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CONCEPT DEVELOPMENT OF A SMART ROCK ENGINEERING SYSTEM FOR REAL-TIME DECISION-MAKING AND RISK MINIMIZATION IN DEEP LEVEL HARD ROCK MINES :A DIGITAL MINING APPROACH

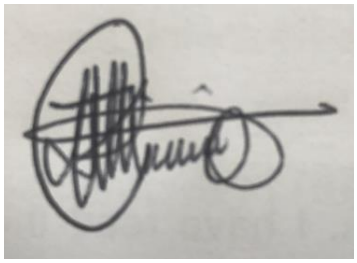
Joseph Kwiri

A research report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the Degree of Master of Science in Engineering.

Johannesburg 2018

DECLARATION

I declare that this research report is my own, unaided work. It is being submitted to the Degree of Master of Science in Engineering to the University of the Witwatersrand, Johannesburg. It has not been submitted before, for any degree or examination to any other university.



Signature of Candidate

25 October 2018

ABSTRACT

Huge milestones have been achieved in an attempt to reduce rock related accidents in the South African mining industry. However, ZERO HARM has not yet been accomplished. Despite the mining industry being active for years, accident statistics are still high compared to the mining industry in Australia and United States of America, in particular gold mining. Gold deposits occur in deep and ultra-deep levels where the stress levels and rock related risks are high making mining, more difficult and riskier. This is further exacerbated by the intensive labour force at such mining depths. Risk management strategies have been formulated and refined over the years and their success is not questionable as there have been, significant reduction of fatalities over the years. However, the number of fatalities over the years is still too high. As an example, fatal accidents exceed twenty from January 2018 to July 2018. These unfortunate statistics indicate that existing strategies to reduce rock engineering risks, have limitations. Surface mining, civil and petroleum engineering have more advanced risk management technologies compared to underground mining. The attributes of these technologies can be used to develop better underground risk management strategies. Such attributes include remote operation, integrated sensor system, and the ability to predict impending danger. Some of these attributes can be compared to human body and brain as it is an ideal system that smart systems should mimic in particular decision making and actioning of decisions made as well as the ability of skin to sense, repair itself and insulate. Used with advanced material science, such properties of the skin (sense, repair itself and insulate) can be used to make a type of support that can reduce support replacement costs and ventilation related operating costs. The conceptual smart rock engineering system developed consist of sensors, expert system for data analysis and decision making, wireless communication system and an emergency and preparedness response plan through automated alerts which are received by the miner in the stope area. The system should measure a number of parameters including stress, water level, convergence, face advance, face profile, loading of support and ground movement. The results are displayed concurrently on a video wall in the control room area. A case study was done to compare what is currently available in the Digital Mine Laboratory and the conceptual smart rock engineering.

From this case study, opportunities to improve the system installed in the Digital Mine Laboratory were identified. The Botswanan earthquake, which occurred on the 3rd of April 2017 at 17:40 Coordinated Universal Time (UTC) was a critical event to test the functionality of the system installed in the Digital Mine Laboratory. Recordings from the Digital Mine Laboratory were compared with other ground sensing technologies (United States Geological Survey (USGS) and GEOFOrschungsNetz Global Seismic Network (GEOFON) systems). which also captured the Botswana earthquake event USGS and GEOFON systems recordings suggested that there are a number of possible mechanisms that could have resulted in the earthquake. Compared to the USGS and GEOFON systems, Digital Mine Laboratory system could not provide a self-analysis data that could be used to determine the source and source mechanisms. The Digital Mine Laboratory system's success in recording the Botswana earthquake event is an indication that the system can be developed and or improved. For a comprehensive analysis, more data from various sensors needs to be collected, for example, by connecting to the national seismic monitoring system or to the local mines seismic monitoring system. Such connections will enable the development of a better self-analysis system and possibly prediction of future events within the Digital Mine Laboratory.

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DEDICATION

In memory of my two uncles, Girison and Kudakwashe

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1 INTRODUCTION

The subsequent chapter provides a background to conceive the research question. Such background is particular to the South African mining industry. The chapter sets the background of the area where the research took place, the problem statement, the scope, objectives and contents of the research report.

1.1 Background of the Wits Mining Institute's Digital Mine

Wits Mining Institute's Digital Mine is a 21st century laboratory mine developing, testing and demonstrating technologies to address the challenges encountered by the mining industry. The laboratory, known as Digi Mine is part of the Wits Mining Institute (WMI). WMI is located at the University of the Witwatersrand within the Chamber of Mines building. Digi Mine is located in the basement of the same building. Figure 1-1 shows the location of the entrance from surface into Digi Mine.



Figure 1-1 Entrance to Digi-Mine through Nick's Tunnel

Nick's tunnel is a 70m arch-shaped tunnel, supported by steel arches and shotcrete, as shown in Figure 1-2. The tunnel has a breakaway that leads to a model stope. The

laboratory is equipped with several sensors that monitor the mock mine environment. These sensors include, gas detecting instruments (GDI's), extensometers, crack meters, stress meters, and seismometers.



Figure 1-2 Nick's Tunnel showing steel arches, shotcrete, ventilation duct and stope breakaway

The model stope in Figure 1-3 is a simulation of a narrow reef stope, typical of the South African hard rock narrow reef mining.



Figure 1-3 Model Stope with support units

The stope area comprises timber packs and mechanical Cam-Lock Props as support. The tunnel and the stoping area both have the following monitoring systems:

- Ground behaviour monitoring system;
- Ventilation monitoring system; and
- Access control and position monitoring system

The list of sensors which include extensometers, crack meters, stress meters, and seismometers are connected to the control room where they form a system that monitors the mock mining environment and the miners in real-time. Such monitoring is there to reduce the risks involved when mining. This research, did not consider all other monitoring systems, but rather focused on ground control monitoring system.

1.2 Problem Statement

Prior to excavations in an underground environment, rock mass stresses are in equilibrium. Once created, excavations disturb the stress equilibrium. If the redistributed stress is greater than the strength of the rock, a failure zone is created, which is evident by spalling and slabbing in brittle rock (Stacey and Wesseloo, 2000). The spalling may take time to be evident or can be instantaneous creating cracks and fractures within the rock mass (Stacey and Wesseloo, 2000). This creates unstable ground, which need support and monitoring to avoid any unplanned ground movement. Such failure and movement of rock occur more often in deep-level underground mining primarily due to increased stresses acting on excavations. The design of the excavations ensures that they remain stable. Failure of transferring the planned excavation dimensions to actual excavation dimensions and the time dependence behaviour of rock reduces the factor of safety. This factor of safety reduction is a contributor to the creation of more hazards in the workplace. These hazards include fall of ground, rock bursts and support failure. The identification and mitigation of such hazards perform a crucial part in ensuring the safety of miners.

Extensive work has been performed by mining companies to ensure the stability of excavations in underground operations. Such work include installation of support to improve the quality of rock mass, use of blasting techniques that do not damage the rock mass extensively and use of mining layouts that reduce the magnitude of stresses acting on support units and the face area. Despite the effort to manage ground movement, accident statistics indicate that zero harm has not yet been achieved as shown by the unnormalized number of fatalities in the mining industry in Australia, USA and South Africa, in Figure 1-4.

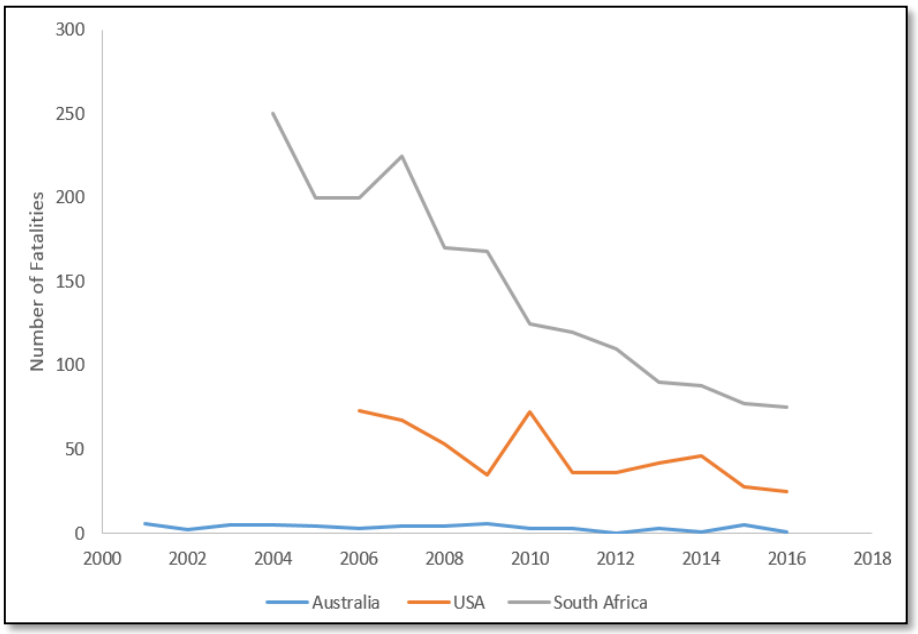


Figure 1-4 Unnormalized number of fatalities in the mining industry (Chamber of Mines South Africa, 2017) (SafeWork Australia, 2017) (National Mining Association, 2017)

Figure 1-4 shows accident statistics of three different countries. It is evident that South Africa, despite having a different mining environment holds a high fatality rate. Sheppard (2017) reiterates the point that the mining industry is still failing to achieve zero harm by saying, *"The first and most pressing of AngloGold Ashanti's key 2017 priorities is to put an end to mine fatalities by improving workplace conditions through technology rollouts and bettering legal compliance".* The high frequency of accidents results in operational stoppages, usually termed section 54. These operational

stoppages affect production efficiencies and resource utilization. Compared to other commodities within the South African mining industry, the gold mining sector holds the highest number of fatalities as shown in Figure 1-5.

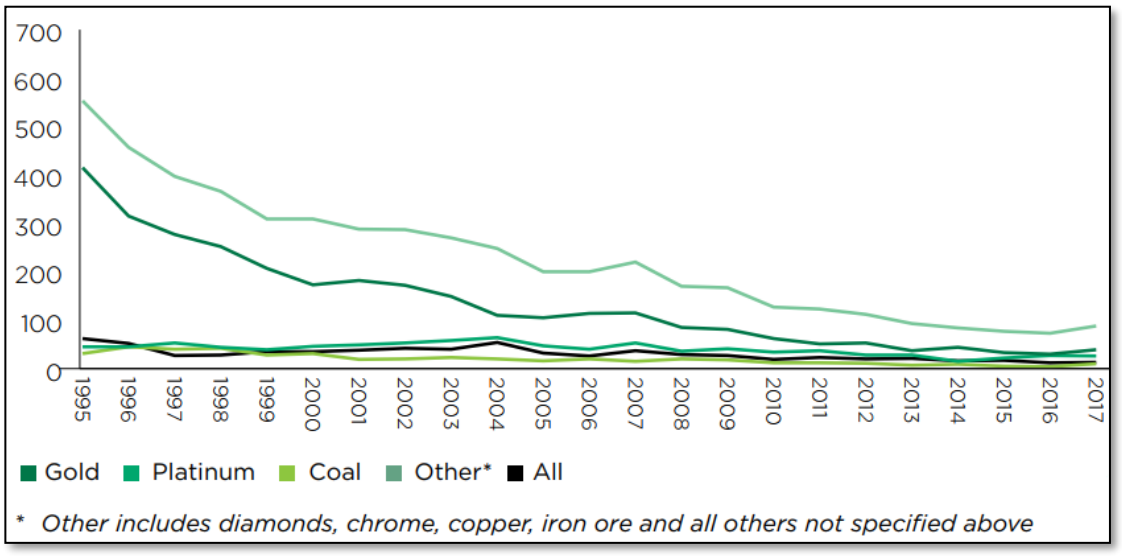


Figure 1-5 Mining Industry Fatalities grouped by sector (Mine Health and Safety Council, 2018)

[*All* refers to the total number of fatalities for gold, platinum, coal, diamonds, chrome, copper, iron ore and others not specified in the graph]

The graph indicates that gold mining sector has reduced the fatality rate by more than 500% from 1993 to 2016. However, the fatality rate is still high despite management's effort. Figure 1-6 shows that, when grouped by accident type, fall of ground (FOG) accidents are the highest. These FOG accidents are primarily a result of ground movement within the face area. Brink and Roberts (2007) identified that at least 77% of rock fall fatalities are related to the stoping area. They further identified that 80% of the fatalities occur within 3.5m from the face with typical fall area of $4m^2$ to $10m^2$. These numbers further indicate that the most hazardous area is the stoping area and to manage FOG accidents, risk management strategies should be directed to this area continuously.

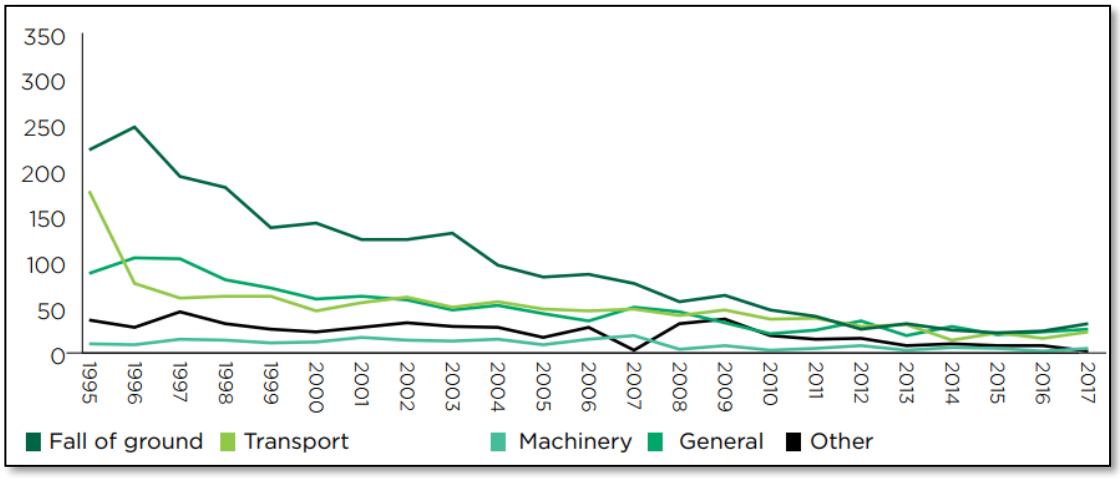


Figure 1-6 Fatalities grouped by accident type (Mine Health and Safety Council, 2018)

[*General* refers to exposure to gases or airborne pollutants, inundation with ore, slipping and falling and struck by an object whilst *othe*r refers to sicknesses due to tuberculosis, silicosis and backfill bursts (Mine Health and Safety Council, 2018)]

Despite an improved understanding of rock deformation and failure mechanisms in the South African mining industry, FOG accidents occur without much warning. Failure to provide enough warning has the potential to cause loss of life, reserves or equipment. The rollout of smart technologies has the possibility of addressing such losses and risks, in particular, by providing at least enough warning to the miner for immediate evacuation.

1.3 Review on Strategies that Achieved a Reduction of Fatalities in South African Mines

Since the 1900's, there have been advancements in theoretical and practical understanding of rock failure mechanisms and the potential ways to control the impacts of rock bursts or rock falls. On the theoretical front, such advancements include:

– Re-evaluation of the important concept of risk management;

- A burgeoning rock-engineering data pool from mines and the introduction of real-time risk management;
- The advancement of computer storage size, functions and processing speed;
- The emerging of smart materials and smart structures; and
- The increased access to simulations and numerical techniques

On a more practical approach, advancements include:

- In excavations, the increased use of smart sensors for example FOG lights;
- In data processing, the increased use of computers in processing and analysis;
- Globally, the rising need for integrated structures;
- In monitoring, seismic monitoring, introduction of FOG warning and the ability to forecast seismicity using historical data and precursors to such events; and
- The use of mining layouts to reduce the occurrence of conditions that accelerate unstable ground.

These advancements, coupled with the goal for zero harm and increased developments in smart technology formed the motivation for this research. The main goal for the smart technology approach to manage rock-engineering risk, is to achieve zero harm and to eventually introduce intelligent mining. The potential benefit of this technology approach includes:

- Safe mining as a result of minimising the impact of the hazard through quicker responses enabling miners or equipment to be moved away from the hazard in time where possible;
- Less lost time because of production stoppages;
- Improved understanding of risks over time;
- Improved mining operational efficiency;
- Improved way to locate area where damage has occurred, as using seismic events to locate such areas is often not satisfactory (Malan, et al., 1997)
- More profit because risk is understood and managed better; and
- Way of earning social licence to operate due to improved safety records.

When such an approach is not supported, risks that negatively affect the mines could arise. These risks include:

- Loss of life and equipment;
- Ore sterilization;
- Section or mine closures;
- Loss of profit due to increased costs (these costs are a result of failure to manage the resulting risks) and lost time for production (McKay, 2016);
- Government loses taxes; and
- The rock-engineering fraternity could be forced into reactive actions if they do not embrace such technology (Mine Ventilation Society of South Africa, 2017)

It is the researcher's opinion that fatalities due to FOG, can be minimised and eliminated through applying real-time technology. This will be achieved by "*giving the rock a voice so that it will communicate to the miner before an event happens providing the stope a chance to make a decision on its own"*. Although numerous risk management systems exist, it was identified that such risk management systems are not adequately addressing the risk, therefore, an introduction of smart technology is addressed. The research aimed at developing a practical and effective concept of a smart rock-engineering system for deep-level hard rock mines.

1.4 Definition of Terms in Context of Research

The term "smart rock-engineering system" describes a system comprising sensors (that may have localised decision-making), communication system, control centre, and servers. These sensors are able to sense a rock engineering parameter and relay the information to the control room in real-time. Such a system delivers a decision to the concerned personnel in real-time. Applying this system leads to intelligent mining, risk minimization and real-time decision-making. The following details the definition of each word or phrase to obtain a complete understanding of smart rock-engineering system.

1.4.1 Smart system

The following definition by (Akhras, 2000) of the smart system seems relevant to the study.

"A system that incorporate functions of sensing, actuation, and control to describe and analyse a situation, and make decisions based on the available data in a predictive or adaptive manner, thereby performing smart actions"

A smart system therefore, is a model that mimics the human nervous system. Such mimicry is what the project aimed to develop as a concept.

1.4.2 Intelligent mining

Intelligent mining is defined as *"a novel technique that integrate sensing with automated reasoning in all processes along the mining value chain without the intervention of human beings or with limited human interaction to improve the performance of the whole mining process"* (University of Alberta, 2002). The mine of the future will not have human beings working in the harsh environments. The intent is to control it remotely. This means that all the processes, including rock-engineering, need to be smart from exploration to mine closure creating an intelligent mine

1.4.3 Risk minimization

Lagendijk (2011) defines risk minimization as "*a set of activities and interventions designed to identify, characterize, prevent or minimize risks relating to rock engineering including the assessment of the effectiveness of those interventions"*. Residual risk is inherent in mining activities. The extent to which such risk is minimized is critical to the goal of achieving zero harm. Risk minimization thus looks at each activity within the mining process including the area of rock-engineering.

1.4.4 Real-time decision making

Martin (1965) defines real-time decision-making as "*one which controls an environment by receiving data, processing them, and returning the results sufficiently quickly to affect the environment where data was extracted at that time."* The crux of a real-time system is consistency in the time it takes to sense and relay a decision to the people concerned.

1.4.5 Conceptualization

Conceptualization *"is the process of specifying what a system is, what it will do, how it is intended to be used, what the system is not, what it cannot do, and how it is not intended to be used"* (Khan and Mario, 2010). This process indicates the main functionalities expected from the system and how key processes within the mining cycle, relate.

1.5 Scope of Research

The technology approach in managing rock-engineering risk aims to use sensors that measure the right risk. These sensors must be robust by rendering their design rugged, water proof, dust proof, drop resistant and be able to sense over a distance through wireless technologies since the mining environment is harsh and dynamic. Reliable real-time wireless communication is required. This entails transferring data from the sensors to the control room to generate risk maps with automated alerts and visual reports to management. Within the value chain, the smart rock engineering system fits into the production process. Figures 1-5 and 1-6 showed that most of the recorded fatalities have occurred in gold mines which are known to be underground deep level narrow reef mining. This project will be limited to such environment. The behaviour of rock described in this project, is too complex. The complexity is exacerbated by unpredictable geological effects. In this project, no inference is made to provide

definitive answers to all rock-engineering problems mentioned but a means to assist in improving safety, is provided.

1.6 Significance of the Research

The research provides a means for drastically reducing the risk of fatal accidents through understanding the use and applicability of smart technology in rock-engineering. Such understanding does not remove the need for a good safety culture but enhances the development of an improved and smarter safety culture.

1.7 Research Objectives

The objectives of the research are as follows:

- Describing the mining environment, rock mass behaviour and associated risks in deep-level mines and available risk management systems and technologies;
- Using the available literature to identify rock-engineering risk management technologies in open pit mines, civil and petroleum engineering and their functionalities that can be used for underground mining;
- To identify smart systems and current research on technologies for managing rock-engineering risk in underground mines;
- Conceptualizing a smart rock-engineering system for real-time decision-making and risk minimization in deep-level hard rock mines; and
- To run a complete system test using the VibraTech Ground Monitoring System as a case study of a conceptual smart rock-engineering system.

1.8 Research Contents

This research report is presented in eight (8) chapters with the underlying theme of developing a smart rock-engineering system.

- The first chapter defines the scope and objectives.
- Chapter two (2) details the behaviour of rock mass and associated risks in deep-level mines and risk management technologies and systems available to reduce rock-engineering risk.
- Chapter three (3) describes risk management technologies and systems in other areas of specialization and how these systems can be applied to rock-engineering.
- Chapter four (4) describes smart systems, their functionalities and current research on smart technologies and systems that can be adapted for underground mining rock-engineering.
- Chapter five (5) describes how the concept is developed and how the case study is performed as a way of analysing the effectiveness of the VibraTech System.
- Chapter six (6) uses information from the five preceding chapters to develop a plausible conceptual smart rock-engineering system.
- Chapter seven (7) analyses the VibraTech Ground Monitoring System and determines the deficiencies of the system, to achieve a proper system.
- The major findings and conclusions are presented in the eighth (8^{th}) chapter.

Despite the efforts to manage rock related risks, accident statistics indicate that zero harm has not been achieved yet. The Wits Digital Mine through its research and its installed system, aims to reduce, and where possible, eliminate such risks. The approach used to reduce and eliminate rock engineering risks involves introducing a smart rock-engineering system signifying the theme of this project. An understanding of rock behaviour is required to develop such a system. The following chapter describes the environment where smart rock-engineering is to be developed. The mining environment described is compared to other environments and the employed risk management strategies are described.

2 HARD ROCK MINING, ROCK MASS RESPONSE AND RISKS IN DEEP-LEVEL MINES

Describing the mining environment, rock mass behaviour, rock-engineering risk in deep-level gold mines and available risk management systems and technologies

2.1 Introduction

The introduction emphasized the need to reduce risk and to understand rock behaviour if the goal of ZERO HARM has to be achieved. In this chapter, the mining environment, rock behaviour and current risk management systems are discussed. The limitations of the current methods considered to mitigate rock-engineering risk are also described.

2.2 Mining Environments

The *'cornucopia of resources'* in South Africa occurs as soft and hard rock deposits. Soft rock minerals include, coal and potash. The extraction of minerals in soft rock occurs in relatively shallow environments with highly mechanised mining systems. The occurrence of rock related accidents in soft rock is relatively low compared to hard rock mining. Hard rock minerals include, gold, platinum, manganese, chrome, and iron ore. Hard rock mining can be defined as the extraction of minerals which occur in host rock that cannot be extracted economically on large scale by the conventional pick cutting or disc cutting (Pickering et al, 2006). Raise boring is largely used for once off projects such as shaft or sub vertical shaft sinking. Reef coring in hard rock has been on trial basis in deep level gold mining and its feasibility is still questionable. Hard rock mining therefore involves the use of high-energy explosives to break the rock for easier mineral extraction.

Figure 2-1 shows a typical narrow reef underground mine (Durrheim, 2010). From Figure 2-1, it is critical to note steep stopes, size of excavations and the nature of the mining environment.

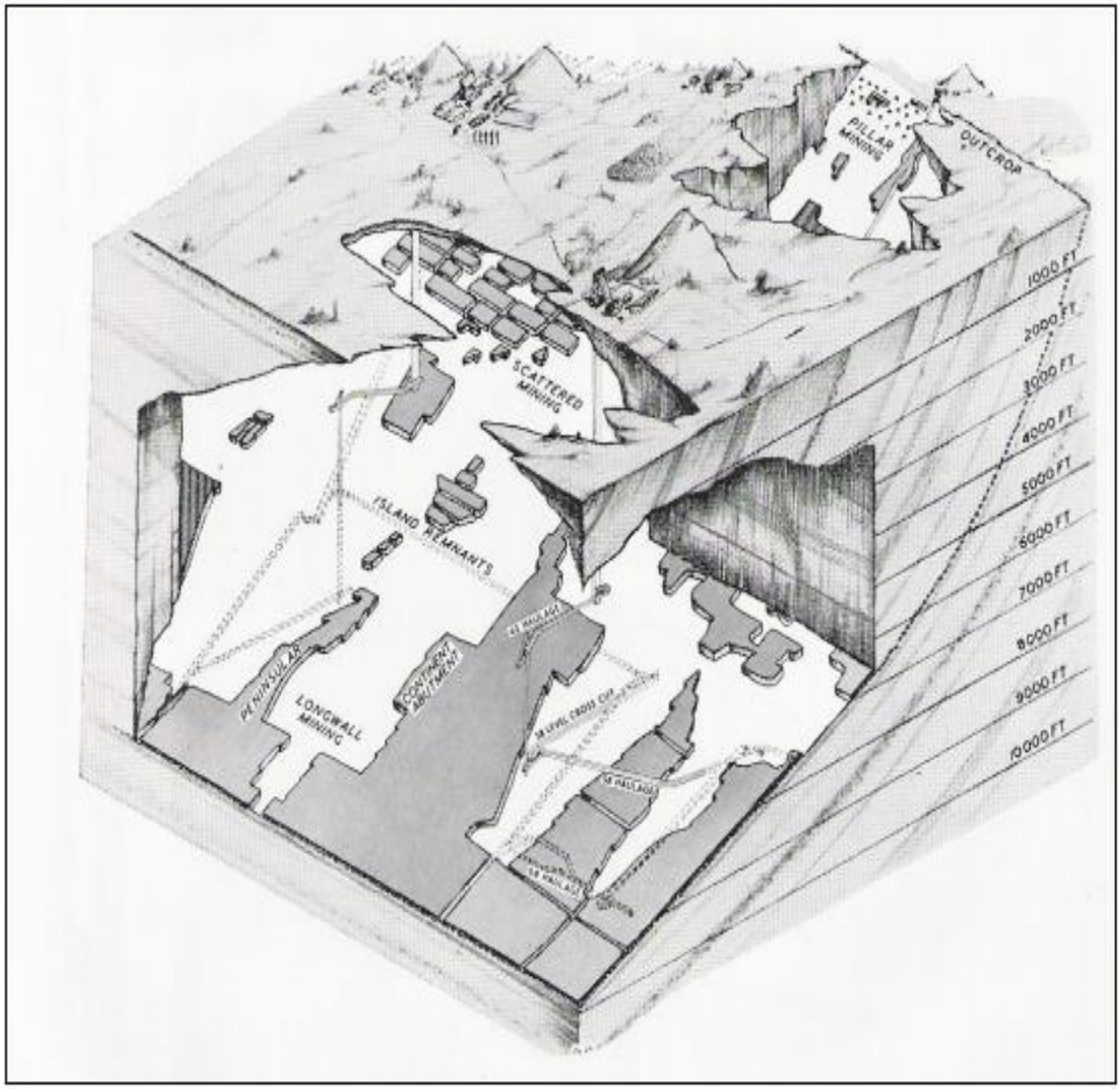
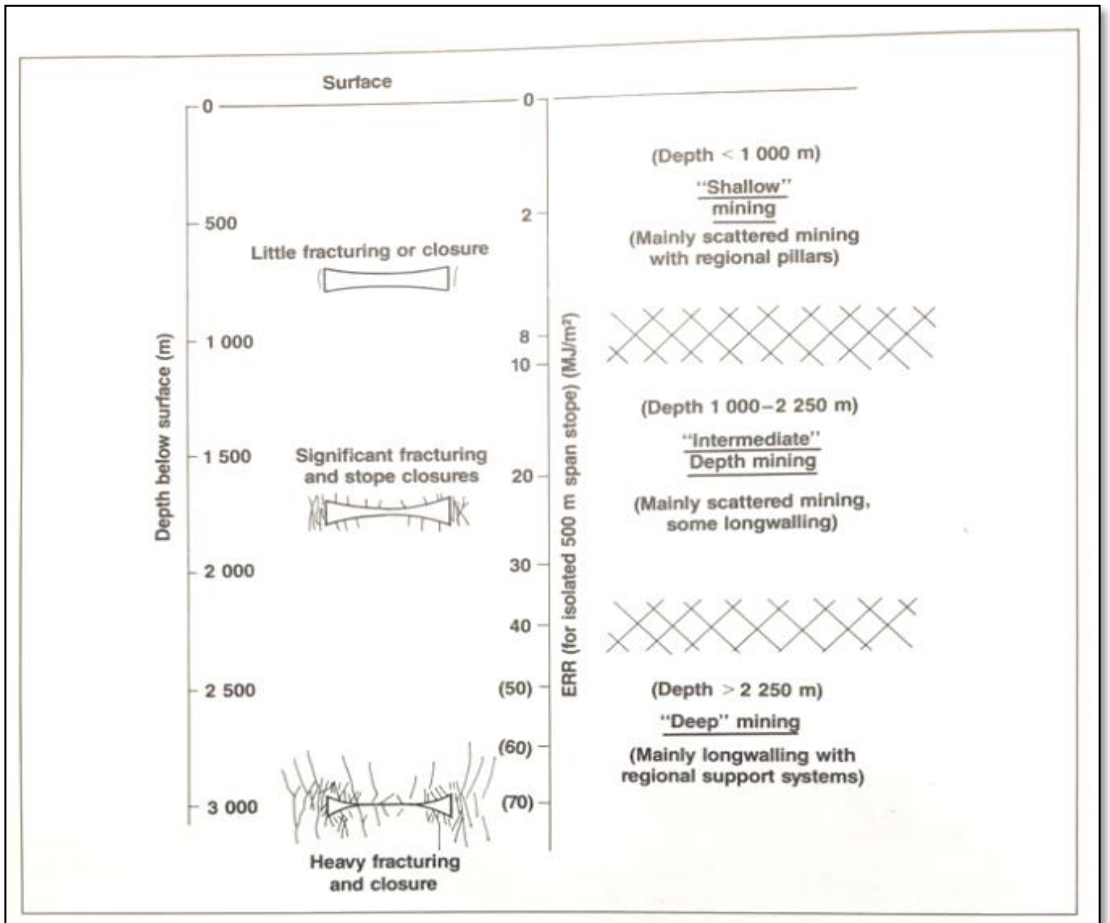


Figure 2-1 Typical gold mining (narrow reef mining) (Durrheim, 2010)

The occurrence of hard rock minerals lies between shallow and ultra-deep mining environment (Chamber of Mines Research Organisation, 1988). Mining environments are thus shallow, intermediate and deep as summarised in Figure 2-2.



	SHALLOW	INTER-MEDIATE	DEEP
Typical depth (m) Average (regional) ERR (MJ/m²)	<1 000 <8	1 000—2 250 8—40	>2 250 >40*
Vertical virgin stress levels (MPa)	Low (<25)	Moderate (25—60)	High (>60)
Stress fracturing	Little	Moderate	Intense
Stope closure rate (mm/m advance)	Low (<10)	Moderate (10—30)	High (>30)
Influence of geology on hangingwall stability	Strong	Moderate	Moderate
Possible extent of falls of ground	Can be large	Often small	Usually small
Rockburst hazard	Minimal	Moderate to Severe	Severe

*if regional support not used

Figure 2-2 Mining conditions and the nature of fracturing around the stope for typical hard rock mining environments (shallow, intermediate and deep mining environments) (Jager and Ryder, 1999)

Depth in competent rock, is the major factor that contributes to the classification of mining environments. Mining depth to 1000m is considered shallow mining and mining depth that ranges from 1000m to 2250m is referred to as intermediate depth mining whereas deep mining occurs at depth below 2250m to 3500m, with ultra-deep mining beyond 3500m (Chamber of Mines Research Organisation, 1988). As depth increases, the mining environment increases gradually from easy to difficult due to the increasing changes in stress levels and geology.

2.2.1 Deep and ultra-deep mining environment

Extraction of resources at depths exceeding 2250m to 3500m is considered as deep mining and beyond 3500m as ultra-deep mining. In this research, both deep and ultra-deep-level mining depths area, classified as deep level mining environment. In deep-level mining, the geotechnical issues are intensely developed giving rise to more rock-engineering problems. These major issues include:

- High stress levels and high-energy release rates causing the rock to fracture more compared to intermediate depth mining (Middindi Consulting, 2012). Unprotected excavations at this depth exhibit intense and extensive fracture zones (Jager and Ryder, 1999) but when placed in overstoped areas, the fracture zones are minimum (Chamber of Mines Research Organisation, 1988).
- Around the excavations, deformation and deformation rate are high, resulting in high and rapid stope closure (Jager and Ryder, 1999). Back area total closure is common. Figure 2-3 shows the rate of closure against the distance from the face at different depths for deep-level mining. As depth increases, the closure rate also increases. The high and rapid closure rates at this depth reduce support effectiveness in particular the hydraulic props used in the immediate face area. This is largely because these rapid closures exceed useful yield ability range of several support units (Jager and Ryder, 1999) resulting in loss of effective support capacity of the units.

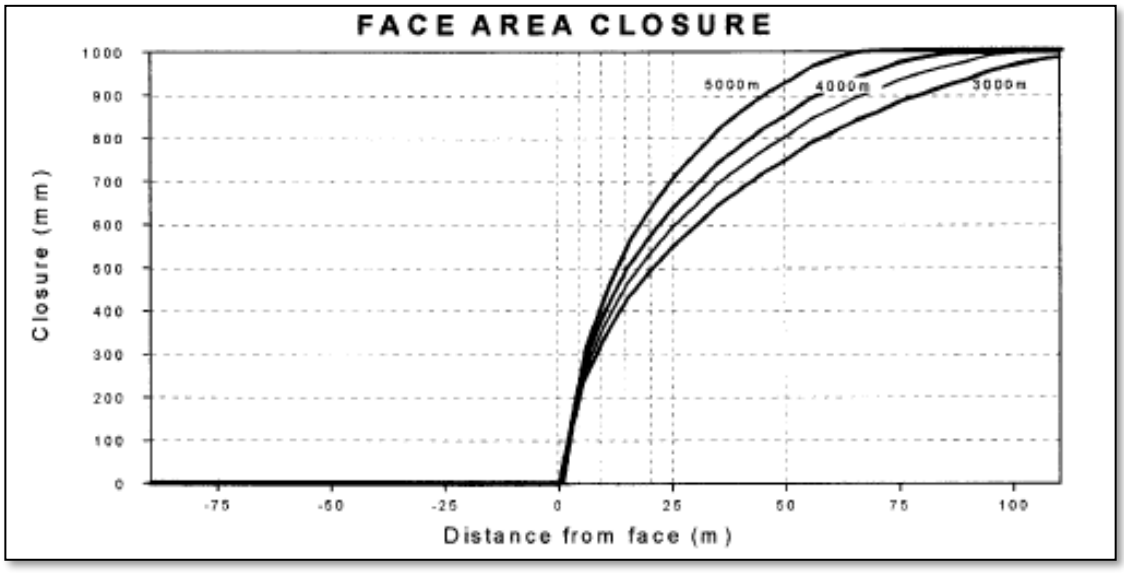


Figure 2-3 Profiles of stope area closure (Johnson, et al, 1995)

– High virgin stresses which may exceed the strength of rock, resulting in unstable ground. (Johnson, et al, 1995). Figure 2-4 shows typical stresses within the face area with peak stresses exceeding rock strength values.

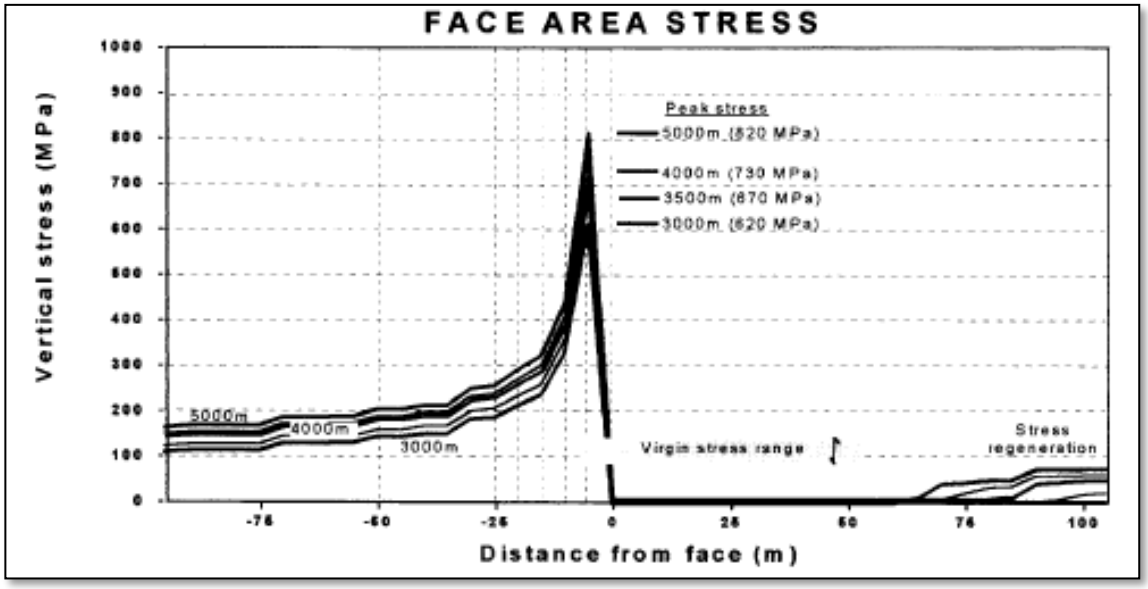


Figure 2-4 Profile of stope area stress ahead of mining face (Johnson, et al, 1995)

Figure 2-4 shows that there are very high-induced stresses within the immediate face area. According to Johnson et al (1995), "*these induced stresses are elastic stress profiles and are redistributed over a large area due to face fracturing*". Johnson, et al (1995) further point that "*this fractured rock maybe highly stressed far more than previously thought".* Immediately after closure, stresses quickly regenerate themselves to virgin stress levels (Jager and Ryder, 1999).

- Rock bursts are common at this depth because of high stresses (Middindi Consulting, 2012) and seismicity is a common feature. Geological discontinuities especially faults and dykes are largely associated with this seismicity. This is because of high-energy release rate. Energy release rate (ERR) is a measure of both mining hazard and seismicity. Figure 2-5 shows the change in depth versus change in energy release rate (Johnson, et al, 1995).
- Figure 2-5 shows an increase in energy release rate as depth increases.

