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Systematic review of georisk in underground hard rock mines

Master's Thesis

Espoo, 26.08.2016

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Title of thesis Systematic review of georisk in underground hard rock mines		
Degree program European Mining, Minerals and Environmental Program		
Major/minor European Mining Course	Code R3008	
Thesis supervisor Prof. Mikael Rinne		
Thesis advisor(s) M.Sc. Lauri Uotinen		
Date 26.08.2016	Number of pages 94+20	Language English

Abstract

Deep mining, driven by the increasing need of the sustainable use of mineral resources yields a possibility to fully extract the untapped deposits. Nevertheless, large depths remain challenging and complex environment. Rockbursts and induced seismicity, considered as georisks, are one of the most relevant risks identified in the field, which threat both safety and economics. Risk management tools and guidelines are essential to maintain safe and economically feasible extraction, but they still need improvements. One such opportunity identified here is the development of on-line georisk management systems, and going even further, a creation of a risk management concept covering the entire mine. This master's thesis is a part of the On-line Risk Management in Deep Mines (ORMID) project, funded by the Academy of Finland, running under the Mineral Resources and Material Substitution programme.

Systematic review of the literature was conducted to enable addressing the thesis goals: identification of the gaps in research concerning on-line georisk management in underground hard rock mines, establishment of the state-of-the-art of the developments in that topic, and providing recommendations for future research. Three databases were used for the search: Scopus, ScienceDirect, and IEEEExplore. To search the databases 12 keywords and phrases were formulated. The search was conducted in three phases: out of 13 767 studies identified, 98 were taken into manual investigation, and 50 of them were finally included in this master's thesis.

The gap identified in this study is the lack of research that examines the methods of rockmass stress calculation and forecasting based on the strain measurements. Only two examples of them were obtained in the study. Another issue that comes out is a need of deeper understanding of rockburst phenomenon. Moreover, a very low number of systems capable of on-line georisk management was identified. Dynamic Intelligent Ground Monitoring (Digmine), Mine Seismicity Risk Analysis Program (MS-RAP) and one standard architecture (AziSA) of the on-line georisk management were recognized as the state-of-the-art. To manage the georisks the state-of-the-art method represents an immediate rockburst warning method based on microseismicity analysis, already utilised in Digmine. BurstSupport software aiming to assist the geotechnical engineers in evaluating different rockburst support options in a burst-prone ground was considered as the state-of-the-art georisk mitigation method identified in the study. Identification of these developments resulted from rigorous inclusion and exclusion criteria, selected keywords and databases. Different choice of these would yield dissimilar results, what indicates that not all of the research about the topic of interest was identified. Recommendations and a roadmap addressing upcoming assignments in the ORMID project are presented in this thesis.

Keywords: deep mining, risk management, geotechnical risk, rockburst, strainburst, mining-induced seismicity, geotechnical hazard, systematic review

Foreword

I would like to express my gratitude to all of the people directly and indirectly involved in writing this thesis. First of all, I would like to thank my supervisor Prof. Mikael Rinne for his support and valuable suggestions at all stages of writing this project.

I want to thank my instructor Lauri Uotinen for his continuous guidance, stimulating discussions, encouragement and endless enthusiasm throughout the whole process of this study. Without your effort completion of this thesis would not have been possible.

Of course I owe big thanks to all of my co-workers from the CORE at Aalto University for making the atmosphere enjoyable, being helpful, and of course thanks for all the coffee breaks and lunches spent together.

I would like also to acknowledge the funding provided for this research by the Academy of Finland under Grant no. 297770 and the European Commission's 7th Framework Programme under Grant No. 280855.

Last but not least, I want to thank my parents for supporting me mentally throughout my whole life, and my loved ones for making it better.

Espoo, 26.08.2016

Martyna Szydłowska

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1 Introduction

Deep mining, driven by the increasing need of the sustainable use of mineral resources yields a chance to fully extract the untapped deposits. Nevertheless, large depths remain challenging and complex environment. Massive extraction induces stresses generating seismic events around the mine workings and associated with them rockbursts (Kaiser, 2012).

A rockburst, always linked with a seismic event, is defined as a sudden and violent damage to an excavation (Hedley, 1992). It remains the main obstacle to the mining operation, causing fatalities, losses of equipment and losses in production. Georisks, defined in this thesis as rockbursts and mining-induced seismicity, are ones of the most relevant risks identified in the field, which threat both safety and economics (Wagner, 1982; Brady, 1990; Young, 1997; Ortlepp, 2005; Hejny, 2015).

Despite considerable upgrades in technology, rockbursts remain severe and not fully understood problem facing mining activities (Gibowicz and Kijko, 1994; Durrheim *et al.*, 2010). They have been a serious concern in deep underground gold mines in South Africa for over than 100 years (Ortlepp, 1997). Also in Australia, Canada, India and some European countries mining-induced seismicity appeared to be a major issue more recently (Hudyma, 2008). In fact, a no-hazard environment, no matter underground or above ground, does not exist in reality, and an incident can happen at any stage of any project. That is why an understanding of causes of seismicity and rockbursting, and comprehensive risk management are the core elements in any mining venture (Hudyma, 2008).

Risk management tools and guidelines are essential to maintain safe and economically feasible extraction, but they still need improvements. One opportunity identified here is development of on-line georisk management systems, and going even further, a creation of the risk management concept covering the entire mine.

Durrheim *et al.* (2007) made a statement that the forecasting of rockbursts might be improved through real-time integration of seismic and rock deformation data. Systems capable of processing its massive amounts, extracting the key elements out of it and therefore creating the patterns of, for instance, rock mass behaviour could significantly support the decision-making processes. Having an on-line access to the crucial points in a mine would enable a full control of the operations without putting at risk any human being and considerably decreasing the possibility of damage to the equipment. As the methodology and experience of an individual is obviously limited, the need for this kind of decision support system for the professionals in a mine has been noticed already years ago, and mentioned several times throughout the literature (Mendecki, 1993; Gibowicz and Kijko, 1994; Durrheim *et al.*, 2007). Employment of abovementioned concept would undoubtedly contribute to the creation of safe, efficient and environmentally sound mine.

In recent years, a series of activities aiming at the development of an invisible, zero impact, deep mine started with the Innovative Technologies and Concepts for the Intelligent Deep Mine of the Future (I²Mine) project funded by the European Commission 7th Framework Programme. The research concentrated on the development of novel methods, technologies and concepts enabling to perform safe operations with low impact underground and zero impact above ground and ended with the promising results.

Work package 3 of the I²Mine focused on the development of new approaches in rock mechanics and ground control to prevent geotechnical related accidents and potential losses in deep mines of the future. The outcomes which are of particular interest for the thesis are methods and concepts of systems capable of on-line risk management in hard rock underground mines of the future. The state-of-the-art of these is presented in the thesis.

The I²Mine project triggered a new initiative aiming to expand the research on utilization of the real-time data in georisk management in deep underground mines which is the On-line Risk Management in Deep Mines (ORMID) project. That research, funded by the Academy of Finland, runs under the Mineral Resources and Material Substitution programme. It is conducted by the Geoengineering research group at Aalto University. This master's thesis is a part of the Work Package 1 of the ORMID project.

The ORMID project aims to advance an understanding of the development of the excavation damage zone and around the mining excavations. This knowledge will be then used to mitigate the geotechnical risks in deep mining resulting in prevention of the loss of life and loss of equipment. Another goal of the ORMID project is promotion and upgrade in the development of suitable research instruments capable of on-line monitoring (Rinne and McKinnon, 2016).

Research in the ORMID is divided into three work packages. The first work package aims to develop a theoretical basis for the formation of the damage zone ahead and around of mining excavations to support geotechnical risk mitigation. The research continues in the second work package with the development of on-line monitoring equipment to predict the strain and stress state evolution. In the third stage of the project, the improved instrumentation capable of on-line monitoring is planned to be installed in a selected mine so that the theory will be applied in practice. The results will then be analysed and the methods verified, enabling an on-line monitoring based geotechnical risk mitigation methodology to be fully developed.

1.1 Objectives

The primary goal of the thesis is to identify gaps in research concerning on-line georisk management in deep underground mines. Another goal is to provide a state-of-the-art on the abovementioned topic. The aim of the thesis is also to give recommendations and guidelines on the further research to be done with regard to the on-line georisk management in underground hard rock mines and address the upcoming assignments in the ORMID project.

The research questions associated with the goals are:

- What is the state-of-the-art of geotechnical on-line risk management in underground hard rock mines?
- What are the missing pieces of knowledge identified in this field which should be taken into consideration for further research and development?
- What can be done to improve the existing methods and concepts of geotechnical risk management?

The updated knowledge will be made available for utilization in research projects involving the development of the geotechnical risk management in underground mines by providing the collection of the available methods introduced by their sources and results.

1.2 Methodology

A method chosen for this master's thesis is a systematic review of the literature. Due to the fact that this method is not used for reviewing the studies in the fields of engineering, except its application in software engineering, an adaptation is proposed for the purpose of this master's thesis. Its aim is to identify and synthesize the findings of existing research concerning geotechnical on-line risk management in underground hard rock mines. Both the theoretical description of the method and its adaptation are presented.

1.3 Structure

The thesis is divided into nine chapters:

Chapter 2: The theoretical background concerning the georisks in underground mines: mining-induced seismicity and rockbursts problem in the underground hard rock mines

Chapter 3: Approaches to georisk management in underground mines used nowadays

Chapter 4: Presentation of the studies preceding the ORMID project. The main findings from the I2Mine project and the development and application of the Dynamine algorithm

Chapter 5: Systematic review of the literature - description and its adaptation for the purpose of the thesis

Chapter 6: Results – quantitative analysis of the results and description of systems, management approaches, assessment techniques, and methods of forecasting and managing georisk

Chapter 7: Discussion of both the research methodology and the results obtained in the study

Chapter 8: Conclusions

Chapter 9: Recommendations for future research and the roadmap for the ORMID project

2 Georisks in underground mines

2.1 Georisks in mining

In 2008 a survey “International Mining Fatality Database” conducted by McNeill was published by the NSW Department of Primary Industries. It contains data about over 2800 incidents and 13800 fatalities in mines around the world. The data covers mainly Australian mines but also contains records from 15 other countries (New Zealand, United Kingdom, USA, Canada, China, France, Germany, India, Japan, Poland, Russia, South Africa, Ukraine, and Zimbabwe). The survey reports on both underground and open pit mining, and hard rock as well as coal mining, but remains a good overview on the causes of fatalities in the mines around the world. McNeill reports, that “fall of roof/sides/highwall” which corresponds to the georisks in this Master’s thesis, was a cause of almost 25% of the overall number of fatalities in the period 1980 – 2008 (see Figure 1). Despite considerable upgrades in technology throughout these years, rockbursts remain severe and not fully understood problem facing mining activities also nowadays (Gibowicz and Kijko, 1994; Durrheim *et al.*, 2010). The high share of georisks in causes of fatalities marks the need of developing their better understanding and a comprehensive risk management to prevent loss of life and ensure safe working environment.

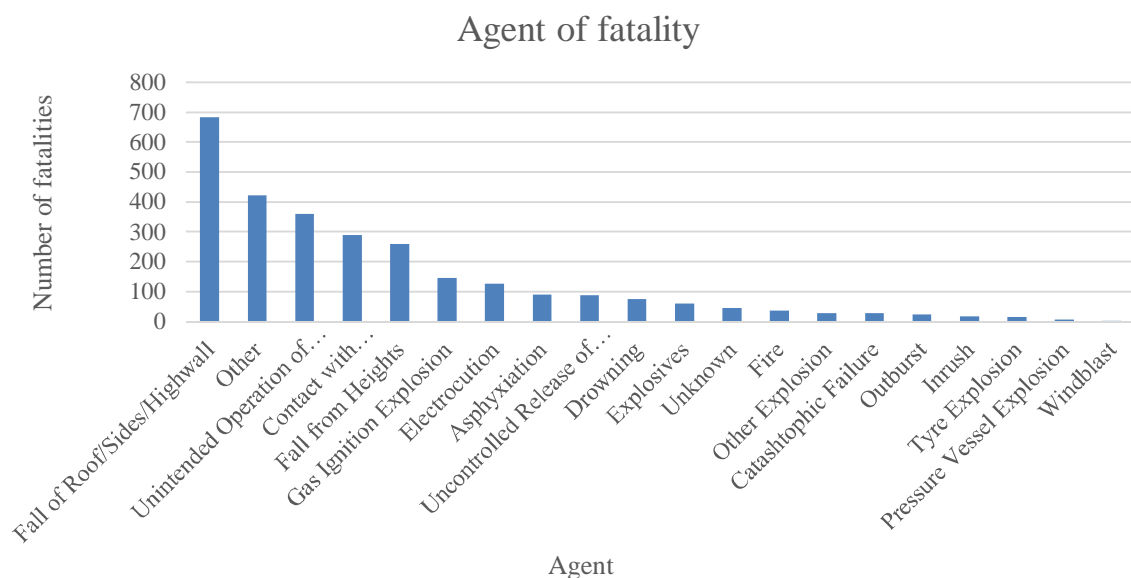


Figure 1. Graphical representation of root causes of incidents in mining industry for years 1980 – 2008 (data covers 16 countries) (McNeill, 2008)

2.2 Seismicity and rockbursting in underground mines

Mining-induced seismicity is defined as the occurrence of earthquakes caused by rock failures, a result of stress changes in the rock mass near mining excavations. Increases in the shear stress or decreases in the normal stress acting on the fault planes commonly cause mining-induced events. It means that the mining-induced seismic events can be generated in places where the ambient stress has been modified significantly by mine excavations (Gibowicz, 2009).

Seismic events that can generate rockmass failure mechanisms are numerous. The interaction between the geomechanical factors such as discrete geological structures, rockmass properties, mining-induced stress environment and used mining practices differentiates a seismic response at each mine. Hudyma (2008) pointed out some of the most crucial factors influencing mining-induced seismicity:

- Mine blasting practices,
- Excavation size and shape,
- Extraction sequence,
- The use of temporary and permanent mine pillars, and
- The type and timing of mine fill.

Rockbursting and seismicity have been found to be a major problem threatening mining industry for years (Hudyma, 2008). Ortlepp (1997) reports, that in South African gold mines it has remained a severe issue for almost a century. The results of a survey conducted by Hudyma (2004) on the seismicity in mines, where 73 mines in 11 countries have been examined, showed that the seismicity, mostly mining induced, occurred in a variety of hard rock mines and for all mining methods.

2.3 Seismic event

A seismic event is defined as a dynamic stress wave caused by inelastic deformation in a rockmass and in general is accepted as an inevitable component of the underground environment (Hudyma, 2008). Seismic events, or in other words mine tremors, are not exclusively associated with underground, hard rock mining, although high stresses make a brittle, hard rock particularly prone to them (Young *et al.*, 1992; Hudyma, 2008). However, almost any environment which might be characterized by inelastic rockmass deformation (coal and soft rock mines, underground civil excavations) hosted seismic events.

Durrheim *et al.* (2006) proposed a distinction between types of seismic events:

- Natural earthquake: Event where human activity (e.g. mining or flooding of mines, the filling of a reservoir, the injection or extraction of fluids, or man-made explosions) does not contribute to it in any way.
- Mining-triggered: Mining activity corresponds to a small fraction of the stress change or energy associated with the event. They are often associated with a slip along pre-existing faults.
- Mining-induced: Most of the stress change or most of the energy required to produce the event results from mining activity. Usually, these events are associated with pre-existing faults. Some induced events involve the creation of a new rupture. These events require such very high levels of mining-induced stress, as would result from an isolated remnant or pillar, that they could aptly be called “mining-created” events.
- Mining-related: A seismic event that is either mining-triggered or mining-induced.

Seismic event can be described quantitatively by collecting the certain characteristics suggested by Mendecki *et al.* (1999) as follows:

- Location of the event,

- Time of the event,
- At least two independent seismic source parameters, such as seismic energy, seismic moment, or source size.

These components of a quantitative description of a seismic event can be used to characterize one seismic event or a population of events (Hudyma, 2008).

2.3.1 Seismic source parameters

A seismic source is referred to as an area within a rockmass in which a deformation or failure resulting in the seismic event is caused by a combination of stress, geological structure, and mining (Hudyma, 2008).

The seismic source mechanism is defined as the type of deformation or failure that results in the creation of seismic stress wave (release of seismic energy). Typically seismic source mechanisms in mines include slip on existing geological features, the creation of new fractures in a rockmass due to high stress, buckling and shearing, and tensile failure of intact rock or a rockmass. It is important to mention that the seismic source mechanism is related to the timing of energy release. Depending on whether the seismic source is stress driven or structurally related, the energy can be released after a mine blast or can be poorly related to mine blasts, subsequently. It significantly influences the strategies of seismic risk management. (Hudyma, 2008)

First parameter considered here is a seismic event source location, which in three dimensions is introduced as the hypocentre of the event (Joughin, 1999). It appears as the first step in analysing seismic events. An accurate location of the seismic event is crucial in order to indicate the location of potential rockbursts, help to interpret individual events and to perform spatial and temporal analysis of seismicity. Sensors number used in seismic monitoring system influences the outcome of the accuracy of seismic events locations. A sufficient number of sensors enables to a very accurate indication of source location in a mine. To ensure high resolution of seismic monitoring system a typical source location error should stay within 10 metres range or less (Hudyma, 2008). (Hudyma, 2008; Potvin and Hudyma, 2001)

Another important aspect when it comes to the location of seismic events is a configuration of the array of seismic sensors in a mine. Joughin (1999) suggests that the sensors should always be spread evenly in three dimensions, around the volume in which it is intended to record seismic events. Figure 2 shows two configurations of sensors in the surrounding of a seismic event. The configuration on the left does not surround the seismic event, thus the calculation of the location is more biased. The likelihood of error is reduced in the case on the right, where the sensors evenly surround the event. In general, the more sensors that can capture seismic event the more accurate the location will be (Joughin, 1999; Heal, 2010). To determine the relative sensors spacing in an array Hudyma (2008) proposes use of Inter-Sensor Spacing parameter defined as:

$$\text{Inter – Sensor Spacing} = \sqrt{\frac{\text{Area Monitored}}{\text{Number of Sensors}}} \quad (1)$$

where,

Area monitored – the product of the two largest dimensions of the seismic array.
Number of Sensors – the total number of triaxial and uniaxial sensors in the array.

Inter-Sensor Spacing corresponds to the completeness of the seismic record. That relation can be used to design the number of seismic events covered by a seismic monitoring system (more about it in Hudyma, 2008).

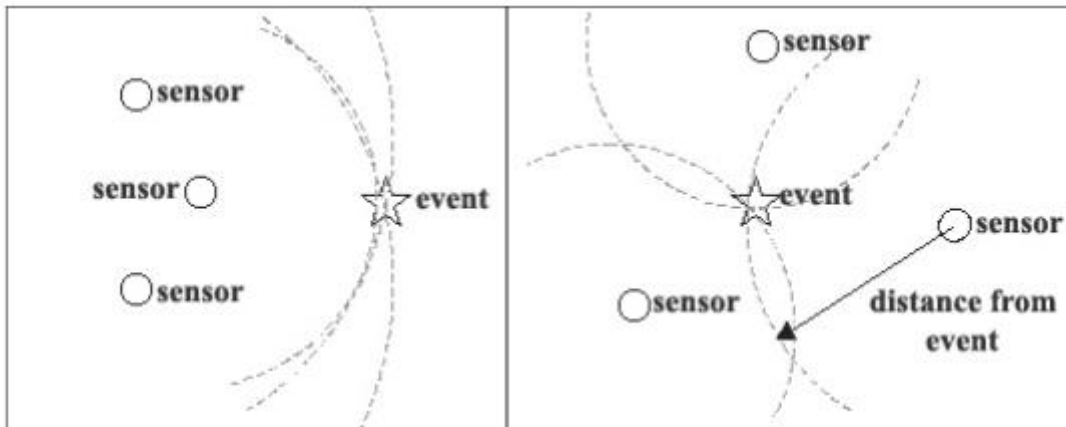


Figure 2. The effect of seismic sensors configuration on location accuracy (Joughin, 1999)

Another parameter to consider is a seismic event time. Capturing the time of a seismic event enables to identify the occurrence of the seismic-related rockmass failure. Hudyma (2008) reports a strong relation between the mine blast and the seismic-related rockmass failure. Stress changes, caused by blasting-induced stope geometry changes, mining or flooding of mines, filling of a reservoir, injection or extraction of fluids or man-made explosions have a direct impact on seismicity in mines. Nevertheless, the seismic response for blasting is unique for each mine. That is why a particular mine blast can be disproportionate to the size of the blast: the smaller the time interval between blasts and seismic events, the greater the relation (Hudyma, 1995; Hudyma, 2008). Time might seem to be the simplest parameter to measure. However, it is still not fully understood how to interpret it. There has been a comprehensive discussion on that matter in the literature during the past years (Kijko *et al.*, 1993; Hudyma, 1995; Brummer, 1999; Basson and Ras, 2005). According to Brummer (1999) the larger the event, the more random the pattern in time of occurrence. Hudyma (2008) notices that the event time may indicate the fundamental drivers for rockmass failure processes. The lack of time-space relations between big and small events at Target gold mine was reported by Basson and Ras (2005). They found that the bigger events were fairly correlated with other bigger events in the vicinity. Another relation was found and reported by Kijko *et al.* (1993) and Hudyma (1995). They indicated that the combination of stress migration and the influence of mine faults might be accounted as causes of large seismic events.

The most common method to describe the size or intensity of a seismic event is a magnitude scale, and it appears as important seismic source parameter. A widely used magnitude scale is the one developed by Richter (1935) called Richter Magnitude, originally developed as a mathematical device to compare the size of earthquakes in Southern California (Heal, 2010). Using this scale, the magnitude of an earthquake is

defined as the logarithm of the maximum amplitude measured at a distance of 100 km from seismic source (Gibowicz and Kijko, 1994). The most often used tool to measure a source strength is a moment magnitude (M_M) (Brady and Brown, 2004). It is also considered the most suitable for measurements of a fault-slip seismic event (Hudyma, 2007). The scale was developed to overcome the shortcomings of the Richter magnitude scale, but it still stays consistent with its predecessor. Moment magnitude is defined by the equation (Mendecki *et al.*, 1999):

$$M_M = \frac{2}{3} \log M_0 - 6,1 \quad (2)$$

where,

- M_M – is the moment magnitude,
- M_0 – is the seismic moment (Nm).

Although Richter Magnitude scale was developed to measure the earthquakes, it is universally accepted measure also used in seismically active mines. Hudyma *et al.* (2003) proposed the relation of Richter Magnitude scale and qualitative description of how the events were felt in the mine as shown in Table 1, based on the investigation conducted in seismically active mines in Australia. Since seismic response to mining differs from mine to mine and it is technically not possible to calculate a widely accepted magnitude scale. Thus, the term local magnitude is of importance, as it describes the magnitude scale developed and calibrated for a specific seismic system.

Table 1. Qualitative relationship between the magnitude of a seismic event and how it is felt in a mine (Hudyma *et al.*, 2003)

Approx. Richter Magnitude	Qualitative description
-3.0	<ul style="list-style-type: none"> · Small bangs or bumps heard nearby. Typically these events are only heard relatively close to the source of the event. · This level of seismic noise is normal following development blasts in the stressed ground. · Events are audible, but the vibration is likely too small to be felt. · Not detectable by most microseismic monitoring systems.
-2.0	<ul style="list-style-type: none"> · Significant ground shaking. · Felt as good thumps or rumbles. May be felt from the source of the event (more than 100 meters away). · Often detectable by a microseismic monitoring system.
-1.0	<ul style="list-style-type: none"> · Often felt by many workers throughout the mine. · Should be detectable by a seismic monitoring system. · Major ground shaking felt close to the event. · Similar vibration to a distant underground secondary blast.
0.0	<ul style="list-style-type: none"> · Vibration felt and heard throughout the mine. · Bump may be felt on surface (hundreds of meters away), but may not be audible on the surface. · Vibration felt on surface similar to those generated by a development round.

Approx. Richter Magnitude	Qualitative description
1.0	<ul style="list-style-type: none"> • Felt and heard very clearly on surface. • Vibrations felt on surface similar to a major production blast. • Events may be detected by regional seismological sensors located a few hundreds of kilometres away.
2.0	<ul style="list-style-type: none"> • Vibration felt on the surface is greater than large production blasts. • Geological survey can usually detect events of this size.

2.3.2 Seismic events mechanisms

Ortlepp (1997) showed that by understanding seismic source mechanism, the largest potential seismic event could be estimated. The basic mechanisms of mine tremors (Figure 3) were proposed by Hasegawa *et al.* (1989) and include subsequently: cavity collapse, pillar burst, tensional fault, and three types of fault-slip.

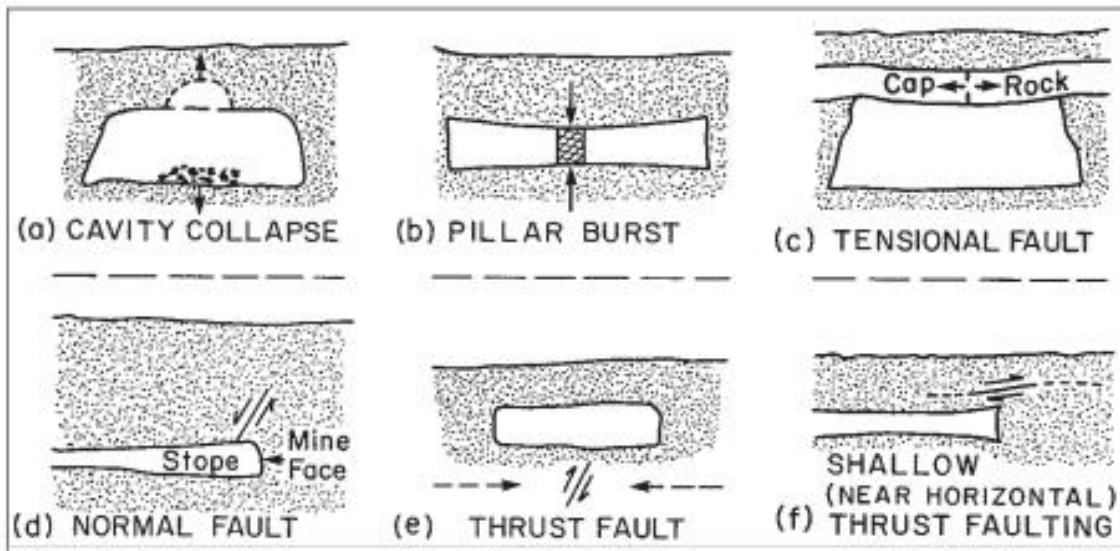


Figure 3. Six basic mechanisms of mining induced seismic events (Hasegawa *et al.*, 1989)

Ortlepp and Stacey (1994) provide a similar classification of seismic events and discusses the mechanisms of damaging rockbursts, divided by their source mechanism, first motion recorded from seismic records, and approximate magnitude range for events of each mechanism (Table 2).

