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UNIVERSITY OF THE WITWATERSRAND

SCHOOL OF MINING ENGINEERING, FACULTY OF ENGINEERING AND BUILT ENVIRONMENT

FACTORS TO BE CONSIDERED WHEN APPLYING ATMOSPHERIC CORRECTIONS TO PRISM MONITORING MEASUREMENTS

A case study of the Leica GeoMoS installation at Orapa, Letlhakane and Damtshaa Mines [OLDM]

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.

Orapeleng Randall

Johannesburg, 2018

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.

……..

Orapeleng Randall

…….day of ……. 2018

at……..

ABSTRACT

When taking measurements for slope stability analysis using prism monitoring systems, there are various measurement errors which could result in incorrect analysis and subsequent reporting and decision making. As measurements are taken across the open pit, rapid fluctuations and spikes in data are introduced due to changes in atmospheric conditions through which the EDM signal travels. The changes in atmospheric conditions across the open pit affects the slope distance measurements to monitoring prisms and adjustments or corrections to the measured distances must be made. The challenge is that the ambient temperature and atmospheric pressure readings used for computing the atmospheric corrections can only be measured at the transfer beacon, and not at the monitoring prism since it is impractical and costly. To achieve optimal prism monitoring results using atmospheric corrections, there are factors which should be considered. These include the suitable position of the meteorological sensor, suitable monitoring times, mitigation of the effect of mining activities and prism monitoring equipment protection.

The objective of this research report is to investigate factors which need to be considered when applying atmospheric corrections to prism monitoring measurements. Trial work was carried out to evaluate the method of adjusting slope distance measurements using GNSS generated reference scale factors. This method also has its limitations, however it is a viable option for adjusting slope distances as the open pit becomes wider and deeper. The method of correcting the slope distances using meteorological data is also an acceptable solution, especially when measurements are taken over short distances. This research report should serve as a guide in making decisions for a suitable method for adjusting slope distance measurements for prism monitoring in an open pit mine environment.

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KEY WORDS AND ABBREVIATIONS

GeoMoS	Geodetic Monitoring System
CORS	Continuous Operating Reference System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System (USA)
OLDM	Orapa, Letlhakane and Damtshaa Mines
SSR	Slope Stability Radar
EDM	Electronic Distance Meter
ATR	Automatic Target Recognition
GIS	Geographical Information System
IT	Information technology
ppm	parts per million
InSAR	Interferometric Synthetic Aperture Radar
Total station	An electro-optical instrument for measuring co-ordinates of points
Reference beacon	A survey concrete monument with known co-ordinates
Transfer beacon	Reference beacon where measurement for deformation monitoring take place
Survey Control Network	A set of reference beacons from which surveys can be taken

Benchmark	A survey monument or point with accurately known elevation and coordinates used as a mine's reference point for geo-referenced identification
Primary Beacon	A survey reference beacon which is used for orientation and check measurement purposes
Secondary Beacon	A survey reference beacon within a control network from which a monitoring point is surveyed. It's usually located on the open pit edge
GeoScope	A computer software which integrates data for various slope monitoring systems
Multi-path	Satellite signal received by a GNSS receiver other than by the direct route, i.e. by reflection off a surface in proximity to the GNSS receiver
Diurnal	Meteorological term that relates to the variation in temperature that occurs from the highs of the day to the cool of night
°C	Degrees Centigrade (temperature)
mBAR	Millibar (pressure)

1 INTRODUCTION

The accuracy of any particular measurement is determined by the type of measuring instrument used, the method of measurement employed and sometimes by the skills of the user, (Rabinovich, 2005). However, as the true value of a measurable quantity is always unknown, the errors of measurements must be estimated theoretically. This research addresses the subject of measurement accuracy concerns with regard to atmospheric correction on prism monitoring measurements using total stations in open pit mining environments. The data used for analysis in this research report is sourced from a trial and the Leica GeoMoS prism monitoring installation at Orapa, Letlhakane and Damtshaa Mines in Botswana.

The accuracy of slope monitoring data is significant in ensuring defensibility of a ground deformation monitoring strategy of any site. The effects of measurement errors caused by atmospheric conditions need investigation and possible solutions.

1.1 Legislation on Slope Stability Monitoring

Prism monitoring measurements form the basis of ground control on specific areas of an open pit mine. Ground in this instance refers to any natural geological materials in an open pit mine which may range from soft to hard rock. An open pit without a ground deformation monitoring strategy can have negative implications on the safety of people, equipment as well as financial constraints resulting in increased legal liability. One of the fundamental responsibilities of a mining engineer in an open pit mine is to ensure that the safety of people working in the mine is not compromised due to slope failure. The person who has management or control of the mine has to ensure that all working sites in the mine are stable and must not allow a worker to enter the mine until the sites are safe to work on again. The risk of slope failure is legally binding as quoted in the Mines,

Quarries, Works and Machinery Act of Botswana, part 32, section 566 and 567. The Act states that:

"Inspections:

1. The manager or a competent person or persons designated by him shall make a daily inspection of the faces and banks, and shall cause all loose or dangerous materials to be dislodged or otherwise made safe.
2. No person shall work or be permitted to work near any face or bank until it has been examined and made safe.
3. The manager shall ensure that at least one in every week a competent person or persons shall inspect the top of all faces and banks for cracks which might indicate the imminence of slides or other movements of the face.

Log books:

1. The manager shall keep or cause to be kept a book in which shall be recorded a report of every such examination required under regulation 566(1) and (3), signed by the person making such examination.
2. A note shall be made of any dangerous condition reported and the action taken regarding it.
3. Such entries shall be read and initialled every week by the manager".

It is necessary for an open pit mine to have effective slope monitoring systems which can help in meeting the requirements of the Act as well as ensuring defensibility of the slope monitoring strategy in the event of a slope

failure. This is emphasised by the Mine Health and Safety Act (1966) of the republic of South Africa in chapter 17 as follows:

> "Where ground movement, as a result of mining operations poses significant risk, an effective ground movement monitoring system is in place".

Slope monitoring systems in open pit mines include the following, but not limited to:

- Prism monitoring systems;
- Laser scanning;
- Radar.

This research report focuses on prism monitoring systems and their measurement accuracy.

1.2 Introduction to Measurement Accuracy

The topic chosen for this research report is mining industry specific and addresses mitigation of one of the highest safety risks in the mining business, that being slope instability and slope failures. One of the primary survey mandates is to provide accurate slope monitoring data which is meaningful to make decisions about the behaviour of slopes in an open pit environment. Mphathiwa (2011) emphasised that it is critical to have a reliable slope monitoring system such that any potential failure can be detected timeously so that personnel and machinery can be evacuated from the hazard areas timeously.

With modern technology, the mine surveyor is able to produce such data to a certain degree of accuracy. Thomas (2011) states that technology has provided tools to enable the mine surveyor to measure the movement of slope faces to a high degree of accuracy which in turn enables the

geotechnical engineer to predict slope failure with a better accuracy. This slope monitoring data is also important in planning of the life of a mine and it informs the stakeholders of the feasibility and profitability of the mine with respect to slope optimisation.

Measurements from the prism monitoring setups are obtained using total stations. A total station is an instrument used to measure vertical and horizontal angles as well as slope distances from the instrument setup station to a prism target (Goldberg and Ream, 1990).The accuracy of three dimensional co-ordinates of the prisms is influenced by the accuracy specification of the total station, the geodetic survey control, as well as atmospheric conditions.

Every measurement has a true value which is difficult to obtain. Measurement accuracy is the relationship between the actual value of a measurement and its exact value. Precision is the closeness of two or more measurements to each other. Prism monitoring measurements therefore take cognisance of both the accuracy and precision. Measurements which are accurate but not precise do not give a good slope analysis model, as such these measurements must be both accurate and precise. The concept of accuracy and precision is illustrated in figure 1.1.

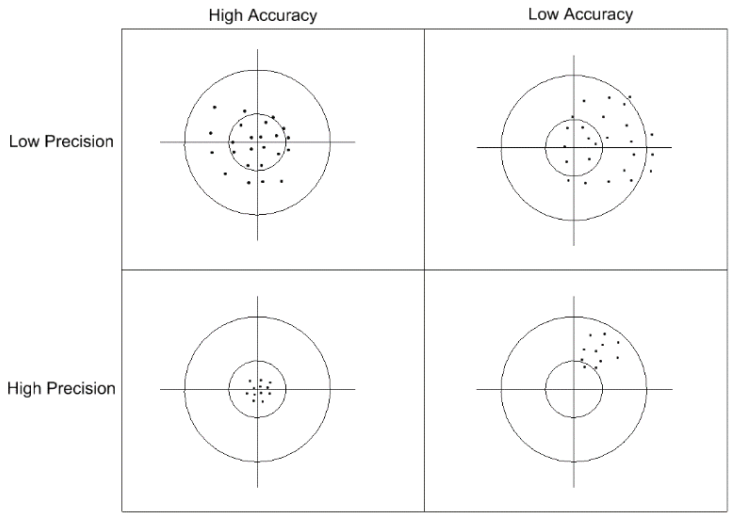


Figure 1.1: Illustration of precision and accuracy.

Figure 1.1 shows that more precise measurements can result in less accurate measurements. The mine surveyor has to understand the consistency of measurements in relation to the accuracy. In this way a highly accurate and precise measurement can be achieved for slope monitoring analysis.

Position fixing of measurements involve the measurement of angles and distances by a total station, however all measurements will contain errors, no matter how carefully they were measured. In other words, the true value of a measurement is never known, therefore if the true value can never be known, then the exact error cannot be known also, as such the position of a point can only be known with a certain level of confidence (Schofield and Breach, 2007).

To ensure risk mitigation and safety of slope failures in open pit environments, there is a need to monitor adequate number of prisms with robotic total stations. One of the challenges which mine surveyors experience is the accuracy limitations of the robotic total stations, that is sighting to prisms, the effect of atmospheric conditions and refraction as well as configuration defects that arise through multiple robotic total stations (RTS) networking solutions (Chrzanowski and Wilkins, 2006). With modern automated slope monitoring technology, the issue of measurement accuracy cannot be neglected, but has to be understood and achieved with at least a 95% level of confidence depending on the open pit mining conditions and requirements. To understand the measurement accuracy, there are three types of errors which occur or influence measurements and have to be eliminated as far as possible. These are:

- Gross errors;
- Systematic errors;
- Random errors.

1.2.1 Gross Errors

These can be attributed to human errors resulting from improper use of the survey equipment or low competency. Some scientists refer to these as blunders, and they can be easily avoided. Mistakes or blunders are often made by inexperienced mine surveyors who are not competent in using the survey equipment, therefore gross errors are mainly due to incompetency and carelessness. If there are no controls to detect a gross error in a survey, then this may result in survey errors on site. It is therefore important that all survey work has observational and computational procedures and checks to be adhered to so that mistakes can be easily identified (Uren and Price, 2006).

The total station may be in good order and may not give any error, but the measurement accuracy may still be influenced and affected by the user. Gross errors include; recording wrong readings, that is transposing of numbers, reading with parallax errors and improper applications of instrument settings, wrong computations, incorrect adjustment. Gross errors can be minimised by doing redundant checks and also engaging another mine surveyor to validate the measurements.

1.2.2 Systematic Errors

They are classified as correctable errors because their magnitude and algebraic signs can be computed and eliminated from the measurements and thus improving the accuracy. Systematic errors will have the same magnitude in a series of measurements which are repeated under the same conditions. If there is some change in the measuring conditions, then the size of the systematic errors will vary accordingly. The main problem with this type of errors is that they will always remain in the measurements until something is done to remove them, moreover they can accumulate if there is more than one present in the measurements.

For instance, prism monitoring measurements will always be affected by ambient temperature and atmospheric pressure. If no corrective measures are taken, then the systematic errors will remain in the measurements and these will reflect on the data displacement graphs of the monitoring data which will show big amplitudes. This research report is based on this type of error. Another typical example of a systematic error in prism monitoring with a total station is the prism constant; if it is not applied correctly or omitted, it will remain as an error in all the readings and will affect the measurements accuracy as temperature and pressure changes throughout the day.

Variations will be evident in any series of measurements recorded by a measuring instrument. The variations in different measurements are also referred to as systematic errors. They are classified into two categories; instrument errors and environmental errors. When human errors are avoided or all checks have been undertaken to avoid such errors, there may still be errors in measurements due to the inherent errors of the instrument. The following may cause the instrument errors;

- Calibration errors due to the age of the instrument;
- Faulty display circuit;
- Errors in vertical and horizontal axis of the instrument.

These errors can only be minimised by following an effective maintenance and calibration schedule of the instruments. Changing atmospheric conditions such as temperature, pressure, humidity and other influences such as magnetic and electrostatic fields and dust can affect the measurement accuracy of the instrument. However the influence of atmospheric conditions on slope distance measurements remains a major challenge, as such this research report is based on the measurement errors caused by varying atmospheric conditions across an open pit environment.

1.2.3 Random Errors

Variations in measurements due to the measurement techniques are commonly referred to as random errors and remain after systematic and gross errors have been removed. No specific reason can be assigned and precaution must be taken to avoid these errors. These errors are however managed by increasing the frequency of measurements to each prism. This will improve the estimating of these errors through statistical analysis.

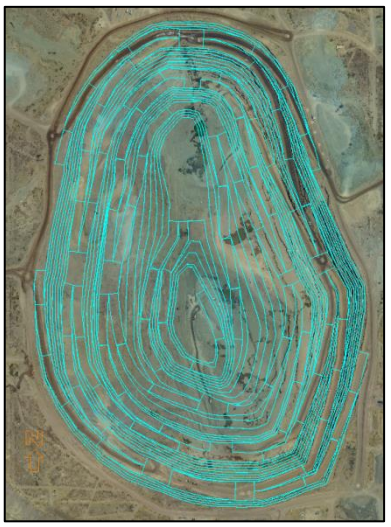
Random errors are associated with the skill and care taken by the mine surveyor. Random errors are also referred to as accidental because they are not common in measurements. When mine surveyors are careful and diligent in taking measurements, the random errors will be of little significance except for high precision surveys. Even if random errors can cancelled in measurements, the final averaged measurement will not be precise (Kavanagh, 2009). Random errors are relatively small and there is no procedure which can compensate for or reduce one single error of this type. The size and sign of any random error is very unpredictable, but a group of errors can be predictable.

1.3 Geotechnical Characteristics of Orapa Mine

Orapa Diamond Mine, known as AK1 open pit, is the biggest open pit of the three sites at Orapa, Letlhakane and Damtshaa mines with dimensions of approximately 2km x 1.8km x 0.3km. Ore and waste materials are mined within the Cut 2 mine design, refer to figure 1.2.



Orapa Mine Open Pit Aerial View



Orapa Mine Open Pit Cut 2 Design

Figure 1.2: Orapa Mine pit overview.

Orapa Mine currently exploits the 2125AK1 kimberlite, which is mostly dominated by crater-facies volcaniclastic and pyroclastic kimberlite in its upper parts. The kimberlite is also hosted by sedimentary rocks of the Karoo Supergroup, which uncomformably overlays tonalitic or granite-gneiss basement. The stratigraphy of the host rocks to the 2125AK1 kimbelite consists of three main components from the base upwards; Achaean gneissic to TT9 basement (Tonalite-Trondhjemite-Granodiorite materials); sedimentary formations of the Karoo Supergroup and the overlying Stromberg basalts (Basson and Stoch, 2014).

It has been established that slope failure risk at Orapa Mine is more pronounced on the sandstone rock type on the southern, eastern and northern sides of the open pit. Slope failure is also pronounced where the contact between the kimberlitic and the country rock trends unfavourably to the Cut 2 haul road on the northern side of the open pit. Therefore any large slope failure that may occur in Orapa Mine would most likely happen in these areas. Total ramp loss due to slope failure in cut 2 slopes would lead to a total stop of Kimberlite ore mining from the open pit bottom. In the event of a slope failure there would be potential loss of fourteen workers as this is the average number of operators transported in and out of the open pit

during shift changeover. There is a potential for hydrocarbon pollution from damaged mining equipment during a slope failure due to vehicle oil and diesel spillage which could seep into the groundwater aquifers. There is possible criminal legal action by the Government Inspector of Mines or affected families against the company if professional negligence can be proved in case of serious or fatal injuries sustained during a slope failure event.

In an effort to mitigate the risk of a slope failure, there are three methods of automatic 24 hour slope stability monitoring at Orapa Mine. The first technique involves the application of the prism monitoring system, that is the Leica GeoMoS. There are three prism monitoring stations around Orapa Mine open pit with a total of approximately two hundred prisms being monitored. This system gives ground deformation for long time trends and when significant movement is detected. Warning alert messages are sent to the geotechnical engineer for investigation (Geotechnical Procedure, 2012).

The second method is the use of a slope stability radar (SSR). A total of three SSR machines are installed around the open pit and achieves 100% coverage of the open pit. A colour graphics image of the ground deformation occurring on the slopes is shown on the computer in real time as shown in figure 1.3. This graphical image also identifies areas of movement using a geo-spatially referenced heat map.

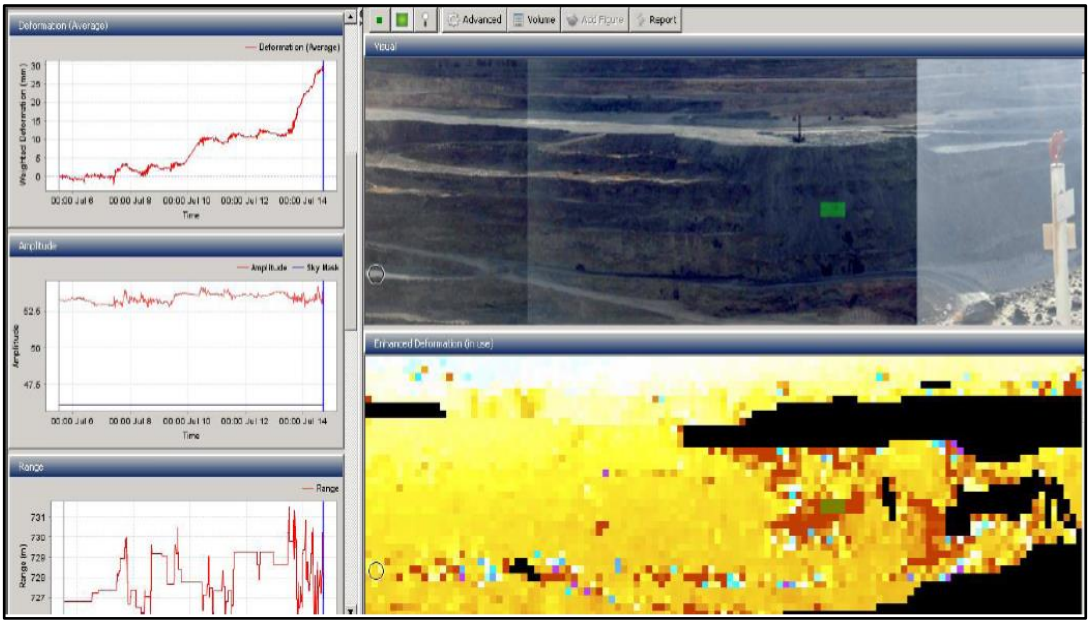


Figure 1.3: Analysis graph for the Slope Stability Radar. Source: Orapa Geotechnical Department.

When abnormal movement is detected, an email and a mobile phone text message are sent to the Geotechnical Engineer who will then inspect the area where the alert has come from.

The third method is the use of a laser scanner system which is installed on the western side of Orapa Mine and strategically monitors the area installed with wire-mesh. Periodic scans are done automatically on a 24 hour basis and any abnormal movement detected by a message is sent through email or a mobile phone text to the Geotechnical Engineer for the appropriate action.

