UNIVERSITY OF THE WITWATERSRAND

SCHOOL OF MINING ENGINEERING, FACULTY OF ENGINEERING AND THE BUILT ENVIRONMENT

Design Principles for a Survey Slope Monitoring System.

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

Naani Mphathiwa.

Johannesburg, 2012.

DECLARATION

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

Naani Mphathiwa

This day of 2012.

ABSTRACT

When slope angles are designed during open pit optimisation, there is a risk factor applied to steepen the slopes. The steepening of slope angles has implications on the safety and economics of the mining operation. The steeper the slope angles, the greater the probability of slope failure and also the higher the benefit of cost saving during waste stripping. The challenge facing the mining engineers involved in open pit design is to maximize the economic benefits of the project without putting the mine workers and the mining equipment at the risk of rock falls. This challenge is addressed by striking a balance between safety of the operation and the cost savings. The ideal situation is to have a slope monitoring system that will predict slope failure by detecting any ground movement before the actual failure occurs. This will allow for the application of the risk factor with a high degree of confidence knowing that the risk will be adequately mitigated with a slope monitoring system.

The objective of this research report is to provide guidelines on how to design an optimal survey slope monitoring system. It is the author's view that for a survey monitoring system to yield desirable results, it should adhere to survey principles such as working from the whole to part and cross checking always. The research report covers all aspects of the survey monitoring systems such as survey control network design, beacon construction, equipment selection, data management, procedures and personnel involved in slope monitoring. The report was compiled with guidance from published papers by various authors and discussions with mine surveyors and geotechnical engineers involved in slope stability monitoring. The findings used for analysis are from Jwaneng Mine. The design strategy outlined in this report can be used as a guideline for setting up a new slope monitoring system or to optimise an existing monitoring setup.

ACKNOWLEDGEMENTS

This research is dedicated to the following;

To the Debswana management for giving me the opportunity to do this research hence allowing me to develop my skills.

To the Debswana mine surveyors and geotechnical engineers for assisting me during the research.

To my supervisor, Professor Frederick Cawood for the guidance and support.

To my family, Ludo, Nlisi and Bokani for the support and sacrifice.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES IN APPENDIX

LIST OF TABLES

KEYWORDS AND ABBREVIATIONS

GeoMos _ Geodetic Monitoring System

SSR _ Slope Stability Radar

GPS _ Global Positioning System

GNSS _ Global Navigation Satellite System

GIS _ Geographic Information System

ATR _ Automatic Target Recognition

InSAR _ Interferometric Synthetic Aperture Radar

ECEF _ Earth- Centre Earth- Fixed

PLATO _ South African Council for Professional and Technical Surveyors

UTM _ Universal Transverse Mercator coordinate system

SLC _ Service Level Contract

GDE _ Graduate Diploma in Engineering

SMS _ Short Messaging System

SWOT _ Strengths Weaknesses Opportunities and Threats

COP _ Code Of Practice

DME _ Department of Minerals and Energy

Survey Control Network _ a set of survey beacons that are inter linked by survey measurements, which form a network of coordinated points from which surveys can be taken

Primary Beacon _ a survey control beacon within a network, which is used for orientation and check measurement purposes

Secondary Beacon _ a survey control beacon within a network from which a monitoring point is surveyed

Monitoring Point _ a point established on the slope or structure being monitored, to which regular survey measurements are taken to determine the presence and characteristics of movement

Piling _ a column of steel or concrete that is driven into the ground to provide support for a structure

Geo-reference _ a position established in terms of a coordinate system

KPA_ Key Performance Area

1 INTRODUCTION

1.1 Introduction to Slope Stability Monitoring

Bartley (2007) defined monitoring as the regular observation of activities taking place in a project or programme and that it is a process of routinely gathering information on all aspects of the project. There are different types of monitoring surveys, but in this report; the author is going to focus on slope stability monitoring surveys.

Slope stability monitoring can be defined as the science of measuring ground movements and detecting instability before failure occurs. Read and Stacey (2009), stated that monitoring is an invaluable tool for assessing design performance and failure risk, and for aiding risk minimization.

The objective of slope stability monitoring is to balance mine safety with the economics of the project. The safety of workers in any mining operation is the number one priority of every mining manager. This is both a moral and legal obligation. It is therefore critical to have a reliable slope monitoring system such that any potential failure can be detected well in time such that workers can be evacuated from the hazard areas promptly. When slope angles are designed, there is a risk factor applied to steepen the slopes. The steepening of slopes results in less waste rock stripping, hence reduces the costs of mining significantly. However, by steepening the slopes, the probability of slope failure is increased. This risk associated with the steepening of slopes is mitigated by slope stability monitoring. It follows then, that the more reliable the slope monitoring system is, the more risk can be taken when designing the slopes, hence reducing the cost per ton mined further. The concept of interfacing slope monitoring with slope designs was emphasized by Cawood and Stacey (2006) when they stated that in the near future data from slope monitoring equipment will add a much needed dimension to slope engineering, when used to improve slope designs and to optimize slope angles.

Detecting slope failure before it occurs will result in the removal of mining equipment before it is buried by the land slide. The advantage for the mining company is significant savings because it avoids premature repair or replacement of damaged equipment. Slope failures can also result in ore dilution, when sliding waste rock mix with the ore. This will inevitably reduce grade and increase mining and treatment costs. A rock slide at Kumtor gold mine in Kyrgyzstan resulted in 100 000 ounces being cut from the 2006 production forecast, Mining News (2006). The slope monitoring system allowed the area to be safely evacuated in advance and there were no injuries, although a diamond drill was covered by rock, Mining News (2006). Given the scenarios mentioned above, it is critical that mining operations have a reliable slope monitoring system in place at all times.

Wang et al. (2010) stated that increasing slope angle in an open-pit mine is an effective way to reduce cost and increase mining benefit, but the possibility of landslide hazard is increased at the same time. They also stated that it is critical to establish an early warning model by means of certain deformation techniques and data analysing methods.

It is the author's opinion that the design of the slope monitoring system is the determining factor in setting up a reliable early warning model stated above. This is so because once the slope monitoring system is not properly designed, the accuracy of the results cannot be achieved. Accuracy is of utmost importance in slope stability monitoring and if it is not achieved, the whole integrity of the system is compromised.

1.2 The focus of the research

In this report, the author will attempt to answer the fundamental question of *How to design a slope monitoring system?* The focus of the research will be on Geo-referenced Systems otherwise known as Survey Slope Monitoring Systems. These systems include, among others, the Geodetic Monitoring System (GeoMos), Slope Monitoring Radar (SSR) and the Global Positioning System (GPS) or Pseudolites technology.

The introduction of automated survey slope monitoring systems was a major step in optimizing the whole concept of monitoring. However, it is the author's opinion that no matter how sophisticated the instrumentation or the software is, if the foundation which is the design is not optimal, the level of confidence on the monitoring results will be low.

Jwaneng Mine, which is owned by Debswana Diamond Company, will be used as a case study in this research. Jwaneng mine is currently extending its open pit mining through its Cut 8 project. The Cut 8 project will extend the depth of the pit from 330m to 624 m, the length will be 2.7 km and the width will be 1.7 km (Debswana, 2010). A prefeasibility study is being undertaken for a Cut 9 project which will extend the mine depth to 850m with a possibility of extending the dimensions of the pit further with a Cut 10 project (Mining Weekly, 2010). The deepening of the pit and the general increase in the footprint increases the risk associated with slope failures. The Cut 8 mining limit will be approximately 100m from the main treatment plant infrastructure. Movement of the ground in the vicinity of the plant infrastructure can result in production losses for the company and huge unplanned replacement or repair costs. The scenarios mentioned above, call for a robust slope monitoring system design so as to successfully mitigate the risk of slope failure.

In this research paper, the author will assess the existing slope monitoring design at Jwaneng Mine and come up with recommendations in order to make it optimal. The projects stated above will also have a significant impact on the positioning of the infrastructure around the pit. The pit extensions brought about by projects such as Cut 8, 9 and 10 offers the mine the opportunity to close gaps in the existing design. For example, when repositioning the primary and secondary beacons to make way for the cut 8 or 9 limit the recommendations from this project in as far as survey network is concerned, can be implemented.

Debswana mines introduced the automated monitoring systems as early as 2001 and has gradually been purchasing and updating the systems for each of their mines. The GeoMos system was introduced to the company and implemented at the Letlhakane Mine in 2002, followed by Orapa and Jwaneng Mines respectively. Similarly the SSR was first implemented at Jwaneng Mine in 2005 then followed by Letlhakane and Orapa mines. Jwaneng Mine has recently started installing Pseudolites in and around the pit to enhance the existing monitoring systems to mitigate the heightened risk of mining Cut 8 which is the close proximity to the Main Treatment Plant.

1.3 Significance of the Study

Although Jwaneng Mine will be used as a case study, the recommendation from this research will be implemented across all Debswana mines. Debswana management has keen interest in the results of this research. The implementation of the research recommendation will also provide the management with the assurance that any risk of slope failure at Debswana mines will be appropriately mitigated.

This research will also be of interest to other professionals involved in open pit mining. These include mine surveyors, mine planners, geotechnical engineers, the mine safety officers and all employees working in the open pit operations. The mine surveyors and geotechnical engineers will have keen interest on this report as it has the potential to improve the accuracy and reliability of the monitoring results. The mine planners will be interested to see how the research will add value to the project by influencing the design of slope angles. The mine safety officers and the general employee population will be more interested on the safety aspect of the project. The research will also be of interest to organisations providing risk insurance to mining companies as they can use it to assess the level of confidence on the mitigation strategies provided on the mine operations.

1.4 Purpose of the Study

Watt (1995) proposed the upgrading of the monitoring programmes at the Letlhakane, Jwaneng and Orapa open pit Diamond mines. The focus of Watt's report was on the actual monitoring using conventional survey instruments such as the Wild DI 2202, precise levelling and the calculation of the survey observations to reduce them to useable information. Most of Watt's recommendations were implemented by all the three Debswana mines and benefits were realized at that time. However, with the passage of time, developments have raised the need for a different approach to monitoring. The mines have gone deeper and wider with mining of additional cuts. For example, the Cut 8 limit in Jwaneng Mine is less than hundred meters from the plant infrastructure.

These developments, especially the deepening of the pits has increased the risk associated with slope failure. To mitigate this heightened risk, Debswana mines responded by intensifying the monitoring by increasing the number of targets and the frequency of the monitoring. All these mitigations proved difficult to do with Watt's recommended manual monitoring, hence the introduction of automated geo-referenced monitoring systems.

Research has been done on automated survey slope monitoring systems, but the focus has been about the equipment, software used in the actual monitoring and the analysis of the monitoring results. For the equipment and software to deliver reliable results there is need for a robust design. It is the purpose of this research paper to provide considerations to be taken when coming up with this design.

1.5 Scope of the Study

The study will focus on large open pit diamond mines, with Jwaneng Mine being used as a case study. The Jwaneng pit is approximately 2.5 km long, 1.5 km wide and up to 300m deep. Additional cuts planned will make it 1.7m wide and to 850m deep.

The following design parameters of survey monitoring systems will be considered:

- **Survey Control Network**: This will be the basis of the design. The integrity of any survey measurements depends on the accuracy of the survey stations which forms the survey network. In the case of slope stability monitoring all movements will be with reference to the survey control network. When designing the survey control network the basic survey principle of working from whole to part will be applied. The first set of survey stations to be looked at will be the primary beacons. The positions of the primary beacons with reference to the geometry of the pit will be established. The optimal distance of the position of the primary beacons from the pit rim will systematically be determined. The next set of survey stations to be considered is the secondary beacons. Their positions with respect to the monitoring beacon (where the measurements will be taken from) will also be determined. The positions of the monitoring targets will also be considered, but to a lesser extent as they are more influenced by the geotechnical properties than the survey principles.

- **Construction of the Survey Beacons :**

  Primary beacons: The study will focus on how to design and construct primary beacons which must be stable and withstand vibrations from continuous blasting of the pit. The stability of primary beacons is critical because they will be used for orientation and to check the stability of the monitoring station. The research will also look at the structural design and construction of the secondary beacons and the monitoring targets.

Monitoring beacons: The monitoring beacon is constructed close to the rim of the pit such that there is a clear line of sight to the prisms used as monitoring targets. Although the beacon stability will inevitable be affected by blast vibrations, because of its close proximity to the pit, there is need for a structural design that can withstand blast vibrations as much as possible.

Instrument shelter: The construction of the shelter for housing the monitoring equipment will also be investigated. Abramson et al (2002) emphasized that instruments should be well protected against corrosion, moisture, other aggressive agents and vandals. The author will look at the construction material that will protect the instrument from the mining conditions such as dust and fly rocks without compromising the accuracy of the monitoring results. There is an on-going research looking at how the glass through which measurements are taken affects the accuracy of the measurements. The author will consider results from these investigations when coming up with recommendations with regard to the construction of the instrument shelter.

- **Equipment Selection**: The next phase in the survey slope monitoring design process is the choice of the monitoring equipment to be used. The choice of equipment will primarily depend on the accuracy that the mine wants to achieve and also the type of movement to be detected. Some instruments like levels are good for vertical movements while others such as Global Positioning Systems are suitable for horizontal movements. The area to be covered by the monitoring also influences the choice of instrument. There are several monitoring instruments that are being used by operations for slope stability monitoring. These instruments include among others, Total Stations, levels, GPS Pseudolites, laser scanners and slope monitoring radars. The author will recommend a selection criterion to be used when choosing the type of equipment needed for the monitoring. The author will look at how to utilize different monitoring equipment to complement each other.

- **Software Selection:** The focus will be on how to present data from various monitoring systems. Most monitoring systems come with software for interpreting and presenting results. The aim is to investigate ways of integrating data from these different systems to ease flow of information. The investigations should lead to software that can perform statistical analysis as the systems usually produce large amounts of redundant data. Once integration has been achieved, relations in data from the different systems can be easily established and decisions made with high confidence.

- **Skills and Competencies**: For the design to produce desired results there is need to have people with right skills and competencies to implement and maintain it. The research will focus on how to develop the skills in areas such as precise levelling, post processing GPS observations and interpretation of monitoring results using the appropriate software. The research will assess the skill levels of the Debswana mine surveyors and recommend relevant training where necessary. The importance of competent personnel is emphasized by Paudits and Bednarik (2002) for applications such as GIS as it is necessary to have a professional and purposeful data selection. This can be achieved by trained GIS practitioners. Jooste and Cawood (2006) emphasized competencies required in the analysis of raw slope monitoring data and that it should be conducted by a suitable qualified person. Abramson et al. (2002) stated that once the slope monitoring requirements have been established, it is essential to organize personnel with proper training to operate and manage the system.

1.6 Methodology and Data

Jwaneng Mine has been running the slope stability monitoring programme since 1989. The author will look at the slope monitoring programme in place as a starting point. Analysis of the slope stability monitoring design in place at Jwaneng will be carried out with emphasis on existing design parameters. It will be interesting to see if some of the unexplainable errors on the results are not due to design deficiencies. The author will not spend a lot of time analysing the data as it is not the intent of the research. The purpose of the research is to come up with the design that will deliver quality results.

1.7 Limitations

There are several limitations that will be considered when coming up with recommendations from this research. The following are some of the limitations:

Mine Infrastructure layout: When designing the survey control network, one will have to consider the buildings and dumps surrounding the site being monitored. While it will be ideal to have the survey network encompassing the geometry of the site being monitored, it might not be possible as some areas are occupied by dumps and buildings hence obstructing the line of sight between survey stations.

Instrumentation: The position of the survey stations and measuring points will have to consider the measuring capability in terms of distance of the survey instruments available in the market. Although it is desirable to have the primary beacons to be as far as possible from the pit, to limit the effect of blast vibrations on their stability, this is not always possible because of the range limitation of the measuring instruments.

Atmospheric Conditions: The varying and harsh atmospheric conditions across the pit make it difficult to come up with a design which will account for errors brought about by these variations.

1.8 Overview of Report

Chapter one starts with an introduction to the fundamental question to be addressed by the research which is, *How to design a slope monitoring system.* The importance of the research will also be discussed, explaining why the approach used will add value to the industry. There will be discussion on the stakeholders and how it might impact their key performance areas. The focus of the research will be clearly defined and scoped at this stage. Furthermore, the case study to be used will be stated and an explanation as to why a particular site was chosen will be discussed. The parameters to be investigated will be stated here so that the reader can know what to expect in the report. A brief overview of how the research will be done in this chapter. Lastly, the author will discuss the limitations that may be encountered during the course of the research.

Chapter two focuses on the fundamental principles of slope stability monitoring. The author will review what other authors have published in relation to the topic of slope stability monitoring. The purpose of the literature review is to discuss how findings by other authors will influence the research. The discussion will be centred on the parameters the author has scoped for research. The author will also scan the environment to look out for emerging topics from discussions such as conferences and workshops to see how they can be addressed during the course of the research. The author will then summarize major findings from the literature review and how the new knowledge will be applied in the research.

Chapter three will describe the existing slope monitoring design at Jwaneng Mine which is the case study of this research. The author will explain how the description and analysis of the existing set up will aid in coming up with the optimal design, which is the aim of this research. By describing and analysing the current design, the author will use learning points from the current system to develop a robust design. Actual information in the form of mine plans, pictures of monitoring equipment and procedures from Jwaneng Mine will be used as illustrations.

Chapter four will focus on the analysis of the slope monitoring system in place at Jwaneng Mine. The aim of this section is to apply the knowledge gathered from the literature review and from general discussions with other fellow professionals to the case study. The author will assess the existing slope monitoring system against the knowledge gathered from the literature review. There will be a brief interpretation and analysis of the results from the existing slope monitoring at Jwaneng mine. The aim of this analysis is to assess how the current design of the slope monitoring system might be influencing the results. Having assessed the design in place at Jwaneng Mine the author will develop a theory on how to improve or build on the current design.

Chapter five will outline a step by step process of how to design a slope monitoring system for a typical large open pit mine. The knowledge gathered from the literature review and learning points gathered during the analysis of the case study will aid the author in developing an optimal design. The author will then discuss how the proposed design addresses the challenges facing mining practitioners involved in slope stability monitoring. There will be a discussion on the new concepts coming from the proposed design.

Chapter six which is the conclusion will summarize major findings from the research and provide the answer to the fundamental question posed at the beginning of the report. The author will also discuss the shortcomings associated with the design and how to mitigate them to get high quality results. The author will propose recommendations that may elevate the slope stability monitoring process to another level or open up other avenues for further research on the topic.

1.9 Conclusion

The purpose of this chapter was to highlight the significance of doing a research in the designing of a slope stability monitoring survey system. It was also established that the fundamental question to be answered is H*ow to design a slope stability monitoring system.* The chapter has highlighted the areas which the research will focus on in order to answer this question. This chapter gave a preview of how the research paper will be organized.

The next area of discussion will be on the principles of slope monitoring systems. This will be a literature review of the work already published by other authors in the area of slope stability monitoring survey system. The review will focus mainly on the current knowledge relevant to the scope of the project.

2 PRINCIPLES OF SLOPE STABILITY MONITORING

Chapter one introduced the purpose of the research to the reader. The aim of this chapter is to conduct a literature review on the work published by other authors in the area of slope stability monitoring.

2.1 Fundamental Principles of Slope Monitoring Design

According to Cawood and Stacey (2006), the design of rock slopes and slope monitoring systems follows the same thorough process which is logical, auditable and provides a design with acceptable risk. They observed that, to come up with a robust design one should follow design principles as developed by Bieniawski (1991, 1992) which are:

1. Clarity of design objectives and functional requirements
2. Minimum uncertainty
3. Simplicity of design components
4. State of the art practice
5. Optimisation and
6. Constructability

To emphasize the importance of these principles, Cawood and Stacey (2006) stated that if the design does not satisfy these principles it will be necessary to review the design and repeat, either partially or completely until the design is optimized.It will be critical to test the slope monitoring design against these principles, before the implementation. When designing a slope monitoring system, Jooste and Cawood (2006) advised that the design should consider aspects such as extent of automation, reliability, accuracy, consistency, flexibility and cost efficiency.

Jooste (2005) concurred with Cawood and Stacey (2006) that there is need for a systematic approach when implementing a slope monitoring programme in an operation. He recommended a proactive approach which entails designing a program which will identify potential hazard areas and relay information to the relevant personnel through an early warning system such that no surprises are encountered during production (Jooste, 2005). Also highlighted is the need for the person responsible for slope stability monitoring to have the ability to analyse the recorded data and also ensuring that diligence is applied in obtaining the measurements. Investigations aimed at finding a solution for correcting for variations of temperatures across the pit over the different bench depths as well as the designing of the instrument housing which will prolong the life of instrument without affecting the accuracy of the monitoring results should be conducted (Jooste, 2005).Jooste (2005) also observed that the glass enclosures used in the construction of the instrument shelter act as a plain parallel table and deflect angular measurements. However, in his research, Afeni (2010) concluded that if glass thickness of 3.0 mm or less is used, there will be no effect on the accuracy of the measurement observed through the glass sheet.

Cawood and Stacey (2006) suggested factors to consider when designing a slope monitoring system. These factors are; Control network design, beacon construction, survey monitoring instrumentation, coordinate systems and presentation of monitoring results.

2.2 Survey Network Design

There is need to adhere to basic survey principles when designing a control network for a survey slope stability monitoring system. This is critical because no matter how sophisticated the monitoring is, when it comes to checking its integrity, the basic survey methods such as triangulation, resection and intersection will have to be applied, (Cawood and Stacey, 2006). Network design considerations include establishing the reference transfer beacons from the control beacons, which must include the mine's survey benchmark, (Cawood and Stacey, 2006). This is the application of the survey principle of working from the whole to part, meaning that the primary beacons are used to establish the positions of the secondary beacons. The geometry of the primary beacons with respect to the monitoring site (pit) will influence the accuracy of the measurements. Kealy (2010) observed that although there are several survey networks such as level network, resection, intersection, control traverse and control network; the choice of type is primarily based on the survey problem, specifications for accuracy/precision and the available equipment.