Table 2. Classification of seismic event source (Ortlepp and Stacey, 1994)

Rockburst Type	Postulated Source Mechanism	First Motion from Seismic Records	Richter Magnitude M_L
Strainbursting	Superficial spalling with violent ejection of fragments	Usually undetected, could be implosive	-0.2 to 0

Rockburst Type	Postulated Source Mechanism	First Motion from Seismic Records	Richter Magnitude M_L
Buckling	Outward expulsion of larger slabs pre-existing parallel to surface of opening	Probably implosive	0 to 1.5
Pillar of face crush	Sudden collapse of stope pillar, or violent expulsion of large volume of rock from tabular stope face or tunnel face	Possibly complex, implosive and shear	1.0 to 2.5
Shear rupture	Violent propagation of shear fractures through intact rockmass	Double – couple shear	2.0 to 3.5
Fault – slip	Sudden movement along existing fault	Double – couple shear	2.5 to 5.0

These damage mechanisms relate to discrete, large-scale rockmass failures, as reports Hudyma (2008). In general, most of the seismic events recorded by seismic monitoring systems installed in mines are smaller than moment magnitude 0 and therefore represent smaller rockmass failures than those described above. The mining-induced seismic events of low magnitude (less than 0) are defined as microseismic events (Young *et al.*, 1992). It is worth noticing, that although microseismic events do not have to always result in noticeable rock mass damage, they are a valuable source of information about the larger events (Hudyma, 2008).

Hudyma (2008) noted that typical seismic source mechanisms in mine consist of all those mentioned by Hasegawa *et al.* (1989) and Ortlepp (1997) but he listed additional ones that include:

- Intact brittle rock fracture (Lynch *et al.*, 2005 in Hudyma, 2008).
- Coalescence of rockmass fractures such as rock joints (Trifu and Urbancic, 1996 in Hudyma, 2008).
- High stresses acting in stope abutments (Andrieux and Simser, 2001, in Hudyma, 2008).
- Crushing, shearing, and volumetric fracturing of mine pillars (Hedley, 1992 in Hudyma, 2008).
- Shear or rupturing of lithological contacts (Mollison *et al.*, 2001 in Hudyma, 2008).

2.4 Rockburst definition and classification

Although all seismic events are associated with rock failure, not all of them pose a hazard to the mine, workforce, and equipment. A wide range of rock failure phenomena is associated with the term “rockburst”. However, first, the distinction should be made for the terms seismic event and rockburst. Gibowicz and Kijko (1994) stated that the

rockbursts are violent failures of rock that result in damage of excavations. That definition was broadly used already twenty years before by Cook (1976) and Ortlepp (1984). According to that, only the seismic events which cause damage to the mine can be considered rockbursts. The severity of a rockburst may vary from minor rock spalling to catastrophic rock mass fracturing or falls of ground (Heal, 2010). Some of the definitions of rockbursts found in the literature are given in Table 3.

In South Africa, it is a common practice to use the two terms which help to distinguish between the cause and the effect of mine tremors. A seismic event is considered to be “the transient energy released by a sudden fracture or failure in the rockmass which results in the emission of a seismic vibration transmitted through the rock”. A rockburst is considered the “significant damage caused to underground excavations by a seismic event”. This division does not deliver any information about a magnitude of the seismic event or the nature of it (natural or induced) but allows to focus on assessment of the level of damage which is considered disruptive to the successful operation of the mine (or facility) (Ortlepp, 2005).

The classification of seismic event types introduced by Ortlepp and Stacey (1994) and presented above in Table 2, classifies rockbursts into five types: strainburst, buckling, face crush/pillar burst, shear rupture, and fault-slip burst. Kaiser and Cai (2012) further elaborate on that and proposes a new division, where bulking is included into the strainburst type of rockburst and shear rupture is considered fault-slip rockburst. Ortlepp and Stacey (1994) stated that strainbursts are probably the most common damage mechanisms observed in civil engineering excavations. Kaiser and Cai (2012) considered strainbursts as the most common rockburst type in deep underground excavations, highlighting their mining-induced origin. Feng *et al.* (2012a) take into consideration the evolution time of a rockburst after excavation. Based on that they suggest that rockbursts can be classified into immediate and time-delayed since the occurrence of rockbursts may last from one to several days, or from two to several weeks. However, it is worth noticing that before a rockburst occurs a series of microseismic events might be recorded in the vicinity of its future occurrence. The characteristics of these microseismic events (temporal, spatial and energy fractal characteristics) make it possible to obtain warnings of immediate rockbursts (Feng *et al.*, 2012a).

Strainbursts are a phenomenon that can be mining-induced or dynamically-induced. Mining-induced are these triggered due to static stress change caused by nearby mining. Dynamically-induced type originates from dynamic stress increase generated by a remote seismic event (called dynamically-induced strainbursts). Kaiser and Cai (2012) outline the prerequisites for strainbursts occurrence as: the tangential stress built up in the immediate skin of the excavation and relatively “soft” loading environment in the rock mass surrounding the fracturing rock, which enables a rock to fail locally in an unstable, violent manner. The origin of the energy released by a strainburst is the stored elastic strain energy in the failing rock and the surrounding rock mass. The distance where strainbursts often occur during tunnel and shaft construction is within three times the diameter from the advancing face. It can happen that they also occur at the tunnel face and in the floor. In general mining-induced strainbursts can happen during the production stage, but there are also delayed strainbursts possible to occur if the maximum principal stress remains constant but the rock strength degrades over time, or the rock strength reduces due to loss of confinement. Strainbursts may be triggered by

a small dynamic disturbance, a production blast, a remote pillar burst or fault slip event. (Kaiser and Cai, 2012)

Pillar burst is defined as a violent failure in the pillar core or the complete collapse of a pillar (Kaiser and Cai, 2012). The released seismic energy is greater than in case of strainburst; also the volume of the detached rock mass affected surrounding is larger. They often occur in deep mines when the extraction ratio is high at a later stage of mining (Kaiser and Cai, 2012). A fault-slip burst is a result of the dynamic slippage along a pre-existing fault or along a newly generated shear rupture. It occurs in deep mines when the extraction ratio is high and large closures are allowed to persist over large mining volumes. Kaiser and Cai (2012) suggest that the most reasonable cause of fault-slip along a pre-existing fault is the reduction of normal stress acting on the fault as a result of nearby mining, although an increase in shear stress or a combination of normal stress decrease and shear stress increase can similarly cause a fault to slip. Seismic energy typically released in association with this type of rockburst is large and maybe cause ground vibrations or ground motions able to damage the excavations (dynamically-induced strainbursts) or trigger strainburst and pillar burst even in relatively remote locations (up to hundreds of meters from the seismic source). (Kaiser and Cai, 2012)

Shear rupture rockburst type are large rockbursts, which originate from the violent propagation of shear fracture through intact rocks. According to Ortlepp (1997), this type of rockburst is one of the most important source mechanisms of major rockbursts. Kaiser and Cai (2012) argue that his statement is biased as it is based mostly on the relatively soft mining system stiffness encountered in tabular ore bodies in South Africa.

Table 3. Definitions of the term rockburst.

Reference	Definition
Cook <i>et al.</i> (1966)	Rockburst is damage to underground workings caused by the uncontrolled disruption of rock associated with a violent release of energy additional to that derived from falling fragments.
U.S. Bureau of Mines (1968)	Rockburst is that phenomena which 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 (1972)	Rockburst is a sudden rock failure characterized by the breaking up and expulsion of rock from its surroundings, accompanied by the violent release of energy.
Ortlepp and Stacey (1994)	Rockburst is a term applied to the damage that occurs in a tunnel as a result of a seismic event, or which is associated with a seismic event. There are no constraints on the magnitude or type of seismic event; only that it must generate sufficient energy to cause violent damage in the tunnel.
Gibowicz and Kijko (1994)	Rockburst is a violent failure of rock that results in damage to excavations.

Reference	Definition
Ortlepp (1995)	Rockburst is a seismic event which causes violent and significant damage to the tunnel or the excavations of a mine.
Scott (1997)	Rockburst is defined as the sudden and sometimes violent release of accumulated energy when a volume of rock is strained beyond its elastic limit. Rockbursts can be classified as strain, crush or slip. Strain bursts are small and localised, while crush and slip bursts can cause extensive damage to drifts and stopes.
Bennett and McLaughlin (1997)	Rockburst is any type of stress-release phenomenon which has been induced by mining activity and which results in the emission of seismic signals.
Heal (2010)	Rockburst is defined as visible damage to an underground excavation caused by a seismic event.

The range of magnitude, when it comes to rockbursts, can extend across nine orders, as shown in Table 4. They may vary significantly, from superficial strain-bursting to the collapse of a mine (Ortlepp, 2005).

Table 4. Indicators of size range of seismic events (Ortlepp, 2005)

Richter Magnitude M_L	Kinetic Energy MJ	Explosive Equivalent ¹ kg	Radius of Source Rupture ² m
-1	0.002	0.04	0.8
0	0.06	1.2	2.6
1	2.0	40	8.5
2	60	1200	26
3	2 000	40 000	84
4	60 000	1 200 000	270

Notes: 1 At 1% “seismic” efficiency

2 Brune model at 10 MPa stress drop

2.4.1 Rockburst damage mechanisms

There are many factors that influence rockburst damage and the severity of the damage (Hedley, 1992, Kaiser *et al.*, 1995, Durrheim *et al.*, 1998, Heal *et al.*, 2006).

The mechanisms of rockburst damage suggested by Kaiser *et al.* (1995) can be seen in Figure 4.

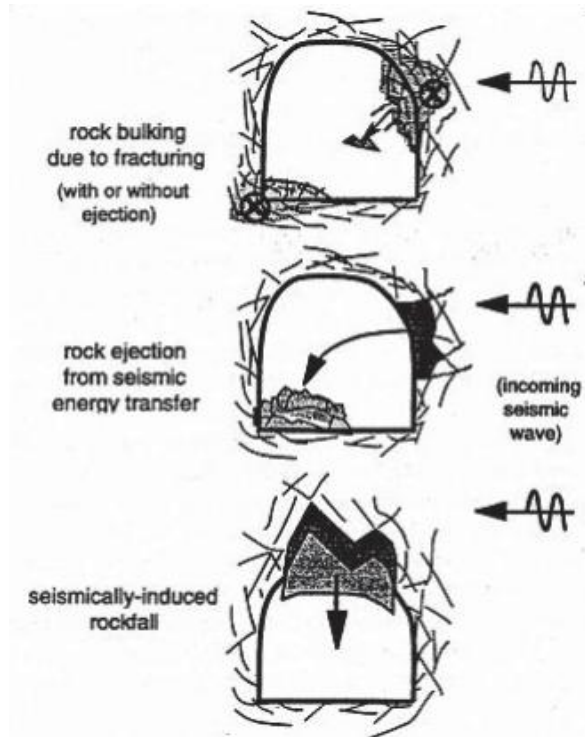


Figure 4. Rockburst damage mechanisms (Kaiser *et al.*, 1995)

The process of rock bulking due to fracturing (see top sketch of Figure 4) occurs when the stresses near an excavation suddenly exceed the rock mass strength and a zone of fractured rock occurs, resulting in an increase in volume, sometimes associated with rock ejection. Typically it is introduced as the damage mechanism of a ‘strain-burst’ seismic event, and often occurs in the newly created excavation (Kaiser *et al.*, 1995). The middle sketch in Figure 4 shows a rock ejection from seismic energy transfer. It develops in the case when rock blocks are violently ejected from the periphery of an excavation due to the transfer of seismic energy to the blocks from an incoming seismic wave. When the rock mass is well jointed and loose or already fractured, this form of rockburst is more likely to occur (Kaiser *et al.*, 1995). Kaiser *et al.* (1995) suggest that an incoming seismic wave accelerates a volume of rock that was previously stable and the energy is transmitted from the distant seismic event (see bottom sketch on Figure 4). Heal (2010) argues that for this form of damage to occur, the volume of loose rock must be very close to failure under static (gravity) loading, prior to lateral shaking due to a seismic event. Heal (2010) continues with a statement that for the shaking in the vertical direction, transmitting a downwards velocity on the loose rock, the damage is better described as rock ejection from seismic energy transfer.

3 Georisk management in underground mines

3.1 Rationale for risk management

The aim of applying risk management process can be expressed as an attempt to proactively and systematically reduce losses. The fundamental rationale for risk management is the need to improve performance (NSW Department of Minerals Resources, 2011). Despite the fact that health and safety issues are of great importance nowadays, the expectations of society are not met yet, as the frequency of major unwanted events still exceeds the commonly acceptable limits (NSW Department of Minerals Resources, 2011). Since risk management aims to improve the performance, it should be focused on supporting the quality of decision-making. As the methodology and experience of an individual is obviously limited, the need for this kind of decision support system for the professionals in a mine has been noticed already years ago, and mentioned several times throughout the literature (e.g. Mendecki, 1993; Gibowicz and Kijko, 1994; Durrheim *et al.*, 2007).

3.2 Risk and risk management definitions

Understanding of basic terms and definitions is an important task in successful risk management. The International Standard ISO 31000:2009 delivers the definition of risk as the effect of uncertainty on objectives. Although risk is usually thought of in terms of negative impact, it can be used to identify positive events or opportunities (ISO 31000:2009 “Risk management – Principles and guidelines”, 2009). According to ISO 31000:2009, risk is often characterized by reference to potential events and consequences or a combination of these. It is expressed in terms of a combination of the consequences of an event (including changes in circumstances) and the associated likelihood of occurrence.

Risk assessment is a process that consists of risk identification, risk analysis, and risk evaluation (IEC/ISO 31010:2009 “Risk management – Risk assessment techniques”, 2009). Risk identification is defined as the process of finding, recognizing and recording risks. Risk analysis means developing an understanding of the risk, while evaluation of risk involves comparing estimated levels of risk with risk criteria defined when the context was established to determine the significance of the level and type of risk. (IEC/ISO 31010:2009 “Risk management – Risk assessment techniques”, 2009)

Risk management is defined as “coordinated activities to direct and control an organization with regard to risk” (ISO 31000:2009 “Risk management – Principles and guidelines”, 2009). It is important to notice that there are no “zero risk” cases. In fact a no-hazard environment, no matter underground or above ground does not exist in reality and an incident can happen at any stage of any project. The point is to manage risk to a level of acceptability or practicality. That is why an understanding of causes of risks and comprehensive risk management are the core elements in any mining venture.

The term “hazard” is defined as a source of potential harm. In mining industry it indicates a very complex collection starting from electricity and mobile equipment, through objects at height to geotechnical hazards. The last ones, which are of interest for this thesis, are still the less understood and one of the most destructive in consequences.

3.3 Risk management process framework

The most common framework for risk management is provided in International Standard ISO 31000:2009, with a step-by-step model of performance. It aims to serve as a basis for designing, implementing, monitoring, reviewing and continually improving risk management throughout the organization.

Risk management process (shown in Figure 5) provided in ISO 31000:2009 standards is described as a “systematic application of management policies, procedures, and practices to the activities of communicating, consulting, establishing the context, and identifying, analysing, evaluating, treating, monitoring and reviewing risk”. It can be seen as three pillars. The left one highlights the importance of communication and consultation in the organization. The right one is monitoring and review, shown as continuous, iterative process. The middle pillar of risk management flowchart presents the methodology for risk evaluation, consisting of establishing the context, risk assessment, and risk treatment.

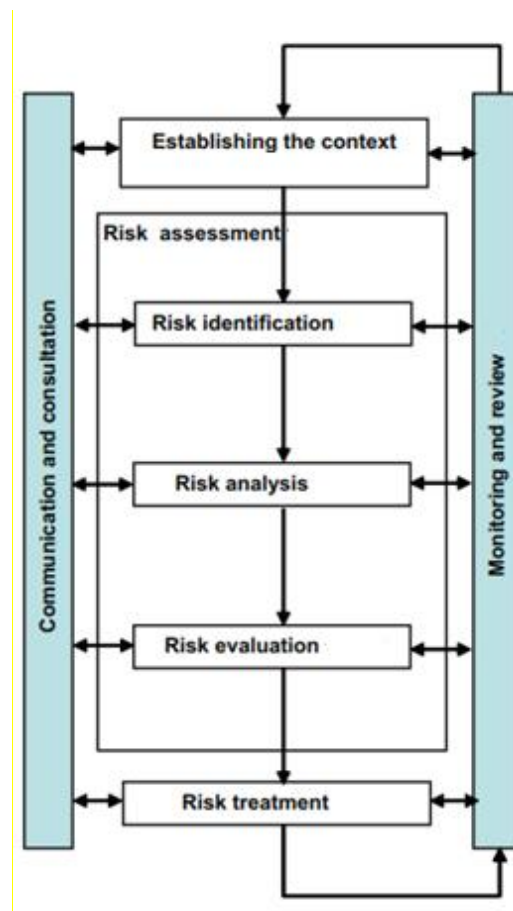


Figure 5. Risk management process (ISO 31000:2009 "Risk management – Principles and guidelines", 2009)

3.4 Communication and consultation

The need to communicate and consult, both within an organization and with stakeholders, is a principal rule in terms of successful risk management. These tasks should be performed throughout all stages of the risk management process. As iterative and continuous processes, they ensure that the information is provided, shared and obtained in a timely manner,

encouraging an open communication. In that way, the reasons for making particular decisions and taking actions are better understood.

3.5 Risk evaluation

From the mining industry point of view, maintaining a good risk management has a direct influence on the company's performance ensuring safe and economically feasible extraction. Although the health and safety parameters nowadays can be assessed with a high accuracy and low uncertainty, the georisks remain challenging. Therefore, the risk evaluation needs to be adapted according to the objectives of certain organization which wants to use it. Its adaptation for deep underground mining purposes was proposed by Janiszewski *et al.* (2015). It is depicted in Figure 6 (shaded in blue) as geotechnical hazard potential (GHP), geotechnical risk assessment (GRA) and risk mitigation and reliability assessment processes.

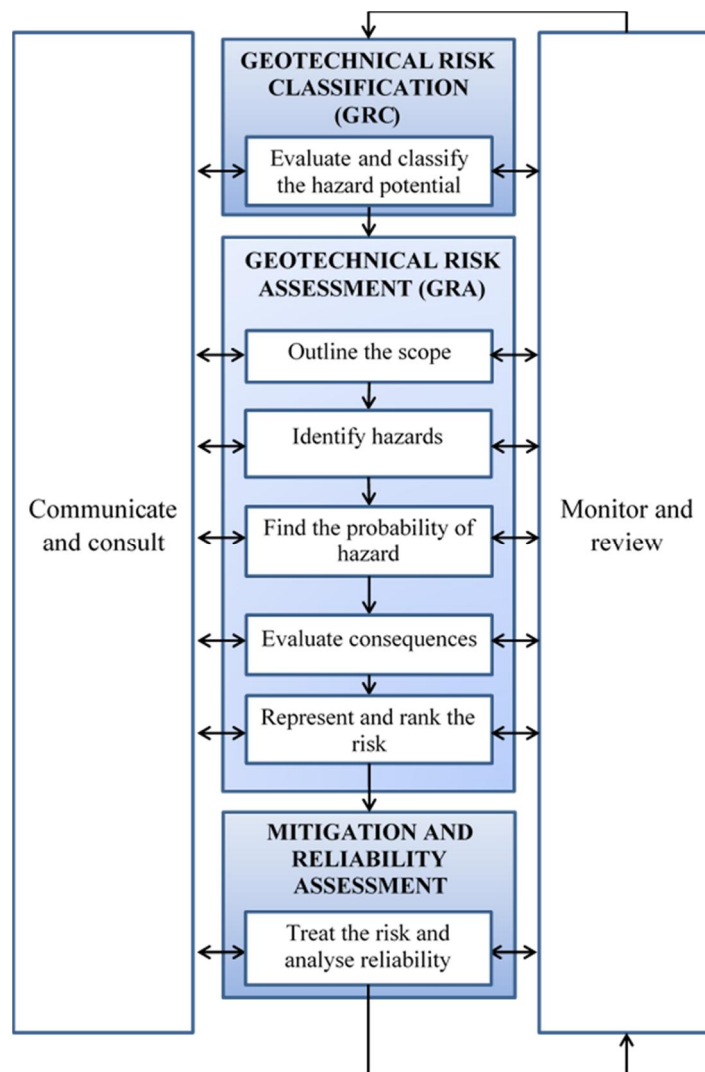


Figure 6. Geotechnical risk management flowchart (Janiszewski *et al.*, 2015)

3.5.1 Establishing the context – Geotechnical Hazard Potential

Establishing the context in the risk management means outlining the organization's objectives and rationale for the entire process. External and internal parameters need to be defined for risk management, scope needs to be developed and the risk criteria for the

remaining processes need to be set up. It is important to notice that the parameters considered for the context need to be more detailed than for the design of risk management. (ISO 31000:2009 "Risk management – Principles and guidelines", 2009).

The external context is described as the “external environment in which the organization seeks to achieve its objectives”. It may include: the social and cultural, political and legal, environment on any range (from local through regional, national to international) and the impact of the relationships with external stakeholders. (ISO 31000:2009 "Risk management – Principles and guidelines", 2009)

The internal context is thought of as “the internal environment in which the organization seeks to achieve its objectives”. It means anything within the organization that might have an impact on the way in which the organization manages risk, for instance, roles and accountabilities, policies and strategies, organization’s culture and values, and information flow (ISO 31000:2009 “Risk management – Principles and guidelines”, 2009).

The geotechnical hazard potential (GHP) is an evaluation that uses an indicative ranking of mining operations based on its potential in causing a geotechnical hazard. It utilises modified Barton’s Q value for rock mass competency classification (ranking from “very good competency” to “very poor competency”. The GHP classification can be used as a preliminary risk assessment to justify a formal hazard-specific risk assessment for a specific area to predict and prevent geotechnical accidents (Mishra, 2012).

3.5.2 Risk assessment

Risk assessment is a comprehensive process which consists of three stages, as outlined above in Figure 6. It aims to “help decision-makers and responsible parties to improve an understanding of risks that could have an influence on the achievement of objectives, and the adequacy and effectiveness of controls already in place”. The overall goal is “to provide a basis for decisions about the most appropriate approach to be used to treat the risks”. In general, risk assessment process attempts to provide the information about the hazards and their consequences, the likelihood of their occurrence in the future, and prevention and mitigation measures that could be undertaken to maintain the risks on the acceptable or tolerable level. (ISO 31000:2009 “Risk management – Principles and guidelines”, 2009; Janiszewski *et al.*, 2015)

Geotechnical hazards that might pose risk need to be identified and investigated in order to assess its possible consequences, and therefore enable a decision-making process to be based on clear and timely information. Geotechnical risk is defined as a combination of likelihood of geotechnical hazard occurrence and severity of its occurrence:

$$Risk = Likelihood \times Severity \quad (3)$$

The geotechnical risk assessment aims to identify and mitigate hazards before they pose a risk to the working environment (Mishra, 2012). The risk assessment process for geotechnical risks is divided by Janiszewski *et al.* (2015) into five phases:

- 1: Outlining the scope of risk assessment.
- 2: Identification of hazards within the scope.
- 3: Evaluation of the likelihood of hazard.

4: Assessment of the consequences (exposure to hazard).

5: Ranking the risk to formulate a strategy of risk reduction.

Definition of a scope of the geotechnical risk assessment is developed in order to determine and allocate the resources needed for subsequent tasks to be performed. The resource allocation needs to be done in an optimized way. The more data is available, the easier it is to quantify risks. Although in the operational stage it is a common practice in mines to use the qualitative parameters for the risk assessment due to their simplicity in usage, it is advised to use the quantitative ones instead. In outlining the scope of GRA, an appropriate approach needs to be selected from deterministic, probabilistic and possibilistic. Mishra and Rinne (2015) report that in deep mines the probabilistic approach is the most suitable as “it incorporates variability and uncertainty and defines the extent of risk in terms of expected cost per year rather than stating whether the accident will happen or not”.

The scope and scale of GRA are used to select the tool for performing hazard identification. The tools enable a breakdown of the system into smaller tasks and therefore identification of the risks in each of them independently. Mishra and Rinne (2015) propose four risk identification tools with the potential to be used for geotechnical risk assessment: workplace risk assessment and control (WRAC), failure mode and effect analysis (FMEA), bow-tie analysis (BTA) and fault tree-event tree analysis (FTA-ETA). Depending on the chosen identification tool, the risk identification can result in one of four identified scenarios for risk assessment suggested by Mishra and Rinne (2015) which are: hazard specific GRA for large scale, site specific GRA for large scale, hazard-specific GRA for small scale and site specific GRA for small scale. In the next step, the likelihood of an event to occur is calculated using the selected approach.

In the next stage an assessment of hazard severity is performed by evaluation of the exposure of people and assets to a hazardous condition and its consequences, and determination of hazard acceptability. Risk representation and risk ranking are performed as the last step of geotechnical risk assessment. The risk can be represented either in graphical or matrix format, depending on the type of data obtained from the mine. In case when both the likelihood and consequence are measured quantitatively it is advised to use the graphical representation of risk. If hazard likelihood or severity classification is not quantitative, the matrix format is appropriate to represent the risk and to rank it. In general, mine management is responsible for the judgment regarding the ranges for each risk category, with regard to the financial, legislative mining or flooding of mines, the filling of a reservoir, the injection or extraction of fluids, or man-made explosions, and other factors involved in risk assessment.

Once the severity and likelihood are assigned, they are put into risk matrix, which is then used to indicate risk with the Risk Number, obtained by multiplication of hazard likelihood and severity. The Risk Number indicates the different levels of risk for a particular location in a mine. This risk representation enables to select appropriate mitigation measures, dependent on the risk ranking. They are implemented in order to reduce the risk to acceptable level.

3.5.3 Risk treatment – mitigation and reliability assessment

First consideration about the treatment of risk management is whether the risk can be afforded in the present form. If the risk has a negligible impact on the routine work, the control or mitigation measures are not essential. Each organization needs to provide its own negligible risk definition. In case the risk cannot be afforded in its present form, the control

measures should be undertaken to minimize the risk. If the control measures cannot be afforded the task/site must be aborted (Mishra, 2012).

Once a risk that needs to be minimized has been identified the control measures need to be defined. Control measures against risk have been a topic of extensive research for a long time. Australian guideline for minerals industry safety and health risk management (2011) provides the following Hierarchy of Control, adopted in many regulatory approaches (the effectiveness of a barrier intended to reduce a risk decreases from the top to the bottom):

- Eliminate the hazard or energy source.
- Minimize or replace the hazard or energy source (reduce the amount of energy to a less damaging level or replace the energy with another that has less potential negative consequences).
- Control the hazard or energy using engineered devices (e.g. lockouts, chemical containers, mechanical roof support, gas monitors, etc.).
- Control the hazard or energy by using physical barriers (e.g. machine guarding, warning signs, etc.).
- Control the hazard or energy with procedures (e.g. isolation procedures, standard operating procedures, etc.).
- Control the hazard or energy with personal protective equipment (e.g. hard hats, boots with toe caps, gloves, safety glasses, welding gear, etc.).
- Control the hazard or energy with warnings and awareness (e.g. posters, labels, stickers, verbal warnings, etc.)

