.
- Pan, B.T., 1979. Effect of initial stress in rock mass on engineering construction. *Exploration Technology* 5, 65–69 (in Chinese).
- Pan, Y.S., Zhang, M.T., Li, G.Z., 1994. Sharp-angle type mutation modeling of cave rockbursts. *Appl. Math. Mech.* 10, 893–900 (in Chinese).
- Qian, Q., Zhou, X., 2011. Quantitative analysis of rockburst for surrounding rocks and zonal disintegration mechanism in deep tunnels. *J. Rock Mech. Geotech. Eng.* 3, 1–9.
- Russenes, B.F., 1974. Analysis of Rock Spalling for Tunnels in Steep Valley Sides (in Norwegian). Master's Thesis, Norwegian Institute of Technology, Department of Geology, Norway, 247.
- Scott, D.F., Williams, T.J., Friedel, M.J., 1997. Investigation of a rockburst site. *RaSiM4 Krakow, Poland. Sunshine Mine, Kellogg, Idaho* 311–315.
- Sharan, S.K., 2007. A finite element perturbation method for the prediction of rockburst. *Comput. Struct.* 85, 17–18.
- Si, X.F., Gong, F.Q., 2020. Strength-weakening effect and shear-tension failure mode transformation mechanism of rockburst for fine-grained granite under triaxial unloading compression. *Int. J. Rock Mech. Min. Sci.* 131, 104347.
- Singh, S.P., 1988. Burst energy release index. *Rock Mech. Rock Eng.* 21 (2), 149–155.
- Singh, B., Goel, R.K., 1999. *Rock Mass Classification: A Practical Approach in Civil Engineering*. Elsevier Publisher, Amsterdam, pp. 48–50.
- Su, G.S., Jiang, J.Q., Zhai, S.B., Zhang, G.L., 2017. Influence of tunnel axis stress on strainburst: an experimental study. *Rock Mech. Rock Eng.* 50 (6), 1551–1567.
- Sun, J., 1996. Some progress in rock mechanics. In: *Rock Mechanics and Engineering for the 21st Century: Proceedings of the Fourth Academic Conference of the Chinese Society of Rock Mechanics and Engineering*, vol. 22. (in Chinese).
- Tan, Y.A., 1991. Characteristics of rockbursts and structural effects on rock masses. *Chin. Sci.: Series B* 9, 985–991 (in Chinese).
- Tang, C.A., 2011. Research on the mechanism of rockburst disaster and its early warning method in deep underground engineering. Chinese society of rock mechanics and engineering, Institute of mining of Siberian branch of Russian academy of sciences, Liaoning University of Engineering and Technology, People's Liberation Army University of Science and Technology, China. In: *Proceedings of the First Sino-Russian High-Level Forum on Rock Dynamics in Deep Mining*, vol. 8. Northeastern University (in Chinese).
- Tang, L.Z., Pan, C.L., Wang, W.X., 2002. Residual energy index for analyzing the tendency of rock explosion. *J. Cent. S. Univ. Technol.* 2, 129–132 (in Chinese).
- Tang, L.Z., Pan, C.L., Wang, W.X., 2002b. Surplus energy index for analysing rockburst proneness. *J. Cent. S. Univ.* 33 (2), 129–132 (in Chinese).
- Terzaghi, K., 1946. *Introduction to tunnel geology. Rock tunneling with steel supports* 17–99.
- U.S. Bureau of Mines, 1968. In: Thrush, P.W. (Ed.), *A Dictionary of Mining, Mineral, and Related Terms*. U.S. Bureau of Mines, Beijing, p. 932.
- Van Der Merwe, N., Madden, B.J., 2002. *Rock Engineering for underground coal mining*. J. S. Afr. Inst. Min. Metall. 7 (SP7). Special publications.
- Vardoulakis, I., 1984. Rock bursting as a surface instability phenomenon. *Int. J. Rock Mech. Min. Sci.* 21 (3), 137–144.
- Wang, S.Y., Lam, K.C., Au, S.K., Tang, C.A., Zhu, W.C., Yang, T.H., 2006. Analytical and numerical study on the pillar rockbursts mechanism. *Rock Mech. Rock Eng.* 39 (5), 445–467.
- Wang, Y.H., Chen, L.W., Shen, F., 2008. Numerical simulation of energy release during rock burst damage. *Geotechnical Mechanics* 3, 790–794 (in Chinese).
- Wang, J., Chen, J., Yang, J., Que, J., 2009. Distance discriminant analysis method and application for rockburst grade determination. *Geotechnics* 30 (7), 2203–2208 (in Chinese).
- Wei, C.C., Zhang, C.G., Canbulat, I., Song, Z.Y., Dai, L.P., 2022. A review of investigations on ground support requirements in coal burst-prone mines. *Int. J. Coal Sci. Technol.* 9 (1), 13.
- Zhang, C., Canbulat, I., Tahmasebinia, F., Hebblewhite, B., 2017. Assessment of energy release mechanisms contributing to coal burst. *Int. J. Min. Sci. Technol.* 27, 43–47.
- Zhao, X.G., Wang, J., Cai, M., Cheng, C., Ma, L.K., Su, R., Zhao, F., Li, D.J., 2014. Influence of unloading rate on the strainburst characteristics of beishan granite under true-triaxial unloading conditions. *Rock Mech. Rock Eng.* 47 (2), 467–483.
- Zhou, Q.C., Li, H.B., Yang, C.H., 2003. A review of rockbursts and their risk assessment in underground engineering. *Geotechnics* S2, 669–673 (in Chinese).
- Zhou, X.P., Qian, Q.H., Yang, H.Q., 2011. Rock burst of deep circular tunnels surrounded by weakened rock mass with cracks. *Theor. Appl. Fract. Mech.* 56 (2), 79–88.
- Zhou, J., Li, X.B., Mitri, H.S., 2018. Evaluation method of rock-burst: state-of-the-art literature review. *Tunn. Undergr. Sp. Tech.* 81, 632–659.
- Zhou, J., Zhang, Y.L., Li, C.Q., He, H.N., Li, X.B., 2024. Rockburst prediction and prevention in underground space excavation. *Undergr. Space* 14, 70–98.
- Zhu, B.Y., 1982. Rockburst phenomenon and its treatment. *Coal Sci. Technol.* 11, 35 (in Chinese).
- Zou, C.J., 1990. Overview of the engineering geology of Tianshengqiao second-stage hydropower station. *Water conservancy and hydropower technology* 3, 24–31 (in Chinese).
- Zubelewicz, A., Mroz, Z., 1983. Numerical-simulation of rock burst processes treated as problems of dynamic instability. *Rock Mech. Rock Eng.* 16 (4), 253–274.