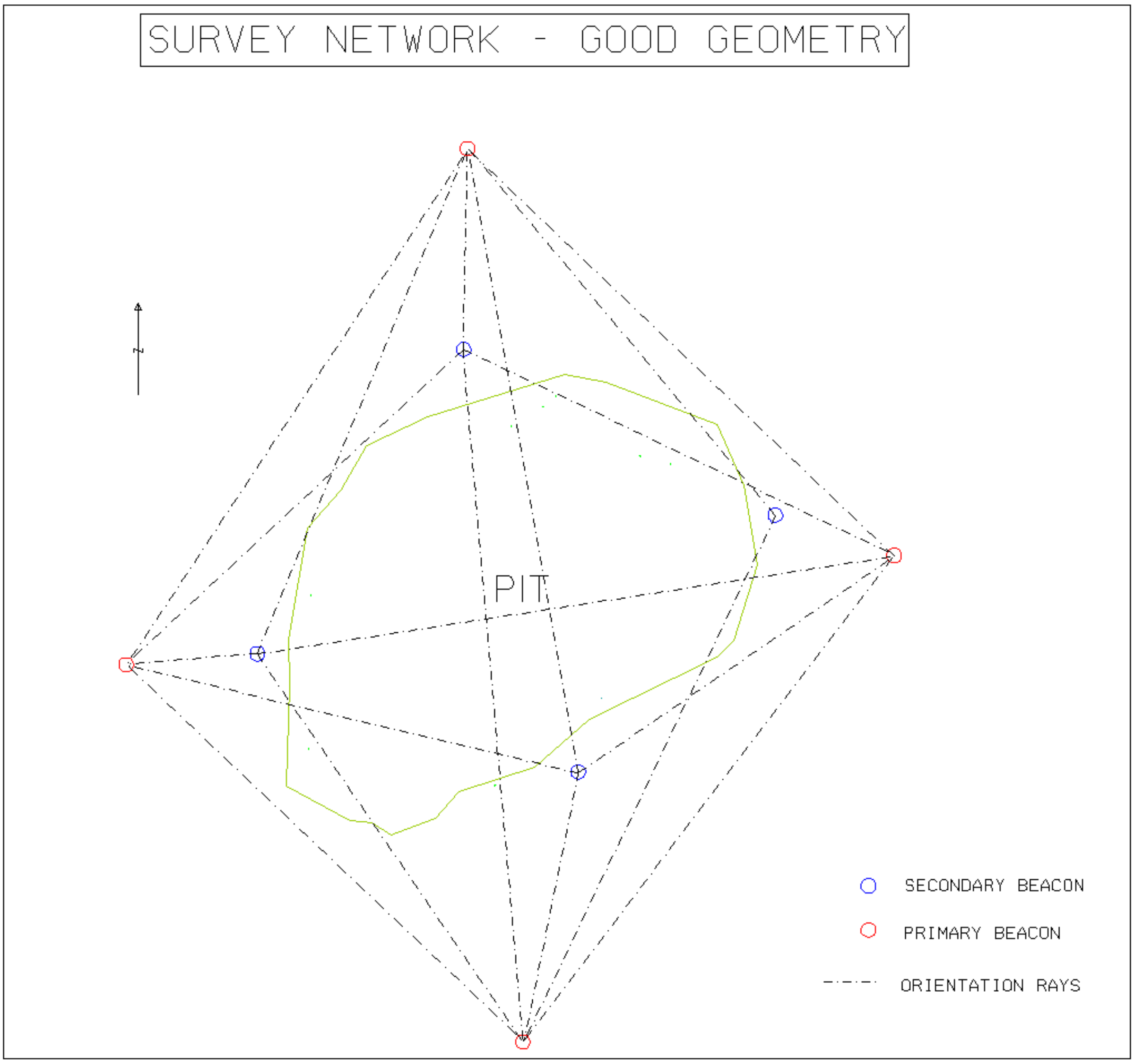
As a guide to designing a control network, Bannister et al. (1998) suggested the following considerations:

- There is need for a thorough reconnaissance of the area using maps, aerial photographs, future development plans etc. These plans and maps will be useful when establishing the positions of the primary beacons. The main priority here is to establish a clear line of sight by avoiding areas with view obstructed by buildings and areas targeted for development on the future plans.

- The geometry of the design should allow applications such as resection and triangulation to be done with minimum geometric constraints. This means that the geometry of the beacons should allow for long sights and avoid acute angles as this might affect the accuracy of the surveys.
- Secondary beacons are to be positioned closer to the points of detail and referenced to the primary beacons. In the case of pit stability monitoring, it is advisable to have them on the edge of the pit to allow clear view onto the pit.

As for the primary beacons, Cawood and Stacey (2006) suggested that they could be anywhere between 100 m and 3 km away from the pit rim depending on the conditions. The conditions will be considerations such as the ability of the ground to withstand vibrations from blasting and the line of sight to the monitoring station. The importance of having a correct control network design is emphasized by Thomson (2005) who observed that poorly designed control network will result in orientation errors outside the limit of tolerance. This will, as a result affect the accuracy of the monitoring surveys. Kealy (2010) recommended that the survey network should be tested for accuracy using suitable independent checks. To emphasize the importance of independent checks, Thomas (2011) highlighted that the survey control network should be surveyed using the GPS post processing mode and the conventional survey methods to provide assurance on the integrity of the network. For the purposes of geo-referencing, Thomas (2011) suggested that the primary beacons be linked to the national control survey. However, he cautioned that the vectors measured to the national trigonometrical beacons must not be included in the final slope stability monitoring beacon network adjustment as that may affect the accuracy. An ideal survey control network is as shown in Figure 1.

Figure 1 Layout of an open pit with a good survey control network



2.3 Beacon Design and Construction

Having established the geometry of the network design with respect to the monitoring site, the next aspect to consider is the actual construction of the beacon structures. Bannister et al. (1998) emphasized that beacons must be rigid and robust. They should be able to survive prevailing conditions such as blast vibrations. Typical regular blasting associated with mining should have minimum impact on their stability. Although vibrations are expected to have impact on the secondary beacons, it is more important that the primary beacons withstand these vibrations.

The primary beacons will be used for orientation during geodetic surveys but most importantly will be used to check the stability of the secondary beacons including the monitoring beacon.

To achieve maximum stability of the beacons, the first step is to identify stable ground. It is advisable to involve personnel from geotechnical engineering to avoid weak ground such as areas along geological faults. This is critical for secondary beacons as they will be constructed near the crest of the pit such that there is a clear line of sight in the pit as per Cawood and Stacey’s (2006) observation. There is also need to consult with structural engineers who will design the optimum beacon structure designed to withstand vibrations from pit blasting.

The structural design of the primary and secondary beacons is similar as observed by Banister et al. (1998). The main difference between the primary and secondary beacons will be the height above ground (Figure 2).

Figure 2 Example of a Beacon Design

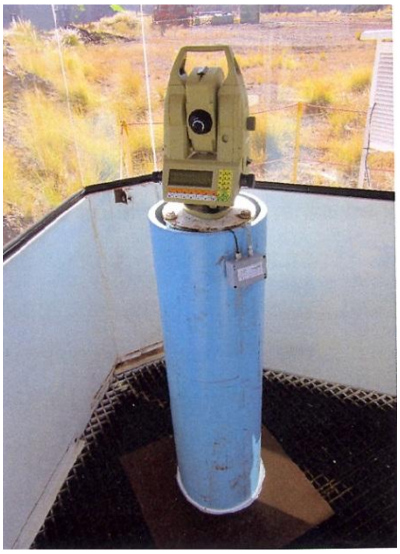
Primary Beacon Secondary Beacon

Source: Orapa Mine Survey Department (2010) and Thomas (2011)

As Cawood and Stacey (2006) suggested, the primary beacons should be at 100 m or 3 km away from the crest of the pit and still maintain a clear line of sight with the secondary beacons. In a typical mine layout, there is usually structures around the pit such as stockpiles, waste dumps, buildings and other infrastructure that might obstruct the line of sight. Where circumstances permit, the primary beacons should be constructed such that they rise above these structures for them to be visible from the monitoring stations. This means that some primary beacons will be very tall. It is critical that the foundation of these beacons be built on hard ground or rock. As per the Leica reporter 50(2004), this might require boring through soil types such as sand to get to the hard stable rock.

The design of the survey beacons should be done by structural and geotechnical engineers. The design of the beacons should describe the work to be done and the conditions to be expected during the construction, (Abramson et al, 2002). Abramson et al (2002) emphasized that the design should relate construction specifications clearly such that contractors should not have to figure out anything for themselves. During the construction of the beacons, building inspectors from the mine should be tasked with the responsibility of seeing that construction is done according to specifications, (Abramson et al, 2002). Thomas (2011) highlighted the importance of construction specifications as a slight change in construction material can compromise the integrity of the beacons. The beacons with a steel casing will expand on one side when exposed to the sun hence causing the beacon to move. Thomas (2011) advised that the casing of beacons be made from thick plastic or concrete so that expansion can be mitigated (Figure 3).

Figure 3 Beacon with plastic pipe casing to mitigate the effect of the heat of the sun on the pillar



Source: Thomas (2011)

Thomas (2011) observed that the change of construction material as stated will lessen the effect of the heat of the sun on the beacon. At the completion of the construction exercise, Thomas (2011) observed that at some mines the survey beacons are given a three month curing and settling period after construction before they can be used for monitoring.

2.4 Survey Monitoring Instrumentation

There are several factors to consider when selecting the survey monitoring instrumentation, but the most important aspect is the accuracy and precision, (Abramson et al, 2002). The question to answer is whether the instrument will detect the expected movement of the structure. Read and Stacey (2009) emphasized this fact by listing the determination of parameters to be monitored and the potential magnitudes as one of the key steps to setting up a movement monitoring program. Cawood and Stacey (2006) advised that when choosing the monitoring instrumentation one should evaluate the economic value add of the system, the required level of confidence of the results; how it will complement geotechnical instruments, ease of interface, GIS adaptability, survey budget for these instruments and the training necessary for its optimal use. Another key factor to be considered is the size of the monitoring area, the number and frequency of measurements

(Cawood and Stacey, (2006). In selecting instrumentation for slope stability monitoring, Abramson et al. (2002), suggested the following steps;

- Defining the purpose of the instrumentation
- Defining the geotechnical questions to answer
- Selecting parameters to answer
- Predicting magnitudes
- Identifying location where the instrument will be used
- Preparing budgets.

Abramson et al. (2002) recommended good quality instruments to avoid unnecessary distractions such as malfunctions.

Once the appropriate instrumentation has been identified, the next exercise is the installation. It is critical to install the monitoring instruments properly as poor installation will result in inaccurate and misleading information. The instruments should be installed by technicians who are fully conversant with the equipment and who have detailed knowledge of the factors influencing the performance of the instruments as the manufacture's installation manuals are seldom adequate. It is further suggested that instruments should be installed well before the actual monitoring starts so that checks and background noise level can be made and baseline established for subsequent observations, (Abramson et al., 2002).

Reliability has been highlighted as one of the factors to consider when choosing slope stability monitoring instruments. There is need to continuously monitor the instruments in terms of reliability by ensuring continuous calibration of the monitoring equipment during their life of operation. It is advisable that the calibration be carried out systematically by a suitably competent person who has an understanding of its purpose. It is further advocated that instruments sensitive to weather and gravity variations should be calibrated on site as accuracy on distance measurements is affected by weather conditions when using geodetic survey instruments (Abramson, 2002). The measuring range of laser scanning equipment is also affected by weather conditions.

Once the instrumentation requirements have been established, Abramson et al. (2002) suggested the following steps to complete the equipping process;

- Procuring the instruments
- Installing the instruments
- Calibrating and maintaining the instruments
- Establishing the factors that influence measurements
- Establishing operating procedures of ensuring data correctness.

Furthermore, Abramson et al (2002) advised that when selecting instrument types one should try and incorporate cross checks in the system by using different types of instruments rather than duplicating instruments of the same type. This kind of deployment also allows the different instruments to complement each other. To ensure that cross checking among instruments is achieved, Thomas (2011) stressed that the slope monitoring equipment must be available at all times to ensure that monitoring duties are met. Avoidable breakdowns on monitoring equipment should be avoided at all costs by purchasing robust and proven brands.

There are several surveying monitoring equipment available but the author will focus on the following; Geodetic Survey, Slope Stability Radar, GPS surveying systems, Satellite imaging subsidence monitoring. The format (coordinate systems) of the data gathered by these instruments will be discussed. This will be followed by analysis and presentation of monitoring results from this equipment. There will be a discussion on how to respond when the above mentioned equipment detect ground movements.

2.4.1 Geodetic Surveying

Geodetic survey is still the primary method of monitoring large open pit mines. Geodetic survey involves the use of survey equipment such as Total Stations and levels. Traditionally, geodetic monitoring involved the use of theodolites to capture distance and angles which were measured by the surveyor in the pit and reduced to three dimensional coordinates. This process was repeated several times until enough spatial data was available to analyse movements using software such as excel, (Watt, 1996).

According to Read and Stacey (2009), this process has now been automated and the modern Total Station can continuously capture data from the targets in the form of three dimensional coordinates and automatically transmit the data to a computer for analysis. The most commonly used automated geodetic survey is the Geodetic Monitoring System (GeoMos) developed by Leica. The GeoMos was developed by Geosystems and uses the Leica TCA2003 which automatically collects data and transmits it to a central computer for analysis. The Central computer is equipped with software which continuously plots graphs for analysis. The accuracy of the TCA2003 when on Automatic Target Recognition (ATR) is specified as 2-3 mm over a distance of 500m, (Leica Geosystems, 2010).Trimble utilizes the Total S8 for geodetic monitoring. The system is designed such that monitoring data is collected using the Total Station sent to a computer for processing. The results are analysed and plotted using the 4D control software (Trimble, 2010). The automation of the geodetic monitoring allows the data to be collected continuously. However, Thomas (2011) advised that, to reduce wear and tear on the instrument, the Total Station used in the GeoMos should be set in such a way that it measures in one hour cycles instead of measuring continuously for 24hrs as is the case in most mines.

When using the GeoMos, it is necessary to construct a shelter on or around the monitoring beacon to ensure that the instrument and the monitoring beacon are in continual shade. The reason for the shelter is to mitigate on the effect of the sun on the instrument and the monitoring beacon itself (Thomas, 2011).

Although automated geodetic monitoring is considered to be robust, as it can detect movement in any direction including velocity and acceleration, it has its own limitations;

a) Geodetic survey uses prism reflectors as targets to continuously collect the spatial data. The reflectors are mounted on iron rods drilled on the monitored ground. The targets are placed along the monitored area. The limitation is that there is usually a spacing of approximately fifty meters between the targets. The spacing is usually reduced depending on the geotechnical risk level of the area being monitored. The area in between the targets is not measured hence its movement is inferred from readings taken from the targets, hence lowering the level of confidence.

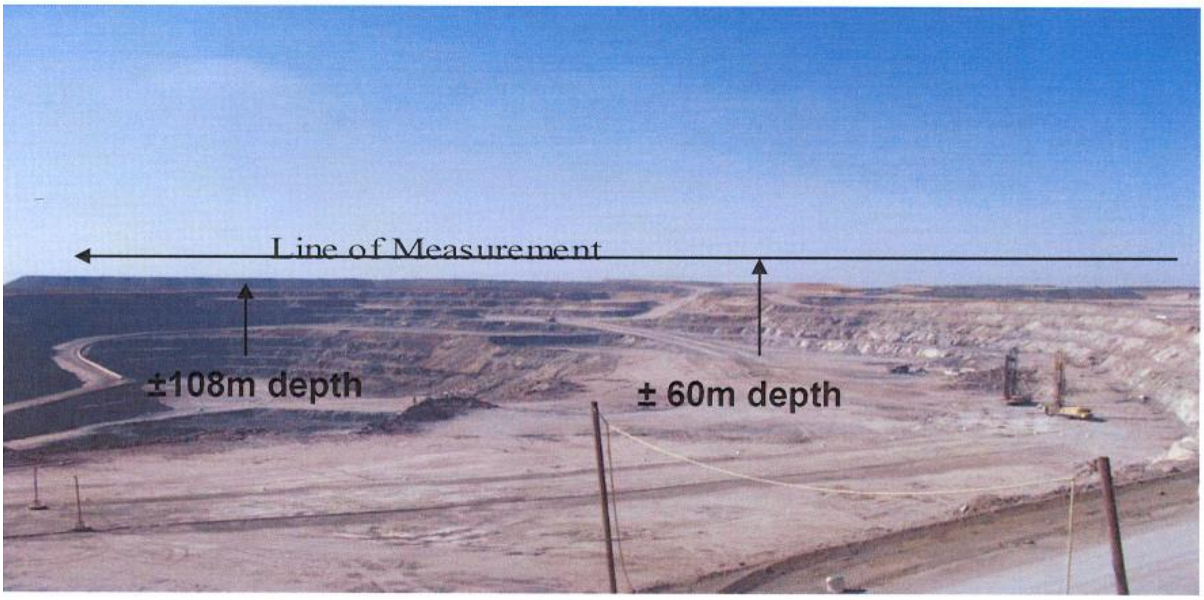
b) Weather conditions, especially dust makes it necessary to do frequent cleaning of the prism used as monitoring targets. This becomes impossible when the prisms are located on previously mined faces which have become inaccessible (Leica Geosystems, 2010) as shown in Figure 4.

Figure 4 Prism installed on a mined face

Source: Thomas (2011)

c) Atmospheric conditions: When using Geodetic Survey instruments, errors are introduced when the line of sight passes through the atmosphere with an uneven density distribution, (Read and Stacey, 2009).A good example is a ray travelling across different benches of the pit from the Total Station to a target which is on the other side of the pit as shown in Figure 5. The different bench depths provides for inconsistent atmospheric conditions such as temperature and pressure variations (Jooste, 2005).

Figure 5 The effect of depths on temperature



Source: Jooste (2005)

d) With temperatures often reaching higher 30s in the summer, which is the case at all the Debswana Mines (Jwaneng, Orapa, Letlhakane), a lot of atmospheric interference is experienced which affects the accuracy of the measurements (Leica Geosystems, 2010).

e) In the past, long distances have been a limiting factor to the ATR; however the Leica TM30 is now available in the market and it can measure up 3 km on ATR mode (Leica Geosystems, 2010). Thomas (2011) cautioned that the acceptable accuracy on measurements will only be achieved when genuine prisms are used for monitoring.

f) The other limitation associated with Geodetic surveying monitoring is that it needs a clear line of sight for orientation and measuring rays. When working in built up areas like the mining environment, it becomes difficult to have a line of sight to all the required survey stations.

To enhance the geodetic surveying instruments, the other monitoring system available are as follows; Slope stability radar, GPS surveying system and satellite imaging subsidence monitoring.

2.4.2 Slope Stability Radar

To address the limitation of point monitoring done by Total Stations, most open pit mines adopted the Slope Stability Radar (SSR). Read and Stacey (2009) stated that the radar has got an advantage in that an entire section of the wall can be monitored remotely in near real life time without the use of reflectors and regardless of atmospheric conditions.

Data from the radar is transmitted to computers in a central office for interpretation and analysis, (Read and Stacey, 2009). Unlike with the GeoMos or The Trimble 4D, the data can also be viewed at the unit in the pit. The SSR's ability to cover large areas and rapid redeployment makes it ideal for operational safety monitoring (Read and Stacey, 2009). This allows for mining equipment such as drills and shovels to work on high risk areas while the radar is monitoring these areas. As stated earlier the data can be analysed on site and the mining equipment can be moved right away if any instability is detected.

On its initial implementation, the radar had a range limitation as it could only measure up to approximately 800m, which has been addressed as units measuring up to 1800m are now available on the market, Read and Stacey (2009). Read and Stacey (2009) highlighted that as the range is increased, accuracy also decreases. According to Read and Stacey (2009) sub-millimetre accuracy is achieved for the range at 800m or less. Recent developments have seen the slope stability monitoring radar being global positioning system enabled, (Mining Weekly, 2009). This has addressed the limitation associated with the inability to link historical data with the current due to non- availability of geo-referencing function as highlighted by Jooste (2005).

Read and Stacey (2009) observed that because the radar does not monitor the 3D aspects of the movement, the system becomes less useful in defining the mode of instability even though it determines the extent of the moving mass accurately. The radar is therefore, frequently used with a survey monitoring system such as GeoMos, which can define the sense of displacement, Read and Stacey (2009).

2.4.3 GPS Surveying

To address the limitation posed by lack of clear line of sight when employing the Geodetic Survey monitoring method, open pit mines usually utilize the Global Positioning Systems (GPS) for monitoring. GPS based on satellites orbiting the earth can be used for real-time positioning at any location 24hrs a day in any weather. The main applications for GPS in an open pit mine is the monitoring of waste dumps and providing high accuracy control for surveying monitoring base stations. The latter involves measuring of the primary and secondary beacons and the post processing of the data for establishment of their positions (Read and Stacey, 2009). The GPS technology is suitable for use where there is clear satellites visibility. Wang et al (2010) cautioned that the number and geometric intensity of visual satellites is susceptible to large slopes in open pit mines.

There has been a development within the GPS technology which has resulted in a product development project addressing the remote monitoring of small movements as found in structures such as buildings, land slide or earth settlements (Manetti et al*.* 2002). Manetti et al. (2002) described the system as consisting of a number of small receivers commonly known as Pseudolites installed on the object to be monitored as shown in Figure 6.