These three techniques are fully optimised by survey and geotechnical departments at Orapa Mine to manage the risk of slope failure. The validity, integrity and accuracy of the data which comes from these three methods is very important for slope stability analysis. This research is based on one factor which could influence the accuracy of measurements from the prism monitoring system (Leica GeoMoS).

1.4 The Problem Statement

The author's area of research is focused on the influence of atmospheric conditions and corrections applied to prism monitoring distance measurements. From basic survey principles, co-ordinates of any unknown point are derived from angles and distances measured from a known point with reference to other known points. The measured slope distances must be first corrected for atmospheric influences that is ambient temperature, ambient pressure and in some cases humidity. Chrzanowski *et al* (2006) states that repeated distance measurements are mainly affected by the varying density of air through which the measurements are made (change in meteorological conditions). The problem statement of this research report is to investigate factors to be considered when applying atmospheric corrections to prism monitoring measurements in an open pit.

It is the author's opinion that the Electronic Distance Measurement (EDM) signal from the prism monitoring total station to various monitoring prism positions in the open pit travels through different mediums of the atmosphere. Current research shows that there is no solution to accurately apply the appropriate atmospheric correction parameter to prism monitoring distance measurements. It is important to understand what affects the EDM signal as it travels to and from the prism across an open pit.

Research shows that most prism monitoring set-ups use a meteorological device which is used to measure atmospheric conditions, and it is usually located at the transfer beacons. The actual atmospheric conditions at the transfer beacon will differ with the conditions at the monitoring prism as well as across the open pit. Therefore an assumed best fit atmospheric correction may not be adequate to accurately correct the measured slope distances to each monitoring prism, resulting in degraded measurement accuracy. This measurement accuracy problem is the basis of this research report.

1.4.1 Primary Research Questions

The research report will address the following fundamental question:

a. How to apply the atmospheric corrections to total station measurements taken through varying atmospheric densities across the open pit?

The following are subsequent questions:

b. Why do displacement graphs show high fluctuations at various intervals in the prism monitoring data?
c. What is the influence of atmospheric conditions to distance measurements?
d. What is the influence of position of the meteorological sensors on atmospheric corrections?
e. What influences the EDM signal from the total station to the prism as it travels across the open pit? and
f. Do mining activities have an influence on atmospheric conditions within the open pit through which the EDM signal measures?

1.4.2 Research Aim and Objectives

The aim of this research is to investigate the factors to be considered when applying atmospheric corrections to prism monitoring measurements in an open pit.

The research objectives are as follows:

a. To investigate the impact of the meteorological sensor position on slope distance measurements;
b. To investigate the impact of atmospheric corrections on distance measurements;
c. To investigate the impact of mining activities on prism monitoring measurements;

d. To investigate the impact of monitoring times on prism monitoring measurements;
e. To elaborate on a theoretical explanation of what actually happens to the EDM signal which travels from the total station to the monitoring prism across an open pit;
f. To find out an alternative method used to adjust the total station slope distances.

1.5 Focus of the Research

The main challenge which most prism monitoring practitioners are experiencing today is fluctuations of the displacement graphs used for slope stability analysis. This research report will investigate if these fluctuations shown in displacement graphs are indeed caused by incorrect atmospheric corrections or not. In this research report the author will elaborate on various topics to answer the fundamental question of “How to apply atmospheric corrections to measurements taken through varying atmospheric conditions and densities across an open pit?”

The focus of the research site will be the prism monitoring installations at Orapa, Letlhakane and Damtshaa Mines. Orapa Mine is one of the three Debswana Diamond Mines operations in the northern part of Botswana and is classified as the second largest producer of rough diamonds in the World. Letlhakane Mine is also operated by Debswana and it is located 35km south of Orapa Mine. It consists of two pits, DK1 and DK2. DK1 pit is the largest at Letlhakane with dimensions of 1km by 1km. The Leica GeoMoS prism monitoring system has been operating at Orapa and DK1 pits for the past 10 years.

1.6 Significance of the Research

This research report is relevant to the mitigation of the risk of slope failures in open pit mines and it also addresses the accuracy in total station measurements, which is a very important aspect of the mine survey discipline. The research report will have practical significance to mine

surveyors, mining engineers, mining planners, geotechnical engineers, mining stakeholders and research institutions. This research report is important because once a new model or alternative of applying atmospheric corrections to prism monitoring measurements in open pit mines is found, then this will improve the accuracy of measured slope distances to monitoring prisms. Mine surveyors will then be able to provide the slope monitoring measurement data to the geotechnical engineers with a greater level of confidence.

This research report may also lead to the implementation of the findings in future prism monitoring system releases to mitigate the issue of distance measurement accuracy with regard to atmospheric corrections. Over and above that, Mphathiwa (2012) emphasised that the corrections of varying atmospheric conditions across the pit is a major challenge in prism monitoring and needs further investigation.

1.7 Literature Review

The subject of atmospheric corrections applied to distance measurements using total stations has been studied by different authors using various methods. There has also been preliminary work done which relates to this research report at Orapa, Letlhakane and Damtshaa Mines. This involved relocation of the meteorological sensors used for recording atmospheric conditions, from the mine office buildings to the monitoring stations at the open pit.

This process did improve measurement accuracy shown in displacement graphs by up to 2mm, and it shows that if the meteorological sensors can be placed very close to where the actual measurements are taken then a significant improvement in prism monitoring data accuracy can be achieved. Another improvement which was carried out at Orapa, Letlhakane and Damtshaa Mines in September 2012 was to protect all meteorological sensors using Stevenson Screens. A Stevenson Screen is a small wooden housing with perforated sides which mitigates the influence of precipitation

and direct heat radiation from the sun and allows the meteorological sensor to measure ambient air temperature and pressure. Figure 1.4 shows an illustration of a Stevenson Screen.



Figure 1.4: Stevenson Screen. Source: Orapa Survey Department.

After this intervention an improvement of up to 1mm was realised in the measurement accuracy shown in displacement graphs. These two processes show that if further research can be done on this subject, then there may be an opportunity for an improvement in prism monitoring data accuracy, hence the reason for this research report. Another test which is still under review is to observe the displacement graphs for certain periods of the day, especially at night when there is minimal variation of atmospheric conditions due to no heat radiation which is mostly caused by the sun heat. The period of monitoring can be a factor to consider when applying atmospheric corrections to prism monitoring measurements.

Thomas (2011) emphasised the importance of measuring the ambient temperature and atmospheric pressure when using total stations for measuring distances. Thomas further stated that if the atmospheric conditions are not compensated for, then the accuracy of the measured distances can be adversely affected because the atmospheric conditions do change over time. It is evident from this paper that the position of the temperature and pressure sensors have a significant impact to the final adjusted slope distances and further research is necessary to find out the most suitable position and setup for the meteorological sensors. Temperature and pressure must therefore be recorded on an ongoing schedule because of the ever varying atmospheric conditions, especially with cloud cover.

Cawood and Afeni (2013) states that the influence of atmospheric conditions is a big problem on prism monitoring. Different researchers have carried out research in this subject, but they realised that there are a number of accuracy effects caused by atmospheric conditions that need further study. Cawood *et al* (2013) further stated the influence of other atmospheric conditions such as rainfall and mist to total station measurements. It is clear from Cawood and Afeni's report that prism monitoring can be affected by rainfall, dust and mist and a long term solution is to ensure that monitoring equipment is protected using a sealed shelter with glass enclosures.

Afeni (2011) carried out tests and analysis to find out the impact of taking measurements through glass with measurements being subjected to the atmospheric effects. His research established that the properties of the glass must be considered when taking total station distance measurements. It is noted that glass does have very little or no impact on the vertical measurements, however its impact on horizontal distance measurements arise as the glass thickens increases. Afeni's research shows that the glass effect remains the same even after the atmospheric corrections have been applied to the measurements. The research also established that the

atmospheric formulae stated in the total stations manuals accurately compensate for variations in atmospheric parameters during distance measurements. Afeni emphasised on the need to correctly position the meteorological sensor as follows: “the GeoMoS meteorological sensor must be installed outside the transfer beacon at the open pit, not outside the mine surveyor’s offices”. Figure 1.5 illustrates this explanation and is part of the research questions of this research.

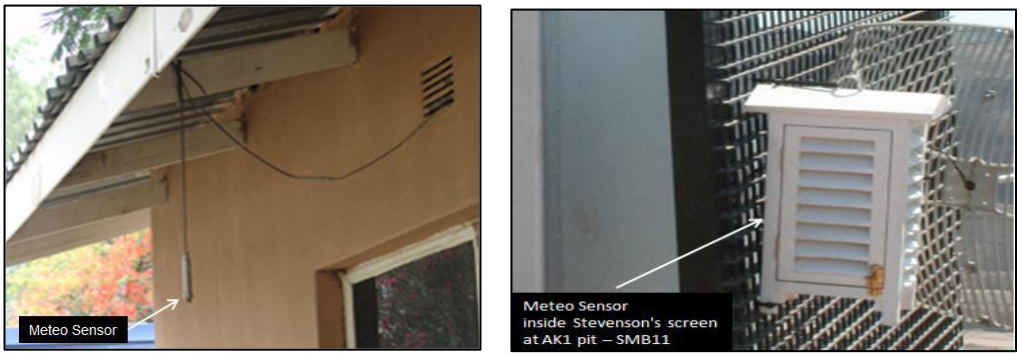


Figure 1.5: Different meteorological sensor positions.

Atmospheric corrections on total station distances were identified as a problem at Venetia Diamond Mine by Jooste and Cawood (2010). This problem was observed to be common over long distances due to variations in temperature and with depth across the open pit. The temperature variations resulted in spikes in the monitoring graphs and errors in the vertical height component. Due to this problem a decision was taken to monitor continuously from 17h00 until 07h00 during which time ambient temperature and atmospheric pressure readings are more stable and better results were obtained. Best practice is however to monitor 24hours a day because slope failures can occur at any time of the day. This paper explains that continuous monitoring during the day times requires fundamental research. The learnings from Venetia Diamond Mine show that monitoring times can prove to be an important factor to consider when applying atmospheric corrections to prism monitoring measurements.

Bertacchini, Capra and Castagnetti (2011) tested how atmospheric corrections could improve the measurement precision and accuracy to exploit total station system efficiency in landslides prediction. Some comparisons were analysed; the first was between the corrected and the uncorrected slope distance observations; the second was between the adjusted corrected co-ordinates and uncorrected co-ordinates.

The author of this paper states in conclusion that meteorological stations should be used in proximity of both total station and reference targets for an ideal continuous monitoring system. The underlying problem is that the atmospheric conditions at the monitoring total station and the monitoring prisms are not the same as in the void of the open pit. The results also showed that for long distances, the problem of the atmosphere strongly influences final results. Some of the tests done in this paper will be further explored by the author. This shows that some work has been undertaken to try and address the impact of atmospheric conditions to total station measurements.

1.7.1 Consideration of the CORS System

The Continuous Operation Reference System (CORS) can be used to investigate if the effect of atmospheric influences on prism monitoring measurements can be minimised by using combined Global Navigation Satellite System (GNSS) satellite receivers and robotic total stations. Prism monitoring systems using have been used in open pit mines for many years and currently best practice for mitigating against atmospheric influences is to correct the measured slope distances using ambient temperature and atmospheric pressure readings from meteorological sensors. The use of GNSS measurements on the control beacons can prove to be a baseline of which reference distances can be computed and a scale factor deduced and applied to subsequent measurement of prism distances in an open pit. The illustration in figure 1.6 shows a layout of the CORS system.

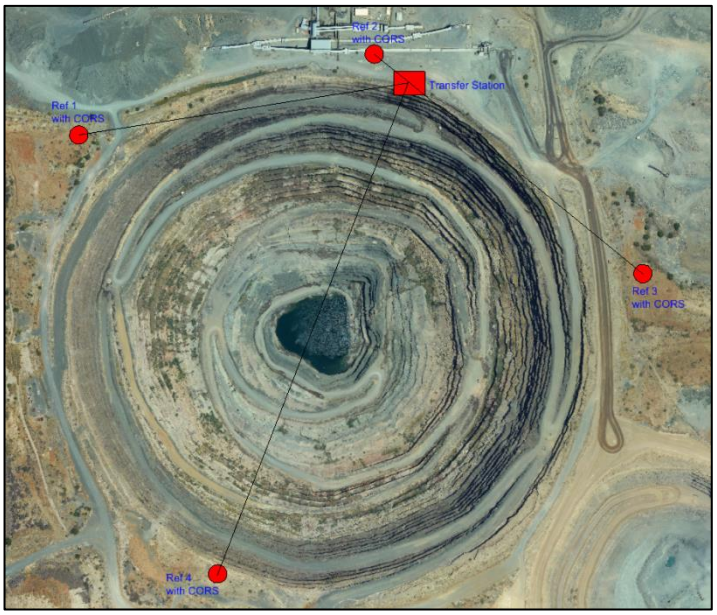


Figure 1.6: Layout of the CORS system. Source: Orapa Survey Department.

If the prism monitoring software can be configured to read real-time co-ordinate values from the GNSS system of the reference and transfer beacons, then reference distances can be computed using this data prior to measurements of prisms. It would be best if the software can also be set to measure the reference distances after every five measurements, so as to compensate for any rapid atmospheric changes.

The accuracy of the real time processing of the reference distance measurements for the GNSS system is related to the geometry of the satellites constellation at the time of measurement. When the geometry of the satellites is poor, a less accurate measurement should be expected, and if the geometry of the satellites is good, then a higher accuracy should be expected. However, research shows that post-processing is a very stable and accurate method for computing and updating reference co-ordinates using GNSS data (Brown, Kaloustian, and Roeckle, 2006).

An experiment which uses reference distance measurements corrections was carried out at Leica, Switzerland, and an accuracy of 1-2mm was achieved in plane co-ordinates. The experiment used automatic post-processing of the GNSS data for reference stations, whereas for the

monitoring points which were located at least 1 km from the total station, an accuracy of 2mm in longitudinal direction, 20mm in transverse and 15mm in height was achieved. The conclusion of this experiment was that combining GNSS satellite receivers with robotic total stations is an effective method of monitoring points in the absence of stable locations (Brown *et al*, 2006).

1.8 Research Design

Chapter 1 focuses on introducing the subject of the research report. It contains an introduction of measurement accuracy, the problem statement, the primary research questions, the aim and reasons of undertaking this research report as well as the theoretical research overview. A preview of the following chapters is also outlined.

Chapter 2 focuses on the fundamental principles of ground deformation monitoring. The author reviews the Leica Geodetic Monitoring System [Leica GeoMoS] and explains what it comprises of, how it works, its implementation at OLDM, its limitations and its suitability for slope stability monitoring. Discussions are based on literature from the Leica GeoMoS supplier as well as findings on the current setup at OLDM. Actual information in the form of photographs of monitoring and Information Technology (IT) infrastructure is used for illustrations.

Chapter 3 outlines a theoretical explanation of the concept of atmospheric corrections to total stations measurements. The author elaborates the measurement mechanism of total stations. An explanation of how total station measurements are performed in a prism monitoring system is explained. This chapter also discusses how the atmospheric corrections are applied to prism monitoring measurements and the findings and conclusions on this subject by other referenced authors.

Chapter 4 describes the Leica GeoMoS data management and analysis for Orapa, Letlhakane and Damtshaa Mines, which is the case study of this research report. The author elaborates the measurement trend of the

GeoMoS data over the years and the impact of atmospheric conditions to this data. Furthermore, the existing model for the atmospheric corrections is discussed.

Chapter 5 evaluates factors which should be considered when applying atmospheric corrections to prism monitoring measurements. These include slope distance, meteorological sensor positions, monitoring times and mining activities. The fundamental question of the research is answered; “How to apply atmospheric corrections on measurements taken over varying atmospheric densities across an open pit?” A trial will be evaluated to find out if there is an optimal method for adjusting slope distances based on learning’s from the literature review.

Chapter 6 reviews all the chapters and highlights the main findings which led to answering the fundamental question of the research report. The author discusses possible limitations of the research report and recommendations for further studies on the subject of measurement accuracy on slope monitoring data.

1.9 Conclusion

The fundamental sources of measurement errors have been outlined in this chapter, in particular the errors arising as a result of atmospheric conditions to total station measurements. Research shows that work has been done on this topic by a number of authors, but more research in investigating factors to be considered when applying atmospheric corrections to prism monitoring measurements is necessary because the atmospheric corrections pose an accuracy challenge with prism monitoring systems. This chapter has explained the significance of undertaking this research report and how it will be undertaken. The research model has been outlined.

Chapter 2 focuses on the principles of ground deformation monitoring. The Leica GeoMoS prism monitoring prism system is discussed; how it works and its suitability to slope monitoring. The chapter will also assess some of the limitations which have been experienced so far with this system in an open pit environment.

2 GROUND DEFORMATION MONITORING

Chapter 2 reviews the fundamental principle of deformation monitoring and explores the prism monitoring system at Orapa, Letlhakane and Damtshaa Mines (OLDM).

2.1 Principles of Ground Deformation Monitoring

Deformation of any structure is the change in shape of a body which is mainly caused by application of force or stress. Deformation also affects the volume of an area of the earth's crust. High walls of open pit mines are subject to deformation because the rockmass are always under pressure and causes them to change in shape and size over time. Temperature and pressure changes in the open pit can also cause the rockmass to expand and contract, which then leads to ground deformation.

Mining operations have significant areas of rockmass movement and surface displacement that potentially lead to slope instabilities with risk to personnel, equipment and production. Ground deformation in an open pit can be due to deep excavations in rock masses or low geo-mechanical quality, blasting practices and rainfall. Waldier *et al* (2014). The consequence of ground deformation in an open pit is a slope failure. To determine which failure modes are possible in an open pit, the geological parameters in various sectors of the mine need to be quantified. The following are some of the slope slope failure modes which may occur in an open pit:

- Plane failure;
- Wedge failure;
- Toppling failure.

Plane failure occurs when a geological discontinuity such as bedding plane, strikes parallel to the slope face and dips into the excavation at an angle steeper than the angle of friction. The wedge failure occurs when two

discontinuities intersect and their line of intersection daylights in the face. Toppling failures are common in open pit mines and occur when vertical or near vertical structures dip towards the pit.

As previously mentioned, deformation of the rockmass in an open pit can lead to a slope failure which can have a huge impact to production and the lives of human resources as well as mining equipment. It is necessary for a mining operation to put up controls which mitigate against the impact caused by slope failures. This is done through ground deformation monitoring and this will be explained in the next sections of this chapter.

There are various geotechnical and survey methods used in open pit mines to mitigate against deformation of slopes. Survey methods include prism monitoring, Laser scanning, Precise levelling, GNSS monitoring (CORS) and satellite imagery monitoring. The geotechnical methods include visual inspections, radar and extensometers. Ground deformation monitoring methods can be integrated in open pit mines so as to have an effective platform for slope stability analysis. Each method will have advantages and disadvantages over the other. The ground deformation monitoring methods are as summarized below.

2.1.1 Prism Monitoring

Prism monitoring uses the basic survey principle of measuring from a total station to a prism using known reference points. This method's accuracy is dependent on the control network infrastructure as well as corrections made on slope distances measured to the prisms. Normally prisms are installed by the geotechnical engineer at a distance on strategic points of the high wall. These prisms can be spaced at a distance of thirty metres or more depending on the type of rock being monitored. The mine surveyor is responsible for collecting data from the prism monitoring system, while the geotechnical engineer analyses the data.