Geotechnical control measures can be defined based on their types. Mishra (2012) proposes four of them (in decreasing order of priority): design based control, engineering/preventive control, best work practices and hazard indicator control. Reliability assessment of control measures is similar to the risk assessment. The engineering controls, design based controls and indicator controls (if it is an engineering component) can be assessed using Failure Mode and Effect Analysis (FMEA). Procedures are assessed for their ease of understanding depending on the type of remaining control measures. Development of control specific reliability assessment tools and reliability standards is an area with the extensive prospect of future work (Mishra, 2012).

3.5.4 Monitoring and review

Monitoring and reviewing processes aim to track adherence to standards and targets. They help to ensure that the controls are in place, as well as ensure that the hazard or conditions that might affect the risk have not changed. They can be conducted occasionally or according to the previously established schedule. The common forms of review are Incident/Accident Investigation, and Auditing. Both of them require a systematic, documented procedure. According to the ISO 31000:2009 standard, all risk management activities should be traceable. Therefore, the results of monitoring and review should be recorded and reported externally and internally to be further utilised as an input to the review of the risk management framework. The records serve as a basis for making improvements in risk management methods and tools (ISO 31000:2009 “Risk management – Principles and guidelines”, 2009).

4 Preceding studies

4.1 I2Mine

The Innovative Technologies and Concepts for the Intelligent Deep Mine of the Future (I²Mine) project funded by the European Commission 7th Framework Programme was a series of activities aiming at the development of an invisible, zero impact, deep mine. The research concentrated on the development of novel methods, technologies and concepts enabling to perform safe operations with low impact underground and zero impact above ground and ended with the promising results. Work package 3 of the I²Mine focused on the development of new approaches in rock mechanics and ground control to prevent geotechnical related accidents and potential losses in deep mines of the future. The outcomes which are of particular interest for the thesis are methods and concepts of systems contributing to the development of an on-line risk management system in underground mines of the future.

The aim of the research was to “improve the overall understanding of the rock mass behaviour and response in deep mines and under different geomechanical conditions, and to improve the understanding of the interaction between the rock mass and the rock support system and the relation between the characteristics of a seismic source and the response of underground openings and rock support systems”.

The project’s deliverables start with a Technology Report that comprises the available knowledge on current practice methods used in ground control in different European mines. The current control practice was distinguished into two groups: mines exploiting flat, bedded deposits (inclined with the angle from 0 to 60) and mines in hard rock formations with deep and steep orebodies (inclined in the range 60-90, depths from around 1000 m and deeper). The review covers past records of the types of failures. It also analyses the measurement data from several companies concerning deformation, hydro-geologic, environmental and seismic phenomena within rock mass. These activities enabled to identify sources of risk inherent for the mining operations associated with different employed mining methods. Investigation on the current ground control was conducted within the three areas. Damage of the rock and support, and development of a database comprising records for numerical analysis and empirical relations was one field of interest. Management of ground control risks in each mine and proposed instability mechanisms were another areas of interest. Finally, a review of current practice in ground support design/selection regarding different geological and mining conditions employed by large mining operators was conducted.

According to the study, the most commonly used technical measures applied for ground control in the reviewed mines are the following:

- Point reinforcement (rock bolts, cable bolts, friction rock stabilizers, etc.),
- Ground control surface measure (cast concrete lining, plain and fibre reinforced shotcrete, thin flexible surface coatings, mesh and strapping, cable lacing, etc.),
- Ground control point measure (timber posts and packs, hydraulic and screw-jack props, etc.),
- Ground control linear measure (timber or steel sets; yielding sets, etc.),
- Ground control volumetric measure (e.g. plain and strength enhanced backfill).

Applied technical solutions and methodologies differ in detail significantly since they have to be suited to various local mining and geological conditions. A division of those was proposed:

- Empirical methods based on precedent experience empirical methods, using usually one of the rock mass classification methods, sometimes modified with respect to the different geological or geotechnical conditions. Another feature is that they are based on a generalization of observations/performance monitoring of the ground control methods which successfully served their purpose in other mining areas.
- Numerical analysis methods able to provide a mathematical picture of strain-stress field within 2D or 3D rock mass and to foresee its behaviour. They transform physical problems into mathematically described mechanical models enabling to “see into the rock mass” considering also time-dependent mining/geological problems. Numerical analysis requires a lot of detailed input data and its results cannot be accepted without the preceding comparison with the actual underground observations.

Two currently acceptable approaches for ground control in mines according to Pytel *et al.* (2013) are: combination of mining experience with one of the established empirical design methods, or empirical design methods merged with numerical analysis, mining experience, and a suitable monitoring technique.

The recommendations for future research included an investigation concerning a constitutive model for spalling, which influences all numerical analyses, so they differ from reality. Also the applicability of the currently used ground control measures on the greater depths should be examined in more detail. Another issue identified by the authors that remains to be unsolved is how to characterize a seismic event from a ground control point of view. Also the effect of local seismic events and rockbursts requires research.

A comprehensive numerical modelling was conducted as a part of a research in the project using FLAC (applies finite differences method) and UDEC (applies the distinct element method). The main conclusion of the numerical modelling is that they have been proved to be useful in seismic hazard prediction in flatly dipping orebodies. The results have also proved the extremely significant effect of rock mass anisotropy (transversal isotropy) on the reliability of any analytical seismic hazard prediction. A need was identified to conduct a further research on deformability and strength of anisotropic rock mass based on the data encountered in seismic mines, as the real data allowed to obtain exceptionally satisfactory results when compared with results from seismic analysis. For flatly dipping orebodies it was proved that the blasting increases the percentage of seismic events. The authors report that blasting used to induce the seismic events is a method which is considered necessary in deep mines employing mechanized, continuous system of mining.

Another study conducted within the I2Mine project aimed to develop a method for geotechnical risk assessment that can be used for evaluation of different geotechnical hazard scenarios in deep underground mines. The methodology was divided in three parts. In the first part it provides the evaluation of geotechnical hazard potential (GHP), which is a form of preliminary hazard classification of underground mining operations based on the combination of rock mass competency and mining method. The division of mining methods and classification of rock mass competency were proposed. The main goal of the GHP is to enable acquiring preliminary information of geotechnical risk level in a mine and using the result to justify a formal risk assessment. Next part of the methodology is the geotechnical

risk assessment (GRA), proposed as the second and more formal phase of risk evaluation. Divided into detailed steps it proposes the assessment approach, guidelines for selection of hazard identification tools, procedures to evaluate the likelihood of a hazard and assess the consequences. The last step of the GRA is risk representation in a form of a matrix or as a graph. The use of guidelines is shown in two case studies with real data, one conducted by Froehlich (2014) in Garpenberg mine in Sweden and the other by Janiszewski (2014) in Pyhäsalmi mine in Finland. The studies proved a high applicability of the guidelines and their usefulness in description of the general hazard level, although still some improvements need to be applied to use their full potential.

In another task assigned to the Work Package 3 is a guide book for cavity and ground support design for safe deep underground mining was developed. Several dynamic and field tests were conducted, and both analytical and numerical analyses were used to contribute to the improvement of the ground control practice in deep mines. In particular, the focus was on better understanding of rockmass – rockbolt type ground support interaction. A ductile ground support made out of rockbolts was proven to help in securing the excavations in high stress conditions (like in deep mines). It was represented by a simplified 2D rockburst model, developed during the study. Another development is a hydraulically powered device that can reproduce a seismic load transfer onto rockbolts. It has an ability to model any static and dynamic load possible to be met in underground environment and all kinds of rockbolts can be tested there, which proves its uniqueness and usefulness (Nordlund *et al.*, 2016). The results of these comprehensive analysis help in rockbursts prediction activities. Besides the abovementioned, the authors report the results of site instrumentations with stress measurements devices and numerical modelling of the obtained data, assessing the performance of both instrumentation and created models. Nordlund *et al.* (2016) provide as well considerations about design and planning of deep mines subjected to dynamic failures and rockbursts.

Amongst the innovative developments of the I2Mine project there are intelligent rock bolts, which objective is monitoring and transferring data for on-line detection of rock mass movements (e. g. seismic activity, blasting, and stress changes). They are designed to use a wireless sensor network which is composed of a large number of heterogeneous sensor nodes, or sources, that sense phenomena in the physical work. The task of the networks is also to forward data from nodes in the internal or external network. The main characteristics of the wireless sensors is that they should use low power, transmit low data rate and should not be costly. Service-oriented architecture is planned to be implemented as a promising technique to bridge the gap between various industrial devices and enterprise applications. As a key in this architecture is the use of common communication protocols on all levels of the process chain.

The architecture of intelligent rock bolt consists of a rock bolt, sensors and a Mulle wireless sensor node. Each sensor is connected to a wireless network. It can communicate with cloud-based services inside the company network or on the public cloud (Internet). Services are deployed on sensor nodes (rock bolts), on gateways or in the cloud. In order to access the physical sensors some services must be deployed on sensors. To monitor a rock bolt, an electronic measurement system has been developed. The system consist of a high-performance AD-converter, amplifiers and sensors. It is capable of measuring stress/strain (with a strain gauge) as well as vibrations (with accelerometer). A first integration has been performed using a standard rock bolt and mounted on its head measurement system and a Mulle platform, so the wireless communication was possible. Tests were performed to

validate that applied forces to the rock bolt are detected by the Mulle. It has been verified that a rock bolt can be equipped with sensors for status monitoring. In order to fully examine the design real field-trials are required. Measurements were sampled by the Mulle and written on its serial port for further analysis by a computer, as it is aimed that only processed information will be transmitted using the wireless network to reduce power consumption to a minimum. That will ensure of maximum efficiency of the system. It is planned later integrate the intelligent rock bolts with suitable traditional mine stress monitoring systems.

The research questions addressing future research on intelligent rock bolts are: measurements issues, networking problems including quality of service and real-time data transmission, and signal processing.

4.2 Dynamic Control of Underground Mining Operations - Dynamine

The Dynamine project undertaken by the Aalto University aimed at the development of the method of estimating stress changes in a rockmass in real-time using strain measurements (Kodeda *et al.* 2015). The project started with development of an algorithm, which as an input uses data coming in real-time from the extensometers or intelligent rock bolts. The objective of this method is support of optimization of mining sequence, reduction of ore dilution, and reduction of ore losses. It can be also useful in real-time prediction of rock failures as a tool supporting the decision-making when it comes to safety of operation. In general, the tool created in Dynamine project aims to monitor the rockmass response to mining activities.

The stress changes are obtained in back calculations, which use linear regression of strain change records, the elastic constitutive relation, and the superposition principle. The algorithm was tested on site and with already analysed data. It was well functioning for synthetic cases, and showed tolerance to noise and missing data, as well as its suitability for the analysis in real-time was proven. Although the method needs verification, as the on-site data calculation turned out to be inconclusive, it should be further investigated as the method has potential especially for utilization in deep underground mines, where simplicity in use and low costs play crucial role in monitoring the rockmass state.

5 Research methods

5.1 Systematic review of literature – theory

“Literature review” is an umbrella term for any study undertaken to explore the literature in order to provide a description, summary, and critical evaluation of the research and non-research taken into consideration. In result, it provides a synthesized knowledge relevant to the particular topic from many different sources. There are a few methods to conduct a literature review, amongst them two most common ones are narrative review and systematic review. The often used narrative review does not use a systematic approach and therefore does not minimize bias during identification of the publications related to a specific topic. One way to systematize the identification and analysis of the studies is using systematic review. The differences and rationale for choosing the systematic review as a method for this study are given in the following subchapters. (Boland, 2010; Kitchenham, 2007).

5.1.1 Systematic review

A systematic literature review is a means of identifying, evaluating and interpreting all available research relevant to a particular research question, or topic area, or phenomenon of interest (Kitchenham, 2007). The main purpose of the systematic review is a critical, in-depth evaluation of research already undertaken on a specific topic, including the current knowledge with substantive findings, as well as theoretical and methodological contributions to a particular topic (Cooper, 1998). According to Torgerson (2003) a systematic review was initially used in health care research and it remains a rather new term. Nevertheless, a few years before Davies (1999) defined the tasks of the systematic review as not unique to medicine. Also Petticrew (2001) notices an increasing utility of the systematic review outside the health care. Kitchenham (2007), inspired by the practices in evidence-based medicine, adapted the method of conducting systematic reviews for software engineering.

A systematic review is accurate and uses repeatable methods open to scrutiny. Its aim is to find as many relevant, available research regarding the given topic as possible, taking into consideration both published and unpublished studies. All of them are included and screened for the quality. The literature is identified, critically evaluated and synthesized using explicit and rigorous criteria. Clear selection criteria and recording the reasons for studies exclusion minimize the bias in the review. (Cronin *et al.*, 2008)

To ensure reliability and validity of the study being performed, the methods used to evaluate and synthesize findings need to be detailed. Parahoo (2006) pointed out five essential steps to be undertaken, which are often used to meet the reliability requirements, and Kitchenham (2007) gives an explanation for subsequent tasks. In combination, they can serve as a frame for better understanding of the systematic review process:

1. Formulate the research questions:
 - meaningful and important for the researchers,
 - leading to changes of current practice in some subject or adding value,
 - highlighting discrepancies between commonly held beliefs and reality.
2. Search strategy development and inclusion/exclusion criteria:
 - developing an iterative search strategy,

- conducting preliminary searches to assess the potentially relevant studies and identify relevant keywords and phrases,
 - setting specific attributes, based on the research questions that a study must have to be included in the review,
 - establishing delimitations to narrow down the search.
3. Select and access the literature:
 - identifying primary sources that meet the inclusion criteria using the search strategy,
 - obtaining the full texts of the studies.
 4. Assess the quality of the literature included in the review:
 - establishing the quality assessment tools.
 5. Analyse, synthesise and disseminate the findings:
 - providing standard information about the papers,
 - collating and summarising the results of the included studies.

A schematic representation of the steps undertaken in the systematic review can be seen in Figure 7. The process starts on the top of the upside-down pyramid and continues to the bottom.

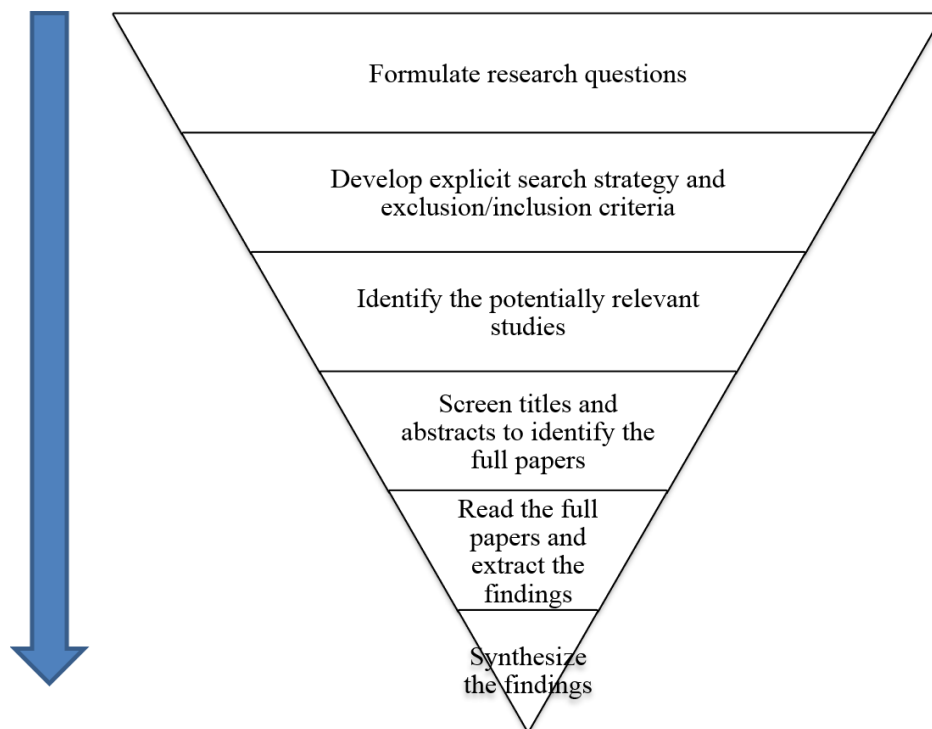


Figure 7. Work flow of systematic review (own elaboration)

5.1.2 Narrative review

Unlike the systematic review, a traditional or narrative literature review does not have to meet rigorous criteria, write Boland *et al.* (2014). Its aim is to summarise, criticize, and synthesize a literature with a research question not necessarily clearly defined. The methodology for conducting the narrative review is not explicit, and the search criteria are usually not pre-defined. The search is not comprehensive and generally relies on published data. Study design does not affect the decision about the inclusion or exclusion of the study. Due to the fact that the criteria for searching are not clearly defined the reproduction of such

a literature review is not easy to perform. The “not precise enough” approach of the traditional review to literature study makes it a non-repeatable method, and therefore cannot be employed for this thesis. Clearly outlined differences between the systematic and narrative reviews were presented by Boland *et al.* (2014) and are given in Table 5.

Table 5. Differences in review processes (Boland *et al.*, 2014)

Stage	Systematic reviews	Narrative reviews
Defining a question	-Clearly defined and well-focused -Always required	-May or may not be clearly defined
Writing a protocol	-Recommended/essential	-Not usually required
Methodology	-Follows explicit and rigorous methodology	-Does not follow explicit or rigorous methodology
Searching	-Exhaustive and with an appropriate balance of sensitivity and specificity -Carried out across a number of electronic databases, hand searching of reference lists from relevant papers and high-yield journals and documents/reports -Unpublished literature/theses sometimes searched -Comprehensive and explicit searching methods used and reported	-No pre-defined search criteria -Not necessarily comprehensive -Generally relies only on published data Search strategies may be based on expert experience
Definition of exclusion and inclusion criteria	-Essential -Study design can be selected	-Not essential -No selection of studies based on study design
Screening titles and abstracts; selecting full-text papers	-Systematic screening and selection -Usually cross-checked by another researcher	-Generally carried out by one researcher by reading through relevant papers and based on their own experience
Quality assessment	Yes	Not necessarily
Data extraction	Yes	Yes
Analysis and synthesis	Can involve meta-analysis, narrative or qualitative synthesis	No clear method of synthesis
Application	Any field	Any field
Timescale	Can be time-consuming due to rigor required	May be carried out relatively quickly
Replication	Explicit methods and therefore replicable	Not easily replicable

5.1.3 Meta-analysis and meta-synthesis

In addition, a tool to synthesise the quantitative findings can be employed in the literature review process. Meta-analysis is a form of systematic review which involves statistical analysis to combine and analyse the quantitative findings from several studies. Statistical procedures are incorporated there to define the relationships and draw conclusions on the results obtained in the examined studies. A meta-synthesis, which is the non-statistical technique aiming to establish the similarities between the studies, can be used to evaluate and draw conclusions on the multiple qualitative studies. The key elements in each study are synthesized and analysed to find their new interpretation. (Polit and Beck, 2006)

Meta-synthesis is a method used exclusively in health care and remains a not fully established technique in literature (Walsh and Downe, 2005). In presented study the synthesis are descriptive (non-quantitative), none of the two methods mentioned above is used.

5.2 Research method step by step

A systematic review of the literature was employed to retrieve the findings from the studies concerning geotechnical on-line risk management in underground hard rock deep mines and establish the state-of-the-art of it.

5.2.1 Review questions formulation

The systematic review started by defining review questions, which correspond to the goals of the thesis. The review questions are as follows:

- What methods and systems are currently employed for geotechnical on-line risk management in deep underground hard rock mines?
- What concepts of geotechnical on-line risk management systems are developed but not yet examined or employed?
- What methods, systems or concepts of geotechnical on-line risk management are under development?
- What improvements to the current state of geotechnical on-line risk management are suggested by the researchers?
- What are the missing pieces of knowledge identified in this field which should be taken into consideration for further research and development in the ORMID project?

5.2.2 Search strategy and inclusion/exclusion criteria

Searching for the papers was performed using keywords and phrases, and combinations of keywords with Boolean operators. The keywords, their combinations, and search tools which were used are given in the Appendix A. The strategy aimed to search for primary, secondary and conceptual/theoretical studies (sources). The definitions of the studies types are given in Table 6.

Search was performed using the electronic databases: Scopus, ScienceDirect, and IEEE Xplore. All three electronic databases cover broad range of peer-reviewed literature: scientific journals, books, and conference proceedings. They were chosen due to their reliability and comprehensive collections of publications they contain (see Table 7).

Table 6. Types of sources of literature (Colling, 2003)

Source	Definition
Primary source	Usually a report by the original researchers of a study
Secondary source	Description or summary by somebody other than the original researcher, e.g. a review article
Conceptual/theoretical	Papers concerned with description or analysis of theories or concepts associated with the topic
Anecdotal/opinion/clinical	Views or opinions about the subject that are not research, review or theoretical in nature.

Table 7. Numbers of records in the databases chosen for the research.

Database	Scopus	ScienceDirect	IEEE Xplore
Overall number of records	60 million	14 million	Almost 4 million
Number of journals covered	Over 21 500	Over 3 800	Over 170
Number of conference papers covered	Over 7.5 million	0	Over 1 400

The keywords were run in the databases to obtain all studies which contain them in titles, abstracts, or keywords lists. Preliminary searches were performed in order to assess the potentially relevant studies and establish the optimum list of keyword and therefore ensure as complete as possible, but also attainable list of articles that will be included in the study. RefWorks Web Based Bibliographic Management Software was employed to manage the searches due to its ease of use and compatibility with Scopus, ScienceDirect, and IEEE Xplore in terms of direct export option, without a need to convert different file formats. The search results were exported to RefWorks and stored there in the folders which allowed for easy access to the references.

After the search strategy was revised and final version was set up based on the preliminary searches, the inclusion/exclusion criteria were developed. In the first step, the duplicates of the papers were found and removed from the created database. Next, the papers were examined against the exclusion criteria as follows:

1. The study concerns coal mines
2. The study concerns salt mines
3. The study concerns opencast mines
4. The study concerns slope stability issues
5. The study concerns petroleum engineering
6. The study concerns soil mechanics

All of the studies which met the exclusion criteria were removed from the further investigation. In case of exclusion of the study, the reason underlying the decision is recorded. All the references to the excluded studies are kept in the references lists available as a supplementary material to this thesis. Once the potentially relevant papers were identified, the titles and abstracts of the found records were read and the final decision

whether the full paper will be read was made. In this step, to assess the relevance of the studies for the thesis, inclusion criteria were used as follows:

1. The study is a primary, or secondary, or conceptual/theoretical source of literature
2. The study concerns the deep underground hard rock mines
3. The study addresses one or more of the review questions (for review questions see subchapter 5.2.1)
4. The language of the study is English

5.2.3 Select and access the literature

The next step was to obtain full versions of the included papers. The reading process started after collecting the full texts. It was performed with a critical appraisal of each paper that has been selected at the first step, to refine whether it should be eventually included in the study, since the abstracts sometimes can be misleading. Checking against the inclusion/exclusion criteria was performed once again at this stage of the methodology used. Again, in case of exclusion of the read paper, the reasons for it were recorded.

5.2.4 Assess the quality of the literature included in the review

Kitchenham (2007) reports that in the systematic review a basic difficulty is that there is no agreed definition of study “quality”. According to the Cochrane Reviewer’s Handbook (2003) the quality is related to the extent to which the study minimizes bias and maximizes internal and external validity. To ensure a quality of the studies taken into the review the databases selected for the search have to be reliable. For that reason the selected electronic databases used for the search are: Scopus, ScienceDirect, and IEEE Xplore.

5.2.5 Analyse, synthesise and disseminate the findings

The results of searches are the studies that met the inclusion criteria. The full references of each included study are given in the references list at the end of this master’s thesis. The articles are divided into categories, for their ease of use and clarity of the results. The categories are: systems, management approaches, assessment techniques, and methods of forecasting and controlling the rockbursts. Methods part of the results is further divided into: methods based on seismicity, stress changes calculation based on strain measurements, statistical methods and numerical modelling for predicting mine tremors, laboratory tests helping to establish the relevant for forecasting correlations, use of neural networks, and various control methods such as destress blasting or no-entry periods approaches, tools assisting in choosing a suitable rock support. Each article is summarised, and its findings are recorded and provided in a form of the table (see Appendix B). The analysis of studies are performed through statistical methods, such as plotting graphs and identifying trends. The main topics of recent research are identified and the research institutions involved in the topic of on-line georisk management in underground hard rock mines are listed.

6 Results

6.1 Results division

This chapter presents the results obtained through the systematic review of the literature. It is divided into 5 parts. In the first part there are the results analysis given. The remaining four parts, named subsequently: systems, management, assessment and methods collect the results in a chronological order, outlining the main findings for each identified article.

6.2 Results of the systematic review of the literature

A systematic review of the literature was a tool used to identify research relevant to the objectives of the thesis. As a first task of the study 5 review questions were stated to help to retrieve from the literature these findings, which address the thesis goals. Three databases were used for the search: Scopus, ScienceDirect, and IEEE. To search the databases 12 keywords and phrases were formulated. To store the references the RefWorks Web Based Bibliographic Management Software was used. The search was conducted in three phases. A preliminary search was the first phase, and it aimed at the identification of potentially relevant keywords and testing them in the databases. The first round, and the second phase of the research was the actual searching for the studies. As a result, a number of 13 767 hits of references were identified. Almost half of them (6 456) were duplicates, and they were deleted from the collection. The remaining studies (7 311) were filtered manually following the established inclusion/exclusion criteria. To the next phase of the systematic review 4973 studies was taken, which met the inclusion criteria. Then the process of reading the abstracts of included studies started, and yield a number of 93 studies taken into consideration as relevant for the set objectives. Nevertheless, reading the full texts and checking them against the inclusion/exclusion criteria revealed a number of 48 studies which were not relevant for the set objectives. That left 45 studies to be included. Due to the fact that during the research a new relevant keyword which needed investigation was identified, another search round was conducted. It yield 63 hits, out of which 5 studies were taken into the final stage. Together 98 full studies were read, and then 50 were summarised, and had their findings identified and collected. Table 8 shows number of hits obtained for each keyword and numbers of studies included in the first and the second round of the search.