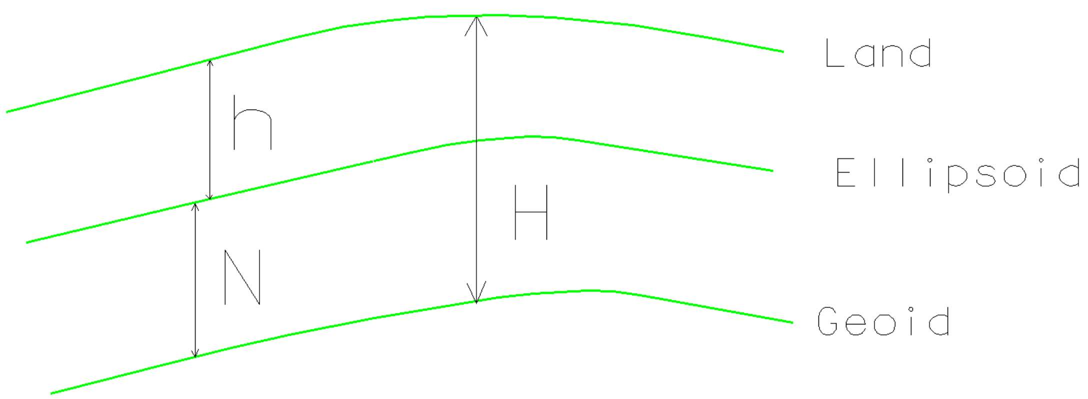
Figure 6 GPS Reference Station

Source: Leica Geosystems (2011)

To complement Manetti et al.'s (2002) assertion, Wang et al (2010) added that Pseudolites technology can increase the number of visible satellites and strengthen their geometric intensity to provide a precision solution for slope deformation monitoring. The data is collected and post processed at a central location. None- real time nature of measurements are noted by Manetti et al. (2002) as one of the limitations associated with GPS monitoring. They also observed that the geometry of the satellite constellation during observations has got a direct influence on the measurement quality. The satellite geometry can be compromised when measuring close to buildings and high walls of the pit.

Another limitation associated with GPS monitoring is the inaccuracy on the height measurements. Jooste (2005) observed that the height component (z) is generally 2 to 3 times more inaccurate than the horizontal component. Milbert (1991) explained that the normal geodetic levelling provides a height above mean sea level while the GPS measures ellipsoid heights (Figure 7). The error is introduced by adjusting the ellipsoid height to the height above sea level, (Milbert, 1991). The accuracy in height measurements makes the GPS unsuitable for subsidence monitoring.

Figure 7 Difference between Height above sea level (H) and ellipsoidal height (h)



Source: Milbert (1991)

2.4.4 Precise Levelling

To mitigate for inaccuracy in elevation measurements by GPS, mines have traditionally used precise levelling for subsidence monitoring. The Durban Corporation (1987) stated that the greatest possible height accuracy can be achieved by precise levelling. It is recommended that the precise levelling observations be carried out only under favourable conditions of weather and light so that a high level of accuracy can be achieved (Durban Corporation, 1987). Davis et al. (1968) emphasized the need to correct for both systematic errors and random errors when applying the precise levelling method. These errors could be due to variations in atmospheric refraction, line of sight not parallel to axis of level tube, temperature changes, earth's curvature, parallax or incorrect settlement of the tripod on turning points. To reduce or eliminate the effects of these errors, Davies et al. (1968), recommended the following procedures;

- Adjusting the instrument to balance the sum of back sight and foresight distances. This method is also known as the collimation correction.
- Focusing carefully and checking the bubble before each sight.
- Shielding the level from the sun.
- Choosing definite and stable points.
- Taking short sights

There have been developments in the industry leading to suppliers producing automated levels with high levels of accuracy. The digital reading and recording of data has improved the accuracy by eliminating human errors (Trimble, 2010). Digital levels are also installed with an automatic compensator which ensures that the line of sight is horizontal so that each staff reading is reliable (Leica, 2010). Examples of the more accurate levels are the Leica NA2 precise automatic level and the Trimble AL200 class of optical levels.

The type of instrument used for precise levelling will also affect the accuracy of the results, however, the skill of the leveller will have a greater influence on the results irrespective of the type of the instrument used (Davies et al., 1968). The disadvantage associated with precise levelling is that it is a point measuring technique, hence becomes a problem when large areas have to be covered. It is also labour intensive.

2.4.5 Satellite Imaging Subsidence Monitoring

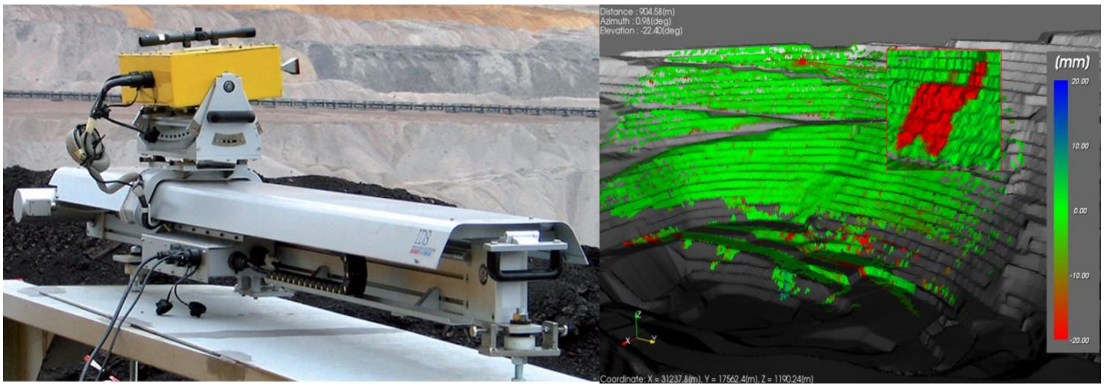
Developments in the area of subsidence monitoring have seen the emergence of the Interferometric Synthetic Aperture Radar (InSAR) technology. Read and Stacey (2009) defined InSAR as a technique that uses the differences in phase between Synthetic Aperture Radar (SAR) images, which can be acquired by aircraft or satellite. When these images from different phases are compared, changes in elevation can be detected, Read and Stacey (2009). Canuti et al. (2002) further observed that the SAR images can also be captured using portable ground based instrumentation, to produce high resolution images. Figure 8 illustrates a ground based SAR and the images it produces. Furthermore, Canuti et al. (2002) noted that the ground based inferometry technique is well suited for applications in emergency conditions as an early warning system. They estimate the accuracy of this system to be 3mm with a precision of 0.75mm.

Doyle et al*.* (2001) stated that Synthetic Radar Interferometry (InSAR) has proved to be a powerful tool for mapping of subtle ground surface deformations over extensive areas. They further stated that the InSAR is capable of imaging surface deformations covering tens or hundreds of kilometres (Doyle et al, 2001). In 1999 the SAR Interferometry successfully derived a map of surface deformation after a mining town of Welkom (South Africa) was shaken by a magnitude 4.5 earthquake (Doyle et al, 2001).

Read and Stacey (2009) list some of the limitations of InSAR as;

- Being less effective at determining subsidence over areas less than 100 square meters.
- Not providing accurate results in areas where the slopes are very steep.
- The method not being real time.

Figure 8 A Ground Based SAR and the images it produces



Source: IBIS-M (2011)

2.5 Coordinate Systems

Most monitoring instruments discussed in this paper record 3D measurement and process them electronically. The results are stored in electronic databases as spatial data. When using different types of monitoring equipment in one mine it is critical to use one coordinate system such that the 3D spatial data from the different sources can be manipulated more effectively. It is also important to choose the appropriate coordinate system. When working with spatial data, it is important to be specific about the underlying coordinate system since the reader deserves to know at all times, Burkholder (2001). The importance of having spatial data properly coordinated is emphasized by Burkholder (2001) who stated that spatial data loose value if it is incomplete, incompatible or it is in the wrong format.

Burkholder (2001) discussed three coordinates systems; earth-centred earth-fixed (ECEF) rectangular Cartesian coordinate system, geodetic coordinate system and the local coordinate system. He highlighted the following points among others when describing the three coordinate systems;

- The geodetic coordinate system matches more closely the physical reality in a global sense than does the ECEF system and is very useful for cartographic visualizations.
- The geodetic system is computationally more complex and more cumbersome to use than rectangular components when working in 3D spatial data
- A local coordinate system assumes that the earth is flat. This assumption does not work when one needs greater precision, working over large areas or needs to establish compatibility between local coordinate systems.

It is critical to consider the points above when the mine decides on which coordinate system to use for the monitoring data.

2.6 Processing and Presentation of Monitoring Results

With all the different monitoring systems discussed working together to complement each other, there is need to integrate the information under one system and present it to the users. The most commonly used system in the mines is the Geographic Information Systems (GIS).GIS is defined by Halounova (2002) as a tool for data archiving, analyses, evaluation, modelling and presentations. Over the years, GIS has evolved concurrently with data acquisition instruments such as the ones discussed earlier in the report, (Wolf and Ghilani, 1997).The GIS' ability to handle data from a variety of sources makes it ideal to handle slope stability monitoring information, (Wolf and Ghilani, 1997). Halounova (2002) reported that data such as slope, slope length, change of slope length and other attributes associated with landslides can be easily obtained from GIS but can be very tedious without GIS. He therefore recommended GIS as the best tool to integrate data from other sources such as GPS, aerial photos, satellite images as it is an open tool and easily adaptable. This is because data from GIS can be used with other tools such as mathematical analysis and other models. To further illustrate the GIS ability to integrate data, Paudits and Bedmarik (2002) observed that apart from the primary input data, it's possible to combine more input parameters of the environment like length of slopes, slopes orientation and more about hydrology and hydrogeology(i.e. micro river basins and ground water levels). The importance of the GIS is also highlighted by Cawood and Stacey (2006) when they observed that when selecting monitoring equipment, adaptability to GIS should be considered.

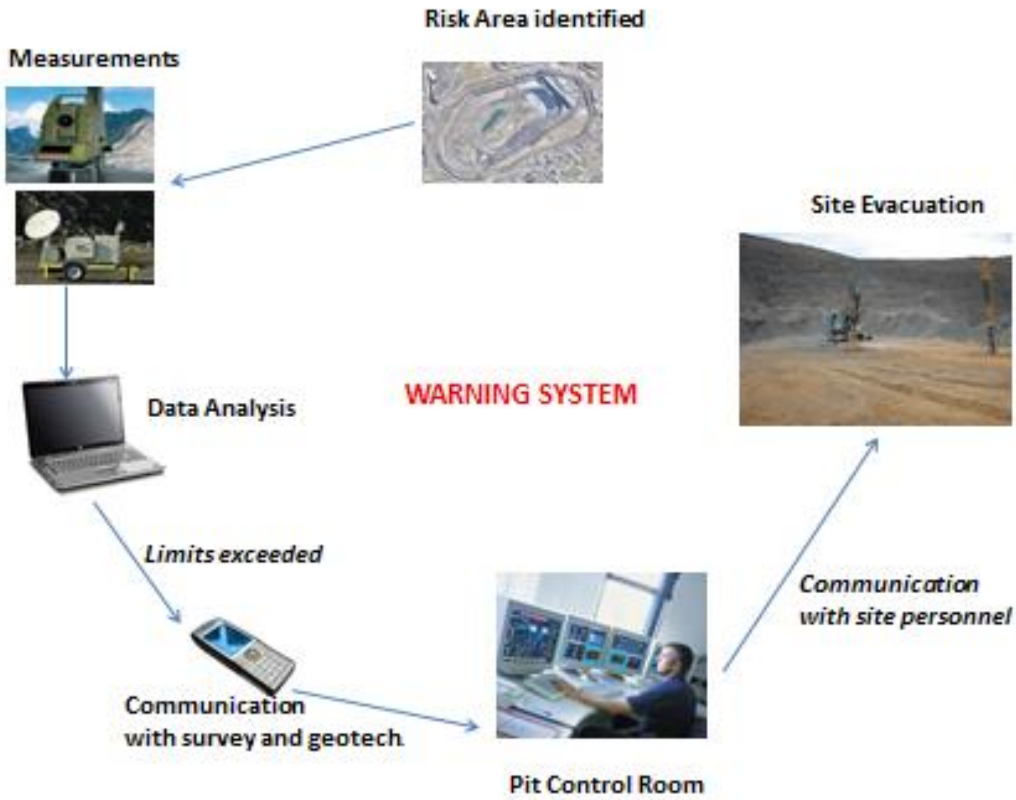
Wolf and Ghilani (1997) stated that before the spatial data can be presented in GIS, it needs to be processed for errors. These errors are introduced when spatial data is obtained from indirect measurements such as slope distance being converted to horizontal components, (Burkholder, 2001). The processes involved in accounting for these errors involve performing statistical analysis to assess error margins and studying their distribution, (Wolf and Ghilani, 1997). Furthermore, Wolf and Ghilani (1997) identified least square adjustment as the most common method used for analysing and adjusting spatial data. The primary purpose of least square adjustment is to compute operational redundancy numbers, standard deviations of coordinates and error ellipses, (Kealy, 2010). Least square adjustments and other statistical functions such as bivariate and multivariate analysis can be performed within GIS together with the functions involved combining data from different sources for interpretation, Paudits and Bedmarik (2002).

2.7 Warning Systems and Response

Once the monitoring information has been plotted on graphs, there is need to develop remedial action when ground movements are detected, (Abramson et al., 2002). Remedial measurements vary from increasing the frequency of measurements to total evacuation from the affected areas. Cawood and Stacey

(2006) emphasized that an appropriate monitoring system should warn employees of the potential danger and that it should be linked with the mine's slope management programme. Figure 9 shows an example of a warning system.

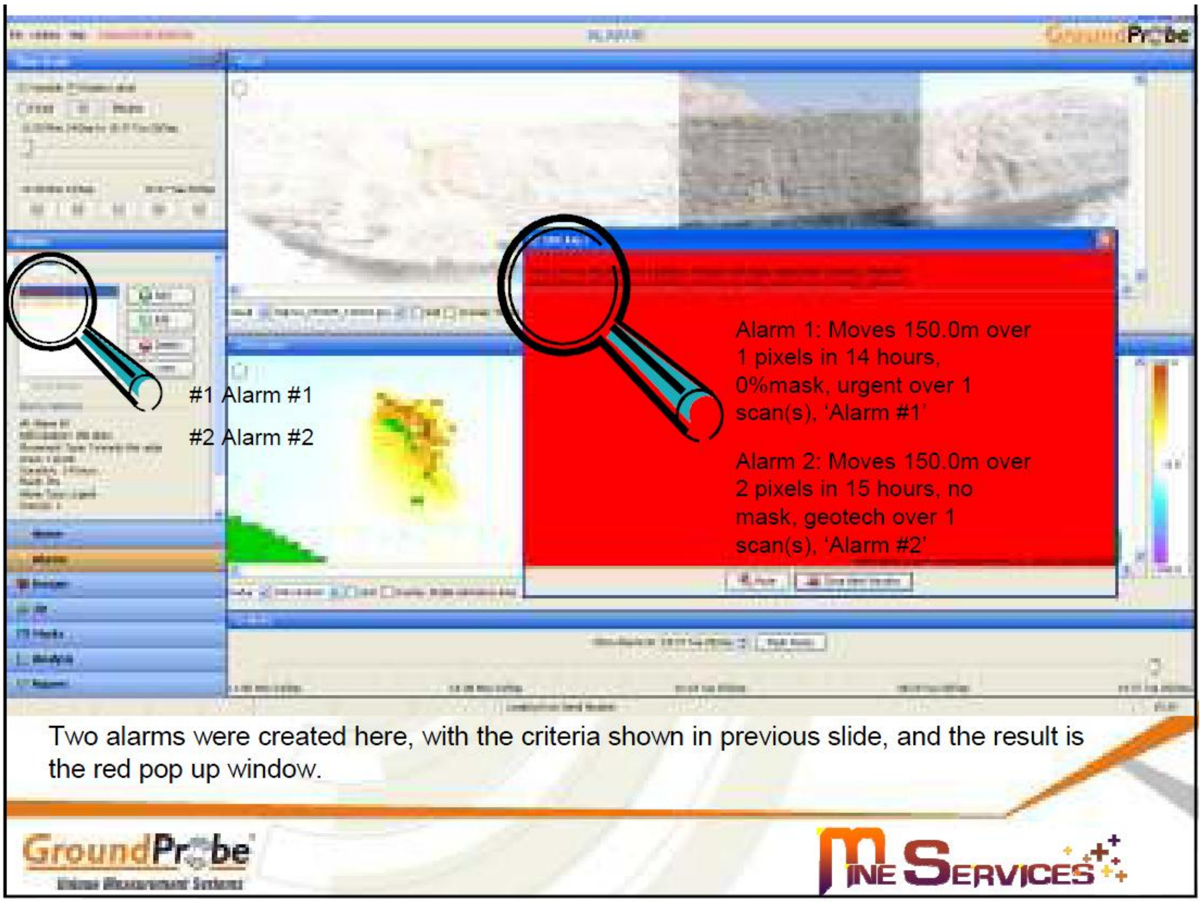
Figure 9 An illustration of a warning system



The De Beers Venetia diamond mine has developed guidelines on how to respond to different sizes of movements, (Jooste and Cawood, 2006). Before any alarm is raised at Venetia mine, exponential cumulative movement on the GeoMos graphs is investigated by the survey and geotechnical departments in order to assess the impact of movement and establish beyond doubt that movement is related to slope instability, (Jooste and Cawood, 2006). This combined investigational approach is aimed at avoiding raising false alarms which might end with the system losing credibility. It is important to have the different warning systems understood by key personnel such as mine supervisors and foremen working in the pit.

At Venetia Mine, movement detected by the SSR occurring after normal working hours, is indicated by a flashing red signal on computer at the main control room as shown on figure 10, (Jooste and Cawood, 2006).

Figure 10 An illustration of a pop up message



Source: Jwaneng Mine Geotech. Department (2010)

The red signal requires contacting of the shift foreman, who must investigate the situation and report to the geotechnical personnel on standby, (Jooste and Cawood, 2006). Both the Leica GeoMos and the Trimble 4D software have a functionality which enables e-mail and short messaging service (sms) messages to be sent to the relevant people if movement limits have been exceeded, (Trimble, Leica Geosystems, 2010). The GroundProbe SSRViwer software also has a unique way of setting off alarms when deformation limits have been reached (GroundProbe, 2010).

2.8 Budget and Personnel Responsibilities

When everything else has been considered with regard to the design of the slope stability monitoring system, the main constraint when it comes to implementation is usually the budget. It is critical to consider the budget limitations when making recommendation for the design. Monitoring equipment and software is very expensive to purchase and maintain. There is need to emphasize the economic value added as a result of the system when justifying the high costs associated with monitoring equipment (Cawood and Stacey, 2006). It is always wise to link the monitoring with the steepening of slope angles as this brings a big economic benefit to the mine.

For the slope stability monitoring program to be successful there is need to have competent people looking after it. Thomas (2011) observed that operations should have slope monitoring strategies which include allocation of responsible personnel. It is recommended that the key personnel, the geotechnical engineer and the mine surveyor should complete accredited courses in ground movement monitoring, to augment their respective qualifications (Thomas, 2011). Furthermore, Thomas (2011) highlighted that, in case of surveying, because of the legal implications, the mine surveyor responsible for slope monitoring should be deemed a competent person. Slope stability monitoring is a very dynamic science with the ever changing technology and the personnel involved in the subject should regularly update their knowledge by reading technical papers and attending technical meetings or conferences as recommended by Thomas (2011).

2.9 Conclusion

The design for slope monitoring systems should follow the same process as the one followed in designing rock slopes. The process should follow established design principles, such as the ones proposed by Bieniawski (1991). There are several systems available for slope stability monitoring. Each system has got its own strengths and limitations. When designing slope stability monitoring systems it is important to deploy the various systems in such a way that they will complement each other. Due to the large amount of spatial data collected by these systems, it is critical to have the data in one format, called the coordinate system. This will allow for seamless flow of information between the monitoring systems. The flow of information can be achieved by the use of software capable of integrating information from the various data sources. The integrating software should be capable of performing statistical data analysis and presenting the results in a graphical format. The advantage of analysing data using integrating software is that similar trends from different data sets can be established easily.

When designing the survey control network, survey principles such as working from the whole to the part should be applied. The construction of the survey beacons, if not done properly, can affect the monitoring results negatively. There is need to engage specialists such as structural and geotechnical engineers during the design and construction of these beacons. During the implementation of the design, there is need to follow a systematic process from construction of survey beacons to the calibration of instruments as recommended by Abrahamson et al (2002).

The next area of discussion is a brief description of the existing slope monitoring system at Jwaneng mine. This description will aid the author when analysing current design strengths and weakness. The author will then combine the knowledge from the literature review and learning points from the existing setup to come up with an optimal design which is the purpose of the research.

3 DESCRIPTION OF THE SLOPE MONITORING DESIGN AT JWANENG MINE

The purpose of this chapter is to describe the slope monitoring design at Jwaneng Mine. As mentioned earlier in the report, Jwaneng Mine of Debswana will be used as a case study. The description will be followed by an analysis which will assess the current design against the knowledge gathered from the literature review. The learning points from the analysis will be incorporated into the process of designing the optimal slope monitoring system.

To assist with the description, the following data was collected from Jwaneng Mine;

- Plans showing positions of the survey stations
- Plans showing existing infrastructure and future developments
- Mine layout
- Monitoring equipment utilized at the operation
- Beacon design and construction specifications
- Data from the monitoring equipment
- Monitoring procedures
- Jwaneng Mine long term planning reports

The above information was obtained from the mine database and was verified by the responsible personnel. There were also verbal discussions and e-mail communications with personnel from mine planning, surveying and geotechnical engineering departments to clarify some aspects of the documents. The description of the existing setup will focus on the control network design, survey beacon design and construction, survey monitoring instrumentation, analysis and reporting of monitoring results, procedures, personnel responsibilities and costs.