All prism monitoring systems have a survey module and an analysis software. The survey module controls the survey instrument to measure and transmit data to the server or computer at set intervals and the data is stored in a computer database. The analysis module of the software is able to graphically represent the survey data, once calculations and adjustments have been made. Graphical representation for slope stability analysis can be shown as longitudinal, vertical or transverse displacement. The software utilised at OLDM is the Leica GeoMoS Analyzer. Figure 2.1 shows a prism monitoring set-up with all the components which allows for automation of the slope stability monitoring system.



Figure 2.1: Prism monitoring station. Source: Orapa Survey Department.

2.1.2 Visual Inspections

Visual monitoring involves physical inspection of slopes in the open pit. It is the responsibility of the geotechnical engineer to carry out this process as outlined in the regulations of Botswana and South Africa. Visual monitoring is done at all times, even where there are slope monitoring systems in place. At Orapa, Letlhakane and Damtshaa Mines, visual inspections are done daily by the geotechnical engineer and any areas which are observed to be unstable are closed off and reported to the mining team instantly for evacuation. Such sites can only be cleared safe again by the geotechnical

engineer only. Figure 2.2 shows a visually inspected wall with some small movement over time.



Figure 2.2: Orapa Mine pit inspection. Source: Orapa Geotechnical Engineering Department.

The visual inspection reports which are compiled on daily basis help the geotechnical engineer to produce a hazard plan which is displayed at the control rooms in the mining area. Figure 2.3 shows an example of a hazard plan. It is best practice for open pit mines to have signage along the ramps which shows the level or probability of rock fall.

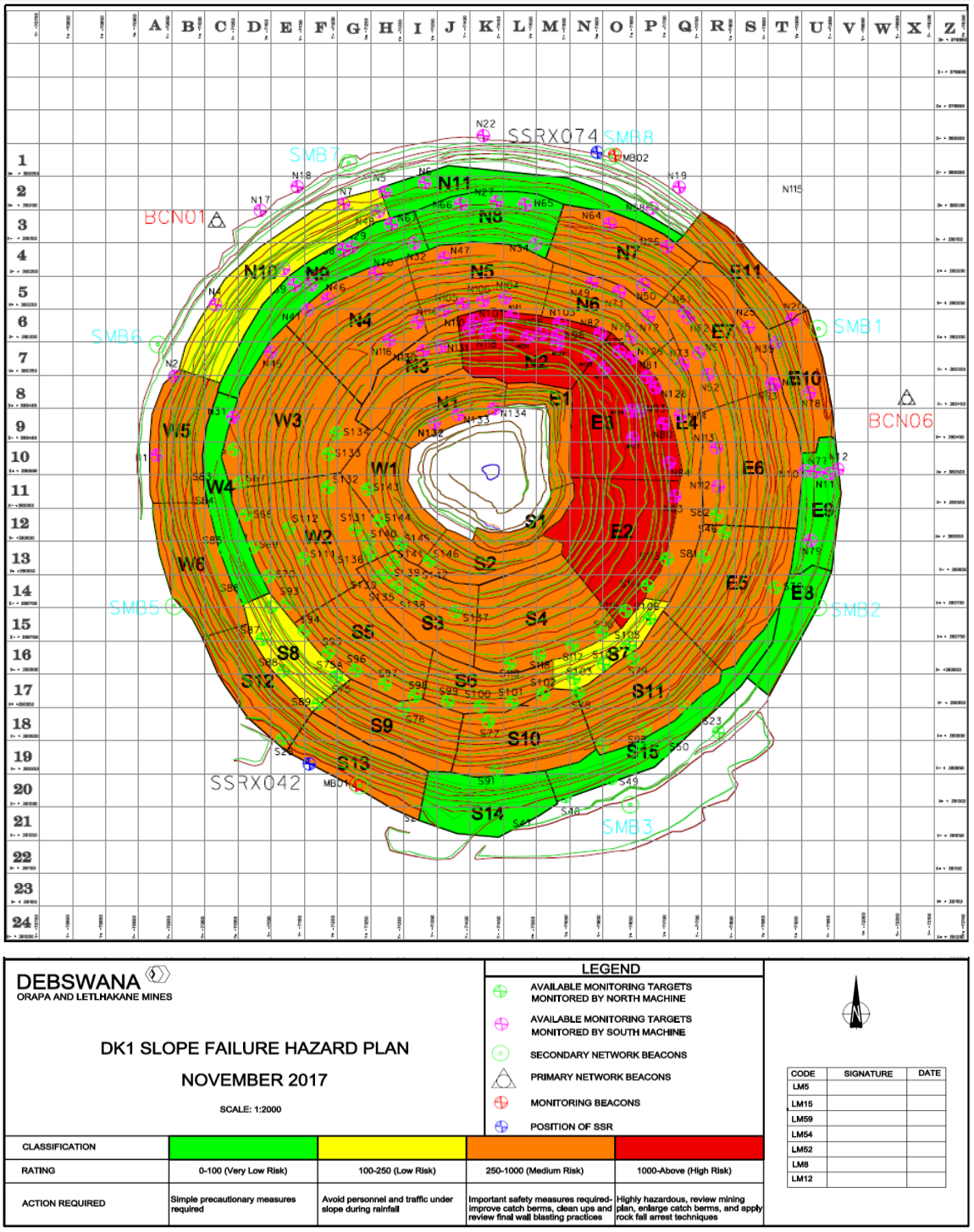


Figure 2.3: Hazard plan. Source: Orapa Geotechnical Engineering Department.

2.1.3 Slope Stability Radar

A Slope Stability Radar (SSR) provides real time early warning of slope instability in an open pit and it consists of a radar and a scanning antenna. This monitoring technique is most ideal for short term warnings of ground

movement. The slope stability radar is a mobile system and it can be moved freely in the open pit. When a radar is set and fixed to a position, the system can detect deformation of different areas of the open pit. A high resolution camera is installed on the antenna to capture photographs of the scan area. A scan area is normally selected by the geotechnical engineer and all other settings are verified prior to any scans. The scan data is transferred to a computer via a radio network for analysis.

The analysis software compares subsequent scans and gives warnings depending on the variance of the scans over a set period of time. Various levels of alarms can be set using different colour coding of red, orange, yellow and green. These colours report deformation situations from critical to minor. The advantage of the SSR system is that it can detect and alert movements of different areas of the open pit with sub-millimetre accuracy. The radar waves can penetrate through rain, dust and smoke, giving reliable information in the mining atmosphere, either day or night (Kumar *et al*, 2005). Many open pit mines have demonstrated that the radar is capable of providing early warnings of ground movement. Figure 2.4 shows a slope stability radar monitoring in an open pit mine.



Figure 2.4: Using Radar to monitor a slope face. Source: Orapa Geotechnical Engineering Department.

There are two modes of monitoring using the slope stability radar:

- Safety continuous monitoring
- And campaign monitoring

During mining production, the safety continuous monitoring is used as a primary monitoring tool whereas in campaign monitoring, the radar is moved around the mine continuously to compare movements at each sites over an extended time. The slope stability radar has created a change in slope failure risk management system which has helped its adoption in many mines around the word. Kumar *et al* (2005).

2.1.4 GNSS Monitoring

The Global Navigation Satellite System (GNSS) is another method which can be used to monitor ground movement. Basic GNSS measurements can be post processed using various software packages such as Spider. This would result in point coordinates being determined with high accuracy. The

accuracy of the points is very dependent on the number and distribution of satellites available during the time of measurements. Other factors which affects accuracy of coordinates is the point occupation time and the type of Global Positioning System (GPS) used that is, either the L1 or L1/2 receiver GPS. It is possible to monitor movement of points through permanent observations using six, twelve or twenty four hourly data processing. Figure 2.5 shows a permanent setup of a GNSS monitoring system. This setup comprises of a reference beacon, Leica GNSS receiver, radio communication infrastructure as well as power supply (solar).



Figure 2.5: GNSS monitoring setup. Source: Orapa Survey Department.

The GNSS has an advantage over the other monitoring methods because intervisibility or line of sight between the stations is not needed. However, GNSS monitoring is most ideal in areas which are exposed to the open sky view, as such this method can be restricted by satellite coverage in certain area of the mine.

Satellite positions technique is most suitable for monitoring reference beacons or structures which are outside the open pit. Prism monitoring software such as the Leica GeoMoS is able to compute and correct final point co-ordinates against any varying atmospheric conditions. Figure 2.6 shows an analysis graph of data from two beacons monitored by GNSS.

The normal graph indicated that the beacon is relatively stable for the period under review.

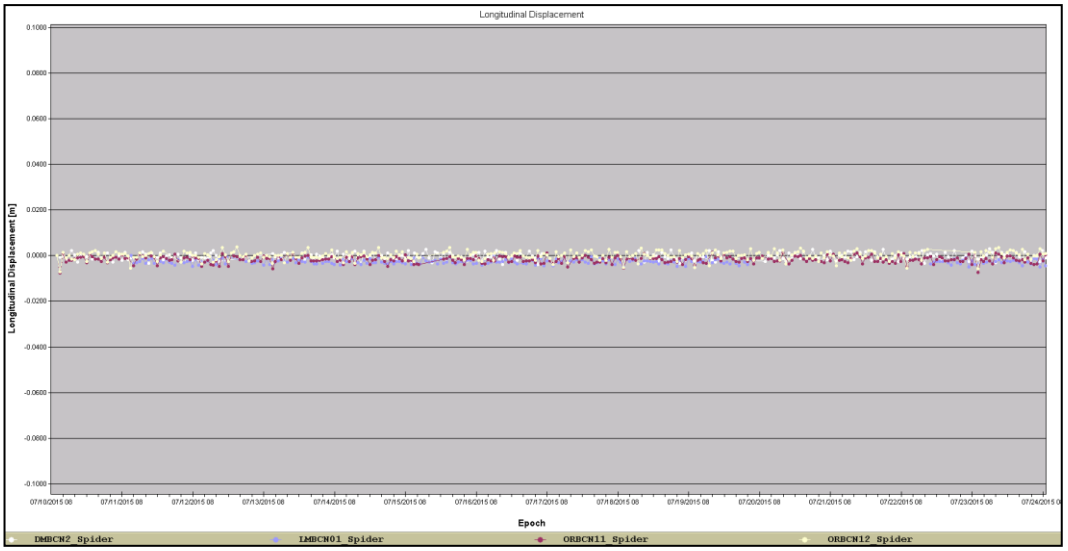


Figure 2.6: GNSS longitudinal displacement graph. Source: Orapa Survey Department.

2.1.5 Precise Levelling

Precise levelling is considered to be the most accurate method of establishing elevations of survey points and these elevations can be used for deformation monitoring analysis. While the process is time consuming, the quality of the results is always important to the mine surveyor when carrying out precise survey of any particular area. A stable bench mark is critical for this method to produce accurate results. Precise levelling is an effective method for detecting even small changes in elevations caused by ground deformation.

Strategically placed benchmarks can determine the extent of deformation for any given area when linking measurements to a stable point. Software such as Trimble T4D can incorporate the levelling data, where ground displacement graphs can display the various changes in height of any particular benchmark. Figures 2.7 and 2.8 show a benchmark as well as a network of benchmarks in a process plant.



Figure 2.7: Benchmark photograph. Source: Orapa Survey Department.

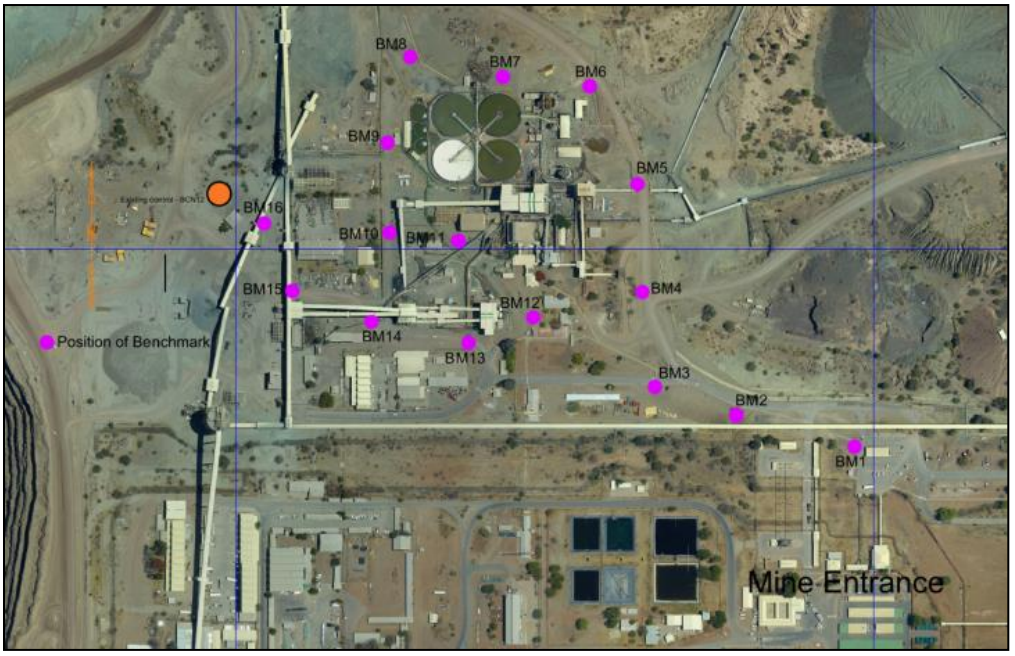


Figure 2.8: Benchmark network plan. Source: Orapa Survey Department.

2.1.6 Laser Scanning

Laser scanning is a technique which can be used for deformation monitoring and measures a relatively large area as compared to the prism monitoring. Points are measured in 3D and a large point cloud can be obtained depending on the type of Laser scanner used. Laser scanners such as the Riegl VZ4000 can scan up to a range of 4000m under normal conditions. Figure 2.9 shows a setup of the Riegl scanner which comprises of the reference beacon, laser scanner, computer and a radio infrastructure.

The laser scanner also has a camera and captures images of the scan area prior to any observations. The laser scanner is controlled by software such as 3DLM SiteMonitor and all the data collected is analysed using a software module such as SiteMonitor Analysis. The point cloud data is very useful as it shows the model of the pit in three dimensional and can be filtered and rotated and the progressive slope movements can be computed from the previous scans. If the variance in the scans comparison exceeds the set limits, then alert messages are sent to the geotechnical engineer for investigation of any ground movement.



Figure 2.9: Laser scanner setup. Source: Orapa Survey Department.

2.1.7 Satellite Imaging Monitoring

The Interferometry Synthetic Aperture Radar (InSAR) is a satellite based radar method of geodesy and remote sensing for detecting surface movements and creation of digital elevation models. InSAR uses satellite imagery technology to measure precise ground deformation over large areas with very high density of measurement points. The deformation reporting can be done monthly, quarterly or annually. All the InSAR methods are suitable or movement of up to four meters per year (Zimmerman, 2008).

The InSAR technology is suitable for detecting ground movement on fine residual deposits and large structures which cannot be monitored by other systems such as Radar, Laser scanner or Prism monitoring. This method is

a long term deformation monitoring method and informs the civil engineer of possible ground movement of an area.

2.1.8 Deformation Monitoring Systems Comparison

Table 1: Deformation monitoring systems comparison.

Method	Georeferenced	3D vector	Line of sight	All weather	Cost	Short/Long term trend	Immediate alarm response
Visual Inspection	No	No	No	No	Low	Short term	No
Radar	Yes	No	Yes	Yes	High	Short term	Yes
Laser scanner	Yes	No	Yes	Yes	High	Long term	No
Prism monitoring	Yes	Yes	Yes	Yes	Moderate	Long term	No
GNSS	Yes	No	No	Yes	High	Long term	No
Satellite Imagery	No	No	No	No	High	Long term	No

Comparison of the various deformation monitoring systems in table 1 show that each system has an advantage or disadvantage over the other. Some systems are more expensive to implement while others are relatively cheaper to install. The only system which is capable of computing the 3D vector movements is the prism monitoring system. This is a very important geotechnical analysis parameter, as such every open pit should have a prism monitoring system in place. Line of sight can cause implementation problems in some sites due to small size of pit, infrastructure and dumps surrounding the pit.

The Radar can actually detect a slope failure which would happen in less than two hours or so, as such it informs the user for immediate response to alarms. Most of the deformations monitoring systems are georeferenced, and this enhances good geotechnical slope data analysis. This comparison shows that it is important to implement as many systems as possible so that

they complement each other. Mphathiwa (2012) emphasize this point by stating that “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”.

2.2 Prism Monitoring at OLDM

In open pit mines, slopes are maintained at a suitable angle which minimises probability of a slope failure. In order to do this in a safe manner, it is essential that slope stability monitoring data relating to the behaviour of the slopes be monitored and made available through an instrumentation system (Jones and Bumala, 1976). The prism monitoring system is therefore one of the methods for monitoring slope stability at Orapa, Letlhakane and Damtshaa Mines.

2.2.1 Why Prism Monitoring Chosen for OLDM

Orapa, Letlhakane and Damtshaa Mines operation was established in 1969. As these mines deepened over the years and the slopes becoming steeper due to mining plan optimisation, slope failure became one of the top ten risks at OLDM. The mine was challenged with implementing models to manage the risk of slope failure as it could lead to negative consequences such as equipment damage and fatalities if not managed. It is difficult to make predictions about the behaviour of a rock slopes and the most efficiently designed slope can become unstable.

Once the slopes become unstable, then any open pit mine would require the design or implementation of adequate monitoring systems such as the prism monitoring system, Radar and Laser scanner. Data from a defensible and effective slope monitoring system should therefore be available at the early stages of the life of the slope. In this way preliminary warnings and mitigations of the emerging instability may be obtained.

The monitoring systems used in open pits must therefore fulfil two essential functions; firstly they must provide the information about the current and

anticipated stability of the slopes and secondly, they must provide data which will enable the geotechnical engineers to make design modifications to optimise the safety and profitability of the operation (Jones *et al*, 1976). When OLDM commenced operation, there was no slope monitoring system in place. Conventional monitoring methods such as visual inspections and manual prism measurements were the only processes in place for slope monitoring and these became inadequate to manage the risk of slope failure. Automated prism monitoring was therefore introduced at Letlhakane Mine in 2002 as a pilot project.

After successful implementation at Letlhakane Mine, the system was installed at Orapa and Damtshaa mines in 2003 and 2006 respectively. The prism monitoring system installed at these sites is the Leica GeoMoS system. This system was chosen because 3D measurement data could be continuously measured of strategic points on the pit slopes. The system installation costs were within acceptable value of BWP600,000 against a budget of BWP850,000 and it also proved to be easy to manage.

The system applies basic survey principles and the mine surveyor is responsible for managing the system. The geotechnical engineer analyses the data from the system and is responsible for setting alarm parameters with reference to movement over a given time. Long term trends of slope movement can be viewed graphically in Leica GeoMoS Analyzer as longitudinal, vertical and transverse displacements as well as 3D vector movements. The prism monitoring system has proved over the years to be strategic at OLDM sites for slope stability management.

2.2.2 Prism Monitoring Requirements

The survey department is responsible for the setting-up of the automated prism monitoring system and validation of the output data with regard to survey integrity. The critical requirements for this system are outlined below.

2.2.3 Standards and Procedures

The prism monitoring system addresses one of the highest risks of an open pit operation and procedures and standards of using such a system must be in place and clearly outlined. All responsible persons must understand the survey and geotechnical processes of slope stability monitoring using prisms and total stations. Livingstone (2005) states that “effective knowledge management and risk mitigation requires that standards and procedures are available to guide practice with minimal dependence on the knowledge held by individuals. The absence of specific documented detail and current standards and procedures can negatively impact on monitoring results due to inconsistent practice”. The prism monitoring procedure must therefore detail all survey and geotechnical measurement objectives, responsibilities as well as the work flow of each task.