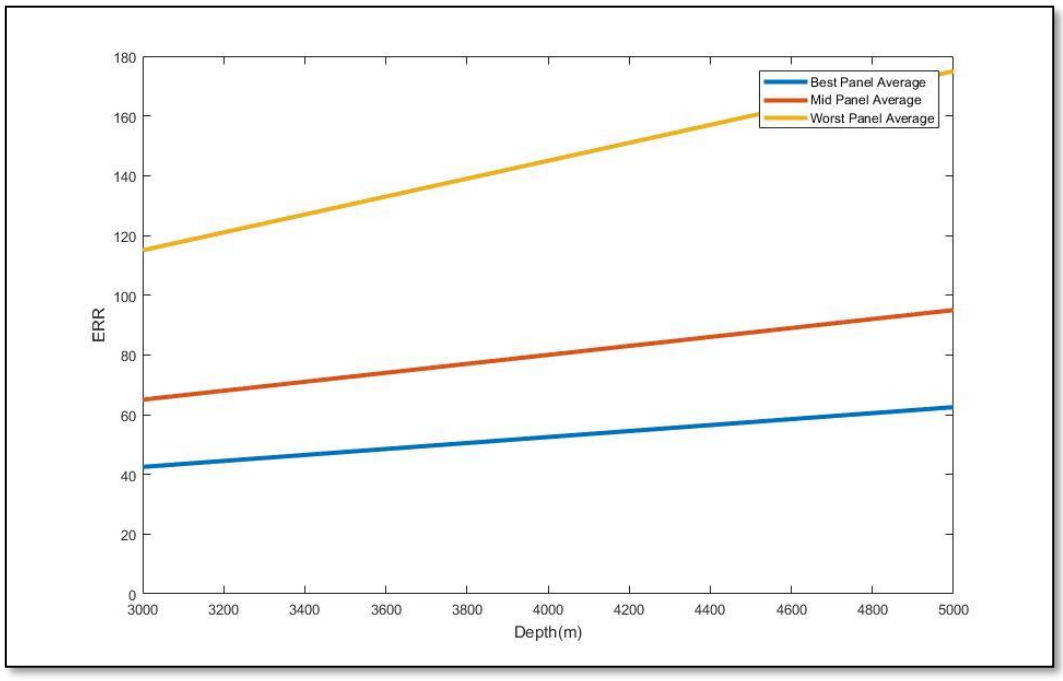


Figure 2-5 Range of ERR panel averages with depth (Johnson, et al, 1995)

- In Figure 2-5 the top line shows the worst panel average, and the middle line shows mid panel average. The bottom line shows the best panel average. These averages are determined by steps of mining (mining a larger panel at once increases ERR and mining it in steps reduces the release of kinetic energy, hence strain burst potential). Other factors include, stoping width, rock mass properties, presence of any support within the immediate face and presence of any adjacent mining faces (Johnson et al, 1995). When a panel is mined following the standard, the best panel averages are obtained and when there is substandard mining, worst panel averages are obtained.

The extraction methods for deep-level mining are sequential grid (Middindi Consulting, 2012) and longwall mining methods. Longwall mining method is not favoured as in most cases this method leaves highly stressed remnants (Handley, et al, 2000).

2.3 Rock Mass Behaviour in Deep-Level Mines

According to Stacey (2017), *"The behaviour of rock and rock mass is complex especially when subjected to a dynamic environment. It therefore behaves in ways it wants to and when it wants to."* The behaviour of rock mass is a function of rock properties and stress field. This relationship has been found to be true in platinum mining where the pre-failure stiffness of pillars is different for the same rock type with different rock properties (Mine Health and Safety Council, 2016). The difference in behaviour of rock at these depths is variable and complex (Brown, 2012). Recent developments in deep-level mining suggest that rock behaviour is not fully understood. The complexity to fully understand rock behaviour is attributed to the following questions:

- How geological discontinuities (dykes, faults, joints) affect rock behaviour?
- How rock properties (rock type, rock texture, rock mineral composition) affect rock behaviour? and

- How the extraction sequence or mining method affects rock behaviour in the vicinity of excavations?

These conditions in deep-level mining result in complex deformation mechanisms (Brady and Brown, 2004). Mining parameters affect the role of geological discontinuities, but their importance is unquestionable (Johnson, et al., 1995). Rock texture and rock composition also vary in both the vertical and lateral extent. According to Schweistzer and Johnson (1997) "*these variations control faults and joint attitudes, geometry, secondary mineral assemblages and excess shear stress".*

The textural composition of dykes, faults and joints affect rock behaviour at depth. As an example, dyke composition ranging from basaltic to rhyolitic determines the proneness of rock bursts (Schweistzer and Johnson, 1997). In particular, siliceous dykes are capable of storing elastic energy, making them the most likely to fail dykes. The failure of rock within and around these structures is evident through closure rates, seismicity and mining-induced extension and shear fracturing (Johnson, et al, 1995). Schweistzer and Johnson (1997) further points that the level of seismicity in deep-level mines is largely affected by:

- The degree of geological disturbance;
- The mining method;
- Rock types; and
- The way in which rock types are assembled.

Where geological discontinuities are absent, rock fractures are minimum resulting in a stable state of mining. In this state (of no geological discontinuities) rock type has been found to be the main factor controlling how rock mass behaves. As an example, siliceous rock tends to be fractured parallel to the fine shale bedding (Johnson, et al, 1995). The lateral extent of fracturing to the face has been found to be controlled by:

- Energy Release Rate;
- Rock strength;
- Presence of bedding planes;

– Other geological discontinuities; and
– Excavation dimensions

The presence of geological discontinuities in fractured areas may result in the termination of fracturing beyond the discontinuity or creating a different form of fracturing beyond the discontinuity (Mine Health and Safety Council, 2016). In the Bushveld Complex, different fracture intensities were observed across a fault (Johnson, et al, 1995). Figure 2-6 shows the extent of fracturing around a typical stope in deep-level mining.

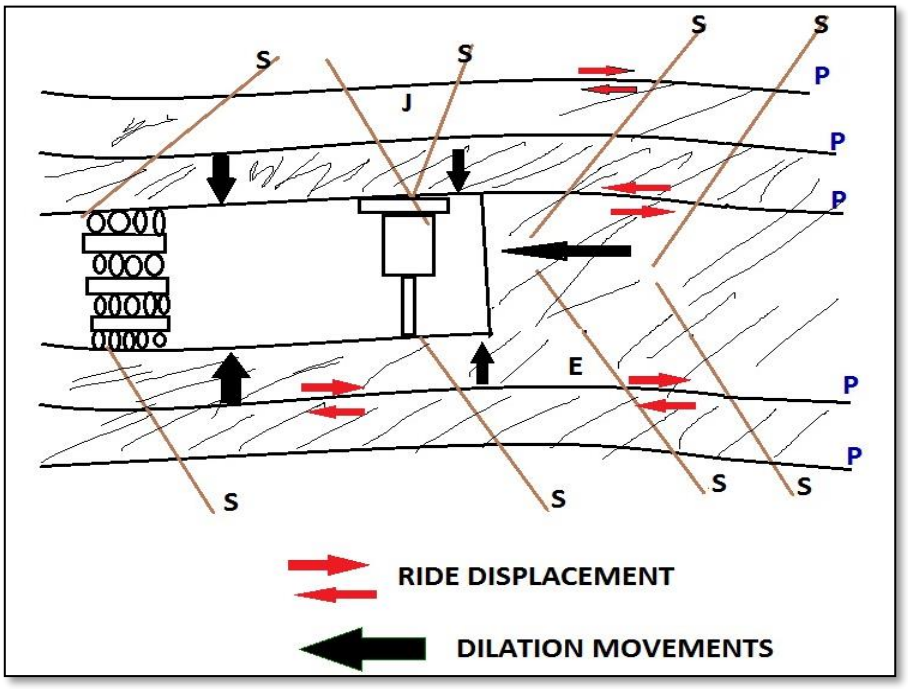


Figure 2-6 Fracture pattern for a typical excavation at intermediate depth (Jager and Ryder, 1999)

From Figure 2-6,

– S is the Shear fractures
– P is the Parting planes;
– E is the Extension fractures; and
– J is the Joints

In this example, deformation of excavation occurs as elastic and inelastic relaxation of rock mass surrounding excavations. Elastic deformations are instantaneous whilst inelastic deformations are time-dependent (Chamber of Mines Research Organization, 1988). The extent of elastic deformation and inelastic deformation depends on:

- Elastic modulus;
- Nature and frequency of geological discontinuities and fractures;
- Depth of mining; and
- Span and mining geometry

Closure rates per day, range from 10mm to 50mm and visible total closure is around 10m behind the face (Chamber of Mines Research Organisation, 1988). In these areas, inelastic deformation is greater than elastic deformation and strongly time-dependent (Chamber of Mines Research Organisation, 1988). High stresses in deep-level mines, where the virgin stress exceeds 50% of the uni-axial compressive strength, are also a major factor in rock fracturing (Jager and Ryder, 1999). This high stress is a result of stressed remnants and increased depth as emphasized in section 2.2.1. High stress areas are also found in and around the stope face, gully-face intersection, and unsupported development end (Mine Health and Safety Council, 2016). In these areas, the magnitude of closure is large such that the resistance provided by support units does not assist in reducing closure. These support units offer reactive loads to closure thereby giving support to hanging-wall.

Ride, defined as the differential lateral movement between the footwall and hanging-wall (Jager and Ryder, 1999), is common in deep-level mines (Chamber of Mines Research Organisation, 1988). Rock quality of footwall and hanging-wall, reef dip and stope geometry affect the magnitude and orientation of ride (Middindi Consulting, 2012). Ride thus affects support performance. In addition to quasi-static deformations, excavations in deep-level experience dynamic deformations in the form of rock bursts. The manifestation of these rock bursts are in the form of:

- Gravity induced falls that largely result from shakedown of fractured hanging-wall or from momentary loss of horizontal clamping stresses living the passage of a seismic wave;
- Violent ejection and possible shattering of rock from face; and
- Rapid and massive stope closure resulting from coherent movement of hanging-wall and foot-wall.

Failure to follow the planned mining sequence usually results in high stoping widths, incorrect pillar sizes and lags between advancing mining faces which, in the presence of geological structures, exacerbates fracturing of rock. Although stress levels and rock strengths are the major drivers for stress fracturing in deep-level mining, their variability depends on the extent of fracturing. Figure 2-7 shows fracturing for deep-level mining (Mine Health and Safety Council, 2016).



Figure 2-7 Fracturing of exposed rock in the Bushveld Complex (Mine Health and Safety Council, 2016)

The exposure of certain rock type increases damage and fracturing in the stope hanging-wall or above pillars, in some areas of deep-level mining (Mine Health and Safety Council, 2016). This kind of fracturing is affected by excavation geometry, and

rock type aforementioned. An example is norite rock, which fractures into thin, curved slabs and or sheets with sharp edges and pyroxenite fractures into blocks as shown in Figures 2-8 and 2-9 within the Bushveld Complex.



Figure 2-8 Dense, curved fracturing of exposed Norite (Mine Health and Safety Council, 2016)



Figure 2-9 Dense, steep dipping and blocky fracturing in Pyroxenite (Mine Health and Safety Council, 2016)

Where potholes are present, higher joint densities and shallow dipping joints are found. The risk of exposing rock that is easily fractured, increases in the vicinity of potholes. However, the risk of seismicity and other rock related risks in platinum mining is low compared to gold mining. Smart technologies and systems to be developed need to address this kind of rock behaviour in different kinds of mining environments.

2.3.1 Precursors to seismic events, panel collapses and falls of ground

Case studies of seismic events, panel collapses and falls of ground indicate that ground failure does not happen without providing a warning. Geotechnical warnings occur prior to a given failure (Watson, 2018). These warnings are identified as indicators, precursors and triggers as shown in Figure 2- 10.

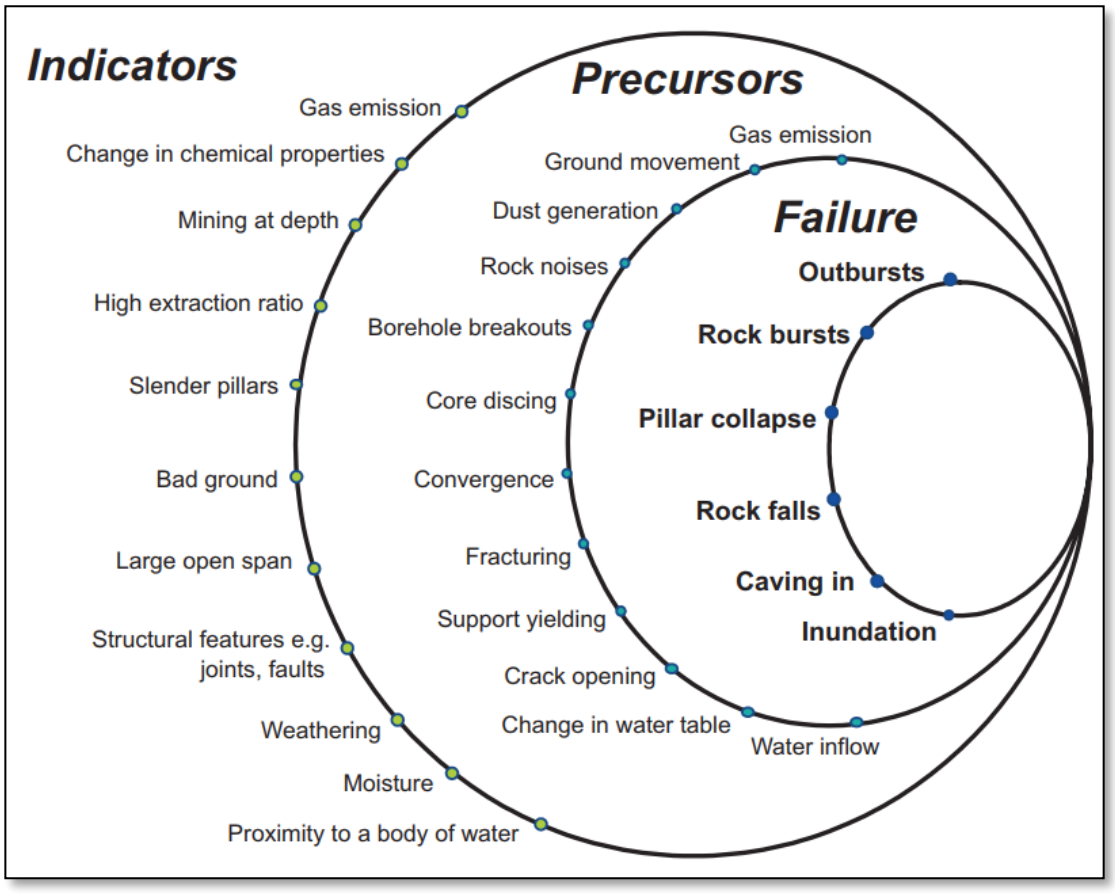


Figure 2-10 Precursors to ground failure (Szwedzicki, 2008)

According to Malan and Basson (1998), the cause of these indicators can be attributed to squeezing of rock at deep level. Squeezing is defined as "*the time dependent large deformation which occurs around the excavation and is essentially associated with creep caused by exceeding a limiting shear stress"* (Malan and Basson, 1998). The presence of triggers exacerbates structural damage and progressive failure of rock. Figure 2-10 showed indicators and precursors that lead to local and regional failure.

- Indicators;
    - According to Szwedzicki (2008), "*an indicator is a sign, state, or contributing factor that points out or suggests that the rock mass may be prone to damage or failure*". Operational mining factors and certain geotechnical factors indicate the potential of failure. Szwedzicki (2008) further asserts that, "*geotechnical indicators suggest that, the properties of the affected rocks are different from the surrounding rock mass failure*". These include:
        - Geological structural features such as faults, folds, shear zones and dykes;
        - Layers of weak rock in the vicinity of excavations;
        - Jointed blocky ground which creates poor ground conditions; and
        - Discolouration of rock due to weathering.
    - Operational indicators signify a possible deterioration of ground that include:
        - Increased blast damage to the surrounding rock;
        - Increasing extraction ratio; and
        - Water accumulations in the vicinity of mined areas being mined.
- Precursors; and
    - Sometimes called a tell-tale, a precursor in rock-engineering is a state that suggests that damage has occurred in the rock mass and there is a possibility of pending failure. Precursors include measurements from closure meters, for example, which warn of excessive ground deformation (Malan et al,

1997). A significant change in one precursor is not adequate to indicate structural failure of rock, therefore more than one measurement is required (for example convergence, stress, acoustic emission). In addition, physical observations play a role in determining the scale of damage of rock. The scale can be local, transitional or regional (Szwedzicki, 2008).

- Local – precursory behaviour of rock on a local scale manifests in the form of:
    - Rock cracks around stope or tunnel openings;
    - Rock slabs or spalling around excavation walls;
    - Local falls of ground or roof sagging;
    - Yielding of pillars and rock hang ups;
    - Popping or spitting of rock (strain bursts); and
    - Drum like sound when walls are tapped using a pinch bar.
- Transitional – This scale is shown by:
    - Propagation of cracks between stopes;
    - Increase in water seepage;
    - Increased dust generation;
    - Movement along a geological structure;
    - Floor heaving due to pillar punching; hour glassing of pillars; and
    - Continued barring down during a shift.
- Regional scale is shown by a progression of damage on a larger distance. This is shown by:
    - Seismicity;
    - Caving of the hanging-wall (This can be due to squeezing of rock (Malan and Basson, 1998));
    - Increase in water flow and water levels;
    - Cracking of areas above the stoping area; and
    - Movement across geological structures.

- Triggers and failure.
    - Damaged rock can maintain stability for some time unless an external trigger, for example, seismic event, blasting or heavy water inflow, initiates or triggers failure. Water in particular leads to geological structure strength loss causing collapses. Mining activities are the major factor causing ground instability primarily due to over breaking. A delay between triggers and subsequent failure has been observed, for example, major rock falls have been identified to occur a few hours after blasting (Szwedzicki, 2008).

Szwedzicki (2008) identified that "*the sequence of geotechnical precursors commences with ground deformation leading to deterioration in ground conditions and concludes with uncontrolled ground movement*". The initiation of such a process starts at a local scale and propagates through transitional to regional scale. During this transition, numerous indicators or precursors couple to exacerbate failure propagation. As an example, spalling and convergence can occur simultaneously increasing span size and worsening ground conditions. These factors show that precursory behaviour of rock has a pattern. When studied in detail, such precursory behaviour can be used to develop improved smart rock engineering system. In addition, Malan et al (2003) showed that for such a typical system to be used optimally and to allow rock engineers to continuously assess and optimise their support, a mine wide monitoring system should be installed with sensors in every working panel. However, Malan et al (2003) note that, measuring the increase in closure (one of the precursors) as a way to identify damaging seismic events is not adequate, as the two have no proven correlation.

2.3.2 Parameters used to develop hazard maps

Hazard maps are plans that show areas within a mine with relative hazards shown as red, green or amber depending on the hazard level. The combination of parameters and or precursors determines which indicator to show on the hazard map. In addition, frequency and severity of the potential losses are also considered. An example of a

hazard map is shown in Figure 2-11. Hazard maps assist rock engineers with identifying areas of high risks (SRK Consulting, 2018).

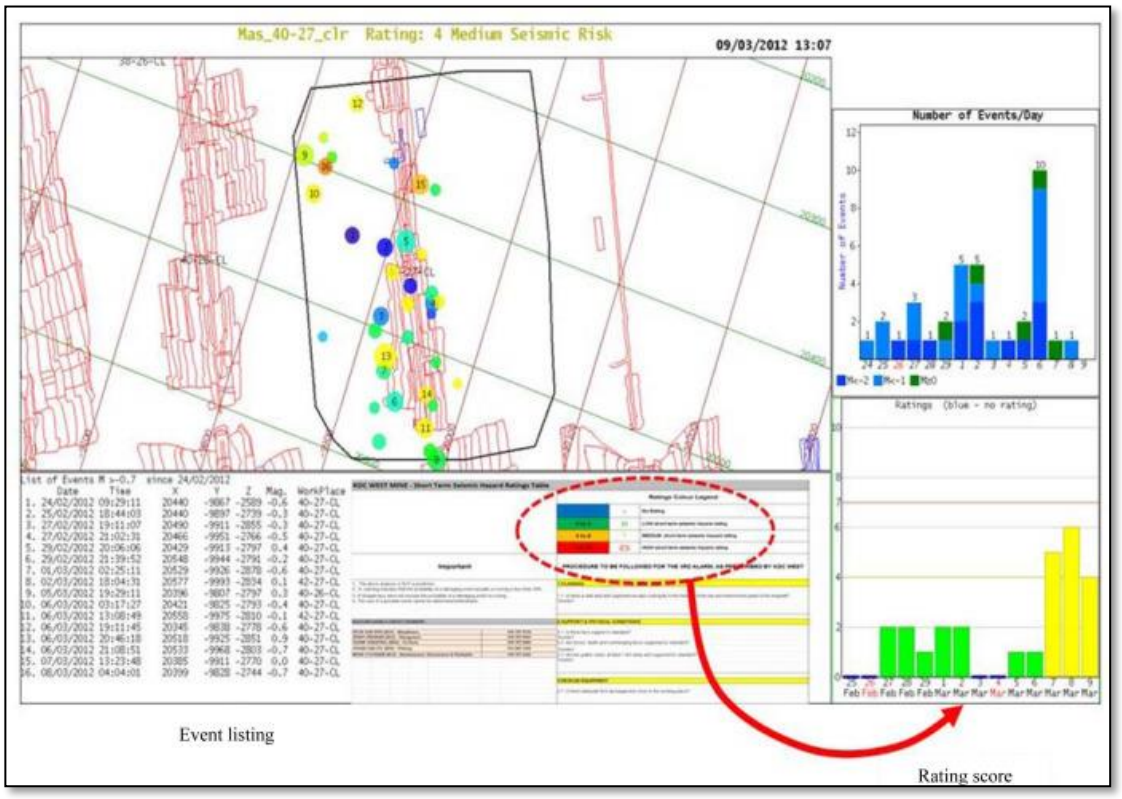


Figure 2-11 Hazard map used for reporting purposes (Riemer and Durrheim, 2012)

Parameters used to create hazard maps include:

- Average Seismic Index;
    - This parameter shows the state of stress in the rock mass and the calculation uses data obtained from previous weeks and the scale ranges from one to eight (Middindi Consulting, 2012).
- Cumulative Apparent Volume;
    - The parameter shows the co-seismic deformation in cubic metres based on more than four weeks of historical data and the rating for cumulative apparent volume ranges from one to twelve (SRK Consulting, 2018)
- Energy Release Rate;

- One of the major parameters used to create hazard maps by measuring the face stresses in megajoules per square metre (SRK Consulting, 2018). The values obtained are based on the layout planned for the next production month.

– Face Configuration Rating;
  - Face configuration refers to the lead/lag distance between faces, position of abutments and remnants and the overall face profile (SRK Consulting, 2018). Information for this parameter is based on plan for the next production month.

– Geology;
  - The rating given by geology is based on mining layouts planned for the next production month. This parameter factors in the dip of the reef, the angle of approaching any major geological features or presence of multiple reefs.

– Production;
  - This parameter measures the total area mined for a set of panels in square metres based on the plan for the next production month.

– Closure Rate; and Closure Ratio
  - The parameter measures the daily deformation using data from closure metres installed in every panel (Malan et al, 2003). Any rapid increase in closure indicates the possibility of a seismic event.

2.4 Rock Engineering Risk in Deep Level Mines

"It is said that it took Plato ten books to provide a definition of justice and even then, the definition was just approximate. In case of risk or rock-engineering risk there are many books, papers, articles that describe risk, however, the definition of risk is still approximate" (Brown, 2012). The literature available on rock-engineering risk and its management contain numerous definitions relating to risk (Brown, 2012). These definitions, significantly or marginally differ from conventional definitions used in other publications. According to Standards Australia (2009), risk is defined as the,

"*effect of uncertainty on objectives"* and risk source is defined as, "*an element which alone or in combination has the potential to give rise to a risk."* Brown (2012) emphasizes that in some areas a "*risk source"* is defined as a hazard. A hazard is defined as, "*a source of potential harm"* (Brown, 2012). Terbrugge *et al* (2006) define the level of risk as the "*magnitude of a risk or combination of risks, expressed in terms of the combination of consequences and their likelihood"*. The definitions highlighted, allow risk quantification in rock-engineering as "*the product of the likelihood of the occurrence of an event and the consequences of that event"*. This event is defined as "an *occurrence or change of a particular set of circumstances"* and the consequence of an event as "*the outcome of an event affecting the objective"* and likelihood as "*the chance that something will happen"* (Brown, 2012).

These definitions allow the application of a risk process in dealing with rock-engineering risk. Figure 2-12 shows a risk evaluation process typically applied to the stope design (Stacey *et al*, 2006). The first column from the left in Figure 2-12 shows the possible causes of failure in the stope area. Using the earlier definition of event, these failures are best described as events. The central column in Figure 2-12 shows the consequences of the risks. These consequences are expressed as fatalities, economic loss, production loss, force majeure, stakeholder resistance and industrial action (Stacey *et al*, 2006). The last column in Figure 2-12 shows the level of risk acceptance. The definitions related to risk and the risk process provide the general definitions. However, the definition of a rock engineering risk remains in question. For consistency and for the purpose of this research, a rock-engineering risk is defined as a rock-engineering related hazard, risk source or uncertainty that when exposed results in events listed in the left-hand column of Figure 2-12 in all areas of underground mining excavations. Using the definition provided and Figure 2-12, it is possible to have a detailed (though not comprehensive) risk list which is similar to the one developed by Brown and Booth (2009).

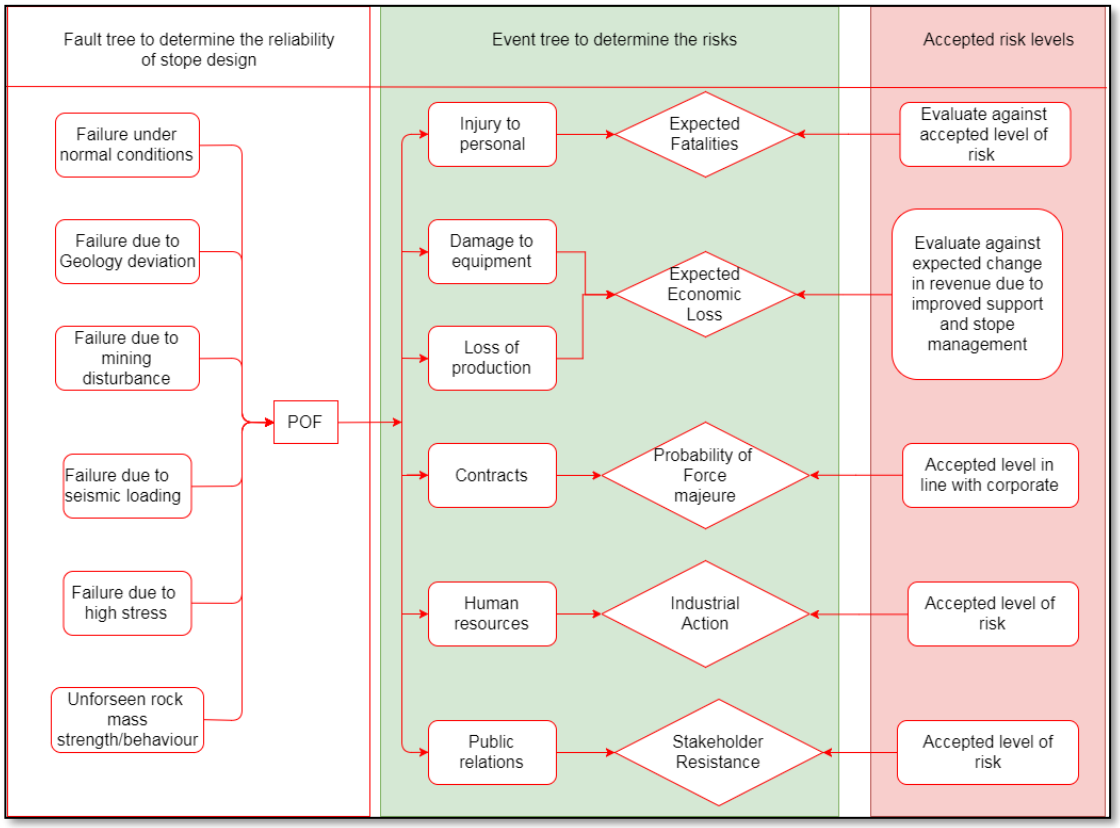


Figure 2-12 Risk evaluation process typically applied to stope design (Stacey et al, 2006)

Brown and Booth (2009) identify rock mass, geology, geological structures, rock engineering models, and hydrogeology as the major hazards in open pit mines. Rock-engineering related hazards and risks in deep-level mines include:

- Hydrogeological aspects (Brown, 2012);
- Geological discontinuities for example faults and weak material in shear zones (Guilfoyle *et al*, 2006; O'Connor *et al*, 2010);
- Weathered and or altered rock (Mercier-Langevin, 2010; Mercier-Langevin and Turcotte, 2006; Potvin and Slade, 2006);
- Criterion used for rock mass rating (Kaiser *et al*., 2010; Valley *et al*, 2011);
- Inadequate (not correctly defined) and unknown geological boundaries (Falmagne and Frenette, 2006);
- Brittle rock susceptible to bursting (Falmagne and Frenette, 2006);

- Strength and elastic properties of rocks and their values and distributions (Kaiser *et al*, 2010; Valley *et al*, 2010a, 2010b);
- Spacings, shear strengths, orientations of joint sets (Gumede and Stacey, 2007; Stacey and Gumede, 2007);
- Natural seismicity (Brown, 2012);
- Seismicity due to mining effects (Beck et al., 2007; Li *et al*., 2002; McGill, 2004; Morrison *et al*., 2002; Orrego *et al*., 2010; Yao and Moreau-Verlan, 2010);
- The effects of anisotropy and heterogeneity (Valley *et al*, 2010b);
- The relationship of rock mass strength and induced stress (Mercier-Langevin and Hadjigeorgiou, 2010);
- Premining stresses and their associated effects (Dight and Dyskin, 2007; Thin et al, 2006; Valley *et al*, 2010b);
- Formulation of models and the resulting analysis;
- Blasting effects (Brown, 2012);
- Ways in which pillar strength is estimated (Board *et al*, 2007; Kaiser *et al*, 2010);
- Mining highly stressed remnants (Andrieux *et al*., 2010; Cockram *et al*., 2004; Kiboko *et al*, 2004; Mikula and Lee, 2002; Pretorius, 2006; Simser, 2006);
- Excavation dimensions (Beck and Sandy, 2002; Mercier-Langevin and Turcotte, 2006; Pretorius, 2006);
- Water inrush and flooding (Ali, 2016);
- Rapid closure rates (Malan, 2003; Chamber of Mines Research Organisation, 1988);
- High face stresses (Johnson, *et al*, 1995);
- Highly fractured rock (Middindi Consulting, 2012);
- Abutment failure (Jager and Ryder, 1999);
- Punching or foundation failure (Jager and Ryder, 1999);
- Pillar failure (Mine Health and Safety Council, 2016);

- Large deformations (Ozbay, *et al*, 1995);
- Rock bursts (Chamber of Mines Research Organisation, 1988); (Jager and Ryder, 1999); (Ozbay, *et al*, 1995);
- Pillar dimension variation (Mine Health and Safety Council, 2016);
- Excavation support method (whether conventional blasting or non-blasting method is used);
- Stoping underneath mined out areas (mining multiple reefs) (Sharrock *et al*, 2002); and
- How installed support performs against the expected performance (Simser, 2007; Swan *et al*, 2006);

The list provided indicates that it is impossible to determine the actual risk as most of the risks manifest only once the excavation process begins. The risks listed vary for each geotechnical environment. The variation in conditions renders it impossible to prescribe absolute layout and support requirements to limit falls of ground and rock burst damage in all situations (Feng and Hudson, 2015). Monitoring such risks enables a better understanding of the risks and possibly an improved way to reduce their effects. The smart rock-engineering system to be developed needs to compliment experience from different mining areas, and provide early warnings.

2.5 Managing Rock Engineering Risk

According to Richards (2015), "*If you do not understand the geology, you do not understand the problem, and it is unlikely that you will be able to provide a good solution"*. Stacey and Read (2009), on risk management, said that, "*to be effective, it requires perception and detailed understanding of the range of risks involved in an undertaking, the development and implementation of risk assessment and risk management procedures, the leadership of management in developing a risk culture, documented procedures, high levels of communication and consultation and personal training and commitment."* In response to rock-engineering risks, major advancements

have been achieved as an effort to kerb the impacts of the risks. Solutions that pioneered from such advancements include:

- New mining methods;
- Mining layouts;
- Blasting; and
- Support types.

In addition to these solutions, the Mine Health and Safety Act, acts as an instrument that assists the mining industry by providing guidelines to ensure a safe mining environment.

2.5.1 Mine Health and Safety Act

According to Simonds (2004), *"After the event, even a fool is wise. However, it is not the hindsight of a fool; it is the foresight of a reasonable man, which alone determine responsibility. It is essential that the reasonable man could have foreseen the possibility of death and not just some injury nor even serious injury."* The ability of a responsible person to foresee a hazard is critical in risk management. This responsible person in the mining industry refers to the employer and managers. The employer or the mining company in this research is statutorily obligated to ensure that the working environment of the employee is safe always. This obligation is contained in the Mine Health and Safety Act (MHSA) Section two (2) and sections five (5) to sixteen (16). It is the duty of the mining company to ensure that such obligations are adhered to (Government of South Africa, 2017a). The criterion that the mining company ought to comply is "*reasonably practicable"* which in MHSA section 102 means, *"practical having regard to –*

a) the severity and scope of the hazard or risk concerned;
b) the state of knowledge reasonably available concerning that hazard or risk and of any means of removing or mitigating that hazard or risk;

c) *the availability and suitability of means to remove or mitigate that hazard or risk; and*
d) *the costs and the benefits of removing or mitigating that hazard or risk".*

Section 2(1) of the MHSA sets out as follows;

"*The employer of every mine being worked must-*

a) *ensure, as far as reasonably practicable, that the mine is designed, constructed and equipped*
    i. *to provide conditions for safe operation and a healthy working environment; and*
    ii. *with a communication system and with electrical, mechanical and other equipment as necessary to achieve those conditions;*
b) *ensure, as far as reasonably practicable, that the mine is commissioned, operated, maintained and decommissioned in such a way that employees can perform their work without endangering the health and safety of themselves or any other person."*

Section 5 of the MHSA asserts that the employer ought to maintain a healthy and safe mining environment;

a) *"As far as reasonably practicable, every employer must provide and maintain a working environment that is safe and without risk to the health of employees.*
b) *As far as reasonably practicable, every employer must –*
    i. *identify the relevant hazards and assess the related risks to which persons who are not employees may be exposed; and*
    ii. *ensure that persons who are not employees, but who may be directly affected by the activities at the mine, are not exposed to any hazards to their health and safety."*

Section 11 of the MHSA requires that the employer performs a thorough risk management and respond to such using prepared measures:

a) *"Every employer must –*
    i. *identify the hazards to health or safety to which employees may be exposed whilst they are at work;*
    ii. *assess the risks to health or safety to which employees may be exposed whilst they are at work;*
    iii. *record the significant hazards identified and risks assessed; and*
    iv. *make those records available for inspection by employees.*

b) *Every employer, after consulting the health and safety committee at the mine, must determine all measures, including changing the organisation of work and the design of safe systems of work, necessary to –*
    i. *eliminate any recorded risk;*
    ii. *control the risk at source;*
    iii. *minimise the risk; and*
    iv. *in so far as the risk remains –*
        – *provide for personal protective equipment; and*
        – *institute a programme to monitor the risk to which employees may be exposed.*

c) *Every employer must, as far as reasonably practicable, implement the measures determined necessary in terms of subsection (2) in the order in which the measures are listed in the paragraphs of that subsection.*

d) *Every employer must –*
    i. *periodically review the hazards identified and risks assessed, including the results of occupational hygiene measurements and medical surveillance, to determine whether further elimination, control and minimisation of risk is possible; and*
    ii. *consult with the health and safety committee on the review."*

MHSA Regulations Section 14.1 also provides that (Government of South Africa, 2017b);

"At every underground mine where a risk of rock bursts, rock falls or roof falls exists, and at every other mine where a significant risk of rock bursts, rock falls or roof falls exists, the employer—

a) may not permit any person, other than those persons examining and making safe, to enter any of the following areas at the mine until such areas are declared safe by competent persons:

i. the area between the face and the nearest line of permanent support; and

ii. access ways, traveling ways or places where persons need to travel or work;

b) must ensure that the examinations for purposes of regulation 14.1(1) are carried out as often as may be required, in terms of the mine's risk assessment, to maintain a safe working environment;

c) must ensure that a record of declarations contemplated in regulations 14.1(1) and 14.1(5) is kept for a period of at least three months;

d) must ensure that where areas contemplated in regulation 14.1(1) have not been examined, made and declared safe, persons are prevented from inadvertently entering such areas;

e) must ensure, if at any time a working place or part thereof becomes unsafe during a shift, that all persons, other than those examining and making safe, are removed from such unsafe area and are not permitted to return thereto until declared safe by a competent person.

f) must ensure that a quality, assurance system is in place, which ensures that the support units used at the mine provide the required performance characteristics for the loading conditions expected;

g) *must ensure that only competent persons install, maintain and remove any support unit; and*

h) *must ensure that the input of a competent person is properly and timeously considered and integrated into mine design, planning and operations"*

The MHSA Regulations emphasize in Section 14.1(6) that *"a quality assurance system is in place, which ensures that the support units used at the mine provide the required performance characteristics for the loading conditions expected".*

Section 14.1(8) of the same regulations requires that the employer must ensure that the *"input of a competent person is properly and timeously considered and integrated into mine design, planning and operations".*

From the sections highlighted, mining companies instigated codes of practice to combat rockfalls and rock bursts that assist in the management of rock-engineering risk. The Act further demands that a miner be warned and evacuated before he or she is endangered. The Act explicitly puts across what the employer must do to ensure that the working environment is as safe as possible. Implementation of these regulations has proved to be difficult to the miner, resulting in a number of section 54's (temporary mine and or section closures). A divergence therefore exists, in what the Act demands and what the miner can practically offer. It is the opinion of the author that a technology approach, for example smart rock-engineering system, can bridge the gap between what the Act demands and what the miner can safely offer.

2.5.2 Data collection

For better understanding of rock behaviour, data is collected on rock type, rock hardness, rock texture, geological structures, orientation and persistence of such geological structures, and stresses and their orientations. After the analysis of this data, corrective measures are constructed and implemented. Data is therefore one of the critical components in rock-engineering. The quality of data used in numerical modelling or in mine design, depends on the experience of the person who collects and

processes such data. Measures to ensure that the right data is collected and processed include, using of experienced rock engineering personnel. Other measures used to ensure that good quality data is obtained include;

- ensuring good core recovery (minimum loss or damage to the core) and core logging;
- ensuring that data collected is sufficiently large;
- using related projects and designs in the same area to validate the data collected.

In rock-engineering, high quality instrumentation is used to assist in data collection. These instruments include, borehole cameras, thermal imaging cameras, extensometers, closure meters, stress meters, crack meters, seismometers, ground-penetrating radar and long drilling probes. In the recent years, 3D reflection seismic is used to locate geological features without advance development. With this reflection, faults with throws greater than 25m can be identified and located from surface. Data collected include, magnitude and extent of deformation, stress levels, joint spacing and fault throws. This data enables rock engineers to at least see into the rock ahead giving them improved ways to manage rock-engineering risk.

2.5.3 Mining layouts and sequencing

The orientation and density of stress fractures is a function of gully layout, gully siding shape, gully depth and mining depth (Middindi Consulting, 2012). This stress fracturing affects the behaviour of rock mass subject to ground vibration by rendering it weak and more susceptible to failure. It is therefore critical to ensure that the ground around excavations is stable through implementing good mining layouts. Good mining layouts refer to layouts that minimize occurrences of stress abutments, minimize fracturing of rock at intersections simultaneously allowing the maximum possible safe and profitable extraction. Mining layouts (effectively the mining method) minimize the effect of rock stress at design stage. The design of layouts considers mining direction, depth of mining, mining span, face shape index, advance rates and middling distances

in multi reef mining. Other mining layout strategies to manage rock-engineering risk include;

- position and size of remnants;
- use of sequential grid and longwall mining method that minimize the deleterious effects of remnants thereby reducing stress and energy release rate (Chamber of Mines Research Organisation, 1988);
- approaching geological features at an oblique angle and using bracket pillars as geological features are potential sources of rock bursts (Jager and Ryder, 1999);
- minimizing leads and lags of advancing faces (Mine Health and Safety Council, 2016);
- minimizing gully headings (Chamber of Mines Research Organisation, 1988).
- cutting gullies to the right depth to ensure that pillar behaviour is not affected by gully scaling (Jager and Ryder, 1999);
- ensuring that where stress fracturing occurs, panel face line is parallel to sidings (Jager and Ryder, 1999);
- the placement of travelling ways and crosscuts is far away from highly stressed areas and around reef pillars (Middindi Consulting, 2012);
- foot-wall tunnels are also placed in low stress areas far enough to avoid long crosscutting distance;

In submission to economic demands and energy release rates, the stoping width is kept to a minimum. This reduces the area exposed to rockfalls and rock bursts. According to Malan, et al., (1997), arch-shaped tunnels give better stability during a seismic event. The preferred tunnel shape, the eclipse, is difficult to excavate and orientate in the right direction, hence arch-shaped tunnels are used (Malan, et al., 1997). To minimize this risk, application of technology to assist in design implementation is critical. Such technology will inform in real-time any presence of excess stress and mining layouts will be modified accordingly.