3.1 Control Network Design

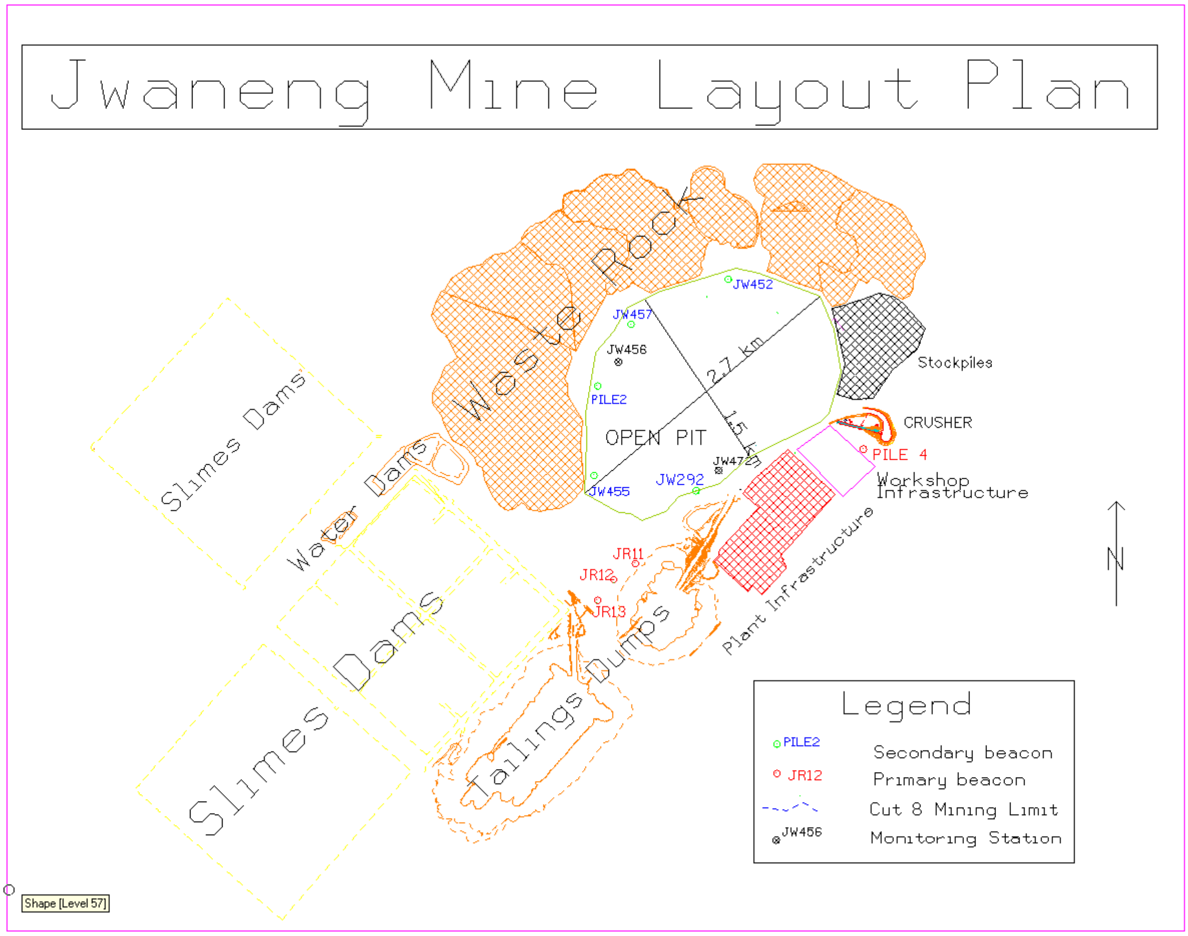
The first aspect to be discussed is the survey control network at Jwaneng Mine. The discussion will be on how the survey beacons used for slope monitoring are positioned with respect to the pit.

Figure 11 Aerial Picture of Jwaneng pit

Source: Jwaneng Mine Survey Department (2010)

The Jwaneng pit is surrounded by structures such as dumps, stockpiles and built infrastructure as shown in Figure 11. This kind of geometry is typical for open pit mines. The logic behind surrounding the pit with infrastructure is to shorten the cycle times to the dumps and processing machinery such as crushers and the plant. The survey network of beacons is setup as shown in Figure 12.

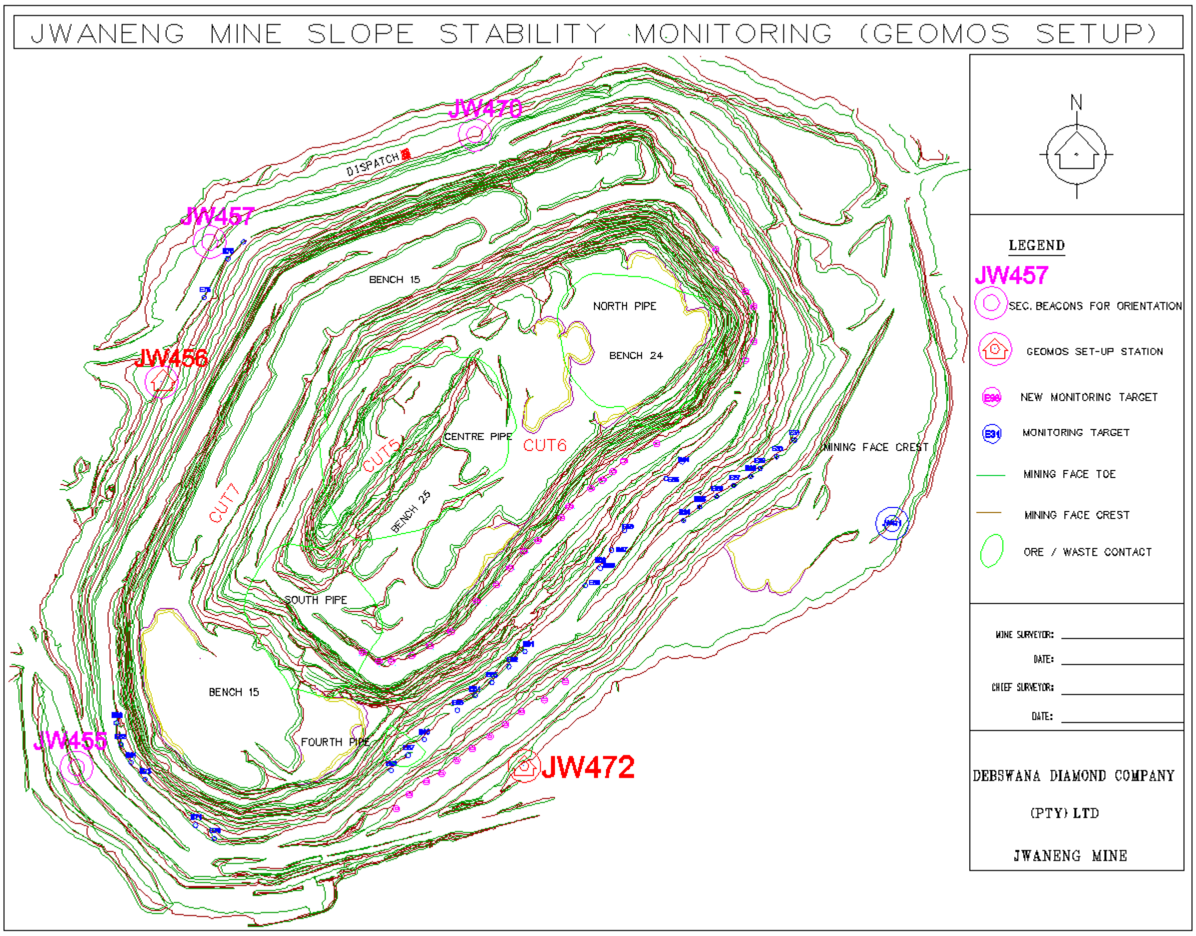
Figure 12 Jwaneng Mine Layout



Source: Jwaneng Mine Survey Department (2010)

The primary beacons were positioned on one side of the pit because of unavailability of space on the other sides of the pit (Figure 12). Although there are other beacons within the mine boundary used as survey control points, the author will focus the discussion on those primary beacons visible from monitoring beacons. These are the primary beacons utilized in slope stability monitoring. They are used mostly when applying the GeoMos and the GPS post processing.

Figure 13 GeoMos Beacon Positions



Source: Jwaneng Mine Survey Department (2010)

The GeoMos at Jwaneng Mine is designed such that it uses the secondary beacons for orientation as shown on Figure 13. The reason for using the secondary beacons for orientation instead of the primary beacons is because of the limited measuring range of the Leica TCA2003 Total Station when on the ATR mode. The Leica TCA2003 can accurately measure up to 1km when on ATR mode, and given the dimensions of the Jwaneng pit as shown on Figure 12 (1.5km x 2.5km), using primary beacons for orientation cannot yield accurate results. The primary beacons are used to check the positions of the secondary beacons using the GPS post processing method and the conventional survey methods. The positions of the monitoring beacons are regularly measured and updated in the GeoMos database. The positions of the primary beacons are measured by the resection method using the secondary beacons as known points. This application is called ‘free station’ determination in GeoMos. This process of regularly establishing and updating the position of the monitoring beacon is critical because the suspicion is that the monitoring beacon is not very stable. The suspicion arises from the fact that the monitoring beacon and other secondary beacons are in close proximity to the blasting sites and therefore affected by the blast vibrations. It is therefore critical to have the accurate position of the monitoring beacon at all times since the monitoring target positions are established from the monitoring beacon.

Figure 13 shows that most monitoring targets are on the southern side of the pit hence are monitored from station JW456. The southern side of the pit has been classified as high risk by the geotechnical engineering department and is the most active area with activities such as drilling, blasting and hauling. This makes the monitoring station JW456 key in terms of the GeoMos setup. A small number of targets are monitored from JW472.

3.2 Survey Beacon Design and Construction

The second design criterion is the construction of the survey beacons. The discussion will focus on how survey beacons are designed and constructed at Jwaneng Mine. Figure A1 (See Appendix), shows the design of the primary beacon as produced by the Debswana projects department. The design is done by a qualified structural engineer. The design for the secondary beacon (Figure A2) on the appendix is similar to the secondary beacon. The difference between the two is the height above ground and extra grouting as shown on Figure A2. The primary beacon is elevated so as to allow a clear line of sight to the monitoring beacons without obstruction from structures such as conveyor belts. The primary beacon is further reinforced with concrete blocks for stability and is equipped with a step ladder for safe access to the top (Figure A2). One important feature to note is the specification of grouting of (17-20) m recommended. This is to address the sand layer on the Jwaneng stratigraphy shown on Table 1. The 17-20m layer of sand is a key feature on the Jwaneng stratigraphy which has to be catered for during the beacon design and construction. It plays a key role in the beacon stability.

Table 1 Jwaneng Mine Stratigraphic Column

Stratigraphic Name (after Beukes, 2006)	Mine Rock Code	TIN Model Code	Colour for Modelling	Typical Thickness (m)	Description (after Dirks, 2001)
Kalahari Sequence	SAND	SAND	Brown	15 – 20	Sand cover
Kalahari Sequence	CALC	CALC	Light Brown	40	Calcrete capstone with cemented conglomerate layers (Custom colour 14: Hue = 34, Sat = 75, Lum =137)
Timeball Hill Formation	LS	LS	Light Red	Residual	Thinly bedded, laminated mudstone-siltstones, felsic volcanics,graphitic shale, with occasional intercalations of sandstone.
lower Timeball Hill Formation	CS	CS1	Red	30	Graphitic shale interbedded with felsic volcanic tuff. Thick units are likely to be tectonically duplicated.
Rooihoogte Formation	QS	QS1	Yellow	135	Thinly bedded, parallel laminated mudstone-siltstone-fine-grained sandstone beds. Graded bedding is common. Low-angle cross-stratification is locally preserved.
Chert pebble conglomerate	Bevets	BVT	Magenta	0 – 4.2	Silicified pebble conglomerate marker horizon
Rooihoogte Formation	QS	QS2	Yellow	375	Thinly bedded, parallel laminated mudstone-siltstone-fine-grained sandstone beds. Graded bedding is common. Low-angle cross-stratification is locally preserved.
lower Rooihoogte Formation	CS	CS2	Red	10	Graphitic shale and/or magnetic shale (iron formation) with diamictite horizons (frequency unclear)
Malmani Subgroup	DM	DM	Blue	Residual	Dolomite with chert inclusions

Source: Barnett (2009)

Once the design has been completed and approved by the various departments such as survey and geotechnical engineering, the drawings are passed on to the contracts department for tendering. The tender for the construction of beacons is open to a specific category of contractors as it is classified as small works. Debswana classifies contracts according to costs involved and contractors are not allowed to tender across classes. If a contractor is pegged on projects above 1 million pula, they are not eligible to tender for projects less than that value. During the tendering process the highest weight is given to the lowest bidder. Considerations such as technical capability of the contractor become secondary.

During construction, supervision is done by the clerk of works from the mine's project department. The areas where the beacons are to be constructed are inspected and approved by the mine surveyor and the geotechnical engineer. There is minimum interaction between the designing structural engineer and the clerk of works who is supervising the construction on site. The clerk of works normally has other mine projects to supervise during the same period.

3.3 Survey Monitoring Instrumentation

The next area of discussion is the slope monitoring instrumentation. The author will only describe the survey monitoring equipment.

Survey slope stability monitoring at Jwaneng Mine started as early as 1989 (Jooste, 2005). The monitoring involved manual collection of data using Total Stations. The analysis of the data was done using excel spread sheets. As the pit grew bigger in size due to increased production, the areas requiring monitoring increased. This proved to be difficult with conventional monitoring which needed the surveyor to be on site during the data collection.

Figure 14 Leica TCA2003 Total Station

Source: Jwaneng Mine Survey Department (2010)

In 2003 the mine introduced the automated GeoMos monitoring. The GeoMos utilizes two LEICA TCA2003 Total Stations as shown in Figure 14. The Total Stations are positioned on either side of the pit on monitoring beacons JW456 and JW472 as illustrated on Figure 13. The Total Stations collect the spatial data and transmit it to a central computer housed approximately 1 km away in the survey office. There are approximately 80 prism targets installed on the pit walls as per Figure 13. Although it had teething problems at an introductory stage the benefits were evident immediately as it could cover large areas in a short time. Since the data collection was automated, the surveyor spent more time analysing the information instead of collecting data. The main challenge that is still unresolved is the atmospheric corrections on the distance measurements collected by the Total Stations. Initially the Meteosensor was installed at the survey offices. The Meteosensor was later moved to one of the monitoring stations in order to capture conditions (temperature and pressure) similar to site that is being monitored which is the pit.

Figure 15 Instrument Shelter

Source: Jwaneng Mine Survey Department (2010)

The monitoring Total Stations are housed in an instrument shelter as shown in Figure 15. The primary purpose of the shelter is to protect the instrument from blasted fly rock and weather conditions such as rainfall and dust. Thieving is not a concern as Jwaneng Mine is protected by the security fence as per the precious and semi- precious act. The shelter was constructed using fibre glass. The view facing the pit was initially covered by glass, but the glass was removed as it was affecting the accuracy of the measurements. This has left the equipment exposed on the side of the pit where the dust and fly rock is most likely to come from.

Figure 16 GroundProbe Radar

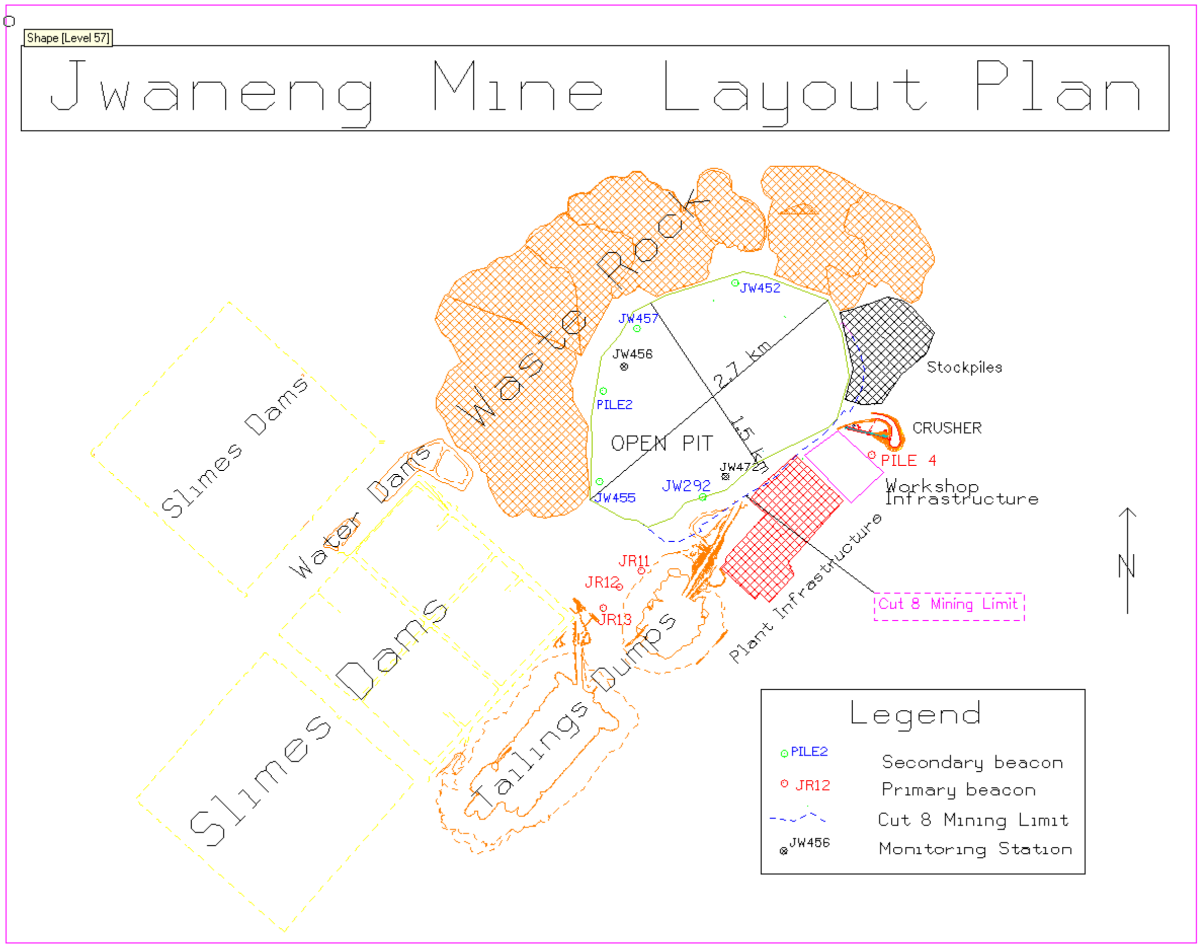
Source: Jwaneng Mine Geotech. Department (2010)

In 2005 the mine introduced another automated monitoring system by purchasing the GroundProbe Radar. The idea behind purchasing the radar was to complement the GeoMos which is a point measuring system. The Radar measures the entire section of the wall. Jwaneng mine currently has two units of the radar (Figure 16). The two units are setup such that the whole pit is monitored at all times. The two SSR units collect data from the field and send it to a central computer for processing. The units also have on board computers allowing for on-site analysis.

Jwaneng Mine utilizes the Trimble R8 GNSS GPS to check the stability of the survey reference stations (primary and secondary beacons).The positions of the beacons are determined by the post processing method which gives better accuracy on the x and y components of the coordinates. To mitigate for inaccuracy associated with GPS measurements on the z, value the mine utilizes precise levelling for subsidence monitoring.

Precise levelling is used to accurately determine the heights of the control points (primary and secondary) on a regular basis. A levelling network has been established commencing from the mine benchmark station. To check for subsidence around risk areas such as the plant area close to the Cut 8 mining limit the precise levelling method is also applied. The mine utilises the Leica NA2 precise automatic level for its precise levelling work

Figure 17 Jwaneng Mine Layout showing the Cut 8 Mining Limit



Source: Jwaneng Mine Survey Department (2010)

Jwaneng Mine has embarked on the Cut 8 project to extend the life of the open pit mining. The Cut 8 mining limit is encroaching onto the existing plant infrastructure as shown in figure 17. Some parts of the plant infrastructure will be moved to make way for the Cut 8 mining. The remaining infrastructure will be within 100m of the Cut 8 mining limit. This has heightened the risk associated with slope stability since any ground movement within the plant area can lead to huge production losses. To mitigate this risk the mine purchased GPS reference stations from Leica Geosystems. The plan is to install the reference stations around the plant area and along the Cut 8 mining limit. The reference stations will continuously collect data such that any ground and infrastructure movement in the area can be detected either in real time or during post processing. The reason for using GPS reference stations in the plant area is to mitigate for the lack of line of sight to the GeoMos monitoring stations. All geo-referenced slope monitoring systems use the UTM Lo coordinate system.

The installation of the monitoring equipment at Jwaneng Mine is the responsibility of the suppliers. The suppliers test and calibrate the instruments on site before handing them to responsible persons on the mine. The after sales maintenance of the instruments is also the responsibility of the supplier. There are Service Level Contracts between the mine and the various suppliers and the mine. The SLCs provide for services such as the support plan agreement, regular equipment calibration and renewal plan and processing software updates.

3.4 Data Collection and Processing

This section will describe how the slope monitoring data is collected and processed at Jwaneng Mine. The focus will be on the data collected by GeoMos, GPS, precise levelling and the SSR.

- GeoMos: When using the GeoMos, data collection involves taking measurements of vertical angles, horizontal angles and distance measurements to a series of monitoring targets. These measurements are then reduced to 3D coordinates for each measured point. The GeoMos is configured such that it automatically corrects for orientation misclosures during the process of monitoring. The system also applies atmospheric corrections on the distance measurements. All the monitoring targets are measured after set intervals and the displacement is calculated with respect to the monitoring station. The velocity and acceleration is also determined and plotted for each monitoring target. The position of the monitoring station is measured and updated on the database after set intervals using the ‘free station’ method in GeoMos. The ‘free station’ method uses a resection to determine the position of the monitoring station, using the secondary beacons as orientation points.
- GPS: The GPS at Jwaneng Mine is used to provide the high accuracy measurements on the control points (primary and secondary). The process involves placing GPS receivers on the beacons. The GPS then collects

satellite signals over a specific time. The processing of the data is done on the Trimble Geomatics Office (TGO) software. The data is corrected for errors using the free net adjustment (minimally constrained adjustment) and the fully constrained adjustment. The minimal constrained adjustment is used to detect bad observations while the fully constrained adjustment is used to transform the measured coordinates to the local coordinate system (Lo 25). The adjusted positions of the beacons are then determined and compared to the known positions to check if there is any movement on the control points. This process is supposed to be repeated every six months as per the guiding procedure.