2.2.4 Dedicated Resources

A dedicated mine surveyor for slope monitoring is essential to run the prism monitoring system in the open pit. The mine surveyor must have dedicated resources such as equipment, assistants, computers and vehicles to ensure good execution of daily slope stability monitoring requirements. Best practice for survey slope monitoring requires that a dedicated and competent mine surveyor must be responsible for data collection, data check and overall prism monitoring system management (Thomas, 2011).

2.2.5 Survey Control Network

Adherence to basic survey principles is very critical in a prism monitoring setup. This is important regardless of 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). These methods require a suitable control network of beacons. At OLDM, the design of the beacons is normally classified into transfer, primary and secondary beacons as shown in figure 2.10.

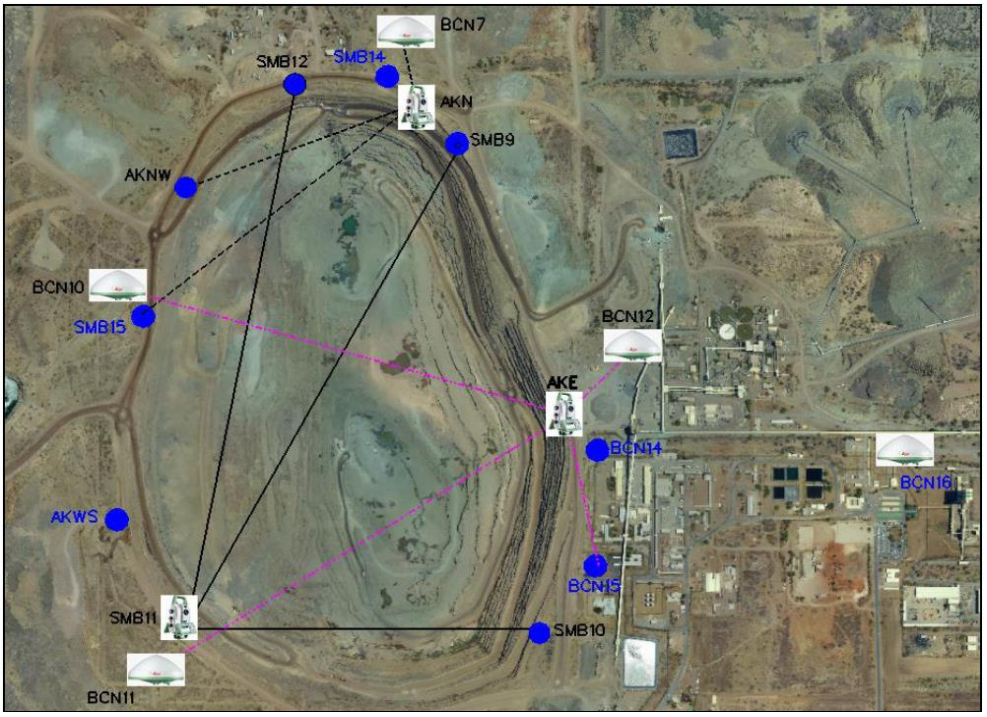


Figure 2.10: Survey control network. Source: Orapa Survey Department.

The transfer beacon is the monitoring station, where the total station is set-up; as such it must be carefully selected with reference to the existing control to ensure accurate measurements. Mphathiwa (2012) states that the geometry of the control network in an open pit should allow applications such as resection and triangulation to be done with minimal geometric constraints. The survey control beacons must be constructed by a certificated civil engineer on a stable ground. Figure 2.11 shows a suitably constructed reference beacon. The design of this beacon was approved by a certificated structural engineer and constructed by a reputable contractor with good experience in civil works.



Figure 2.11: Reference beacon. Source: Orapa Survey Department

Existence of a good survey control network with good line of sight is the base of all prism measurements which takes place in the pit, as such it is a critical requirement for prism monitoring. Sufficient number of beacons is also important in cases where others get destroyed by mining activities.

2.2.6 Monitoring Instrumentation

The accuracy of the prism monitoring data is dependent on the type of monitoring instrumentation used. Total stations which are capable of measuring 1” of an arc are preferable for precise measurements. Cawood *et al* (2006) states that when choosing the monitoring instrumentation one should evaluate the economic value add of the systems and the required level of confidence of the results. The type of prisms used may also influence accuracy since the signal from the total station travels through different atmospheric medium to reach the prism, so the distances measured will always have some systematic error. Suitable prisms such as the Leica GPR112 must be used for slope stability monitoring, refer to figure 2.12.



Figure 2.12: GPR112 prism. Source: Leica Geosystems.

For automation of monitoring measurements, a telemetry infrastructure connected to the monitoring station and to the control computer or server in the office is required. The telemetry must be able to handle large packets of data to avoid loss of radio link resulting in monitoring delays. A transfer beacon also has meteorological sensors which measures the ambient temperature and atmospheric pressure at set intervals. These measurements are used by the monitoring software to correct all distance measurements for atmospheric conditions. A continuous power supply is necessary for the whole setup to function, and this is the practice at OLDM.

2.2.7 Monitoring Instruments Shelter

Open pit mines are exposed to extreme weather conditions such as heat, cold, wind and rain. The survey instrumentation is permanently set on a transfer beacon for continuous slope monitoring measurements. It is critical to protect survey instrumentation by using a shelter. However, the shelter must not jeopardise the measurement process which may degrade accuracy. Most shelters are fully enclosed with glass windows. Research by Afeni (2011) shows that glass of up to three millimetres has no influence on the accuracy of survey measurements. Figure 2.13 shows various instrument shelters at OLDM.



Figure 2.13: Prism monitoring shelters. Source: Orapa Survey Department.

The shelters are in the form of cabins as shown in figure 2.13. Blast protection for the monitoring cabins is also necessary to protect the entire station from fly rock. Good housekeeping and lockout for the shelters is important for the protection of the survey equipment at the transfer beacon.

2.2.8 Information Technology (IT) Infrastructure

IT infrastructure is a big requirement for an automated prism monitoring system. Monitoring instruments are controlled by software which is installed on the computers. The monitoring data is also stored in a computer and backed up on daily basis in the database. This is a critical part of the prism monitoring system because all the survey monitoring data is stored in the computer.

The IT infrastructure must have provision for an auto recovery of data in the event of a computer system failure. Thomas (2011) emphasises that it is important for monitoring data to be stored in a manner that allows for effective data retrieval for further use that is as empirical data. Access to the IT infrastructure is normally restricted to the IT specialist responsible for slope stability monitoring. The computer is kept in a secure environment where security and temperature control is suitable.

2.2.9 Prism Monitoring Software

An automated prism monitoring system requires software and associated licences to function. The software is classified into the following categories:

- Survey module;
- Analysis module.

The survey module is managed by the mine surveyor and the analysis module is managed by the geotechnical engineer. There are a number of settings in the survey module to ensure that the total station measures continuously. These include; installing instrument co-ordinates, orientation setups and sequence, defining measurement groups of prisms, defining measurement cycle times, limit classes and alarm settings for movement threshold and adding monitoring prisms to orientation and measurement sequences.

The analysis module is able to show graphical representation of the survey data from the survey module. The graphs show relative or absolute displacement of the prism co-ordinates. The monitoring software is configured by the vendor and requires updates as and when required. The software upgrades generally have some additional features or functional improvements as per user requests and requirements.

2.2.10 System Alert

A prism monitoring system should be able to alert the user on any abnormal trend of data; this is important for slope stability analysis. For instance, if the set limit of variance of co-ordinates is exceeded, then a notification must be automatically sent to the responsible mine surveyor or geotechnical engineer via email or text message alert. Also if the system stops working, an alert message must be sent to the mine surveyor for investigation. These alerts are important because they inform the user of correct action that is required. Cawood *et al* (2006) emphasise 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.

2.3 Deformation Monitoring with Leica GeoMoS

The Geodetic monitoring system, that is Leica GeoMoS is a deformation monitoring system which was established by Leica Geosystems in Switzerland. It uses total stations to measure co-ordinates of prisms. It continuously observes for any change in movement of prisms on structures such as buildings, slopes, and dams. User defined limits of the x, y and z displacements are set in the monitoring software as baseline. Subsequent measurements which take place are then compared with the base readings to compute any displacement readings in three dimensional.

The measurement limit class of movement values are provided by the geotechnical engineer based on the type of rockmass being monitored. If these limits are exceeded, then the Leica GeoMoS sends a notification to the end user in the form of an email or text message. The system has provision of connecting different types of sensors such as total stations, GNSS, meteorological sensors and crack meters.

The Leica GeoMoS system has a measurement cycle functionality which controls sequence and times of measurements. The mine surveyor sets up the measurement cycle as per the geotechnical engineer's requirements. The system has a programme for calculating atmospheric corrections to slope distance measurements. These calculations are based on the readings from the meteorological sensors, that is for ambient temperature and atmospheric pressure. The Leica GeoMoS system has a number of graphical and numerical representations for the slope monitoring data.

2.3.1 Leica GeoMoS Monitor

The monitoring setup and control is performed in the Leica GeoMoS Monitor by the mine surveyor. The sensor settings and maintenance is done in this module, for example a Leica TM50 total station would be defined and set under 'sensor manager'. The co-ordinates of the transfer beacon are configured and assigned to the instrument and thereafter the orientations take place before the actual measurements of the monitoring prisms.

Figure 2.14 shows an illustration of the Leica GeoMoS Monitor interface which is simple and easy to use.

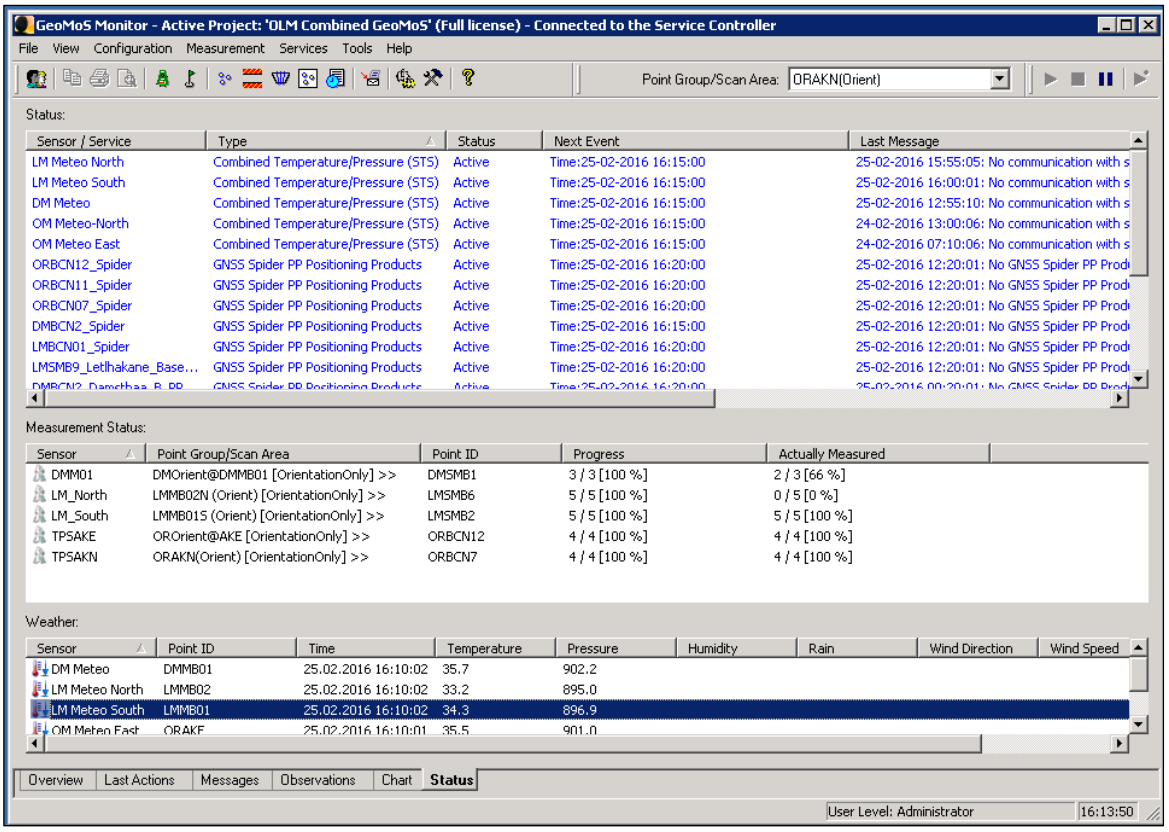


Figure 2.14: Leica GeoMoS Monitor interface. Source: Orapa Survey Department.

Various functionalities are used on the user interface and enable selection of any ‘tabs’ quickly with a single mouse click. The Leica GeoMoS Monitor is also used for the measurement of prisms, storage and computation of data, measurement checks, and alert messages.

2.3.2 Leica GeoMoS Analyzer

The Leica GeoMoS Analyzer is a graphical display interface and it is used for analysing the slope monitoring measurement data. Data is read from the computer through the Leica GeoMoS Monitor module for slope stability analysis. There are five customised graphs which can be viewed by one user per single licence. The graphs include:

- Longitudinal displacement;
- Vertical displacement;
- Transverse displacements;
- Site map of the monitoring prisms.

Various tools on the software have different functionalities, and on the main menu all monitoring prisms and stations of the slope monitoring project are displayed. The user has an option to constrain the graphical view for a desired date period. There is a comments tool which loads all new activities on the system, for example changing of total stations (sensors) at the reference beacon and system breakdowns. This is an important functionality for both the mine surveyor and geotechnical engineer because a record of changes to the system can be tracked and understood for data analysis.

2.3.3 Leica GeoMoS System Setup

The Leica GeoMoS monitoring system has components which are permanently installed at the monitoring sites and ones installed at the office. The monitoring site consists of the following components:

- Reference beacon;
- Total station;
- Meteorological sensor;
- Radio transmitter;
- Power source;
- Cabling;
- Cabin/shelter.

The components of the entire system are installed on a stable reference beacon. The total station and meteorological sensor are linked together by a cable which is also linked to the power source as well as the radio transmitter. Provision of a shelter protects the components of the system and keeps them safe from vandalism and theft. The shelter has to be locked at all times to avoid third party interference.

The following system components are installed at the office:

- Computer;
- Radio transmitter;
- Leica GeoMoS software;
- Power source.

The system software and its associated licences are installed on the computer and configured by an accredited Leica technician and an Information Technology (IT) specialist. The radio transmitter is connected to the computer as well as the power source. Once a radio link is established between the office and the transfer beacon, then the Leica GeoMoS monitor software can be configured to control the entire measurement process. For the system to be fully functional and automated, all components at the office and at the transfer beacon must be functional.

2.3.4 Leica GeoMoS Data

The Leica GeoMoS system stores data in the Monitor software in real time. This data shows the following:

- Time of measurement;
- Name of sensor;
- Prism name;
- Vertical and horizontal angles;
- Slope distance;
- 3D vector;
- Longitudinal displacement;
- Vertical displacement;
- Transverse displacement;
- Co-ordinates.

The data is backed up in the computer database at set intervals. The data can be exported from the Leica GeoMoS monitor to Microsoft Excel for further analysis. Mine surveyors use the data in Microsoft Excel spreadsheets to calculate the system availability and utilisation percentage figures. Figure 2.15 shows the Leica GeoMoS Monitor data.

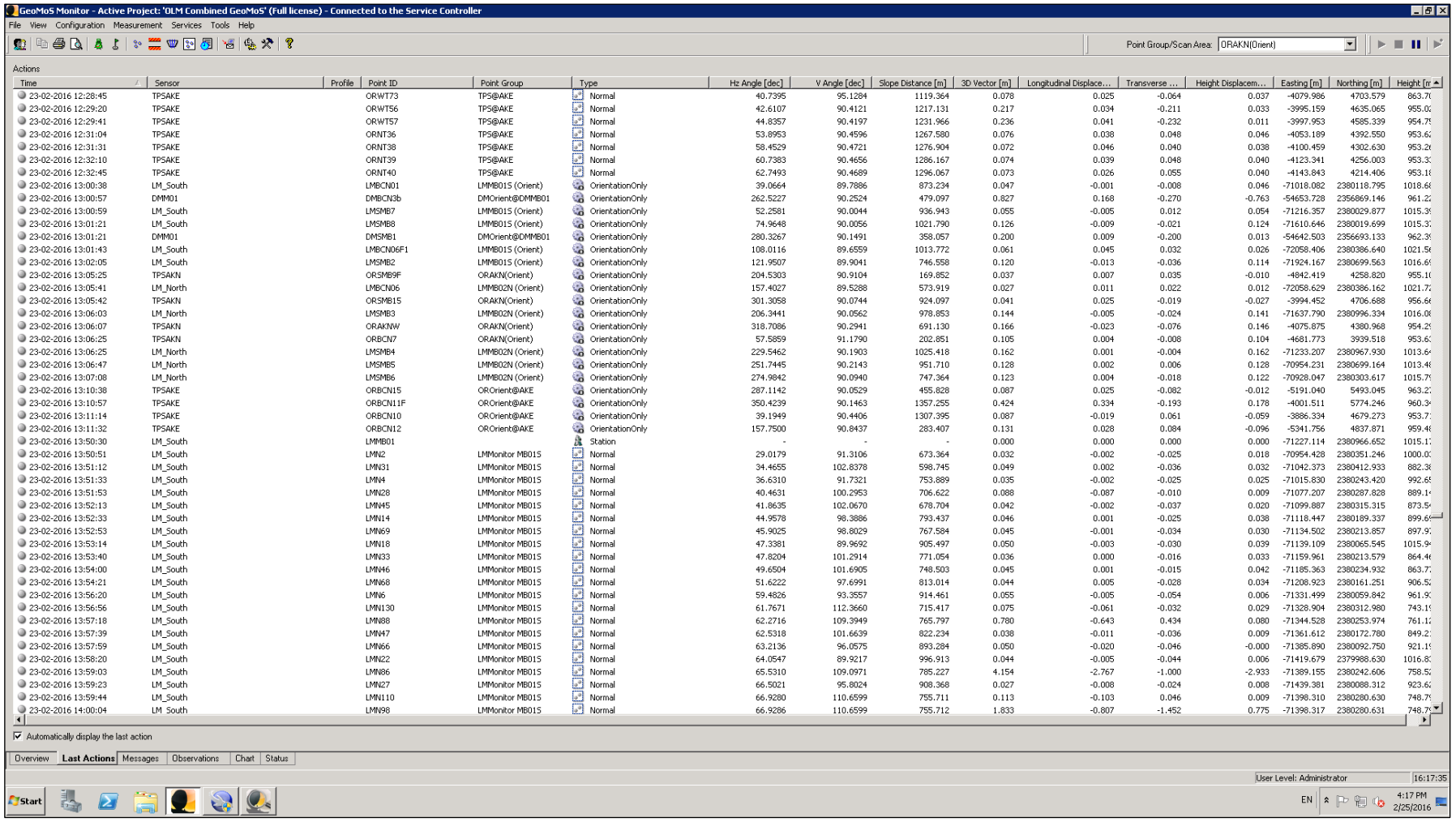


Figure 2.15: Leica GeoMoS data. Source: Orapa Survey Department.

The same data can be viewed in Leica GeoMoS Analyzer, where it is possible to isolate all the outlier slope monitoring measurements which may cause noise in the displacement graphs. The Leica GeoMoS data from the Analyzer module can be exported to Microsoft Excel for further analysis and validation. The geotechnical engineer uses Excel spreadsheets method to compute the vector movement analysis. It is therefore important to maintain good data integrity to accurately analyse slope movements of an open pit.