2.5.4 Blasting techniques

Most hard rock mines in deep-level environments use high explosives, causing major ground vibrations. Blasting practices affect the properties of rock mass as the detonation of the explosive creates a shock wave that propagates through the rock mass. The wave propagation causes vibration of the rock mass near the excavation being blasted. This vibration results in rock displacement and in some instances support failure. The extent of the vibration is affected by explosive type, hole diameter, hole length and orientation, initiation system used and drilling accuracy. To reduce these effects, blast designs are optimized by:

- using presplitting and post-splitting techniques to ensure improved hanging-wall conditions in tunnels and access ways;
- ensuring that the drilling patterns are adhered to and drilling accuracy is strictly monitored; and
- ensuring that the blast holes are not overcharged or undercharged.

Despite the extensive work to ensure correct blasting is performed, the vibrations due to the high-energy explosives is still present. Although not commercially feasible, other methods of rock breaking can reduce these vibrations. These methods include, reef coring, hydro fracturing, thermal, electrical, plasma blasting, impulse water breaking and controlled form injection. The absence of a feasible alternative to rock blasting, means that risks due to blasting, still exist and need to be addressed through implementing a reactive smart system.

2.5.5 Preconditioning, support units and systems

Pre-conditioning, as shown in Figure 2-13, is a means to improve rock mass within the face area. Strain bursting at the face can be reduced by pre-conditioning ahead of the mining face (Durrheim, 2010). This is achieved by transferring the stresses to a distance ahead of the current mining face as shown in Figure 2-13. Falls of ground and seismic effects are reduced by using support systems.

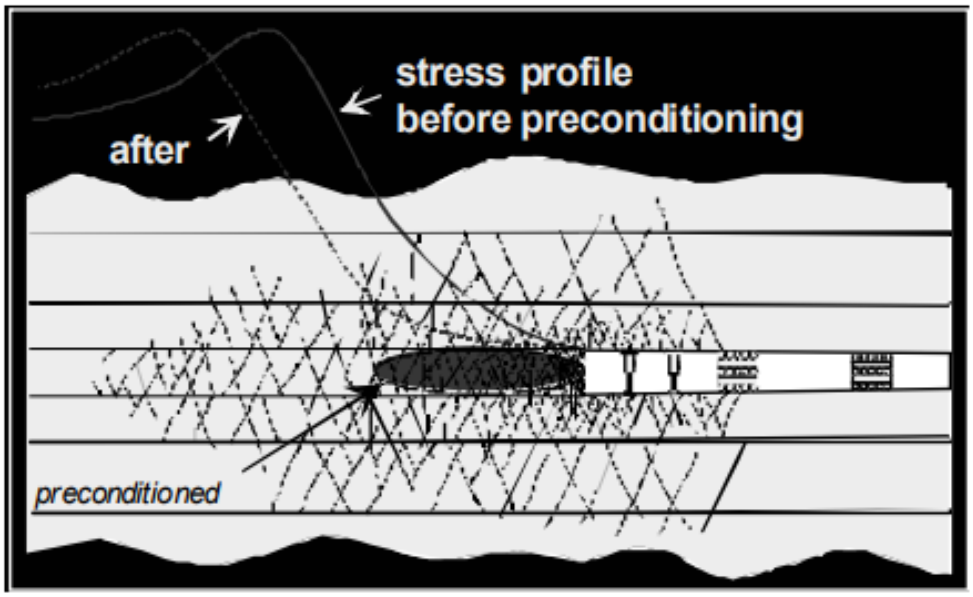


Figure 2-13 Stress profile when pre-conditioning is used in the stope area (Durrheim, 2010)

Their use to address unstable ground conditions and ensure the stability mining excavations, is a well-known practice difficult to implement. To maintain excavation stability, the support system needs to have sufficient support resistance to hanging-wall, side-wall and foot-wall as well as sufficient energy absorption capacity (Stacey and Wesseloo, 2000). Support systems used include:

- Regional support system; and
- Local support system.

Regional support includes, strike pillars, dip pillars, bracket pillars, boundary pillars and backfill as examples. The role of regional support as a way of managing rock-engineering risk is to reduce back area closure thereby reducing both face stress and seismic potential (Mine Health and Safety Council, 2016). Local support includes, tendons, shotcrete, mesh and lace, thin skin liners, elongates and packs. It is used to improve ground conditions within the face area and the area in-between pillars (Jager and Ryder, 1999). The high concentration of workers in the stope face area and the proneness of face area to rock bursts and rockfalls makes the use of local support to remain a high priority. Despite the extensive application of support units and systems,

several fatalities due to support failure or failure of rock in between support elements have been recorded. This indicates that support alone does not adequately address rock-engineering risk. However, in deep level mines, apart from backfill, rapid closure reduces the effectiveness of support.

2.5.6 Monitoring systems and on-going management training

Monitoring is a way to manage residual risks. The main objective of a monitoring program is to measure any changes in the set parameters using instruments developed to take such measurements. The methods used to monitor are visual methods (performed by regular audits of work areas) and instrument method (instruments are placed in strategic positions to monitor specific parameters). Parameters measured or monitored directly and indirectly, and examples of the instruments or methods used to measure them include;

- rock stress;
    - load cells
- rock deformation;
    - closure meters, borehole extensometers, surface extensometers and tilt meters
- support performance;
    - pull tests on tendons,
- mining layouts; and
    - face shape, lead / lag distance, pillar dimension, position and shape
- geological structures.

Determination of points is critical. The systems used for monitoring are mostly manual, as they need human intervention during data acquisition, data transmission and integrations. A need exists to improve data transmission and system interactivity through introducing smart technologies that automates decisions such as when an area must be evacuated.

On-going training includes, the introduction and review of standard operating procedures, having adequate supervision, support quality control, training and overall awareness on the risks and hazards expected to be encountered in deep-level underground mining. The use of such extensive training enables miners to be aware of the hazards expected in their working areas, making it easier to manage them by ensuring that appropriate and adequate mitigating measures put in place.

2.6 Conclusions

South Africa's mineral resources, hard rock minerals occur at depths varying from shallow to ultra-deep. Gold and platinum occur in the deep to ultra-deep mining environment. These two mining environments contain areas of high stress. When disturbed, they become areas of potential hazard and mining in such areas is disrupted. Because of the increased stress levels due to increased depth of mining, other areas become more hazardous. These areas include, back areas, areas with inadequate support, areas near dykes, faults, potholes and areas with pillar robbing leading to smaller dimensioned pillars. Most of rock-engineering challenges at depth are stress related. As such, understanding the behaviour of rock mass is critical. Continuous monitoring of rock enables an improved understanding of rock behaviour. Such understanding will enable improved use of numerical model formulations and implementation of better risk management strategies. Management of rock-engineering risk uses numerous techniques, that include:

- Blasting techniques;
- Support systems;
- Pre-conditioning;
- Mining layout and sequencing; and
- Data collection.

These methods reduce unstable rock mass behaviour by limiting the change in stress and energy due to mining. However, their effectiveness lies in the implementation of

good mining practice. To minimize rock-engineering risk, application of technology to assist in design implementation is critical. Such technology will inform in real time any presence of identifiable hazards enabling a quicker response to risk management. State of the art ways of breaking the rock are also required and these include reef coring, hydro fracturing, thermal, electrical, plasma blasting, impulse water breaking and controlled form injection. Residual risk is monitored using different methods and using different instrumentation. The systems used for monitoring are manual, as they need human intervention during data acquisition, data transmission and integrations. A need exists to improve data transmission and system interactivity through the introduction of smart technologies that automate decisions. The following chapter explores how risk is managed in open pit mines, civil and petroleum engineering as a way of identifying appropriate technologies that can be used or translated to deep-level mining rock-engineering risk management.

3 RISK MANAGEMENT TECHNOLOGIES IN OTHER AREAS

Using the available literature, identify rock engineering risk management technologies in open pit mines, civil and petroleum engineering and their functionalities that can be used for underground mining

3.1 Introduction

Chapter two discussed the behaviour of rock mass in deep-level mines, associated risks and risk management measures and their limitations in addressing such risk. The environment where risk-mitigating measures are implemented exacerbates the limitations of such measures. Unlike underground mining, rock-engineering risk management in open pit mines and risk management in civil and petroleum engineering are more technologically advanced. Systems used in these areas include global positioning system (GPS), radar systems and robotic total stations. Compared to underground mining, high factors of safety are used in civil engineering construction work as such areas are entered or used by the public who have limited knowledge of the expected hazards. This chapter details how engineering risk is managed in open pit mines, civil and petroleum engineering. The chapter further emphasizes on functionalities that can be used in developing a smart rock-engineering system for underground mining.

3.2 Risk Management Technologies in Open Pit Mines

The design of slopes in open pit mines is performed through smaller benches, separated by berms for stability purposes (Safe Work Australia, 2011). The primary function of berms is to contain any rock falls from bench slope and as a result improve slope stability (Wyllie and Mah, 2005). A ramp is used to access the pit. This ramp can be

placed in a spiral way down to pit bottom or as switch backs on one side of the pit (Safe Work Australia, 2011). Figure 3-1 shows a typical open pit mine showing ramp access to pit bottom. Figure 3-1 indicates that pit walls are critical, as access ways are constructed on it. Their stability is thus crucial, as it is a huge factor in profitability of open pit mines.



Figure 3-1 An example of an open pit mine (Hexagon Mining, 2017)

Pit wall stability is affected by rock mass strength and composition, presence of geological structures, rock stress, presence of water in the ground and mining practice. Despite good blasting and support practice, monitoring technologies have been implemented to manage the risk of pit slope failure. Technologies used to manage rock-engineering risk include:

- light detection and ranging (LiDAR) (Wyllie and Mah, 2005);
- digital photogrammetry (Eberhardt and Stead, 1992);
- robotic total stations (Wilkins et al, 2003);
- piezometers and tilt meters (Safe Work Australia, 2011);
- extensometers and crack meters (Eberhardt and Stead, 1992);
- shaped accelerometers (Abdoun et al, 2009);

- time domain reflectometry (Wyllie and Mah, 2005);
- satellite interferometric synthetic aperture radar (InSAR) (Farina et al, 2013);
- surface radar (Farina et al, 2013); and
- global positioning system (GPS) (Bond et al, 2007)

The aforementioned technologies are used in three categories in open pit slope monitoring. These categories are surface monitoring, water level and pore pressure monitoring, and sub-surface monitoring (Wyllie and Mah, 2005). In this section, selected technologies and or systems that capture common monitoring parameters are described.

3.2.1 Micro-electrical mechanical systems

The Micro-Electrical Mechanical System (MEMS) is an autonomous soil monitoring system used to monitor open pit soil structure (Abdoun, et al., 2009). The MEMS based system uses an inclinometer and shapedaccel-array (SAA) that simultaneously measures 3D permanent ground deformation and soil acceleration (Bennet, et al., 2009). The depth of these measurements is up to 100m with an accuracy of +/-1.5mm for every 30m (Abdoun, et al., 2009). A wireless sensor node is used to connect sensor arrays, that enables monitoring, and sensor configuration in real-time. The accelerometers used in this system are temperature based and their calibration is performed in the factory, prior to any installation (Abdoun, et al, 2009). Once the sensors are installed, they do not require calibration or assembly whilst in operation (Bennet, et al., 2009). During installation and operation, the sensors allow the geotechnical practitioner to view a deviation of installation on the computer enabling an appropriate response to be taken prior to real data being measured (Abdoun, et al., 2009).

A wireless data acquisition system called Wireless Earth Station is used to transmit data. (Abdoun, et al, 2009). Data obtained from the Wireless Earth Station system represent any deviations from the initial set or recorded value. The transmission of data from the station is performed wirelessly over cell phone networks. It is received by an

automated server, which provides access to all available users using a specific viewing software through an internet connection (Abdoun, et al, 2009). When a MEMS based system is used to monitor for a long-term period, data can be collected once a day or once every few days. However, the frequency of data collection can be changed remotely using the same wireless network to receive data, making it suitable to collect data from a dynamic and or seismic event (Bennet et al, 2009). The MEMS system uses a high sampling frequency rate of 128Hz. In addition to the high sampling frequency rate, each SAA has a sensor that automatically switches from a low sampling rate to a high sampling rate during a seismic event (Abdoun, et al, 2009).

From the MEMS based system used in open pit soil structure monitoring, the following should be considered in developing a smart system for underground mining.

- The collection of data from the system is as and when necessary and at low frequency for long term monitoring. The data collection rate also changes with the response of rock mass to a dynamic event;
- The system uses cell phone networks;
- Data acquisition is strictly wireless;
- The system uses a high sampling frequency rate in the event of a dynamic environment;
- The system can be accessed remotely through an internet connection; and
- The system uses sensors that once manufactured, are ready to be used, avoiding costs related to assembly and field construction.

For the system to work in a smart system, the following adaptations are required:

- Instead of using cell phone networks, WiFi network system will be used both for surface and underground communication.

3.2.2 Global positioning-based system

Global Positioning System (GPS) is widely used in monitoring surface structures, including pit walls in open pit mining. Figure 3-2 shows the block diagram for a GPS

system. Its use has been attributed to the fact that it offers a fully automated system, real-time measurements and continuous measurements from all stations in a pit (Bond et al, 2007). GPS uses GPS sensors and pseudo satellites (ground-based transmitters) technologies to realize full functionalities. Failure of rock in open pit slopes starts slowly followed by rapid acceleration (Wyllie and Mah, 2005).

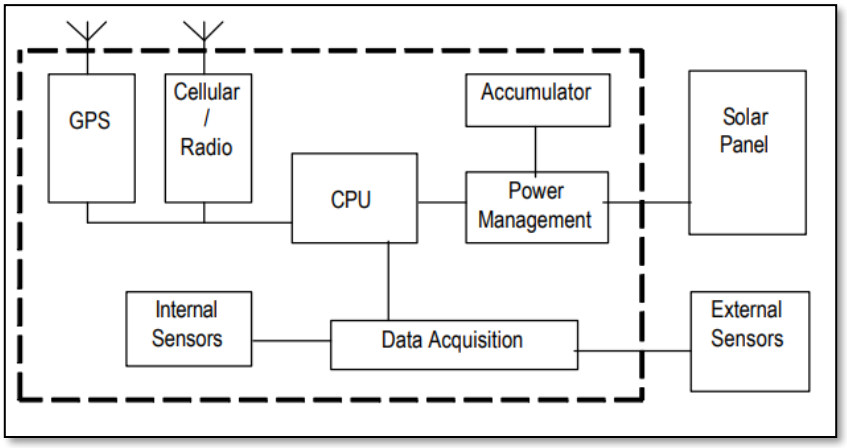


Figure 3-2 GPS System Block Diagram (Manetti et al, 2002)

This rapid acceleration is evidenced by failure of rock through slides, or rock falls (Wyllie and Mah, 2005). The continuous monitoring of slopes using a GPS enables adequate time for a warning to be provided for the safe evacuation of miners and equipment. With no multipath errors and tropospheric zenith delay, accuracies of measurements can be +/-5mm at approximately 95% level of confidence (Manetti et al, 2002). The components of a GPS system include:

- A measurement station and receivers installed on a monitored object;
- A control station for;
    - Data collection; and
    - Post processing of data collected.
- Radio link, cellular modem or Ethernet (cable) as means of communication between the control station and the receivers.
- Ancillary sensors added to receiver units such as:
    - Distance meters;

- Pluviometers and inclinometers;

When used in landslide monitoring, an accumulator and a solar panel can be added to a GPS to enable autonomous operation for extended periods (Manetti et al, 2002). The system therefore does not need any maintenance. The receivers placed on monitored objects, compute their standalone position when they are in view of at least four (4) satellites (Remondi, 1984). The measured positions achieve an accuracy of 5m to 10m and when CodePhase (a processing correction software) is used, the accuracy obtained can be at most 1m (Bond et al, 2007). Remote control is enabled through internet dial-up connection where all the operations, communication and measurement tasks are scheduled (Bond et al, 2007). From a GPS based system, the following need to be considered in developing a smart system for underground mining:

- Remote access and control allow remote diagnostics and sensor parameter definition, alarm setup and activation of ancillary sensors (Manetti et al, 2002);
- It is impossible to have four (4) satellites in view
- Measurements are near real-time as the tropospheric zenith delay can be greater than 20 minutes (Chen et al, 2000); and
- The cost of GPS instruments is relatively high, limiting them for control purposes (to control other sensors) rather than full monitoring of the whole pit (Bond et al, 2007).

Adaptations required for the system to work in a smart rock engineering system include:

- The requirement to have 4 satellites in view from the receivers is virtually impossible in underground environments. A very low frequency (VLF) system with “satellites” placed around the orebody can be used (Infomine, 2008); and
- Survey pegs can be fitted with a chip that communicates with surface pseudo-satellites or underground very low frequency system “satellites”. The sensors will then communicate with the survey pegs.

3.2.3 Robotic Total Stations with ALERT software system

Robotic total stations (RTS) have been in use for a long time in assisting geotechnical practitioners in slope monitoring. Their use has shown that they can be used in a real-time monitoring system (Wilkins et al, 2003). Developments in using RTS with ALERT software, enabled RTS to satisfy fully automated monitoring system requirements (Wilkins et al, 2003). Onsite operational intervention from geotechnical personnel is not required and control of the stations can be performed remotely (Duffy et al, 2001). Remote operation of RTS enables the scheduling of data collection cycles and access of measurements performed for the period concerned using internet access (Wilkins et al, 2003). Iterative weighted similarity transformation is used to eliminate the effects of unstable RTS. GPS is also used to monitor the RTS position and possibly update such positions if stable reference positions are inadequate (Lutes et al, 2001). On a weekly reporting schedule, RTS displacement measurements have produced results with +/-5mm accuracy (Wilkins et al, 2003). RTS can be combined with meteorological sensors to provide an automated monitoring system that enables the influence of weather on slope stability to be observed (Wilkins et al, 2003).

In slope stability, RTS with ALERT software system functions efficiently well. However, it is difficult to establish stable reference points (Lutes et al, 2001). Systematic errors, including refraction, unstable points of reference, tropospheric zenith delay (the presence of large height variations in open pit between stations for RTS causes the zenith delay), and multipath (there are many surfaces in open pit where reflection of signals can occur affecting the working of GPS in establishing reference points) are reduced within the ALERT software (Duffy et al, 2001). For each cycle of measurement, a GPS antenna mounted on the total station allows independent observation of the position of the RTS. Geotechnical instrumentation for example, inclinometers or tilt meters are then used to monitor any changes in GPS antenna position (Wilkins et al, 2003). Observing and processing are done automatically, and any power failure or power outages do not affect the system as it recovers or continues from the last executed task (Wilkins et al, 2003). The results are plotted showing

displacement trends and the system allows advanced trend analysis for example finding the mean values or grouping results with possible similar interpretations.

From the RTS system with ALERT software, the following functionalities should be considered in developing a smart system for underground mining:

- Automatic identification of unstable reference positions (Newcomen et al, 2003);
- There is no operator after installation that decodes any data from the total stations. All data is collected remotely and automatically (Wilkins et al, 2003);
- Remote control of settings on all sensors and automatic reduction and processing of errors (Duffy et al, 2001);
- The effects of multipath and tropospheric zenith delay affect the use of GPS in monitoring in pits with large height variations on benches. These effects are exacerbated in underground mines; and
- RTS system can be integrated with other sensors (in this example, meteorological sensors). This integration is important in underground mines.

The following adaptations are required for RTS to be used in underground ground movement monitoring:

- Total stations can be replaced by fixed survey pegs (with smart chips embedded in them);
- Tiltmeters and inclinometers, are replaced by closure meters and smart bolts; and
- To reduce the effects of multipath, more stations (smart survey pegs) will be installed.
- Using advanced trend analysis for example finding the mean values or grouping results with possible similar interpretations for data processing

3.2.4 Slope stability radar systems

Slope stability radar is a technology that transmits electromagnetic pulses to a reference point and with the pulse reflected by the reference point (Wolff, 1998). The reflected pulse is recorded as an echo. The basic design and components of a radar system are shown in Figure 3-3.

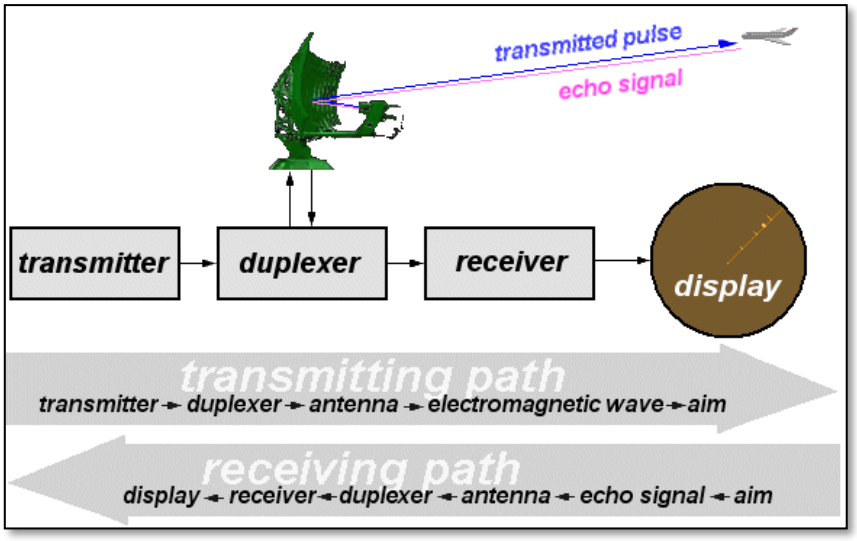


Figure 3-3 Basic design of a radar system (Wolff, 1998)

Slope stability radar uses this echo to determine the distance to target point and the direction of the target point, from reference point (Wolff, 1998). Other parameters measured from the system include:

- Height of target point; and
- Speed, if any movement occurs, of the target reference point.

The electromagnetic wave is generated by a strong transmitter and is received by a sensitive antenna (receiver) (Wolff, 1998). The system components and their functions are described below:

- Transmitter;
    - Produces high power electromagnetic pulses for a short period and transmitted into space by an antenna (Wolff, 1998)

- Duplexer;
    - Only one antenna is used in sending and receiving the electromagnetic pulses. A duplexer switches off and on, the receiving or sending function on the antenna so that the antenna has one function at a time (Wolff, 1998). The switching on and off the antenna protects it from any damage from the strong signals sent from the transmitter if it transmitted and received simultaneously (Wolff, 1998).
- Receiver;
    - The received signals are demodulated and amplified by the receiver providing the output with video signals.
- Radar Antenna; and
    - Antenna (inside the duplexer) receives and sends signals into space from the receiver and transmitter respectively at the required distribution rate and required efficiencies.
- Indicator
    - It is a form of visualization (graphic picture) where the geotechnical practitioner can see, interpret and understand the data continuously being sent and received.

The slope stability radar in open pit mines is used to observe rock slopes for the purposes of detecting any movement of the slope surface over a wide area (Harries et al, 2006). Any movement recorded is alerted to responsible personnel who will take appropriate measures. According to Klappstein et al (2014), precisions in the order of submillimetre can be obtained from slope stability radar measurements. The detection of slope movement or monitoring of pit slopes, does not use mounted reflective targets as the pulses can traverse through various media. The system allows four different alarms to be set, with different action plans and different levels of management that must be notified (Harries et al, 2006). Triggering thresholds for the different alarms are set by the geotechnical practitioners locally. These thresholds can be displacement

based, or time and displacement based (to calculate velocity) or size of the area of failure of the slope surface (Klappstein et al, 2014). As soon as the threshold value is exceeded, an alarm is triggered with instructions and appropriate action plans for the control room operator to act upon.

From slope stability radar-based system, the following should be considered in developing a smart system for underground mining:

- The system does not use of reflective targets. Existing surfaces of the slope or rock are used instead;
- The precision of measurements is relatively good as it is submillimetre;
- A strong transmitter is required;
- Four alarms, or thresholds can be set;
- Instructions to the control room operator are provided for each alarm level and responsible management alerted of any alarm that has been triggered;
- The system relies on communication of control room operator to management and the miners; and

Adaptations that are required for radar systems to be used within the smart rock engineering system include:

- Communication across all the stakeholders should be automated;
- Radar systems work best when they monitor from one position. Therefore, installation of such a system will be done in large permanent or long-term excavations; and
- Reduction in their size will allow their use in smaller tunnels;

3.2.5 DMS Automated Monitoring System

The DMS automated monitoring system is a multiparametric borehole monitoring system that uses inclinometers, piezometer and temperature sensors (Olivieri et al,

2012). Figure 3-4 shows the DMS early warning system as used in Valle Boidi landslide monitoring (Olivieri et al, 2012).

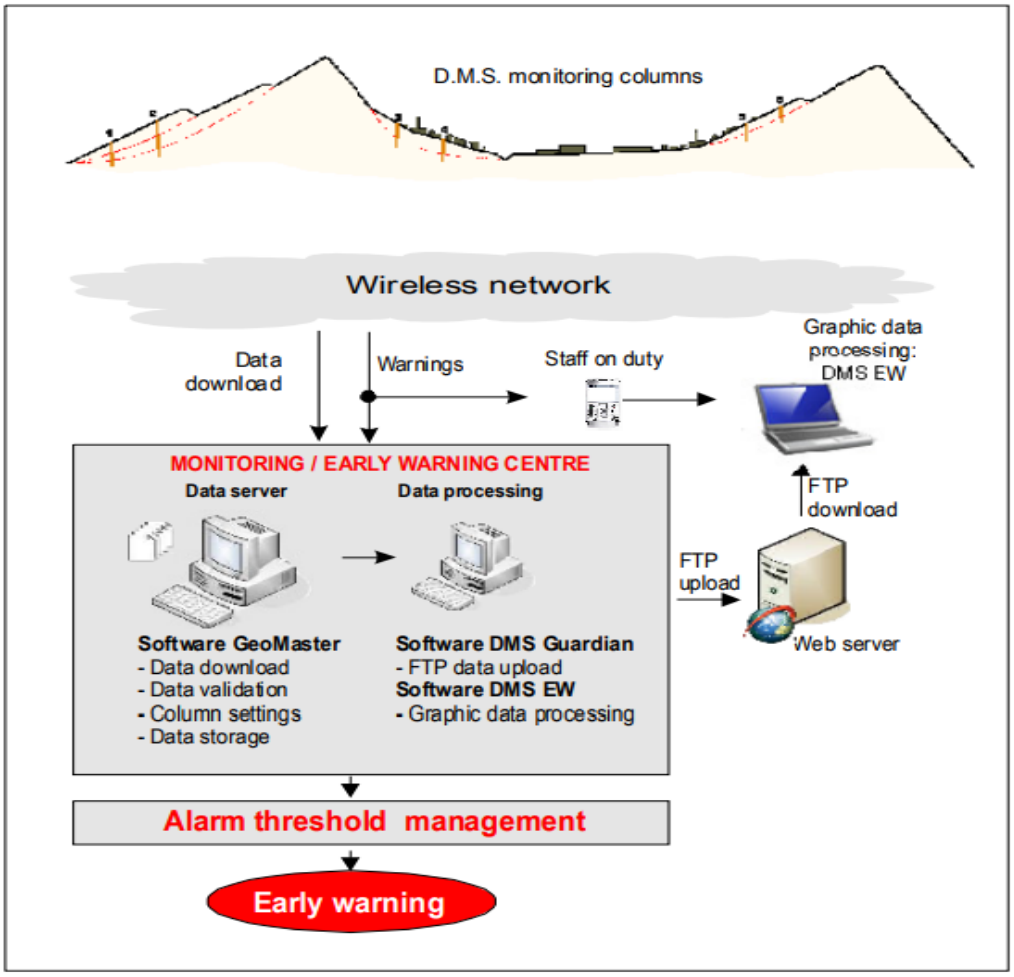


Figure 3-4 DMS warning system functioning scheme (Olivieri et al, 2012)

The sensors are connected using a special 2D cable with considerable flexibility in bending and twisting (Lovisolo et al, 2004). The design of the system is such that, when the set threshold is exceeded, a text message or direct call is initiated to the responsible person (Olivieri et al, 2012). Data collection from all the sensors is continuous. The installation of a weather station as an add-on, allows the system to detect correlations between rainfall and slope wall displacement and "*the delay time between perturbation and reactivation"* of slope movement (Olivieri et al, 2012). This allows the system to forecast any possible movements within the slope surface. The modules used in the

DMS automated monitoring system comprise the necessary elements for measuring, controlling and transmitting recorded or received data (Lovisolo et al, 2004). The control centre encompasses:

- GeoMaster software, used to download any data stored in the memory buffer of the control unit (Olivieri et al, 2012); and
- DMS early warning software, for visualization of subsurface data (Lovisolo et al, 2004).

The GeoMaster software can communicate with numerous sensors or monitoring stations directly.

From the DMS automated monitoring system, the following is important for developing a smart system for underground mining:

- The ability of DMS system to operate appropriately with numerous sensors is critical for underground mining;
- The system's functionality of forecasting events is crucial as it aids in scenario planning for mining, resulting in improved disaster management plans;
- DMS system can be connected to the internet enabling offsite operations; and
- DMS system can notify the responsible person of any unexpected behaviour of the subsurface rock mass.

For the system to work in a smart rock engineering system, the following adaptations are required:

- Sensors will be disconnected from each other and will work independently. Multi – sensors will be developed in areas where more than one parameter is required to be measured; and
- Integrating the two softwares (GeoMaster and DMS Early Warning software).

3.3 Risk Management Technologies in Civil Engineering

Civil engineering unlike mining, constructs structures on surface and underground with high safety factors. This is largely because, first, their use is more by the public who, mostly lack knowledge of the risks or hazards involved and second, some are designed to stand for a life time compared to underground mines where some excavations may be required to be stable for a few months or years. Using high factors of safety does not remove the risk of these structures from failing. The management of these structures is much more critical given their public use. These structures include subway tunnels, buildings, dams, bridges and roads. The largest risk in these structures is cracking or deformation of the structure leading to collapse. The service life of the civil structure is shortened because of cracking or premature deterioration.

The presence of cracks in civil structures does not always equate to failure or structural deficiency. Their presence makes it possible for deleterious or aggressive fluids to flow through them, accelerating the deterioration of the concerned structure. The management of risk in civil engineering structures involves advanced monitoring of the built structures using various systems and sensing technology in real-time. The technology used includes, smart rocks, sensing skin, GPS, Radio Frequency IDentification (RFID), Ultrasonic imaging, X-ray tomography and systems such as global analyser, Geo-DMS, Argus, Di-Test AIM and Monitoring Point.

3.3.1 Tomography based sensing skin system

The detection of damages in concrete structures is critical as alluded in the previous section. The initiation of these damages can be detected using sensing skin-based technology. The sensing skin is an electrically conductive skin made of "*a thin layer (in order of micrometres) of electrically conductive copper paint"* (Hallaji et al, 2014). When the sensing skin covers the concrete structure, any cracking in the concrete results in the cracking of the sensing skin. The cracking or rupture of the sensing skin causes a change in the electrical conductivity properties for the sensing skin (Peled et al, 2001). The change in electrical conductivity of the sensing skin is detected using

electrical impedance tomography (EIT) imaging (Hallaji et al, 2014). The results or data of EIT are both qualitative and quantitative (Cheney et al, 1999). Figure 3-5 shows a typical cracked concrete with EIT images. The equipment used to take measurements include, a computer, voltmeter and switches. Equally spaced electrodes are placed along the perimeter of a concrete structure sprayed with sensing skin (Peled et al, 2001). An electrical current is applied between electrodes placed on the perimeter. The flow of the current is interrupted by developed cracks. The presence of moisture within the concrete structure or on the surface of the concrete structure affects the results obtained (Hallaji et al, 2014).

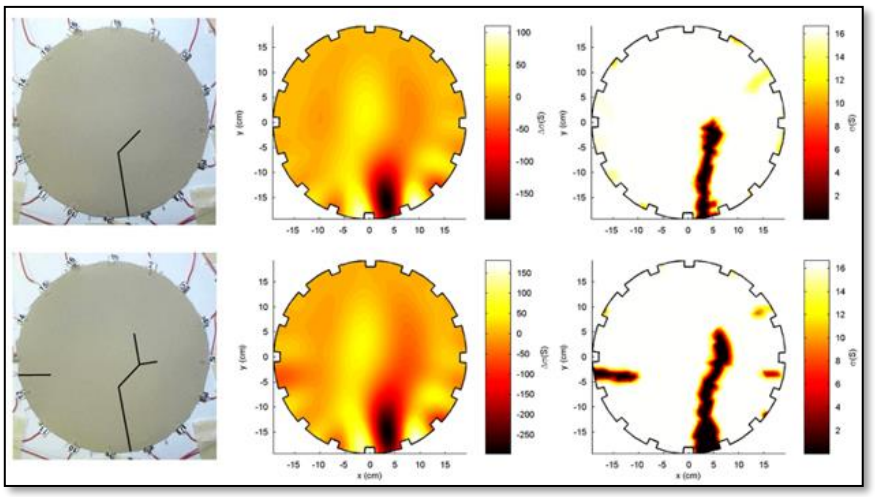


Figure 3-5 Typical EIT images from cracked concrete (Hallaji et al, 2014)

From tomography-based sensing skin monitoring technology, the following should be considered in developing a smart system for underground mining:

- Reconstruction of images from EIT is difficult, making their interpretation difficult (Peled et al, 2001);
- The conductivity of concrete affects the conductivity of the sensing skin (Hallaji et al, 2014). This background conductivity can be worse in underground mines where the host rock can have very high electrical conductivity; and

– The placement of electrodes on the perimeter of the excavation is limited in underground mines as there are several surfaces and several excavations, rendering it financially impossible for use in underground mines.

Adaptations that are required for tomography-based sensing skin to work within the smart rock engineering system include:

– Using advanced material science, new sensing skin properties must be included. An example being the ability to work in moist environment and working in highly reactive rocks; and
– The applicability of sensing skin will be limited to large permanent excavations

3.3.2 Photogrammetric deformation monitoring system

Photogrammetric monitoring is a system used to monitor deformation in bridges (Avsar et al, 2014). The deformation in bridges is caused by bridge material fatigue, aging of the bridge material, dynamic and intensive loads and changing weather conditions (Apaydin and Erdik, 2001). The system is an online and real-time system that uses a distant camera from the bridge for taking pictures. The length and width measurement precisions based on the pictures captured are +/-14mm and +/-30mm respectively (Avsar et al, 2014). Total stations are used to map the area where the camera is placed and the area where pictures are captured. The map is used in photogrammetric network simulation (Avsar et al, 2014). The network simulation allows the geotechnical practitioner to evaluate project parameters including appropriate camera location, type of lenses to be used, and format of the pictures to be captured (Apaydin and Erdik, 2001). The camera captures images of target points. The captured frames are stored within the camera and later processed using MATLAB pools functionality in MATLAB software (Avsar et al, 2014). The target points have their own accumulators for energy. The software for image processing is also capable of: automatically tracking the target points and finding any correlation with weather factors that affect bridge deformation with target movement (Avsar et al, 2014). From photogrammetric

deformation monitoring technology, the following should be considered in developing a smart system for underground mining;

- The system is real-time and available online, ensuring ease of access anywhere with an internet connection;
- The use of total stations and later cameras, makes the work tedious;
- One camera position is used to take pictures of twelve (12) stationary target positions. Such method of taking pictures for deformation monitoring is virtually impossible in an underground environment as several places need to be monitored; and
- The self-calibration and analysis of the system is crucial for forecasting of bridge movement, which if used in underground mining, will enable prediction of rock movement and or failure.

For the system to work in a smart rock engineering system, the following adaptations are required:

- Total stations should have cameras mounted on them, thus reducing the amount of work done in setting a monitoring station;

3.3.3 Precise point positioning with geographical information system

Precise point positioning system with geographical information systems (PPP with GIS), is a monitoring system used in rail transport. Figure 3-6 shows the system architecture. The system monitors track deformation in real-time and performs continuously irrespective of the weather conditions (Gao et al, 2008). PPP with GIS comprises of two systems. The first system is the Real Track Monitoring System that uses PPP technology to locate deformed components of the rail system (Gao et al, 2008). The second system is the GIS system that is used for real-time visualization of attribute and spatial data sets and for development analysis (Gao et al, 2008). The precision of measurements using PPP is in the order of millimetres and no reference stations are required (Zumberge et al, 1997).

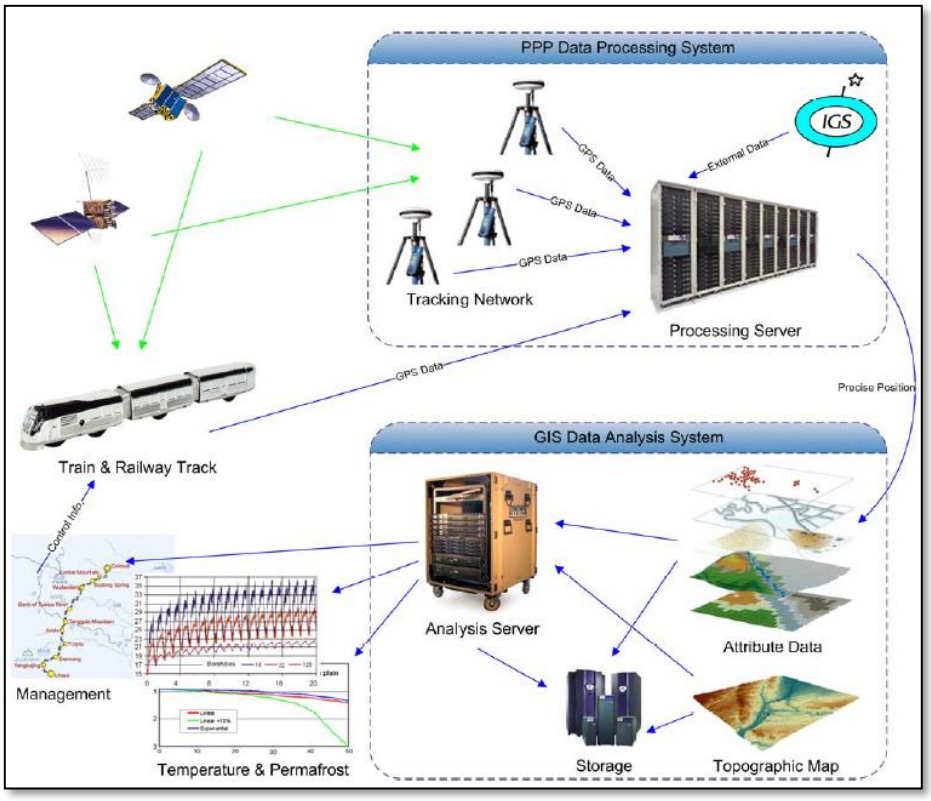


Figure 3-6 System architecture for rail monitoring system (Gao et al, 2008)

The addition of GIS to the PPP system allows the following to be performed extensively:

- Analysis of spatial data;
- Improved visualisation of data; and
- Improved decision-making because of improved display of results

The GPS receiver collects all the deformation data from the track and transmits the data to a processing centre using the Global System for Mobile Communications – Railway (GSM-R) or satellite communication system (Gao et al, 2008). The received data will be used to determine the precise position of the train using satellite orbits and clock calculations (Zumberge et al, 1997). The results of such calculation will be shown as 3D coordinates and as a point on the map in the GIS system (Gao et al, 2008). The received data, and calculated results will be stored in the GIS database. Stored data can

be used to predict rail condition or deformation making the database the core of the PPP with the GIS system (Gao et al, 2008). From precise point and positioning system with geographical information systems, the following should be considered in developing a smart system for underground mining;

- The system can operate in all kinds of weather and in real-time;
- The system has the same disadvantages of GPS described in Section 3.2.3;
- The ability to self-analyse and predict deformation along the track is a crucial feature of the system; and
- There are no warning features within the system. This makes it difficult to use in underground mining where warning is inevitably required.