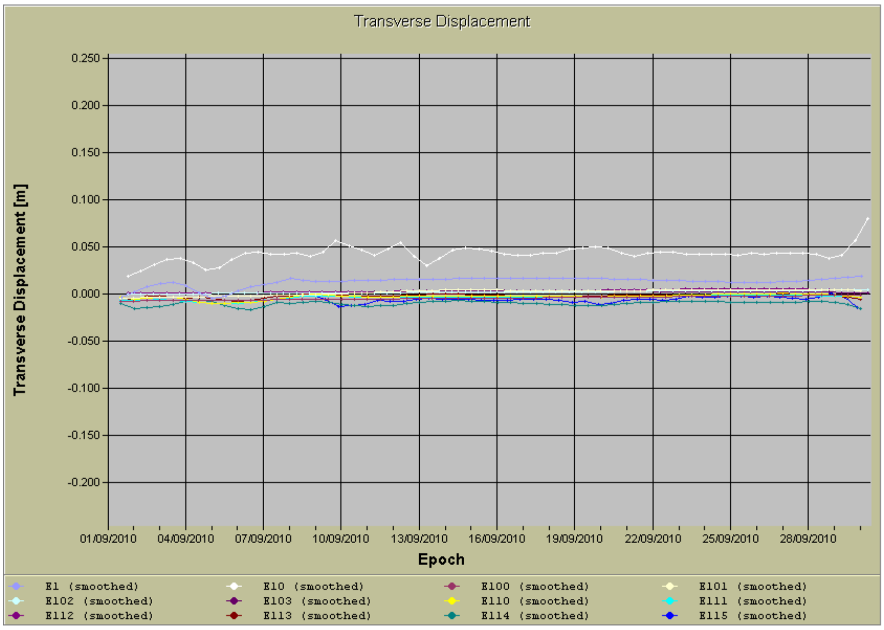
- Precise levelling: Precise levelling is used to determine the heights of the control points. The logic behind using the precise levelling method is to mitigate for the errors on the z measurements when using the GPS post processing method. A levelling network connecting the control points has been determined with the starting point being the mine's bench mark station. Before every levelling session a collimation correction (C factor) is done using the peg test method. With the Jwaneng temperatures being very high the level is protected from the sun using an umbrella to prevent thermal expansion.

  The levelling data is processed using the DNA/sprinter software. The software converts the raw data to a standard levelling book format. Random errors such as parallax and variations in atmospheric refraction are adjusted for within the software. The calculated heights of the control points are then compared to the known heights. This process is supposed to be repeated every six months. Precise levelling is also used for subsidence monitoring on areas identified to be at risk of subsidence.
- SSR: Jwaneng Mine uses the SSR to scan risk areas as identified by the geotechnical engineers. The data from the SSR is transmitted to a computer at the dispatch office where it is plotted using the SSRViewer software. The SSRViewer plots displacement graphs over time. These graphs can also be plotted on site on the SSR unit.

3.5 Analysis and reporting of Monitoring Results

Having discussed the data collection at Jwaneng Mine, the focus now turns towards presentation of the monitoring results from the above mentioned set of equipment. The discussion will now focus on how the monitoring results are analysed and reported.

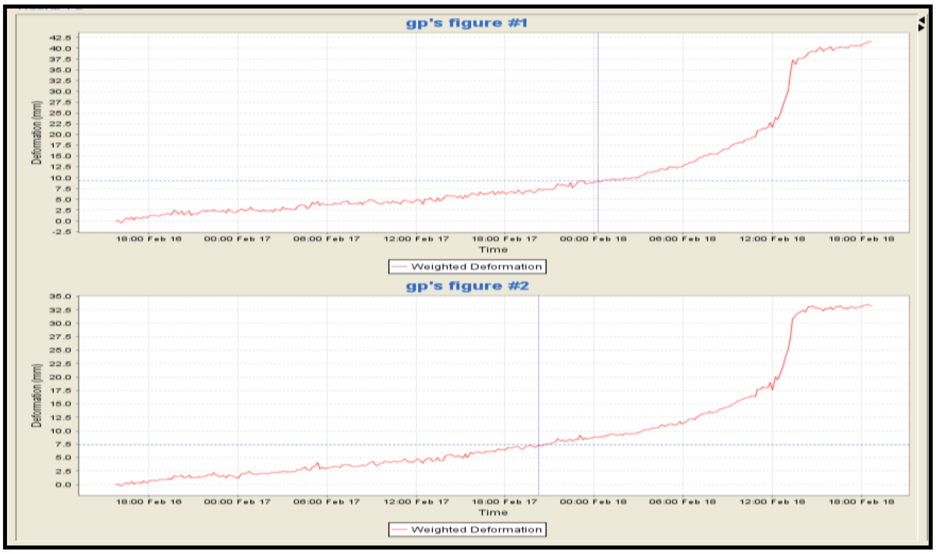
Figure 18 Movement graph from the GeoMos analyser



Source: Jwaneng Mine Survey Department (2010)

Monitoring data from the GeoMos system is analysed using the related software called the GeoMos analyser. The software can plot and present movements in any of the XYZ directions. The GeoMos analyser can also plot velocity and acceleration graphs. An example of a movement graph from the GeoMos analyser is as presented in Figure 18.

Figure 19 Movement graph as plotted on the SSRViewer



Source: Jwaneng Mine Geotech. Department (2010)

Data from the slope monitoring radar is plotted using software called the GroundProbe SSR Viewer. Unlike the GeoMos analyser this software cannot plot the movement directions but can plot the magnitude, velocity and the acceleration of the movement. A typical movement graph from the GroundProbe SSR Viewer is shown in Figure 19.Despite processing large amounts of redundant data, the GeoMos analyser and the GroundProbe SSRViewer has got no statistical adjustment functions. Therefore, the data from which the movement graphs are plotted from is unadjusted and can be classified as raw. There is no error propagation during the processing of the slope monitoring measurements. Atmospheric conditions at Jwaneng Mine have got a huge influence on the accuracy of the slope monitoring measurements. The lack of error propagation when processing these measurements lowers the confidence on the reported results. Other than the main software mentioned above, the mine has got other software used to process slope monitoring data. The Trimble PathFinder Office is used to process data collected by the GPS using the post processing method. The mine uses the Leica DNA/Sprinter software for processing precise levelling data.

3.6 Warning Systems and Response

Slope monitoring at Jwaneng Mine is guided by a set of procedures. This section will now focus on the procedures utilized at the mine.

Jwaneng Mine has a number of procedures guiding the slope stability monitoring programme. Some procedures are kept in the survey offices while others are with the geotechnical engineering section. The geotechnical engineering department has a generic code of practice which briefly covers slope monitoring in one of the chapters. Similarly the Survey department has a mine surveying code of practice which is also generic and touches on slope monitoring. The mine has got Service Level Contracts (SLCs) with the Leica Geosystems and GroundProbe with regard to the maintenance of the instruments purchased. The SLCs are more on general maintenance of the equipment to ensure continuous availability. There are also operational procedures meant to guide users on the operation of the equipment. The survey department has mapped the survey slope monitoring process. Operational procedures on GPS post processing and precise levelling are also available from the survey department.

3.7 Personnel Responsibilities

The next aspect of the slope stability programme to be discussed is the people who have been tasked with the monitoring. The principal players in the programme are the mine surveyor and the geotechnical engineer. The mine surveyor oversees the operation of the GeoMos system. He sends out daily reports on his observations to the geotechnical engineer. The mine surveyor also does checks on the primary and secondary beacons using the GPS post processing method. Precise levelling is also carried out to monitor subsidence in specific areas of concern. The geotechnical engineer is responsible for the SSR. He analyses information and alerts the production team where there is an area of concern. He is also responsible for relocating the SSR when need arises. Both the mine surveyor and the geotechnical engineer are fully qualified with Bachelor's degrees in their respective fields. The geotechnical engineer has also completed a Graduate Diploma in Engineering (GDE) (Rock Engineering). The two of them have got over ten years of experience in the area of slope stability monitoring. Both the mine surveyor and the geotechnical engineer have other responsibilities added to slope stability monitoring. The mine surveyor, for instance is also responsible for measuring and analysing ore flow in the production stockpiles. In a nutshell, the current arrangement is such that the mine surveyor, supplies the geotechnical engineer with movement graphs and the geotechnical engineer does the analysis.

The second set of personnel responsible for slope stability monitoring is the dispatch foremen. When movement limits are exceeded, electronic mails (e mails) and short messages (sms) are sent to the responsible personnel. The responsible personnel include the mine surveyor, the geotechnical engineer and the dispatch foreman. The dispatch foreman's role becomes very critical after the dayshift working hours and during weekends when the mine surveyor and the geotechnical engineer are offsite. The dispatch foreman's responsibility during this time is to relay critical messages to the mine surveyor and geotechnical engineer. The role also involves the coordination of the evacuation of personnel and equipment, as advised. The dispatch foremen's qualification is an ordinary diploma in mining. The dispatch foremen go through an on-site training course which covers risks associated with mining. The geotechnical department also inducts the dispatch foremen on slope management in order to raise their level of awareness. The Information Technology professionals are responsible for providing the systems processing, storage and backup facilities.

3.8 Costs

The final aspect to assess is the cost incurred in setting up the existing slope stability monitoring programme. The analysis will assist in determining the budget to be incurred in designing the optimal slope stability monitoring programme. The cost will also be weighed against the cost benefits of the project.

Table 2 Equipment expenditure Jwaneng mine

Description	**Quantity**	**Supplier**	**Price(Rands)**
GPS Reference Stations and accessories	6	Geosystems Africa	R 769 342.00
TM30 Total Station and accessories	2	Geosystems Africa	R 1 129 338.00
Slope Stability Radar (SSR-XT) and accessories	2	GroundProbe	R 12 155 000.00
Total			**R 14 053 680.00**

Source: Jwaneng Mine (2010)

Jwaneng Mine has spent over fifteen million rands on their slope stability monitoring programme. Table 2 shows a high level summary of the amount on major equipment only. It excludes costs incurred in activities such as construction of beacons and installation of monitoring targets. The expenditure indicated on Table 2 demonstrates the mine's commitment to the slope stability monitoring programme.

3.9 Conclusion

The aim of this chapter was to describe the existing design of the slope monitoring system at Jwaneng Mine. The description offered a high level summary of the key components of the system. The information gathered from the various departments was confirmed by the responsible persons through verbal conversations and e-mail conversations.

The next chapter will focus on the analysis of the just described slope monitoring design at Jwaneng Mine. The strengths and weaknesses of the current design will be discussed in detail. The learning points from the description and analysis, together with the information gathered during the literature review will aid the author to come up with an optimal design for Jwaneng Mine which is the purpose of this research.

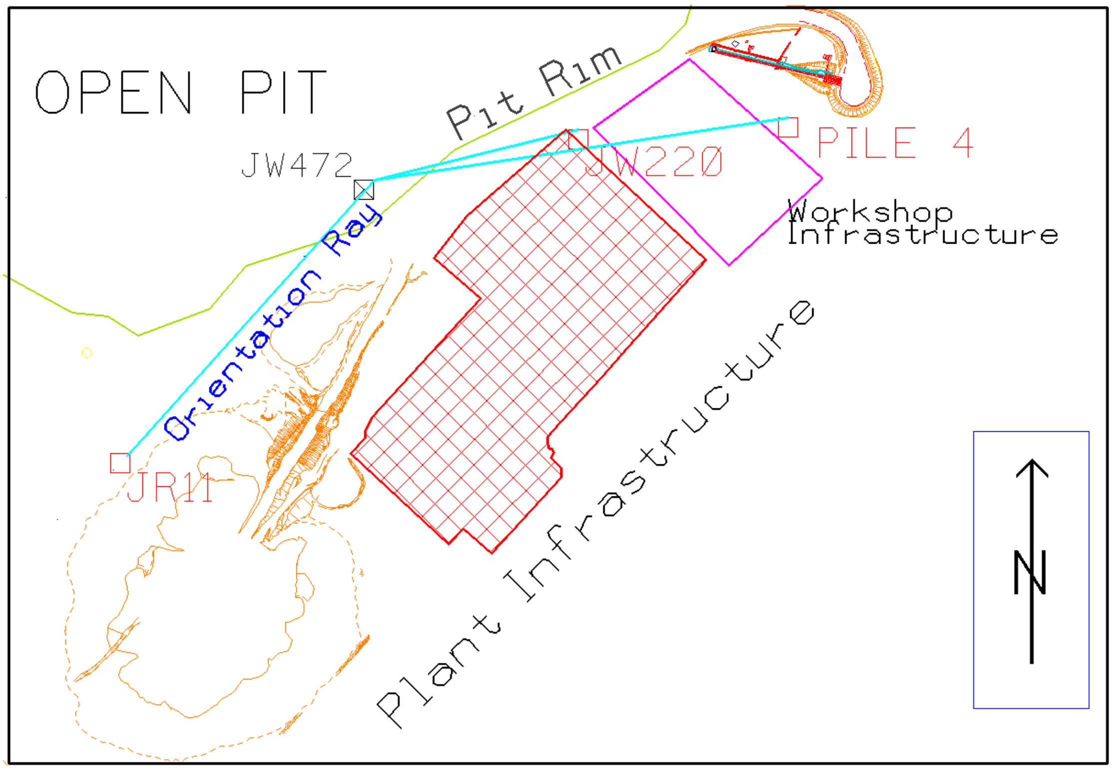
4 ANALYSIS OF THE SLOPE MONITORING SYSTEM AT JWANENG MINE

This chapter assesses the existing slope monitoring design at Jwaneng Mine against the principles discussed in chapter 2. The analysis will identify strengths and weaknesses in the current monitoring system as described in chapter 3. In assessing the current design the author will consider the constraints and challenges facing Jwaneng Mine. This will aid the author in coming up with an optimal and practical slope monitoring design. The analysis will follow the same process as the description by looking at the control network design, beacon design and construction, survey monitoring instrumentation, analysis and reporting of monitoring results, procedures, personnel responsibilities and costs.

4.1 Control Network Design

The first design criterion to be assed is the survey control network design. The discussion will focus on the survey beacons used for geodetic slope stability monitoring.

Figure 20 Insert Showing Resection Geometry.



Source: Jwaneng Mine Survey Department (2010)

The primary beacons at Jwaneng Mine are positioned at a distance greater than 100m from the pit rim. The nearest beacon to the pit rim is approximately 125m, which is within the 100 m and 3 km range recommended by Cawood and Stacey (2006).The geometry of the primary beacons with respect to the monitoring Beacon JW472 is not ideal for a survey application like resection (Figure 20). For a resection to yield accurate results, all three control points should be visible from the free station and should subtend angles of not less than 30 degrees and more than 115 degrees, Banister et al. (1998). Figure 20 shows that the current geometry of the primary beacons does not meet the recommended standard set by Banister et al. (1998) as it subtends angles of 6 degrees and 140 degrees.

The use of secondary beacons for orientation during monitoring and for resection purposes when using the GeoMos is inappropriate. As alluded to earlier, the secondary beacons are deemed unstable because of their close proximity to blasting activities hence being affected by blast vibrations. Cawood and Stacey (2006) observed that secondary beacons are unstable when they are located near the crest of the pit. It can be concluded that the monitoring results obtained when using secondary beacons for orientation are likely to have errors as it will not be clear whether deformations are due to movement of secondary beacons or the points being monitored. The reason for using secondary beacons for orientation was because of the limited range of the Leica TCA2003 Total Station when on the ATR mode. The TCA2003 can accurately measure up to 1 km when on ATR mode. The existing primary beacons are more than 1.5 km away from the monitoring beacon JW456 as shown on Figure 12. The measuring range constraint has been eliminated by the introduction of the Leica TM30 which can measure up to 3 km on ATR mode.

The above analysis shows that the current control network is not adequate for geodetic monitoring especially when using the GeoMos. A poorly designed survey network will result in orientation and free station errors as observed by Thomson (2005). It is evident that the geometry of the control network was influenced by the lack of space and the measuring range of the Total Stations, but with that considered a better model can still be achieved.

4.2 Beacon Design and Construction

The next criterion to assess is the design of the survey beacons and their construction. The discussion will focus on the existing designs (Figure A1 and A2) (see the appendix). The author will also look at the process followed to implement the designs. The competencies of the personnel involved in the design and the construction of the beacons will also be assessed.

The engagement of a structural engineer by Jwaneng Mine to design survey beacons is commended as the management realizes the implications of getting the design wrong. The design (Figure A1 and A2), shows the intent to produce a robust design as per Bannister at al.'s (1998) recommendation. Figure A1 shows that the base of the secondary beacon has been reinforced with concrete to make it more rigid. The base of the primary beacon as illustrated on Figure A2 is reinforced with concrete bricks to make it more rigid. To cater for the top layer of sand on the Jwaneng stratigraphy, piling has been incorporated into the design. This is in line with the advice from the Reporter 50 (2004) emphasizing the importance of pilling in order to build the beacons on a solid rock foundation. The designs of the primary and the secondary beacon are similar as per Banister et al.'s (1998) recommendation. The primary beacon is designed such that the height above ground is higher to allow for a clear line of sight to the monitoring beacon even when constructed further away from the pit rim as is normally the case. The need to position primary beacons away from the pit is emphasized by Cawood and Stacey (2006) who advised that they should be at least 100 m away from the pit rim. The reason behind locating the primary beacons a distance from the pit rim is to minimize the impact of blast vibrations on the stability of the beacons. The stability of the primary beacons is critical because they are the first point of reference on the mine. The positions of other survey stations such as secondary and monitoring beacons are transferred from the primary beacons using the survey principle of working from whole to part (Cawood and Stacey, 2006). To further stabilize the primary beacons extra piling is added on the design as compared to single piling on the secondary beacon (Figure A1 and A2).

The challenge facing Jwaneng Mine lies with the implementation of the design, i.e. the actual construction of the beacons. While the design of the beacons is done by a qualified structural engineer holding a senior position in the mine, the construction is done by a local contractor with no understanding of structural designs and geotechnical properties of the soil. The mine's tendering policy prohibits bigger companies with better technical skills from competing for "smaller" projects because they are lower than their designated category. Because of this policy the contract for the construction of the beacons is allocated to smaller local companies. It is common for local companies to have a trade B certificate in bricklaying as the highest qualification in their crew. The disparity in competencies between the designer and implementer is an area of concern. While the construction specifications are clearly outlined (Figure A1 and A2) as emphasized by Abramson et al. (2002) local contractors struggle to figure them out as they don't have the technical competencies required for the job. The construction of the beacons is supervised by the mine clerk of works. Although the clerk of works has got a qualification in construction management, it is of the author's opinion that the supervision of the project should be done by a competent structural engineer because of the precision needed in the job. The challenge with regard to the supervision of the contractor is further compounded by the fact that the clerk of works normally has to supervise other mine projects running parallel to the beacon construction project. This divides the clerk's time leading to the contractor passing through critical phases of the design without proper supervision. The author has observed that while the design of beacons at Jwaneng mine are of world class quality, the structure on the ground needs improvement. There is need for a more rigorous system of monitoring the construction of the beacons. The mine should consider the system used during the construction of other mine infrastructure such as plant buildings where an independent consulting engineer is engaged to oversee the construction and report back to the designer.

4.3 Instrument Shelter

This section will discuss the instrument shelter, its design and construction. The instrument shelter was built using fibre glass material. The shelter is designed such that there is an opening on the side of the pit. The opening was left to ensure that there is no interference with the ray travelling from the instrument to the pit when taking readings from the monitoring targets.

The fibre glass used to build the house will easily crack when hit by fly rock. This means that the risk of the instrument being damaged by fly rock is very high. In case the instrument gets hit by the fly rock, the mine bares the repair or replacement costs. The opening on the side exposes the instrument to dust and rain. As a result of this exposure, the instrument has to be cleaned more frequently. Experience has shown that when the instrument is mounted back on the beacon after cleaning, it does not assume the same position as before. This has an effect on the monitoring results. The continuous exposure to dust results in high maintenance costs and reduces the functioning life of the instrument. The instrument shelter in its current state is therefore not efficient. There is need to construct housing using appropriate material that will adequately protect the instrument from fly rock. The opening through which measurements are taken should be covered by glass to protect the instrument from dust and rain at all times without affecting the accuracy of the measurements. Afeni and Cawood (2010) observed that a glass thickness of 3mm or less will affect the measurements, but the errors will still be within tolerance.

4.4 Monitoring Instrumentation

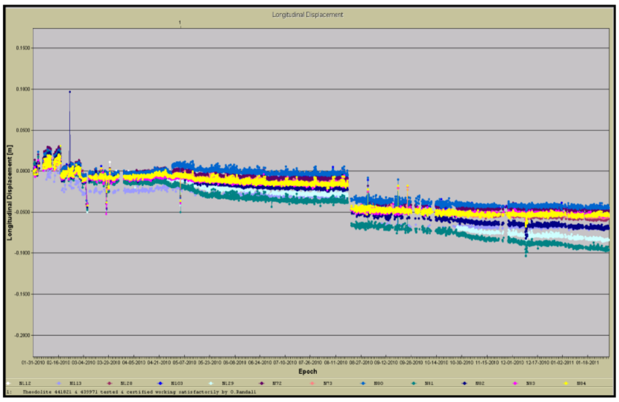
Having discussed the positioning of beacons, their design and construction, the focus turns to the monitoring instrumentation. The discussion will be on the type of instruments the mine uses for slope stability monitoring. Jwaneng Mine has got a number of monitoring equipment; however, this discussion will focus on the survey related equipment.