Table 8. Results of the first and second round of searches

Keyword	Hits	Excluded	Included 1st round	Included 2nd round
Deep mining AND NOT coal	2122	1081	1041	25
Seismic hazard underground mines AND NOT coal	1432	1130	302	15
Mining-induced seismicity AND NOT coal	622	284	338	13
Rockburst risk	1441	1389	52	12
Seismic monitoring underground mines AND NOT coal	354	316	38	8
Rockburst management	813	782	31	7
Real-time risk management AND underground mines AND NOT coal	1570	492	1078	5
Strainburst	63	58	5	5

Keyword	Hits	Excluded	Included 1st round	Included 2nd round
Geotechnical risk management	4327	2524	1803	3
Mine seismology AND deep mines	66	41	25	3
Geomechanical risk management	840	590	250	2
Deep hard rock mine	117	107	10	0
TOTAL:	13767	8794	4973	98

Figure 8 and Figure 9 represent the keyword hits in graphical format. The most of the hits in the initial search was obtained from the keyword “geotechnical risk management” (4327), and the least of the hits gave the keyword “strainburst”. Although the biggest number of hits was obtained from the keyword “geotechnical risk management” only 3 studies were further taken into investigation, due to the fact that the keyword gave a lot of studies that did not meet the inclusion criteria (e. g. main topics were civil engineering and open pit mining). Next keywords yielding the biggest amount of hits were “mining-induced seismicity AND NOT coal”, and “rockburst risk”. Nevertheless, the most of the studies included in the review yield the keyword “deep mining AND NOT coal” (25). That keyword was followed by “seismic hazard underground mines AND NOT coal” (15). No studies were included in the final stage resulted from the keyword “deep hard rock mine”. One of the reasons of exclusion in case of this keyword was the language of the full text of the study (3 initially identified as relevant articles were written in Chinese and therefore excluded).

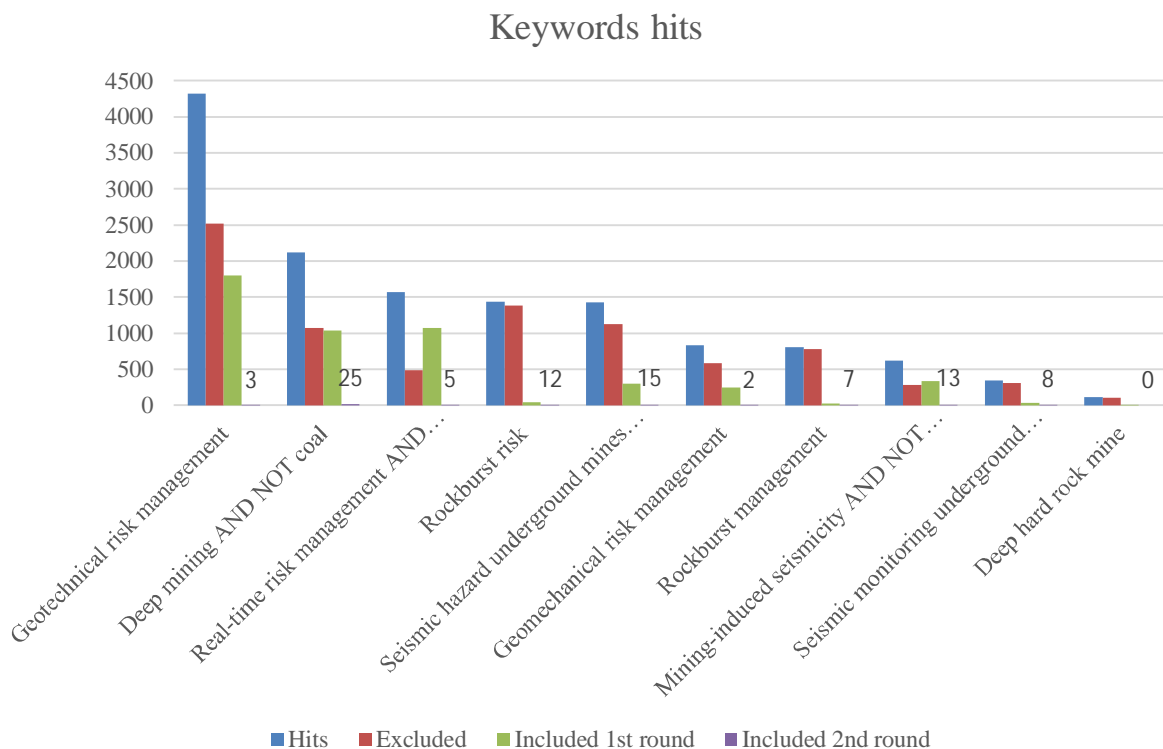


Figure 8. Keywords hits and included studies in the first and the second round

A number of studies found initially was significantly different than the number of studies taken into investigation in the second round of the search. A graphical representation of the latter studies is shown in Figure 9.

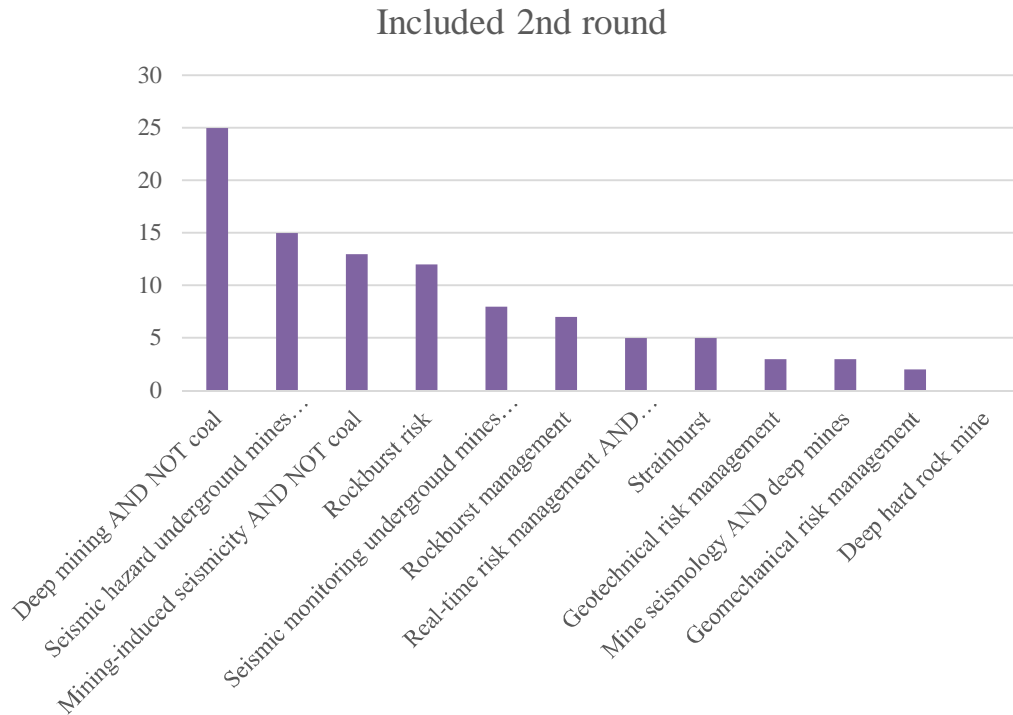


Figure 9. Graphical representation of the studies included in the second round of search

For clarity, the results are divided into systems, management approaches, assessment techniques, and methods used for prediction and prevention of rockbursts (see Figure 10). There are 3 systems identified, which are employed nowadays in the deep mines to manage the georisks in real-time. There are 9 studies about management included in the review. Another 5 studies discuss an assessment of geotechnical risks in the underground mines.

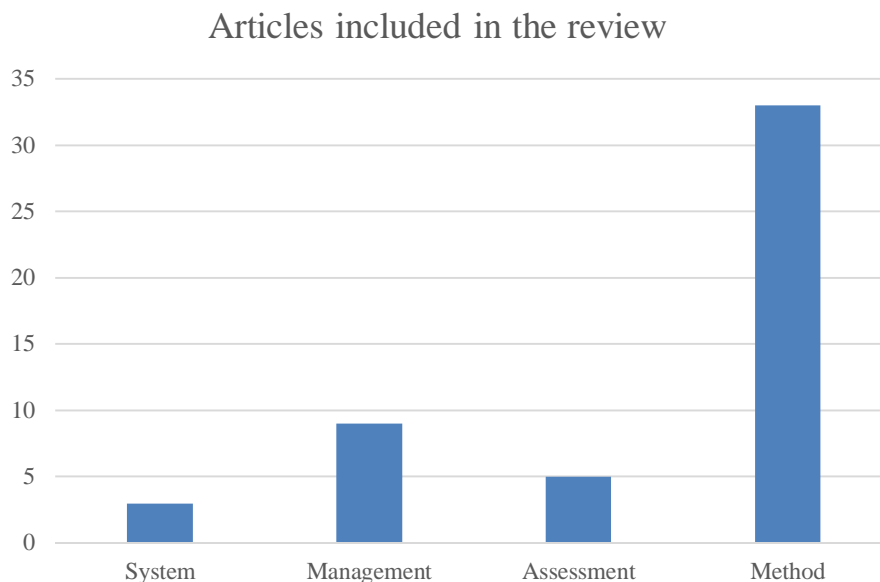


Figure 10. Share of the articles included in the review

There is in total 33 methods of rockburst forecasting and control identified, and the details are given in Appendix B. For the ease of reading they are divided in the thesis as follows:

- methods based on seismicity (16),
- stress changes calculation based on strain measurements (Orzepowski and Butra, 2008),
- statistical methods and numerical modelling for predicting mine tremors (11),
- laboratory tests helping to establish the relevant for forecasting correlations (Valley *et al.*, 2011; He *et al.*, 2012; Wang *et al.*, 2014),
- use of neural networks (Van Zyl and Omlin, 2001; Guangcun *et al.*, 2014),
- and various control methods such as destress blasting or no-entry periods approaches, tools assisting in choosing a suitable rock support (McMahon, 1988; Andrieux and Hadjigeorgiou, 2007; Saharan and Mitri, 2011; Kaiser and Cai, 2012).

In Figure 11 a share of articles about aforementioned methods included in the review is presented. Some of the statistical methods are also seismicity based, that is why there were used in both categories (seismicity based methods and statistical methods) to create a graphical representation of the results.

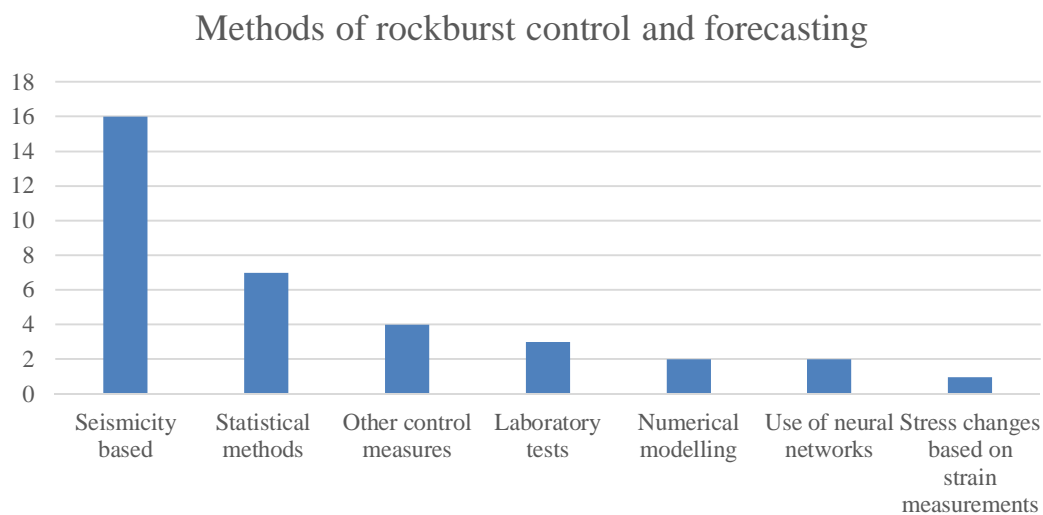


Figure 11. Share of articles about the methods of rockburst control and forecasting

The studies identified through the systematic review of the literature come from the period 1972 – 2016 (while the year 2016 is covered until May, as the searches were performed that time). In Figure 12 it can be observed that the year which yield the biggest number of the articles is 2008, and a gap can be noticed in period 1977 – 1983. It must be mentioned that the peak in 2008 is caused mainly by the release of a big number of studies concerning the statistical methods of predicting rockbursts in underground mines. Starting from the year 2008 a number of the articles concerning the on-line georisk management in underground hard rock mines published each year is noticeably bigger than throughout the previous years.

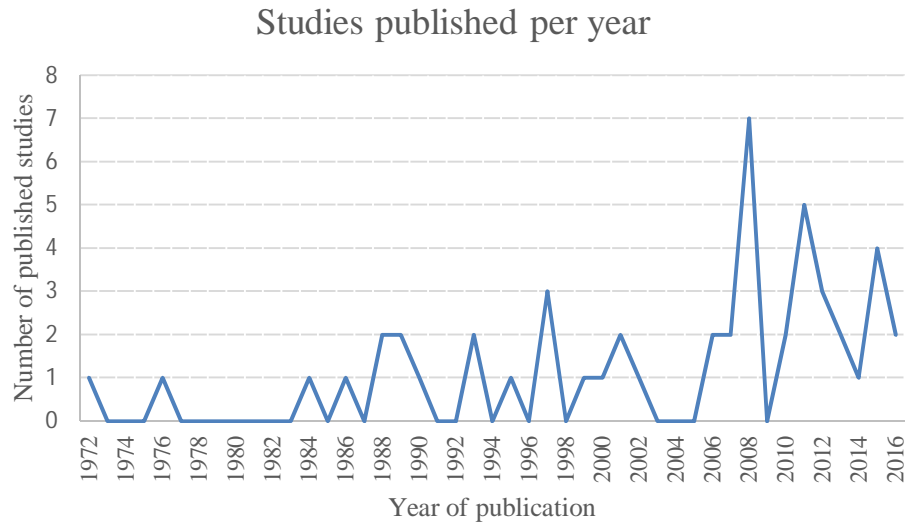


Figure 12. All the studies identified through the systematic review of the literature shown by the year of publication

A share of the articles identified through the systematic review of the literature per their country of origin is shown in Figure 13. The most of the studies come from Canada (13) and South Africa (8). These countries are followed by Poland (7), Australia (6), and China (6). Also USA (5), Russia (3), Finland (1), and India (1) have the publications included into the review.

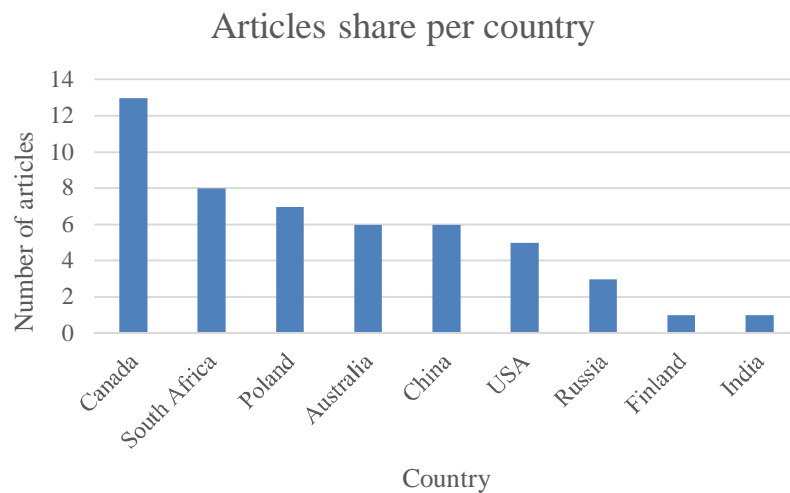


Figure 13. Share of the studies found in the systematic review shown by the country of origin

All of the countries included in the review face rockburst or strainburst problem in underground mining. From the data presented in Table 9 can be noticed that the research on georisk management in underground hard rock mines is active with a steady trend throughout the years. In the most of the years since 1972 at least one article regarding the topic of interest was yield each year.

Table 9. Years of issued publications divided by their country of origin

Country of origin	Year of issue
Australia	2013, 2012, 2008, 2007, 2002, 1997
Canada	2013, 2012, 2011, 2011, 2010, 2008, 2007, 2006, 2000, 1999, 1990, 1989, 1988
China	2016, 2016, 2015, 2015, 2014, 2012
Finland	2015
India	2011
Poland	2008, 2008, 2008, 2008, 2008, 2006, 1993
Russia	2015, 2011, 2001
South Africa	2011, 2010, 2001, 1995, 1993, 1989, 1984, 1972
USA	1997, 1997, 1988, 1986, 1976

In recent years (2010 – 2016) the most active countries in research concerning georisk management in underground mines are China (6 articles) and Canada (5 articles) (see Figure 14). Amongst the papers from China the focus is on the laboratory tests that reproduce the rockbursts and strainbursts and therefore enable to extract the most relevant characteristics of the processes. They concern also the development of real-time microseismic monitoring systems for rockbursts early warning, and use of neural networks to predict the stresses at various depths in the mine. The focus of the studies from Canada is more scattered: from approaches to the seismic monitoring system in a mine, through establishing correlations of sonic parameters and rock properties, and correlations between mining factors and decay time, to the development of the rock support design software. The articles from remaining countries focus on the development of the standard architecture for early warning systems in the mine and back analysis of rockbursts (South Africa), destress blasting techniques (India), geotechnical risk assessment guidelines development (Finland), and mining-induced seismicity management (Australia, Russia).

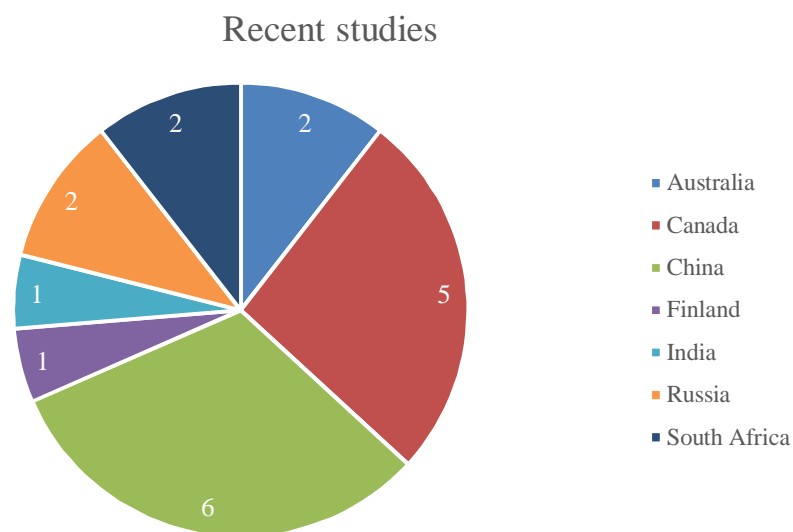


Figure 14. Most recent studies presented by the country of origin

A list of the most recent studies (coming from 2010 – 2016) included in the thesis are presented in Table 10 by their authors, country of origin, affiliation, and main research topic.

Table 10. The most recent studies (2010 – 2016) identified in systematic review of the literature

Author	Country	Affiliation	Main topic of research
Cai, 2016	China	School of Civil and Environmental Engineering, University of Science and Technology Beijing	Assessment of the rockburst proneness of the rocks to establish the countermeasures
Xu <i>et al.</i> , 2016	China	State Key Laboratory of Hydraulics and Mountain River Engineering, College of Water Resource and Hydropower	Real-time microseismic monitoring system of immediate rockburst early warning
Feng <i>et al.</i> , 2015	China	State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences	Real-time microseismic monitoring system of immediate rockburst early warning
Mishra and Rinne, 2015	Finland	School of Engineering, Department of Civil and Environmental Engineering, Aalto University	Development of geotechnical risk assessment guidelines for underground mines
Vinogradov <i>et al.</i> , 2015	Russia	Mining Institute of Kola Science Centre of Russian Academy of Sciences	Development of the 3D model for location of seismic events
Wang <i>et al.</i> , 2015	China	Key Laboratory of Geomechanics, Institute of Geology and Geophysics, Chinese Academy of Sciences	Laboratory tests of rockburst reproduction
Guangcun <i>et al.</i> , 2014	China	Key Laboratory of High Efficient Mining and Safety of Metal Mine Ministry of Education, University of Science and Technology Beijing	Use of the neural networks to predict the stresses at various depths in the mine
Badri <i>et al.</i> , 2013	Canada	Mechanical Engineering Department, University of Quebec, École de technologie supérieure	Adaptation of hazard concentration risk management method to underground mining

Author	Country	Affiliation	Main topic of research
Hills, 2013	Australia	Pitt and Sherry	Case study of mining-induced seismicity management
He <i>et al.</i> , 2012	China	State Key Laboratory for Geomechanics and Deep Underground Engineering, China University of Mining and Technology, Beijing	Laboratory tests using strainburst testing machine to establish relevant characteristics of the process
Hills, 2012	Australia	Pitt and Sherry	Case study of mining-induced seismicity management
Kaiser and Cai, 2012	Canada	Centre for Excellence in Mining Innovation, Sudbury, Ontario, Canada	Development of the software that assists in the design of the rockburst support
Hofmann and Scheepers, 2011	South Africa	AngloGold Ashanti Limited, Marshalltown	Use of back analysis of rockburst cases in order to establish a modelling method towards safer mining
Saharan and Mitri, 2011	India	Central Institute of Mining & Fuel Research, Seminary Hills, Nagpur	Destress blasting techniques applicability with a focus on strainbursting
Tsirel <i>et al.</i> , 2011	Russia	State Mining Institute (Technical University), Saint-Petersburg	Development of the cluster location procedure for mining-induced seismic events
Vallejos and McKinnon, 2011	Canada	Robert M. Buchan Department of Mining, Queen's University	Establishment of the statistical correlations between mining factors and decay time of mining-induced seismic sequences

Author	Country	Affiliation	Main topic of research
Valley <i>et al.</i> , 2011	Canada	Geomechanics Research Centre, MIRARCO - Mining Innovation, Sudbury	Assessment of in-situ rock stresses and rock mass quality based on sonic parameters
Hudyma and Potvin, 2010	Canada	Laurentian University, Ramsey Lake Road, Sudbury	Approach of seismic risk management in underground mines
Vogt <i>et al.</i> , 2010	South Africa	CSIR Centre for Mining Innovation	Development of the standard architecture of networks capable to transfer and process the data in harsh underground environments

The research institutions and companies that have undertaken research on the georisk management in underground hard rock mines which were identified through the systematic review of the literature are given in Table 11.

Table 11. Articles affiliation and number of identified issued papers per institution

Affiliation by country	Number of articles
Australia	6
Allstate Explorations NL	1
Australian Centre for Geomechanics	1
Pitt and Sherry	2
The University of Melbourne, Department of Civil and Environmental Engineering, Parkville	1
University of Western Australia	1
Canada	13
Centre for Excellence in Mining Innovation, Sudbury, Ontario, Canada	1
Department of Mining and Metallurgical Engineering, McGill University, Montreal, Quebec	1
Department of Mining Engineering, Queen's University, Kingston	2
Department of Mining, Metallurgical and Materials Engineering, Université Laval, Québec	1
Engineering Seismology Group Canada	1
Geomechanics Research Centre, MIRARCO - Mining Innovation, Sudbury	1
Itasca Consulting Canada Inc., Sudbury	1
Laurentian University, Ramsey Lake Road, Sudbury	1

Mechanical Engineering Department, University of Quebec, École de technologie supérieure	1
Placer Dome Ltd., Campbell Mine, Red Lake	1
Robert M. Buchan Department of Mining, Queen's University	1
School of Engineering, Laurentian University, Sudbury	1
China	6
Key Laboratory of Geomechanics, Institute of Geology and Geophysics, Chinese Academy of Sciences	1
Key Laboratory of High Efficient Mining and Safety of Metal Mine Ministry of Education, University of Science and Technology Beijing	1
School of Civil and Environmental Engineering, University of Science and Technology Beijing	1
State Key Laboratory for Geomechanics and Deep Underground Engineering, China University of Mining and Technology, Beijing	1
State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences	1
State Key Laboratory of Hydraulics and Mountain River Engineering, College of Water Resource and Hydropower	1
Finland	1
School of Engineering, Department of Civil and Environmental Engineering, Aalto University	1
India	1
Central Institute of Mining & Fuel Research, Seminary Hills, Nagpur	1
Poland	7
AGH University of Science and Technology, Faculty of Geology, Geophysics and Environmental Protection	5
Central Mining Institute, Department of Geology and Geophysics	1
KGHM CUPRUM Ltd. - Research, Development Centre, Wroclaw	1
Russia	3
Mining Institute of Kola Science Centre of Russian Academy of Sciences	1
Siberian Aerospace Academy	1
State Mining Institute (Technical University), Saint-Petersburg	1
South Africa	8
AngloGold Ashanti Limited, Marshalltown	1
CSIR Centre for Mining Innovation	2
Department of Computer Sciences, Stellenbosch University	1
East Rand Proprietary Mines Limited	1
Rock Mechanics Laboratory, Chamber of Mines of South Africa	1
Steyn Gold Mining Co., Ltd.	1
University of Witwatersrand	1
USA	5
Los Alamos National Lab & The Sunshine Mining Co.	1
Spokane Research Enter, National Institute for Occupation Safety	1
The Bureau of Mines	2
University of Minnesota, Department of Geological Engineering, Minneapolis	1

6.3 Systems

An attempt at the development of in-situ rockburst precursor warning system has been reported by Archibald *et al.* (1990). The aim of the research was to identify characteristics of the microseismic emissions frequency spectra and use them as precursors of rockbursts. It was a follow-up of the research conducted by the Queen's University research group and reported by Archibald *et al.* (1988) two years earlier. The research aimed at developing a method for fast detecting of a change in local stress conditions and providing a tool for warning of a violent rock failure. To achieve that the Queen's research group started developing a system which correlates acoustic emission and rock failure data. The main characteristic of the system was the ability to monitor a broad range of acoustic emission frequency output at high frequencies (40 to 400 kHz). Based on the laboratory and field experiments it was established that microseismic waveforms differ in areas producing different stress fields. Further study included an adaptation of pattern recognition technology proposed by Korenberg (1985). After this development, an acoustic emission monitoring at the frequency of 300-500 kHz was enabled, exceeding the initially established frequencies of 100 kHz. The waveform data was recorded, stored, and analysed. Acoustic emission characteristics were used to determine stress magnitude conditions within pillars and their vulnerability to failure, to be then correlated with known ground stress information. That enabled stress prediction in case when signals of unknown origin occur. The main goal was to provide a low-cost system capable of estimating rock stresses which could be used by the operators for rockburst prediction in real time. As a result, a microseismic system capable of detecting stress variation in the rock mass during mining cycles based on the waveform observation and characterization was introduced by the Queen's University, Department of Mining. Archibald *et al.* (1990) reported that analysing the acoustic emissions was performed keeping in mind that any effect produced in the rock mass might be a predecessor of rock failure. Field tests showed that the system is reliable to operate in harsh environmental conditions. It was proven that high-frequency seismic waveform data was highly dependent on the event rate parameters. A significant increase in event rates was identified as a phenomenon preceding the rockburst. The research has shown also that the waveform duration is a valid precursor to stress change. At that point, the authors recommended combining the microseismic system with locator-type networks to make use out of the low-frequency seismic data. In the meantime of Archibald's work, Spottiswoode (1989) reported on extensive rockburst research activities in South African deep-level gold mines over the period 1983 – 1987. The research focus was on developments in the areas like seismic data acquisition and processing, source mechanisms and near-source effects on seismic wave transmission, mine layouts, strong ground motion studies, and rockburst prediction and control. Especially worth mentioning are the attempts to improve rockburst prediction activities. One of them is the use of PC-based systems for seismic monitoring in Kloof Mine, pioneered by R.W.E. Green. Another outcome was an equipment capable of on-line processing of microseismic data underground designed by P. Grobler. Researchers continued their work over the years. Finally, twenty years later, still facing rockbursts risk but being given the advanced technology, Vogt *et al.* (2010) introduced a standard architecture for application in deep hard rock underground mines. The AziSA, which is the architecture's name, is described in the following subchapter.