2.3.5 Data Assurance

The responsibility of the mine surveyor is to ensure that the Leica GeoMoS data is checked and verified for slope stability analysis. Thomas (2011) emphasised that survey accuracy can be ascertained by interrogation of the survey data being measured and recorded in Leica GeoMoS Monitor under the 'last actions' tool, for example orientation angles and measured distances. From this measurement data, it is important for different measurement types to show normal repeatability.

2.4 Leica GeoMoS Implementation at OLDM

The Leica GeoMoS system at Orapa, Letlhakane and Damtshaa mines comprise of six transfer beacons and it is considered to be one of the biggest in the Anglo American group because it is installed in three pits which are at least 30km apart from each other. The setup consists of world class infrastructure to match.

2.4.1 Instrumentation Infrastructure

The first implementation of the Leica GeoMoS system at Letlhakane mine in 2002 comprised of the Leica TCA2003 total stations. There has been advancements on the Leica technology instrumentation over the years. OLDM mines consist of six active transfer beacons which are fully equipped with Leica TM30's and TM50's robotic total stations. The annual calibration of these instruments is well managed as it has an implication on the accuracy of the monitoring data. Mphathiwa (2012) emphasises this point by stating that "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". The system utilises the robust mesh network for radio communication which comprise of a radio modem and an antenna. Each monitoring station is equipped with a 220V main power and UPS power backup units. High precision prisms of model Leica GHP1P are installed at all the reference beacons. The transfer beacons are also equipped with meteorological sensors whose position and housing is well managed as shown in figure 2.16.



Figure 2.16: Meteorological sensor position in Stevenson Screen and a high precision prism (Leica GHP1P). Source: Orapa Survey Department.

The Leica GeoMoS instrumentation at OLDM was suitably chosen to meet the important aspects of effectiveness, defensibility, accuracy and precision, reliability, movement detection, as well as the economic value add of the system and its ease of interface with other slope monitoring systems. The instrumentation at all the transfer beacons is well protected in cabin shelters as shown in figure 2.13. The shelters are fully enclosed and have been designed to suit each transfer beacon.

2.4.2 Control Network

The control network for the Leica GeoMoS monitoring system comprise of primary and secondary beacons at all the three sites of OLDM. The secondary beacons are constructed around the pit edge whereas the primary beacons are constructed at least 100m from the pit edge. The position of the beacons was carefully selected to ensure that there is good geometry from the transfer beacon. The geometry of the control beacons has an influence on the measurement accuracy of the beacons network. Thomas (2011) emphasises that a poorly designed control network will result in orientation errors outside the limit of tolerance, and resulting in poor accuracy of the orientation measurement. The reference beacons at OLDM were constructed by accredited civil engineering contractors. The construction was based on approved drawings from the structural engineers.

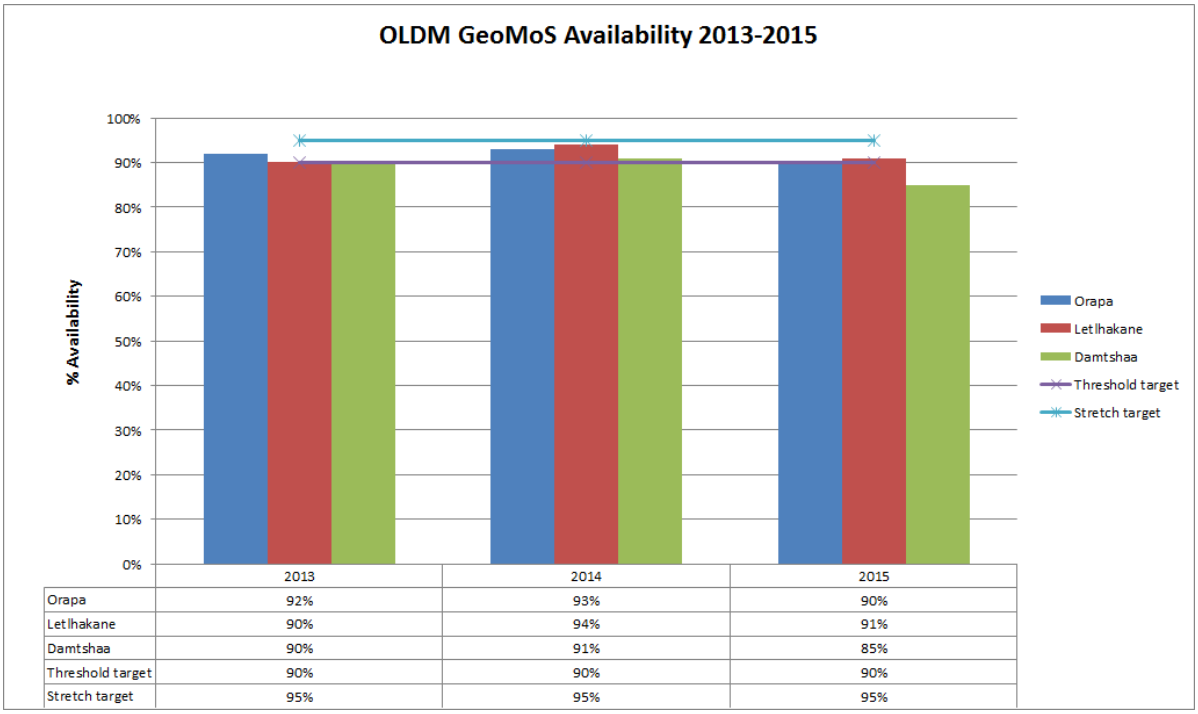
The position of the beacons is checked annually for movement using different survey methods, that is GNSS post processing and precise levelling. Refurbishment and maintenance of the beacons is done as and when the need arises. In instances where the mining activities affect a beacon by grading or blasting, then the mine surveyor finds a suitable position to construct a new beacon which integrates well into the existing control network.

2.4.3 System Performance

The Leica GeoMoS system performance is measured by two variables known as availability and utilisation. Availability of the system is the total hours that the system operated continuously over a specified period of time; percentage availability is computed using the target of 24 hours per day. Utilisation of the system is the number of measurements that are recorded relative to the set measurement cycle in the Leica GeoMoS system.

For example, if the system has been set to measure every four hours, expectation is that every monitoring prism must return six measurements in

a twenty four hour period. The ratio of actual measurement and the target is expressed as a percentage and is referred to utilisation. Figure 2.17 shows the performance of the Leica GeoMoS system for period 2013 to 2015.



	2013	2014	2015
Orapa	92%	93%	90%
Letlhakane	90%	94%	91%
Damtshaa	90%	91%	85%
Threshold target	90%	90%	90%
Stretch target	95%	95%	95%

Figure 2.17: OLDM three year performance graph. Source: Orapa Survey Department.

The threshold and stretch targets have been set to 90% and 95% respectively. These targets have been set at this level because it is necessary to ensure that slope monitoring is continuous and data is made available consistently. The graph in figure 2.17 shows good performance of the system at OLDM over a three year period.

Delays in monitoring are mainly due to power interruptions as well as loss of radio link between the transfer beacon and the computer. If prisms cannot be measured, then it affects the system utilisation. Mining activities affect monitoring prisms in many ways, for example fly rock can damage the prism, dust can make the prism very dirty and difficult to measure, and excessive vibration can misalign the prism from the total station. The system performance of the entire system is updated on a daily basis by the mine surveyor and system performance reports are produced on monthly basis.

2.4.4 The Road to Excellence

The Leica GeoMoS slope monitoring system plays an important role in predicting medium and long term trends of the behaviour of slope movements when it is well managed. In an effort to improve the system at OLDM, there were a number of developments carried out over the past five years. One of the major projects which was conducted by survey was construction of twenty reference beacons at Orapa, Letlhakane and Damtshaa Mines to facilitate new Leica GeoMoS and Trimble T4D slope monitoring installations. External auditors were invited to evaluate the OLDM Leica GeoMoS system and valuable contributions in establishing a change model were made. In an effort to ensure that the Leica GeoMoS system is well supported in terms of maintenance, a service level agreement with a preferred supplier was proposed and implemented during this period.

Four audits were carried out by independent auditors who investigated different areas requiring modification of the Leica GeoMoS system at OLDM. This was carried out to identify opportunities for improvement in the entire system. The details are as explained below:

<u>Leica GeoMoS technical investigations by Mr. Naani Mphathiwa</u>

Mr. Mphathiwa, Survey Manager – Deformation Monitoring, based at Debswana Head Office, Visited OLDM site during the month of June 2012 specifically to evaluate the Leica GeoMoS slope monitoring system. Recommendations were based on research publications by personal experience and conversations with mine surveyors and geotechnical engineers at OLDM. A SWOT analysis model for the entire Leica GeoMoS setup and the following were his key recommendations:

- Redesigning of the beacons network at OLDM to improve accuracy of measurements;
- Design of beacon structures should be done by a qualified structural engineer;

- Shelters for the Leica GeoMoS Stations to be implemented or modified for an enhanced equipment protection;
- Acquisition of additional GNSS rovers specifically for static surveys;
- The Survey team to consider relocating the Meteorological sensors from the office to the monitoring stations;
- High accuracy surveys must be done regularly to check the integrity of the beacon control network;
- The mine to consider purchasing an integration software, for example MS Cubed, to integrate data from the existing monitoring systems;
- The mine should evaluate all slope monitoring procedures and add the ones which do not exist;
- The mine surveyor responsible for slope monitoring should focus on the monitoring key performance areas only, for example data checks, systems management and slope monitoring projects.

Leica GeoMoS hardware inspection by Aciel Geomatics (Pty) Ltd

Aciel Geomatics (Pty) Ltd is a South African based company which specialises in Leica Survey products is accredited by Leica Switzerland. The company consists of well trained and experienced personnel, especially in the area of slope monitoring. Their first site visit in May 2012 was to introduce themselves to Debswana and propose a service level agreement. Inspection of the OLDM Leica GeoMoS hardware was then done in June 2012. Their investigations were based on experience and exposure to the best practice of Leica GeoMoS setups globally.

Their overall recommendation was to replace most of the existing hardware and upgrade components such as communication radios, cables, total stations meteorological sensors and power backup at the transfer beacons. To ensure that the OLDM Leica GeoMoS system is well covered in terms of support and maintenance, a service level agreement (SLA) was developed between Debswana and Aciel Geomatics (Pty) Ltd in June 2012. This SLA was finalised in December 2012 after consultation with all the relevant

stakeholders and was launched in June 2013 at Orapa, Letlhakane and Damtshaa Mines.

Shelters for Leica GeoMoS and site inspection by Optron (Pty) Ltd

Optron (Pty) Ltd is a South African based company which specialises in Trimble Survey products. After careful assessment of suitable companies in the market, Optron was invited by Debswana (Orapa, Letlhakane and Damtshaa Mines) to inspect the shelters used for Leica GeoMoS at all the three operations in September 2012. Optron sent a shelter design specialist to site and a suitable solution for all the Leica GeoMoS setups at OLDM was recommended. Figure 2.18 shows the transition of the instrument shelters from the old design to the new “Optron” design.

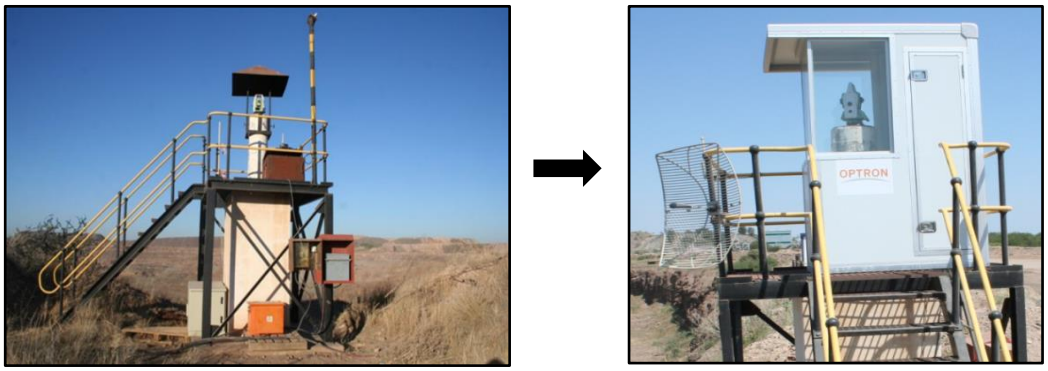


Figure 2.18: Photos showing shelters for the total stations before and after shelter infrastructure upgrade. Source: Orapa Survey Department.

After assessment of the recommendations from the external auditors, a decision was taken to upgrade the most critical components of the Leica GeoMoS system at OLDM operations. Replacement of most of the old equipment and installing state of the art equipment such as intuicom radios, Leica TM30’s, shelters and power backups was successfully carried out. This process was carried out to match the OLDM Leica GeoMoS with some of the best practice global users in the mark*et* In September 2012, all meteorological sensors were relocated from the office to the transfer beacons. These meteorological sensors were installed in a Stevenson Screen. A Stevenson Screen is a wooden housing used to protect

meteorological sensors against precipitation and direct heat from external sources, for example the sun. These were also installed during the September 2012 upgrade. Switch boxes were also installed at all the total stations in 2012 and 2013. They facilitate an automated rebooting mechanism of the total stations in the event that they go on shutdown (freeze mode). The units resolved the machine “freezing” problem which was experienced in the Leica GeoMoS system at OLDM. In September 2012 all cables at the transfer beacons were protected with trunking in an effort to increase their lifespan.

In October 2012, a decision was taken to relocate the Leica GeoMoS software from the central computer at the survey office to a central server. This was done in line with IT requirements for data security. The accuracy of the Leica GeoMoS data is dependent on the reference beacon control network. A decision was taken in November 2012 to engage a registered Land surveyor to accurately measure all slope monitoring beacons at Orapa, Letlhakane and Damtshaa Mines. This survey serves as a quality check and assurance regarding the existing information of the slope monitoring beacons.

The report of this survey was presented by the Land surveyor from TBM Surveying (Pty) Ltd of Gaborone, in June 2013. Two new Leica GeoMoS setups were installed at Orapa Mine during the month of February 2013; one system on the east and the other at the south western sector of pit respectively. A blast protection cabin was installed at the south west transfer beacon to protect the instruments from fly rock.

It is very important for the Leica GeoMoS system to measure from accurately surveyed reference beacons. In an effort to precisely monitor the primary reference stations in real time, a system known as a GNSS Spider network was installed at OLDM in May 2013. The GNSS Spider system adopts a real time centralised baseline processing of up to 50Hz per rate

and it also executes automatic post processing of 10 minutes to 24 hours of data. Other major projects which were introduced at OLDM post 2012 include the following:

- Trimble T4D installation at Letlhakane mine – Dk2 pit;
- Satellite imagery monitoring using INSAR ;
- Laser scanner monitoring at Orapa Mine;
- Slope monitoring systems integration.

A dedicated mine surveyor and technician for slope monitoring were appointed. Survey actively participated in the annual Geotechnical Review Board (GRB) audit from 2013.

2.4.5 Suitability of the Leica GeoMoS for Monitoring

The Leica GeoMoS is a suitable deformation monitoring solution and has been in operation at OLDM since 2002. The system is reliable and has produced accurate monitoring data for slope stability analysis. The system does detect ground movement and is able to send alert messages to the relevant users timeously. Figure 2.19 shows a graph from Letlhakane mine where a slope failure was detected using the Leica GeoMoS.

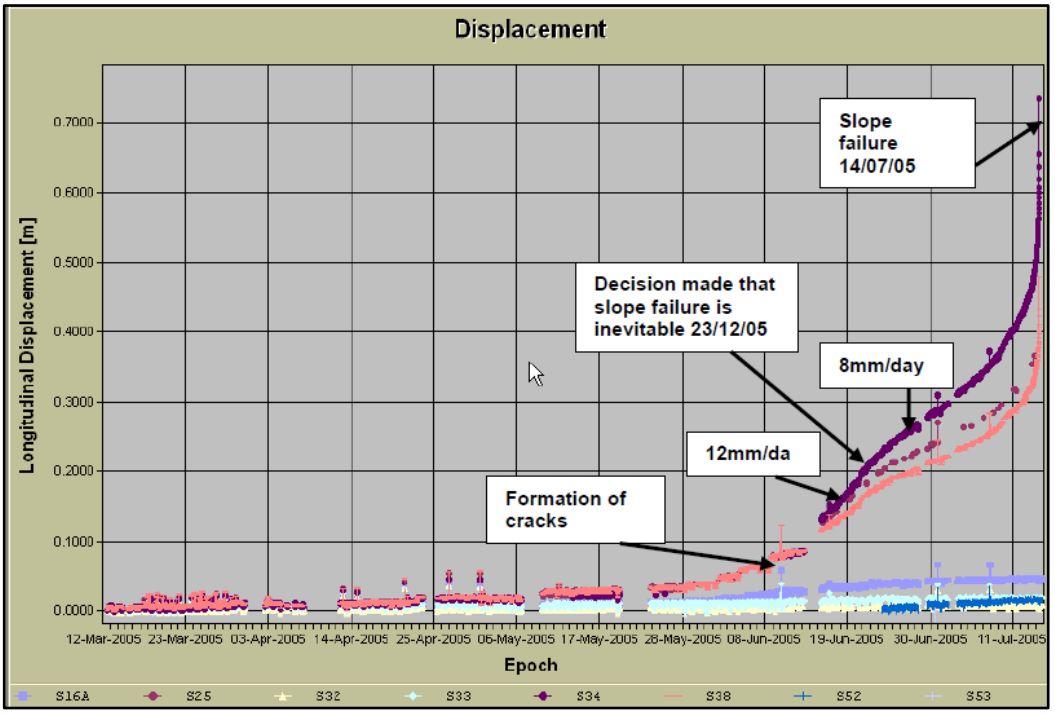


Figure 2.19: Leica GeoMoS graph showing cumulative movement of targets from 12 March 2005 until slope failure on 14 July 2005. Source: Orapa Geotechnical Engineering Department.

Kayesa (2005) emphasised that the Leica GeoMoS slope monitoring system was successfully used in management of the slope failure that occurred at Letlhakane mine on 14th July 2005 by assisting in proactive decision making that avoided personnel injury, damage to equipment and loss of production. The Leica GeoMoS slope monitoring system is therefore an effective slope stability management system and it is suitable for an open pit deformation monitoring.

2.5 Conclusion

The various deformation monitoring systems used in open pit mines for mitigation of the risk of slope failure have been outlined. Implementation of a prism monitoring system requires capital and appropriate resources and planning. The Leica GeoMoS is suitable for slope stability monitoring; however, slope failure management becomes more effective only when additional slope monitoring systems are utilised in an open pit so that they complement each other.

Chapter three focuses on the theoretical explanation of the concept of atmospheric corrections to total stations measurements. The author elaborates the measurement mechanism of total stations. An explanation of how total station measurements are performed in a prism monitoring system is outlined. Chapter three also discusses how the atmospheric corrections are applied to prism monitoring measurements.

3 ELECTRONIC DISTANCE MEASUREMENTS

Chapter 2 discussed the fundamental principle of deformation monitoring and the various methods of monitoring, including the Leica GeoMoS system and its implementation at OLDM. This chapter explains the concept of electromagnetic distance measurements using total stations for a prism monitoring system. Further discussion is on the concept of atmospheric corrections to total station measurement and how they are applied to prism monitoring measurements.

3.1 An Overview of Total Stations

The introduction of total stations for distance and angle measurements in survey has simplified the process of computing position in x, y, and z. Accurate distance measurements were considered to be a very difficult part in survey processes, but today the measurement process is simplified. total stations went through several innovations which were aimed at simplifying the use of this instrument. Afeni (2011) states that the first innovation was to motorise the horizontal and vertical movements so that the instrument could transit automatically followed by target detection and acquisition.