Adaptations required for the PPP with GIS system to work in a smart rock-engineering include:

- Addition of warning features to alert the miners within the stope;
- Installation of smart survey pegs in conjunction with very low frequency system for communication purpose.

3.3.4 Smart rocks or brilliant pebbles

Monitoring bridge foundations is complex, considering that they are buried deep beneath the water surface. Smart rocks and brilliant pebbles (SR & BP) have been developed to monitor bridge foundations (Fulps, 2014). SR & BP are placed at the bridge's foundation and their design allows them to roll to any scour hole that would have been formed in the bridge foundation (Singh et al, 2012). Once a smart rock or brilliant pebble settles in a scour hole, it relays data on scour depth back to any reader (Fulps, 2014). SR & BP are manufactured in three formats:

- Active;

    - Comprises a timer, pressure sensor, battery level indicator, and gyroscope. Data collected by these are communicated through wireless communication to the appropriate reader (Eager, 1997; Fulps, 2014)
- Semi-active; and
    - Contains a magnet that can freely rotate using an electronic circuit (Fulps, 2014).
- Passive.
    - They use a magnet embedded in the smart rock. This magnet can easily be read by a magnetometer (Singh et al, 2012; Fulps, 2014)

Once a smart rock or a brilliant pebble is placed in the bridge foundation, it can take readings for five (5) to ten (10) years depending on the frequency of the data sent to the readers (Fulps, 2014). The data collected can only be transmitted to a reader after a reader has interrogated the smart rock or brilliant pebble. Without any request or interrogation from the reader, no information will be sent, and the smart rock or brilliant pebble will be in position for many years, collecting data (Eager, 1997). The following components comprise the system for smart rocks and brilliant pebbles:

- Smart rock core electronic board;
- Handheld transponder;
- Base station with receiver;
- Graphical user interface; and
- Digital signal processing software

From smart rocks and brilliant pebbles technology, the following should be considered when developing a smart system for underground mining;

- The ability to develop a sensor that can be used in inaccessible areas is important. Back areas, for example, eventually become inaccessible and having a system that can work to measure rock engineering parameters is crucial in understanding their behaviours long after mining is completed;

- Where data collection and transmission are continuous, (as the case in underground mining), battery life for such a system can be less than five (5) years;
- The working principle of the system is good, but it is not automatic in some smart rocks as they require a "wake-up call"; and
- When placed on a cliff, the system notifies the user as they approach a cliff, making it more of a "collision avoidance" system. There is no detail on how it triggers alarms when scour depths reaches values close to and above the thresholds.

The following adaptations are required for smart rocks and brilliant pebbles to be used in underground ground movement monitoring:

- Sensors embedded in the smart rocks need to transmit data autonomously without waiting to be invoked;
- Smart rocks will be embedded and glued in pillars or advancing face. However, once the face is blasted, they will be used for ore tracking; and
- Data loggers will be installed close to the location of the smart rocks or brilliant pebbles.

3.3.5 Radio frequency identification technology system

Radio Frequency IDentification (RFID) technology system is a real-time monitoring system that uses ultrasonic sensors and temperature sensors (Hosseyni et al, 2011). The sensors are used to accurately measure and monitor water level within the slopes and associated temperatures (Jaselskis et al, 1995). Data captured by the sensors are sent to the control room for slope stability analysis using GSM technology. The RFID technology uses transponders (tags with antennas), receivers (also called readers with antennas), and a terminal (Hosseyni et al, 2011). The system architecture (shown in Figure 3-7) include:

- Onsite or field monitoring; and

- The hardware components of the system including the sensors, transmitters and receivers, rainfall gauge and a levelling package with an RFID active tag

– An office data processing sub-system.

- Comprises two servers which are the application server and database server for GIS system and warning system respectively.

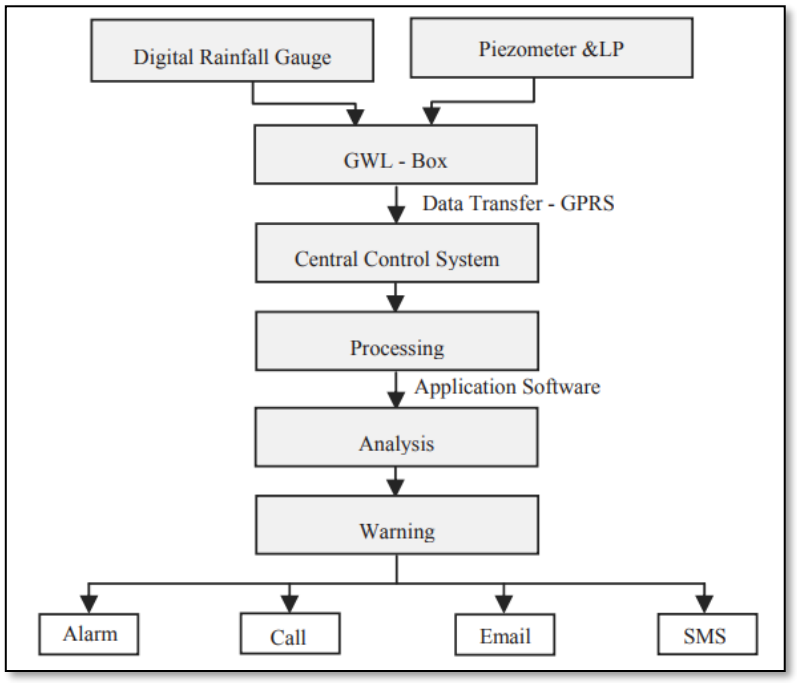


Figure 3-7 Architecture of RFID system and its implementation flow (Hosseyni et al, 2011)

The number of sensors used in the system and their locations are determined through optimization using a neural algorithm (Hosseyni et al, 2011). The data collected is shown graphically in real-time in the control room where it is used to calculate the factor of safety. This data is also used for prediction and identification of potential dangers (Ward et al, 2004). The calculated factor of safety is required to be greater than one (1) at all times. Once it approaches one (1), warning alarms are triggered, and calls, emails and text messages are automatically sent to responsible persons and local

authorities (Hosseyni et al, 2011). Areas where the factor of safety is less than one are shown on the GIS map. Alarms in the areas where factor of safety is close to one or less than one is triggered alerting the personnel in those areas (Ward et al, 2004; Hosseyni et al, 2011; Erabuild, 2006)).

From Radio Frequency Identification Technology, the following should be considered when developing a smart system for underground mining;

- The system is real-time and uses wireless communication system from loggers to the control centre;
- Data from all sensors are used to find correlations, later used in predictive analysis;
- All stakeholders are alerted of imminent danger (Jaselskis et al, 1995);
- A hazard map can be generated indicating high risk areas with measured values greater than thresholds;
- The sensors or instrumentation can also be read off manually in the event of system failure (Hosseyni et al, 2011). This can be difficult in inaccessible areas; and
- Connections between data loggers and sensors may be affected since they are cable based (McLandrich et al, 2013). This may affect data transfer.

In order to use the RFID system in a smart rock engineering system, the following adaptations are required:

- Changing cabled connections between data loggers and sensors to wireless; and
- The system should re-boot by itself after a system failure and should send data as soon as it re-boots

3.4 Risk Management Technologies in Petroleum Engineering

The reduction of offshore accidents and incidents is a way of protecting the environment and reducing business loss (Long, n.d). The surveillance of oil rigs is a

critical component in oil spill management. According to Long (n.d), "*advances in remote sensing technologies can help identify potential threats and minor spills before they cause widespread damage and can provide the industry with a proactive defence"*. Although no single sensor can provide all the information required in oil spill disaster management, using remote sensing technologies is still useful. The sensors provide information on early and rapid detection of oil spills and information on clean-up and control operations. Other information that the sensors provide include:

- Detection, location, time and spread (Bigliani, 2013);
- Thickness of distribution and estimate of quantity of oil spilled (Topouzelis, 2008); and
- Oil classification type, which enables an estimation of environmental damage (as damage depends on the oil type) (Long, n.d).

Sensing technologies used in the petroleum industry include, photographic imaging, microwave radiometers, visible and infrared or ultra violet scanning sensors, Side Looking Airborne Radar (SLAR) and Synthetic Aperture Radar (SAR) (Long, n.d).

3.4.1 Scanning laser environmental airborne system

Scanning Laser Environmental Airborne Flourosensor (SLEAF) system uses fluorescence properties of oil to detect any oil spill (Zhong et al, 2015). When oil is exposed to ultraviolet (UV) light, it absorbs the UV light, thereby increasing their energy and exciting the oil. The excitement is evident by emission of light largely in the visible spectrum of light (Brown and Fingas, 2003). The difference in physical and chemical properties of oil types allows different spectra of the fluorescence to be recorded thereby classifying the oil spilled (Zhong et al, 2015). Figure 3-8 shows the system architecture. To record any changes in water surface (detecting oil spill), a system called "event driven system" is required (Eugster et al, 2003). This system is interactive and requires users to choose the cases or topics that describes certain oil spills (Eugster et al, 2003). The system matches the descriptions when there is an oil

spill and relays the information back, in real time (Eugster et al, 2003). This principle of operation functions in a similar fashion with triggering systems.

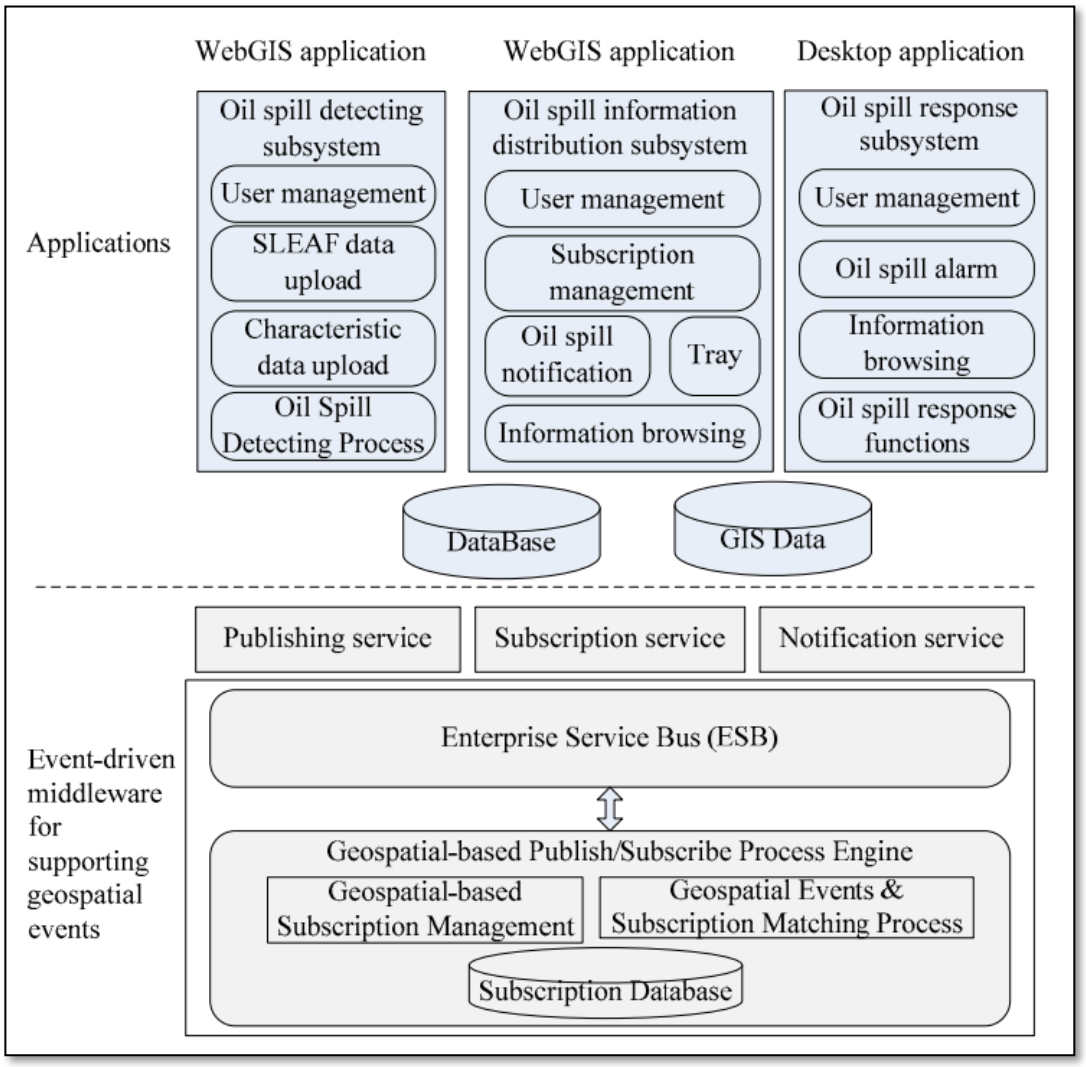


Figure 3-8 SLEAF system architecture (Zhong et al, 2015)

The system used in SLEAF comprises two subsystems which are; the event driven middleware (the core of the system as described earlier) and the application (Zhong et al, 2015). The middleware comprises a geospatial based publish/subscribe process engine (GPSPE) and an enterprise service bus (ESB) (Topouzelis, 2008).

The ESB is an information channel that receives and pushes published events to the users (Zhong et al, 2015). The GPSPE manages and matches geospatial events and has a subscription database for storage of captured data (Topouzelis, 2008). Since the system is web based, access is open to all users to view the extent of soil spills and this is done through the subscription service. Any new spill is invoked on the user's screen as a flashing icon notifying the user of new oil spillages (Zhong et al, 2015). From the SLEAF system, the following should be considered when developing a smart system for underground mining:

- Using physical and chemical properties of oil when it spreads over water and exposed to UV light, the system classifies the oil and appropriate action plans are taken to kerb the spread and cleaning up. The same principle of changing properties as a material fails can be used underground when rock properties change during failure. This can assist in understanding the different types of rock failure;
- The system allows the user to query certain attributes and have them displayed (Zhong et al, 2015);
- The alarm system shows through an icon on the desktop suggesting that the control room operator always have to see such, which is impractical. A sounding alarm or flashing floodlight need to complement the flashing icon for improved response of an oil spill; and
- Response operations (clean-up operations) are automated. These are stored in oil spill response subsystem database (Zhong et al, 2015).

The use of such scanning technologies requires modifications. These include:

- Adding rock scanning capabilities to identify changing rock mass behaviour; and
- Flashing icon on the desktop to be replaced by hazard maps, which can be seen by all the control operators

3.4.2 Wireless sensor networks

Wireless sensor network (WSN) is a technology that uses tiny sensors with embedded communication technology (Tilak et al, 2002). The sensors can sense in real-time and, process the measured data and transmit processed data to the user in need of the information (Yi et al, 2010). Their size and functionalities enable them to be used in borehole drilling for oil extraction. Within the borehole, the sensors measure temperature and pressure (Yi et al, 2010). The measurements are sent to the database where it can be browsed over the internet and users can receive any alarm when there is a data overflow (Goldner et al, 2003). With webserver functionalities, the user can switch the sensor on or off for any data collection until the data overflow is resolved. The system structure is divided into a data acquisition unit and monitoring centre as shown in Figure 3-9.

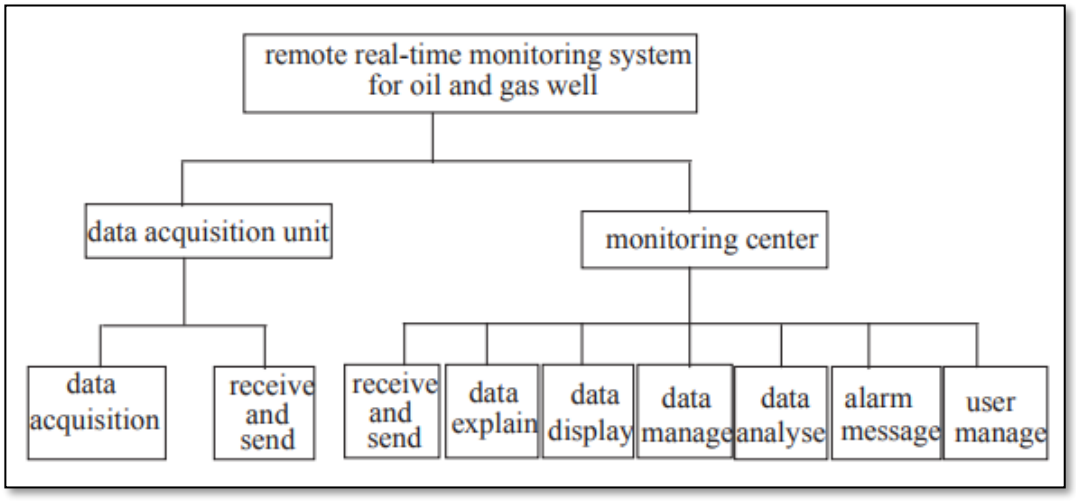


Figure 3-9 WSN system structure (Yi et al, 2010)

The monitoring centre is the core of the system as it executes numerous functions as indicated in Figure 3-9. From wireless sensor networks, the following should be considered when developing a smart system for underground mining

- The size of sensors is small thus making them easy to carry and install. Simplicity in installation and operation are crucial in underground mines;

- The system uses existing cell phone communication systems, making it easy to operate from the palm of the user's hand; and
- Notification to affected stakeholders is through a message which is inadequate for complete risk management.

Adaptations that are required wireless sensor networks to be used within the smart rock engineering system include:

- Additional notifications through phone calls, hazard maps, emails should be added; and
- Communication from the sensors to the monitoring centre will use WiFi instead of cell phone communication system

3.5 Conclusions

The management of risk in open pit mines, civil and petroleum engineering is more advanced compared to underground mining. This is largely attributed to the differences in the working environments and easy access to areas of work. Despite such huge differences, technologies used to manage risks in these areas can be used in underground mining environment, possibly with a few changes or as is. Risk management in open pit mines uses wireless systems that include, GPS and radar systems. Their applicability to underground mining is limited due to the requirement that a GPS receiver ought to be visible to four satellites. Pseudo-satellites can be used to solve visibility issues, but the challenge remains for underground mining where there is no visibility to satellites at all. Some risk management technologies do not require an operator after installation, no manual calibration and their operation can be done remotely. The ability to operate autonomously removes the influence of human error and judgement in taking measurements thus improving on the quality of data collected. Improving data collection improves mine planning and design thereby reducing the risk of rock failure. RTS allows integration and reduces the number of "silo" based risk management systems. Only one management system that allows "plug and play" is

used and reduces the need for continuous change management training. The DMS system, based on data collected, forecasts and predicts the events. The ability to forecast allows improved disaster management plans to be put in place. However, forecasting rock behaviour in underground mines is difficult and as such, collecting data over extended periods of time may improve the understanding of such behaviour. Risk management systems in other areas have shown that visualization in the form of maps showing hazard level and location of hazard as is the case with sensing skin technology is also crucial for disaster management. The ability of PPP with GIS system to work in any forecasted weather is a functionality with enormous benefits. Using the change in rock properties as rock fails, it is possible to determine when a rock is about to fail, the same way fluorosensors are used in SLEAF technologies. The following chapter discusses such attempts to apply existing technologies from other areas and their failures or limitations.

4 SMART SYSTEMS, TECHNOLOGIES AND CURRENT RESEARCH FOR UNDERGROUND ROCK-ENGINEERING RISK MANAGEMENT SYSTEMS

To identify smart systems and current research on technologies for managing rock-engineering risk in underground mines

4.1 Introduction

Chapter three outlined risk management technologies used in surface mines, civil and petroleum engineering. The majority of the technologies described, used GPS, which is impossible to use in underground mines due to its requirement of the satellites being visible to the receivers. This chapter provides a description of what smart systems are, smart decision-making and expected functionalities. Furthermore, technologies and systems that have been used and are currently being developed for underground mining are described. These technologies are compared to an ideal smart system. The limitations and failures, are emphasized.

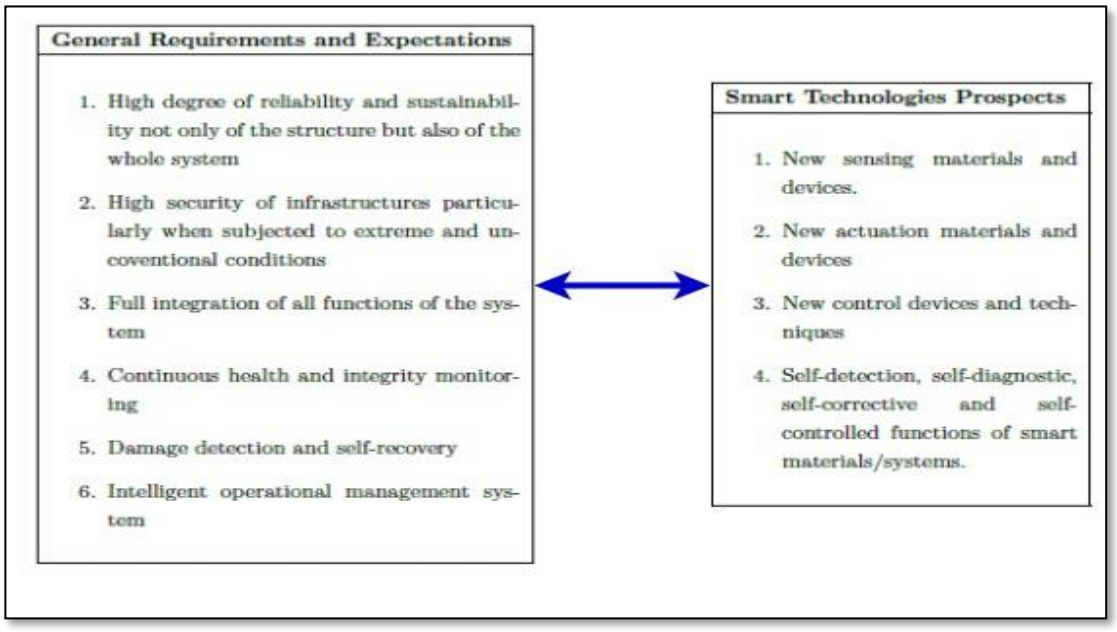
4.2 Smart Systems

The design of mining and other engineering structures is a complex process. The complexities in design for the past centuries were made simple by studying nature and the secrets of nature. This study of nature, termed bionic study assisted engineers in understanding complex systems in living organisms, later providing them with solutions to their problems aiding in developing improved technology. The human being is one of the living organisms that has been studied, with the aid of engineering and science concepts, to solve structural problems in civil engineering (Taghizadeh and

Bastanfard, 2012). The human body can be considered to be "*a system that can be observed to develop smart systems"* (Taghizadeh and Bastanfard, 2012). The origin of smart systems can be traced back to a study that envisioned systems, structures, materials and devices that mimic the central nervous system and the muscular system of a human being (Akhras, 2000). According to Akhras (2000), "*the essential idea is to produce non-biological systems that will achieve the optimum functionality observed in biological systems through emulation of their adaptive capabilities and integrated design"*.

The developed "non-biological" systems are called smart systems and comprise sensors and actuators (Morris, 2007). The integration of sensors and actuators form a system performing in predicted ways and have their behaviour emulating a biological function (Taghizadeh and Bastanfard, 2012). This makes the human body an "*ultimate"* smart system, that every system endeavour to emulate (Allison et al, 2007). Table 4-1 shows the expectations, requirements for smarts systems and the result (in terms of what smart materials and systems ought to be) of these expectations (Akhras, 2000).

Table 4-1 Requirements, expectations and results of smart systems (Akhras, 2000)



From Table 4-1, it is suggestive that innovative smart technology materials will include different properties. The change in properties of sensing materials still require the following to be satisfied.

- Have zero or low toxicity levels and no pollution to the environment (Akhras, 2000);
- Should be sustainable for the business, that is, they should be re-used or recyclable (Allison et al, 2007; Akhras, 2000; Taghizadeh and Bastanfard, 2012); and
- Their accessibility (raw material supply) should be simple, less expensive and readily available (Akhras, 2000).

4.2.1 Smart system structure

According to Akhras (2000), a smart system is primarily made of two functions, which are sensing and actuating. With the right control centre, these two functions result in the system performing smart actions. The components of a basic smart system are shown in Figure 4-1.

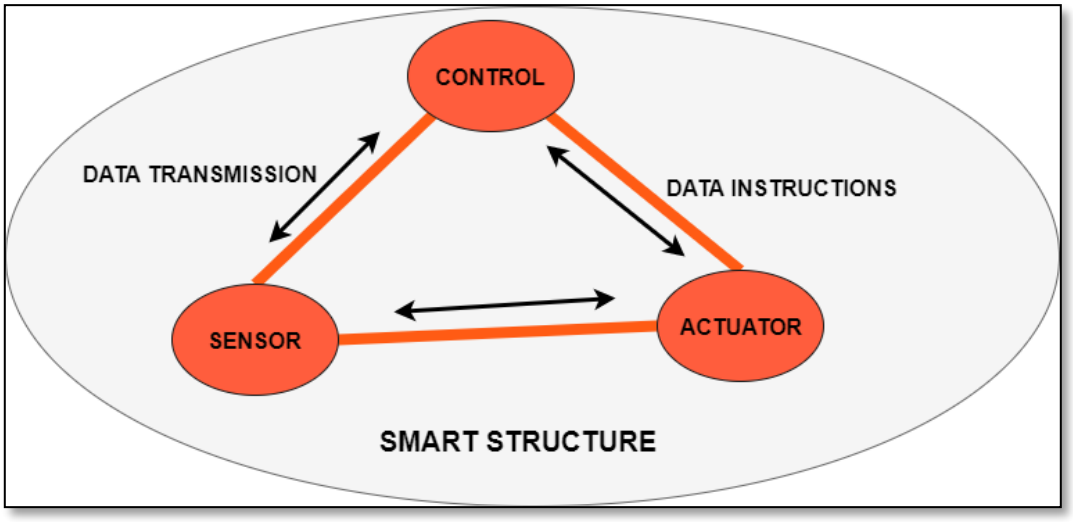


Figure 4-1 Components of a smart system and their interrelationships (Akhras, 2000)

- Data acquisition;
    - The components of a smart system designed for sensing, are based on what they need to sense (the type of event to be sensed) (Taghizadeh and Bastanfard, 2012). This event can be mechanical, radiation, thermal, magnetic or chemical (Akhras, 2000). The type of sensing components also depends on how the output or the results are required (Akhras, 2000). The design of sensing components also considers other factors including geometry, size of area where sensing is to be performed and the conditions in which the sensors are placed. Operational factors, which include bandwidth, range and sensitivity, are also considered in the design of data acquisition components (Krishna and Thirumal, 2015).
- Command and control unit;
    - The command and control unit (CCU) represents the brain of the system as it controls day-to-day operations (Allison et al, 2007). The CCU monitors the condition of the systems through real-time communication networks functions (Akhras, 2000). The CCU comprises two main function, which are processing and analysing.
        - Processing function
            - Information received is analysed, sorted, arranged, classified, stored and processed and the origin of data, its quality and nature and the frequency at which it is collected determine if the data should be stored, classified, processed or analysed (Morris, 2007). These actions within the processing function are done with little or no human intervention and interaction. Damage detection and behaviour control can be added to these actions in the processing function through writing

special algorithms (Allison et al, 2007). Expert systems within the processing function, performs the retrieval, storage, management and classification of processed data (Akhras, 2000).

- Analysis function
    - An intelligent way of examining collected data is performed with the analysis function (Taghizadeh and Bastanfard, 2012). Results obtained are exploited and the condition of the system determined. The analysis performed includes comparing variables and features to thresholds set according to codes of practices, regulations or company standards (Akhras, 2000). Once the comparison of data is performed, a conclusion is reached, and any adverse condition is sent to devices controlling actions of the system (Akhras, 2000).

– Action devices.
    - They act based on instructions transmitted by triggering units controlling the system (Allison et al, 2007).

– Data transmission; and
    - Forwards all the collected data to the control centre (Akhras, 2000).

– Data instructions
    - Transmits the decisions made by the command centre back to the system components (Akhras, 2000).

The system structure described emulates the human body system. With the skin as the sensing system, the human body is a path to develop intelligent structures. The skin with its properties of "self-repairing, energy absorption, and thermal insulation" could

be an ideal blue print to designing areal support system that self-heals to reduce rehabilitation costs, insulates to reduce ventilation costs, and can sense rock-engineering parameters which trigger ground movement. The brain acts as the command centre, and the nervous system as the communication that decide and relay conclusions to actioning body parts. Decision-making and relaying of decisions, is thus critical in developing a smart system.

4.2.2 Smart decision making

Provided several alternatives, decision-making is the process of selecting one course of action based on a cognitive process (Trieloff, 2015). Figure 4-2 shows the position of decision-making in a smart infrastructure anatomy (Bowers et al, n.d).

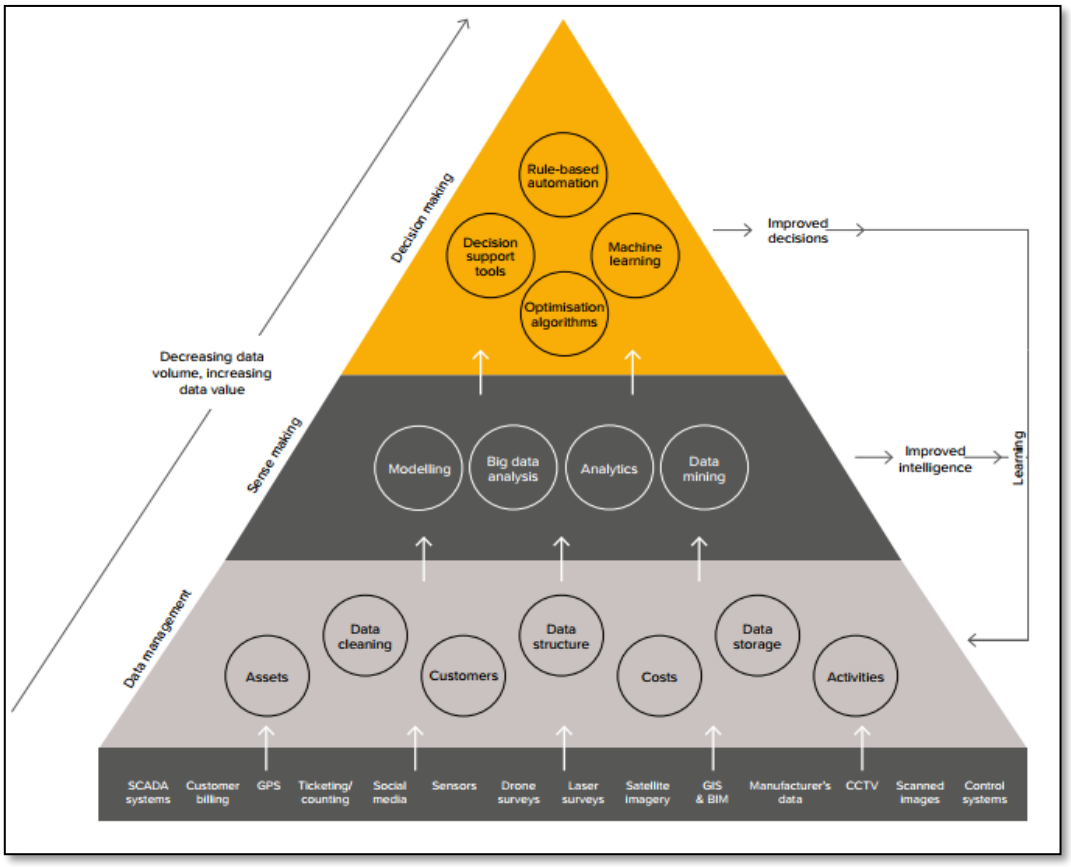


Figure 4-2 Pyramid showing decision making level (Bowers et al, n.d)

This process of choosing from possible alternatives may result in prompt actions. The cognitive process referred to, uses collected data or existing knowledge to acquire innovative or generate innovative knowledge (Merriam Webster Inc., 2017). The art of decision-making is critical in developing a smart system. The base of the pyramid comprises raw data collected by multiple sensors and decisions are at the apex (Bowers et al, n.d). From pyramid base to apex, the value of information increases and the volume of data increases from apex to pyramid base (Bowers et al, n.d). The increase in value of information is made possible by the enormous volume of collected data. With little or no data, the quality of information does not change. Smart systems thus have to collect more data that can be used for improved and smarter decision-making. In the current systems in rock-engineering, decisions and detection of errors and their correction are conducted manually.

The traditional approach (or the manual approach) in making decisions is shown in Figure 4-3.

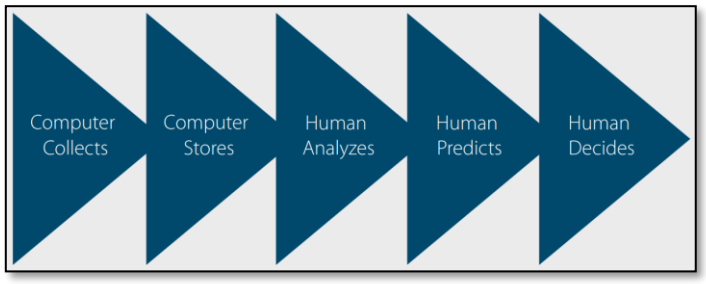


Figure 4-3 Traditional approach to decision making (Trieloff, 2015)

Such an approach, however has not been effective due to communication breakdown where there is human interaction with the system. Figure 4-4 shows the common position where communication breakdown likely occurs in the decision-making process. Such a communication breakdown is a result of numerous factors, which include:

- Misunderstood and distorted drill down data analysis (Ernst and Young, 2013);

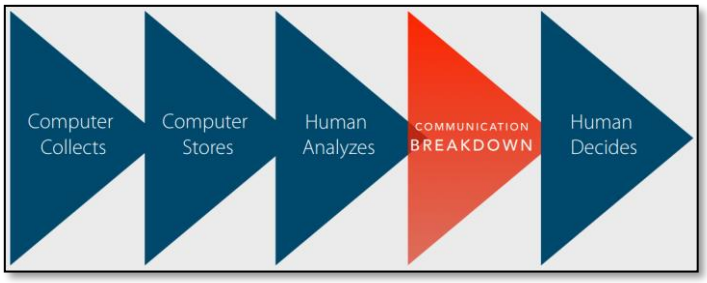


Figure 4-4 Communication breakdown in the traditional approach to decision making (Trieloff, 2015)

- Monthly reports ignored and abandoned after running iterations once or twice (Trieloff, 2015);
- Contradiction or confusion concerning the metrics used on dashboards (Trieloff, 2015); and
- Overworked and powerless analysts, who once they realise that they are powerless, put less effort on data analysis.

To reduce the risk of communication breakdown, tasks can be offloaded to computers or smart systems. Offloading such tasks to a smart system reduces the time geotechnical personnel consume to correct errors and enabling them to work on more productive tasks, reducing operating costs significantly. The ideal flow of data and ultimately decision-making is performed using computers as shown in Figure 4-5.

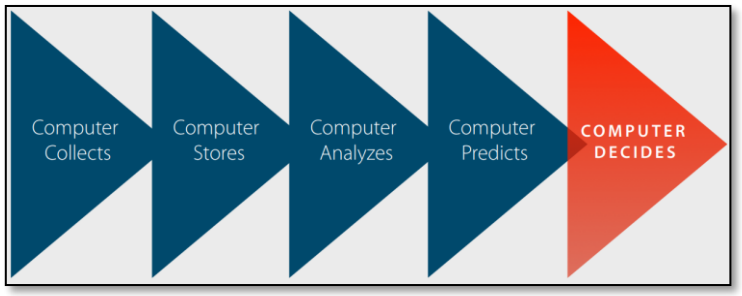


Figure 4-5 Ideal automated decision making (Trieloff, 2015)

In addition to reducing costs, a smart system with decision-making runs all day and all week, allowing a response any time of the day. Smart decision-making, "*is thus used to make the workflow more intelligent by adapting to incoming data dynamically, to make the workflow capable of responding to errors and to make the workflow enforce regulatory or contractual requirements"* (Pallet, 2011).

This automated system structure assists mining houses in reducing "compliance mistakes" resulting in fines, section or mine closure and penalty reduction (Pallet, 2011). Where exceptional cases arise, human experts, review results from automated systems and make judgement on such cases. The quality and quantity of data collected should be high considering, "*garbage in, garbage out"*. Thus, automated decision, require oversight from management using expert systems. The understanding of automated decision-making and smart systems is also critical in developing technologies for underground mines. Section 4.3 describes technologies and systems developed or being developed and their functionalities and limitations compared to smart systems and smart decision-making's functions.

4.3 Rock Engineering Current Technologies and Research for Underground Mining

Extensive research for smart monitoring technologies for underground mining has been ongoing for years. These technologies include RockWatch and RockGrabber from GroundWork Consulting, smart bolt with internet of things (IoT) from Lulea University, fall of ground (FoG) light and stick from New Concept Mining, subsurface profiler from ReuTech, Geo4Sight tilt and Geo4Sight pressure from Elexon Mining, AziSA system from Council for Scientific and Industrial Research (CSIR), Malan's Rock mechanics technology Telltale system and Maptek's Sentry monitoring system. System of working and their architecture, capabilities and limitations of these technologies are described in this section.

4.3.1 Maptek Sentry monitoring system

Maptek Sentry monitoring is a system that monitors surface stability and visualizing the results (Maptek, 2017). The system uses a laser scanner through Maptek I-site and a specific software developed for Sentry to ensure monitoring and analysis of concerned excavation surface is performed continuously (Maptek, 2017). The delivery of the Sentry to a mining site is through a custom-built trailer (Figure 4-6) that includes; power and a communication module, cellular and WiFi networking, and a stable stand for placing a laser scanner (Maptek, 2017).



Figure 4-6 Maptek Sentry deployable monitoring system (Maptek, 2017)

Using the laser scanner and inbuilt storage, Sentry system maintains monitoring data and records rock fall's origin and landing position allowing calculation of volume and updating of rock fall data base. A heat map is used to visualise areas where rock movement could occur (Richards, 2014). In addition to the heat map, displacement time graphs and velocity time graphs are also used for visualization (Richards, 2014). Further analysis of data collected is performed using I-Site Studio. From a single set, up of a Sentry system multiple points can be monitored (Maptek, 2017), for example in Figure 4-7. Notifications through emails are sent to the geotechnical personnel when set tolerances are exceeded (Richards, 2014).

The use of Maptek's Sentry monitoring system in hard rock underground mining is limited by:

- The number of zones to be monitored from a single monitoring point is inadequate for underground mining;
- The system monitors displacement, and velocity;
- The system does not monitor stress within the rock;
- Notification through automated phone calls is unavailable;
- Automated decision-making is unavailable;

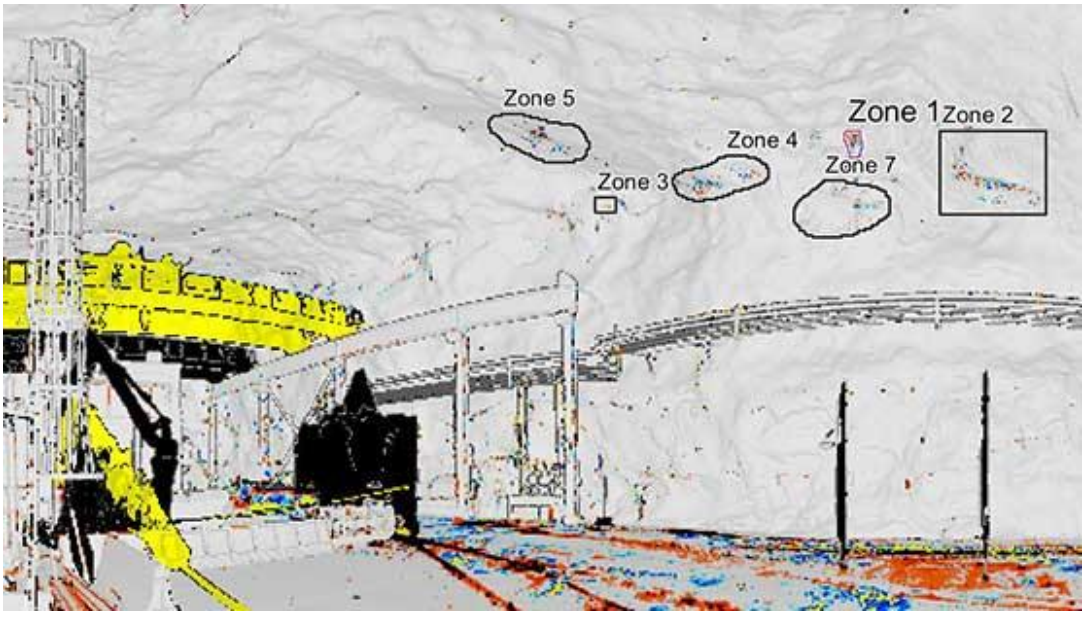


Figure 4-7 Multiple areas of monitoring defined by the zones marked (Maptek, 2017)

- The system does not monitor support performance; and
- The size of the deployable monitoring station is big for narrow reef stopes.