6.3.1 AziSA

The AziSA (means “to inform” in isiZulu language) is an architecture and a set of protocols developed by the Council of Scientific and Industrial Research (CSIR) for measurement and

control networks. It can be utilised to collect, store and facilitate the analysis of data from challenging underground environments (Stewart *et al.*, 2008; Vogt *et al.*, 2009; Vogt *et al.*, 2010a; Vogt *et al.*, 2010b). In simple words, it defines how data should be transmitted between sensors and a central database, where the data is processed in such a way that it can support decision making in real-time. The goal of the AziSA system is to provide an open standard for application in underground mining, where limited power and poor communication infrastructure need to be faced on a daily basis. The authors say that with the AziSA they want to provide a way for different suppliers to work together with the same communication and database infrastructure. The idea is that the system uses existing open standards to chain them together. In case when the desired functionality cannot be obtained from an existing standard, another one can be added, depending on the current need. The aim of the system is also to incorporate the sensors and devices processing data that are cost-effective, use very little power, and can stand the harsh conditions of the underground environment like dust, heat, humidity, etc. One of the assumptions of the system is that the communication between the sensors would be wireless. (Stewart *et al.*, 2008; Vogt *et al.*, 2009; Vogt *et al.*, 2010) Stewart *et al.* (2008) state that real-time management can occur only if three conditions have been met:

1. Parameters to be managed have to be measured.
2. Measurements have to be communicated sufficiently quickly to affect the parameters being managed.
3. Measurements have to be processed and transformed into a form that is suitable to provide support for decision-making.

Each measurement needs to be marked with the time and location to enable data integrity. Sensors must be easily identified with their position in the network, be able to send data to an aggregator, and respond to instructions from the aggregator. If the sensor does not have an ability to store this kind of data itself, it remains a responsibility of its parent aggregator. One of the main characteristics of the system based on the AziSA is that it should be robust to enable a continuous monitoring to provide in-mine communication even in case if the link with the outside world is disrupted. This implies a distribution of the data, so it is not fully dependent just on the central database. Another important assumption here is that some of the decisions should be made as close to the source of the data as possible. Due to the low-power requirement, the processing power of the sensors is limited. The solution for that might be a design of the network where the sensor sub-networks are coordinated by local intelligent gateway devices, which aggregate the data and alert streams, and pass them on to the central controller while passing instructions back to the network.

The assumptions of the architecture summary:

- To provide an open standard for collecting and storing the data from harsh underground environments and facilitating its analysis.
- To support decision making in real-time by minimizing the amount of data delivered to the operator in the central station (distribution of data between the classes).
- To incorporate the sensors into the system, which are cost-effective, robust, and use little power.
- To employ mainly wireless communication between the sensors.
- The sensors need to be capable of identifying themselves in the network (time and location) and send data to an aggregator.

- The sensor sub-networks are coordinated by local intelligent gateway devices, which aggregate the data and alert streams and pass them on to the central controller while passing instructions back to the network.

The AziSA is based on the data-information-knowledge-wisdom hierarchy developed by Ackoff in 1989. Data are raw measurements, marked with time and date. Data collected in a database enables connections to be identified and that is called information. The knowledge is generated out of information by extracting key parameters and identifying patterns in it. Wisdom means making decisions and forecasting based on the obtained knowledge and information. (Vogt *et al.*, 2009)

The logical architecture of the AziSA based system comes from its physical architecture (see Figure 15).

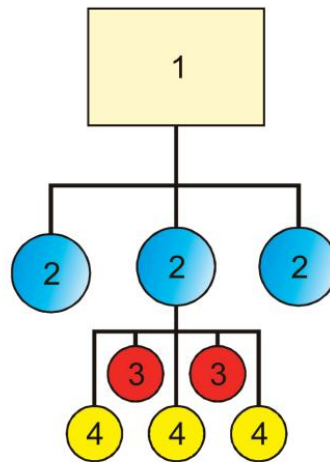


Figure 15. The AziSA logical architecture (Vogt *et al.*, 2009)

At the top of the sketch there is a class 1, which is the network controller and data warehouse. The communication of class 1 can be made with all the class 2s. The sensors installed in working places are further classified as class 3s and 4s and can communicate with class 2s or with each other. The hierarchy of classes is defined based on the decision-making power of the subsequent classes:

- Class 4 devices – make measurements, pass them to the class 2s and the class 1.
- Class 3 devices – make measurements, make decisions based on their own information (for example initiate local alarms in case if the threshold is exceeded).
- Class 2 devices – collect data from all the class 3s and 4s in their wireless network, make decisions (can raise alarm over a wider area than class 3s).
- Class 1 devices – have access to all the data in the network, collect and store data, analyse data (can issue a warning with advice or corrective action based on the analysis of all data stored in the system). (Vogt *et al.*, 2009)

For the AziSA specification, the authors advice to implement the sensor metadata through IEEE 1451 transducer electronic data sheet or TEDS specification. Communication between class 2s, 3s and 4s is proposed to be implemented via the AziSA Zigbee standard (suitable for low power, low data rate, wireless mesh networking). Another suggestion from the authors for the hardware to implement is the AziSA TCP/IP profile, Ethernet. A typical AziSA installation can be seen in Figure 16.

The reference implementation as an example of physical AziSA system and the devices already implemented or under development were described in a few studies (Stewart *et al.*, 2008; Vogt *et al.*, 2009; Vogt *et al.*, 2010a; Vogt *et al.*, 2010b). The main highlights are:

- Closure meter sensor (implemented) with its low power design and low costs is able to work over the relatively long time (a couple of weeks).
- Environmental sensor (implemented) is used for the temperature, humidity and airflow rate measurements (Vogt *et al.*, 2009).
- The system of locating mobile sensors have been developed (prototype hardware).
- Implementation of the commercially available methane sensor matched with an AziSA radio to enable real-time methane analysis (planned to be done).
- Development of a tilt sensor for rock monitoring is under development.
- Integration of the existing crack counter with a Zigbee radio is planned to be done.
- Still camera sensor as a tool for delivery of the pictures from the workplaces is planned to be developed.
- Thermal infrared camera to identify the loose rock based on its temperature (under development).
- Electronic sounding tool for the rock mass state assessment to deliver the information on the ongoing processes in the hangingwall and substitute the performance of the experienced miners is being tested.
- Geotechnical information determined from drilling rate is planned to be added to the network.
- Application of the personal dosimeters integrated into the AziSA system to enable personal environmental monitoring to prevent or mitigate exposure of workers to hazards such as noise or diesel particulate matter (under development).
- Investigation on the use of spatial augmented reality (AR) to present data in an intuitive manner to users underground in a way that the spatial AR would be projected onto real scenes. The ‘safety torch’ would illuminate rocks in colours that would depend in their likelihood of coming loose (under development).
- Development of a robot that can independently undertake the entry examination before the shift reaches the working place; the robot will likely mark areas of the hanging wall directly using spray paint (under development).

Vogt *et al.* (2009) shown an example of AziSA’s application in a case study of rockfall early warning system. An AziSA compliant sensor network was being deployed at a gold mine in 2009. The system included Zigbee closure meters with a class 2s, PLS communications and a class 1. The parameter that was primarily monitored at a short term was the excavation closure. Expected effect were the alarms generated at all levels of the hierarchy as follows:

- A class 3 device can raise a local alarm based on the measurements from the closure meter.
- A class 2 device can raise an alarm in the panel in case when the occurring failure is indicated by multiple sensors.
- A class 1 device can combine the data throughout the several locations so the system’s user can issue a warning of the increased risk.

Nevertheless, since there is no specific precursor of a rockfall discovered yet, other parameters like microseismic activity in the panel, the thermal signature of loose rocks in the hangingwall, and the state of rock as determined by barring are of interest.

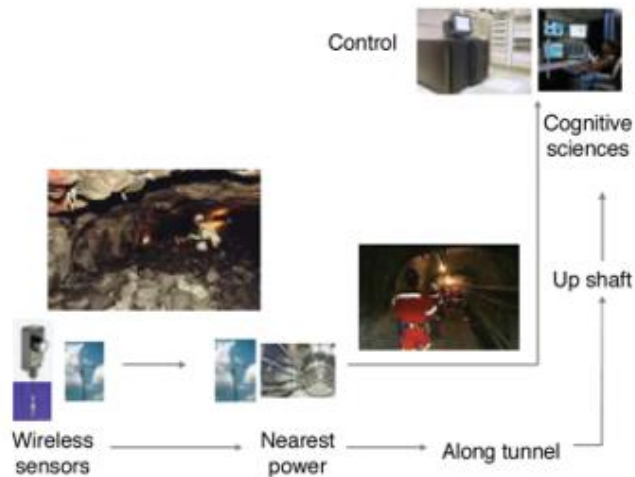


Figure 16. A typical AziSA installation. Class 3s and 4s sit in the stope and communicate wirelessly to the power at the nearest winch. From there, data travels along power line carrier to the mine's IT infrastructure, then up the shaft to a database and to the control room (Vogt *et al.*, 2010)

6.3.2 Mine Seismicity Risk Analysis Program – MS-RAP (myrap)

The Mine Seismicity Risk Analysis Program (MS-RAP) is a software developed by the Australian Centre of Geomechanics under Mine Seismicity and Rockburst Risk Management project. Its aim is to quantify the seismic risk based on the data obtained from the seismic monitoring system installed in a mine and it is employed in a number of mines in the world since 2002 (Hills, 2012). The Seismic Hazard Scale (SHS) method developed by Hudyma (2004) is utilised in MS-RAP for quantification of seismic hazard. The parameters that are used in the method are: the rate of occurrence of events of a certain magnitude, the power law relation for mine seismicity, and the maximum observed event magnitude.

The risk assessment performed in MS-RAP is done in a few steps (see Figure 17):

- In the first step data is grouped into clusters of events which represents a single seismic source.
- For each cluster the SHS parameter is calculated in order to assign it to the points in the seismic hazard map which is created using the mine plans and knowing mine geometry.
- Peak Particle Velocity (PPV) is then calculated at each location of interest, and it is scaled for distance.
- Excavation vulnerability potential for damages (EVP) is assessed based on the parameters named subsequently: stress conditions, utilised ground support, excavation span, and geological structure. The EVP is used to represent the increasing probability and severity of rockburst damage.
- The rockburst damage potential is calculated by multiplication of the EVP and the PPV at each specific location.

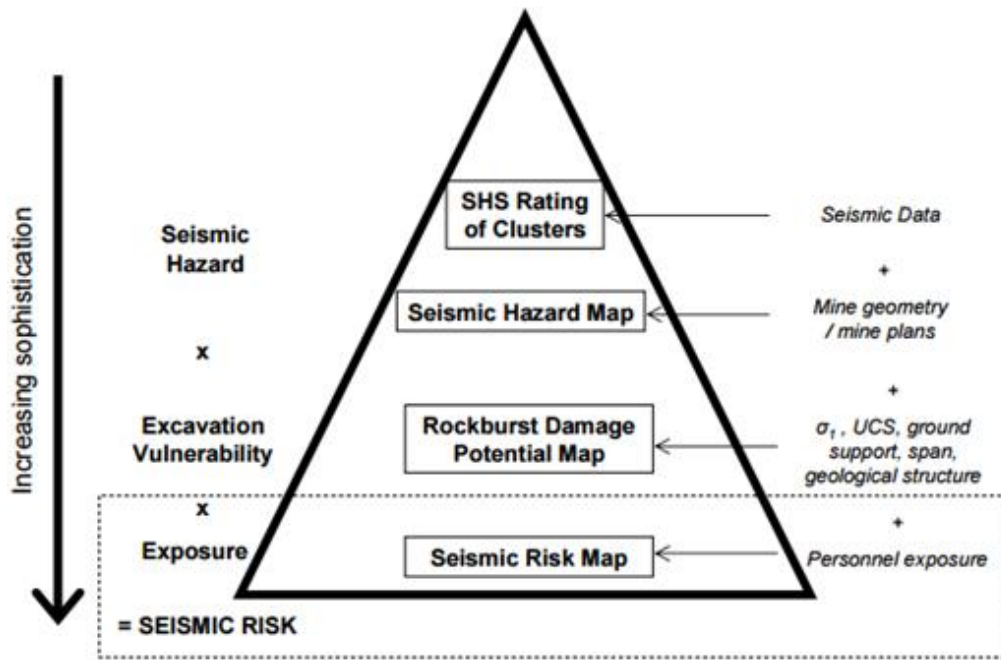


Figure 17. Flowchart representing risk assessment process used in MS-RAP (Mikula *et al.*, 2008)

As soon as the steps are completed the result can be checked against the empirical scale representing rockburst damage, introduced by Mikula *et al.* (2008) (from no damage to complete destruction of the support system). The rockburst damage potential increases with increasing EVP and PPV. Calculation of seismic risk takes into account also exposure of personnel based on the exposure ratings introduced by Owen (2004). The result is the seismic risk ratings (SRR) expressed in qualitative way, from very low (VL), through low (L), moderate (M), high (H), very high (VH), to extreme (E). It is represented in a form of matrix and can be seen in Figure 18.

	RDP=EVP x PPV	<25	25- 65	65- 115	115- 170	170- 225	225- 280	>280
Excavation type/ activity	Exposure rating							
Restricted access (no entry)	100	VL	VL	L	M	M	H	H
Decline	1000	VL	L	M	M	H	VH	VH
Travelway - no active mining	1000	VL	L	M	M	H	VH	VH
Travelway - mining on the level	2000	VL	L	M	M	H	VH	VH
Production mucking area	3000	VL	L	M	M	H	VH	VH
Busy level / travelway drive / access	4000	VL	L	M	M	H	VH	VH
Development mining	7000	L	M	M	H	VH	VH	E
Production drilling	10000	M	H	H	H	VH	E	E
Production charge-up	10000	M	H	H	H	VH	E	E
Infrastructure areas / workshops	14000	M	H	VH	VH	E	E	E

Figure 18. Seismic risk assessment matrix (Mikula *et al.*, 2008)

The MS-RAP is a predecessor for the new software called *myrap* (under development). The new software is a geotechnical data analysis and monitoring platform with specific data analysis tools. Its use is extended outside mining-induced seismicity, from which it originated. As a platform it creates the basis on which Apps dedicated at specific tasks are developed. By now there are a few Apps already in use:

- “Mining induced seismicity – general analysis” provides tools for the general analysis of mining-induced seismicity like combinations of complex spatial and range filters, tables, and 3D views (Wesseloo *et al.*, 2015),
- “Grid based analysis” introduces the tools for evaluation of the spatial distribution of seismic source parameters, an outcome is a 3D colored display of results, using transparency and gridpoint scaling (Wesseloo and Harris, 2015),
- “Plane fitting App” enables fitting a plane through selected seismic events, can be used in other Apps as display or directly as a stand-alone tool (Cumming-Potvin *et al.*, 2015),
- “Hazard Assessment” provides a tool to access the current seismic hazard in a mine based on the recent seismic records, the results of assessment of a mine-wide value for M_{max} are presented in space using iso surfaces and pseudo volumetric rendering (Wesseloo and Harris, 2015),
- “Rockburst Damage potential” is based on the Rockburst Damage Potential (RDP) system developed by Heal (2010). As an outcome it can display and interrogate the components of the method used (Cumming-Potvin *et al.*, 2015),
- “Large Event Analysis” provides an easy and quick first assessment of the distribution of strong ground motion at excavations for a given event. It displays plots for a uniform and a double couple shear mechanism (Duan *et al.*, 2015),
- “Omori Analysis Tools” provides several functions. It displays cumulative event distribution of the blasts selected for the examination. It performs a best-fit of the Modified Omori Law (MOL) to the events associated with a selected blast. Besides, it performs MOL statistical analysis which provide input to the re-entry analysis (Woodward *et al.*, 2015),
- “Seismic Event Quality” provides tools to evaluate the quality of the database and highlight potential bad quality data (Morkel and Wesseloo, 2015),
- “System Design” provides tools to assess the system sensitivity in 3D space based on the seismic database (Wesseloo, 2011; Wesseloo *et al.*, 2015).

6.3.3 Dynamic Intelligent Ground Monitoring - Digmine

The DIGMINE platform (Dynamic Intelligent Ground Monitoring Internet Network) is a new real-time Global Stress Monitoring concept introduced by INERIS in 2015 (Tonnelier and Bouffier, 2015). New methodologies of stress and seismic near-to-real time measurements employed in the system are capable of monitoring the stress changes in the vicinity of mining works in deep mines. The innovative equipment can monitor both quasi-static and dynamic stress fields, using global network monitoring arrays and mobile local-scale arrays. In addition, the system aims to incorporate mine production data to create an overview of the overall progress of mining works. Continuous measurements of geotechnical and geophysical data would enable early detection of high stress concentrations and unexpected microseismic activity. First applications of the approach used in DIGMINE are described by Feng *et al.* (2014), and the method underlying the system is outlined there. The hardware developed for the acquisition of data consists of several components. Microseismic probes enable to estimate the dynamic stress regime, being deployed over the mine.

The quasi-static stress regime is monitored by the 3D stress cells. Data acquisition is conducted via modules and units connected to clusters of sensors in the mine and with access to the Ethernet mine data flow. Seismic risk assessment is done by the database technology tailored to manage, process, and report stress data measurements coming from the devices connected to the network. Keeping in mind harsh working conditions in deep underground mines, INERIS proposes in their approach that low-power-consuming and autonomously-self-running devices should be used to ensure an undisturbed data flow even in the case of power failure. The data should also be automatically sent to external servers to optimize its sampling frequency and save data storage space (see Figure 19). Determination of initial stress state of a rockmass is performed by back-computation. The stresses are first measured with CSIRO cells and stored in a database with the numerical model according to the range of measured stress states for each location. After the sufficient amount of data is collected, the next step is fitting polynomial functions. Finally, a computation from input stress state (initial or induced) the corresponding induced or initial stress state without 3D complex modelling. Improvement of the accuracy of initial stress back-computation is achieved by minimizing the tortuosity of a 3D surface of (initial or induced) stresses from (induced or initial) input stresses (Tonnelier and Bouffier, 2015). The method has been tested in the Garpenberg mine, where instrumentation with CSIRO cells was performed and based on the obtained data the analysis were successfully conducted (Al Heib, 2015). The modelling was proven to allow following evolutions of principal stresses, safety factor, minor plastic strain, maximum shear stress, and elastic energy. The system enables to display time-varying curves of measured and calculated stress shifts and enhance detection of caving by analysis of microseismicity. Currently, the system is functional and able to correlate the stress variation and seismicity to the volume of mining. The data is recorded in real-time and supplies the user with analysis on a daily routine.

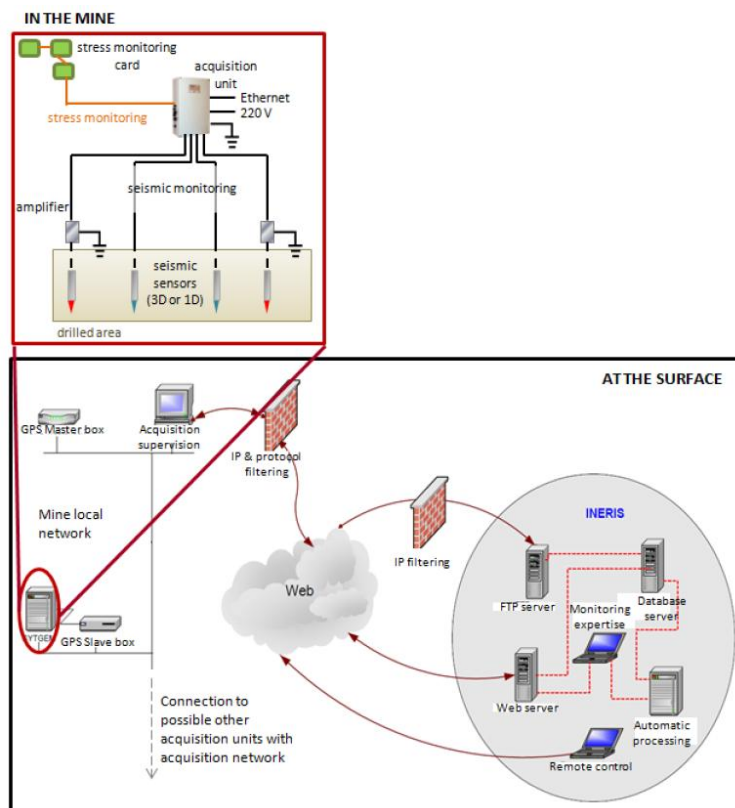


Figure 19. Example of configuration of monitoring data web (Tonnelier and Bouffier, 2015)

6.4 Management

The management of rockburst and mining-induced seismicity faced by mining companies differs from site to site. It must be tailored in detail to the characteristics of a mine, orebody, mining method, etc. Examples found in the literature provide an overview of the available and already utilised management methods. Some of these, obtained through the systematic review of the literature, are collected in this subchapter.

In the Witwatersrand, South Africa, the problem of rockbursts started to be serious already in 1908 (Ortlepp and Steele, 1972). The deep need for an understanding of rockburst processes and development of methods which would minimize their occurrence started at that time, and together with them adjustment of mining methods and use of artificial support became a crucial task for any mining venture. The efforts and history of activities conducted throughout the years are discussed by Ortlepp and Steele (1972) in their publication about management of rockbursts. Based on the case of the East Rand Proprietary Mines Limited (E.R.P.M.), South Africa, the authors notice the problem of lack of rockburst incidence records. Having an industry-wide, uniform and simple in use system of records of rockbursts was found to be a necessity for the entire industry. The main reason underlying their statement was very difficult or even impossible estimation of the problem magnitude. That decreased the speed of research and development of rockbursts countermeasures, as the comparison between the effectiveness of different methods employed in various mines was not possible. Apart from stressing out the obvious mining industry needs, Ortlepp and Steele (1972) provide an exhaustive description of rockburst management on the E.R.P.M. The countermeasures, such as novel for that time mining methods (longwall mining), and artificial support (yielding rockbolts), are discussed in the paper.

The research on rockbursts problem magnitude and its nature in South African gold mines is also reported by Dempster *et al.* (1984). The paper discusses the differences in seismicity in the various gold mining districts of South Africa and highlights the role of local geology in developing different approaches to mining. The authors conclude that a mine cannot operate efficiently and safely without proper management. The functions of management in mines, which at that time still were a rather new topic, and mine design considerations are presented based on the cases from various sites in South Africa. An integrated approach which combines rock mechanics with the development of computer techniques to model mining situations, and introduction of seismic technology to the mining industry, are emphasized as probably one of the most important steps in the field achieved by that time.

Clearly, that integrated approach became accepted, applied, and tested throughout the mining industry over the next years (Delgado and Mercer, 2006; Hills and Penney, 2008; Hudyma and Potvin, 2010; Hills, 2012; Badri *et al.*, 2013; Hills, 2013). As Ortlepp and Steel wished in 1972, the records of rockbursts incidents became registered, and seismic technology was widely applied for that purpose. Various authors reported about the performance of management approaches and improvements to seismic systems employed in the mines, not only from South Africa, but also from other places in the world. Delgado and Mercer (2006) discuss the case of Campbell Mine, in Canada, where the mine-wide microseismic system was installed since the early nineties, and was expanded by 2006. The Campbell Mine in 2006 operated one of the largest mine microseismic systems of that time with 136 channels of installed capacity and 128 sensors. The details about the microseismic instrumentation including its design, the evaluation of system's performance and management of data are discussed in the study and further followed by two case studies.

Delgado and Mercer (2006) conclude that the insight into the rock mass state changes through the real-time and accurate location of the seismic events creates the basis for the safe and profitable operation of the mine. Another example of managing mining-induced seismicity comes from the Beaconsfield Gold Mine in Tasmania. Hills and Penney (2008) introduce the history of seismicity in that mine and employment of seismic monitoring system, together with seismic hazard evaluation methodology. The approach for seismic analysis, including details on instrumentation of the mine, methods of stress measurements, and numerical modelling to determine stress levels around excavations are discussed in the paper. Amongst the methods of seismic hazard management, the authors list:

- de-stress blasting in strainbursting areas,
- strainburst management plan (provides all the controls needed to minimize the risk of operation in strainburst prone areas),
- and avoiding areas of high seismic hazard (exclusion periods), which were identified using Mine Seismicity and Risk Analysis Program (MS-RAP) software.

The dynamic impact of seismicity for shakedown and strainburst conditions is taken into account in Beaconsfield when it comes to the engineering of ground control measures, report Hills and Penney. A follow-up of Hills and Penney's (2008) study on the Beaconsfield Mine comes back a few years afterwards with the papers by Hills (2012, 2013). Again, a need for proper management of the geotechnical environment is highlighted. Amongst the new methods mentioned by Hills, there is the implementation of the Safe Working Procedures document and development of the Ground Control Management Plan. The latter provides a set of control measures and procedures that need to be strictly followed to maintain safe and feasible extraction. For the sake of applicability, it contains a number of flowcharts, which simplify its use to the mine personnel.

The work on seismic risk management was continued, and in the meantime of Hills and Penney and Hills's studies, Hudyma and Potvin (2010) introduced an engineering approach to seismic risk management. Their methodology relies on the fundamental steps of general risk management. Identification of active seismic sources in the mine, characterization of sources in terms of hazards, estimation of the potential damage in case of occurrence of the large events, and risk mitigation to minimize the consequences (if the damage occurs) outline the phases which need to be achieved. In their study, a spatial clustering of microseismic events is introduced and proposed as a useful tool in hazard location identification. Hudyma and Potvin (2010) write that the high-resolution microseismic monitoring systems are useful data collection tools. Nevertheless, to perform reliable seismic risk evaluation, an understanding of seismic sources plays a crucial role. The authors provide a list of parameters, which characterizes the failure mechanism and hazard at a seismic event source to further use it for description of seismic hazard of cluster groups:

- the frequency-magnitude relation of events,
- the timing of events as a result of stress field changes,
- the timing of larger events vs. smaller events,
- the ratio of S-wave to P-wave energy,
- the level of Apparent Stress associated with the failure process.

In the bigger perspective, the parameters analysis, together with clustering of seismic events, hazard assessment, hazard mapping, and rockburst damage potential assessment are

incorporated into the MS-RAP (currently m χ rap), which is used in over 30 mines since 2002 (Hudyma and Potvin, 2010).