A total station is a surveying instrument which integrates an electronic theodolite with an electronic distance meter. The total station use electronic transit theodolites in conjunction with a distance metre to measure any slope distance from the instrument to any point. Modern total stations can measure to most surfaces with a limited range, for example three hundred metres; however the use of prisms enhances long range measurements

A prism is an object which has a triangular glass with refracting surfaces at acute angles. It reflects transmitted signals from an EDM instrument for slope distance measurements. Figure 3.1 shows an example of a total station and a prism which is used for slope stability monitoring at Orapa Mine.



Figure 3.1: Leica TM50 total station and a GPR112 prism. Source: Leica Geosystems.

The total station measures angles and distances to survey points and the coordinates (x, y, z) of surveyed points relative to the total station position are calculated using joints and trigonometry. To determine the position of a survey point for slope stability monitoring, the total station must be set up on a point whose co-ordinates are known, and there must be a clear line of sight from the total station to the survey point to be measured. The total station is integrated with a microprocessor, electronic data collector and a storage system.

The data collected and processed can be downloaded to computers using appropriate software for further processing. Total stations with different accuracies in angular measurements as well as different range measurement capabilities are available in the market today. The five major manufacturers of total stations are as follows:

1. Leica;
2. Trimble;
3. Sokkia;
4. Pentax;
5. Topcon.

For this research report, a Leica TM50 is used in the prism monitoring system under review. The specifications of the Leica TM50 are outlined in figure 3.2:

ANGLE MEASUREMENT		
Accuracy [1] Hz and V	Absolute, continuous, quadruple	0.5" (0.15 mgon) or 1" (0.3 mgon)
DISTANCE MEASUREMENT		
Range [2]	Prism (GPR1, GPH1P) [3] Non-Prism / Any surface [4]	1.5 m to 3500 m 1.5 m to >1000 m
Accuracy / Measurement time	Single (prism) [2,5] Single (Any surface) [2,4,5,6]	0.6 mm + 1 ppm / typ. 2.4 s 2 mm + 2 ppm / typ. 3 s
Laser dot size	at 50 m	8 mm x 20 mm
Measurement technology	System Analyser	coaxial, visible red laser
IMAGING [7]		
Overview and telescope camera	Sensor Field of view (overview / telescope) Frame rate	5 Mpixel CMOS sensor 19.4° / 1.5° Up to 20 frames per second
MOTORISATION		
Direct drives based on Piezo technology	Rotation speed Time to Change Face	max. 200 gon (180°) / s typ. 2.9 s
LONG RANGE AUTOMATIC AIMING (ATR)		
Range ATR mode [2]	Circular prism (GPR1, GPH1P) 360° prism (GRZ4, GRZ122)	3000 m 1500 m
Accuracy [1,2] / Measurement time	ATR angle accuracy Hz, V	0.5" (0.15 mgon) or 1" (0.3 mgon) / typ. 3–4 s
GENERAL		
Autofocus [8] Telescope	Magnification / Focus Range	30 x / 1.7 m to infinity
Display and Keyboard	VGA, colour, touch, Face 1 standard (Face 2 opional)	36 keys, illumination
Operation	3x endless drives, 1x Servofocus drive, 2x Autofocus keys, User-definable SmartKey	
Power Management	Exchangeable Lithium-Ion battery with internal charging capability	Operating Time 7–9 h
Data storage	Internal memory Memory card	1 GB SD card 1 GB or 8 GB
Interfaces	RS232, USB, Bluetooth®, WLAN	
Weight	Monitoring Station incl. battery	7.6 kg
Environmental specifications	Working temperature range Dust & Water (IEC60529) / Blowing rain Humidity	–20°C to +50°C IP65 / MIL-STD-810G, Method 506.5-I 95%, non-condensing

Figure 3.2: TM50 total station specifications. Source: Leica Geosystems.

The Leica TM50 total station is suitable for continuous measurements using the monitoring software application. The Leica TM50 has a prism measurement range of up to 3500m and angular accuracy of 0.5". The instrument is designed to withstand the roughest use in the most severe environment. The Leica TM50 operates in all weather conditions and forms

one component of the unique monitoring solution which integrates total stations, GNSS and geotechnical sensors.

The use of a total station for normal topographic survey is a manual process which requires the mine surveyor to take manual observations. However, technology advancements now enable automisation of measurements using software such as the Leica GeoMoS or the Trimble T4D monitoring solutions. This software is configured to operate the total station remotely through a telemetric network. When the total station is correctly set, it is able to locate prisms by ATR, taking observations and transferring the readings in the monitoring software.

Cruden and Masoumzadeh (1987) explained that the recent development in total stations have made reliable remote monitoring of rock slope movement possible. Observations of slope movements in surface mines can now be reliably extrapolated to predict slope stability or instability and the event of possible failure.

3.2 Electronic Distance Measurements

Electronic distance measurement is an advanced technique used in survey instruments to measure the slope distance from a known point to an unknown point. An instrument with an EDM is known as a total station and it measures and computes distances using phase changes which occur as electromagnetic energy of known wavelength travelling from instrument to target and returning to the instrument. EDM instruments are classified according to their type of wavelength of the electromagnetic energy generated or according to their operating range.

The accuracy required in distance measurements is such that the measuring wave cannot be used directly due to its poor propagation characteristics. The measuring wave is therefore superimposed on high frequency waves called carrier waves (Afeni, 2011).

The lower frequency waves provide a larger range, but need large transmitters and are susceptible to the atmospheric effects and therefore less accurate for EDM purposes than those of high frequency. Field instruments for surveying require high frequency waves as the instruments can be designed to be small and the propagation through the atmosphere would be more stable.

The challenge with a high frequency wave is that it is more difficult to measure the phase changes which are required for distance computation. The solution is therefore to modulate the high frequency wave with a lower frequency and to use the modulated wave for measurement purposes. When modulating the high frequency, certain characteristics of the carrier wave are selected in accordance with another signal (Karaman, 2005).

Various survey instruments use an amplitude modulation, while others use frequency modulation. In frequency modulation the amplitude of the carrier wave remains the same, whereas for the amplitude modulation, the amplitude of the carrier wave is varied above and below its unmodulated value by an amount proportional to the amplitude of the modulation signal and the frequency of that signal (Karaman, 2005). Figure 3.3 shows the amplitude modulation and frequency modulation of a carrier wave.

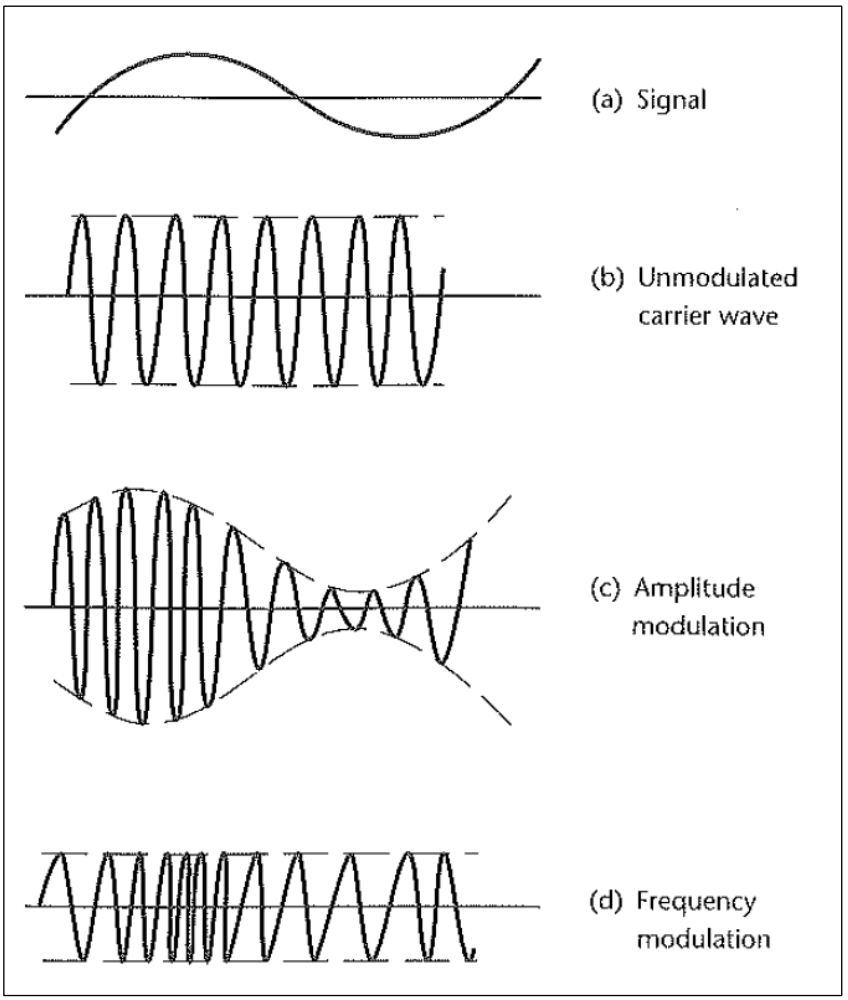


Figure 3.3: Modulation types of a carrier wave. Source: Karaman (2005).

There are two types of EDM instruments, namely the electro-optical and the microwave. The electro-optical instruments transmit light with a wavelength in the range of 0.7 to 1.2 micrometres, whereas the microwave instruments transmit microwaves with frequencies in the range of 3 to 35 GHz (Karaman, 2005). The fundamental principle of EDM instruments operation is that the electromagnetic energy from the instrument propagates through the atmosphere in accordance to the formula below:

$$V = f * \lambda$$

Where V is the velocity of the electromagnetic energy in metres per second, f is the modulated frequency of the energy in hertz, and λ is the wavelength

in metres (Karaman, 2005). This propagation is illustrated in figure 3.4, the positions of points along the wavelength are given by phase angles.

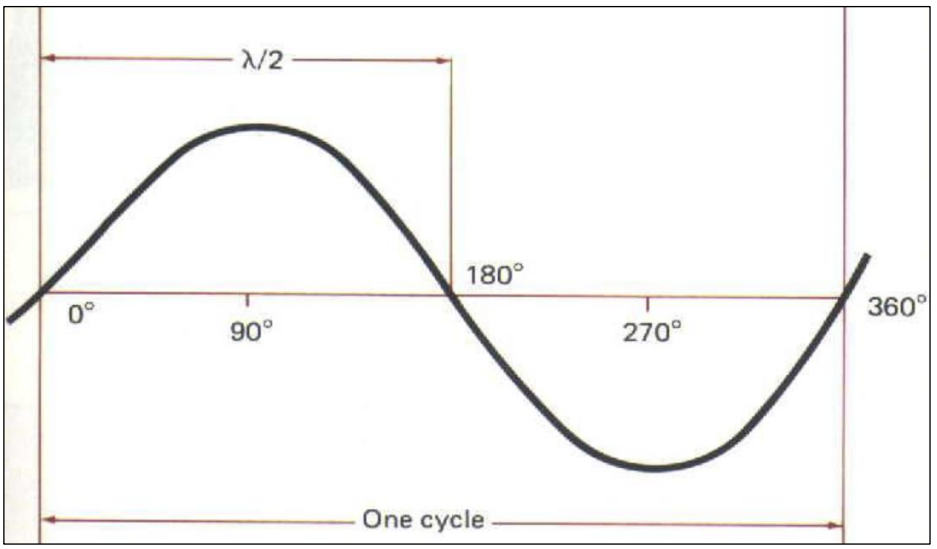


Figure 3.4: Wavelength of electromagnetic energy with phase angles. Source: Karaman (2005).

Figure 3.5 shows an EDM device that is a total station set on station A and levelled. Co-ordinates for station A are known and orientation angle is obtained from the existing survey control network. A carrier signal from the instrument at A is transmitted to a reflector (prism) at station B. This carrier signal is of electromagnetic energy on which a reference frequency has been superimposed or modulated.

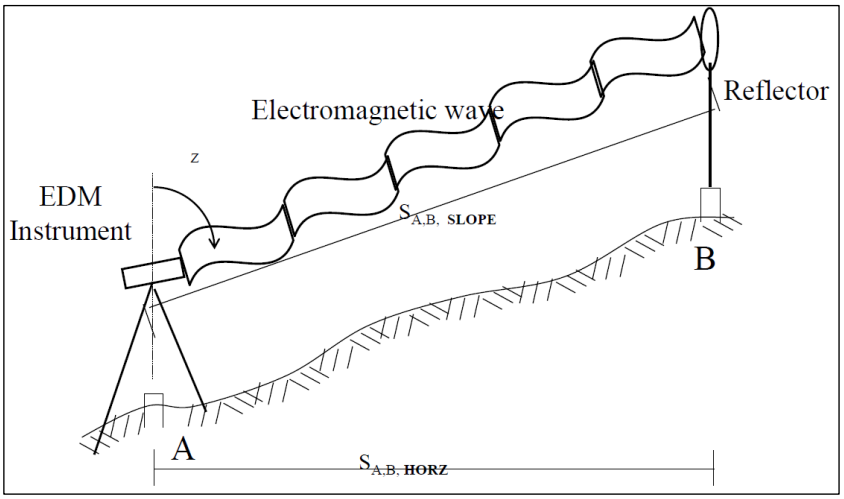


Figure 3.5: Mechanism for electronic distance measurement. Source: Karaman (2005).

The carrier signal is then reflected back from station B to the instrument at station A, therefore its travel path is double the slope distance AB. The modulated electromagnetic energy is represented by a series of sine waves, each having wavelength λ. The horizontal distance is then computed using the slope distance S_{AB} and vertical angle z.

3.3 Errors in Electronic Distance Measurements

While survey measurement can be very accurate, observations are never exact, and therefore always contain some errors (Wolf and Ghilani, 2001). As mentioned previously, in surveying, there are three types of errors, which are systematic errors, random errors and gross errors. For instance, gross errors are classified as blunders or simple mistakes that should be found using checks during the survey. Best practice in open pit mines for a mine surveyor is to calibrate an EDM instrument on a known baseline to determine instrument constants and errors. Corrections should be applied to the total station measurements taken subsequent to a calibration. Errors in measurements arise from different sources, such as the operator, the equipment and the atmospheric conditions. The three distinct systematic errors that may occur in total station measurements are:

- Index error;
- Scale error;
- Cyclic or short period error.

<u>The index error</u>

The index error comes from the difference between the physical and electro-optical zero points of the instrument. The value for this error is usually the same and unique for each EDM instrument and reflector. This constant can be changed by combining different reflectors. The index correction is an algebraic constant to be applied to every measured distance to mitigate this error.

The scale error

The scale error is proportional to the distance of the line measured and is caused by errors in the measured ambient temperature, atmospheric pressure, relative humidity and a change in frequency of the quartz crystal oscillator in the instrument. An error of 1 part per million (ppm) in the value of a measured distance will be introduced by an error source of 1°C increase in the ambient temperature. The scale error frequency can be checked by direct comparison against frequency testing apparatus and measurement over a base of known distance (Surveyor-General of the Australian Capital Territory, 2014).

The cyclic error

The cyclic error is a function of the internal phase measurement of an EDM. The error in the internal phase measurement is caused by an unwanted feed through the transmitted signal onto the received signal. For an instrument in good adjustment, this error is normally small, however its presence must be determined as an indication of the instrument's adjustment. A cyclic error normally repeats itself for every unit length contained within a measured distance.

Other errors in electronic distance measurements may arise as a result of mistakes from the user, for example if a wrong orientation is used or if the total station is not properly levelled. There are instances where the mine surveyor is not able to properly sight to the reflector, so this can result in cumulative errors in the measurements. When the instrument is out of calibration, errors can also arise in the distance measurements.

The possible sources of errors in total station measurements have been summarised and it is evident that errors in EDM arise from different sources such as the instrument, the atmospheric conditions, the prism constant as well as the operator. Various checks can be done to mitigate against errors which arise in total station measurements. To minimise the effect of errors,

the mine surveyor has to observe utmost care when taking readings, checks on data must be done whilst on site, and only serviced equipment must be utilised. The equipment must be serviced and calibrated annually for best practice.

3.4 How Temperature and Pressure Affects EDM

The reality in an open pit environment is that there are various atmospheric conditions which occur at different areas due to mining activities. One side of the pit can be hot and dry, while the other side of the pit can be cooler and humid. This can happen when there is cloud cover on one side of the pit. Conditions could actually deviate from the ideal, especially due to dust which is caused by wind and earthmoving equipment. Extreme weather conditions can also be experienced in an open pit. For instance at Orapa Mine, temperatures can reach up to 45°C and rainfall of up to 250mm can be experienced between December and April.

Errors will always be introduced when using optical survey instruments to measure prisms, because the carrier signal from the instrument propagates through different atmospheric conditions to and from the reflector prism. The overall distance measured may therefore be incorrect due to an uneven atmospheric density distribution as the carrier signal moves across the pit. Figure 3.6 shows an illustration of varying ambient temperature and atmospheric pressure around the transfer beacons at Orapa Mine pit.

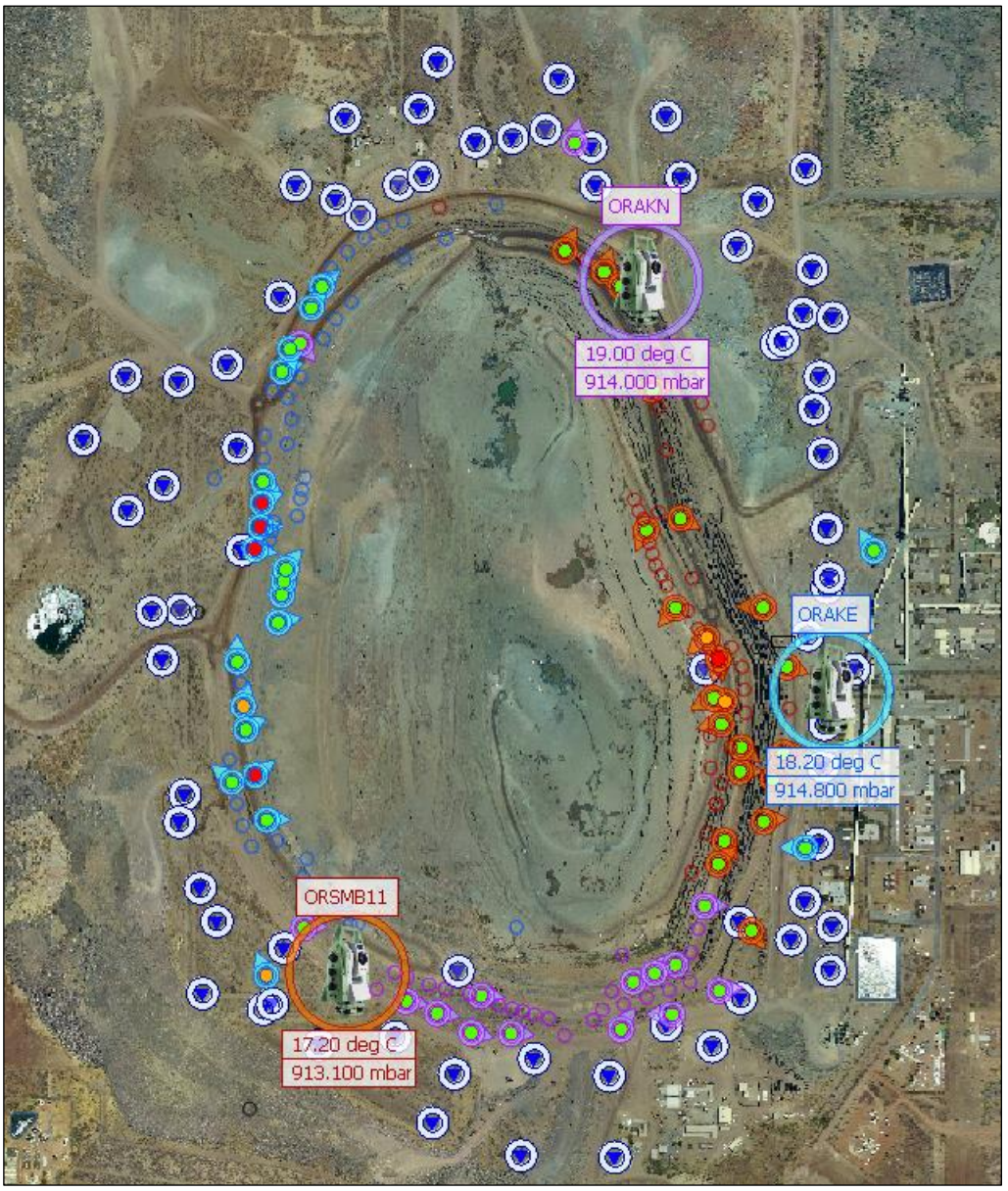


Figure 3.6: Varying atmospheric conditions around Orapa Mine pit. Source: Orapa Survey Department (2016).