4.3.2 ReuTech subsurface profiler

The subsurface profiler (SSP) is a monitoring technology developed by ReuTech. Figure 4-8 displays the subsurface profiler.

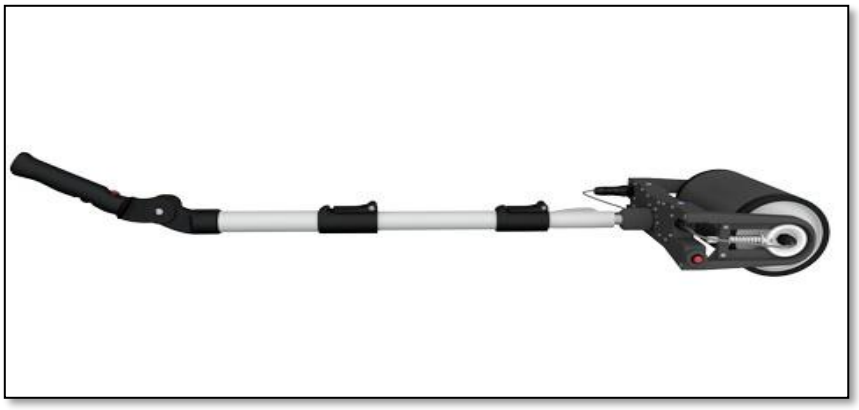


Figure 4-8 Subsurface profiler (ReuTech Mining, 2017)

The profiler manages falls of ground in real-time and facilitates dynamic decision-making to the geotechnical practitioner. The profiler's working principle emulates a paint roller (ReuTech Mining, 2017). Data collected from the roller (where radar technology is), is transmitted to a tablet or computer for processing in real-time wirelessly (ReuTech Mining, 2017). Two practitioners are thus required, one who rolls the profiler on excavation wall and one who hold the tablet or computer for visualisation as shown in Figure 4-9.



Figure 4-9 Working principle of a subsurface profiler (ReuTech Mining, 2017)

The results obtained from the profiler indicate support performance. SSP is battery powered and the two practitioners carry rechargeable batteries as they last

approximately four (4) hours with continuous operation (ReuTech Mining, 2017). SSP's use for real-time rock-engineering risk management is limited due to:

- Two (2) people need to carry and use it to monitor ground condition. This means that there are two more people at risk in addition to those already present in production stopes;
- Rolling the SSP becomes heavy for extended hours of operation;
- The system does not monitor remotely, and battery life is low, as it cannot last one complete shift therefore, it does not operate continuously (day and night); and
- Decision-making is still expected from humans, even after the results are visualised on the tablet or computer.

4.3.3 Thermal imaging

Compared to other technologies, AziSA is a form of architecture used for sensor data communication (Vogt et al, 2009). Figure 4-10 shows the typical AziSA architecture.

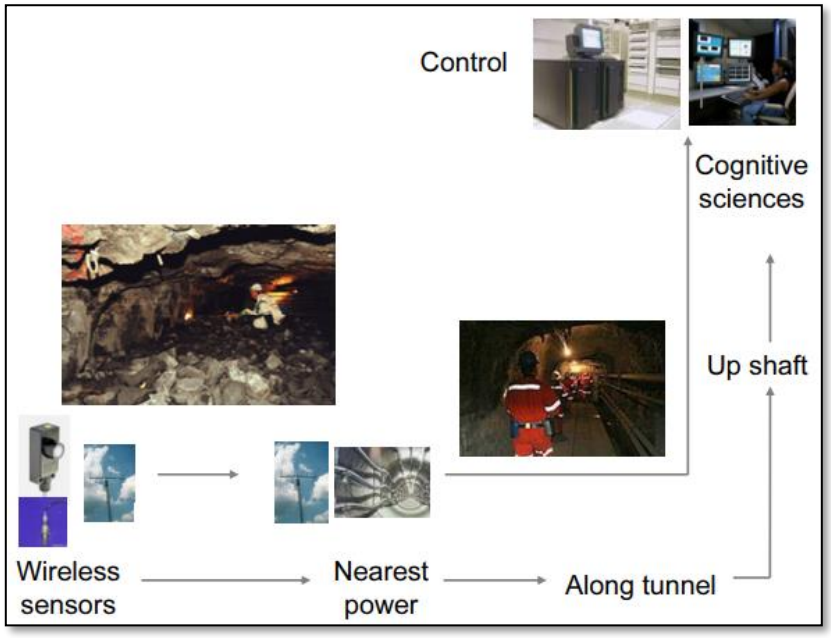


Figure 4-10 AziSA architecture (Vogt et al, 2009)

The architecture is open for connection to any wireless sensor type. This technology has been tried in areas where there is risk of rock falls using thermal imaging sensors (Vogt et al, 2009). Thermal imaging sensors replaces the processes of sounding to identify potential bad hangings, lessening the work of the miner in charge when making an area safe for their crew (Stewart et al, 2008). The results from thermal imaging are combined with location data and time stamps making it possible to generate risk maps and possibly pave way for predicting risk into unmined areas (Vogt et al, 2009). By using time stamps in thermal imaging, the time a re-entry procedure was taken is recorded and the areas that the miner barred down identified (Stewart et al, 2008). The architecture to which thermal imaging sensors are connected consist of 4 layers of devices distinguished by the functionalities of the devices:

- Class 4 devices;
    - These are basic sensors that can send collected data, receive instructions and raise an alarm based on alarm conditions set in the system (Stewart et al, 2008).
- Class 3 devices;
    - These sensors can collect data and raise an alarm on their own based on collected data (Vogt et al, 2009).
- Class 2 devices; and
    - These sensors can raise an alarm based on information within the network where alarm values were triggered or exceeded (Vogt et al, 2009)
- Class 1 devices.
    - Class 1 devices use data found in the system to raise an alarm to the concerned area or device (Stewart et al, 2008).

Class 2 sensors are connected closer to a power supply, which in narrow reef mines is the winch area and Class 3 and 4 are connected in the stope area (Vogt et al, 2009). Class 1, is a software analysing data and presenting it to the control room operator for decision-making.

To determine the location of sensors, ultrasonic beacons are used, and their location accuracy is in the order of tens of centimetres (Stewart et al, 2008). The limitations of thermal imaging using AziSA systems are:

- Thermal imaging still requires human intervention to operate;
- Thermal imaging operates for loose rocks and not stressed rock with potential to bursting;
- AziSA is an ongoing research therefore inadequate data exist to test all its assumed capabilities;
- Location accuracy of ultrasonic beacons is relatively poor (order of tens of centimetres); and
- The operator has to make decisions based on collected data, shown in control room screens.

4.3.4 Smart bolt with internet of things

An estimate of more than 100 million iron bolts per year are used to support excavations globally (Eliasson et al, 2013). Figure 4-11 shows the position of sensors relative to the complete smart bolt.

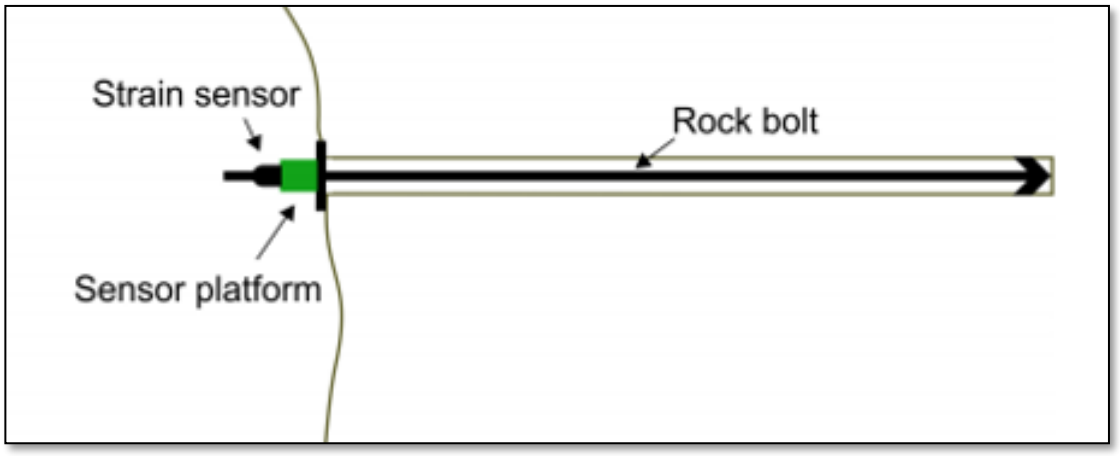


Figure 4-11 Smart rock bolt installed in a tunnel wall (Delsing et al, 2015)

These bolts, once installed, cannot be checked for quality as that will compromise the support system performance. As such smart bolts are being rolled out or tested to ensure that bolt quality and performance can be checked continuously. Smart bolts are defined as, "*steel or iron bolts with internet of things that is embedded electronics that connect to internet"* (Ekelund, 2015). The bolt can monitor ground movement by detecting strain simultaneously monitoring its own condition using an accelerometer (Delsing et al, 2015).

Any changes in stress, strain, bolt condition (abrasion or necking or bolt about to break) is communicated wirelessly (Eliasson et al, 2013). Any change greater than the set threshold, is transmitted to the system out as a warning signal. The system can also send instructions to the bolt which are reflected through flashing light emitting diodes (LED's) installed on the bolt (Delsing et al, 2015). The critical component of this technology is the head containing all the sensors. The head of the smart bolt is shown in Figure 4-12.

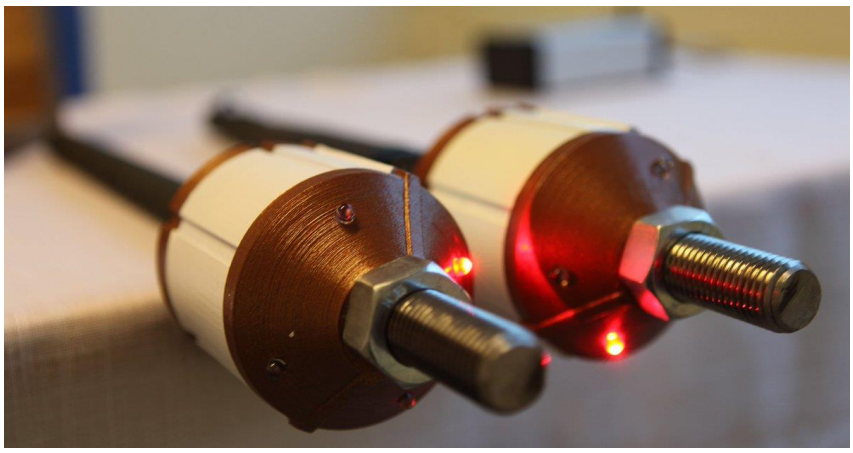


Figure 4-12 Head of a smart rock bolt (Eliasson et al, 2013)

A non-rechargeable battery is used to power electronics in the head with the ability to last a couple of years (Ekelund, 2015). The system used to connect bolts allows interaction between bolts, enabling geotechnical practitioners and rescue teams to locate miners in the event of an incident (Eliasson et al, 2013). This interaction connects

to a cloud service for each bolt installed using WiFi, 4G cellular network or wired Ethernet (Eliasson et al, 2013).

The use of smart bolts is currently limited by:

- A need for a longer battery life;
- LED lights that only flash according to the set limits. LED lights should flash in a way or sequence enabling the miner to be directed to a refuge bay using the safest path;
- Large memory storage is required; and
- Information regarding the effect on production cycle is unavailable as the head is the critical component, installation is critical otherwise there is increased risk to damaging the head.

4.3.5 Rock mechanics technology remote reading telltale system

Rock mechanics technology remote reading telltale system (telltale system) was originally designed to monitor bed separation and roof displacement in collieries (Bigby and DeMarco, 2001). Figure 4-13 shows the roof mounted remote reading telltale. In this system, electronic telltales are used as transducers (Bigby et al, 2010). Boreholes are drilled into which mechanical telltales (with the same working principle as extensometers) are installed. These mechanical telltales provide a warning of possible rock deformation through indicator movements (Malan et al, 2003). The system connects up to 400 telltales enabling real-time monitoring of the roof (Bigby and DerMarco, 2001). The rock mechanics telltale system comprises:

- The roof mounted remote reading telltale which takes the readings for any ground movement (Malan et al, 2003);
- An underground interrogation unit that processes signals from telltale, transmitting it to the surface (Bigby and DeMarco, 2001);
- Surface interrogation unit that converts signals from underground interrogation unit to a format readable by the surface computer (Bigby et al, 2010);

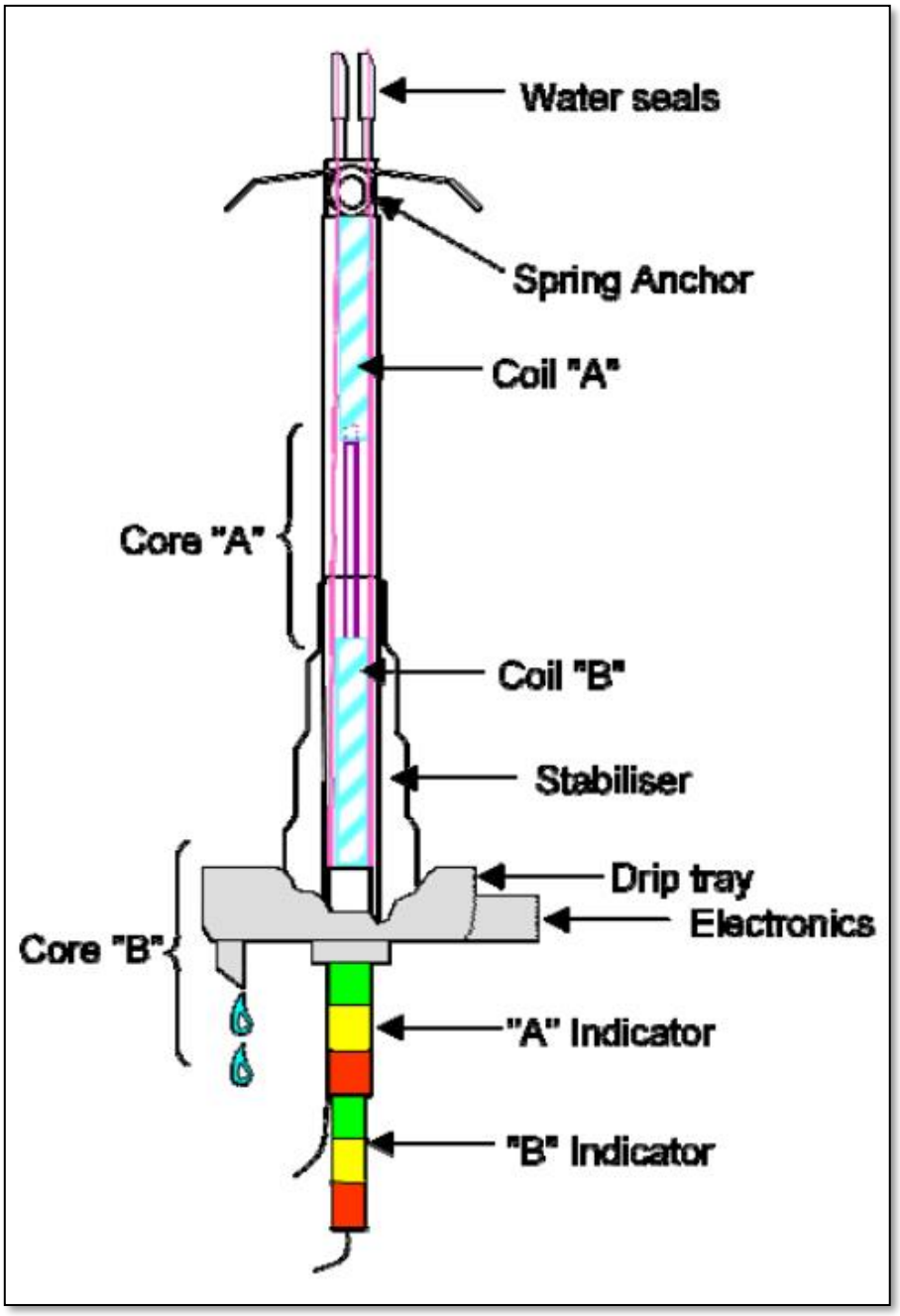


Figure 4-13 Remote reading telltale (Bigby et al, 2010)

- Cable network that links all the components of the system in a stope as shown in Figure 4-14 (Malan et al, 2003); and

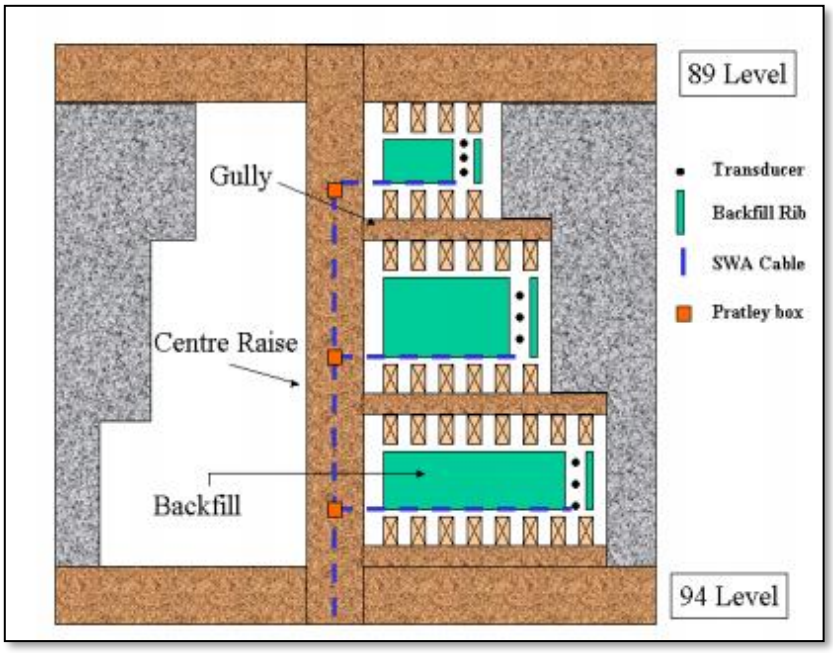


Figure 4-14 Relative position of telltale (transducer) and cables in-between levels (Malan et al, 2003)

- Computer in a control room on surface controlling the whole system (Malan et al, 2003).

The interrogation units and the telltale components can be installed by mining personnel with little or no understanding of electrical engineering (Bigby et al, 2010; Malan et al, 2003). Interrogation units are also used for running system diagnostics (Bigby and DeMarco, 2001). Though used in an underground mining environment, the use of Telltale system in hard rock mining is limited. This is due to:

- The system is cable based, hence problems are experienced in communication from surface to underground;
- Maintenance of cables within the stope area is difficult due to numerous production equipment used; and
- The Telltale can only be seen by a person at a close distance, to view the indicators. Anyone from a distance cannot see any changes in the indicators, hence they cannot see if ground movement has occurred.

4.3.6 Mine Design Technology suite

The Mine Design Technology (MDT) Suite consist of softwares, data acquisition, tools and instrumentation for geotechnical monitoring. Softwares include, Mine Monitor, Mine Monitor Web, Mine Hop Web Interface and Vista Data Vision. Data acquisition tools include, MDT load sensing LS-G6, wireless MDT-RTU, wireless VW-RTU, wireless SAA-RTU and smart log. Instrumentation includes, Smart MPBX, Smart cable bolt, smart ground movement monitor, smart contractometer and smart cable-SP.

Softwares

- Mine Monitor
  - Mine Monitor is a database software that works for all MDT instrumentation. Access to data can be performed by multiple users provided the data is available on a mine server (Mine Design Technologies, 2017a). The availability of data on the server allows for instrumentation configuration and alarm setting. (Mine Design Technologies, 2017a).
- Mine Monitor Web
  - Mine Monitor Web is a "web-based software" that works with MDT instrumentation and allows access through internet from any location, whether onsite or offsite (Mine Design Technologies, 2017b). The software is not installed on any mine computer as it is web based. It is managed by the MDT team (Mine Design Technologies, 2017b).
- Mine Monitor Web Interface
  - The interface provides dashboard notifications and real-time reports and any events and or alarms are notified to the geotechnical personnel through sms and email (Mine Design Technologies, 2017c).

Data acquisition

- Wireless MDT-RTU
  - The logger can collect data from three (3) MDT smart instruments wirelessly (Mine Design Technologies, 2017d). The logger is battery

powered and the batteries have a life span of three (3) years (Mine Design Technologies, 2017d).

- Wireless VW-RTU and Smart Log
    - These loggers acquire data from any instrument with a working principle of a vibrating wire (Mine Design Technologies, 2017e). Smart logger is battery powered and the batteries can last for one and half (1.5) years (Mine Design Technologies, 2017f). Data collected by a smart logger is downloaded into MDT software using a universal serial bus (USB) cable

Instrumentation

- Smart MPBX (100m length) and Smart cable bolt (30m)
    - The smart multipoint borehole extensometer (SMPBX), is an instrument comprising four components, which are, SMPBX body, load wire, instrument head and a connector, connecting to a read-out unit (Bawden et al, 2015).
- Smart contractometer
    - This instrument measures convergence in an excavation using a collapsible structure (Strickland et al, n.d). The instrument is coupled with an electronic head, connecting wirelessly to smart loggers (Mine Design Technologies, 2017g).
- Smart ground movement monitor
    - This instrument monitors ground movement largely in salt and potash mines and does not require any form of grouting during installation (Mine Design Technologies, 2017h).

MDT suite has been used with success on different sites. However, its use in hard rock narrow reef mining is limited by:

- The loggers are battery powered hence they will require replacement;
- Notifications through automated phone calls are not performed; and

- The system does not make autonomous decisions as it waits for the control room operator for further action plans.

4.3.7 Other technologies

New Concept Mining developed the FOG light and FOG stick. Figure 4-15 shows a FOG stick in a horizontal position and two flashing LED's.



Figure 4-15 FOG stick (New Concept Mining, 2017a)

The FOG stick provides a warning of a possible closure within the working area (New Concept Mining, 2017a). The FOG stick also flashes a red light in the event of closure beyond the set threshold. The FOG light provides a warning to mining crews using LED flashing lights (Figure 4-16) after a separation of rock within the hanging wall (New Concept Mining, 2017b). When the installed unit flashes green, it means the unit was installed correctly and is functioning properly and red flashes indicate a potential movement of rock within the hanging-wall as shown in Figure 4-16 (New Concept Mining, 2017b). Both the stick and the light operate continuously on battery with battery life of three months and twelve months respectively (New Concept Mining, 2017a; New Concept Mining, 2017b). FOG light once triggered, cannot be removed unlike the stick that can be removed safely to a new location.



Figure 4-16 FOG light (New Concept Mining, 2017b)

GroundWork Consulting (2017) developed a rockwatch robot and a rockwatch grabber as shown in Figure 4-17. The working principle of the rockwatch robot is similar to the FOG stick that is, the robot flashes depending on the level of movement that would have occurred. Up to seven flash light levels can be set depending on the history of closure in the mining environment to be monitored (GroundWork Consulting, 2017). Data collected by the rockwatch robot is stored on the logger, which is installed on the robot (GroundWork Consulting, 2017). A rockwatch grabber as shown in Figure 4-17 wirelessly connects to the data logger to a distance of 15m and downloads the data (GroundWork Consulting, 2017). Once the data were downloaded, it is then uploaded to a computer on surface where data analysis is performed.



Figure 4-17 Rockwatch robot and rockwatch grabber (GroundWork Consulting, 2017)

MinTek, SIMRAC and the Department of Science and Technology (DST), developed a smart bolt that changes its microstructural properties in a unique way after ground deformation (Moema et al, 2008). The change in steel property is from non-magnetic to magnetic and the extent of plastic deformation affects the magnitude of change (Moema et al, 2008). Ultrasound velocity of the steel bolt changes as a result of microstructural changes. The installation of smart bolts in underground mines is performed in the same way as conventional roof bolt support. Once installed, the smart bolt records (through changes in structural properties) ground movement. Periodically, sound velocity is measured across the length of the bolt using a portable ultrasonic device (Moema et al, 2008). The changes in sound velocity are translated to the stresses that generated the change in microstructural properties (Moema et al, 2008).

The use of these other technologies in rock-engineering risk management is limited by:

- Once a FOG light is set to monitor, it cannot be reset;

- There is no data collection for a FOG light as it only alerts through flashing lights when a possible movement is sensed. Hence data analysis to understand rock behaviour impossible;
- The battery life span for both the stick and light is short. This means that they cannot be used in areas where mining is no longer taking place, or where mining is suspended for extended periods of time; and
- The rockwatch robot and the MinTek smart bolt require a geotechnical person to be close to download data and have it sent to surface for further processing. This is time-consuming and re-introduces human bias in processing of data.

4.4 Benefits of Installing a Smart Rock-Engineering System

The purpose of smart instrumentation used in rock-engineering is to aid to the process of decision-making through identifying possible rock engineering risks and the modes of rock mass failure. Appropriate actions are then taken based on the risk level or impact that the hazard can cause. The correct use of such a smart system requires an understanding of the sequence of events leading to failure and the value of appropriate early interventions. The smart rock-engineering system allows analysis of ground behaviour by measuring changes in critical values (displacement, water level, stress and acoustic emission, support yielding, crack opening, and convergence). These critical values are identified through indicators and precursors as highlighted in Section 2.3.1.

The concept of a smart system is to have a system that achieves optimum functionality through adaptive capabilities and integrated design (Akhras, 2000). Improved productivity, reduction of operational costs and improved safety are obtained through real-time monitoring and communication to the personnel and equipment in areas impending danger. The benefits accrue over time once installation is completed. These benefits include:

- The right instrument for the right risk.

- Smart sensors and associated infrastructure, can improve understanding and appreciation of the risk. The analysis from such a system shows that failure is not random and can be predicted when the right instruments measure the right risk. Malan et al (2003), identified that falls of ground occurred in areas with the highest amount of instantaneous seismic closure. Therefore, the measurement of closure as a precursor using smart instrumentation, provides the right information for decisions to be carried out.

- Protecting miners, reliability and easy access to data.
  - Real-time location tracking of miners, two-way communication, and monitoring of stoping areas allow proactive responses to be taken ensuring that evacuations are performed on time. Measured indicators which include gas emission, wall convergence as mentioned in section 2.3.1 provide data that can be used reliably to back analyse these major events and use such analysis for future prediction.
- Identification of useful parameters that can be used to create hazard maps
  - The closure ratio (ratio of instantaneous blasting closure to total closure after a blast), is a quantity that can be used to identify possible hazards and different ground conditions (Malan et al, 2003). The measurements obtained from installing smart rock-engineering system allow mines to identify parameters that can be used for the creation of hazard maps.
- Low energy consumption, durable and scalable.
  - The simplicity of the system infrastructure allows the sensors to provide years of reliable service. Extra sensors can be added easily by automatically joining to the wireless mesh.
- Rapid installation and or deployment.
  - Short time is needed to install the sensors and infrastructure, compared to cabled systems. This frees up time projects departments, to fulfil other activities.
- Minimum maintenance.

- Using wireless system reduces the need to check and maintain kilometres of cabling. Maintenance in wireless system involves, changing batteries on the sensors every few years.

4.5 Conclusions

With the recent developments and advancements in technology and artificial intelligence, mining is no exception to submit to the pressures of changing operating processes. Rock-engineering (a component of the mining process) faces the same challenges. Smart systems are developed to improve productivity across the mining value chain. The human body, as the ideal smart system, is what industrial smart systems endeavour emulating. The art of decision-making and how timely the decisions are relayed to actioning devices in a human body, makes the human body an ideal system to imitate. From existing technologies, several factors contribute to their limited functionalities. These factors include, limited battery life on sensors and loggers, data collection still requiring geotechnical personnel to be close to data collections sites and systems being limited to single functionalities and unable to integrate to monitor a number of parameters using one system.

Smart systems in rock-engineering are however in their initial stages of development. The engineering fraternity is starting to scratch the surface of its potential, and with a technology amalgamation, enormous benefits to the mining industry can be seen. A smart system should be able to govern itself and make informed decisions without coercion. Smart systems should also be installed once and run for long periods with minimum requirements on maintenance. It is thus possible to develop sensors or systems that charge or power themselves using for example ventilation (that is using temperature gradient and or air velocity differences). The following chapter details the methodology for developing a plausible conceptual smart system for rock-engineering. This smart system is described in Chapter 6.

5 METHODOLOGY

Describing how the conceptual smart rock engineering system was developed and how the VibraTech case study was done including instrumentation used, instrument set up, setting of threshold limits and data analysis

5.1 Introduction

The preceding chapters (Chapter 2, 3 and 4) have described rock engineering risks and their mitigation strategies, technologies used to manage risk in surface mining, civil and petroleum engineering and limitations on current systems being developed for underground mining. In this project a conceptual system for underground mining that addresses these limitations was developed. A methodology for developing a plausible smart rock engineering system is described in this chapter. The approach to such methodology description looks at leading practices in smart systems for monitoring structures as described in surface mining, civil and petroleum engineering. Sources of data, research questions, observations made, and ways of analysing data are also described. A brief background of the problem and factors that have an influence to the development of a smart rock engineering system and the case study are identified and discussed.

5.2 A brief background to the problem

The creation of excavations underground, causes instability of rock mass which may have been subjected to extensive folding, faulting and metamorphism. A number of strategies including good mining practice and good support installation are used to control the area or size of unstable rock mass. However, their efficiency in controlling unstable ground is limited as they largely depend on the miner and their experience in a particular mining environment. Rock engineering risks thus remain within an

underground mining environment and in order to reduce and eliminate such risks, monitoring and smart strategies need to be introduced. A number of systems and technologies have been developed in surface mining, civil and petroleum engineering to manage risks in these areas. Examples include digital photogrammetry, robotic total stations, global positioning system, global analyser, sensing skin and microwave radiometers. From these systems a number of attributes can be used to the benefit of managing risk in underground mining environment. These attributes include:

- Ability of systems and technologies to work in real time;
- Automated response operations for example in oil spill management;
- Wireless system;
- Alarms being alerted to all stakeholders; and
- Systems that can work in all kinds of weather;

Following these attributes extensive work is being done to develop similar systems for underground mining. Such work includes the development of AziSA system, smart bolts and smart loggers, telltale system and rockwatch robot. These systems however, do not monitor all the rock engineering parameters using one system. An example is the telltale system that monitors deformation and the subsurface profiler that monitors or checks the presence of weak planes in the surrounding rock. It is thus prudent to develop a system that makes use of most, if not all, of the rock engineering parameters, reporting and giving alarms in real time to the miner and management. As a way to provide focus to the study, questions were formulated to aid an understanding of developing a better smart rock engineering system. These questions include:

- What must be monitored for a comprehensive rock engineering system?
- What kind of systems are currently being used to manage rock-engineering risk in deep level hard rock mines?
- How successful are such management systems in managing such risks?
- In what way can technology being used in surface mines, civil structures and petroleum engineering be used to improve rock engineering risk management system in underground mines?

– When and how must a decision be made?

The methodology used is in two parts. The first part discusses how the concept was developed and the second part describes a case study using the VibraTech system installed at the Wits Mining Institute's Digital Mine.

5.3 Conceptual Model

Conceptual model refers to the development of a conceptual smart rock engineering system for real time decision making and risk minimization. This conceptual system is rather an "ideal system" where every parameter is measured and reported in real time and decisions are automated. The development used an approach that looked at leading practices in smart systems for monitoring structures in surface mining, civil and petroleum engineering. From these systems, principles of operation and their functionalities were discussed. Extensive information was gathered from existing practices on rock engineering risk management systems in underground mining. These practices were analysed, and their capabilities and limitations documented. The analysis of existing systems identified functionality gaps and gave ideas for the development of a smart system. The approach to developing the smart system looked at the needs of the hard rock deep level mining, desired features on the smart rock engineering system through literature survey.

5.3.1 Needs assessment

The primary goal of the research was to develop a smart rock engineering system for real time decision making and risk minimisation in deep level hard rock narrow reef mining. In this mining environment, safety is a key element to profitable mining. In order to keep a high safety record (a record with no incidents or accidents and if any, they ought to be injury and fatality free, or with minimum loss of production or equipment), a needs assessment was done. Personal communication, brainstorming sessions with the Digi Mine group, observations from VibraTech system was done as

a way of gathering information on the rock engineering needs in this mining environment. The literature review done identified types of risks and areas where such risks occur. Existing risk mitigation strategies were identified from literature primarily from projects conducted by Council for Scientific and Industrial Research (CSIR), Southern African Institute of Mining and Metallurgy (SAIMM) journals and personal experience of the researcher within the mining industry.

5.3.2 Data collection and preparation

Data for the development of the smart system was obtained by studying smart systems in surface mining and civil engineering work. An additional study of petroleum engineering risk management was done despite being in a "non-rock" related environment. The motivation to look at petroleum was because of the advanced technologies that are being used in mitigating risks in oil and gas industry. Functionalities, features, system components and the limitations of such systems were listed. Systems and technologies that are being developed for underground mining were identified from leading mining support and monitoring technology company websites, brochures and case studies done using such technologies where available.

5.3.3 System development

The development of the smart rock engineering system combined needs assessment results, attributes of smart systems from surface mining, civil engineering, and petroleum engineering. The development also looked at the limitations of current work for rock engineering risk management in underground mines. For this particular study, expected functionalities were first identified through discussions with Digi Mine researchers, specialists in rock mechanics within the School of Mining Engineering at the University of Witwatersrand and colleagues working in the rock engineering departments in different mines. These discussions pointed out that despite, having developed the conceptual system, the VibraTech system needs to be tested against the conceptual system developed for comparison purposes and improvement purposes.

5.4 VibraTech System Test

The conceptual system developed was used as an ideal system to which the VibraTech system was compared to. VibraTech system is a geotechnical monitoring system installed in the Wits Mining Institute's Digital Mining Laboratory. The testing of such a system aimed at improving monitoring technologies within the Digital Mining Laboratory. The setup and system description of VibraTech are described in the following subsections.

5.4.1 Concept and theory of operation

The monitoring concept of VibraTech system is based on point to multipoint Wi-Fi network designed specifically for the project (Hinkle, 2017). A central computer with a software package remotely communicates via Wi-Fi with a number of data collection nodes (data loggers) at each monitoring station. Data collection nodes were installed in the mock tunnel (located in the basement of Chamber of Mines building), 2nd floor postgraduate (PG) office and on the roof of the same building. Each station has a data logger to ensure that data is stored and preserved in the event of Wi-Fi interruption or any communication interruption (Hinkle, 2017). In addition, these data loggers can operate as standalone station servers which can be remotely operated and programmed. The system consists of a central computer with dedicated software, data collection nodes, Wi-Fi communication module and sensors.

5.4.2 System description

Central PC and Software

The whole remote monitoring system and operation was designed around the central computer, located at the Wits Mining Institute's Digital mine control room making the central computer a critical component of the system. Figure 5-1 shows the central computer within the control room. The computer is connected to a dedicated Wits

“Mine Tunnel” Wi-Fi network designed for VibraTech system. Logger Net software package was installed on the central computer.



Figure 5-1 Central computer

This software package consists of programs used to run data loggers, create remote network, download data from remote data logger nodes, build data base, create customised data plots and graphics and hosting web pages (Hinkle, 2017). The principle of operation of the VibraTech system is such that all the nodes transmit data back to the central computer which runs the data acquisition software. The data acquisition software compiles and builds a database. The data is presented through a project website as shown in Figure 5-2. The project website was designed in a way that it is accessible with a password outside the control room. In addition to data presentation, the software allows email alarm notification and web page visuals as shown in Figure 5-2. The software also allows customization of the number of web pages, alarms and sensors that can work in the system.

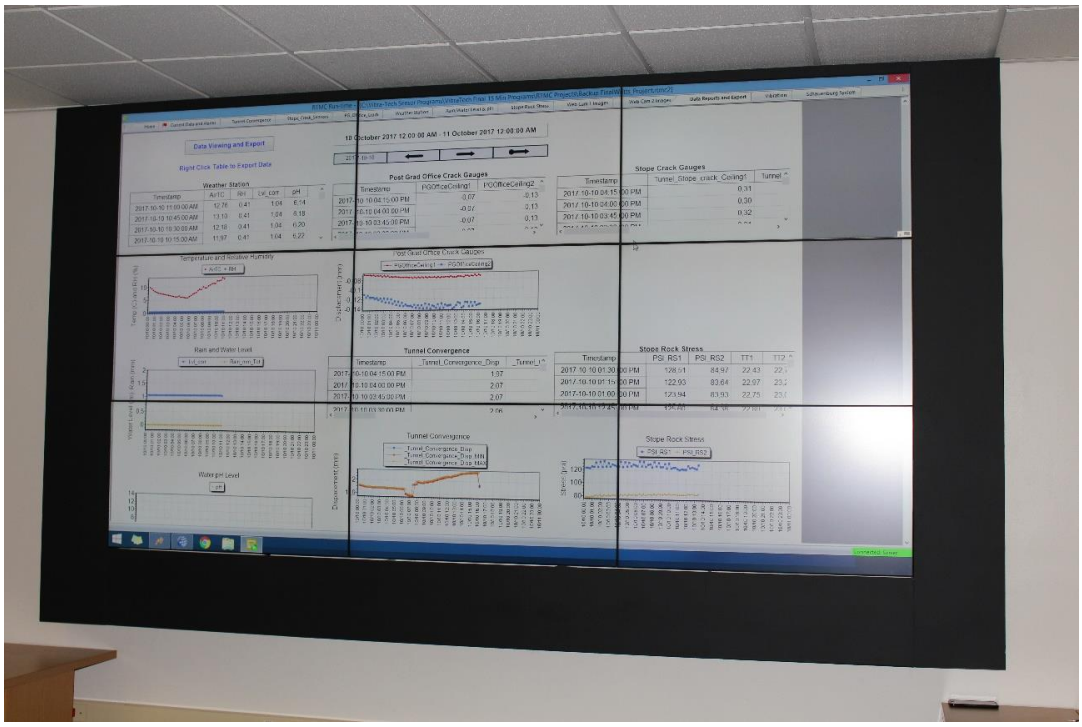


Figure 5-2 Project Website showing collected data

Data Collection Nodes

Data collection nodes consist of a multichannel data logger shown in Figure 5-3 and Wi-Fi radio contained within a fibreglass enclosure. These nodes collect and store data from the sensors and transmit data to the central computer.

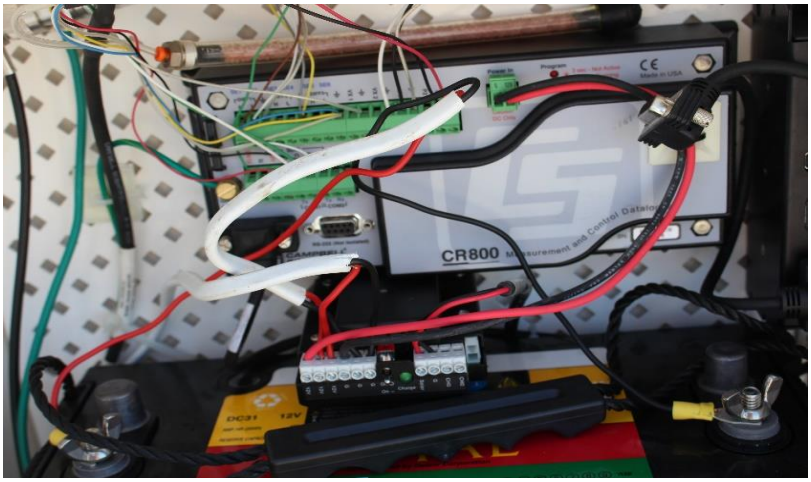


Figure 5-3 Multichannel data logger

A Wi-Fi communication module, shown in Figure 5-4, provides Wi-Fi connectivity to the data loggers for each node.