Three years later, Badri *et al.* (2013) came up with an approach of adaptation of risk management methodology used in open-pit mining in Canada to Canadian underground gold mining. The aim of the study was to integrate occupational health and safety (OHS) into risk management in mining projects in Quebec. Based on a novel concept called “hazard concentration” the method is combined with the multi-criteria analysis technique known as the Analytic Hierarchy Process (AHP). Badri *et al.* explain that “the hazard concentration concept is used to estimate the potential for these hazards to lead to undesirable events”. Moreover, they further continue that “the AHP method is used to form and evaluate various categories of hazards and to monitor expert judgements in order to provide reliable estimates of risk”. Hazards identification is performed through interviews, questionnaires, observation etc., and based on that experts can evaluate potential risks.

6.5 Assessment

Geotechnical risk assessment and seismic risk assessment in deep underground mines have been a topic of discussion over the years (Singh, 1988; Cichowicz, 1993; Stewart, 1995; Singh *et al.*, 2002; Mishra and Rinne, 2015). The approaches and methods of risk assessment identified through systematic review of the literature are given below.

Singh (1988) introduces a rockburst proneness assessment of certain areas in a mine and their further classification considering the rockburst occurrence. He proposes a classification of mine workings using the burst-proneness indicators: burst-proneness index, decrease modulus index, burst-energy release index, relative violence of rupture, burst-efficiency ratio, and rock dynamic index. These indices in combination with the application of in-situ approaches (e.g. microseismic monitoring, energy release rate measurements, excess shear stress criterion, electrical resistivity of rocks measurements, seismic velocity technique, and state of stress measurements) can be combined to determine the rockburst proneness of the mine workings. The correlation between the modulus index and burst-proneness index, strength, brittleness, and the strain energy stored in the rock specimen introduced by Singh can also contribute to more accurate rockburst occurrence assessment. As a result, an arbitrary scale for the burst tendency of hard rocks is proposed, which enables to distinguish between the areas of low, medium, and high burst tendency. Having identified the areas with high tendency of burst occurrence, the author proposes the application of rockburst prevention measures. Cichowicz (1993) proposes another, more developed method. In his study he presents a prototype of the stand-alone tool, combining multidisciplinary experience for seismic hazard evaluation in underground gold mines. A concept of an expert system for seismic hazard analysis was proven in a case study to be practical in estimating the probability of occurrence of seismic events. The system hierarchy relies on analysing seismic hazard in four steps:

- estimating the maximum expected magnitude of a seismic event to occur,
- estimating the unconditional probability of occurrence,
- analysing seismic patterns based on past seismicity,
- incorporating other recognized relevant precursors into evaluation to increase evaluation’s confidence (see Figure 20).

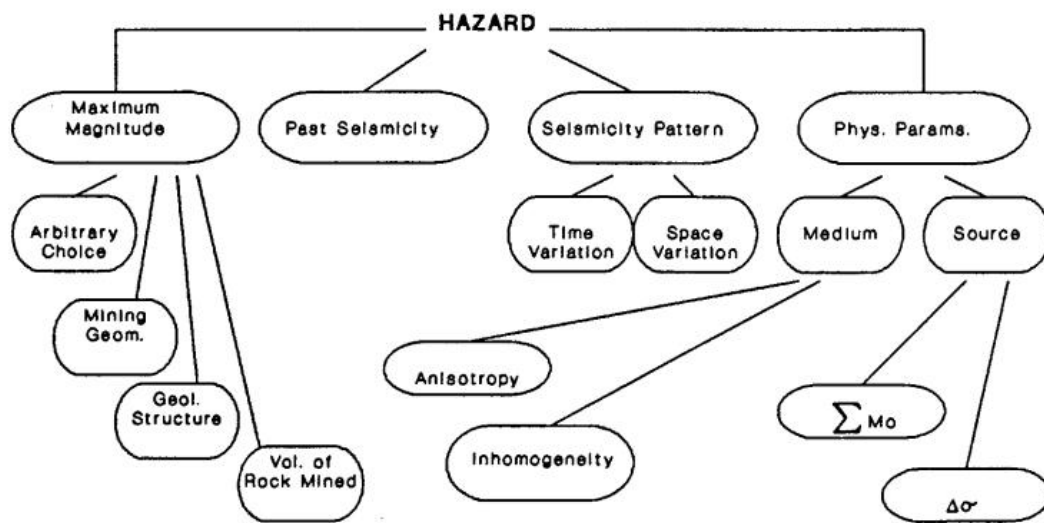


Figure 20. Graphical structure of hierarchy in expert system for seismic hazard analysis (Cichowicz, 1993)

The occurrence of a seismic event probability can be estimated after the second, third, or fourth step. The accuracy of assessment can be considered high. However, Cichowicz identified that to enable the use of this system it should be incorporated into existing software and hardware systems as well as human experts. In that way, it could be used to support decision-making in safety-related situations in mines.

A seismic risk assessment method in rockburst prone deep mines with a comprehensive seismic monitoring system was introduced to the industry by Stewart (1995). The method uses several seismic hazard parameters at the same time and assesses daily the seismic risk in investigated areas parameters:

- apparent seismic risk,
- variations in the dimensionality of the spatial clustering of the recorded microseismicity,
- volume of rock in which the dynamic stresses are greater than some critical value,
- changes in the measured stress-drop values of the recorded microseismicity,
- and changes in the intensity of spatial clustering of the recorded microseismicity.

Initially, it was developed for up-dip mining, to be further adapted to mining on strike at an experimental preconditioning site. Application of this technique to a selected 15 months long data set was found rather successful (Stewart, 1995). Nevertheless, the refinement of the method before its implementation and incorporation of more seismic parameters to enable more accurate hazard assessment were required.

Both qualitative and quantitative techniques are used to maximize the accuracy of seismic hazard assessment in the Junction Gold Mine in Australia (Singh *et al.*, 2002). Qualitative hazard assessment aims to identify what role plays each of the primary factors associated with mining-induced seismicity. Amongst the parameters are properties of the rock mass, geological structures, mine development, and stoping. An output from analysis of these parameters is a qualitative seismic hazard map. It evaluates the influence of several factors

on the planned mine works. Hazard is divided into categories (high hazard, geological hazard, mining-induced hazard, and future mining-induced hazard) and displayed on the map. The Integrated Seismic System (ISS) is used to assess seismic hazard in quantitative way. It monitors the level of mining-induced seismicity and provides a time-history database of seismic source parameters generated in a mine. Singh *et al.* (2002) provide a comparison between qualitative and quantitative seismic hazard assessment, highlighting their strengths and weaknesses. They notice a need for developing a real-time quantitative seismic hazard map.

Apart from the risk assessment methodologies focusing on seismic features of the rockmass proposed by a number of researchers worldwide, a more extensive risk assessment method tailored to the mining industry purposes introduce Mishra and Rinne (2015). Their approach to planning and organizing a geotechnical risk assessment (GRA) can become a useful tool for decision-making support in risky areas at the stages as early as mine design. Depending on the nature of the GRA, its division on proactive (done in advance) and reactive (done on existing operation) is proposed. Mishra and Rinne consider the extent of area covered by the GRA, from workplaces and drift networks, to an entire mine system. That flexibility makes the method more efficient. Also, hazard identification can be performed either by individual hazards determination or consideration of hazards from the perspective of a specific area in a mine. Several tools for hazard and risk identification and assessment are provided in the study, together with guidelines for choosing the appropriate one for each case. The outcome of the GRA is proposed to be represented in either matrix or graphical format so that it is easy to read and interpret. Hazards can be identified at a site equipped with this tool, and mitigation measures can be applied before the hazards pose a risk to the workforce.

6.6 Methods

Development of methods for rockburst monitoring and control measures, their prediction, detecting hazardous rockmass conditions, or reducing the stresses is a task undertaken by number of researchers since the occurrence of mine tremors started to pose a serious risk for the mining ventures. These methods include processing data from monitoring the microseismicity and stress changes in the rockmass, extracting the relationships and patterns from them to interpret further and represent the data in a form which is easy to use and support the decision-making in a way that increases efficiency and ensures safe operation. Amongst the most commonly used methods there are:

- methods based on seismicity (McLaughlin *et al.*, 1976; Van Eeckhout *et al.*, 1984; McMahon, 1988; Poplawski, 1997; Friedel *et al.*, 1997; Scott *et al.*, 1997; Urbancic and Trifu, 2000; Albrecht and Sharrock, 2007; Hudyma and Brummer, 2007; Cianciara and Cianciara, 2008; Lesniak and Pszczola, 2008; Orlecka-Sikora, 2008; Tsirel *et al.*, 2011; Vallejos and McKinnon, 2011; Feng *et al.*, 2014; Xu *et al.*, 2016),
- stress changes calculation based on strain measurements (Orzepowski and Butra, 2008),
- statistical methods and numerical modelling for predicting mine tremors (Lasocki, 1993; Mitri *et al.*, 1999; Mansurov, 2001; Kornowski, 2006; Lasocki and Orlecka-Sikora, 2008; Lesniak and Pszczola, 2008; Hofmann and Scheepers, 2011; Tsirel *et al.*, 2011; Vallejos and McKinnon, 2011; Vinogradov *et al.*, 2015; Cai, 2016),
- laboratory tests helping to establish the relevant for forecasting correlations (Valley *et al.*, 2011; He *et al.*, 2012; Wang *et al.*, 2015),
- use of neural networks (Van Zyl and Omlin, 2001; Guangcun *et al.*, 2014),

- and various control methods such as destress blasting or no-entry periods approaches (McMahon, 1988; Andrieux and Hadjigeorgiou, 2007; Saharan and Mitri, 2011; Kaiser and Cai, 2012).

6.6.1 Seismicity based methods

Microseismicity and seismic parameters that can be obtained from monitoring of the rockmass are very useful data in tracking and predicting the rockbursts. The systematic review shows research either developing new methods of obtaining, processing, and interpreting the seismic data or reporting the application of seismic monitoring systems performance in the mines. Sharing the experience and creating databases with records of mine tremors enable evaluation of the problem magnitude, which despite the considerable upgrade, remains serious. McLaughlin *et al.* (1976) introduced the first state-of-the-art of rockburst control performance. They provide a list of studies on that topic, where the oldest by Obert and Duval comes from 1945, and discusses microseismic method of predicting rock failure in underground mining. Mc Laughlin *et al.* (1976) report on the improvements in the field and based on the case of the Coeur d'Alene Mining District they show the development and application of microseismic and surface monitoring equipment (e.g. microseismic magnetic-tape recorder, portable microseismic unit, broad-band microseismic equipment, short-period, photographic-type seismograph, strip chart recorder, and direct-readout, short-period seismographs). Apart from making use of seismic characteristics of rockmass response to mining, the researchers suggest the use of several control measures against rockbursts, such as methods of stope-pillar destressing. The latter is further under investigation for a number of years, and its application and effectiveness are proven in many cases.

Next attempt of improving rockburst monitoring system of one of the Coeur d'Alene Mining District mines report Van Eeckhout *et al.* (1984). In the study of the Sunshine mine, three methods of calculations of bursts are discussed and compared. The authors provide a description of all stages of data analysis. They show the final output in graphical format and compare it, considering the accuracy of three burst location codes. Reporting about the Coeur d'Alene Mining District case continues in the literature (McMahon, 1988). The paper by McMahon issued by Bureau of Mines is a report which further describes the rockburst problem and undertaken countermeasures in the district. Microseismic method of determining locations of seismic events, after several years of its utilization, is finally proven to be useful and effective for the case of Coeur d'Alene Mining District. The report provides the characteristics of the mines and setups of the microseismic monitoring systems, and can be used for further research and improvement of the method. Another significant result reported by McMahon is effectiveness of already examined methods of destress blasting and rock preconditioning in a burst-prone mine area. Useful developments in the Coeur d'Alene Mining District triggered further investigation of new mining methods suitable for highly burst-prone areas in the mine.

A method for monitoring mining-induced stress changes in the rockmass using 3D seismic tomography presented Friedel *et al.* (1997) and Scott *et al.* (1997). The authors discuss tomographic surveys conducted at the Homestake gold mine and Lucky Friday silver mine in the USA. They outline the stages of tomographic imaging:

- process of data acquisition,
- obtaining a proper seismic resolution,

- model parameters and grids selection,
- tomographic reconstructions process,
- and uncertainty evaluation.

Stress changes due to ground failure, and stope advancement obtained from data processing are given and discussed. The method enables to represent even difficult-to-image low-velocity features (after ground failure) in an accurate way and identify stress gradients within a short distance from mine openings. The authors write that despite some limitations, the model can be applied as a tool for ground stability hazard evaluation.

Works on the development of more advanced seismic monitoring systems were ongoing in South Africa throughout the years (Poplawski, 1997), yet no studies were obtained on that topic through the systematic review. Nevertheless, in 1997 Poplawski reports the results of the implementation of the first modern seismic monitoring program in Australia at Mt Charlotte underground gold mine, purchased from CSIR (South Africa) in 1994. The system was the first modern system of this kind in Australia. Poplawski describes system's setup, stressing that orebodies and major geological features were enclosed within geophone network. The entire process of data collection, processing, and interpretation is controlled from the office area on the surface. The study discusses extensive work being done to assess potential rockburst indicators for Mt Charlotte. Development of a new method for rockburst hazard evaluation is presented. The seismic system was proven to be a useful tool for seismic event location and magnitude investigation. During utilization of the seismic monitoring system, a new "departure indexing method" for rockburst analysis of seismic characteristics was being developed and tested, which aimed to rockburst hazard evaluation and was supposed to be valuable for rockburst prediction.

Urbancic and Trifu (2000) provide a note with an overview of the status of seismic monitoring instrumentation in Canadian underground mines for the year 2000. They show an example of seismic instrumentation for data acquisition and processing (see Figure 21). A typical seismic monitoring installation is configured using twisted pair cable, fibre optics, radio telemetry, or a hybrid combination of the above. "Digitization rates are up to 40 kHz with 16-bit resolution, allowing for the effective recording of events with magnitude down to -3. Acquisition units employ complex trigger logic to reduce mistriggers due to mine noise. Installed sensors are typically either uniaxial or triaxial accelerometers. For surface installations, geophones are used most often. A Global Positioning System (GPS) is employed to time-link regional and local systems." write the authors. A common software operates in a multi-tasking environment, enabling simultaneous run of several applications. Database stores all seismic parameters, where the processes of records filtering based on established constraints are conducted. Data can be visualized and plotted in real-time, also for 3-D viewing. Urbancic and Trifu highlight that the advances in seismic monitoring enabled already to estimate the deformation and relative stress state of the rockmass in the vicinity of excavations. They also notice the potential for evaluating hazards related to ground issues in mines. Apparently also other researchers triggered that topic.

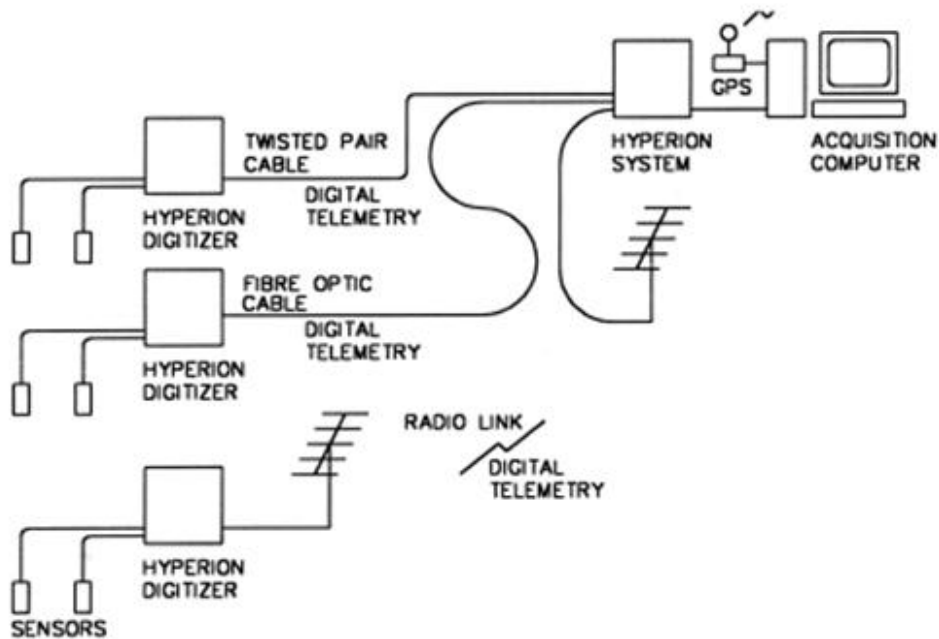


Figure 21. Schematic diagram of seismic monitoring instrumentation (Urbancic and Trifu, 2000)

Albrecht and Sharrock (2007) published a study where they discuss the methods used for evaluation of seismic events damage potential at the excavation boundary. The authors propose the use of the ground motion relationships. They suggest to use them for identification of the areas in a mine that are prone to damage or these which may have sustained rockburst damage from a seismic event. The cumulative peak particle velocity (PPV) parameter is proposed to be used to identify areas that have sustained repeated, potentially damaging seismic loads in a mine. Albrecht and Sharrock summarize their study with a suggestion that focusing just on plotting locations of the seismic events around the mine is not enough, and propose a change of approach into plotting ground motion parameters on the boundaries of the excavation. In that way the operators could see the unsure locations which need inspection or other means of support. In the same year, Hudyma and Brummer (2007) release the study with guidelines for accurate design and efficient operation of seismic monitoring systems in mines. They show tricks and traps concerning seismic arrays implementation and data analysis, together with the general rules of a proper design of seismic monitoring systems. This undoubtedly useful study informs about a “good system” design, highlighting the crucial aspects of an efficient and valuable implementation and operation of the seismic system in a mine, such as frequent data analysis, and routine auditing of the system.

In 2008 a couple of statistical methods of predicting mine tremors based on seismicity were introduced (Cianciara and Cianciara, 2008; Lesniak and Pszczola, 2008; Orlecka-Sikora, 2008). Cianciara and Cianciara (2008) present a method of tremor risk estimation on the basis of seismic emission registered in mining exploitation zones. In the technique, they consider the stress changes in the rockmass and accompanying them processes of compaction (hardening), dilatancy (softening), and then possible tremors. The authors used a mechanism of changes in attenuation values and based on that proposed a technique for determination and monitoring of tremor risk. The method was tested in several mines and proved to be effective.

For assessment of errors in the seismic events magnitude estimation, Orlecka-Sikora (2008) proposed use of resampling methods. The development of an algorithm based on the bias-corrected and accelerated method and its performance is introduced in her study. For mine tremor location Lesniak and Pszczola (2008) present an adaptation of already existing and used method from Lubin Copper mine (Poland). The two-step combined location method uses P-waves first arrival times and P-waves directions and is mostly applicable where the accuracy of the vertical hypocentre coordinate location needs to be increased. Another method to provide positioning of horizontal coordinates of seismic events with a sufficient accuracy present Tsirel *et al.* (2011). Their new, cluster location procedure for mining-induced seismic events uses the algorithm called SPAM. Its tests showed relatively high inaccuracy, although it is tolerant for strong disturbance and capable of sound positioning of hypocentres (even those with considerable errors in the initial data).

Vallejos and McKinnon (2011) presented the research that focuses on the establishment of statistical correlations between mining factors and the decay time of mining-induced seismic sequences. A method of estimating background levels of seismicity rate for re-entry protocol development in combination with used re-entry practices is described in their study. They present a theoretical development of a link between the productivity of seismicity and decay time to background levels, using modified Omori's law. The authors show the evaluation of the method through the case studies. Vallejos and McKinnon propose a procedure for estimating seismicity rate thresholds for re-entry protocol development. They suggest it can be useful for evaluating the global response of the seismic environment or to isolated seismic sequences for back-analysis. They notice a need for further investigation of the controlling parameters in decay time of mining-induced seismic sequences (volume of mined rock, depth, and magnitude of the main event) to enable development of a methodology showing how to account for these factors for a general re-entry protocol.

In the most recent study about methods of predicting rockbursts based on seismicity found in the systematic review, a methodology of immediate rockburst warning is introduced by Feng *et al.* (2014). The method deals with the immediate rockbursts, which predecessors are usually a series of microseismic events around the area in which the rockburst occurs (Feng *et al.*, 2014). These microseismic events make it possible to obtain dynamic warnings. Microseismic data is applied in rockburst warning formula, which is the crucial part of the whole method. It consists of several steps: rockburst database creation, determination of typical rockburst cases, identification of the relationships between microseismicity and rockbursts, determination of the optimal weighting coefficients, and dynamic updating. Feng *et al.* (2014) give the detailed explanation of subsequent stages. The authors also introduced a division of strain and strain/structure slip rockbursts regarding their intensity. This makes the method rather innovative, as currently there is no research presented in the literature which deals with rockburst intensity warning based on microseismic monitoring (Feng *et al.*, 2014). A successful application of given method at the Jinping II hydropower station in China described by Feng *et al.* (2014) is further discussed in the study by Xu *et al.* (2016). Again, the topic of the Jinping II hydropower station in China is outlined, and the microseismic monitoring system design and application are presented. The authors discuss the results of 2 years long microseismic monitoring process during tunnels excavation and highlight a successful forecasting of strainbursts using microseismic monitoring method. The technique used in the study proves its suitability for the purpose of forecasting the strainbursts and effectiveness in the process of strainbursts hazard assessment and mitigation.

6.6.2 Statistical methods and numerical modelling for predicting mine tremors

Analysis of data obtained through various types of measurements systems employed in the mines is the most crucial stage in the process of predicting mine tremors and forecasting large rockbursts in the mines. The systematic review revealed that important role play here the statistical methods of analysing data (Lasocki, 1993; Mansurov, 2001; Kornowski, 2006; Lasocki and Orlecka-Sikora, 2008; Cianciara and Cianciara, 2008; Lesniak and Pszczola, 2008; Orlecka-Sikora, 2008; Tsirel *et al.*, 2011; Vallejos and McKinnon, 2011; Cai, 2016), and with the time more and more advanced methods of numerical modelling (Hofmann and Scheepers, 2011). Based on the outcomes of statistical or numerical investigations the operators in a mine can make decisions which are based on the reliable information.

Attempts to develop statistical methods of predicting mine tremors by processing and analysing local mining-induced seismicity introduces Lasocki (1993). The basis of the methodology are relations between the properties of time series of tremors originating directly from mining operations. An outcome is a forecast in a form of a function of all assumptions included from the stage of constructing the model of tremor generation, empirical data used in the procedure of model identification, and estimation technique. Having all of that an estimation of time-varying probability of strong tremor occurrence in a stope vicinity can be performed. Another method for predicting strong rockbursts occurrence in mines presents Mansurov (2001). Based on the case of North Ural Bauxite Mines region he describes the development of rockburst prediction algorithm and discusses its application in retrospect to a chosen set of data, where a high efficiency of the method was obtained. Another statistical tool for rockburst occurrence probability estimation introduces Kornowski (2006). An application for this tool, using history records of rockbursts occurrence, can be found in the areas in a mine with installed seismic and seismoacoustic sensors. The identified rockburst probability can be translated as the rockburst hazard.

A numerical modelling methods for predicting rockbursts by Mitri *et al.* (1999) and Hofmann and Scheepers (2011) were also identified through systematic review. Mitri *et al.* (1999) discusses a numerical modelling approach which aims to calculate mining-induced seismic energy release rate and the strain energy storage rate, taking into consideration in situ stress conditions, mine geometry, and geomechanical properties of rock mass. An application of the technique is presented in a case study of a cut-and-fill stope of a Canadian underground mine with a record of rockburst in the crown pillar. The steps taken into consideration in the numerical modelling process are outlined in the study and the results are discussed. Mitri *et al.* (1999) conclude that the energy release rate and the energy storage rate parameters introduced in their research can help in strainburst caused by mining potential estimation. To estimate the strainburst occurrence the authors present a burst-potential index, which can help to estimate the potential of strainburst occurrence given in percentage. Nevertheless, it should be mentioned that the model obtained in numerical modelling remains conservative, as it uses linear elastic rock behaviour that lowers the values of the aforementioned parameters and index. Back analysis of two mining induced tremors at Great Nologwa Mine, in South Africa discuss and Hofmann and Scheepers (2011). They perform the back analysis using a boundary element numerical modelling program to find out whether a boundary element program could successfully simulate shear slip seismic sources. Another aim of the study is to establish a modelling method toward safer mining in the underground tabular mining environment. Data used for the modelling, the boundary element model, calibration parameters, and back analysis are described in the study. The

model gave satisfactory results regarding quantitative estimates of seismic potency. The data obtained from the model can support identification of seismic hazards in a mine.

6.6.3 Laboratory tests helping to establish the relevant for forecasting correlations

The rockburst phenomenon research is undertaken through a variety of laboratory tests, attempting to establish the crucial mechanisms occurring in the rockmass and find the correlations between them (Valley *et al.*, 2011; He *et al.*, 2012; Wang *et al.*, 2015). The outcomes of such research contribute to the overall state of knowledge about rockbursts and help to design safe and efficient methods of extraction.

The study of sonic parameters correlation and rock properties present Valley *et al.* (2011). The paper describes the processing methods necessary to extract sonic parameters from full waveform sonic logs which can be further used to assess in situ rock strength and rock mass quality. Based on the data acquired from one borehole the processing methodology is performed using a semblance analyses. Extraction of attenuation information, median frequency, and the power are presented. In the study it was proven that exists a correlation between P-wave velocity and strength of a rock. However, use of P-wave velocity to predict rock strength is not recommended.

He *et al.* (2012) describe the laboratory tests conducted using the strainburst testing machine and impact-induced rockburst testing machine. The aim of the experiments was to investigate the rockbursts mechanisms. As a result of the research authors propose a new classification of rockbursts (see Figure 22). These are classified in two major types, which are strainbursts, (subdivided into instantaneous burst, delayed burst, and pillar burst) and impact-induced burst (subdivided into the rockbursts induced by blasting or excavation, by roof collapse, and by fault slip).