Temperatures will vary because it depends on the average velocity of the air molecules and their mass, so the higher the density, the higher the temperature. Atmospheric pressure also varies with different altitudes. Figure 3.7 shows an illustration of prisms which are installed at different altitudes.

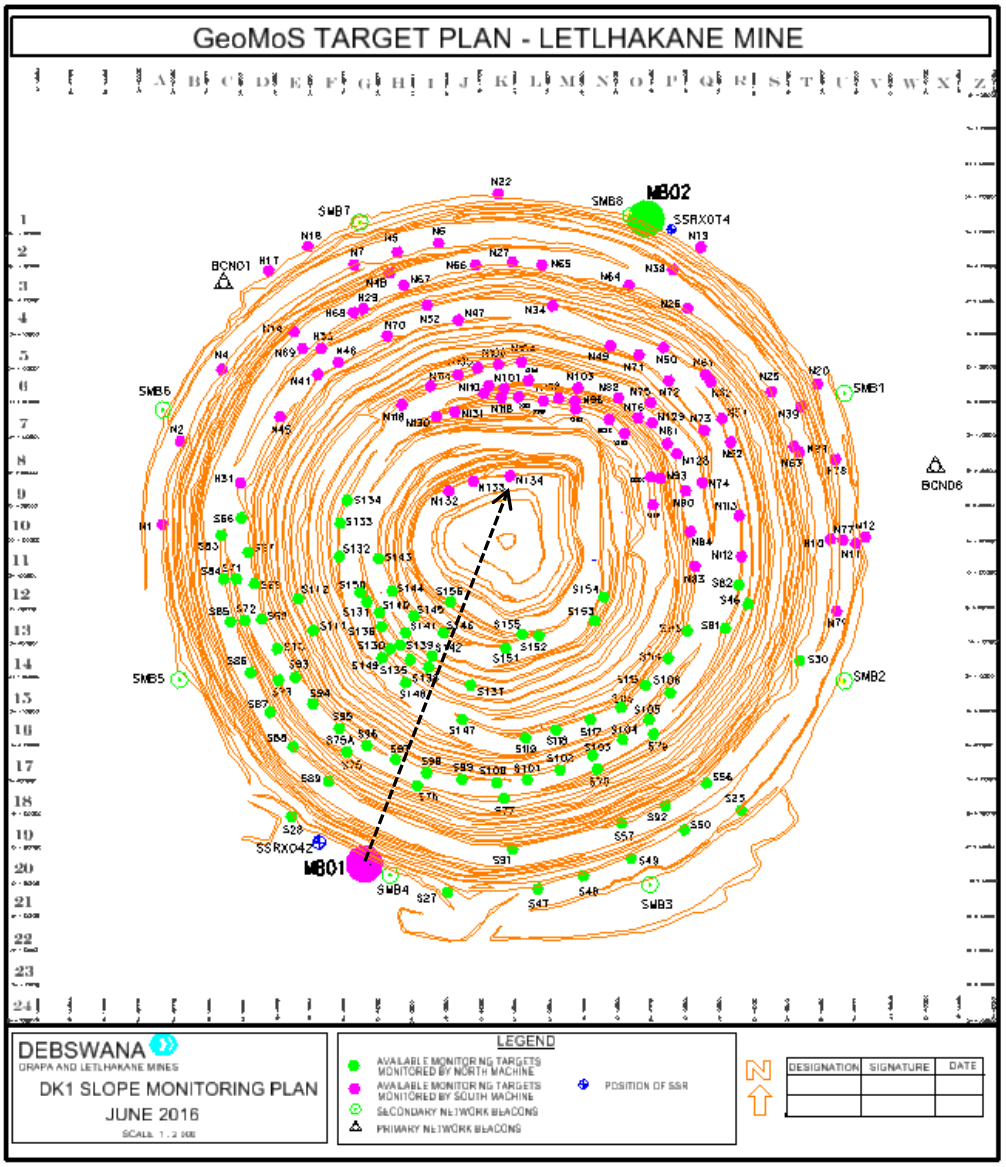


Figure 3.7: Prisms plan for an open pit. Source: Orapa Survey Department.

As the carrier wave from the transfer beacon (MB01) to the reflector (for example N134) passes through an open pit, the carrier wave goes through different atmospheric pressure values. Ambient temperature and atmospheric pressure affect the air density and this affects the velocity of the measuring signal and therefore results in incorrect distances being measured. The meteorological sensor is able to measure the atmospheric parameters at the transfer beacon, but it's unable to model the atmospheric conditions across the open pit. This is one of the major problems for prism monitoring in an open pit environment.

These varying atmospheric conditions in the open pit affect the EDM signal which travels from the instrument to the reflector. Under normal circumstances, the signal would follow a straight line to the reflector, but under varying conditions, the signal would follow a more sophisticated path resulting in what is known as refraction. Figure 3.8 shows an illustration of refraction. The signal travels from TSI, where the instrument is set, to the prism point. Instead of the signal following the straight dotted line, it follows a bent path S, and this is known as refraction.

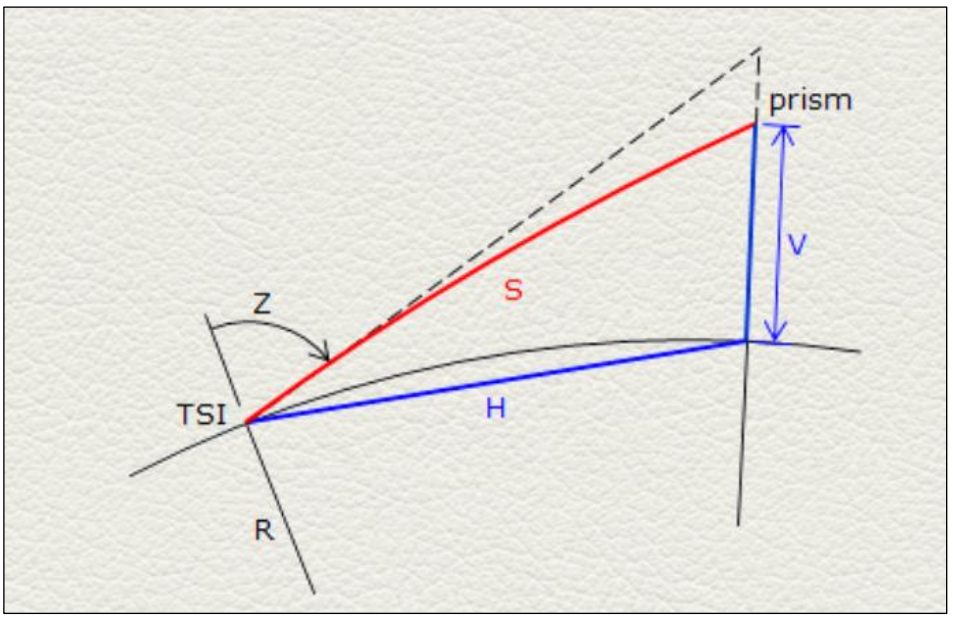


Figure 3.8: Illustration of refraction. Source: Mahun (2016).

Refraction is the bending of a beam or change in direction of a carrier wave as illustrated in figure 3.8. Once this happens, then the EDM readings are affected. Varying ambient temperature and atmospheric pressure therefore affects the electronic distance measurements through refraction. This impact cannot be totally eliminated; however there are methods used to minimise this impact. Ambient temperature and atmospheric pressure readings are recorded at the measuring instrument. The atmospheric corrections parameters are then computed and applied to the measured distances.

The co-ordinates computed using corrected distances will usually show a low displacement value, whereas when there are no corrections the displacement are high and can be more than 20mm. Figure 3.9 illustrates this difference.

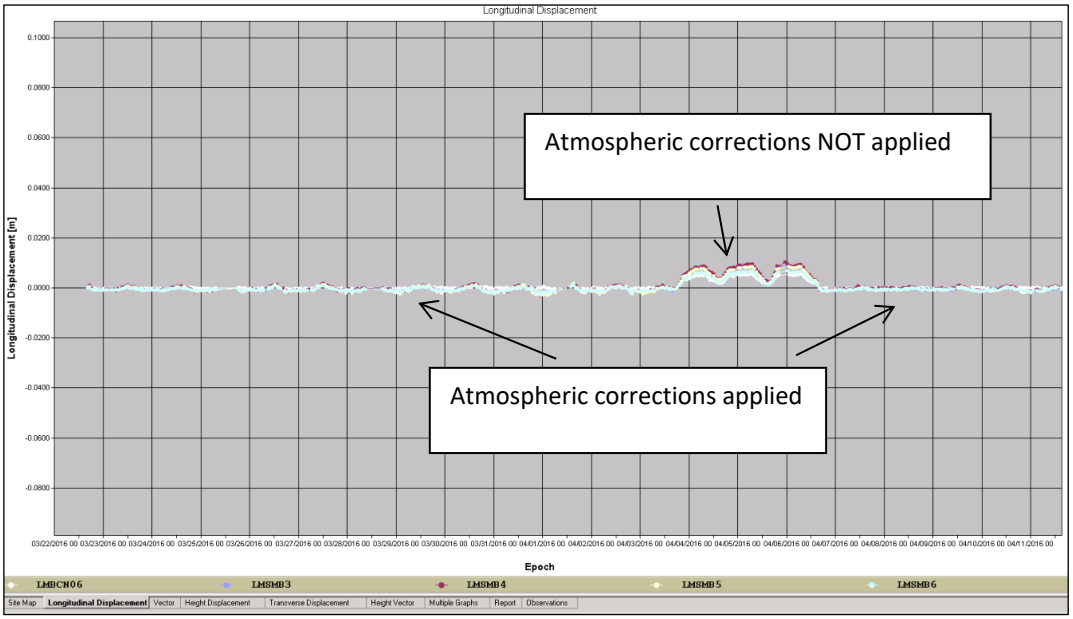


Figure 3.9: Leica GeoMoS displacement graph. Source: Orapa Survey Department.

The graph in figure 3.9 shows that when atmospheric corrections are applied to the monitoring data, the displacement graph is relatively normal, but once the meteorological sensor goes on breakdown or gets damaged, no corrections are made resulting in a high amplitude graph.

3.5 How Atmospheric Corrections are Applied to EDM Measurements

The EDM distances should always be corrected for the refractive index along the measurement path. In ideal situations, best practice would be to measure atmospheric conditions at several points along the optical path, for example at intervals of 200 metres. This is however difficult to achieve in an open pit environment. The ambient temperature and atmospheric pressure are used to give a correction factor which is stated in parts per million; this correction is then applied to the slope distance.

The problem of prism monitoring is that the meteorological conditions are measured only at the transfer beacon, which is the most common practice, as such errors of a few parts per million will always be present. In order to achieve an accuracy better than 1ppm, it is important to measure meteorological conditions at shorter intervals (Bertacchini and Capra, 2011). Calculating and applying the correct atmospheric (ppm) to an EDM distance measurement is extremely important (Crook, 1995). The ppm application to correct for distances is outlined below:

$$D_C = \left[\left(\frac{ppm}{1\times10^6}\right) D_m\right] + D_m$$

Where D_C = field corrected distance;

ppm = parts per million;

D_m = measured distance with zero ppm set in total station.

The refraction correction is then calculated as follows:

$$d = \left(\frac{nR}{nL}\right) \times d_m$$

Where d = corrected distance;

nL = ambient refraction index;

nR = reference refractive index (instrument);

d_m = measured distance.

Source: Bertacchini *et al* (2011).

Accuracy of the ppm correction is directly affected by the validity of the ambient temperature and atmospheric pressure. The most accurate ambient temperature and atmospheric pressure is obtained using a meteorological sensor; this is the normal practice in a prism monitoring setup. The meteorological sensor must be placed away from the monitoring shelters to mitigate the effects of shadow and radiation. Best practice is for

the meteorological sensor to be placed in a Stevenson Screen as shown in figure 3.10.



Figure 3.10: Meteorological sensor in a Stevenson Screen. Source: Orapa Survey Department.

The meteorological sensor must be set to measure ambient temperature and atmospheric pressure readings at intervals of 5 minutes or less. These measurements must be recorded at this interval to ensure that correct atmospheric corrections are applied to the slope distance measurements. In an automated monitoring setup, the last reading from the meteorological sensor is used by the monitoring software to compute atmospheric corrections and apply them to the measured distances; this process is all done within the software.

When the atmospheric corrections are not applied, the displacement values shown in both longitudinal and vertical graphs will be high in amplitude, and this can be misinterpreted by the geotechnical engineer when analysing slope stability. Cawood *et al* (2006) emphasises this point by stating that “atmospheric corrections on total station slope distances are problematic when measuring over long distances across voids where the temperature variations along the line of measurement vary significantly. These variations

cause exaggerated fluctuation graphs and errors in elevation and they can make interpretation of continuous monitoring difficult".

3.6 Alternative Approach to Atmospheric Corrections

The atmospheric corrections to distance measurements only minimise the impact caused by varying atmospheric conditions in an open pit. As the pits become wider and deeper, the measurement of prisms on longer distances becomes very complex. The most limiting factor in an automated monitoring system is that ambient temperature and atmospheric pressure can only be measured at the transfer beacons, but not at the prisms because of costs, access and practicality.

The other limiting factor is that the ambient temperature and atmospheric pressure values are continually changing and the true values may not be used for correcting the slope distances along the line of sight. It is therefore necessary to find out an appropriate alternative approach to correct the slope distances from total station measurements. The Global Navigation Satellite System (GNSS) can provide high accuracy controls on total station measurements in unstable environments (Brown *et al*, 2006). The distance between control points can be accurately computed through GNSS real-time monitoring. If there is a fixed network of beacons with good geometry, then post-processed co-ordinates of these control points can be computed every 1hour, 6 hours, or 24 hours.

Once the co-ordinates of the control points are known in real time, then the distance between any two reference beacons within the control network can be computed in real-time also. An alternative approach which can be used for the correction of the total station distances is to measure reference beacons or points where the distance is accurately known so that a reference scale factor can be directly computed and used to correct the distances measured to the prisms in the open pit. Figure 3.11 illustrates how this method works.

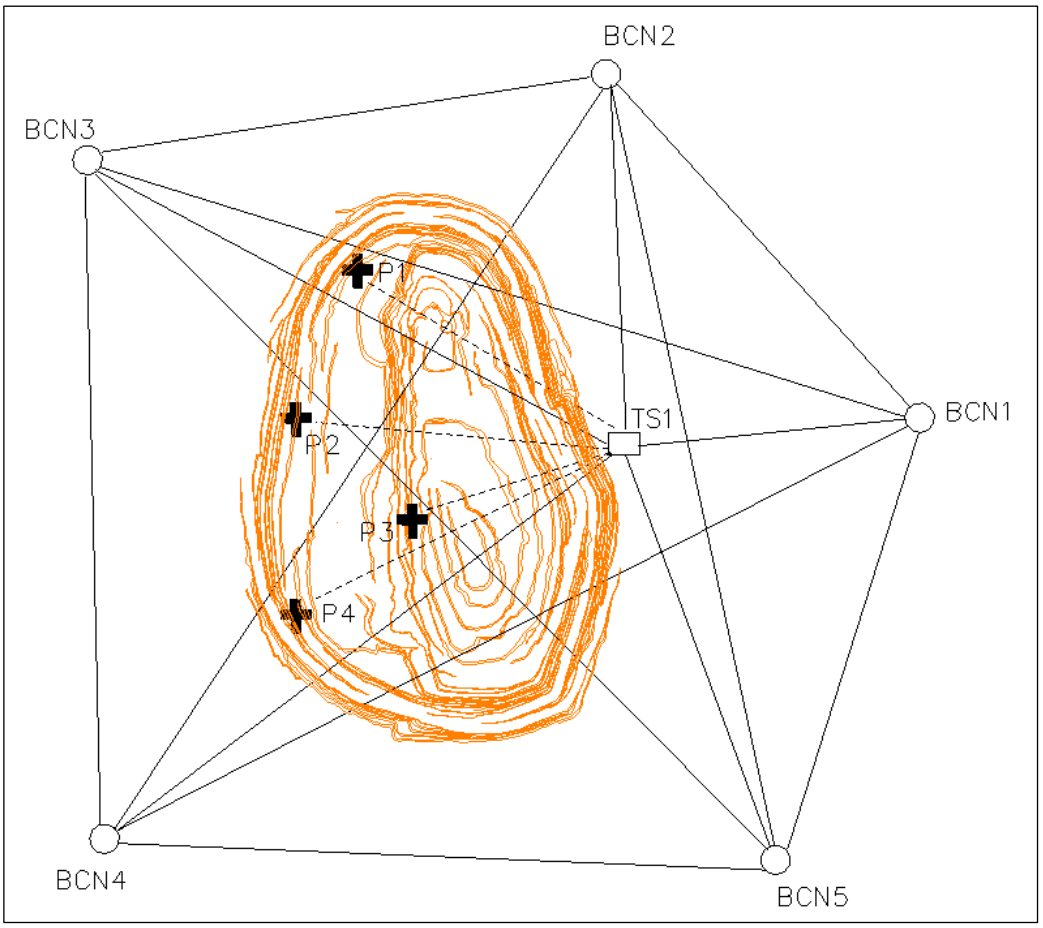


Figure 3.11: Combined GNSS and EDM total stations for prism monitoring

A monitoring software, for example Leica GeoMoS, can be configured to have a periodic measurement of reference distances and apply a reference scale factor to subsequent measurements to prisms. Figure 3.10 shows a network of control beacons, that is TS1, BCN1-BCN5, which are continuously monitored by the GNSS system. Post-processed co-ordinates for each beacon can be obtained using software such as the Leica Spider, which can be integrated with Leica GeoMoS monitor such that real time co-ordinates of the beacons can be copied from the Leica Spider software to the Leica GeoMoS software.

This is an automated process which requires appropriate software settings If for instance the base or known distance between the transfer beacon (TS1) and reference beacon (BCN1) is equal to 100m, and the new distance

measured using GNSS co-ordinates is equal to 100.003m, then the reference distance scale factor is computed using formula below:

$$S_R = \frac{d}{d'}$$

Where S_R= reference scale factor;

d = originally known distance;

d' = new distance computed from GNSS co-ordinates.

The reference scale factor for this example will be as follows:

$$S_R = \frac{100}{100.003}$$

=0.999970001

The reference scale factor is applied to distances measured to the prisms (P1-P4) in the pit. This approach is anticipated to only work accurately when few prisms are measured, that is the computed reference scale factor should be used for a limited time period depending on the conditions in an around an open pit. For total station distances, the reference scale factor will require change or updating as ambient temperature and atmospheric temperature may change rapidly.