Figure 5-4 Wi-Fi communication module (Campbell Scientific, 2017a)

Nine nodes were installed for the project. Four of these nodes measure data from vibrating wire sensing instruments, which are crack meters, rock stress meter and convergence meter. Two nodes were configured to capture images and videos from two web cameras. Two other nodes were integrated with seismographs and the last node was connected to the weather station. Each node is powered by a 12V, 100Ah battery with an integrated alternating current (AC) charging circuit and plug. A power budget for the nodes was calculated based on the total current drawn. With this power budget, each node runs for at least 30 days with data measurement and collection interval of every 15 minutes before another charge is required. The weather station and roof seismograph were equipped with 20W solar panels and charge control units for continuous operation.

Sensors and Sensor Set up

Nine sensors were installed for the project. These include:

- Crack meters;
    - Four (4) Geokon Model 4420VW crack meters were installed.

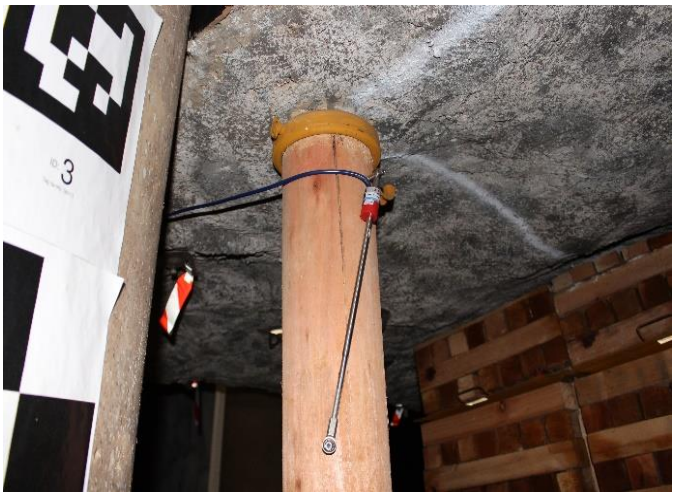


Figure 5-5 Crack meter

- Two (2) crack meters were installed in the second floor PG office over two existing cracks in the concrete ceiling. Two other crack meters were installed in the mock mine; one along a crack in stope support (pole in Figure 5-5) and another across a control joint on the concrete ceiling outside the stope.
- The crack meters, have a total measurement range of 50mm. The crack meters were extended to an approximate midrange point of 25mm and bolted over the crack. The initial reading from the crack meters was used as a zero point to compare all future readings. This provided a range of 25mm in crack expansion and 25mm in crack contraction.

– convergence meter;

- One (1) convergence meter (Geokon Model 4425VW), shown in Figure 5-6, was installed in the mock tunnel spanning the width of the tunnel closer to the hanging wall. The measurement range of the convergence meter is 100mm. The convergence meter was pulled to a midrange of 50mm and bolted in place giving a 50mm range for convergence and divergence.



Figure 5-6 Convergence meter

- stress meter;
    - Two (2) Geokon Model 4300 1EX-5 stress meters were installed, as shown in Figure 5-7.
    - One of the stress meters was installed inside a support unit (wooden pole) and another inside a block of sandstone located close to the stope area.
    - Both stress meters were preloaded and zeroed.
    - 

Figure 5-7 Stress meter

- The range in stress measurement is -3MPa to +70MPa, representing a tension of 3MPa and a compression of 70MPa.

– web cameras;
  - Two (2) Campbell Scientific Instrumentation Model CC5MPX Web Cameras, shown in Figure 5-8, were installed to capture still and video images.



Figure 5-8 Web Camera (Campbell Scientific, 2017b)

  - One camera was installed close to the mock mine tunnel entrance and the other was installed on the roof facing the weather station and seismic sensors.
  - The cameras capture still images (up to 5 megapixels) every hour.

– Temperature, Relative humidity sensor and Rain gauge;
  - A Rontronic Model HC2S3 temperature and relative humidity sensor (Figure 5-9) was installed on the Chamber of Mines building roof.
  - Humidity sensor measures relative humidity for a range of 0% to 100%, and temperature range is -40^{o}C to 100^{o}C



Figure 5-9 Temperature and Relative humidity sensor

- The rain gauge is a Texas Electronics Model TE525USW rain gauge. Figure 5-9 shows:
    - An opening at the top of the device allows rain to be funnelled into a small tipping bucket.
    - Once the bucket is full, a switch is closed which makes it possible to measure the amount of rainfall.
- Water level;
    - A Campbell Scientific Model CS451 water level sensor (Figure 5-10), was installed on the roof of the Chamber of Mines building.



Figure 5-10 Water level sensor (Campbell Scientific, 2017c)

- This sensor is a pressure transducer for water level measurements with a measurement time less than 1.5 seconds.
- The operating temperature range is 0^{o}C to 60^{o}C

– pH sensor; and
  - Campbell Scientific CS526 pH sensor (Figure 5-11) was installed on the roof of the building to measure the pH of water in the column for rain gauge.



Figure 5-11 pH Sensor (Campbell Scientific, 2017d)

  - The measured pH range is from 2 to 12
  - Operating temperature ranges from 10^{o}C to 40^{o}C

– Seismographs
  - Two (2) Geosonics Model 3000LC seismographs were installed. One on the roof and one in the mock mine close to the stoping area for measuring ground vibration. Figure 5-12 shows the seismometer and data logger in the mock mine.
  - Seismographs were used to measure vibration
  - These seismographs are originally designed to monitor blast vibrations which lie in the high frequency events like rock bursts in underground deep level mines.
  - The seismographs work with an advanced *Seismic Analysis* software which was installed on the central computer in the control room.
  - This *Seismic Analysis* software is integrated with the VibraTech system through the developed customised website.



Figure 5-12 Seismograph and data logger

- This integration is limited to a link (a tab named VibraTech on the Website). Detailed results are shown when the link is selected.
- An integration (one that shows results instead of a link) is currently being developed.

Creating remote node network

Using the device configuration program with Logger Net, each Wi-Fi radio was configured and joined to the Wits “Mine Tunnel” Wi-Fi network. In order to ensure direct and consistent communication among all nodes, a range of static IP addresses was provided. Each node (Wi-Fi radio) in the system was assigned a specific static IP address.

5.4.3 Instrument calibration

The crack meter, convergence meter, stress meter, seismographs, rain gauge, water level, temperature and humidity sensors had their calibration up to date as, the

Vibratech team visited the site in January 2016 and August 2017 making sure that all instrumentations are in order and well calibrated.

5.4.4 Setting of thresholds (alarm levels)

Seismographs

The potential to cause damage to buildings is most closely correlated with the Peak Particle Velocity (PPV). Humans can perceive ground vibration at levels as low as 0.8 mm/s, far lower than the level of vibration that will damage even the most fragile structures (Durrheim, 2017). Perceptible vibrations, for walking, jumping, and slamming the door are 0.8mm/s, 7.1mm/s and 12.7mm/s respectively (Durrheim, 2017). Minor damages to buildings occur at 10 mm/s, while severe building occur when PPVs exceed 200 mm/s (Durrheim, 2017). Seismographs installed in Digital Mine Laboratory have a monitoring amplitude range of 0.5mm/s to 130 mm/s. Normal movement (walking in and around the tunnel) produced a maximum PPV of 1mm/s. An arbitrary minimum threshold of 2mm/s was set to ensure that most events that may be perceived are detected and to avoid triggering false alarms due to normal movement in the Digital Mine Laboratory.

Convergence meter and Crack meter

Due to movement of people, equipment and material in the tunnel, measuring of closure (convergence) for hanging wall and foot wall was practically difficult, as there was a high risk of the convergence meter being tampered with. As such the convergence meter was installed across a tunnel (sidewall to sidewall), to measure closure for the sidewalls. Convergence values of -2mm (compression) or +2mm (tension) were suggested as a start, based on structural monitoring results in civil engineering (Durrheim, 2017). Based on the same results in civil engineering Durrheim (2017) suggested similar thresholds for crack meters (Hinkle, 2017). The recorded values after installation would suggest a movement in the tunnel and would be referenced to the initial values for further analysis.

Stress meter



Figure 5-13 Loaded concrete block with stress meter installed inside the block

The presence and magnitude of stresses in deep level excavations is largely the main factor that contributes to seismicity and related falls of grounds. Magnitudes of virgin stress greater than 60MPa (Jager and Ryder, 1999) have been recorded in these deep level excavations. Stress acting on support units and concrete block was arbitrarily set at 0.34MPa (this assumes that the building is 18m, acceleration due gravity is 10m/s^2 and the density of concrete used is 1.9t/m^3 and that the total weight of the building acts on the concrete block and or the support installed in the stope) No stress simulations were done on the support unit due to its location in the model stope. Sand bags were used to add the load onto the concrete block for test purposes as shown in Figure 5-13.

pH meter

The average pH for water with limited effects is 6.5 to 8.5. pH values less than 6.5 are acidic and greater than 8.5 are alkaline. The influence of water pH on intact rock strength in deep level is minimum. However, water has a detrimental effect on joint infill or fault infill material which when the pH is low or high reacts more, thus

reducing joint strength and subsequently rock mass strength. A threshold that spans from 6.5 to 8.5 was set. However, in this environment the pH of rainwater is not expected to be out of this range and set up of pH meter is rather to test functionality of the sensor within the whole system.

Temperature and humidity sensor

Section 9(2).2b of The Mine and Health and Safety Act of 1996 states that, "*The employer must establish and maintain a system of occupational hygiene measurements, as contemplated in Section 12, of all working places where the following hazard limits prevail:*

(b) Thermal stress

i. heat >25.0°C wet bulb and/or >32.0°C dry bulb and/or >32.0°C mean radiant temperature; and

ii. cold <10.0 °C equivalent chill temperature"

The threshold values set for the project were <10°*C* (considered cold) and >25°*C* (considered hot) due to the location of the sensor (on the roof). This location alerts the temperature and humidity outside the building. Humidity threshold was set at an average of 50% as any values below causes a risk of sinusitis (CONTEG, 2013).

Rain gauge

The average rainfall for Johannesburg area is approximately 600mm per year with the lowest in July at 0mm and highest in January at 113mm (South African Explorer, 2017). Huge quantities of rain have an effect on geological structure properties and they pose a large risk on mine flooding. A threshold of 55mm was set for rain gauge values as it is the median value.

Water level

The presence of water has a deleterious effect on the strength of rock mass as it acts on joint and fault infill material. Prolonged accumulations of water increase the risk of acid mine drainage in old workings. Given enough bulkhead, water pressure may add

to local stresses thus aiding to local seismicity. The level of water thus need to be kept to a minimum. Water level threshold for the project was set to be 1m being measured in a column located on the roof. The setting at 1m was random. The presence of a water level meter aids to test the functionality of the sensor as a component of the whole system.

5.4.5 Data collection, preparation and analysis

The design of the VibraTech system is such that data is collected (extracted from data logger) autonomously from each sensor at intervals of 15 minutes to the control room central computer where it is displayed on the video wall. The presentation of data is through graphs custom built for each sensor, excluding seismographs, and a tab showing if threshold values have been exceeded. Seismic Analysis software is used to analyse and display data from seismographs. The extraction of data from seismographs was set at 15 minutes and a log file is created that shows communication between logger and the seismometer. A time period of 15 minutes was set because the software and system cannot check for new data and transfer at the same time. Using 15-minute intervals kept the transfer time very low. An earthquake that happened on the 3rd of April 2017, called the Botswana earthquake, is a critical event that forms a major part of the research. This is largely because, the event is a natural event which simulates underground mining seismic events.

5.4.6 Assumptions

During data collection, preparation and analysis, the following assumptions were made:

- The mock mine is a representation of underground mining;
- The model stope with timber, pack and mechanical prop support is a representation of a stope;

- Thresholds for triggering alarms for temperature, humidity, water level represent conditions of underground mining environment despite the sensors being on the roof;
- The Botswanan earthquake that happened on the 3rd of April 2017 was taken as surface event and an induced underground seismic event;
- Cracks in ceiling of the Post Graduate office and concrete ceiling in the mock mine represent geological discontinuities; and
- The concrete block where one of the stress meters was installed represents a pillar where extra bags loaded represent additional loading to the pillar as mining progresses

5.5 Conclusions

This chapter described the way in which a conceptual smart rock engineering system was developed and how the VibraTech system case study was done. It is evident that developing a concept requires looking at the needs (or the problem), similar systems in other areas and leading technologies. Once developed, testing the functionality of such a system is required and this is done through case studies. Such testing ensures that an analysis can be done to improve system effectiveness and functionality. Using this approach, an analysis was done on the VibraTech system as a way to find areas where improvement can be implemented. The next chapter describes in detail the conceptual smart rock engineering system while Chapter 7 presents the results and analysis of the case study.

6 SMART ROCK-ENGINEERING SYSTEM

Conceptualising a smart rock-engineering system for real time decision-making and risk minimization in deep-level hard rock mines

6.1 Introduction

The description of the mining environment, associated rock-engineering hazards, risks and risk management strategies were discussed in Chapter 2. This chapter identified that existing strategies do not address all the risks adequately and as such, looking at how risk is managed in other areas is beneficial to addressing residual rock-engineering risks in deep level mining. Chapter 3 considered technologies used in risk management for open pit mining, civil engineering and petroleum engineering in finding technologies and systems that can be used or manipulated for underground mining rock-engineering risk management. The working principles and functionalities of technologies and systems currently being developed were described in Chapter 4. These systems and technologies have limitations, and some have not yet been tested for their full functionalities. In this chapter, a conceptual smart rock-engineering system is described. This system consolidates the needs as highlighted in Chapter 2, the attributes of systems working in open pit, civil engineering and petroleum engineering, and addresses the gaps that current technologies for underground mining have. The development of such a conceptual system considers future technology advancements that can be incorporated in the standard way of addressing rock-engineering risk. The following aspects were considered during concept development;

- The mining environment and existing infrastructures;
- System requirements and data acquisition technologies;
- Data integration for decision-making and system self-check;
- Tolerance levels and standard operating procedures for determined tolerance levels;

- Risk map generation and automated alarms and decisions; and
- Smart evacuation system.

6.2 Concept Development

A concept is defined as an abstract idea or a building block of a person's thoughts where thoughts are constructed from experience and improvement of existing ideas (Merriam-Webster, 2017). Concept development or conceptualization refers to the process in which the building blocks can be translated into variables that can be tested or observations that can be made. According to O'Shaughnessy and Sturges (1991), conceptualization starts with listing several questions and ends with a document of detailed specifications. O'Shaughnessy and Sturges (1991) further mention that time, resources, market, technology, and design evolution affect the way in which conceptualization is done. As such, concept development is a never-ending process. Factors considered in conceptualization include system safety, design capability, availability of raw materials, time to develop and test the concept, any related costs to such development and impact on existing and future research and development (Chetal et al, n.d).

The developed concept aims at creating a real time rock engineering system that allows smart decisions to be taken and initiates evacuation systems where necessary. Such a system development is driven by several factors which include:

- An increased pressure across the mining industry to improve on safety and production. Such improvement demands better data and information acquisition facilitating better decisions to be made. The acquisition process inherently offers accountability and transparency to such a system;
- Increased advancement in computerised mining which if the South African industry does not take part of, it becomes a recipient of rules written elsewhere for computerised mining rather than the one to write the rules. The use of computerised mining has a possibility of improving safety and the generation

that is currently being employed is technology savvy, making it easier to implement such smart system;

The success of a smart rock engineering system depends on a well-crafted conceptual design with given set of specifications including what a system ought to do and what the system is not capable of doing and the ability of system to produce auditable files that at least meet the minimum legal requirements. These are further explained as what the system needs and the desired attributes.

6.3 Needs and Desired System Attributes

As mines get deeper, rock engineering problems have increased and the flow of information from current mining faces to the miner in the stope and to surface offices has become critical to the productivity of deep level underground mines. The demand for systems that are able to record, support and communicate any recorded measurements has increased significantly. To effectively manage rock engineering related risks, the flow of information from current mining faces to the miner in the stope and to surface or to responsible rock engineering personnel need to occur in real time. This suggests that data flow is time stamped which assists in analysing risks, as rock engineering risk evolves over time. The development of a smart rock engineering system uses an approach that looks at the needs (what kind of risks that need to be managed, where do we find these risks), and desired system attributes (what the system ought to have and do).

6.3.1 Needs to be addressed

The needs to be addressed were described through the environment in which a smart rock engineering is being developed as discussed in Chapter 2. In addition, hazards and risks associated with such mining environment, and risk management strategies are also described in the same chapter. The needs are thus risks that need to be managed

and the areas where such risks are found. Areas in the underground mining environment that were found to have higher risks include:

- Areas in close proximity to major geological discontinuities and areas where there is a sudden decrease in rock mass quality;
- Face area, where current mining activities are taking place. This is the critical area as miners are working in such areas and any protective measures put in place attempt to first address risk in these areas;
- Old and abandoned areas, especially where there is a possibility of being re accessed. In these areas, there is increased risk of support deterioration be it pillars or tendon support;
- Abutments and pillars. These areas have increased stress levels and prone to seismicity;
- Areas where there is accumulation of water;

The list of hazards provided results in certain parameters being able to be monitored. A list of parameters classified according to their areas is shown in Figure 6-1 (Ali, 2014). The hazards and risks associated in such areas include:

- Water and its influence on rock mass properties;
- Blasting effects, rapid closure rates, high face stresses, pillar failure and abutment failure
- Inadequate or unknown geological boundaries;
- Pillar dimensions and excavation dimensions variation,
- Strength and elastic properties of rocks and their values and distributions;
- Spacings, shear strengths, orientations and persistence of joint sets;
- Support performance;
- Stress and seismicity and the relationship of the two with mining layouts

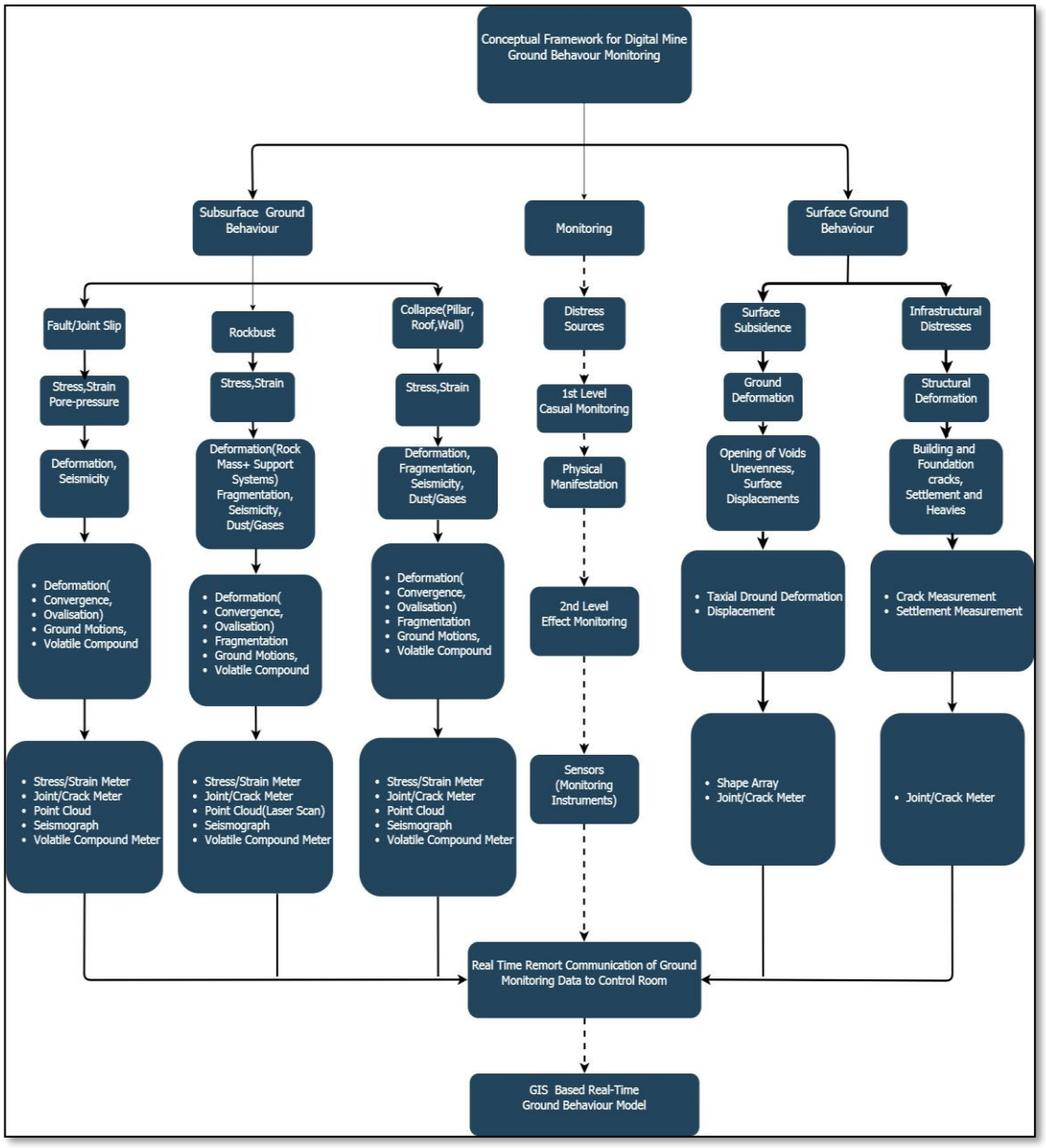


Figure 6-1 Measurable parameters (Ali, 2014)

As alluded in Chapter 2, current risk management strategies do not address fully, the hazards and risks that result from mining in an environment described in the same chapter. Systems from other areas of engineering provide possible ways in which risk can be managed using advanced technologies and systems. Such systems have desired attributes that can be used to develop a smart rock engineering system.

6.3.2 Desired system attributes

The expected capabilities and functionalities of the smart rock engineering system are defined as desired system attributes. Such attributes were derived from systems described in Chapter 3 and they include capacity, robustness, reliability, adaptability, connectivity, real time communication and real time evacuation.

Capacity

Existing mines have installed network infrastructure which need to be exhausted of its capability and extended to meet current and future demands of networks. Such design ensures that operational needs are met with minimum capital being injected into infrastructure development to meet current and future requirements. The smart rock engineering system makes use of existing infrastructure and accommodates all existing applications and deliver exceptional quality of service by allowing integration with other systems.

Robustness and reliability

Deep level mining environment comes with challenging and varying circumstances which the infrastructure described in "capacity" need to be used. The ratings for such infrastructure could be IP67 or IP68 referring to water and dust proof international protection standards. Impact from heavy machinery and increased humidity and temperatures are some of the harsh conditions that the instrumentation encounters and should be able to withstand. Even with such exposure to these conditions the sensors and associated instrumentation should be able to give correct data all the time.

Adaptability

Mining faces advance every blast and within a quarter of a financial year, extensive stopping and or tunnelling would have occurred. This means that sensors and instrumentation may need to be moved from time to time. Mining conditions also change as the faces advance. Sensors and all instrumentation need to run optimally as they are moved or once they have been relocated.

Extensibility

The smart rock engineering system should be able to be expanded and extended as and when needed (System upgrade). During such an upgrade, the system should remain online, or the system should be offline for a very short period of time only.

Connectivity

Connectivity is the most critical desired attribute. The smart rock engineering system should be connected at all times to ensure that data is send to the control room continuously. This also means that the system is required to accommodate the large number of sensors without any connection interruptions from any of the sensors. The system should also be connected to the internet to allow remote control and monitoring.

Integration

The rate at which technology is advancing is large enough to make a system redundant in a couple of years. The smart rock engineering system needs to ensure that it remains compatible with new technology and should be included by researchers in their active research drive for new technology advancement. This ensures that integration with new technology becomes easier and less capital intensive. When smart rock engineering equipment is made compatible with new technologies, system infrastructure remains virtually the same despite new sensors being installed or new software being implemented, thus reducing capital costs.

Security and prioritization

Like any other system developed, smart rock engineering system is susceptible to cyber risk especially on a mine where a number of systems are integrated to one main system. Control over access to the system and the recording of who logged and what was checked is critical as a way to manage cyber risk. The logging into such a system should be time stamped and be able to produce auditable reports that meet the minimum legislative requirements.

Agility

Smart rock engineering system needs to be simple and user friendly thus enabling automation to be implemented with minimum challenges. The simplicity of such a system need to have infrastructure that is responsive and dynamic to any changes (where need arises, a system that can be moved from one place to the other with minimum challenges. Smart rock engineering system thus need to match business agility (that is the ability of a mining company to respond to changes in the markets without deviating from the set vision and objectives). Smart rock-engineering system needs to measure and monitor the right risks in a changing underground environment)

Standardised technology architecture

The architecture of a smart rock engineering system consists of sensors, command and control unit and actioning devices as highlighted in Chapter 4. The sensors installed can power themselves and heal if they are exposed to any damage. The powering of sensors can be done using the velocity difference or pressure difference of moving air. These sensors should have limited maintenance and should last the life of the stope (stopes are mined out in months and are left redundant thereafter) or durable enough until the next generation of sensors has been developed. System should allow easy "fit in" of new technology.

Data management

The capacity of smart rock engineering system consists of a large number of sensors which send data every second to the control room. The critical processing path thus require a good data management through installing a large data base and expert systems that analyse data. Although a database requires "a disk write of a log record", thus creating latency issues, a "straight through" processing of data can be used (Stonebraker et al, n.d). The "straight through" processing of data, should be integrated with the data base so that the present can be compared to the past using expert systems and experience of the rock engineering personnel.

Alerts

Following measurements that are above the set threshold, real time alerts in form of automated emails, phone calls, text messages, visual lights, and sirens are given. These alerts are sent to the miner within a stope and at the same time to the rock engineering personnel in charge of that particular section. Where required, alerts are sent to other departmental heads. From time to time, the inspectorate department may be alerted on major incidents. Caution should however be taken which information is allowed in the public domain.

Control room

Data processing (analysing normalities to decide on maximum tolerances) and visuals (in form of graphs, signalling lights, and geohazard maps (an example of a geohazard map being developed is shown in Figure 6-2)) are done in the control room.

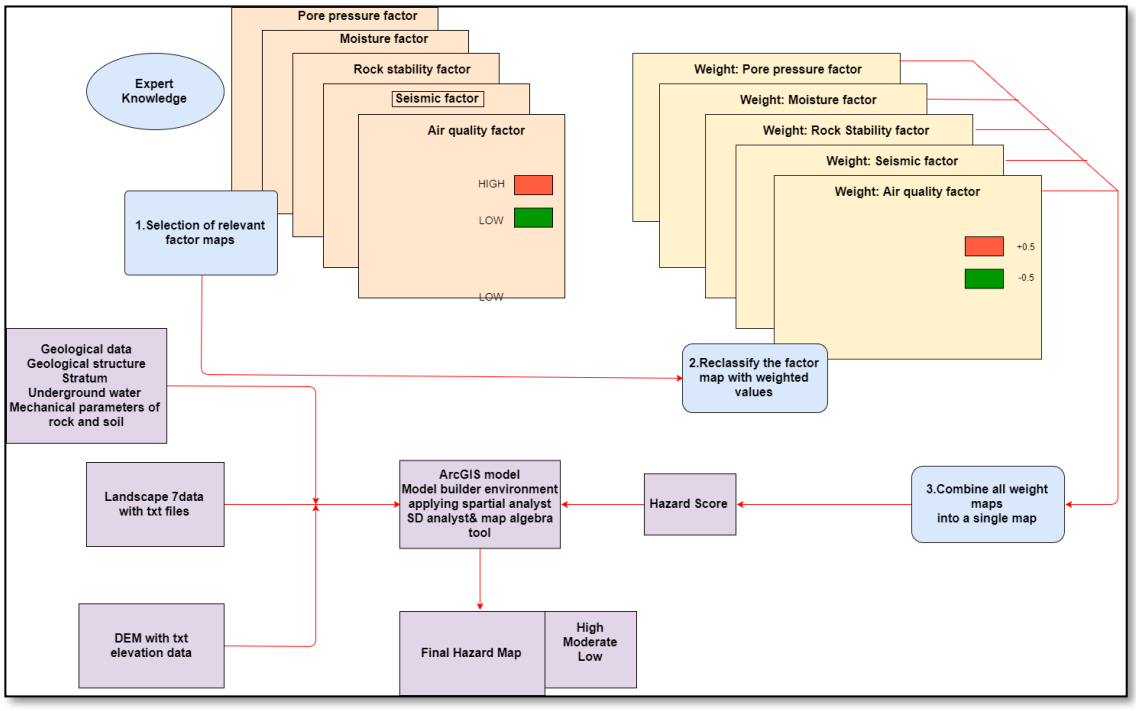


Figure 6-2 Developing a GIS geohazard map (Ali, 2014)

Communication infrastructure

Communication infrastructure required include routers, switches, firewalls, servers, wireless access points, network cables, database for software plugins, virtual private network for cloud systems. The connectivity of such components is through wireless system. Wired parts of the system are done in permanent excavations for example in the shaft.

Data required

Measurements from sensors installed include deformation (convergence, extension or ovalisation), ground motions (peak particle velocity), gases (as a percentage), load carried by a support system, fragmentation, face profile, face shape index, water level, humidity, temperature, crack expansion.

Real time evacuation

Once an alert is activated, real time evacuation system is also activated. In this system, the miner within the area, gets a message through the cap lamp, and the light emitting diodes on the support system units direct the path to a safe area, which in this case, is the refuge bay.

Decision making

The smart rock engineering system has automated dynamic decision-making capability. The rock engineering personnel oversees the decisions made by the system and where additional input is required, they adjust the decision-making process.

6.4 Conceptual Smart Rock Engineering System

The smart rock engineering system gathers data on its own and makes decisions on itself relieving the rock engineering personnel of such duties and making them have more time on other tasks. The system attempts to have more information extracted from

the data gathered rather than being “data rich and information poor”. The architecture of the system and description are described below.

6.4.1 System architecture

The smart rock engineering system is a component to the digital mine system architecture and Figure 6-3 shows the digital mine system architecture with other systems linking to it. Circled in dashed blue is the smart rock engineering system, in this case it is the Vibratech ground monitoring system. The digital mine system architecture allows a plug and play (this means that any sensor can be installed and or connected) system, to any system. The smart rock engineering system attempts to emulate this functionality. The architecture of the smart rock engineering system consists of the following components:

- Smart sensors and data loggers;
- Wireless communication system with internet access;
- Control room with servers, visual display screen and software for automated alerts; and
- Smart decision making and evacuation system.

From Figure 6-3, all the data from a Smart Rock Engineering System or Vibratech is stored in a spatial database which is accessible through the internet. Once data is sorted using data analysis tools, information is stored on a sever where it can be accessed by video analytic software for display in the control room video wall. As soon as data is received in the spatial database, processing starts and reports, and alerts are sent to responsible personnel in real time. For long-term data analysis, other institutions with access to the server, for example National University of Sciences and Technology (NUST) and China University of Mining and Technology (CUMT) can run modelling given their facilities of high-speed processing computers in attempt to find correlations of the received data and any other relevant relationships between measured parameters.

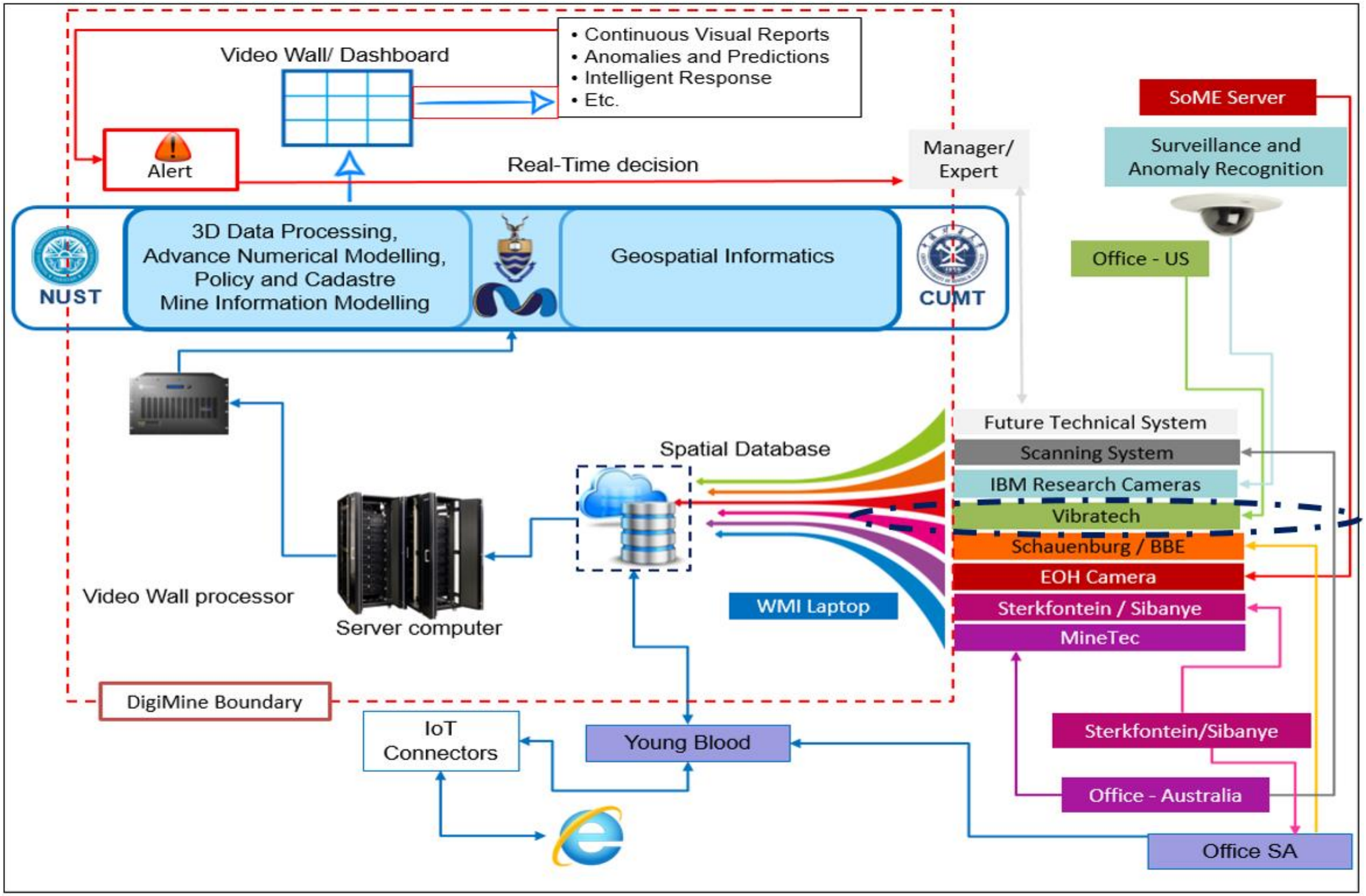


Figure 6-3 Smart rock engineering system's (Vibratech) link to a digital mine system (Wits Mining Institute, 2017)

6.4.2 System description

The smart rock engineering system shown in Figure 6-4 fits in the production process along the mining value chain. When linked to the Department of Mineral Resources (DMR), the system fits in the DMR value stream as it provides the statistics of incidents occurring in the mines creating a more accurate database for the DMR. Figure 6-4 also shows the relationship between the smart rock engineering system with other departments through their respective models. As shown in Figure 6-4, the smart rock engineering system is made up of:

- Measuring instruments and sensors;
- Servers and video wall display;
- Communication system with internet connectivity; and
- Alert systems.

The most critical key performance indicator is communication reliability and health status of sensors and other system infrastructure components. The functionalities of the system address the needs that were highlighted in Chapter 2 and fills the gaps of existing systems as highlighted in Chapter 3 and 4.

Measured Parameters, Measuring Instruments and Sensors

The parameters measured include stress, deformation, ground movement, water level, face advance, pillar dimensions, face shape, and temperature. Associated instrumentation and sensors for each parameter are:

- Stress;
    - Stress meters, smart bolts with internet of things,
- Deformation;
    - Closure meters, crack meters,
- Ground movement
    - Geophones, accelerometers, seismometers
- Water Level;
    - Piezometer
- Temperature;
    - Thermal Imaging, Thermometer

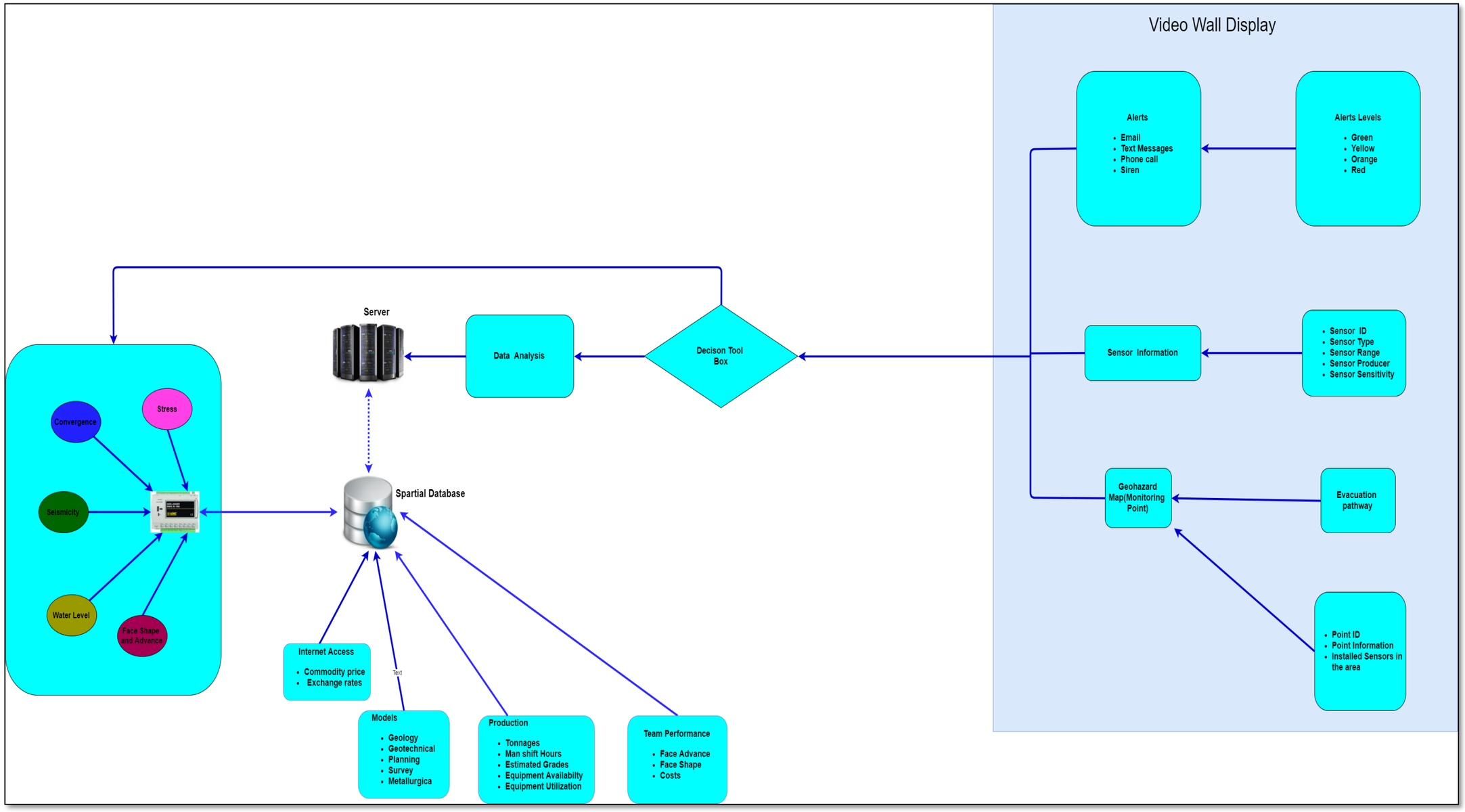


Figure 6-4 Conceptual Smart Rock Engineering System

- Face advance and face shape
    - Laser scanners
- Rainfall
    - Rain gauge

Smart rock engineering system works with sensors and instrumentation that have certain properties derived from Chapter 3 and 4, where systems in other areas were discussed. These properties include:

- They use wireless communication system to send data from one point to the other;
- They have electrical power that last for a life time (they can power themselves);
- They require minimum to no maintenance at all;
- They are easy to install and inexpensive, robust, and light in weight;
- They can be tracked of their geographical position and can connect to internet;
- They can sense over distance because of the dynamic mining environment;
- They can provide the health status of itself and other sensors in the system;
- They can communicate by sending a message to the miner's cap lamp
- They can activate a safe path of travelling away from the danger;
- Thy are able to detect a lagging face and a missing installed support unit;
- The support system units are able to sense and when damaged, heal themselves similar to what the human being skin can do;
- They can temporarily store and process data before sending it.