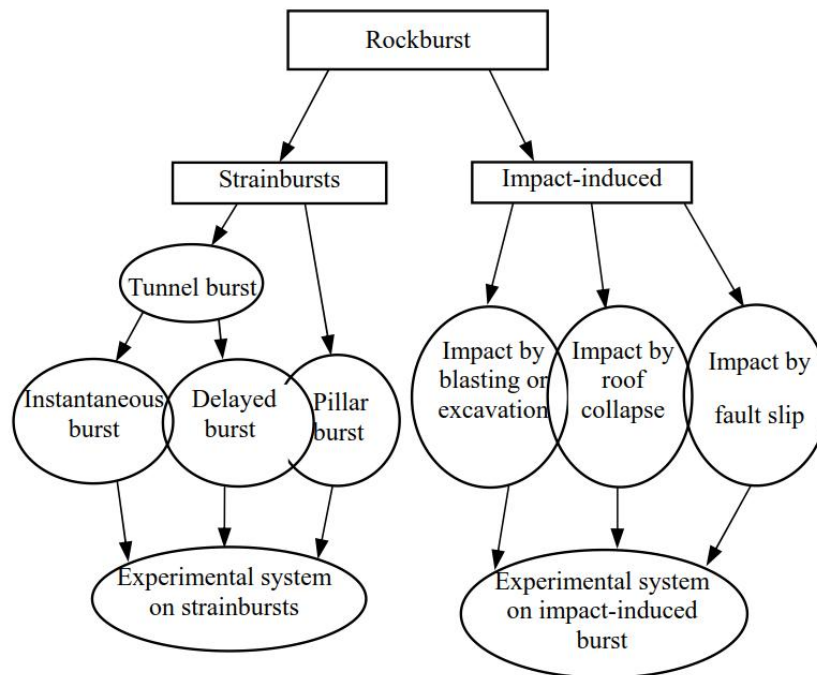


Figure 22. Laboratory experimental methods based on rockburst classification (He *et al.*, 2012)

The study discusses also the development of constant-resistance and large-deformation bolt (CRLDB) and shows its possible application and performance in Jinping II hydropower station in China. Its tests shown that it absorbs the impact energy during the rockburst events. It was proven that it can be used as a rockburst control and prevention tool in deep underground excavations. Another study, reported by Wang *et al.* (2015) describes granite instantaneous rock burst process reproduction using Deep Underground Rockburst Analogue Testing Machine (DURATM). To perform quantitative analysis of a rockburst, describe the images of tracer particle, obtain displacement and strain fields, and describe debris trajectory the Particle Image Velocimetry (PIV) technique was used. The PIV method was proven to be able to track the tracer particles in the flow field of rockburst and it can be used in the experimental study of rockbursts. Wang *et al.* (2015) in their study proposed also a new method of calculating the energy of rockburst, which uses values obtained from the displacement field and crushing ratio. That method can be used to establish the energy criterion of a rockburst, and to support rockburst prediction (Wang *et al.*, 2015).

6.6.4 Use of neural networks

Similarly to the advancement of numerical modelling used for rockbursts prediction potential for utilization in rock mechanics for rockbursts occurrence prediction present also neural networks (Van Zyl and Omlin, 2001; Guangcun *et al.*, 2014).

Investigation of their usage for that purpose conducted Van Zyl and Omlin (2001). They used neural networks for modelling seismic time series in hard rock mines based on the data obtained from a hard-rock gold mine in South Africa. The results obtained for two time series (one with energy and one with other moment measurements) are presented and discussed in the study. A possibility of utilization of neural networks in modelling seismic time series was proven. Van Zyl and Omlin notice in their study a need for the development of new measuring devices for seismic monitoring technology, capable of performing accurate measurements which could serve as an input for training neural networks. Different application of neural networks found Guangcun *et al.* (2014). In their study a training of neural network model with stress measurements data from Jinchuan Mine is discussed, with aim to obtain models with predictions of stresses at various depths in the mine. The models are then processed and statistically analysed to identify hazardous areas. Guangcun *et al.* report the development of an artificial neural network model based on the geostress data from the Jinchuan mine. However, they notice that the forecasting data is not of high accuracy and it can be used only as a practical reference.

6.6.5 Other control methods

Apart from the methods mentioned in the chapters above, several other techniques were identified to predict rockbursts, and control the stress changes in the rockmass, such as destress blasting or application of stress measurements devices in the vicinity of the excavation (Andrieux and Hadjigeorgiou, 2007; Orzepowski and Butra, 2008; Saharan and Mitri 2011; Kodeda *et al.*, 2015). To maintain safe extraction also a tool for evaluating the suitable options of rockburst support in the burst-prone areas in the mine was developed (Kaiser and Cai, 2012).

Andrieux and Hadjigeorgiou (2007) discuss the destress blasting applied as a technique for reducing ground stresses in a selected zone of a mine. They list the critical parameters that control destress blasting process study the interactions between these parameters using rock engineering systems methodology (RES). The authors propose a new empirical method used

for quantifying the likelihood of success of a large-scale choked distress blast in an underground mine pillar and its application to back-analyse a fully instrumented large-scale confined distress blast at Brunswick Mine in Canada. The distressability index methodology was tested in back-analysis and proved to work well – it was able to predict a good destressing outcome for the blast. Destress blasting to control effects of rockbursts and improve mine safety was also broadly discussed in the study by Saharan and Mitri (2011). The authors present an evolution of the method and its mechanism and discuss possible applications with a focus on controlling strainbursts. Nevertheless, the authors conclude that more research is required for addressing destressing and stresses in the rockmass to fully understand the occurring mechanisms. They notice though a potential for numerical modelling for the purpose of improvement of the distress blasting techniques.

Orzepowski and Butra, 2008 propose a method for rock-mass instability detection in copper mining panels and a practical procedure for forecasting the rock-mass state. They introduce new borehole deformation sensor which measures changes of the distances between opposite sides of the vertical borehole in two different directions. Measurements done by sensors provide an input data for the “rockmass state index” (wsg) function, which can be used for comparing the relative rock-mass destabilization in vicinity of each borehole. However, the authors report that wsg value (MPa) is not applicable for the quantitative stress evaluation.

Kaiser and Cai (2012) give the considerations concerning burst-prone ground and discuss the rock support design. They outline the rockburst problem background including rockburst damage mechanism and parameters influencing it. The methodologies of rockburst support design and main highlights helping to choose the appropriate one are given. The authors show the development of a tool called BurstSupport which aims to assist the engineers in evaluation of the different rockburst support options in quick and systematic way. It is able to assess the load, displacement, and energy demands and therefore equip the design engineers with a tool for more effective mine planning. The BurstSupport can also contribute to the rockburst risk management, once it is employed together with other methods for rockbursts prediction.

7 Discussion

7.1 Discussion division

This chapter, divided into two parts, discusses the methodology employed for the research and its results. In the first part, a systematic review of the literature as a tool for identifying studies concerning on-line georisk management in underground hard rock mines is discussed. The strengths and weaknesses of chosen method are outlined. In the second part, the results of research are discussed and their relevance to the thesis objectives is evaluated.

7.2 Systematic review of the literature as a tool for identifying research

A systematic review of the literature was a tool used to identify research relevant to the objectives of the thesis. Since this method is originally used mainly in healthcare, its adaptation had to be made for the purpose of this master's thesis. The background of the systematic review of the literature from healthcare and software engineering were combined and adjusted. Some of the parts of the method were difficult to adapt, like establishing the tools for quality assessment of the identified studies, or stating the clear inclusion/exclusion criteria. The selection of databases, keywords, and inclusion/exclusion criteria had the most impact on the final results of the research; that is why they are discussed below as separate topics.

In overall, the systematic review of the literature performed in a way presented in this thesis can be repeated, and the final result should not be significantly different than the one obtained. Nevertheless, a lot of research on the topic of interest was omitted, such as the proceedings from the conferences not covered by the chosen electronic databases.

7.2.1 Databases

A large number of hits and duplicates might be a result of the selection of databases used for the search. Since Scopus and ScienceDirect cover a lot of the same journals, the records were often overlapping. It should be noticed that ScienceDirect yield more catches than Scopus, although the content of the databases (Scopus covers more than 60 million records, where over 21 500 are journals, while ScienceDirect covers more than 14 million records, where over 3 800 are journals) might suggest opposite share of the possible hits. That fact puts into question suitability of both databases for search in mining. The IEEE database yield in total and for each keyword the least amount of hits which is most likely caused by the least number of records the database covers (currently almost 4 million records). The thesis was time-bounded, which gives a reason for selecting just the three databases.

Selection of databases has a high influence on the results of the search. For the future use, it is advised to focus on smaller databases, which are more field-related. The suggestions can be electronic libraries of the scientific research centres and universities known from the research conducted in the field of interest (e. g. CSIRO, CSIR, Aaltodoc) or the databases directly related to mining (e. g. OneMine). A useful source can also be conference proceedings, such as DeepMining or International Symposium on Rockburst and Seismicity in Mines proceedings. However, this activity would be very time-consuming due to necessary laborious manual searches. Besides, some of the databases have restricted access which makes them not easily available.

7.2.2 Keywords and phrases

In total there were 12 keywords and phrases formulated for the search (see Appendix A). The selection and formulation of these were based on the preliminary search and general knowledge about the topic of interest. A large number of hits generated by the keywords was not related to mining; they belonged most often to computer science (e.g. data mining), health care (e.g. risks of underground environment for health), or environmental sciences (e.g. impact of mining on the environment). The reason can be the ambiguity of some of the keywords. For instance, a term “risk” or a term “management” have a wide use nowadays in any project of any field. On the other hand, such search yielding hits not related to the topic of interest might have an external basis. An observation made throughout the study is that the researchers do not put a lot of attention to the proper formulation of keywords. Also, the abstracts might be misleading, as the actual written body does not always reflect the highlights in the synopsis. Since the electronic databases examine the titles and the abstracts of records they cover against the given keywords, the importance of both keywords and abstracts is found very high. When using a systematic review for the purpose of identification of studies in the topic of mining more attention should be placed on formulation the keywords which are most appropriate. That can be based on collecting the keywords from articles found in preliminary searches, and analysing them using simple statistical analysis (e.g. identification of the trends) to extract the most common and therefore the most appropriate ones. Also, another approach for searching can be employed. Instead of short keywords and phrases, which generate lots of hits that need manual filtering in the bibliographic software databases, long strings of keywords with exclusion criteria can be used. An example of that was tested during the study and it yield a good result. Again, time boundaries of this research made it not possible to conduct additional rounds of search using adjusted approach. One exception was made for the keyword “strainburst”, which was identified in the late stages of research as relevant to the topic.

7.2.3 Inclusion/exclusion criteria

Some papers identified by title and abstract to be relevant and published in English turned out to be written in other language (most often in Chinese, but also in German). As long as the exclusion criteria were applied for manual filtering of the studies in RefWorks, there was no bias in selecting the studies. Nevertheless, the further steps which involved reading the abstracts and then full texts of the papers could be biased by subjective judgement whether the study addressed one or more of the review questions, or not. It should be noted that formulation of clear inclusion/exclusion criteria helps to minimise the bias in identification and classification of findings.

7.3 Results discussion

There are two systems and one standard architecture identified which are currently capable of on-line risk management in deep underground hard rock mines – MS-RAP, Digmine, and AziSA. All of these can be taken as the state-of-the-art in the topic. MS-RAP (currently being replaced by myrap) is a software providing engineering analysis and facilitating monitoring actions to manage mining-induced seismicity. It is employed in a number of mines worldwide since 2002, although it is constantly being developed. Produced in this software seismic hazard maps used for seismic hazard assessment in the underground mines can be used as an example of visualising data obtained from the sensors installed underground. Digmine, however, employs new methodologies of stress and seismic near-to-real time measurements and one of its objectives is a continuous measurement of

geotechnical and geophysical data, which is similar to the ORMID project goals. Besides, it also aims in early detection of high stress concentrations, and similarly to the ORMID project uses back-computation of stresses. The method is novel, although advanced to a level where an instrumentation in a mine has been conducted. This approach might be of interest for the ORMID project researchers, to get an overview of the similar approach. AziSA provides procedures for monitoring and handling the data in the harsh underground environment. The architecture is already used in the deepest mines of South Africa, and its development by incorporating new sensors in the system is frequently reported in the literature. AziSA, as a set of standards and procedures, can be used in the ORMID project in two ways. One way is to directly use the given system and employ in it the already existing sensors and methods of data analysis. Another way is to develop a novel set of procedures for data transfer, storage, and processing in an analogous way to the AziSA. It can be said that this system addresses one of the questions from the ORMID project research plan: “how to collect, group, analyse, and preprocess the data for faster decision making.”

The systematic review of the literature did not help to identify any state-of-the-art management system of geotechnical risks. All of the methods found are based on an integrated approach introduced already in the seventies, which aims to combine rock mechanics, seismic technology, and computer techniques to model the mining situations. As a basis they use general risk management guidelines adapted to the mining industry purposes. The reason might be that following the worldwide established standards is just a necessity, not only in mining but the industry in general. Another reason might be their ease of use, as an adaptation of already existing guidelines is much easier than the development of novel procedures from the scratch.

Amongst the assessment methods, a geotechnical risk assessment guideline can be taken into consideration as the state-of-the-art technique. It uses most recent risk assessment techniques and provides the guidelines for choosing the most appropriate methods for given mine conditions. This method can be utilised in the ORMID project in two ways. First, the geotechnical risk assessment shows potential to have incorporated identification of potential impacts resulting from risks on business, introduced in financial terms. This addresses the question of the research plan: “how to evaluate the financial benefits of the complete risk management process”. Another way where the GRA can be used is the employment of the algorithm developed in the Dynamine project where measurement of the stress state evolution in a mining area can be utilised for evaluation of the probability of hazards associated with stress changes.

Within the methods identified in the study special attention takes a methodology of immediate rockburst warning based on microseismicity (Feng *et al.*, 2014), already utilised in the Digmine described above. It is one of the most recent methods used for georisk management in underground mines and one of the most advanced, therefore it can be taken as a state-of-the-art method. Another method worth mentioning is a tool called BurstSupport, aiming to assist the geotechnical engineers in evaluating different rockburst support options in a burst-prone ground. From the perspective of the ORMID project, it can be taken into consideration as one of the possible mitigation tactics for the burst-prone conditions of deep underground mines. Another method of high stresses mitigation identified in the review is destress blasting, however, it still needs research and evaluation of its actual impact on the rockmass. Nevertheless, as the ORMID project continues, this method also can be taken into consideration. Based on results obtained, it can be seen that most of the methods of managing rockbursts used nowadays are employ monitoring a seismic response of rockmass to mining.

There is just one method purely based on the strain measurements identified, what highlights a need for this kind of research. Besides the methods identified by systematic review of literature, there is a method for estimating the in situ stress change around an excavation in elastic rock in real-time using measurements of changes in the displacement field (Kodeda *et al.*, 2015) developed by Aalto University. Its potential use is proposed above in the section about the assessment techniques.

8 Conclusion

8.1 Gaps in research concerning on-line georisk management in deep underground mines

The results revealed that most of the methods of managing georisks in underground hard rock mines are based on the mining-induced seismicity analysis. The gap identified in this study is the lack of research that examines the methods of rockmass stress calculation and forecasting based on the strain measurements. Only two methods are identified – one in the studies preceding the ORMID project, and one obtained through the systematic review of the literature. Moreover, a very low number of systems capable of on-line georisk management is identified (two systems and one standard architecture).

8.2 The state-of-the-art of the developments in the on-line risk management in hard rock underground mines

Two systems and one standard architecture are identified through the systematic review of the literature which are currently capable of on-line risk management in underground hard rock mines – MS-RAP, Digmine, and AziSA. All of these can be taken as the state-of-the-art in the topic. The management of georisk in underground mines is mainly conducted by employing the mine-wide microseismic monitoring systems to get an insight into rockmass behaviour. Within the methods that can be used to manage the georisks in real-time a methodology of immediate rockburst warning based on microseismicity, already utilised in the Digmine system, is considered the state-of-the-art method. A rockburst mitigation tool which is seen as the state-of-the-art is the BurstSupport software, aiming to assist the geotechnical engineers in evaluating different rockburst support options in a burst-prone ground to allow for making quick decisions based on reliable data.

In conclusion it can be said that the goals of this master's thesis were achieved partially. The identified amount of the state-of-the-art developments in the on-line georisk management topic result from rigorous inclusion and exclusion criteria, selected keywords and databases. Different choice of these would result in dissimilar results, what indicates that not all of the research about the topic of interest was identified by means of the systematic review of the literature. It can be therefore concluded that the state-of-the-art proposed in this thesis may not be comprehensive enough. In the following chapter the propositions of its improvement and recommendations for future research are given.

9 Recommendations

Use of systematic review as a tool for identifying relevant research in the field of mining and rock mechanics should be improved according to the following:

- It is recommended to focus on reviewing smaller databases, which are more field-related. The suggestions can be electronic libraries of the scientific research centres and universities known from the research conducted in the field of interest (e. g. CSIRO, CSIR, Aaltodoc) or the databases directly related to mining (e. g. OneMine). These can be searched through to retrieve also the technical reports and other deliverables which can be produced as a result of projects undertaken by such institutions.
- Conference proceedings from the field of interest should be taken into consideration separately to ensure a comprehensive review (e.g. DeepMining or International Symposium on Rockburst and Seismicity in Mines proceedings).
- More attention should be put to the proper formulation of keywords. That can be based on collecting the keywords from articles found in preliminary searches, and analysing them using simple statistical analysis (e.g. identification of the trends) to extract the most common and therefore the most appropriate ones for specific category.
- Instead of short keywords and phrases, which generate lots of hits that need manual filtering in the bibliographic software databases, long strings of keywords with exclusion criteria can be used.

Development of the systems capable of on-line risk management can be improved through the following:

- AziSA, as a set of standards and procedures for data transfer and analysis is advised to be used in the ORMID project directly and the already existing sensors and methods of data analysis should be employed in it.
- The geotechnical risk assessment method shows potential to be used for identification of impacts resulting from risks on business. It should be taken into further research to be broadened with the tools capable of estimating the risks severity resulting from the mining operations in financial terms.
- The geotechnical risk assessment should employ the algorithm developed in the Dynamine project. The measurement of the stress state evolution in a mining area can be utilised for evaluation of the probability of hazards associated with stress changes (e.g. strainbursts).
- BurstSupport, aiming to assist the geotechnical engineers in evaluating different rockburst support options in a burst-prone ground can be taken into consideration as one of the possible mitigation tactics for the burst-prone conditions of the underground hard rock mines in the ORMID project. Another method of high stresses mitigation suggested to be used in the ORMID project is destress blasting, however, it still needs research and evaluation of its actual impact on the rockmass. These methods should be utilised for georisk mitigation in the ORMID project.

All of the recommendations relevant to the ORMID project are presented as a Roadmap (see Figure 23)

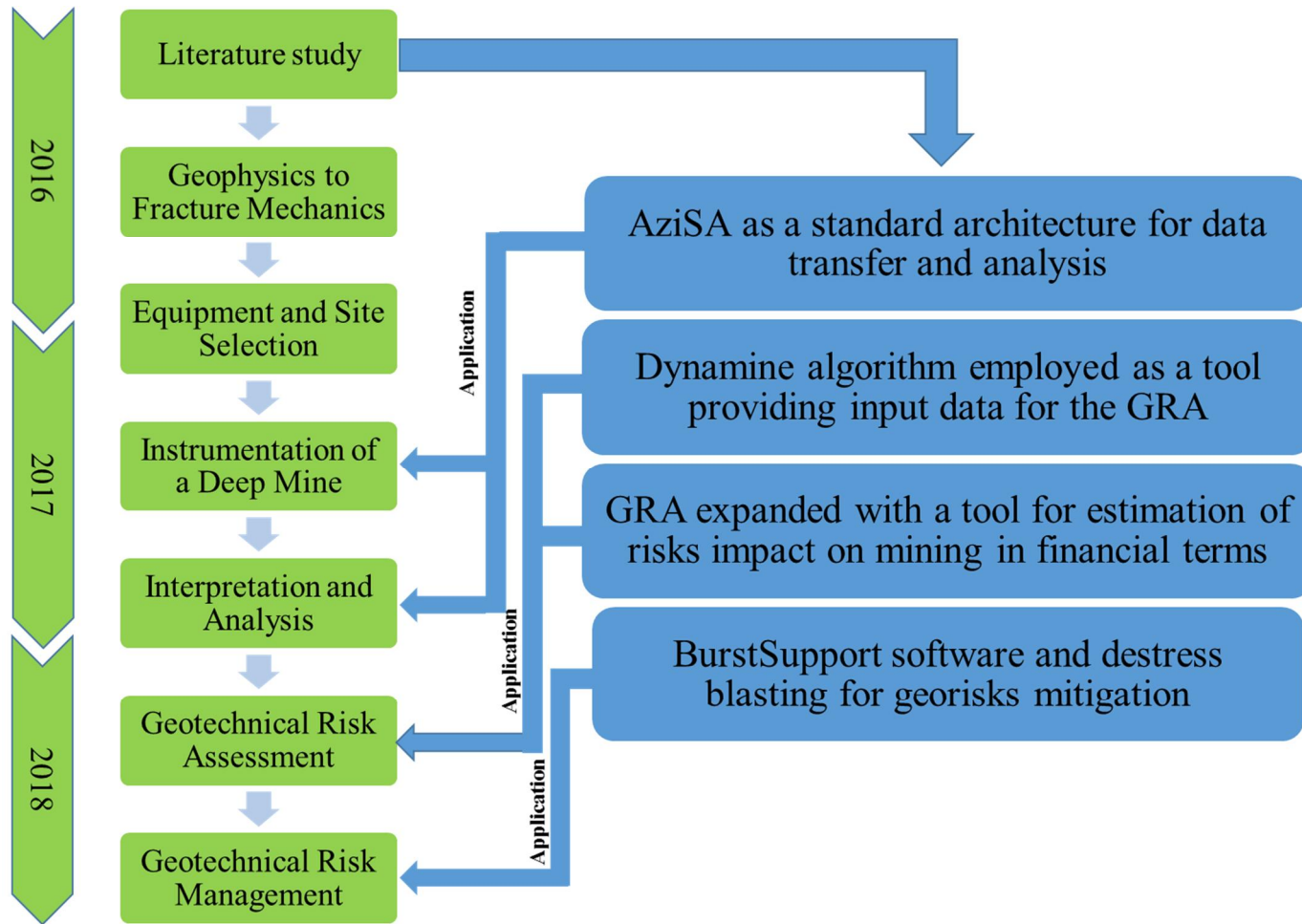


Figure 23. Roadmap for the ORMID project

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Appendices

Appendix 1 Keywords and searching tools

KEYWORDS

Geotechnical risk management
Geomechanical risk management
Rockburst management
Mine seismology AND deep mines
Rockburst risk
Deep mining AND NOT coal
Seismic monitoring underground mines AND NOT coal
Deep hard rock mine
Seismic hazard underground mines AND NOT coal
Real-time risk management AND underground mines AND NOT coal
Strainburst

SEARCHING TOOLS

Scopus
Sciencedirect
IEEE

Appendix 2 Included studies

SYSTEMS			
No	Reference	Content	Results\Conclusion
1	Archibald <i>et al.</i> , 1988	The research aimed at developing a method for fast detecting of a change in local stress conditions and providing a tool which enables warning of a violent rock failure. To achieve that a system which correlates acoustic emission and rock failure data was developed. The main characteristic of the system is that it was able to monitor a broad range of acoustic emission frequency output, at high frequencies (40 to 400 kHz). Based on the laboratory and field experiments it was established that microseismic waveforms differ in areas producing different stress fields. To investigate on that matter, an adaptation of pattern recognition technology proposed by Korenberg (1985) was implemented.	It was shown that acoustic emission originating from the rock under different stress conditions varies significantly. That difference can be used for characterization of in-situ rock mass stress levels. Adapted pattern recognition techniques combined with acoustic monitoring methods at high frequencies can be employed to determine the rock mass state (whether it is in a low stress, non-failure and high stress or essentially-failing).
2	Archibald <i>et al.</i> , 1990	The aim of the research was to identify characteristics of the frequency spectra of microseismic emissions and use them as precursors of rockbursting. Acoustic emission monitoring at the frequency of 300-500 kHz was employed, the waveform data was recorded and stored. The acoustic emission characteristics were used to determine stress magnitude conditions within pillars and their vulnerability to failure, and correlated with known ground stress information to enable a stress prediction in case when signals of unknown origin occur. The main goal was to provide a low-cost system capable of estimating rock stresses, used as a support for operators in rockburst prediction in real-time.	A microseismic system capable of detecting stress variation in the rock mass, during mining cycles, based on the waveform observation and characterization was developed. Field tests showed that it is reliable to operate in harsh environmental conditions. High-frequency seismic waveform data was shown highly dependent on the event rate parameters. Significant increases in event rate preceded the rockburst. Waveform duration was shown to be a valid precursor to stress change, as shifts in energy release created changes in waveform duration.

SYSTEMS			
No	Reference	Content	Results\Conclusion
3	Vogt <i>et al.</i> , 2010	The study introduces an architecture and a set of protocols for measurement and control networks, which can be utilised to collect, store and facilitate the analysis of data from challenging underground environments. The system incorporated the cost-effective, low power sensors and devices processing data, able to stand the harsh environment conditions and support the decision making in real-time.	Thermal infrared camera to identify the loose rock based on its temperature (under development). Development of a robot that can independently undertake the entry examination before the shift reaches the working place; the robot will likely mark areas of the hanging wall directly using spray paint (under development). Implementation of the Physiological Strain Index to manage heat stress, and to quantify the effect of other stressors.

MANAGEMENT			
No	Reference	Content	Results\Conclusion
1	Ortlepp and Steele, 1972	The paper discusses the rockburst problem and countermeasures undertaken in East Rand Proprietary Mines Limited, South Africa. Development of longwall system, placing the waste fill, and support methods such as concrete sandwich packs, hydraulic props, and yielding rockbolts to counter the rockburst problem are described.	New means of countermeasures were developed such as the barrier pillars, the improved pack support, waste-ribs, and use of rapid-yield props.
2	Dempster <i>et al.</i> , 1984	The paper discusses the differences in seismicity in the various gold mining districts of South Africa, and the role of local geology in developing different approaches to mining. Also the roles of management in mines and mine design considerations are presented based on the cases from mines taken into the review.	The magnitude and nature of the rockburst problem in South African gold mines vary from district to district. An approach is introduced to combine rock mechanics with development of computer techniques in order to model mining situations

MANAGEMENT			
No	Reference	Content	Results\Conclusion
			as well as application of seismic technology to the mining industry. It provides a basis for the support for decision making.
3	Spottiswoode, 1989	The paper is a review of seismic and rockburst research activities done in South African deep-level gold mines over the period 1983-1987. The areas described are seismic data acquisition and processing, source mechanisms and near-source effects on seismic wave transmission, mine layouts, strong ground motion studies, and rockburst prediction and control.	First attempts of use of PC-based systems for seismic monitoring by R.WE. Green and designing equipment to do on-line processing of microseismic data underground by P.Grobler are reported. Advances in rockburst prediction are reported such as continuous monitoring of both source (seismic moment, corner frequency, stress drop and effective stress) and ray path effects (Q, mean-free path, and polarization parameters).
4	Delgado and Mercer, 2006	The paper discusses the activities conducted in Campbell Mine, Ontario (Canada) concerning the monitoring of the changes of state of the rock mass using the microseismic monitoring system. The details about the microseismic instrumentation including its design and expansion process in Campbell Mine are outlined. The evaluation of system's performance and management of data are discussed, and further followed by two case studies.	Expansion of microseismic system in Campbell mine resulted in a higher accuracy of recording seismic events in the mine. The rock mass response to mining can be monitored over a wide range of conditions after microseismic system expansion. The real-time and accurate location of seismic events enabled improvements in ground-clear and re-entry protocols.
5	Hills and Penney, 2008	The paper presents an approach to the management of seismicity at the Beaconsfield Gold Mine, Tasmania. The geology and mining methods, as well as geomechanical considerations, are introduced in the paper. The history of seismicity in the mine and employment of seismic monitoring system together with its further expansion are outlined. The approach for seismic analysis, including details on instrumentation of the mine,	The mine engineered all ground control measures in a way that they consider the dynamic impact of seismicity for both shakedown and strainburst conditions. Remote activities were designed for the stoping method in seismic-prone area of the mine.