The choice of monitoring instrumentation at Jwaneng mine is largely influenced by the accuracy requirements and the size of the monitoring area. Cawood and Stacey (2006) listed accuracy and size of monitoring as some of the key factors to be considered when selecting monitoring instrumentation. On discussion with the geotechnical engineer responsible for slope stability monitoring, he stated that they seek instruments which can detect 15mm movement. They also look for instruments which can measure large areas because their main monitoring site, the pit is, 2.7 km by 1.5 km in size (Figure 12). The large monitoring site means that there is a large amount of monitoring data to be collected, making automation a necessity. The main monitoring systems such as the GeoMos, SSR and the GPS reference stations are fully automated, can monitor large areas and can detect 15mm ground movements. The other monitoring equipment such as the precise levels is used to cross check the instruments mentioned above. The cross check among the monitoring instruments is in line with Abramson et al.’s (2002) recommendation.

It is quite clear that Jwaneng Mine has very sophisticated monitoring equipment and there is clear criterion used to select the appropriate equipment. The challenge facing the mine is the interfacing of the monitoring equipment. The main (SSR and GeoMos) monitoring equipment are deployed in isolation and collect data independently without cross checking each other even though there is opportunity to do so. This is contrary to Abramson et al (2002) who emphasized cross checks among the equipment to enable them to complement each other. There is need for a clear criterion on how the existing equipment will be deployed to complement each other. For example, the criterion can state that when a specific movement limit is reached when using the GeoMos, the SSR can be deployed in that area to measure the entire section of the walls suspected of movement.

Correction for atmospheric conditions remains a challenge for Jwaneng Mine when using the GeoMos. The ray that travels from the monitoring station to the end of the pit travels through varying atmospheric conditions. The relocation of the Meteosensor from the office building to the instrument location which is on the edge of the pit has minimised the ‘fluctuations’ on the movement graphs as shown on Figure 21.

Figure 21 Graph showing ‘noise’ due atmospheric corrections



Source: Jwaneng Mine Survey department (2010)

The mine is about to install GPS reference stations on and around the plant infrastructure to mitigate the risk brought by the mining of Cut 8 which is within 100 m of the plant infrastructure (Figure 17). The need for GPS reference station was justified on the basis that the GeoMos could not be used as it was difficult to establish a clear line of sight to the proposed monitoring targets. The ground around the plant, being so close to the pit excavation, carrying heavy loads of plant structures will be susceptible to subsidence movement .The GPS as observed by Jooste (2005) and Milbert (1991) is inaccurate on z measurements and is unsuitable for subsidence monitoring. The mine intends to use the precise levelling technique for subsidence monitoring to complement the GPS reference stations. The challenge posed by precise levelling is that it's a point measuring technique hence covering small areas along the levelling route. Precise levelling is also labour intensive and time consuming and usually results in the monitoring being irregular and not as frequent as desired. The other problem that can be anticipated upon using the GPS reference stations around the plant infrastructure is the multi-pathing of signals.

Another area of concern at Jwaneng Mine is with regard to equipment maintenance. Although regular maintenance is being done as communicated by the mine personnel and confirmed by statistics on the availability of the instruments, the disturbing factor is that there is no paper audit trail to show as evidence. A calibration certificate is one of the items an auditor will look for in case there is a dispute over the reliability of any slope monitoring equipment. Abramson et al. (2002) observed that reliability is a key factor in equipment selection and can be ensured by regular calibration.

4.4.1 Data Collection and Processing

This section will discuss the way data is being collected and processed at Jwaneng mine. The focus will be on the frequency of the data collection and the error propagation

The GeoMos is programmed in such a way that it is continuously collecting data with only a half hour break at end of every measurement cycle. A measurement cycle is when all targets in the monitoring group have been measured. There are two monitoring groups at Jwaneng mine; one group is monitored from the west and the other from the east side. The SSR also collects data on a continuous basis as deployed by the geotechnical engineering department. Although it is good to have ample data for analysis, the continuous collection of data for 24 hours for 7 days in a week, will cause unnecessary wear and tear of the equipment without the extra data collected providing any new information about the slope movements (Thomas, 2011).

The frequency GPS measurements known as post the processing method carried out to accurately check the positions of the control points is not adequate. The procedures state that the measurements will be done on a bi-annual basis, but in reality the measurements are done haphazardly and sometimes a year elapses with them not being done. Precise levelling is also facing the same challenge of in adequate data collection. The reason behind this non-performance is usually attributed to lack of resources as surveyors are pre occupied with production related duties such as pit measuring and drill hole layouts. The regular checking of the positions of control points is very important as the coordinates of these control points are used to determine the relative movement of the monitoring targets. The use of unconfirmed coordinates of the control points can result in misleading information (Thomas, 2011). Regular checking of the network integrity is also emphasized by Cawood and Stacey (2006) who recommended that survey applications such as resection should also be used as second checks.

The processing of monitoring data for errors is a concern. The software used to convert the measured value (angles and distances) to the 3D spatial data, is customised to carry out basic adjustments such as correction for angle misclosure during orientation and atmospheric corrections during distance measurements. The omission of statistical analysis such as least square adjustments on such large quantities of redundant data brings the validity of monitoring information into question. Performing statistical analysis on redundant measurements will determine the magnitude of errors; this will allow the user to study the error distribution to assess whether they are within acceptable tolerance. If the measurements are acceptable, they will be adjusted to account for errors in the observations and increase the precisions of the final calculations (Wolf and Ghilani, 1997). The increase in the precision of the final calculations will raise level of confidence on the monitoring information.

4.5 Analysis and Reporting of Monitoring Results

The aim of this section is to assess the software that is used to analyse slope monitoring results. The software that is used to plot and analyse monitoring results, the SSRViewer and the GeoMos analyser have been utilized successfully to their strengths. Many failures have been predicted using this software.

The lack of statistical analysis functions is a major setback for the software. The lack of statistical functions results in observed (raw) data being used for analysis. The use of the observed raw data for analysing and reporting monitoring results is, in the author's opinion, a misrepresentation of figures and can be misleading. Statistical analysis is a very critical process when dealing with large quantities of redundant data similar to that collected by slope stability monitoring instruments. Observed raw data is reduced to adjusted (truthed) data using methods such as least square adjustments as emphasized by Kealy (2010). The adjustment is important because the observed (raw) data contains errors which, according to Burkholder (2001), are introduced when spatial data is obtained from indirect measurements such as slope distance being converted to horizontal components. Adjustment methods such as least squares compute observational redundancy numbers, standard deviations of coordinates and error ellipses as per Kealy's (2010) observation.

The other challenge facing the Jwaneng Mine slope stability monitoring programme is the lack of integration between the software used for the analysis and reporting of monitoring results. The software plot and analyse the monitoring results independently and in isolation. The movement graphs from the GeoMos analyser are plotted by the mine surveyors, while the SSRViewer plots are interpreted and analysed by the geotechnical engineers. The opportunity to link monitoring results from the SSR and the GeoMos with trends from other activities such as pit dewatering which also has a bearing on the stability of slopes is lost when there is no integrating software to aid the analysis and reporting. Halounova (2002) emphasized that the various data attributes associated with landslides which can be obtained easily obtained from GIS can be tedious without it.

4.6 Warning Systems and Procedures

Jwaneng Mine has a number of generic procedures guiding slope stability monitoring processes. The mine also has different warning systems to alert the relevant personnel when certain movement limits have been exceeded. These procedures have served the mine well resulting in a commendable slope management program.

Although the slope management programme is commendable, most of the procedures at the mine are too generic as far as the author is concerned. For example, the SLCs between the suppliers Leica Geosystems and Groundprobe briefly addresses soft issues such regular software updates and 24 hour help desk assistance amongst others. In principle, technical aspects such as calibration of instruments should be covered in detail in a SLC as they affect the reliability of the monitoring results. The SLC should stipulate how often the calibration should be done, how it will be done and where (onsite or in the labs) as per Abramson et al.'s (2002) recommendation. One of the main challenges facing GeoMos at Jwaneng Mine currently is the atmospheric corrections when taking measurements across the pit to the monitoring targets. Jwaneng Mine would certainly benefit from the onsite calibrations. The lack of more detailed procedures for processes such as, precise levelling, network adjustment can result in people using their own discretion during monitoring, leading to disastrous results.

Similarly, procedures relating to warning systems do not cover much detail. The procedures describe what needs to happen when movement limits are reached, there is no detailed procedures of how the movements picked up will be validated before drastic actions such as evacuations are executed. Detailed procedures are necessary when dealing with critical processes such as those relating to slope stability monitoring which can affect the lives of employees.

The other challenge facing Jwaneng Mine concerns the management of slope stability monitoring procedures. The current arrangement where some procedures are stored at the survey offices while others are stored at the geotechnical engineering department makes it difficult for the reconciliation of their contents. The isolation of procedures can result in some procedures contradicting each other or repeating the same information. The optimal arrangement will have the procedures stored in one place and easily accessible.

4.7 Personnel Responsibilities

Having assessed the procedures guiding slope stability monitoring at Jwaneng Mine, the focus now turns to people responsible for the application of the procedures during the monitoring process. The qualifications and the experience of the two principal personnel, the geotechnical engineer and the mine surveyor are adequate. The geotechnical engineer has a BSc. degree in geological sciences and GDE in rock mechanics. The mine surveyor responsible for slope monitoring has a BSc. degree in surveying science. Their competencies are evident in the way they manage the monitoring process and the high quality reports that they produce.

The area of concern is the added responsibilities that the mine surveyor and the geotechnical engineer have on top of slope stability monitoring. With so many systems operating at the same time, the large quantities of data that need to be analysed, slope stability monitoring needs full time attention from the mine surveyor and the geotechnical engineer. Added responsibilities will result in some aspects of monitoring being overlooked. An example is the precise levelling and GPS post processing of survey control points which is irregular and is not done as frequent as it should. Precise levelling and GPS post processing are critical survey applications in slope stability monitoring as they provide cross checks to other monitoring systems such as GeoMos and GPS reference stations. Cross checking across systems is highly recommended by Abramson et al (2002) as it is a way of validating monitoring results by using a different method. The mine should consider engaging private surveyors for routine jobs such as stockpile measurements to enable the mine surveyor ample time to focus on slope stability monitoring.

The other set of support personnel such as mine supervisors, mine foreman and IT network administrators are well qualified in their own subject matter, however there is need for them to be continuously made aware of the implication of slope failures. The awareness will give them the urgency when carrying out tasks supporting the slope stability monitoring process. The continuous rotation of staff, especially the support staff affects the monitoring process as the new members of staff have to be retrained and usually take time to reach the required competency level.

4.8 Costs

The final design criterion to be assessed is the costs incurred by Jwaneng Mine to setup the existing slope monitoring system. Jwaneng Mine has already purchased the major slope monitoring equipment such as the SSR and instruments needed for the GeoMos system as shown on Table 2. Minimal costs will be needed to optimize the system further. The cost benefits of the system should be weighed by considering the impact of a slope failure on costs that will be incurred replacing a shovel damaged rock failure or the costs involved in moving diluted ore resulting from waste collapsing onto ore.

The challenge facing the geotechnical engineering and the mine surveying departments who are the custodians of the slope stability monitoring program is to demonstrate the economic value added by the system when designing slope angles. If the value added is demonstrable by steepening of slope angles, it will be easy to convince the mine senior management to release more funds needed to optimize the current system. Cawood and Stacey (2006) emphasized the need to assess the value add when selecting slope stability monitoring instruments.

4.9 Conclusion

The purpose of this chapter was to assess the current slope stability monitoring design at Jwaneng Mine. The learning points gathered from the analysis will be used to design an optimal slope stability monitoring system.

The next chapter will focus on the design of a slope stability monitoring system. The author will combine concepts learnt from the other authors with the knowledge gathered from the analysis in chapter 2 to come up with the design.

5 A DESIGN STRATEGY FOR SLOPE MONITORING AT JWANENG MINE

The aim of this chapter is to develop a slope stability monitoring strategy for Jwaneng Mine. Since there is an on-going monitoring program at the mine, the strategy will focus more on the optimization of the current setup rather than start a new system. To aid with the optimization of the current setup, the author will summarise the Strengths, Weaknesses, Opportunities and Threats (SWOT) as shown in Table 3. The SWOT is based on the analysis done on chapter 4.

Table 3 A Summary of the SWOT of the existing design

Strengths	**W**eaknesses	**O**pportunities	**T**hreats
• World class monitoring equipment. • Qualified personnel • Considerable amount of money already spent, hence lower optimization costs	• Poor Survey control network design • Poorly built beacon structures • Inadequate procedures • Lack of integration of monitoring data • Lack of statistical analysis and adjustment of the redundant data • Lack of role clarity and focus	• Cut 8 expansion allows for re positioning and reconstruction of survey beacons • Integration of data in one system will be easier since the mine uses one coordinate system • Redeployment of existing monitoring equipment is easy	• Infrastructure around the pit makes positioning of beacons with an appropriate geometry extremely difficult • Proximity of cut 8 mining limit to the plant infrastructure is huge threat to production

The design strategy will follow this process; control network design, beacon design and construction, instrument shelter, selection of monitoring instrumentation, analysis and reporting of monitoring results, monitoring procedures, personnel responsibilities and the budget.

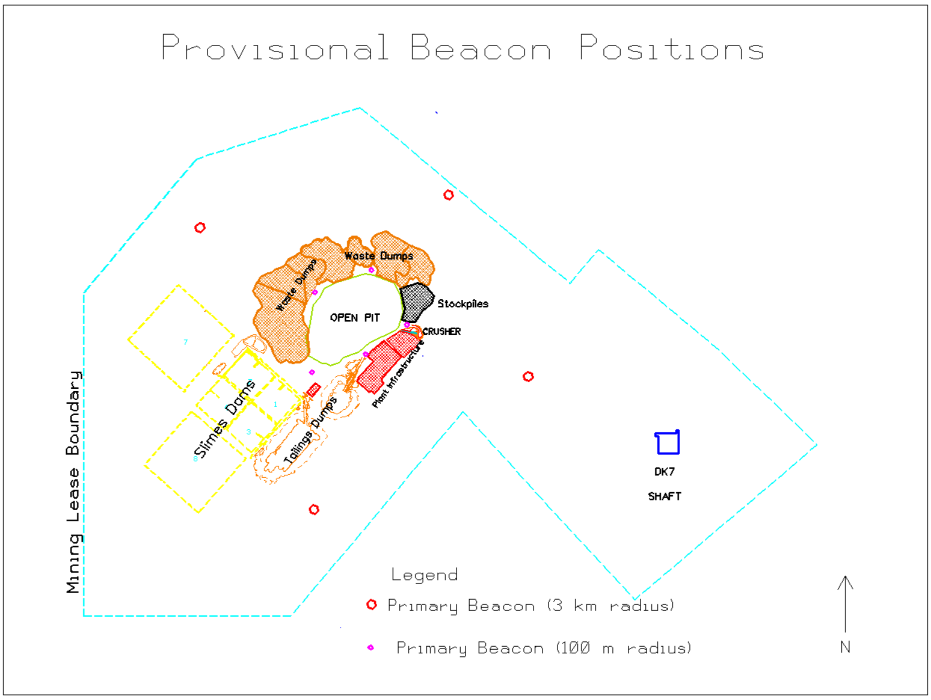
5.1 Control Network Design

The survey control network design will follow a process recommended by Kealy (2010) which is as follows;

- A desktop exercise to determine the provisional positions of the survey beacons.
- Determination of line of sights to be used during geodetic surveys.
- A reconnaissance to adjust the positions of the provisional positions to the more practical positions.
- Computation of observations from coordinates using survey applications such as resection.
- Testing the network accuracy by computing standard deviations of coordinates calculated from redundant observations

The provisional positions of the primary beacons will be established using Cawood and Stacey's (2006) principle of having the control points being anyway between 100m to 3km away from the pit rim. Figure 13 shows conceptual positions of the primary beacons from a desk top study.

Figure 22 Provisional Positions of the Primary Beacons



The design entails two sets of primary beacons as shown in Figure 22. The first set of primary beacons will be positioned 100m away from the pit. Because of the build-up of dumps and infrastructure around the pit, it will be a challenge to place the primary beacons further away from the proposed 100m.That may compromise the line of sight. Where there is availability of space to position a beacon without compromising the line of sight such as the south western side of the pit, the primary beacon will be placed further away. The idea is to place the primary beacons further away from the pit to minimize the impact of blast vibrations on the stability of the beacons but still maintain a line of sight to the monitoring beacon. These set of primary beacons (100m radius) will be used for orientation during monitoring. They will also be used to check and update the position of the monitoring beacon using the resection method. The checking and updating of the monitoring beacon position is done regularly when using the GeoMos method. To check the stability of the first set of primary beacons, the author proposes that another set of primary beacons be constructed 3km away from the pit rim as shown on in Figure 22. The first set of primary beacons, being 100m away from the pit rim, will not be very stable as they will be affected by blast vibrations. It is therefore critical to regularly update their coordinates; using the second set of primary beacons (3km radius) as control points by using the survey principle of working from whole to part .The 3km radius set of primary beacons will be tied to the national grid.

The next step after the determination of the provisional positions is to do a reconnaissance to confirm the positions of the primary beacons. The reconnaissance will involve the use of aerial photographs, maps and plans showing future infrastructure developments. This reconnaissance was recommended by Bartley (2007) and the reason for it is to confirm the availability of space for beacon construction. The aerial photographs and maps required from the reconnaissance are available from the survey office. A field reconnaissance is also necessary to physically check the line of sights and also to confirm the stability of the ground where the beacons will be constructed.

The secondary beacons will be constructed on the rim of the pit, the guiding principle being to maximise the view onto the pit as recommended by Bartley (2007). The current GeoMos design requires only two monitoring beacons but Cawood and Stacey (2006) advised that additional secondary beacons should be built in case where there is loss of line of sight on one of the two beacons or the stability of the ground they are built on is compromised. The line of sight can easily be affected by repositioning of the overhead electric cables as Jwaneng mine uses electric powered drills. The ground close to the crest where the secondary beacons are positioned will be unstable because of its close proximity to drilling and blasting activities.

After confirmation of the positions of the beacons, the next step is to test the integrity and the quality of the survey control network. This will involve using applications such as least square adjustments to compute observational redundancy numbers, standard deviations of coordinates and error ellipses, Kealy (2010). Kealy (2010) recommends network testing as that will help identify and rectify the weak areas of the network.

5.2 Beacon Design and Construction

Having completed the design of the survey control network, the focus now shifts to the beacon structural design and its construction. There are four fundamental questions to consider when designing and constructing survey beacons;

- Is the beacon design compatible with geotechnical properties of the ground on which the beacon will be constructed?
- Is the design easy to implement?
- How will the designer ensure that the structure is implemented as designed?
- Does the contractor have the right competencies to implement the design specification adequately?

As mentioned earlier in the report, the structural design was correctly done and is appropriate for the Jwaneng Mine stratigraphy. The 17-20m top layer of sand has been designed for by incorporating piling in order to have the foundation of the beacon built on solid rock as advised by the Reporter 50(2004). They will be no need to alter the current beacon structure as it is adequate. The construction notes explaining how the design will be implemented are clear and easy to understand, making the design easy to implement. The simplicity of the construction specifications is recommended by Abramson et al. (2002).

To ensure that the beacon design is constructed to the correct specification, the company needs to address the following;

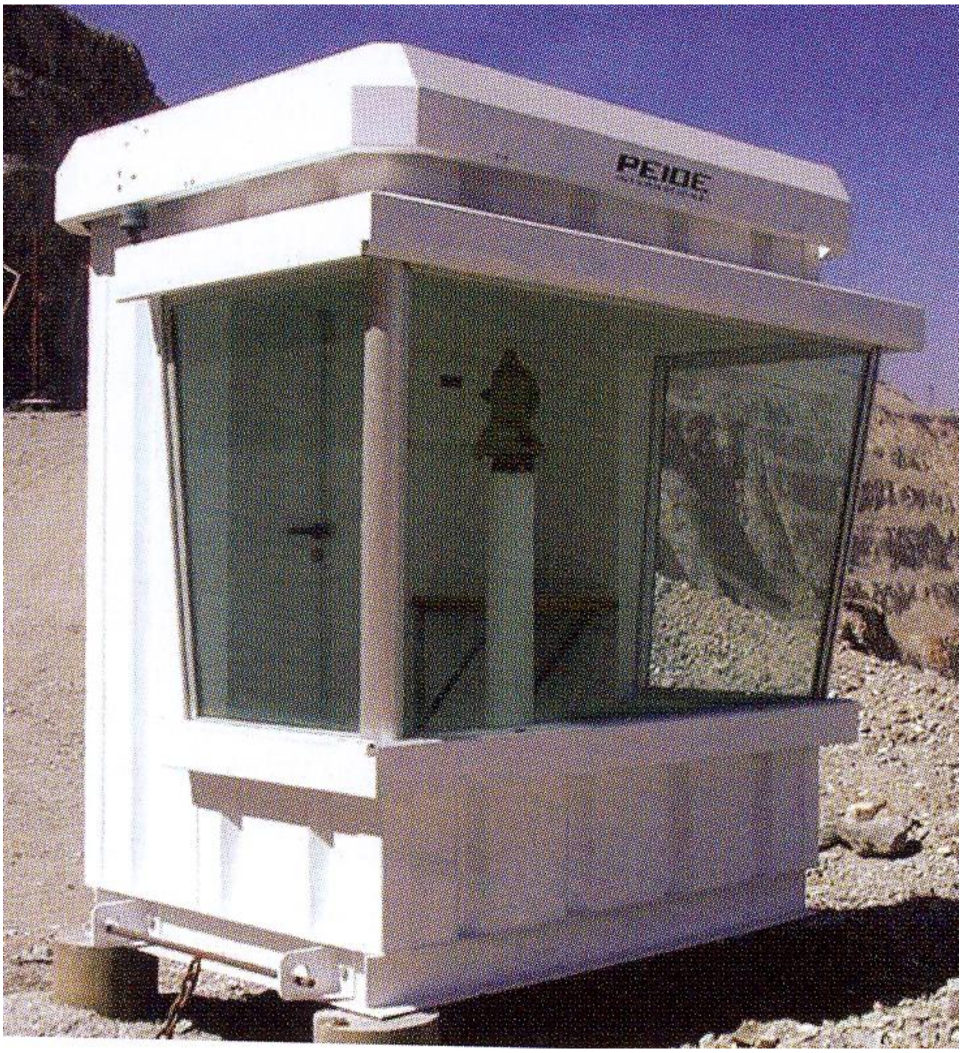
- When evaluating tenders for the construction of the beacons, more weight should be given to the technical competencies of the company rather than current practice of giving the lowest bidder more points. This will require the company checking the contractor's qualifications and experience in carrying out similar projects.
- There is need for a construction schedule to accompany the structural design. The construction schedule should have gate release clauses stating stages of construction where progress cannot be made to the next stage until the built structure has been inspected and signed off by the relevant personnel.
- The supervisor of the project should have a good understanding of the design. The designer of the structures is the rightful person to do the supervision.
- The owners of the project, the mine surveyor and the geotechnical engineer should also get involved during the construction of the beacon to ensure that their needs are met. For example, they might be a need to increase the height of a specific beacon to clear an object such as a conveyor belt that might be obstructing the line of sight.