Database and Models

The smart rock engineering system creates large quantities of data which are stored in a local server and backed up remotely and over the internet. Security measures are as described in section 6.3.2. The database also serves as a link to the geological, geotechnical, mine planning, and metallurgical models. Based on current information available, the geology, geotechnical, mine planning and metallurgical models are updated in real time.

Internet connectivity and Production tonnages

The system can be remotely accessed via an internet connection. Data relating to metal or commodity prices and exchange rates can be pulled out. Specific algorithms that make use of such data and production tonnages are used to calculate and show the performance of the company. The effects of rock engineering parameters being measured by the system are considered by such algorithms.

Decision Tool Box

The decision maker in the smart rock engineering system is the decision tool box (DTB). Using received data from all the sensors, the DTB analyses the data and decides which information is critical to put on the visual display, which kind of alert should be initiated, which kind of message should be sent to the miner, what kind of action is required from all the stakeholders.

Alert System

Alerts are given in form of a siren and flashing amber or red lights in the area where danger is imminent. Emails, phone calls and text messages are sent to all stakeholders in real time. Different levels of thresholds activate different alerts and different action plans. These alerts and false alarms as a result of faulty or tempered instruments are managed by the responsible manager(s) who ensure that the data and decisions are correct, and the action plans made are appropriate. Communication of action plans and how they are executed is facilitated by an up and down line of command that enables acknowledgement by manager (s).

- Green;
    - This type of alert signifies normal operations and scheduled information review and checks will be done as and when the standard operating procedures determine. For example,
        - When there are no values above the thresholds and the system is working properly;

        - When a value exceeds the threshold, but a quick investigation shows that it is a result of instrument error or damaged sensor; and
        - When the trends show that the values are within acceptable limits by the rock engineering personnel.
    - A summarised report is given, and no additional notifications are sent to the responsible geotechnical personnel.

– Yellow;

    - This type of alert is activated when a number of sensors for the same parameter shows systematic deviation from the threshold value. The deviation measured indicates a possible movement of ground;
    - Once the system observes such, an automated phone call is made to the rock engineering personnel responsible for that section. Automated reports on a weekly or daily basis are produced and send to the responsible personnel until the values are below the thresholds;
    - The system automatically changes the frequency of data acquisition and reviewing collected data.

– Amber; and

    - When the system detects an acceleration in the values being measured, an amber alert is activated. The accelerated measurements indicate a possible future failure.
    - An automated call is made to the responsible rock engineering personnel and the miners are alerted through flashing red lights on their cap lamps or automated call through headphones or earmuffs and those outside the affected area are notified through preprogramed messages that can appear on their cap lamp battery pack.

- Evacuation preparations are made according to the emergency preparedness and response plan procedures in place.
- Due to the number of people being notified, the rock engineering personnel need to verify the status, as misdiagnosis may lead to wasted production time and unnecessary delays.

– Red

- Red alert signifies that danger is imminent and evacuation within the affected areas has to be done immediately.
- Automated calls, text messages, emails are sent to the rock engineering managers, miners in sections and other departmental heads respectively.
- The way to the refuge bay is activated through flashing LED lights and where miners gather waiting for further instructions.
- Detailed reports are automatically sent to the rock engineering manager for further analysis before being circulated.

Evacuation System

Once an alert has been activated, the miner and his/her crew follow a designated path to a refuge bay. The designated path directs the miners through a safe area as shown by green flashing LED lights from smart bolts. Once in the refuge bay, conventional means of communication are used.

Output parameters

Measured and processed data from all the sensors is shown graphically on a real time information dashboard on the video wall display. As an example, Figure 6-5 shows a typical GIS based real time dashboard for WMI Digital Mine (Opiti, 2017). In each case, where a threshold has been exceeded, an automated report is created. This report addresses the minimum legislative requirements for that particular data.

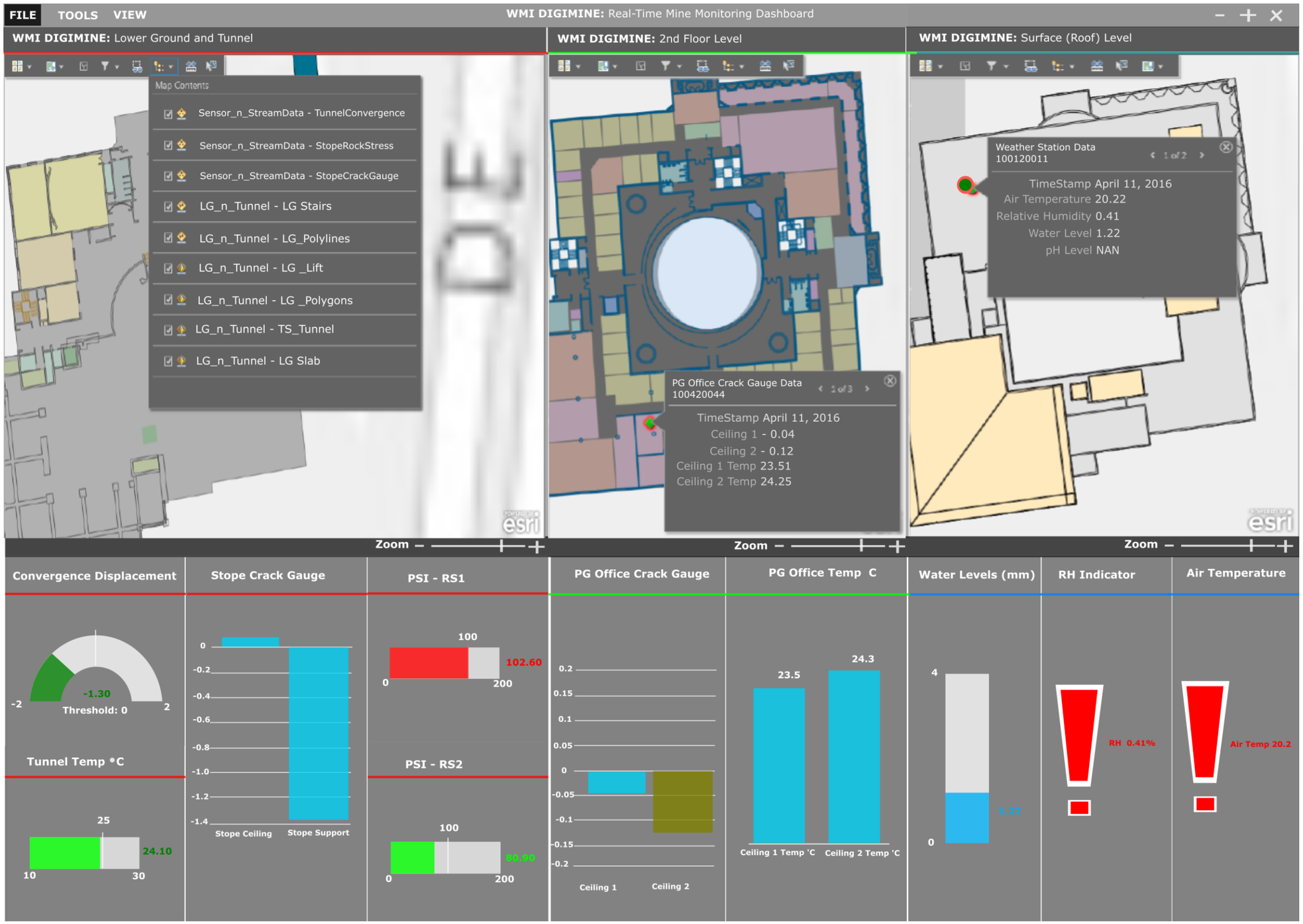


Figure 6-5 Typical real time dashboard screen (Opiti, 2017)

6.4.3 Constructability and implementation

The environment to which the smart rock engineering system is implemented is a harsh environment that requires robust, reliable, maintenance free sensors and associated instrumentation. This environment also demands an easy and safe to install system as it is more important to have a simple but working system rather than a complex system with a “fatal flaw”. Bieniawski (1992) described the six principles of design and one of the principles is constructability. Constructability refers to the easiness, safe and efficient implementation of the developed system (Bieniawski, 1992). The sensors and instrumentation available currently in the market, do not possess all the desired attributes. These attributes are largely on availability of power, hence powering using batteries similar to the ones used in smart bolts is proposed as a start, as it is more practical.

The use of wireless communication for all the sensors and instrumentation is possible, although numerous network points will be required underground. It is feasible to use wireless communication from surface control room, down the shaft to the shaft station, through permanent haulages into the sections, but, it has been noted by Malan et al (2000) that a clear line of sight cannot be guaranteed. This line of sight is blocked by rock movement in a stope and support elements. Furthermore, the extent of road networks in underground mines stretch for several kilometres making the installation to be challenging and expensive if not well planned. Connectivity of other systems to the smart rock engineering system is governed by the smart rock engineering system specifications. These specifications require other systems to have smart sensors, smart data loggers and wireless communication from the sensors to the control room. The specifications further require simple integration of results. As an example, integrating the Schaunberg system with the smart rock engineering system is only on the user interface where the location of miners provided by Schaunberg is shown on the hazard map displayed by the smart rock engineering system. The different softwares run independently and data is integrated on the server for further analysis and display.

6.5 Conclusions

The conceptual smart rock engineering system is made up of sensors, communication system, data processing, analysing, alerting and an evacuation system. The development of such a system is a continuous process as new information is received continuously, and the understanding of ground movement behaviour can change rapidly. A number of factors are considered during the design of smart rock engineering system. These factors include level of safety the system can bring and cost of developing a smart system. The smart rock engineering system described uses sensors that can power themselves for a lifetime and communicate wirelessly with data loggers and the control room. The location of sensors is largely in areas where there is active mining and areas where residual risk is high. These areas include face area, abutments, pillars, excavations used for services such as pump chambers and areas close to major geological discontinuities. The sensors measure stress, deformation, water level, face advance and shape, temperature and ground movement.

The data obtained from such measurements is processed to give auditable files and to give warning to the miner of any impending danger. A decision tool box, forms part of the smart system as it processes, analyses and decides on the appropriate action without any intervention from the rock engineering personnel. This reduces the amount of time such personnel have to oversee the system and concentrate on other tasks. The development of a smart rock engineering system enables further development into areal support systems that can sense, heal (when damaged), and act as a heat insulator. This development is a contributor to the mine of the future, termed “smart mine”, where any system can be added using “plug and play” functionalities. The conceptual system developed is compared to the Vibratech’s system installed at WMI Digital Mine laboratory in the next chapter.

7 CASE STUDY: VIBRATECH SYSTEM, BOTSWANA EARTHQUAKE AND FINDINGS FROM SOUTH AFRICAN GOLD MINES

To run a complete system test using the Vibratech Ground Monitoring System as a case study in comparison to the conceptual smart rock-engineering system

7.1 Introduction

Chapter 6 elaborates on the development of a conceptual smart rock-engineering system. The system developed aims to send data in real-time from the sensors to the control room and having the decision returned to the miner for an appropriate action plan. The sensors and other system components use wireless communication. In this chapter, a case study was done using Vibratech ground monitoring system to demonstrate some if not all, functionalities described in Chapter 6. An earthquake that happened on the 3rd of April 2017 in Botswana, is a critical natural event that some of sensors within the Vibratech system recorded. The results from such recording were analysed to find possible measures of improving system performance. Current rock engineering risk management practices in South African gold mines are described.

7.2 Vibratech Monitoring System

Vibratech is a ground monitoring system, installed in the Digital Mine laboratory. The system consists of stress meters, crack meters, seismometers, weather station, extensometers and web cameras. The connection of loggers to the control room is a wireless system while sensors are connected to the data loggers using cables. The working principle of the system was described in Chapter 5, Section 5.4. Figure 7-1 shows the architecture of the VibraTech ground monitoring system as installed in the Digital Mine Laboratory.

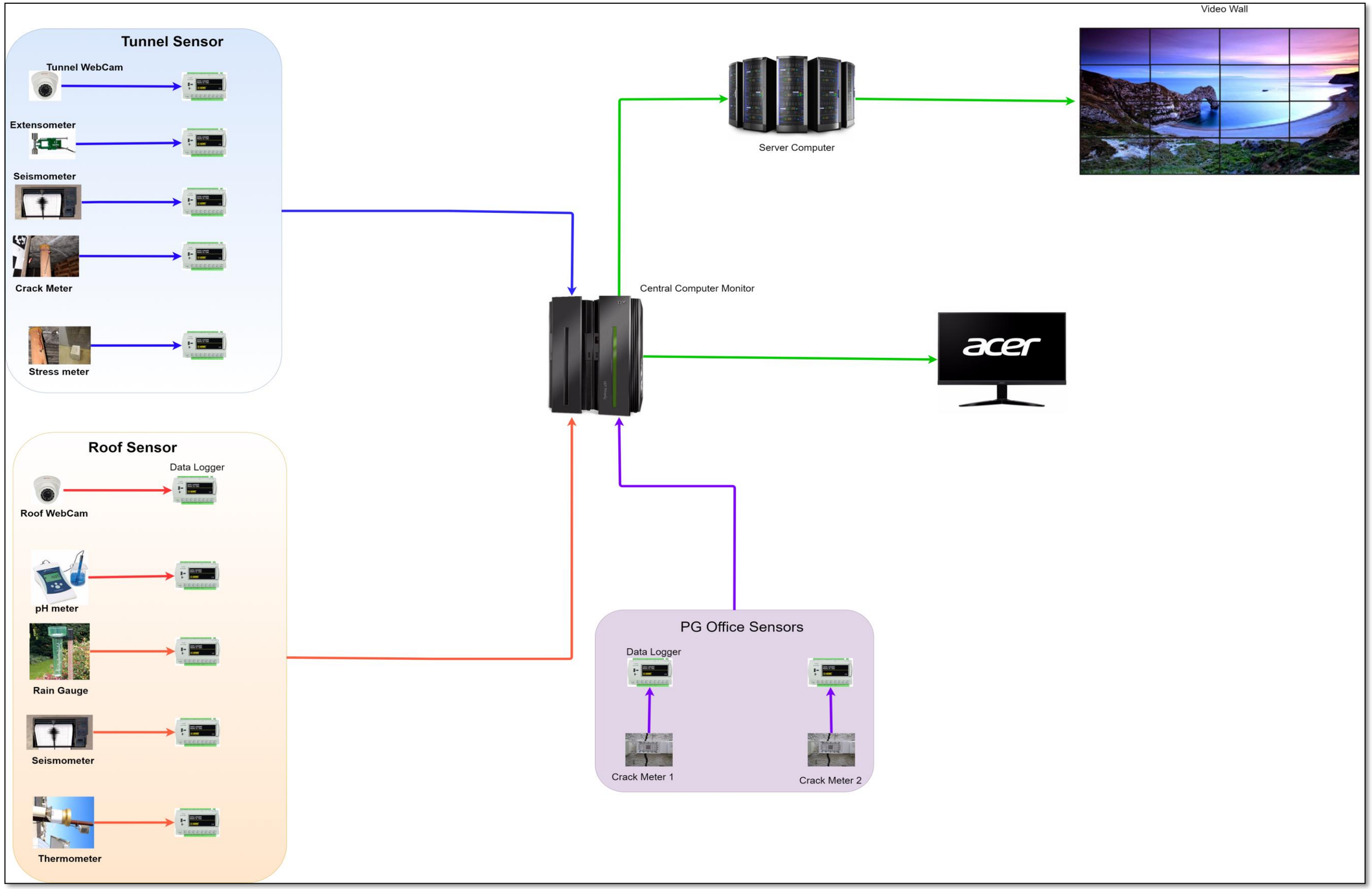


Figure 7-1 Vibratech system architecture

7.2.1 Real-time data from connected sensors

Connected sensors and instrumentation within the VibraTech ground monitoring system include, stress meters, crack meters, extensometers, rain gauge, thermometer, seismometer and cameras. The results recorded during the period of study are shown for each parameter measured.

Stress Meters

Two stress meters recorded data from support unit (mine pole installed in the stope) and concrete block along the way to the stope area. Figure 7-2 shows recordings from mine pole.

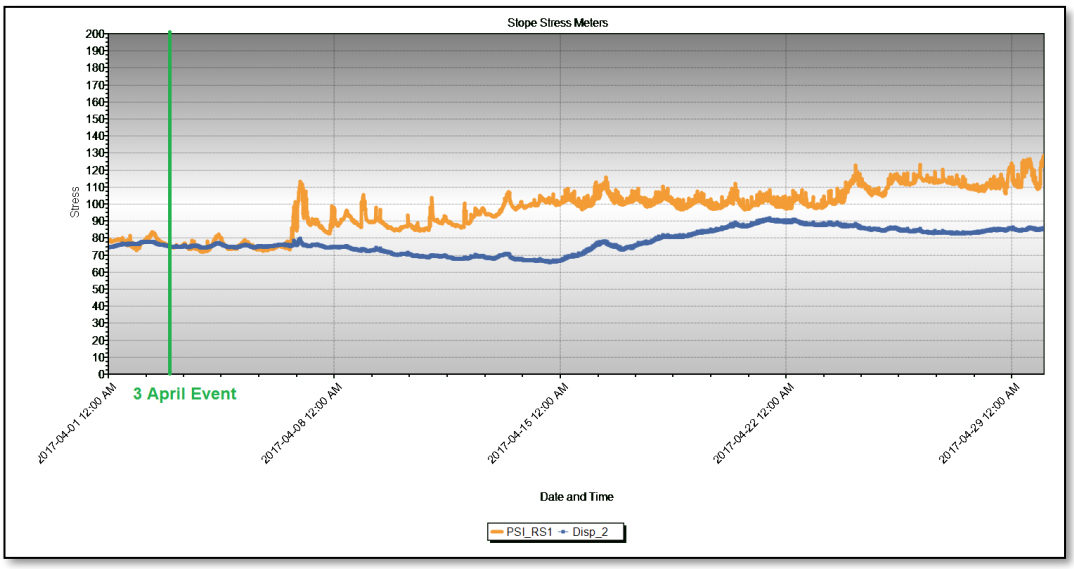


Figure 7-2 Stope Stress Meter Measurements

PSI_RS1 refers to the stress measurements in a mine pole whereas Disp_2 refers to stress measurements within the concrete block. The units of stress used are psi (pound force per square inch), where one psi is equivalent to 6.9kPa. The use of imperial units (for example psi) for display is a result of the system being developed and largely used in the United States of America. The support stress on the day of the event, was a constant. The spikes in the mine pole measurements occurred when the stope experienced movement during mock mine site visit. The increase in stress after the 7th of April was a result of additional load put above the stope and on top of the concrete block after the 15th of April. These additional weights were added

to see if the sensors would work on increased loads. The continued fluctuations in deformation with reduced and or constant stress indicate that the yield point of the support unit was reached.

Tunnel Extensometer

Tunnel extensometer recorded measurements in the crosscut to the stoping area. Convergence measurements recorded are side wall, rather than hanging-wall and foot wall. Figure 7-3 shows the results.

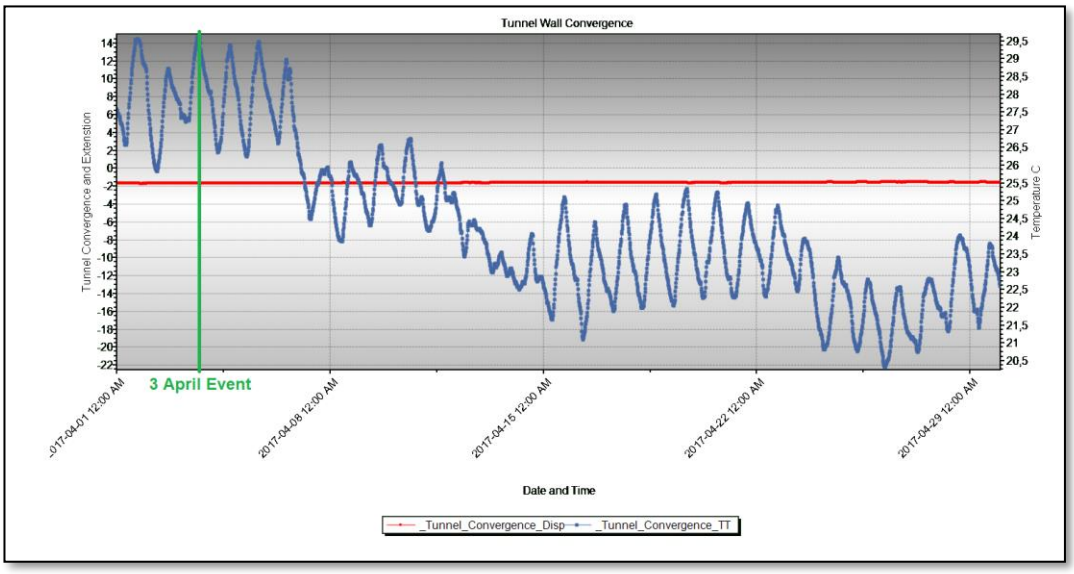


Figure 7-3 Tunnel Extensometer Measurements

Temperature of the surrounding environment was also recorded by the tunnel extensometer as it has a temperature sensor as mentioned in Chapter 5. Tunnel_Convergence_Disp refers to convergence of the tunnel at a given date and Tunnel_Convergence_TT refers to the temperature measured for the same period. There were no changes to the extension or contraction of the tunnel despite the changes in temperature. Failure to observe change is a result of the crosscut being located in a position where there are no stresses large enough to induce any movement within the sidewalls. Within the temperature ranges observed, no correlation exists between temperature and tunnel extension or contraction. These temperature changes are in tandem with surface atmospheric changes.

Crack Meters

Crack meters recorded results from the stoping area and the Post Graduate (PG) office. Figure 7-4 shows the results from stope crack meters and Figure 7-5 shows results from PG office crack meters. Both crack meters showed a constant reading. The -1.4mm for tunnel stope crack, was the initial crack meter reading as the pole was already cracked as shown in Figure 5-5.

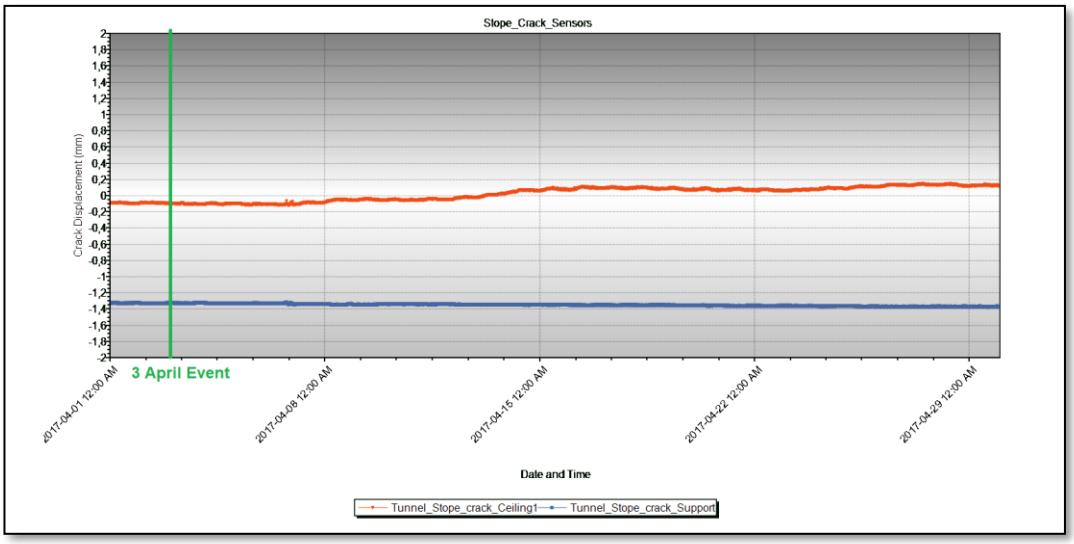


Figure 7-4 Stope Crack Meters

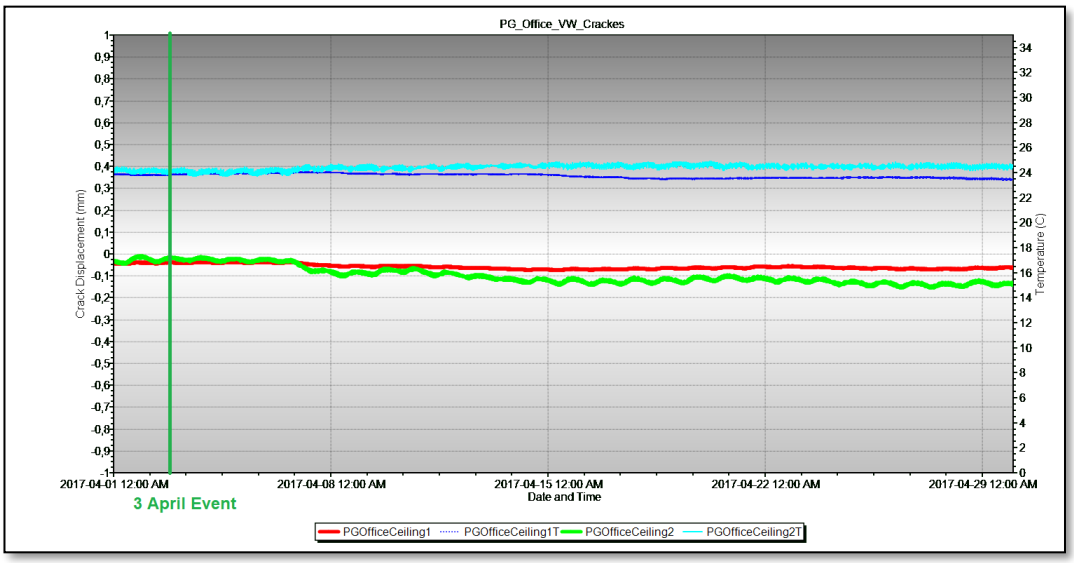


Figure 7-5 Post Graduate office crack meter results

Observations for crack meters in the Post Graduate office also showed that on average, there was minimum movement within the period that measurements were recorded. These small movements can be attributed to personnel walking around in the floors above the Post Graduate Office. This shows that the small changes in room temperature do not have an influence on crack expansion or contraction. In addition, stresses generated within the ceiling are not large enough to induce any change in the cracks. However, failure to observe any change could be a result of low sensitivity of the crack meters.

Cameras

Figure 7-6 and 7-7 show web cameras connected to the VibraTech system with time stamped video feed.

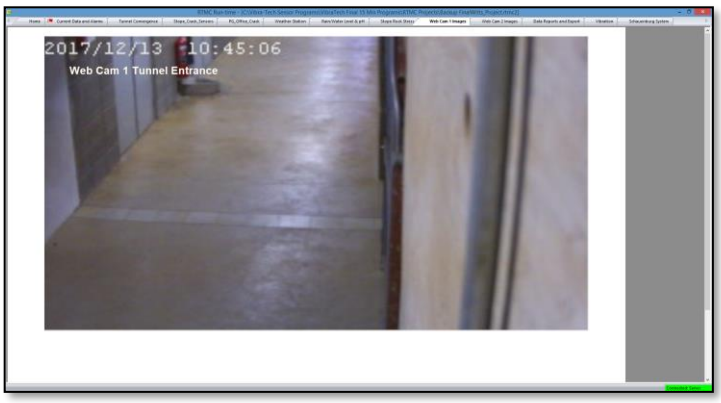


Figure 7-6 Tunnel entrance web camera

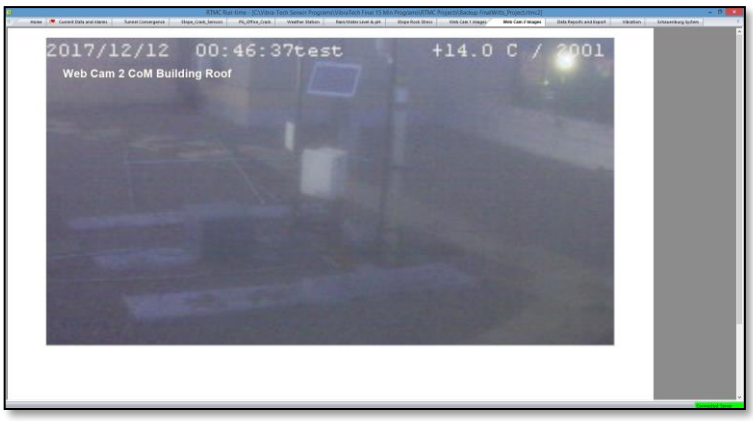


Figure 7-7 Chamber of mines building roof web camera

The videos and pictures captured do not show anything related to ground movement. Their inclusion aimed to test functionality (that is, showing that they were recording videos) within the complete smart rock engineering system. However, given full exploitation of their functionalities, they can record ground movement when triggered by a seismic event.

Water level, Rain Gauge and pH

Figure 7-8 shows results from three sensors which are rain gauge, pH meter and piezometer.

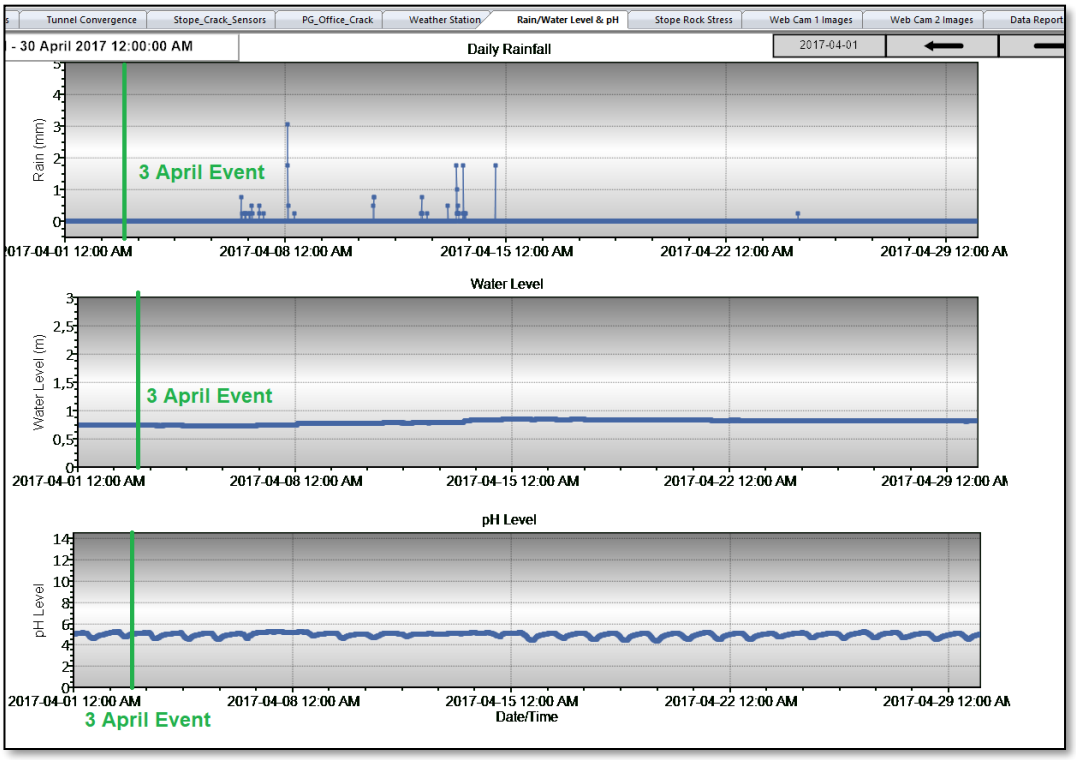


Figure 7-8 Results from rain gauge, piezometer and pH meter

The rain gauge showed when there was precipitation on the 7th and 8th of April followed by 13th and 14th of the same month. This was followed by an increase in water level in the water column. However, pH readings remain fairly constant with minor fluctuations that follow the trend of atmospheric temperature changes. This shows that there a possible relationship between pH and temperature. A drop in pH readings was observed as the temperature increased during the day and the pH dropped early morning and at night. pH is a measure of the concentration of

hydrogen ions (H^+ ions) in water. Temperature rising increases the concentration of H^+ ions thus reducing the pH.

Overall System Results

Figure 7-9 shows a screen-shot of all the results combined with summaries of current data in small table formats above each graph. The tables show the actual values in case a query is run at a point on the graph selected. This tab also allows exporting the values or the graphs for reporting purposes.

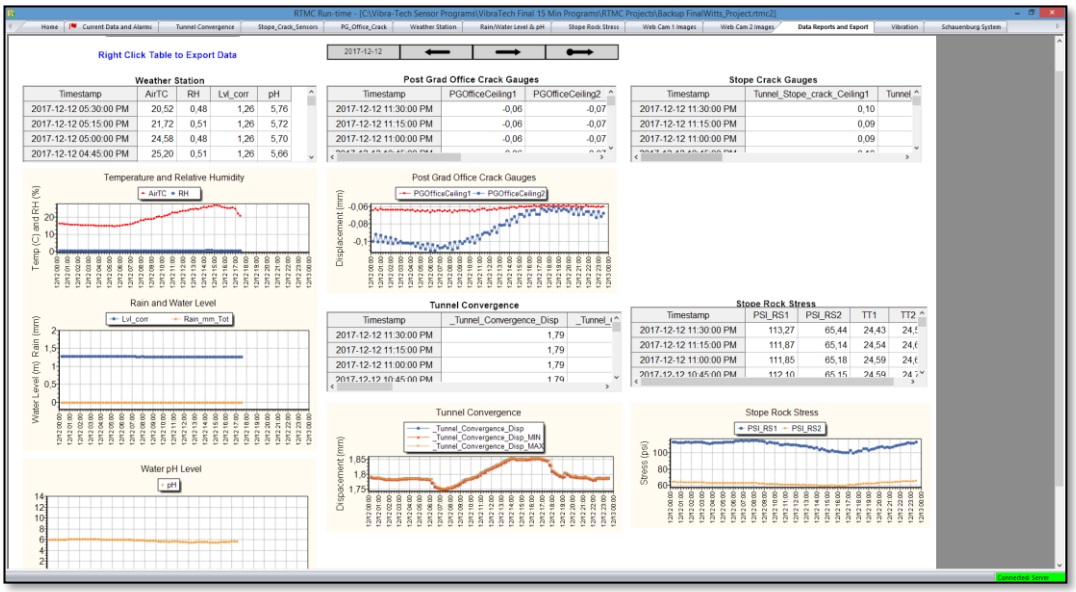
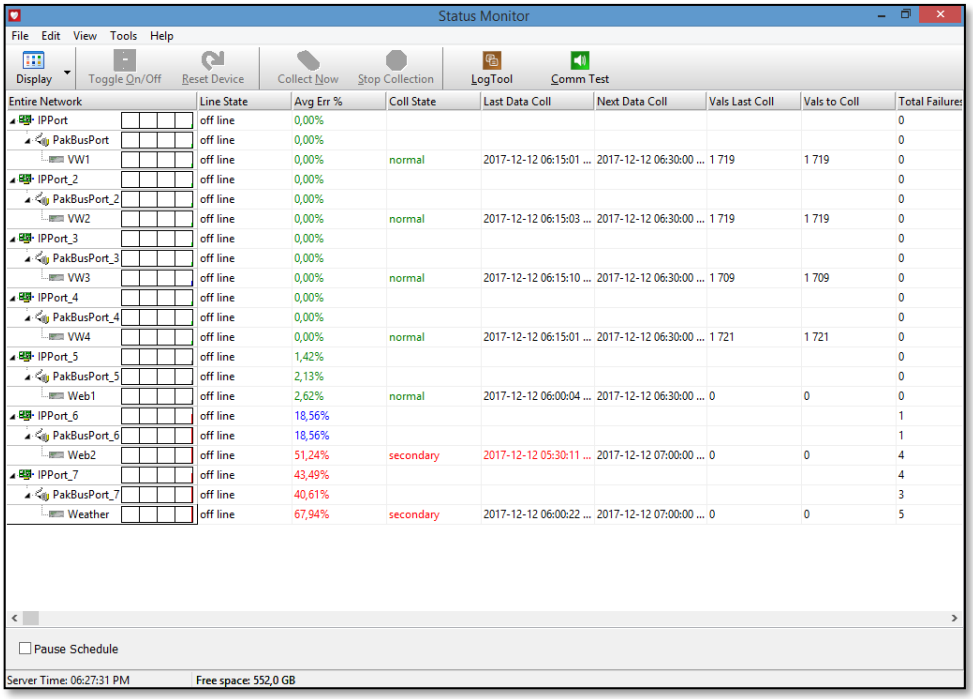


Figure 7-9 A screen-shot of all the results combined

Alarms and Notifications

Where the system failed to communicate between the data logger and the control room, information is displayed in Figure 7-10. Green readings show that the system connectivity and communication is good. Blue shows that connectivity and communication between loggers and control room is not stable and requires review. Red shows that there are major issues with connectivity and communication. The Average Error Percent (Avg Err %) is the number of times the system attempted to send information from the data loggers to the control room expressed as a percentage. From Figure 7-10, the weather station has the highest number of Avg Err %. This is attributed to communication challenges caused by poor WiFi network on the roof.



Entire Network	Line State	Avg Err %	Coll State	Last Data Coll	Next Data Coll	Vals Last Coll	Vals to Coll	Total Failures
IPPort	off line	0,00%						0
PakBusPort	off line	0,00%						0
VW1	off line	0,00%	normal	2017-12-12 06:15:01 ...	2017-12-12 06:30:00 ...	1 719	1 719	0
IPPort_2	off line	0,00%						0
PakBusPort_2	off line	0,00%						0
VW2	off line	0,00%	normal	2017-12-12 06:15:03 ...	2017-12-12 06:30:00 ...	1 719	1 719	0
IPPort_3	off line	0,00%						0
PakBusPort_3	off line	0,00%						0
VW3	off line	0,00%	normal	2017-12-12 06:15:10 ...	2017-12-12 06:30:00 ...	1 709	1 709	0
IPPort_4	off line	0,00%						0
PakBusPort_4	off line	0,00%						0
VW4	off line	0,00%	normal	2017-12-12 06:15:01 ...	2017-12-12 06:30:00 ...	1 721	1 721	0
IPPort_5	off line	1,42%						0
PakBusPort_5	off line	2,13%						0
Web1	off line	2,62%	normal	2017-12-12 06:00:04 ...	2017-12-12 06:30:00 ...	0	0	0
IPPort_6	off line	18,56%						1
PakBusPort_6	off line	18,56%						1
Web2	off line	51,24%	secondary	2017-12-12 05:30:11 ...	2017-12-12 07:00:00 ...	0	0	4
IPPort_7	off line	43,49%						4
PakBusPort_7	off line	40,61%						3
Weather	off line	67,94%	secondary	2017-12-12 06:00:22 ...	2017-12-12 07:00:00 ...	0	0	5

Figure 7-10 Sensor status monitor

The system did not send any notifications through email, text messages or phone call. Where values exceeded the threshold values, a red notification on the screen was shown as indicated in Figure 7-11 below.