MANAGEMENT			
No	Reference	Content	Results\Conclusion
		<p>methods of stress measurements, and numerical modelling to determine stress levels around excavations are discussed. Application of the MS-RAP program for calculation of an excavation vulnerability potential of all positions in the existing and designed mining horizons is described. Methods of seismic hazard management are given (i.e. de-stress blasting, exclusion periods), as well as considerations about geotechnical design are summarized. The analysis of a seismic event is shown to illustrate an example of the management of seismicity at Beaconsfield.</p>	<p>To gain more insight into rock mass response to mining and the state of stresses and seismicity, a geotechnical instrumentation was employed in the mine and expansion of the seismic array was conducted. Comprehensive training was given to the workforce to raise the awareness of the hazards in the mine. All the protocols and plans required for management of hazards were adjusted according to the current state of information.</p>
6	Hudyma and Potvin, 2010	<p>The paper elaborates on the approach to seismic risk management, following the steps: identification of active seismic sources in the mine, characterization of sources in terms of hazards, estimation of the potential damage in case of occurrence of the large events and risk mitigation to minimize the consequences, if the damage occurs. Spatial clustering of microseismic events is presented as a useful tool in hazard location identification. High resolution microseismic monitoring systems are indicated as a good data collection tool. The study treats also about the parameters used to characterize the failure mechanism and hazard at source (the frequency-magnitude relation of events, the timing of events as a result of stress field changes, the timing of larger events vs smaller events, the ratio of S-wave to P-wave energy, the level of Apparent Stress associated with the failure process). Techniques to quantify and visualize seismic hazard are described.</p>	<p>Clustering of seismic events, seismic parameters analysis, hazard assessment, hazard mapping and rockburst damage potential assessment are incorporated into the Mine Seismicity and Risk Analysis Program (MS-RAP) which is used in over 30 mines since 2002. Seismicity parameters like: the frequency-magnitude relation of events, magnitude-time history, diurnal charts, S:P energy ratio and Apparent Stress Time History are useful parameters which can be used to assess the level of hazard.</p>

MANAGEMENT			
No	Reference	Content	Results\Conclusion
7	Hills, 2012	The paper discusses the history of mining at the Tasmania Mine with the evolution of mining methods, and outlines importance of a proper management of the geomechanical environment. The article is a follow up of Hills and Penney (2008) to which the author relates so that the details on the management strategy are not given. An overview of stress measurement, seismic monitoring system, instrumentation, and seismic management considerations is given.	Adaptation of mining methods in a way that they limit the exposure of personnel to areas of identified seismic risk is advised. Creation of protocols for ground support and reinforcement is reported. Improvements in seismic and rock mass monitoring as well as the engagement of the workforce to ensure a high level of understanding and compliance with the overall process is advised.
8	Badri <i>et al.</i> , 2013	The paper discusses the development of a new practical approach to risk management in mining projects, based on a novel concept called “hazard concentration” combined with the Analytic Hierarchy Process. The approach is an adaptation from open-pit mining. . The aim of the study was to integrate occupational health and safety into risk management in mining projects in Quebec. Hazards identification is performed through interviews, questionnaires, and observations, (action method) and based on that experts can evaluate potential risks.	It was proven that the adaptation of the approach of evaluating the hazards used for open-pit mining can be used for goldmines in Quebec. Occupational health and safety database created for the underground mine is similar to the one used for open-pit mines. The proposed approach enables to evaluate a broad range of hazards in mining projects and minimize the risk of neglecting possible threats.
9	Hills, 2013	The paper discusses the procedures and methods of mining-induced seismicity management in Tasmania Mine in Australia.	Remote stoping methods and a holistic approach of measurement, monitoring, modelling, and observation was employed. Sampling programs were performed to measure the rock properties. Stress measurements in the backs of access and footwall development for the purpose of calibrating stress change

MANAGEMENT			
No	Reference	Content	Results\Conclusion
			<p>monitoring were utilised. Overcoring measurements were undertaken. HI Cells were installed to enable to track stress changes and calibrate numerical models accordingly. Instrumented cable bolts (SMART Cables) and extensometers were installed to observe the rock mass behaviour and its impact on the reinforcement. A permanent twelve-channel real time array with one triaxial and nine uniaxial geophones was installed. For scheduling purpose, a numerical modelling was undertaken. That activity was supported by geological and geotechnical mapping, which also contributed to support and reinforcement design. The Ground Control Management Plan for the mine was developed and implemented as a controlled document, which has been updated with the time and available to any employee and subcontractor.</p>

ASSESSMENT			
No	Reference	Content	Results\Conclusion
1	Singh, 1989	The study discusses the possible approach of classification of mine workings based on the bursting indices (burst-proneness index, decrease modulus index, burst-energy release index, relative violence of rupture, burst-efficiency ratio, rock dynamic index), rock properties and in-situ approaches (microseismic monitoring, energy release rate measurements, excess shear	The correlation was shown between the modulus index and burst-proneness index, strength, brittleness, and the strain energy stored in the rock specimen.

ASSESSMENT			
No	Reference	Content	Results\Conclusion
		stress criterion, electrical resistivity of rocks, seismic velocity technique, and state of stress).	It was proven that the burst-proneness index depends on the Schmidt rebound hardness and the shear wave velocity.
2	Cichowicz, 1993	The paper describes a prototype of the stand-alone tool, combining multidisciplinary experience for seismic hazard evaluation in underground gold mines. It provides a four stages concept of an expert system for seismic hazard analysis which was proven in a case study to be practical in estimating the probability of occurrence of seismic events.	A concept of a system that analyses seismic hazard in four steps: - by estimating the maximum expected magnitude of a seismic event to occur, - estimating the unconditional probability of occurrence, - analysing seismic patterns based on past seismicity, -and involving other precursors recognized to be relevant for evaluation.
3	Stewart, 1995	The study introduces a seismic risk assessment method which can be utilised in rockburst prone deep mines with a comprehensive seismic monitoring system. The method uses several seismic hazard parameters at the same time and assesses daily the seismic risk in investigating areas (parameters: apparent seismic risk, variations in the dimensionality of the spatial clustering of the recorded microseismicity, volume of rock in which the dynamic stresses are greater than some critical value, changes in the measured stress-drop values of the recorded microseismicity, and changes in the intensity of spatial clustering of the recorded microseismicity) .	A method of seismic risk assessment initially developed for up-dip mining further is adapted to mining on strike at an experimental preconditioning site.
4	Singh <i>et al.</i> , 2002	The paper discusses the qualitative and quantitative means of seismic hazard assessment applied at Junction Gold Mine, Australia. Factors responsible for mining-induced seismicity and rockbursting at Junction mine are outlined. The influence of mining and geology on seismicity is discussed. Qualitative	Development of qualitative and quantitative seismic hazard assessment tools

ASSESSMENT			
No	Reference	Content	Results\Conclusion
		seismic hazard map is introduced and methods of assessment of types of hazards outlined in the map are described. Quantitative seismic hazard assessment with its main aspects is provided. The rockburst hazard assessment analysis used at Junction mine is presented. Also, a comparison between qualitative and quantitative seismic hazard is given.	
5	Mishra and Rinne, 2015	The focus of the paper is in planning and organizing a geotechnical risk assessment in a mine. It provides necessary elements of risk assessment tailored for the mining industry and provides guidelines for establishing its scope. The study also proposes a method for selection of tools used for geotechnical risk assessment and guidelines for their utilization.	Geotechnical risk assessment division by its type, area scale, and hazard scope is proposed. Reporting requirements in the process of geotechnical risk assessment are outlined for internal and external reporting. The tools for conducting the geotechnical risk assessment and guidelines for their selection are given. Approaches for risk assessment are proposed (deterministic, probabilistic and possibilistic), and a guideline for their selection is provided. A method for representation of a geotechnical risk in a mine is proposed.

METHODS			
No	Reference	Content	Results\Conclusion
1	McLaughlin <i>et al.</i> , 1976	The paper elaborates on the development and application of microseismic and surface monitoring equipment in the underground mines of the Coeur d'Alene Mining District.	Development and application of the microseismic underground geophones and recorders was conducted, subsequently: microseismic magnetic-tape recorder, portable

METHODS			
No	Reference	Content	Results\Conclusion
			microseismic unit, broad-band microseismic equipment, short-period, photographic-type seismograph, strip chart recorder, and direct-readout, short-period seismographs. State-of-the-art of rock burst control for 1976 is provided.
2	Van Eeckhout <i>et al.</i> , 1984	The study reports an attempt of improvement of rockburst monitoring system in Sunshine Mine. Three methods of calculations of bursts are discussed and compared. The results of the comparison are reported. Stages of data analysis are given and the final output in graphical format is discussed.	Comparison of the accuracy of three burst location codes is presented.
3	McMahon, 1988	The paper is a report from Bureau of Mines which describes the rockburst problem and countermeasures undertaken in the Coeur d'Alene Mining District. It discusses a microseismic method employed in the district as well as destressing and preconditioning methods applied to control the rockbursts.	Microseismic method was proven to be a useful tool for determining locations of seismic events. Destress blasting and rock preconditioning methods used were proven to be effective in a burst-prone mine area.
4	Lasocki, 1993	The study presents an outline of attempts to develop statistical methods of predicting mine tremors, by processing and analysing local mining-induced seismicity. The use of the method is presented on the mining seismicity data from rockburst prone coal mines in Poland.	Statistical method of estimation of time-varying probability of strong tremor occurrence in a stope vicinity.
5	Friedel <i>et al.</i> , 1997	The study presents the use of 3D seismic tomography for monitoring mining-induced stress changes using the data from the Homestake gold mine and Lucky Friday silver mine, USA. The stages of tomographic imaging are outlined: process of data acquisition, obtaining a proper seismic resolution, model parameters and grids selection, tomographic reconstructions process, and uncertainty evaluation. Stress changes due to	Imaged velocity structure that can be interpreted qualitatively. An output obtained are stress anomalies which go in line with measured in situ stresses. The method enables to represent even difficult-to-image low-velocity features (after ground failure) in an accurate way.

METHODS			
No	Reference	Content	Results\Conclusion
		ground failure, and stope advancement obtained from data processing are given and discussed.	Despite some limitations, the model can be applied as a tool for ground stability hazard evaluation.
6	Poplawski, 1997	The paper discusses the results of implementation of the first modern seismic monitoring program in Australia at Mt Charlotte underground gold mine which started with commissioning of a portable seismic system in 1994. The elements of seismic monitoring system, and seismic parameters are discussed. Development of a new method for rockburst hazard evaluation is presented.	The seismic system was proven to be useful tool for seismic event location and magnitude investigation. Development of a new method for rockburst hazard evaluation called departure indexing.
7	Scott <i>et al.</i> , 1997	The study discusses the use of three-dimensional seismic tomography for detection of hazardous ground conditions and monitoring of the mechanical integrity of a rock mass. An application of the technique is shown based on the study conducted in Homestake Mine, where the determination of relative stress in an underground pillar was conducted.	Use of seismic tomography in order to identify high velocity gradients in a pillar of the Homestake Mine. The methodology is a useful tool in identifying stress gradients within a short distance of mine openings.
8	Mitri <i>et al.</i> , 1999	The study discusses a numerical modelling approach which aims to calculate mining-induced seismic energy release rate and the strain energy storage rate, taking into consideration in situ stress conditions, mine geometry, and geomechanical properties of rock mass. The technique described in the study is presented on a case study of a cut-and-fill stope of a Canadian underground mine with a record of rockburst in the crown pillar.	It was concluded that the energy release rate and the energy storage rate parameters can help in strainburst potential estimation due to mining. A burst-potential index is introduced as a tool to estimate in percentage the potential of strainburst occurrence. The model obtained in numerical modelling remains conservative, as it uses linear elastic rock behaviour which lowers the energy parameters and the burst-potential index.
9	Urbancic and Trifu, 2000	The paper is an overview of the status of seismic monitoring instrumentation in Canadian underground mines for the year	Seismic analysis provides the means to remotely monitor active fractures throughout

METHODS			
No	Reference	Content	Results\Conclusion
		2000. An example of seismic instrumentation for data acquisition and processing is presented. Use of passive seismic monitoring techniques for evaluation of fractures and stress conditions of the rock mass is shown. Possibilities of remote monitoring of active fractures are highlighted and use of seismic hazard analysis is described.	the mine using space-time distribution in microseismicity and fault-plane solutions. Using P-wave and S-wave energy release ratio may make possible to evaluate the types of failures occurring in progressive mining. Defining a systematic pattern of fracture behaviour with advancing excavation could help to improve the design of extraction methods.
10	Mansurov, 2001	The paper presents a method of probabilistic estimation for predicting an occurrence of strong rockbursts in mines based on North Ural Bauxite Mines region. Development of an algorithm for prediction procedure is discussed and results are given and discussed.	Probabilistic estimation method of strong rockburst time forecasting was developed and tested for retrospective rockburst prediction in burst prone North Ural Bauxite Mines mining region.
11	Van Zyl and Omlin, 2001	The paper presents an investigation of the use of neural networks for modelling seismic time series in hard rock mines based on the data obtained from a hard-rock gold mine in South Africa. The stages of study are outlined, subsequently: preprocessing of the raw data, choosing of appropriate data, and methods of measuring performance. The results obtained for two time series (one with energy and one with other moment measurements) are presented and discussed.	It was proven, that neural networks are useful in modelling seismic time series. Models of predicting both, large and smaller events were found, although extraction of exact models remains very hard task.
12	Kornowski, 2006	The study presents development of a statistical tool for rockburst probability prediction in the areas in a mine where the seismic and seismoacoustic sensors are employed.	A statistical method of predicting the rockburst probability was developed. The method can be used for identifying the rockburst hazard, when the space of possible hazard values is divided into subspaces and identified as states of hazard. Predictions are based on previous observations.

METHODS			
No	Reference	Content	Results\Conclusion
13	Albrecht and Sharrock, 2007	The article discusses the methods used for evaluation of seismic events damage potential at the excavation boundary such as using the ground motion relationships. Their utilization for identification of the areas in a mine that are prone to damage or these which may have sustained rockburst damage from a seismic event is proposed.	A cumulative peak particle velocity (PPV) criteria is proposed to be used to identify areas that have sustained repeated, potentially damaging seismic loads in a mine. PPV use is also proposed to approximate the kinetic energy demand on an excavation resulting from a seismic load. Comparison of energy demand at the excavation boundary with energy capacities of support systems is proposed to assess the potential for rockburst damage in existing excavations or to tailor the new support designs.
14	Andrieux and Hadjigeorgiou, 2007	The paper discusses the destress blasting applied as a technique for reducing ground stresses in a selected zone of a mine. The framework for establishing the critical parameters that control the destress blasting process is provided and study of the interactions between these parameters is described using rock engineering systems methodology (RES). A new empirical method used for quantifying the likelihood of success of a large-scale choked destress blast in an underground mine pillar is proposed and its application to back-analyze a fully instrumented large-scale confined destress blast at Brunswick Mine in Canada is discussed.	A novel methodology was developed that defines the likelihood of success of large-scale choked destress blasts in pillars. Coding of the RES interaction matrix for large-scale choked panel destress blasts was done. The proposed methodology can be used to help design the described type of destress blast. The destressability index methodology was tested in back-analysis and proved to work well – it was able to predict a good destressing outcome for the blast.
15	Hudyma and Brummer, 2007	The study provides guidelines for accurate design and efficient operation of seismic monitoring systems in mines. Considerations, tricks and traps concerning seismic arrays implementation and data analysis are given.	The general rules of a proper design of seismic monitoring systems are given. Guidelines for operation of seismic systems are provided.

METHODS			
No	Reference	Content	Results\Conclusion
16	Cianciara and Cianciara, 2008	The paper presents a method of tremor risk estimation on the basis of seismic emission registered in mining exploitation zones. Considerations about the stress changes in the rock mass and accompanying them processes of compaction (hardening), dilatancy (softening), and then possible tremors are provided. Utilization of the described method in a selected mine is provided.	The determination of tremor risk based on time variation of a parameter describing the attenuation of seismic vibrations of the rock medium is presented. The method was proven to be effective (based on the studies carried out in several mines).
17	Lasocki and Orlecka-Sikora, 2008	The study was conducted on application of the probabilistic analysis of time-independent (stationary) seismic hazard. The non-parametric approach to source size characterization combined with a method of uncertainty analysis based on resampling techniques providing point and interval estimates of size distribution functions and related hazard parameters was used in analysing mining seismic data from two different copper mines in Poland. The data analysis using that method is described in the study.	It was proven with high significance that the probability densities of the logarithm of seismic energy in analysed data had multi-bump shapes and therefore they are complex source size distributions. The non-parametric kernel estimator is recommended for complex source size distributions. An assessment of the uncertainty of the kernel estimates was made.
18	Lesniak and Pszczola, 2008	The study presents a modified method of location of mine tremors utilized in Lubin Copper Mine, Poland, which can be applied in mines where accuracy of the vertical hypocenter coordinate location needs to be increased. Based on the data from Lubin Copper Mine the authors describe development of the method, setup of devices for obtaining sufficient data output, and introduce used algorithms in the two-step location procedure. The complete procedure capable of solving the non-linear location problems is given.	Two-step combined location method for determination of mine tremors location, that uses P-waves first arrival times and P-waves directions. Creation of location error maps using numerical Monte-Carlo experiments, showing high vertical resolution of the combined array of geophones. It was proven that additional triaxial geophones array in the area of interest in a mine can significantly increase the vertical location precision.

METHODS			
No	Reference	Content	Results\Conclusion
19	Orzepowski and Butra, 2008	The study describes a method for rock-mass instability detection in copper mining panels and a practical procedure for forecasting the rock-mass state utilised in Polish copper mines.	Borehole deformation sensor which measure changes of the distances between opposite sides of the vertical borehole in two different directions is introduced. Rockmass state index function, its application, and interpretation for comparative evaluation of the relative rock-mass destabilization in vicinity of a borehole are given. An improvement of rock burst safety evaluation is proven with this method.
20	Orlecka-Sikora, 2008	The study proposes the use of resampling methods in the seismic hazard parameters evaluation in the nonparametric approach for assessment of errors in the seismic events magnitude estimation. The development of an algorithm based on the bias corrected and accelerated method and its performance is introduced based on the data from an underground copper mine in Legnica-Glogow Copper District in Poland. The study includes a supplementary material with a description of the nonparametric kernel estimator of the magnitude distribution used in the presented technique.	It was proven that estimating the confidence intervals of the unknown parameter on the basis on only one data sample is possible using the resampling methods. These methods are still applicable even in case when the probability distribution of the estimator of this parameter is unknown. Based on the Monte Carlo simulation it was proven that the iterated bias corrected and accelerated algorithm enables to estimate seismic event size cumulative distribution function.
21	Hofmann and Scheepers, 2011	The paper describes a back analysis of two mining induced tremors at Great Nologwa Mine, in South Africa. The aim of the back analysis, performed using a boundary element numerical modelling program, was to find out whether a boundary element program could successfully simulate shear slip seismic sources. Another aim of the study was to establish a modelling method towards safer mining in the underground tabular mining	Development of a model that provided a satisfactory results when considering quantitative estimates of seismic potency. Following the methodology and modelling parameters provided in the study accurate model building is required, including geometrical surfaces of faults using the best

METHODS			
No	Reference	Content	Results\Conclusion
		environment. Data used for the modelling is discussed in the study. Boundary element model, calibration parameters, and back analysis and model calibration are described in the study.	information available. Identification of seismic hazards in a mine might be supported by the knowledge gained based on the detailed studies of the results from the model.
22	Saharan and Mitri, 2011	The study discusses distress blasting as a method to control effects of rockbursts and improve mine safety. Evolution of the method and its mechanism is described and possible applications are outlined with a focus on strainbursting control.	Distress blasting is recommended as a tool for application as a proactive measure or as a preconditioning.
23	Tsirel <i>et al.</i> , 2011	The paper presents a new, cluster location procedure for mining-induced seismic events. The algorithm, called SPAM, used in the method has relatively high inaccuracy, although it is tolerant for strong disturbance and capable of sound positioning of hypocenters (even those with considerable errors in the initial data).	The method was proven to be able to provide positioning of horizontal coordinates of seismic events with a sufficient accuracy. The vertical coordinate provided with the method has intolerable error in particular cases. Seismic event location can be improved with the cluster method, although it is a comprehensive task since it includes calibrating blasting. More accurate location of seismic events enables to gain knowledge about tectonic structures of the rock mass.
24	Vallejos and McKinnon, 2011	The research focuses on establishment of statistical correlations between mining factors and the decay time of mining-induced seismic sequences. A method of estimating background levels of seismicity rate for re-entry protocol development in combination with used re-entry practices is described. A theoretical development of a link between the productivity of seismicity and decay time to background levels is presented, using modified Omori's law. The evaluation of the developed method is shown in the case studies.	A procedure for estimating seismicity rate thresholds for re-entry protocol development was proposed. It can be useful for evaluating the global response of the seismic environment or to isolated seismic sequences for back-analysis. A linear correlation was established that can be used for developing a proactive re-entry protocol.

METHODS			
No	Reference	Content	Results\Conclusion
			It was shown in the study that as a direct consequence of the in-situ stresses that increase with depth a larger number of seismic sequences with longer decay times are found.
25	Valley <i>et al.</i> , 2011	The paper describes the processing methods necessary to extract sonic parameters from full waveform sonic logs which can be further used to assess in situ rock strength and rock mass quality. Based on the data acquired from one borehole the processing methodology is performed using a semblance analyses. Extraction of attenuation information, median frequency, and the power are presented. Correlation of sonic parameters and rock properties are outlined.	In order to retrieve reliable P-wave velocity from full wave sonic wirelogs in hard rock the full semblance analyses are necessary. It was proven that exists a correlation between P-wave velocity and strength of a rock. However, use of P-wave velocity in order to predict rock strength is not recommended. Correlation between fracture frequency and attenuation is evident if the scale of observation is matched. This can be used for rockmass quality evaluation.
26	He <i>et al.</i> , 2012	The paper reports the results of laboratory tests conducted using the strainburst testing machine and impact-induced rockburst testing machine on rockbursts mechanisms. Based on that a classification of rockbursts is proposed. The development of constant-resistance and large-deformation bolt (CRLDB) and its characteristics are discussed. Application of the CRLDB is shown based on a case study in Jinping II hydropower station situated mostly in marble.	A new classification of rockbursts was proposed. A system to simulate the impact-induced burst was developed, called deep rock nonlinear mechanical testing system. As an output it generates different types of disturbance wave signals, in analogy to impacts induced by the drill-and-blast method. The constant-resistance and large-deformation bolt tests shown that it absorbs the impact energy during the rockburst events. It was proven that it can be used as a rockburst control and prevention tool in deep underground excavations.

METHODS			
No	Reference	Content	Results\Conclusion
27	Kaiser and Cai, 2012	The study presents the considerations concerning burst-prone ground and discusses the rock support design. The rockburst problem background is outlined in the study, including rockburst damage mechanism and parameters influencing it. The methodologies of rockburst support design and main highlights helping to choose the appropriate one are given. The development of a tool called BurstSupport which aims to provide support in evaluating different rockburst support options is presented.	Principles of rockburst support design and main factors influencing the rockburst damage are outlined. Development of a tool that aims to assist ground control engineers in fast and systematic evaluation of the different rockburst support options is presented.
28	Guangcun <i>et al.</i> , 2014	The study discusses training of the neural network model with stress measurements data from Jinchuan Mine in order to obtain models with predictions of stresses at various depths in the mine. The models are then processed and statistically analyzed to identify hazardous areas.	Development of an artificial neural network model based on the geostress data from the Jinchuan mine. The horizontal displacement is not taken into consideration though, what effects in the fact that the forecasting data is not of high accuracy and it can be used only as a practical reference.
29	Wang <i>et al.</i> , 2015	The study describes granite instantaneous rock burst process reproduction using Deep Underground Rockburst Analogue Testing Machine (DURATM). Experiment setup and steps undertaken during the study are outlined. Particle Image Velocimetry (PIV) technique was used to perform quantitative analysis of a rockburst, and describe the images of tracer particle, obtain displacement and strain fields, and describe debris trajectory.	PIV method is able to track the tracer particles in the flow field of rockburst. It can be used in the experimental study of rockbursts. A new method of calculating the energy of rockburst is proposed, which uses values obtained from the displacement field and crushing ratio.
30	Feng <i>et al.</i> , 2015	The study introduces a methodology of immediate rockburst warning based on microseismicity. Microseismic data is applied in rockburst warning formula, which consists of: rockburst database, determination of typical rockburst cases, identifying the relationships between microseismicity and rockbursts,	A method of dynamically warning of rockbursts using microseismicity is proposed, which provides the probability of strain and strain/structure slip rockbursts.

METHODS			
No	Reference	Content	Results\Conclusion
		determining optimal weighting coefficients, and dynamic updating. The authors present a division of intensity of strain and strain/structure slip rockbursts. The method development is described and followed with its application at the Jinping II hydropower project which proved the method to be successful.	Classification of rockburst intensity is proposed (extremely intense, intense, moderate, slight, and none), and the method of estimating likelihood of rockbursts of each intensity are given.
31	Vinogradov <i>et al.</i> , 2015	The papers discusses a development of a simple 3D velocity model of the Khibiny and Lovozero massifs by means of the software called The Seismic Configurator (SC). The SC is capable of locating seismic events in 3D medium and estimating the location errors. An overview about the software, data processing, and model fitting is given.	A 3D velocity model was created using The Seismic Configurator software that fits the data recorded by a temporary seismic network.
32	Xu <i>et al.</i> , 2016	The study discusses rockburst problem which occurred during tunnels construction at the Jinping II hydropower station in China. The design and application of real-time microseismic monitoring system to record and analyse the spatiotemporal distribution evolution of microseismic events prior to and during strainbursts is outlined. The results from strainbursts forecasting are presented and discussed.	It was proven that the precursors to microcracking can be identified by means of microseismic monitoring. The forecasting of strainbursts locations was successful for more than half of the cases during microseismic monitoring period. Microseismic monitoring technique used in the study proves its suitability for the purpose of forecasting the strainbursts and effectiveness in the process of strainbursts hazard assessment and mitigation.
33	Cai, 2016	The author presents an application of disturbance energy analysis in a case study of Sanshandao gold mine in China. 5 mechanical parameters of rocks are taken into consideration to assess the rockburst proneness of rocks: brittleness coefficient of rocks, linear elastic energy, burst energy coefficient, strain energy storage coefficient, rock quality designation of rock mass. The	Establishment of the measures for prevention and control of rockburst in Shashandao gold mine.

METHODS			
No	Reference	Content	Results\Conclusion
		total accumulated disturbance energy induced by mining is obtained based on numerical modelling.	