When the issues raised above have been addressed the mine will have reliable beacon structures to use as survey control points.

5.3 Instrument Shelter

The next design aspect to look at is the instrument shelter that houses the Total Station when using the GeoMos for monitoring. The purpose of the shelter is to protect the instrument from dust and rainfall. The shelter also serves to protect the instrument from fly rocks during blasting activities. When designing the instrument shelter, there is need to balance the need to protect the instrument without compromising the accuracy of monitoring measurements. The ray that travels from the Total Station through the glass walls of the shelter can be distorted by the type of material used to build the shelter. The distortion will result in inaccurate measurements. The choice of material when constructing the shelter is therefore very critical. Figure 23 shows a typical design of an instrument shelter.

Figure 23 Proposed Instrument Shelter



Source: Read and Stacey (2009)

The walls of the shelter are partially constructed from glass. This allows the Total Station to site to any beacon or targets within its line of sight without hindrance from the shelter. Jwaneng Mine has had problems with measuring through glass as it was affecting the accuracy of monitoring results. A decision was made to remove the glass hence exposing the instrument to dust and rainfall for the sake of getting more accurate measurements. Afeni and Cawood (2010) observed that glass with a thickness of 3 mm or less does not affect the accuracy of the monitoring results. To protect the glass from fly rock during blasting, the shelter can be equipped with pull down metal doors. The doors can be left open during monitoring and pulled down during blasting.

The design shown in Figure 23, together with the alterations suggested to protect the glass walls, will suit Jwaneng Mine well.

5.4 Selection of Monitoring Instrumentation

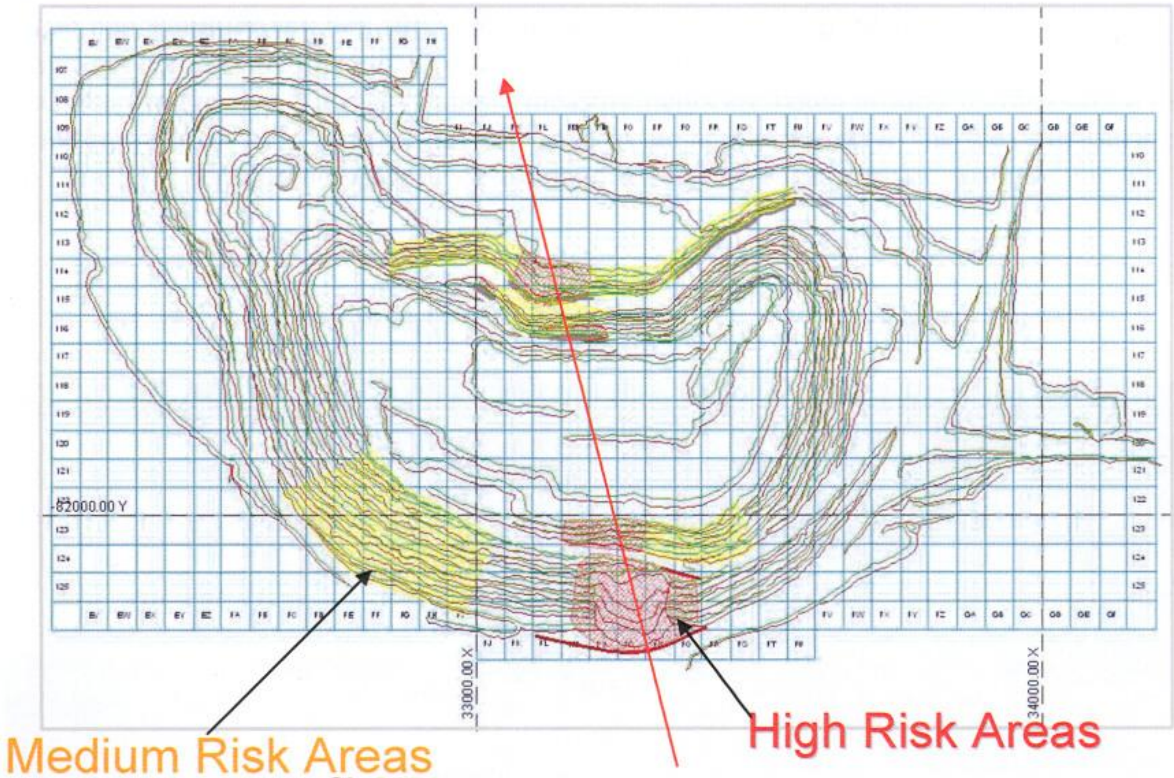
The first sections of this chapter focused on the infrastructure that enables slope stability monitoring. After setting up the infrastructure such as control survey beacons and the housing of the instrument, the next design process involves the selection of suitable monitoring equipment. The selection process will consider the following factors as suggested by Cawood and Stacey (2006);

- the expected magnitude of the ground movement
- most likely movement direction (horizontal or vertical)
- accuracy and precision of the instrument
- number and frequency of measurements
- size of area to be monitored
- Level of automation
- ease of interface with other monitoring instruments
- GIS adaptability.

The rock at Jwaneng Mine as per the geotechnical engineering department is expected to move by 15mm. Given the large size of the pit (1.7 x 2.5 km) and risk posed by the mining of Cut 8 at such a close proximity to the Main Treatment Plant infrastructure, there is need to strategically position monitoring equipment such that maximum value is derived from each instrument by ensuring that any possible ground movement is adequately detected.

The monitoring process will be started by the identification of risk areas by the geotechnical engineers as highlighted by Jooste (2005). The areas are then classified depending on the severity of the risk (high, medium and low) as shown in figure 24. The severity of the risk is one of the determining factors in equipment positioning.

Figure 24 Risk Areas

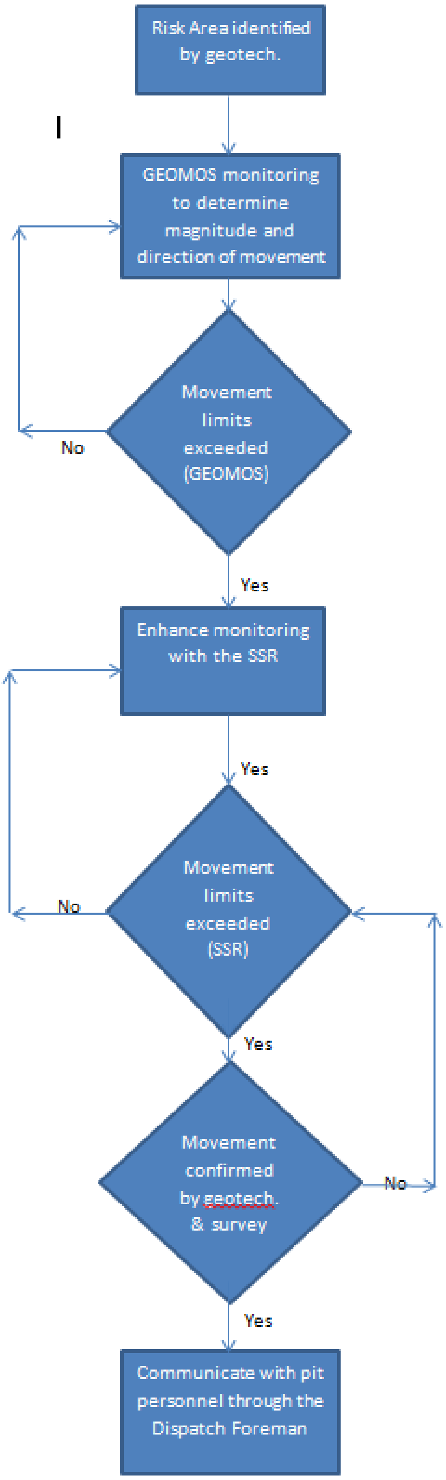


Source: Jooste (2005)

Jwaneng mine has two Total Stations connected to the GeoMos, two SSR, six GPS receivers (Pseudolites), one digital level and one GPS/GNSS surveying system as part of the slope stability monitoring equipment. The combination of the above listed equipment can provide an optimal monitoring solution if they are appropriately utilised with little addition. To achieve the optimal solution, Jwaneng mine should consider positioning the current monitoring equipment as follows;

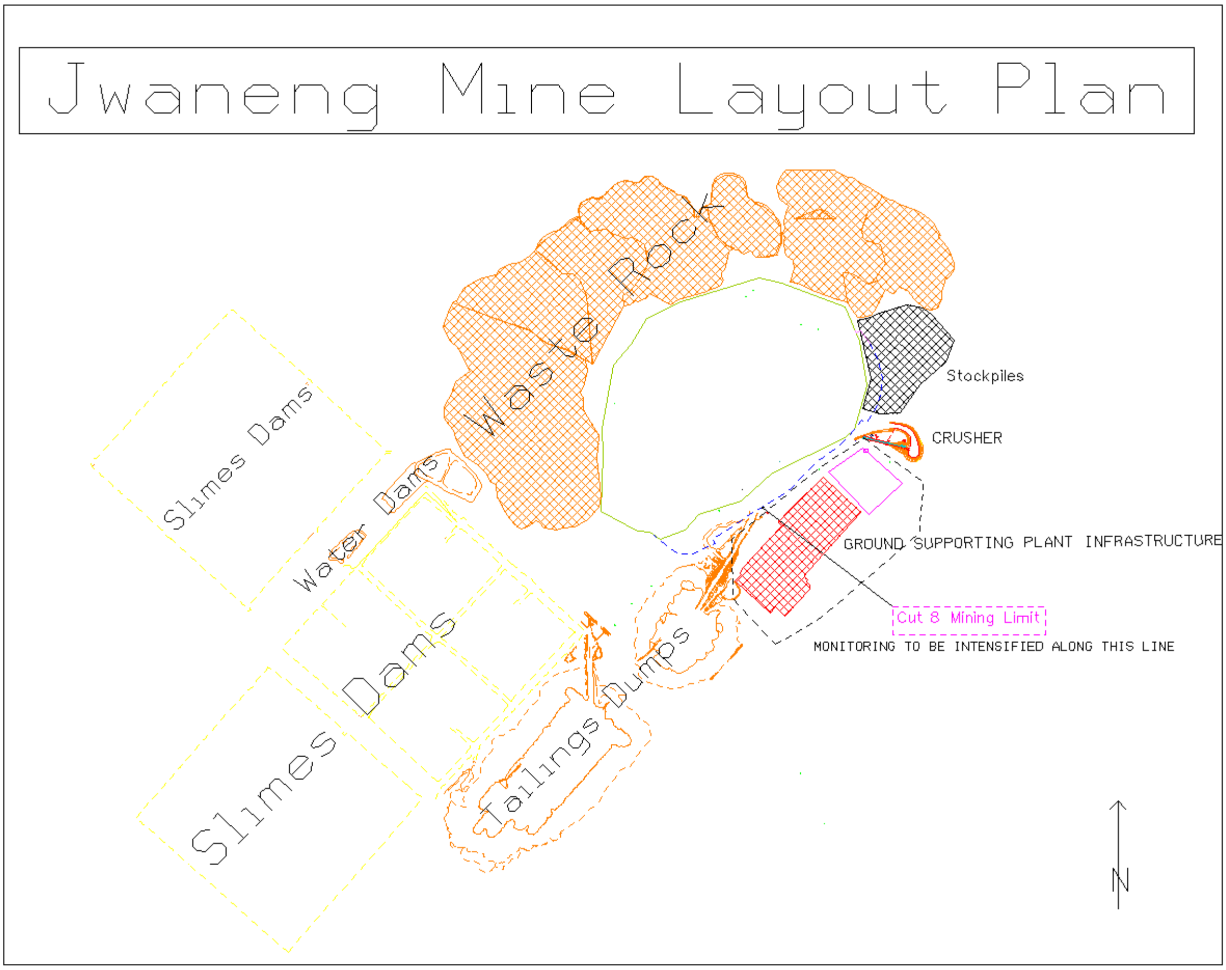
The two Total Stations which are components of the GeoMos should continue to monitor either side of the pit as per the current design. The GeoMos will track the movement vectors enabling the mine surveyor and the geotechnical engineer to track both the magnitude and direction of the movement. There is need for a systematic link between the SSR and the GeoMos. For example, when specific movement limits are reached when monitoring with the GeoMos, monitoring can be intensified by incorporating the SSR. Jooste (2005) suggested that before taking any actions when movement limits are reached the responsible personnel should confirm that the cause is actual ground movement. This is illustrated in Figure 25. Due to its easy deployment as observed by Reading and Stacey (2009) the same SSR unit can also be quickly moved to monitor areas being worked on by the mining equipment whenever a risk has been identified. This could be a drill, working under an unstable high wall.

Figure 25 A systematic utilisation of monitoring equipment.



The other SSR unit should be deployed such that it will continuously monitor the Cut 8 mining section area which is in close proximity to the Main Treatment Plant infrastructure as shown in Figure 26.

Figure 26 High Risk Area Associated with Cut 8 Mining



Source: Jwaneng Mine Survey Department (2010)

The area close to the Cut 8 mining limit has been identified as a high risk area and its monitoring should be intensified by dedicating a SSR unit to continuously monitor the high walls in the area as shown on Figure 26. GeoMos targets should also be installed in the area to assist with the establishing the direction of movement if detected. To enhance the monitoring further, GPS receivers should be installed on the high wall in that area to provide a cross check to the GeoMos and the SSR. Cross checking among the different equipment is critical as emphasized by Abramson et al. (2002).

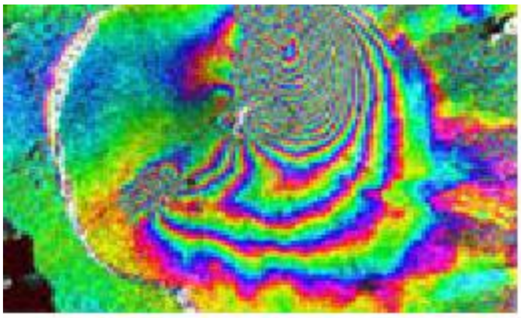
Since the Main Treatment Plant infrastructure will be so close (within 100m) to the mining activities in Cut 8, there will be need to monitor the ground it is built on for movement. To monitor the ground for any movement the mine should consider installing GPS receivers in the area. The use of GeoMos is not possible because there will be no line of sight to the monitoring station as it will be obstructed by the plant infrastructure. The GPS receivers should be strategically positioned to avoid measurement errors brought by multi-pathing and dilution of geometric intensity of satellites because of the plant infrastructure. Wang et al. (2002) cautioned about multi-pathing and satellite availability when monitoring around tall structures such as high walls using GPS receivers. To compensate for the inaccuracies of GPS height measurements as observed by Jooste (2005), the mine can use the precise levelling method. The challenge brought about by the precise levelling method is that it is a point measuring method and will not adequately cover the large area in the vicinity of the plant infrastructure. To enhance the precise levelling method the mine should consider other monitoring methods suitable for subsidence monitoring and can cover large areas such as the InSAR technology. Canuti et al. (2002) recommended portable ground technology that produces high resolution SAR images. Figure 27 illustrates the proposed deployment of the monitoring equipment at Jwaneng mine.

Figure 27 Monitoring equipment positioning

To monitor the stability of the survey control points (primary and secondary beacons), the mine should continue to utilize the GPS post processing method. The elevations will be monitored using the precise levelling method. To cross check the GPS post processing method the mine should utilise the available geodetic instrument to survey the control traverse network.

Satellite images from the Altamira InSAR will be used to reconcile the monitoring systems at Jwaneng Mine. The Altamira InSAR will track the impact of ground movement on infrastructure around the pit, dumps and slimes dams. Figure 28 shows a sample of a satellite image produced by the Altamira InSAR. The quantity of movement is presented in colour fringes, when comparing satellite images from different dates. The images will be purchased on a quarterly basis and then more frequently if there is need. At the start of monitoring, archived images will be used to identify hazard areas based on historical movements

Figure 28 A Satellite image from Altamira InSAR



Source: Altamira InSAR (2011)

All the instruments discussed above work on one coordinate system which is tied to the national grid. That enables the different instruments to easily cross check each other as recommended by Abramson et al. (2002). The instruments are also adaptable to the GIS.

5.4.1 Data Collection and Processing

This section will discuss the data collection strategy suitable for Jwaneng Mine. The discussion will focus on the frequency of measurements and processing of the data for errors.

The frequency of the slope monitoring measurements should be systematic and guided by rock behaviour. The movement rate of the rock should determine the frequency of the measurements. The frequency of the measurement can be determined as follows as recommended by Jooste, (2005);

- Movements of 0 to 2 mm per day are monitored once a month
- Movements of 0 to 5mm per day are to be monitored once a week
- Movements of 5 to 10mm per day to be monitored once every 2 days
- Movements of 10 to 50mm per day will be monitored ponce per day
- Movements greater than 50mm will require constant observation.

The geotechnical engineering and survey departments will determine suitable rate of measurements for the Jwaneng rock-types and the risk associated with monitored areas. The plant area in the proximity of the Cut 8 line will require constant monitoring even when there are no movements because of the level of risk. The structured data collection will help prolong the life of equipment as the wear and tear will be minimised as observed by Thomas, (2011). Data processing will be much quicker because of reduced amount of measurements as opposed to dealing with large amounts of redundant data with the same information.

The mine needs to be consistent with the checking of control points' positions using the GPS post processing method and precise levelling. These processes should be carried every six months as per survey procedures and be repeated more frequently when movement limits are exceeded.

Due to the high accuracy required in slope stability monitoring, there is need to process all measured data for errors to determine their magnitudes and the influence they might have on the results. After determining the error sizes a decision can be made, depending on the set standards on how to use the data. The data can either be adjusted to correct for the errors or be discarded completely. The analysis and adjustment of data for errors was emphasized by Wolf and Ghilani (2002) who stated that every measurement contains errors which should be fully understood by the data users.

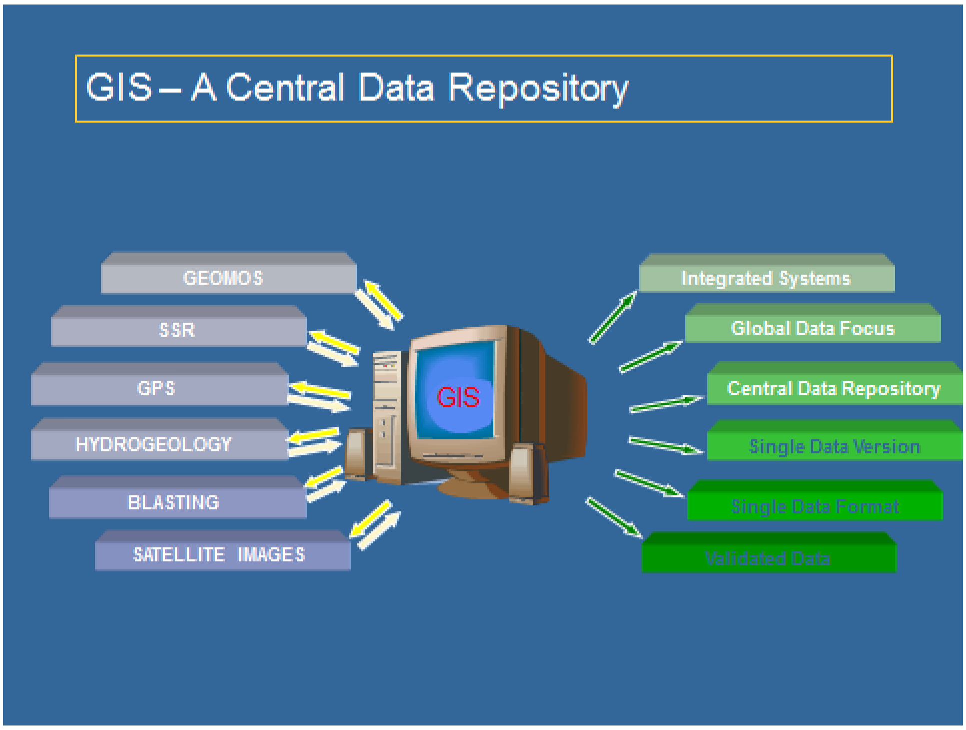
5.5 Analysis and Reporting of Monitoring Results

Having discussed the data collection and processing at Jwaneng Mine, the next step is to discuss how best to analyse the data that they collect and report it as information. Given the huge amount of data that is collected by these instruments, it is only appropriate to consider software with database management functionality.

The mine should consider the following aspects when selecting the appropriate software to be used to analyse and report slope stability monitoring results;

Since there are various instruments being used to collect slope stability monitoring data, there is need to integrate this data and analyse it from one point so that it can be subjected to the same level and standard of interpretation. If the data is analysed using the same software it becomes easy to establish trends in data from different sources. Integration also allows for cross checking between data sources as emphasized by Abramson et al. (2002). Figure 29 illustrated how data from different sources can be integrated and the benefits derived.