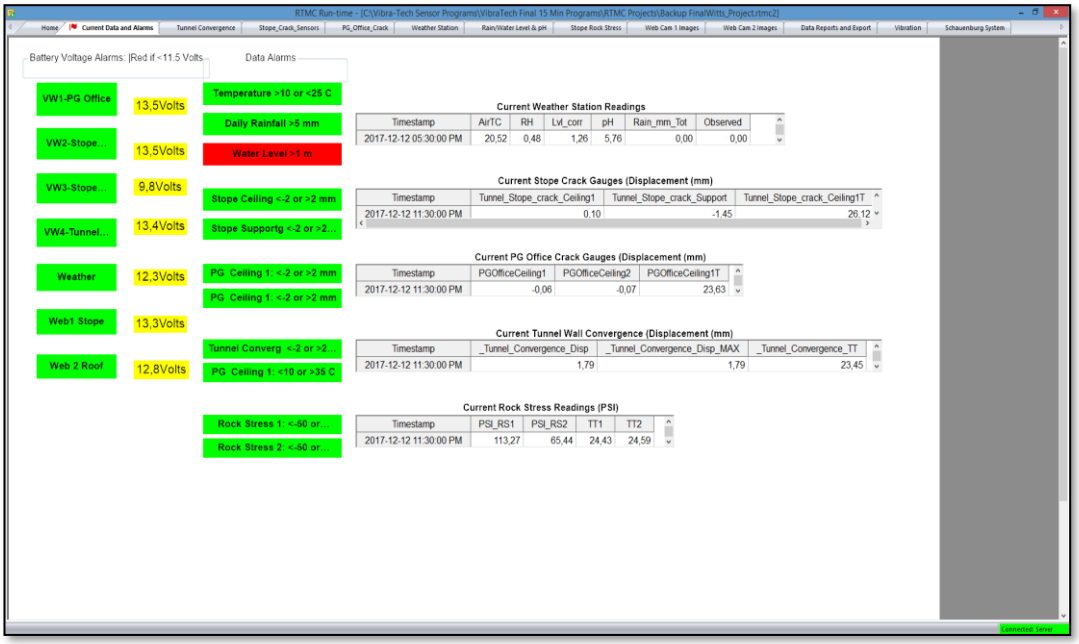


Figure 7-11 Display screen as seen by the operator all the time

Seismometers

Seismicity results are fully described in section 7.3 following the Botswana earthquake. However, seismic results use a different software (Seismic Analysis software) for analysis and display of results as compared to the results shown from Figure 7-2 to 7-11. Integrating the results from seismometers with the data and alarms tab on the customised website is still being developed. However, the two software programs are currently integrated on display on the customised user interface through two different tabs as shown in Figure 7-11. Typical Seismic Analysis software user interface is shown in Figure 7-12.

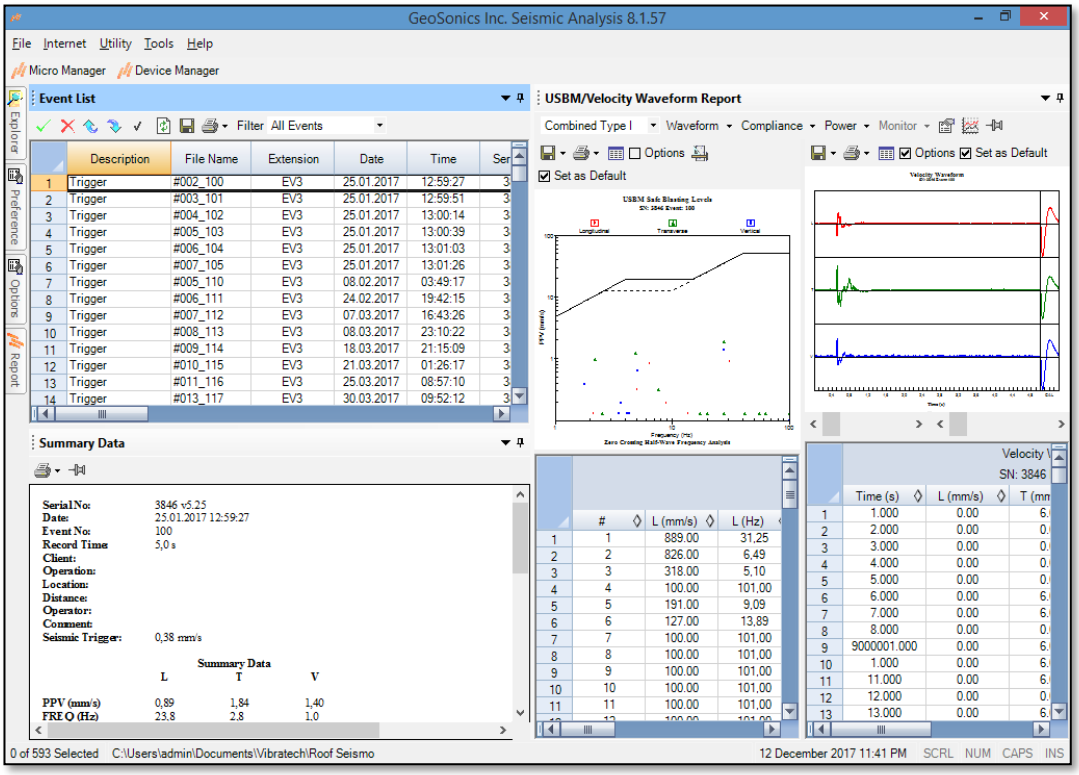


Figure 7-12 Typical user interface for seismic data analysis

7.2.2 Shortcomings of VibraTech system compared to the ideal smart rock-engineering system functionalities based on real time data obtained

The conceptual system described in Chapter 6 provided an insight into desired attributes of the smart rock-engineering system. These attributes include, system capacity, adaptability, connectivity, decision-making, evacuation system,

extensibility and integration. From the results shown in Figures 7-2 to 7-12, the VibraTech monitoring system is discussed against the desired attributes to determine its limitations and find ways of improving it. The evaluation of the system is based on usability, performance, security and ease of maintenance.

Capacity and Integration

The smart rock-engineering system uses existing infrastructure and accommodates all applications and deliver exceptional quality of service by allowing integration with other systems and needs to ensure that it remains compatible with new technology.

The VibraTech system has multiple sensors and data loggers connected and transmitting data to the control room concurrently. The system also allows additional sensors (of any type) to be added to the system if they meet the minimum specifications for power, connectivity, and storage requirements. The system also allows integration with other systems for, example Schaunberg and VibraTech system as shown in Figure 7-11. Figure 7-11 shows a tab where the VibraTech results can be accessed (seismometer information). However, the integration is limited to a link (a tab named VibraTech on the Website). Detailed results are shown when the link is selected. An integration (one that shows results instead of a link) is being developed and this is one area for improvement for the Digital Mining Laboratory.

Robustness and reliability

Vibrations from heavy and moving machinery, increased humidity and temperatures are some of the harsh conditions that the instrumentation encounters and should be able to withstand. Even with such exposure to these conditions the sensors and associated instrumentation should be able to give correct data all the time.

The design of VibraTech instrumentation is rugged and can withstand adverse environmental conditions. Although, the Wits Mining Institute's Digital Mine Laboratory is a mock mine, the time from installation in 2014 to date, instrumentation has remained in place and functional. Data flow from the sensors

was sent to the control room daily despite incidents where communication was a challenge. Examples of communication challenges include:

- Failure of sensors to connect and communicate over WiFi
- WiFi signal strength being poor resulting in intermittent receiving of data; and in some cases, sensors would not connect for two to three days.

Smart rock-engineering system uses stronger WiFi extenders and routers with longer coverages. This enables sensors to transmit data reliably.

Adaptability

Mining conditions also change as the faces advance. Sensors and all instrumentation need to run optimally and remotely and this can be achieved by installing instruments on machinery such as drones that can-do mapping. Artificial intelligence trains these machineries so that they can fly to and fro without human intervention in underground environments. In areas where a sensor has to be fixed in one position for some time, the sensors have to run optimally as they are moved to the next position.

All sensors connected to the VibraTech system are in fixed positions and as such, no movement of sensors has occurred to date. However, sensors continued to sense and transmit data to the control room during a system maintenance that happened in January and August 2017 showing that VibraTech system can run optimally even after being tampered with, during maintenance.

Extensibility and Connectivity

The smart rock engineering system should be able to be expanded and extended as and when needed (System upgrade). During such an upgrade, the system should remain online, or the system should be offline for a short period only. The system should also be connected to the internet to allow remote control and monitoring. The connectivity of such components is through wireless system.

As mentioned in capacity, the VibraTech system allows extension as more sensors and instrumentation can be added. Loss of connectivity during January and August 2017 maintenance, only affected the components of the system being maintained

whereas the other components remained online. VibraTech system can be accessed remotely through the internet. Connectivity of data loggers to the control room is wireless.

Security and prioritization

Control over access to the system and the recording of who logged and what was checked is critical as a way to manage cyber risk. The logging into such a system should be time stamped and be able to produce auditable reports that meet the minimum legislative requirements.

Access to the VibraTech system is password protected and any remote access required seeks authorization from the user in the control room. The results however, are only graphical as shown in Section 7.2.1. No incident document is automatically generated from the system. This report should include, events leading to the incident, likely causes of the incident and recorded measurements before and after the incident and any action plan proposed by the system

Standardised technology architecture and instrumentation

The architecture of a smart rock engineering system consists of sensors, command and control unit and actioning devices. The sensors installed can power themselves and heal if they are exposed to any damage. The powering of sensors can be done using the velocity difference or pressure difference of moving air. These sensors should last for a lifetime with no or limited maintenance.

All sensors except, seismometers do not have actioning devices (alarms and sirens) to notify the miner in the section of any impending danger. All other units of a smart system exist. Seismometers have flashing amber lights and sirens providing an alarm when a certain threshold is exceeded, giving the miner time to evacuate from high risk areas. Power to the data loggers and sensors is through 12V batteries which are charged when their voltage reduces to 11.5V. When sensors are damaged, they need to be replaced as they cannot “heal” themselves.

Control room

Data processing (analysing normalities to decide on maximum tolerances) and visuals (in form of graphs, signalling lights, and geohazard maps)

The processing of data provided by the VibraTech system is limited to choosing what values to display and when to activate a notification for values greater than the threshold. Geohazard maps, which show which areas (in real time) that are susceptible to imminent danger are not shown at all.

Data management

The critical processing path thus require a good data management through installing a large data base and expert systems that analyse data. Although a database requires "a disk write of a log record", thus creating latency issues, a "straight through" processing of data can be used (Stonebraker et al, n.d). The "straight through" processing of data, should be integrated with the data base so that the present can be compared to the past using expert systems and experience of the rock-engineering personnel.

A server exists in the control room area where all the data from the sensors is stored. Data from the sensors is temporarily stored in the data loggers before it is sent through to the server where it is processed and then displayed on the screen graphically. Therefore, there is no processing of data whilst it is in transit.

Data required

Measurements from sensors installed include, deformation (convergence, extension or ovalisation), ground motions (peak particle velocity), gases (as a percentage), load carried by a support system, fragmentation, face profile, face shape index, water level, humidity, temperature, crack expansion.

Results from the VibraTech system do not show face profile, face shape index, stress in the advancing face (measured through acoustic emission method and predicted through numerical modelling (Qinjie et al (2016)) or fragmentation, as these factors contribute to increasing rock-engineering risk. All other parameters are shown graphically in the system.

Alerts

Following measurements that are above the set threshold, real-time alerts in form of automated emails, phone calls, text messages, visual lights, and sirens are given. These alerts are sent to the miner within a stope and at the same time to the rock engineering personnel in charge of that particular section. Where required, alerts are sent to other departmental heads. From time to time, the inspectorate department may be alerted on major incidents

Visual alerts indicated by the red (above set threshold), yellow (measured value close to the set threshold) and green (measured value below set threshold) columns for each parameter measured, are shown in Figure 7-11. No alert is provided for stress meters, crack meters, extensometers, rain gauge, thermometer, and cameras to the miner in the stope. In this instance, the miner does not receive an automated alarm or notification except through telephone communication from the control room personnel. Seismometers have a flashing amber light and a siren when ground movement exceeds the threshold. There are also no automated phone calls from the system.

Real time evacuation and Automated Decision Making

The miner within the area, receives a message through the cap lamp, and the light emitting diodes on the support system units direct the path to a safe area, which in this case, is the refuge bay. The smart rock-engineering system has automated dynamic decision-making capability. The rock engineering personnel oversees the decisions made by the system and adjust the decision where required.

The available notifications from the VibraTech system only alert the control room operator and for seismic sensors, flashing amber light and a siren are provided. However, the alarm system leaves the decision to the miner to decide on the safest path to the refuge bay. The Vibratech system does not have such functionality to make automated decisions. The control room operator and rock-engineering management can oversee the performance of the system and make amendments where necessary.

7.3 Botswana Earthquake

The Botswana earthquake, that occurred on the 3rd of April 2017 at 17:40 Universal Time Coordinated (UTC), is a major event that forms a case study to test the functionality of VibraTech system as a monitoring system for natural ground movement. According to Durrheim (2017), this earthquake is one of the largest to have occurred in over a decade, as earthquakes are rare in Botswana. Traditionally, the largest earthquakes are concentrated on the East-African rift valley as indicated in Figure 7-13 (Hicks, 2017).

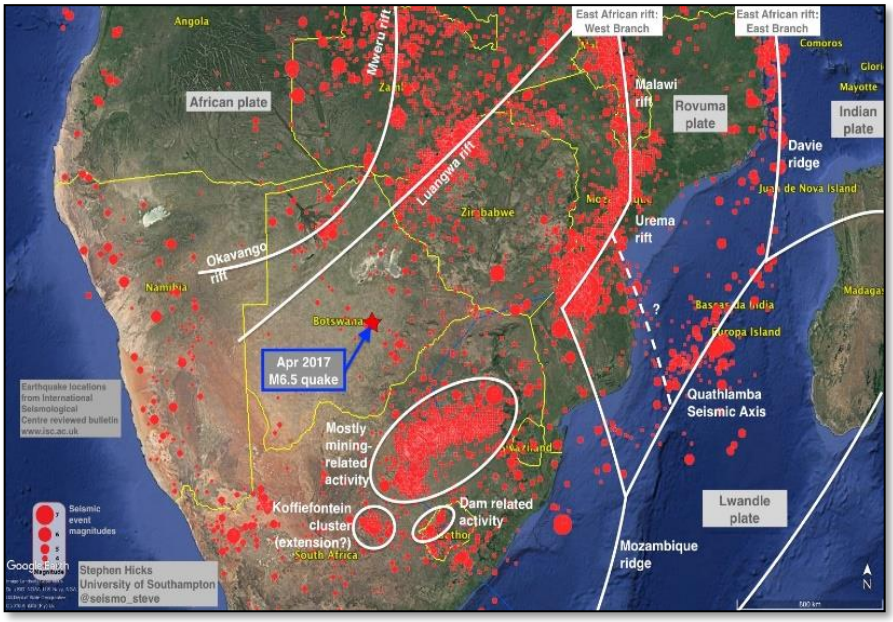


Figure 7-13 Earthquakes location across Southern Africa (Hicks, 2017)

According to the United States Geological Survey (USGS), this event had a magnitude of 6.5 as indicated in Figure 7-14 (USGS, 2017). The USGS station that recorded the event is 270 km away from the estimated epicentre (USGS, 2017). From Figure 7-14, smaller sized shocks (aftershocks) can be seen to have occurred hours after the main shock. The GEOFOrschungsNetz Global Seismic Network (GEOFON) also recorded two aftershocks with magnitudes of 4.6 and 4.1, which are in the same range with the USGS measurements (GEOFON, 2017). According to Bath's aftershock law, for such an event with a magnitude of 6.5, aftershocks of magnitudes as high as 5.4 are expected and the recorded aftershocks are within the expected aftershock magnitudes (Helmstetter and Sornette, 2003).

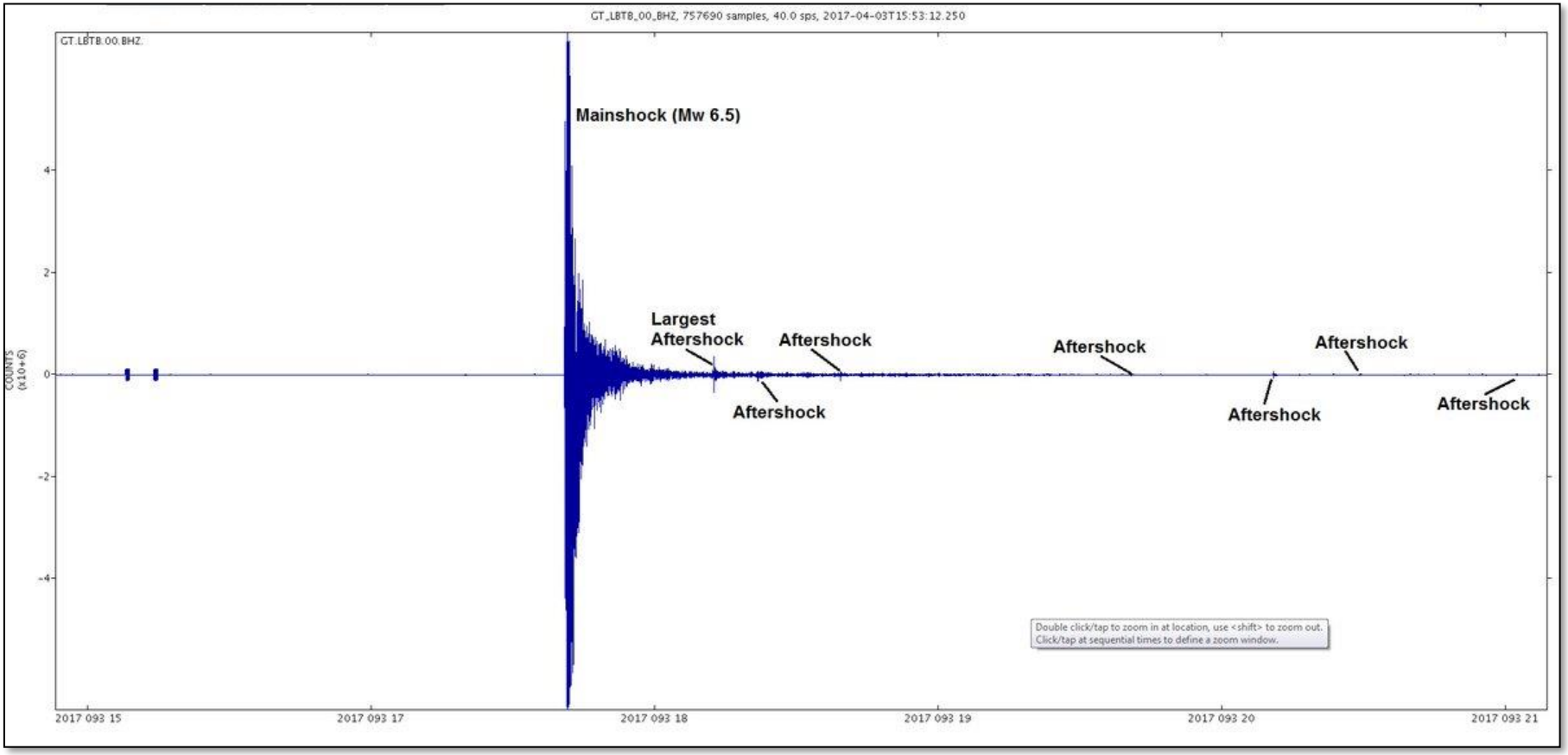


Figure 7-14 USGS recordings of main shock and aftershocks (USGS, 2017)

7.3.1 Recordings from ground monitoring instrumentation

In the event of ground movement, seismometers, crack meters, and stress meters are sensors expected to have some readings. The VibraTech roof seismometer did not record any movement due to connectivity failures (the seismometer was disconnected at the time as connectivity issues were being fixed) whereas the tunnel seismometer captured the earthquake as shown in Figure 7-15. In Figure 7-15, three graphs (longitudinal, transverse and vertical) are shown from left to right respectively. These graphs relate to the movement in the three-dimensional axis. The stepped line in three graphs represent the threshold or the limit of peak particle velocity for ground movement set using the United States Bureau of Mines standards.

The recordings in the directions, shown by the dots, did not exceed the threshold. The maximum peak particle velocity from the tunnel seismometer was 1.1mm/s. Furthermore, the velocity waveforms in Figure 7-15 did not show distinctively the arrival of primary and secondary waves and the recording time was five seconds. The tunnel extensometer and crack meters did not indicate any changes in readings recorded before, during and after the earthquake event because the ground motion caused by the earthquake was not strong enough to induce significant crack expansion and or contraction. Failure to measure any change could also be a result of the low sensitivity of crack meters or extensometers.

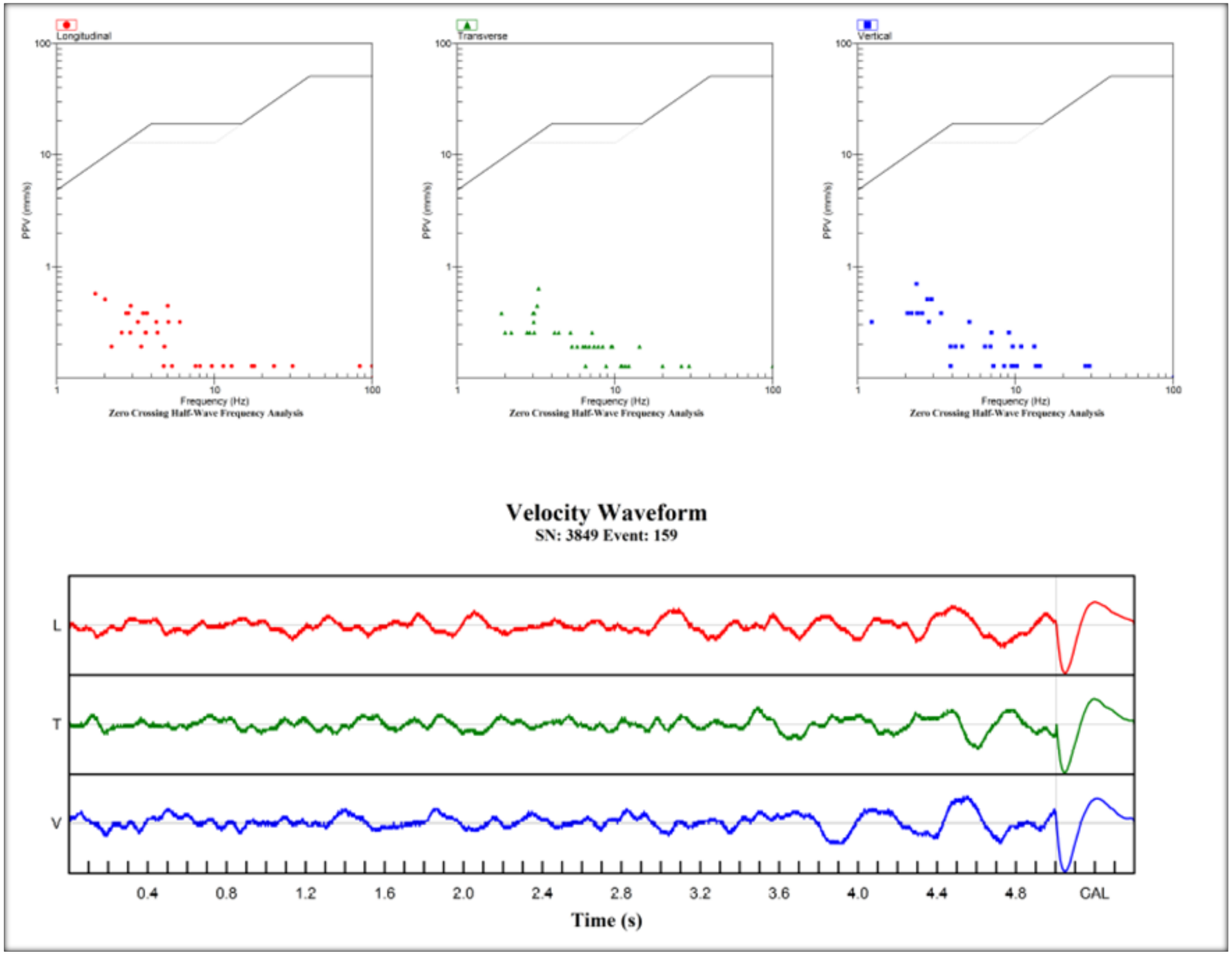


Figure 7-15 Tunnel seismometer readings

7.3.2 Recordings from other systems and possible analysis

The United States Geological Survey (USGS) and Germany's GEOFON instrumentation indicated that there is a form of movement possibly from two faults as shown by a moment time graph in Figure 7-16 (Hicks, 2017). The graph shows that the amount of energy released by the earthquake changed during the rupture and that the multiple peaks indicate that multiple faults caused the rupture.

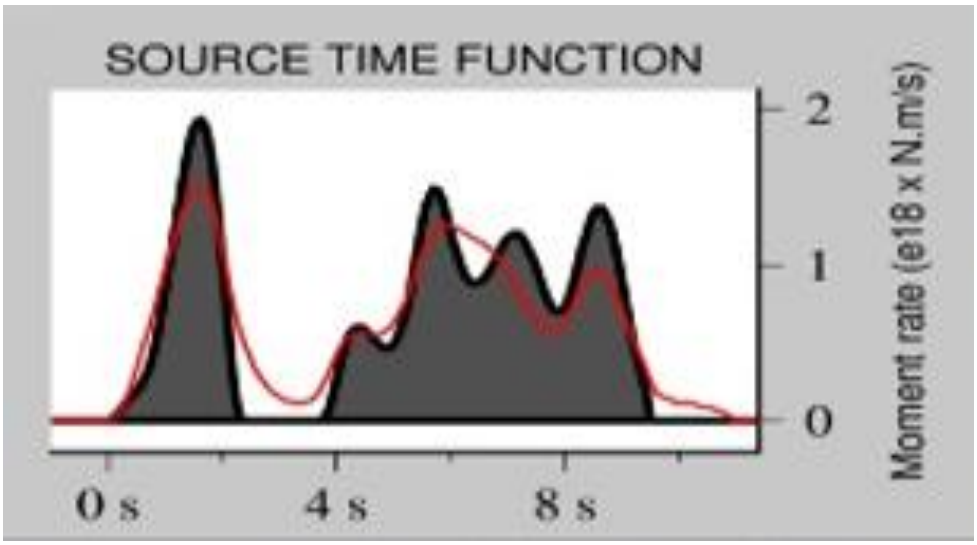


Figure 7-16 Moment Rate vs. Time graph (Hicks, 2017)

Most of the deep-level mines in South Africa have similar systems and are already monitoring seismicity. From the recordings obtained from VibraTech system, it can be seen that, the system failed to do anything more than what the mines are currently doing. The potential analysis that a smart rock engineering system can do includes measurement of stress, convergence, rock noises, water flow or gas emission and using such results to predict when an incident of a rock fall or rock burst will occur. It can also integrate the results with numerical modelling of stress rapidly.

7.3.3 Comparison of WMI Digi Mine recordings to USGS and GEOFON systems

The recordings from USGS and GEOFON provide better data for analysis compared to the data from Digi Mine tunnel seismometer. The tunnel seismometer recorded the peak particle velocity to be $1.1 mms^{-1}$. Although unlikely used to

determine the source, this data from the tunnel seismometer is not adequate to determine or deduce the possible source mechanism. In addition, the time span that the tunnel seismometer recorded the event is small (seismometer only recorded for five seconds) making it difficult to see the arrival of the P-wave and S-wave which are critical in back analysis of the event. However, the ability of system components (seismometer) to capture the event is a big step towards better understanding of ground movement measurement within the Digi Mine area.

The roof seismometer did not record any movement due to communication failures. This is an ongoing challenge when installing technology systems, that is, to get the system working reliably all the time. As such, there is no comparison between tunnel and roof seismometer for a differential displacement analysis. However, the spatial position of the roof seismometer allows the determination of event location through triangulation with other seismometers (assuming it had recorded the event). By using the two seismometers (tunnel and roof), wave attenuation can be determined, which would assist in understanding the properties of the rock (concrete structure). The delay time at which the event was recorded and the time the data became available in the control room was more than five seconds, making the system not “real time”. This is attributed to the time set for synchronization (data synchronises every 5 minutes to avoid system lag) to the control room. There is therefore a need to ensure that when a triggering event happens, data is sent immediately without waiting for the set syncing time.

Several small events occur within Johannesburg from old mine workings and a busy highway close to the mock mine induces some vibrations around the Chamber of Mines building. The instrumentation in the mock mine did not capture any triggering events. This is attributed to two factors. The first is that the geophone installed is not sensitive enough for high frequency events around Johannesburg (an accelerometer is needed for such sensitivity). Secondly the vibrations from a busy highway do not exceed the minimum threshold of 2mm/s therefore they do not trigger an event and as such the values are treated as noise. Compared to the USGS and GEOFON systems, Digi Mine system could not provide a self-analysis system which could give possible source mechanisms, suggesting a recalibration of the instruments and sensors.

7.4 Current Practices and Technologies used in South African Deep Level Gold Mines

Statistical analysis of mine fatalities shows an encouraging improvement. Despite such improvement trend, deep-level mines still experience several challenges which include rock-engineering risk. These challenges are perceived to remain in the foreseeable future (Durrheim, 2007). An understanding of existing technologies in South African mining industries, is important in building technologies that will address recurring challenges. A survey was done through interviews with rock engineering practitioners on existing practices and technologies on deep level mines. These practices and technologies are described in this section.

7.4.1 Existing technologies and instrumentation

Numerous technologies and or instrumentation have been developed to assist in rock-engineering risk management. Such technologies include borehole cameras, extensometers, ground penetrating radar (GPR), closure meters, geophones, fall of ground lights and sticks, piezometers and laser scanners. The use of fall of ground lights, fall of ground sticks and laser scanners is described in Section 4.3. In deep-level mines, geophones are used extensively because of increased seismic activity within these mining depths. As an example, a total of 660 seismic events per month are recorded around shaft pillars for mines around the Witwatersrand basin (Durrheim, 2018). A minimum of four seismic monitoring stations is the common standard to locate the source of these events. However, their configuration is an important factor in determining sensitivity and location accuracy. Mathematical programs such as Exploration and Graphics for RivEr Trends (EGRET) are used in identifying the possible spatial position a seismic monitoring station (Durrheim, 2018). Results from seismic monitoring are used to create hazard maps which are described in section 2.3.2 and section 7.4.6.

Borehole cameras are used to identify parting planes within the rock mass. The results from borehole cameras are used for ad hoc reports which can be used to address identified hazards (Watson, 2018). Ground penetrating radar (GPR) is also used to identify structures within the hanging-wall. The live imaging obtained from

GPR allows instant decisions to be made which can alleviate the impact of the potential risk. In squeezing drifts, extensometers are used to measure the amount of closure experienced in the tunnels (Watson, 2018).

7.4.2 Integration with other instrumentation

Results from the instrumentation described are published independent of each other. There is no integration of all the instrumentation used on shafts. As a result, it is difficult to determine any correlations between the results. The introduction of these technologies has however, shown that there is value in installation and effective use as seen by the encouraging improvement in underground mine fatalities.

7.4.3 Managing false alarms and determination of trigger levels

Watson (2018) conducted a statistical study to determine how many times a hazard map showing a potential seismic event, in comparison to how many times such an event was successfully a seismic event. In his study no, conclusive answer was obtained. According to Watson (2018), loss in confidence in the monitoring system continued to drop, as more often, the system was not successful. False alarms thus continue to be a major challenge for deep level mines. Generally, false alarms are ignored unless they recur for three to four days getting the management to worry and to take appropriate action plans. Once a day, during pre-shift safety talks, hazard maps are discussed and any areas where notifications have been recurring, are not mined for that shift until the alarm or alert level is reduced and or managed. Where an alarm shows during the shift, underground miners are alerted through telephone and appropriate actions are taken which may include changing the area to mine.

The alarm levels are based on trigger levels set for each mine. These trigger levels are based on back analysis of data from all the measurements across the mine. Durrheim (2018) highlights that mining houses outsource personnel for such data analysis, in particular, analysis of seismic data. Alarm levels are set according to a combination of parameters being measured. In a case where there are 3 parameters,

the occurrence of one parameter will always show green on the hazard map, and a combination of two parameters show amber (potential hazard) and three parameters show red (highly hazardous).

7.4.4 Challenges to existing systems

The occurrence of injuries and fatalities in underground workings suggest that there are numerous challenges faced by rock engineering personnel. These challenges include:

- Mines being changed owners which result in monitoring gaps and loss of databases (Durrheim, 2018);
- Loss of sensor sites due to cable theft, fall of ground, fire and power surges;
- Getting the geophones to be installed in the right place. Most of the seismicity takes place on the face or ahead of the face. These locations are difficult to get the instrumentation in place. Where boreholes have been drilled ahead of face to install geophones, shearing of holes occurs resulting in closed holes;
- Instrumentation installed closer to the face is prone to blast and equipment damage;
- There are not enough experienced personnel on the mines to conduct extensive data analysis;
- Integration of results from seismicity and closure has not yet been achieved. Although not conclusive, Watson (2018) identified that there is a sudden increase in closure just before a seismic event. Integration of results will prove to be invaluable to determine any correlations;

7.4.5 Improvements to current practices and existing technologies

The primary objective of installing instrumentation and modifying current practices is to reduce the number of injuries and fatalities caused by ground movement. Improving the current practices is an ongoing action process that attempts to

address rock engineering risk using current technologies. Such improvements include:

- Using wireless or fibre optics-based communication system to curb cable theft;
- Upskilling current personnel so that data analysis can be done on site. Where possible employing an onsite data analyst working with all the rock engineering personnel;
- While prediction of rock bursts is still a figment of imagination, increased use of seismic hazard assessment will certainly increase awareness to the miners. Seismic hazard assessment is desirable and achievable.

7.5 Conclusions

The measurements from VibraTech ground monitoring system have shown that real-time data can be obtained from different sensors and displayed in an integrated system. However, the time taken from data collection to display is significantly large resulting in a system falling short of expectations. Compared to an ideal smart rock-engineering system, VibraTech ground monitoring system does not have automated decision making, complete wireless communication, self-powering sensors and self-healing sensors. This limits the functionalities aimed for, in a smart rock-engineering system. The recordings from USGS and GEOFON have showed that there is a significant gap to be covered by the Digi Mine researchers to construct the system to analyse and record "better" data. By virtue of capturing the event, the system is functional. The occurrence of the Botswana earthquake in an area where such events are rare, induced the question whether there are significant stresses building up in the earth's crust, which one day could result in a much larger earth movement. Pre-knowledge of such an event is extremely important in mine planning. Current practices in rock engineering risk management include use of instrumentation (geophones, closure meters) and approved codes of practices. Implementation and operation of these instrumentation has proved to be challenging due to issues around cable theft, inexperienced personnel and absence of an integrating platform to better visualise and or analyse the results.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Introduction

Developing a system that monitors rock-engineering risks in real-time assists deep-level mines to achieve high levels of safety, demanded by all mining stakeholders. This research developed a conceptual smart rock-engineering system for real-time risk minimization and decision-making in deep-level mines. Whilst the majority of exertion was conducted to minimise rock-engineering risks and improve safety in underground mines, effort was devoted to developing an integrated smart rock-engineering system forming a part of the future smart mine. To achieve such an objective, extensive research on current technologies used in risk management, was undertaken. Appropriate conclusions and recommendations were formulated based on the literature review and the VibraTech system test.

8.2 Key Findings of the Research

The research commenced with a review of the state of mining industry towards achieving zero harm in particular rock related accidents and incidents. Extensive literature review was completed to appreciate the deep-level mining environment where the developed system will be used or implemented. This was followed by a review of current risk management technologies as found in surface mining, petroleum and civil engineering environments. This review led to developing a system, tested within the Digital Mine Laboratory. The following are key findings from the research.

- Although huge milestones in reducing rock related accidents have been achieved, the South African mining industry has not achieved acceptable levels yet. Despite the mining industry being active for years, accident statistics are still high compared to the mining industry in Australia and USA. The presence of the South African mining industry has been on the world map for centuries, demanding improved solutions in managing rock related risks. The recent developments in computer technologies and

increased mechanization offer a possible way of developing a solution to minimize rock related risks. Such a way includes developing a smart rock-engineering system.

- Gold deposits occur in deep and ultra-deep levels where the stress levels and rock related risks are high. Mining at these depths is difficult as it favours a labour-intensive mining over existing mechanized mining techniques, due to the nature of the orebody. Significant rock fracturing and high stress areas have been found to be around major geological structures that include faults and dykes. Several strategies have been developed to manage rock related risks in this mining environment. These strategies include using preconditioning, effective support systems and mining layouts, and monitoring any residual risks. The success of these risk management strategies is not questionable as significant risk reduction is indicated over the years. The continued high fatalities, however, indicates a need for a new strategy.
- The failure of rock follows a pattern. This pattern starts with indicators, followed by precursors and lastly by failure. The initiation of such a process, starts at a local scale and propagates through a transitional to a regional scale. During this transition, several indicators and or precursors can join to exacerbate failure propagation. Findings from continued studies of precursory behaviours can be used to develop better smart rock-engineering system.
- Risk management technologies in surface mining, civil and petroleum engineering are more advanced compared to underground mining. These technologies' attributes can be used to develop underground risk management strategies. Such attributes include, remote operation, self-maintenance, integrated sensor system, and the ability to predict any impending danger. These attributes allow better risk management when implemented in underground mining. It is however prudent that, applying these attributes to a system that functions in an underground environment is challenging, due to the nature of the environment.

- The human body is an ideal system that smart systems attempt to mimic. Smart rock-engineering systems endeavour to mimic decision-making and actioning of decisions made. The ability of skin to sense, repair itself is an example of how sensor systems of the future should behave. This requires integration with material science to produce such a product. Current research on technologies for underground mining have several limitations which include limited battery life of sensors and loggers, data collection still requiring geotechnical personnel to be close to data collections sites and systems limited to single functionalities and not being integrated to monitor several parameters, using one system.
- The conceptual smart rock-engineering system developed, comprise sensors, an expert system for data analysis and decision-making, a wireless communication system to surface and an emergency and preparedness response plan through alerts. The system measures several parameters including stress, water level, convergence, face advance, face profile and ground movement. The results are displayed concurrently on a video wall. The alert system allows the miner in the stope to receive messages on what action plan to take, to prevent an incident where measured values are greater than the threshold values.
- The functionalities displayed by the VibraTech system are a fraction of what a smart rock-engineering system ought to be. VibraTech system showed that an integrated system is possible to develop. However, the time taken from sensing to displaying data on the video wall is long, causing the system to be *non-real-time*. VibraTech ground monitoring system does not have automated decision-making, complete wireless communication, self-powering sensors and self-healing sensors. The event captured by the VibraTech system on 3 April 2017, the Botswana earthquake, showed that the system can work but needs more effort to make it a full real-time system.
- False alarms are a major concern for mines. The occurrence of false alarms has caused a loss in confidence from miners and increased unnecessary production interruptions. Management of risk include discussions of hazard

maps in daily production meeting. False alarms need to be dealt with by experts in fields of rock engineering, seismology and statistical analysis.

8.3 Recommendations and Further Research Work

After the evaluation of key findings from the research, the following recommendations are suggested:

- The use and testing of VibraTech system as a smart rock-engineering system requires an upgrade by installing more geophones or accelerometers for ground movement and stronger WiFi routers for enhanced coverage.
- The recordings from the Botswana earthquake indicated that more seismometers are necessary around the mock mine for example the Genmin laboratory for an improved understanding of ground movement around the mock mine area and for improving location accuracy.
- Communication between sensors in the mock mine and the control room requires enhancement. Even with the change of antenna that occurred in August 2017, transmission is still intermittent;
- The Vibratech system requires an additional analysis module for data processing and analysis; and
- Additional sensors for example the smart bolt need to be installed in the mock mine to test functionality of a completely wireless system.
- For inaccessible underground areas, drones need to be used for collecting information such as mapping after blast, condition of the rock after blast or major event. These drones will function best in new areas where instrumentation still needs to be installed

To gain a better understanding of the smart rock-engineering system, more research needs to be done in the following areas:

- Investigating data transportation within the VibraTech system as way to evaluate to what extent can the VibraTech system be real time and how fast can the decision process be

- Investigating system performance once a complete wireless sensor is installed;
- Implementing sensors from mines (seismometers) and investigating the effect of added sensors on system performance;
- Implement the VibraTech system on a mine scale level and evaluate its performance based on real data;
- Developing areal support with the characteristics of a human skin (sensing, healing and insulating). This requires finding a material that achieves similar or improved support capabilities through material science investigations. Such material will then be explored using similar technologies to thin spray liners; and
- Developing a camera with the potential to capture a video and map the rock face (rock mass classification) during and after a seismic event based on seismic triggers set and rock mass classification system set. This provides researchers with an improved understanding of rock behaviour rather than routine installations of instrumentations or sensors.
- Integration of various instruments with numerical modelling of stress, updated for every blast.

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