Figure 29 Using GIS for data integration



GIS is the most common software used to integrate data from various sources for analysis and presentation. Most GIS packages have the least square adjustment functionality for error analysis, graphic display functionality and can produce movement graphs. Wolf and Ghilani (2002) observed that GIS evolves with data collecting instruments which make it suitable for the ever developing slope monitoring technology. The other advantage with GIS is that, because of its ability to handle large quantities of data as observed by Wolf and Ghilani (2002), it can be used to manage other mine data such as rainfall figures, blasting data, pit dewatering information and other hydrological data that has influence on the stability of pit slopes. This information can become useful when analysing slope monitoring measurement and will be easily accessible when stored in the same database.

Given the analysis above, Jwaneng Mine should consider using the GIS for analysis and reporting of monitoring results. The mine will derive other benefits from GIS such as land use management, asset management and legal plans management among other activities. GIS is already an established data management system that will be easily implementable by Jwaneng Mine.

5.6 Monitoring Procedures

The next design criterion to discuss is the monitoring procedures guiding the slope stability monitoring process. Jwaneng Mine procedures will be categorized as follows;

Code of Practice (COP): The mine should develop a code of practice guiding slope stability monitoring. Although there are acts guiding slope stability monitoring in Botswana, they are not very comprehensive. The mine should look at acts guiding slope stability monitoring in other countries for guidance as the principles are the same. Cawood and Stacey (2006) highlighted that the South African Department of Mineral Resources (DMR) has prepared a guideline for the preparation of a COP to combat rock fall and slope instability related incidents in open pit mines. The guideline is available on the website (www.dme.gov.za). In developing a COP, the mine could be guided by the following principles developed by Gudmanz (1998);

- Identification and documentation of rock related incidents
- Development of appropriate strategies to eliminate or reduce risk caused by these hazards
- Allocation of duties for the execution of these strategies
- Training of persons to enable them to carry out their duties.

The COP should be reviewed regularly to keep up international standards guiding slope stability monitoring.

Process Flows: These set of procedures will list the step by step processes of slope stability monitoring activities. Examples of these procedures will include the GeoMos operating procedure, SSR operating procedure, precise levelling procedure and the GPS post processing procedure amongst others. When developing these set of procedures, risks that might affect the efficiency of the process will be identified and mitigated accordingly. The development of these procedures will be a team effort. While the other members of the team will be involved in the actual writing of the procedures, the other members will review them.

Warning Systems and Response: This will focus on the action that will be taken when ground movements have been detected. The mine will develop guidelines on how to respond to the different magnitudes of movements. For example, when movement limits are exceeded in GeoMos, the guidelines can call for enhancing monitoring by deploying the SSR. Similarly when movement limits are detected using the SSR, the guidelines can call for the area concerned to be evacuated. The important aspect is having guidelines on how to logically deal with detection of ground movements. The guidelines will also list names of personnel to be contacted when ground movements are detected and how they will be contacted.

These procedures listed above should be tested for practicability by running mock-ups regularly. The procedures listed above will be reviewed by the Government Inspector of mines for assurance. The procedures must be stored in one place and made easily accessible.

5.7 Personnel Responsibilities

After the slope monitoring system has been implemented and procedures developed, there is need to look at the personnel who will be operating the system. The discussion will focus on roles and competencies of the personnel.

The geotechnical engineers will be responsible for identifying risk areas. They will then classify the areas according to the level of risk, high, medium and low. The geotechnical engineers will then specify the precision and the frequency of the measurements. The interpretation and analysis of the data will also be the responsibility of the geotechnical engineers. The reporting of monitoring results will be done by the geotechnical engineer.

The mine surveyors will be responsible for managing and maintaining the slope monitoring equipment in terms of availability and utilization. Furthermore, the surveyors will be responsible for managing the data acquired by the monitoring equipment. They will ensure that the data is processed for errors before being plotted for analysis as well as managing the software used for reporting movements. The mine surveyor will also be responsible for the maintenance of the survey network. This will be done by carrying out activities such as GPS post processing and precise levelling. The management of slope stability monitoring procedures will be a joint responsibility of the mine surveyors and the geotechnical engineers.

The Information Technology personnel will be responsible for the databases storing the slope stability monitoring information in terms of its security and the backups.

They will ensure that the communication system used to relay slope stability information is always available.

Having allocated the responsibilities as above, a competency matrix will be developed for each individual involved in slope stability monitoring. The competency matrix will be used to assess the level of competency which will then inform the development programme for the individual.

Looking at the size of the monitoring area, the size of the slope monitoring equipment and the amount of data to be processed and analysed, the mine surveyor and geotechnical engineer will have to focus on slope stability monitoring only. To add responsibilities to their heavy work load will negatively affect the slope monitoring programme.

5.8 Budget

The next section will look at the expenses that Jwaneng Mine will incur to optimize the slope stability monitoring system. The mine has already spent a considerable amount of money on the existing monitoring system. Table 4 shows costs already incurred by the mine and the money that will need to be spent to optimize the existing setup.

Table 4 Cost Analysis for Jwaneng Mine

Description	Quantity	Supplier	Price (Rands)
Costs Incurred			
GPS Reference Stations and Accessories	6	Geosystems Africa	R 769 342.00
TM30 Total Station and Accessories	2	Geosystems Africa	R 1 129 338.00
Slope Stability Radar (SSR-XT) and Accessories	2	GroundProbe	R 12 155 000.00
Sub Total			**R 14 053 680.00**
Expenses to be Incurred			
Ground based Monitoring Radar	1	ProudAfrique	R 2 000 000
GIS System		FFM Botswana	R 565 512
Satellite monitoring annual fee (includes archived data)		Altamira InSAR	R 968 000
Sub Total			**R 3 533 512**
Total			**R 17 587 192**

Source: Suppliers (2010)

The amount of money already spent by the mine indicates the level of commitment towards slope stability monitoring. The cost of replacing survey beacons which will be affected by Cut 8 mining has not been included as they are regarded as maintenance costs and are to be covered by the project funds. To justify for the extra expenditure aimed at optimizing the existing design, the value add of the new components will be clearly stated in the proposal as per Cawood and Stacey's (2006) advice.

5.9 Conclusion

The aim of this chapter was to outline a step by step process followed to come up with slope stability monitoring design for Jwaneng Mine. The following is a summary of design considerations for Jwaneng Mine;

- Control Design Network: The mine should consider having two sets of primary beacons. The first set, which will be constructed 100m away from the pit rim, will be used for orientation purposes during GeoMos monitoring. The second set which will be 3 km from the pit rim will be used during high level accuracy surveys to check the movements on the 100m primary beacons used for orientation. The primary beacons used for orientation are susceptible to movements because of their close proximity to mining activities such as blasting. The secondary beacons should be constructed on the rim of the pit to allow for a clear line of sight into the pit. Two of the secondary beacons should be used as monitoring stations hosting the instruments. The other secondary beacons should be positioned strategically with a maximum view of the monitoring targets such that they can be used as alternative monitoring stations when necessary. All the survey beacons should be geometrically positioned to enable survey applications such as resection and traversing to be carried out with minimum constraints.

- Beacon Design and Construction: The current construction procedures should be reviewed to allow for more scrutiny on the contractors tendering for the building of the survey beacons. The construction specifications should be simple and have gate release clauses at any critical stage of the construction. The contractors responsible for the construction should be monitored by a competent structural engineer to ensure compliance to the design standards.

- Instrument Shelter: The mine should rebuild the instrument shelters with construction material which will protect the instrument from the harsh atmospheric conditions prevailing in open pit mining. The instrument shelter should help prolong the life of the equipment without affecting the accuracy of the monitoring measurements.

- Monitoring Instrumentation: The mine already have the key monitoring instrumentation in place. There is need to utilise the instruments such that they complement each other with regard to accuracy. The monitoring instruments should also be positioned such that they are constantly cross checking each other's measurements. Cross checking is a basic survey principle which should be applied at all times when taking high accuracy measurements. The mine should consider purchasing equipment such as the ground based InSAR to enhance monitoring of the high risk plant infrastructure which is in the close proximity of the Cut 8 mining limit. To reconcile the whole monitoring system, the mine should purchase satellite images from the Altamira InSAR, to track areas susceptible to movement. The regularity can be intensified whenever movements exceeding set limits are detected.

- Analysis and Reporting of Monitoring Results: To raise the level of confidence on the monitoring results, all measurement should be processed for errors. The errors should be classified and adjusted accordingly. The mine should consider purchasing software with least square adjustment capability to process and adjust for errors. To integrate data from various monitoring instruments on the mine, packages such as GIS should be considered for analysing and reporting of monitoring results.

- Procedures: The existing procedures need to be reviewed such that they are specific and cover all aspects of monitoring such as warning systems and response, equipment maintenance and calibration, personnel training and responsibilities. A COP developed by the South African Department of Mineral Resources (DMR) to combat rock fall and slope instability related incidents in open pit mines will be a good reference document for Jwaneng Mine when developing standards and procedures.

- Personnel Responsibilities: For the slope monitoring programme to be successful, there is need for all role players to be clear on their KPAs with regard to whole process of slope stability monitoring. The role players should be well trained and competent for them to meet their objectives. To ensure competency at all levels the mine should consider developing a competency matrix for all the personnel involved in the monitoring program. From the competence matrix, weaknesses will be identified and addressed by way of development training. The key players, the geotechnical engineer and the mine surveyor should be registered with recognised professional bodies as competent persons in the fields of expertise. The registration addresses ethical and legal issues that may arise from any external audits.

- Budget: Since the mine has already spent a substantial amount of capital in purchasing the state of the art equipment used for monitoring, the optimisation costs will be relatively low. In justifying for additional costs, value adding initiatives such as the possible steepening of slope angles should emphasized to the mine management.

The next chapter, which will cover the conclusion and recommendations, will summarize the learning from the research. The author will also come up with recommendations on how to move the Jwaneng slope stability monitoring programme forward in the medium and long term.

6 CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

The purpose of this research was to identify means of optimising a survey slope monitoring system for a large open pit mine. To answer the fundamental question of how to design a slope monitoring system, the following should be considered;

- Survey Control Network: The key to an optimal geo-referenced slope monitoring system is the survey control network. There is need for an appropriate geometrical setup of control beacons with respect to the site being monitored. An inadequate geometrical set up of control points will result in a weak network. A weak network will yield errors during survey applications such as resection. These errors will be carried forward to the monitoring data, hence yielding misleading results.

- Beacon design and construction: The quality of the beacon structure designs is critical for an optimal monitoring system. The construction of the beacons has to be carried out by competent people using the appropriate building material. Wrongly designed and constructed structures can yield unstable survey beacons which will move at the slightest shaking of the ground due to blasts. Unstable beacons result in misleading monitoring results as it can be difficult to distinguish whether the ground movement detected is authentic or a result of beacon movement.

- Equipment selection and Utilisation: An optimal monitoring solution can be achieved by utilising the monitoring equipment in such a way that they complement each other's weakness in terms of accuracy and measuring capability. The instruments should be positioned such that they cross check each other for errors in measurements. Checking is of utmost importance in survey measurements and any survey data that has not been checked is unacceptable by survey standards.

- Coordinate system: It is important to have all the various monitoring systems operating in one coordinate system. This will allow for easy cross checking of results without running the risk of introducing new errors by transforming coordinates from one system to another. In selecting a coordinate system to use, the following factors have to be considered;

- How close the coordinate system match the physical reality as this will affect the precision of the monitoring results.

- The simplicity of the coordinate system when dealing with computations such as least square adjustments.

- Data management: The measurements from the various monitoring instruments have to be processed for errors before being used for ground movement analysis. The errors need to be classified and distributed accordingly to adjust the measurements to true values. It is therefore, critical to have software capable of performing the error propagation and adjustments. The monitoring data cannot be used in isolation. For the monitoring data to give meaningful results, it has to be used with other data which has bearing on the stability of the ground. This data can be of hydrological or blasting information amongst others. Software capable of integrating all this data into a central repository is very important.

- Warning systems: With an optimal monitoring system in place, it follows that ground movements will be detected before failure occurs. It is critical for the mine to have a response strategy in place in order to mitigate the risks associated with slope failure.

- Personnel: Role clarity is very important when dealing with tasks that require personnel from various disciplines. Slope stability monitoring requires input from disciplines such as survey, geotechnical engineering, mining and information technology amongst others. It is important for each individual to be clear on their responsibilities and are well trained and equipped to carry them out.

- Budget: When developing a monitoring strategy one needs to be cognizant of the budget as some monitoring equipment can be very expensive. It is always advisable to justify the budget with value additions such as the steepening of slope angles resulting from proper monitoring.

- Procedures: To guide the whole monitoring system, it essential to have procedures and standards in place.

6.2 Recommendation

This research developed a slope stability monitoring strategy for Debswana, in particular, Jwaneng Mine. In addition to the strategy outlined in chapter 5, it is recommended that;

- The survey control network at Jwaneng Mine should be redesigned. The Cut 8 pit expansion presents the mine surveyors with an opportunity to address the weaknesses in the current design as most of the existing beacons will be demolished to make way for the expansion. The beacon construction shortcomings will also be addressed.

- Repositioning of the existing monitoring equipment is necessary in order to maximise benefits from all the instruments and at the same time allowing for cross checking. A good example is the use of GPS reference stations and occasionally cross checking the z movements with a precise level.

- The mine should purchase a ground based InSAR to enhance the monitoring of the ground and the plant infrastructure in the proximity of the Cut 8 mining limit. This is a high risk area which requires a combination of monitoring methods as outlined in chapter 5.

- There is need to revise the slope monitoring procedures such that they are detailed and specific as compared to the current ones which tend to be generic. The procedures, together with the monitoring data should be stored in one place which is secure and have controlled access.

- All personnel involved in slope monitoring should have well defined roles with specific objectives. The competencies of this personnel should be assessed and the gaps closed by the appropriate training. Added responsibilities to principal players such as the mine surveyor and the geotechnical engineer should be kept to a minimum as they can easily distract them from the core functions of slope stability monitoring

- The mine should speed up the implementation of the GIS as this will assist in integrating the monitoring data with other slope stability related information from other sections such as hydrology and blasting. When selecting GIS software the mine should consider capability of carrying out functions such as least square adjustments as this will allow for error analysis before data is actually used.

- To reconcile the whole monitoring system, the mine should regularly purchase satellite images from the Altamira InSAR to confirm movements picked by other monitoring systems already in place at the mine and to identify new movements. The images should cover strategic areas such as the pit, dumps, tailings dams and the plant infrastructure. Initially, the satellite images can be purchased on a quarterly basis and frequency adjusted depending on the movement trends.

There is need to carry out further research in the following areas;

- The correction for varying atmospheric conditions brought about by depth changes in the pit remain a challenge when using GeoMos and need to be investigated. It is critical to understand what actually happens to that ray that travels from the Total Station to the monitoring point. The varying temperatures and atmospheric pressure, coupled with dust and fumes in the pit is affecting the accuracy of distance measurements and need to be investigated.

- There is need to come up with a systematic approach of how to manage the large amounts of data collected by the different monitoring systems such that one version of the truth can be detected from them. This approach should encompass data validation, processing and interpretation.

- There is need to investigate ways to devise a formula on how to incorporate slope monitoring information onto the designing of the pit slope angles. This will go a long way in demonstrating value derived from the system.

- There is need to develop beacon design and construction standards. This will ensure that the reference points for monitoring are robust and not easily affected by blasting activities.

Challenges in the area of slope stability monitoring will always exist, the onus lies with mine surveyors and geotechnical engineers to turn them into opportunities for continuous improvement by exploring and understating the challenges. This can be done through reading technical papers and participating in conferences.

REFERENCES

Abramson L.W., Lee T.S., and Boyce G.M., Design, Construction and Maintenance (Chapter 8) in Slope Stability and Stabilization methods, second edition, Wiley-Interscience Publication. Pp. 604,607,608-609, 626-627,629.

Afeni T. B. and Cawood F. *Do the properties of glass matter when taking Total Station distance measurements through an observation window?* International Society for Mine Surveying XIV International Congress, 20-24 September 2010, Sun City, South Africa, P. 167.

Altamira Information, Ground motion InSAR. Available from www.altamira-information.com, accessed 01/08/2011.

Bannister A., Raymond S. and Baker R., Surveying. (Pearson Education Limited, 1998) pp. 190, 207, 337-338, 431.

Barnett, W., *Jwaneng Country Rock Model: Update 2008.* SRK Consulting (Canada) Inc. Vancouver.2009.p.4

Bartley P. *The Nature of Monitoring and Evaluation; Definition and Purpose*, 2007. Available from www.scn.org/cmp/modules/mon-wht.htm, accessed 27/7/2010.

Bieniawski, Z.T. *In search of a design methodology for rock mechanics*, Rock Mechanics as a Multidisciplinary Science, Proc, 32nd U S Symp. On Rock Mech., 1991, Roegiers (ed.), Balkema, pp. 1027-1036.

Burkholder E. F., *Spatial Data, Coordinate Systems, and the Science of Measurement,* Journal of Surveying Engineering vol.127 no.4, November 2001., pp. 145-147, 155.

Canuti P., Casagli N., Moretti S., Leva D., Sieber A. J., and Tarchi D., *Landslide monitoring by using ground-based radar differential interferometry*. Proceedings of the first European conference on landslides, Prague, Chech Republic, June 2002, pp.523, 527.

Cawood F.T. and Stacey T.R., *Survey and geotechnical slope monitoring considerations.* The Journal of the South African Institute of Mining and Metallurgy, July 2006. pp. 495-497, 500-501.

Davis R. E., Foote F. S., Anderson M.J. and Mikhail E. M., Surveying Theory and Practice. (McGraw-Hill, Inc. 1968). Pp.158, 165-167.

Debswana, Jwaneng Long Term Plans.2009.

Doyle G.S., Stow R.J. and Inggs M.R., *Satellite radar interferometry reveals mining induced seismic deformation in South Africa,* 2001 IEEE, p. 2037.

Durban Corporation, Survey Handbook. (The Institute of Topographical and Engineering Surveyors of South Africa.1987) Pp.93-94.

GroundProbe 2010, INTERNET. www.groundprobe.com, accessed 1/12/2010.

Gudmanz, K.M. *The implementation of codes of practice,* Proc.Symp. Rock Mechanics and Productivity and The Implementation of Codes of Practice,1998, M.F. Handley (ed.), S.Afr. National Group of Int. Soc. Rock Mech., pp.3-6.

Halounova L., *GIS as a tool for landslide analyses.* Proceedings of the first European conference on landslides, Prague, Chech Republic, June 24-26, 2002, pp186-187.

IBIS-S, Preventing structural failures using microwave interferometry. Available from www.olsoninstruments.com, accessed 16/03/2011.

Jooste M. A. and Cawood F.T, *Survey slope stability monitoring: Lessons from Venetia Diamond Mine.* International Symposium on Stability of Rock Slopes in Open Pit Mining and Civil Engineering, 3 -6 April 2006, Cape Town., pp. 361-363.

Jooste M. A., Slope Stability Monitoring In Open Pit Operations. Investigational Project for Masters Degree in Engineering, University of the Witwatersrand, Johannesburg, 2005, pp., 16,27,36,37.

Kealy, A., *451-200 Survey Networks Theory, Design and testing*. Department of geomatics, The University of Melbourne, Victoria. Available from http://www.geom.unimelb.edu.au/kealyal/200/Teaching/net_design_test.html. Accessed 13/12/2010.

Leica Geomos, INTERNET. Available from www.leica-geosystems.com, accessed 01/12/210

Manetti L., Frapolli M. and Knecht A., Permanent, autonomous monitoring of landslide movements with GPS. Proceedings of the first European conference on landslides, Prague, Chech Republic. June 24 – 26, 2002. p. 249.

Milbert, D.G., Computing GPS-derived orthometric heights with the GEOID90 geoid height model. Technical Papers of the 1991 ACSM-ASPRS Fall Convention, Atlanta, Oct.28 to Nov.1, 1991. American Congress on Surveying and Mapping, Washington, D.C., pp. A46-55.

Mining News, *Rockslide at Kumtor*. Available from www.miningnews.net 19 July 2006, accessed 29/07/2009.

Mining Weekly, *Botswana, De Beers investing R25bn in ultra-rich Jwaneng Diamond Mine.* Available from www.miningweekly.com 19 October 2010, Accessed 25 November 2010.

Mining Weekly*, Mine evaluations in Botswana*. Available from www.miningweekly.com, 27th February, 2009, Accessed 01/12/2010.

Paudits P. and Bednarik M., *Using GIS in evaluation of landslide susceptibility in Handlovskakotlina basin.* Proceedings of the first European conference on landslides, Prague, Chech Republic. June 24-26, 2002. pp. 437, 441.

Read J. and Stacey P Guidelines for Open Pit Slope Design. (CSIRO, 2009), pp. 342, 346-353.

Reporter 50, Leica Geosystems, April 2004, p.12.

Thomas, H. W., Slope Stability Monitoring: A guide for practising mine surveyors. A research project submitted to the faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, 2011, pp.46, 56, 59, 65,108.

Thomson C., *Importance of good quality Survey Control Network in an Automated Slope Stability Monitoring Programme.* Geosystems Africa Circular, 28 September 2005.

Trimble, INTERNET. Available from www.Trimble.com, accessed 01/12/.2010

Wang J., Gao J., Liu C. and Wang, J., *High precision slope deformation monitoring model based on the GPS/ Pseudolites technology in open-pit mine.* Mining and Science Technology 20, 2010, p126.

Watt I.B., *Monitoring Surveys at Letlhakane and Orapa open pit mines,* Consulting Report. March 1996.

Wolf R. and Ghilani D., Adjustment Computations: Statistics and Least Squares in Surveying and GIS. (John Wiley and Sons, 1997). Pp.1-11

APPENDICES