Different areas of the pit would be affected if GNSS is not used. For better accuracy, the reference scale factor should be used for a maximum time of five minutes, and should be continuously updated. When an open pit has at least fifteen prisms, then the monitoring software can be configured to have different measuring groups from the same transfer beacon. Each measuring group should have a maximum of fifteen prisms.

Brown *et al* (2006) states that the use of GNSS receivers to provide a stable reference frame for total stations sited in any environment is a viable option and one that has many advantages. In order to validate this statement,

Brown *et al* (2006) conducted a practical test at the Leica factory in Switzerland using dual frequency combined GNSS receivers to update the position of the transfer beacon and reference beacon. The conclusion was that combining GNSS satellite receives with total stations is an effective method for monitoring points, based on the accuracy of results found in the practical test.

3.7 Conclusion

The use of robotic EDM instruments is one of the best methods used by open pit mines for slope stability monitoring. However, the accuracy of the prism measurements can be highly influenced by the ever changing topographic conditions in the open pit. This effect is minimised by applying atmospheric corrections to slope distance measurements. This correction is based on atmospheric parameters of ambient temperature and atmospheric pressure readings at the transfer beacon.

These parameters are measured using meteorological sensors. Apart from the effect of the atmospheric conditions on distance measurements, other sources of errors can arise in EDM readings, and these can be systematic, random and gross errors. The author will carry out a trial for an alternative approach to total station distance corrections which is based on application of reference scale factors from known reference beacons.

The next chapter focuses on the Leica GeoMoS data management and analysis for Orapa, Letlhakane and Damtshaa Mines. The author explains the measurement trends of the Leica GeoMoS data over the years and the impact of atmospheric conditions to this data. The existing model for the atmospheric corrections will also be discussed.

4 LEICA GeoMoS DATA MANAGEMENT

The purpose of this chapter is to describe the prism monitoring data management and analysis for Orapa, Letlhakane and Damtshaa Mines (OLDM).The data collection process is outlined as well as the requirements for the Leica GeoMoS system. Furthermore, the impact of atmospheric conditions to the prism monitoring data is discussed. A description of the existing model of the atmospheric corrections will focus on the infrastructure set-up and the implications of varying ambient temperature and atmospheric pressure on distance measurements. Various data analysis trends are also discussed.

4.1 Leica GeoMoS Data Requirements

Slope instability can be expected at any surface mining operation, but the unpredicted movement of ground may endanger lives and destroy property. Unstable slopes result in unsafe conditions for personnel who work beneath them (McHugh, Long and Sabine, 2004). It is necessary to implement an effective monitoring programme to predict the slope failure. Slope failure is one of the highest risks at OLDM, as such there is a need to understand requirements and outputs of all deformation monitoring systems. The driving force for mining diamonds safely cuts across all the processes at OLDM and slope stability monitoring data is a critical requirement for decision making.

Slope movement is most common in open pit mines and many mines continue to operate safely for years with moving slopes that are suitably monitored (Afeni, 2011). The main objective of the Leica GeoMoS system is to measure and record deformation data of all positions which have been strategically selected by the geotechnical engineer. Acquisition of the Leica GeoMoS data is therefore a process that takes into account geotechnical information and applies the fundamental principles of survey concepts aimed at mitigating slope failure risk through prediction and alarming, that is, early warning. The data processing and presentation is a rapid

assessment of information to detect changes that require immediate action. Acquisition of the prism monitoring data is carried out to present the data to show trends and compare observed with predicted behaviour of monitoring prisms so that any necessary action can be initiated. The Leica GeoMoS monitoring data for OLDM is presented in a graphical format which is easy to read. Identification of problematic areas is executed timeously and an example of a typical graph for presenting the Leica GeoMoS data is shown in figure 4.1.

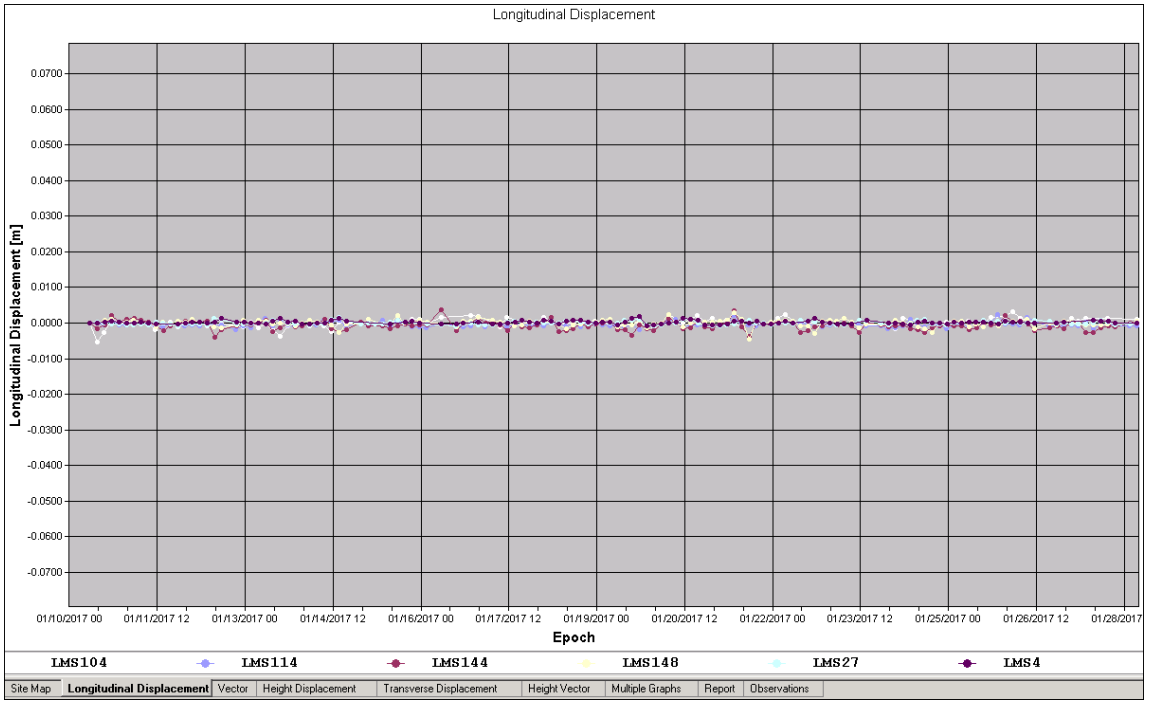


Figure 4.1: Leica GeoMoS displacement graph. Source: Orapa Survey Department.

The data presented in figure 4.1 shows a longitudinal displacement graph of prisms monitored using the Leica GeoMoS system. The displacement ranges from -0.005m to 0.005m over a period of one year. The fluctuation in data is minimised by the application of atmospheric corrections to measured distances. “The development of a sophisticated monitoring system such as the Leica GeoMoS system is not only driven by the desire to simultaneously improve safety and mining economics, but also to meet the moral and legal obligations of mine owners in an effort to protect the workforce from harm” (Klappstein *et al*, 2014).

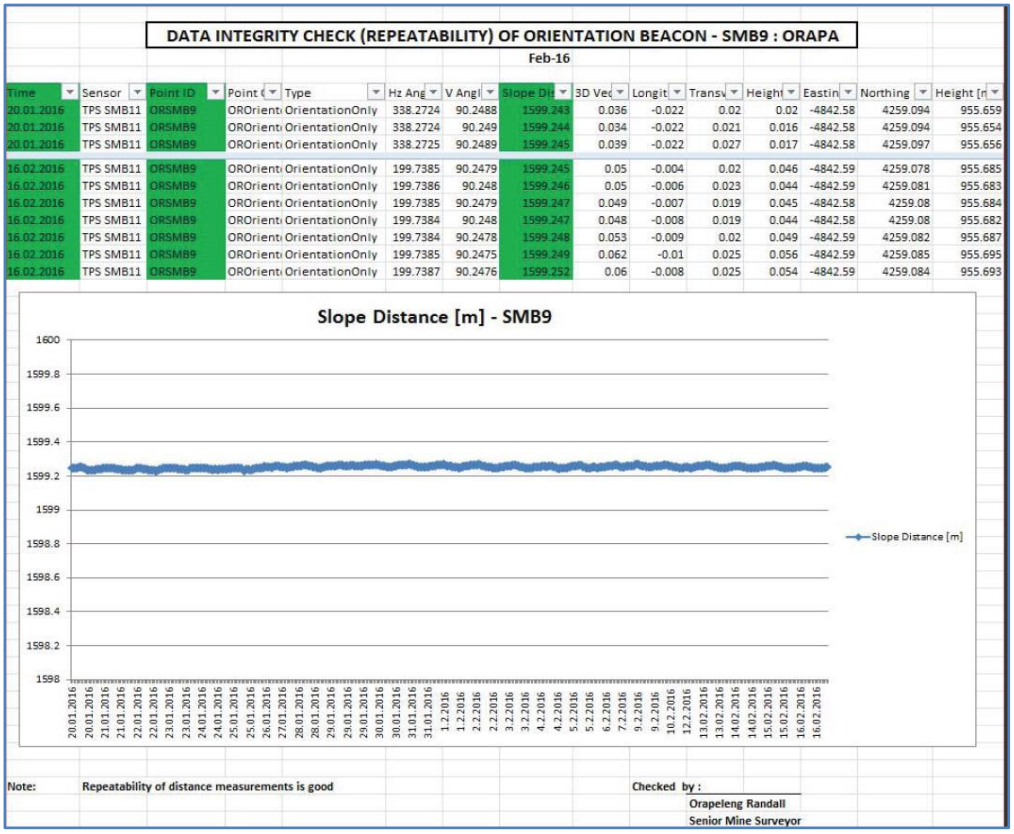
One of the fundamental requirements for the prism monitoring data is to be able to build a history of information to determine different rock behaviours over an extended period of time of monitoring. Procedures and guidelines for the overall prism monitoring data management are also a critical requirement. Such guidelines ensure consistency in data collection, presentation and analysis by the mine surveyor and geotechnical engineer.

The prism monitoring data acquisition is a complex process; therefore the mine surveyor needs guidelines and procedures to be able to compile and produce this data. Livingstone (2009) emphasised this point by stating that "effective knowledge management and risk mitigation requires that standards and procedures are available to guide practice with minimal dependence on the knowledge held by individuals. The absence of specific documented detail and current standards and procedures can negatively impact on monitoring results due to inconsistent practice".

The other critical requirements for the prism monitoring data in open pit mines is defensibility of the data, that is in the event of a slope failure, the mine surveyor must be able to present in an investigation that the prism monitoring data is effective, that is correct and reliable. This must be done with archived records as evidence and defensibility of the data is directly linked with consistent effective data. The quality of the data is measured by accuracy and precision and at OLDM, the data integrity check is carried out by the mine surveyor prior to geotechnical analysis.

Thomas (2011) states that "Survey related slope stability monitoring requires that the incumbent ground deformation monitoring mine surveyor performs the duties of spatial data collection, taking responsibility of data integrity and accuracy after which the data is forwarded to the geotechnical engineer for slope stability interpretation and analysis". As mentioned previously, the prim monitoring data is checked on daily basis and there is

weekly sign off of data, refer to figure 4.2.



DATA INTEGRITY CHECK (REPEATABILITY) OF ORIENTATION BEACON - SMB9 : ORAPA

Feb-16

Time	Sensor	Point ID	Point (	Type	Hz Ang	V Angl	Slope Di	3D Vec	Longit	Transv	Height	Eastin	Northing	Height [r
20.01.2016	TPS SMB11	ORSMB9	ORORient	OrientationOnly	338.2724	90.2488	1599.243	0.036	-0.022	0.02	0.02	-4842.58	4259.094	955.659
20.01.2016	TPS SMB11	ORSMB9	ORORient	OrientationOnly	338.2724	90.249	1599.244	0.034	-0.022	0.021	0.016	-4842.58	4259.094	955.654
20.01.2016	TPS SMB11	ORSMB9	ORORient	OrientationOnly	338.2725	90.2489	1599.245	0.039	-0.022	0.027	0.017	-4842.58	4259.097	955.656
16.02.2016	TPS SMB11	ORSMB9	ORORient	OrientationOnly	199.7385	90.2479	1599.245	0.05	-0.004	0.02	0.046	-4842.59	4259.078	955.685
16.02.2016	TPS SMB11	ORSMB9	ORORient	OrientationOnly	199.7386	90.248	1599.246	0.05	-0.006	0.023	0.044	-4842.59	4259.081	955.683
16.02.2016	TPS SMB11	ORSMB9	ORORient	OrientationOnly	199.7385	90.2479	1599.247	0.049	-0.007	0.019	0.045	-4842.58	4259.08	955.684
16.02.2016	TPS SMB11	ORSMB9	ORORient	OrientationOnly	199.7384	90.248	1599.247	0.048	-0.008	0.019	0.044	-4842.58	4259.08	955.682
16.02.2016	TPS SMB11	ORSMB9	ORORient	OrientationOnly	199.7384	90.2478	1599.248	0.053	-0.009	0.02	0.049	-4842.59	4259.082	955.687
16.02.2016	TPS SMB11	ORSMB9	ORORient	OrientationOnly	199.7385	90.2475	1599.249	0.062	-0.01	0.025	0.056	-4842.59	4259.085	955.695
16.02.2016	TPS SMB11	ORSMB9	ORORient	OrientationOnly	199.7387	90.2476	1599.252	0.06	-0.008	0.025	0.054	-4842.59	4259.084	955.693

Note: Repeatability of distance measurements is good

Checked by :

Orapeleng Randall

Senior Mine Surveyor

Figure 4.2: Leica GeoMoS data integrity check. Source: Orapa Survey Department.

Figure 4.2 shows that there is repeatability of slope distance measurements and this is one of indicators for effectiveness and defensibility of the prism monitoring system at OLDM.

4.2 Data Collection and Analysis

When using the Leica GeoMoS software, data collection involves taking measurements of vertical angles, horizontal angles and distance measurements to a series of monitoring prisms (Mphathiwa, 2012). At Orapa Mine, monitoring prisms are installed at a regular spacing of approximately 30m horizontally and 15m vertically in critical areas of the open pit. Installation of the prisms is done by the geotechnical engineer. Figure 4.3 shows the distribution of monitoring prisms at Orapa Mine.

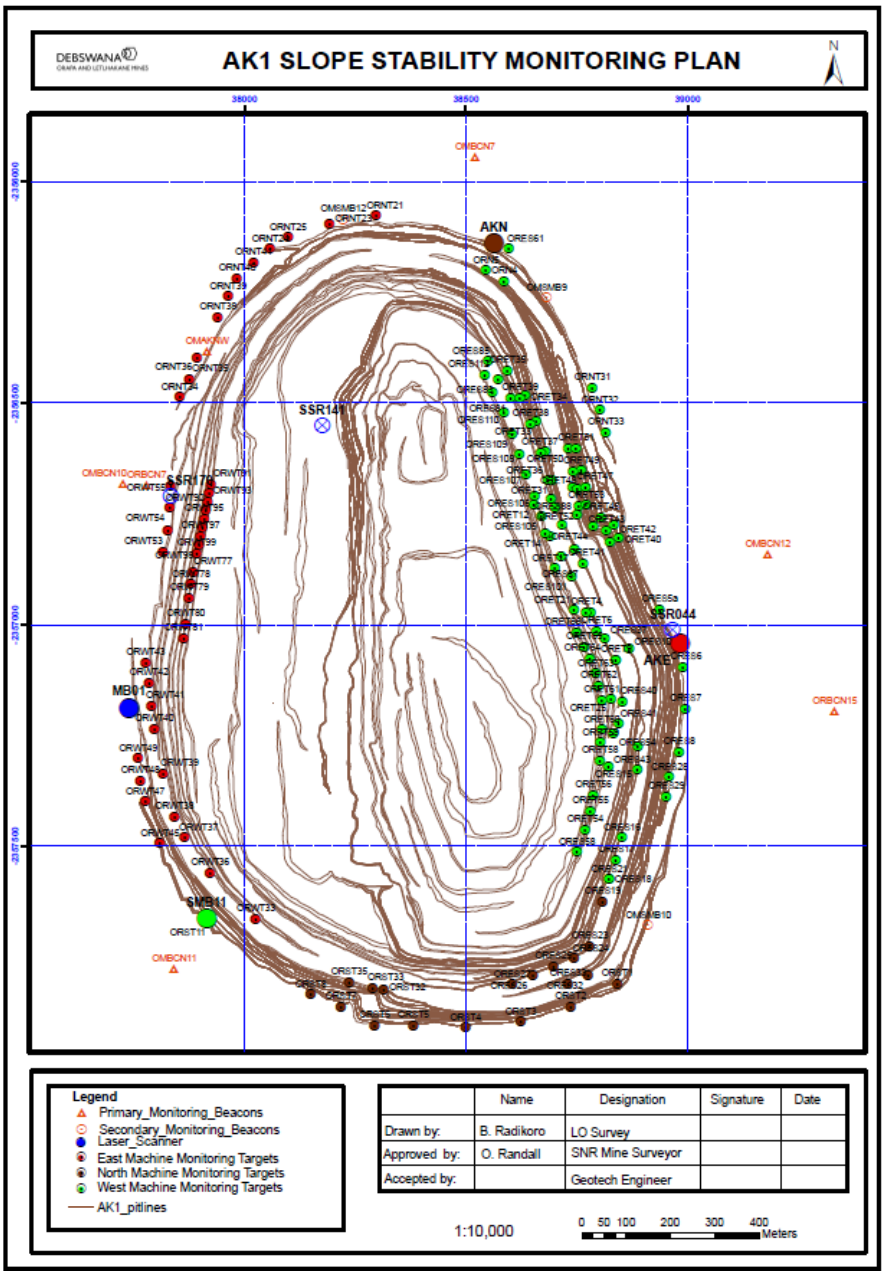


Figure 4.3: Monitoring prism distribution plan. Source: Orapa Survey Department.

Once the locations of monitoring prisms have been discussed and approved by the geotechnical engineer, the mine surveyor ensures that the prisms are continuously measured for ground deformation monitoring.

Measurement of the prisms is performed using a robotic total station which uses reference beacons for orientations and data accuracy checks. Figure 4.4 shows a transfer beacon used to measure monitoring prisms.



Figure 4.4: Leica GeoMoS transfer beacon. Source: Orapa Survey Department.

The monitoring prism positions are measured every three hours by three permanent robotic total stations which are located on the north, east and south of Orapa Mine pit. The transfer beacon comprise of a Leica robotic total station which is connected to a meteorological sensor and a wireless radio communication device. The entire system is powered by a 220 volts mains power which is backed up by an uninterrupted power system (UPS).

Figure 4.4 shows that the monitoring instrument is well protected in a glass enclosure. Real time prism monitoring measurements are controlled by the Leica GeoMoS software which is installed at the survey office, where the server or computer is located. The monitoring data is sent across to the server via the radio communication device as and when the measurements are taken. The data is stored and archived on a daily basis

by the Information Technology Analyst at the mine. The Leica GeoMoS software does computations and reductions which include orientation misclosures, atmospheric corrections and free stations calculations.

Analysis of the data is carried out using the Leica GeoMoS Analyzer software. The user is able to filter the data and plot various graphs of displacement, velocity and vector movement of one or multiple prism. The user is also able to constrain the data for any period of time, for example daily, weekly or annually. There are three displacement plots in Leica GeoMoS Analyzer, namely;

- Longitudinal displacement;
- Transverse displacement and;
- Height displacement.

These are for movement along the x, y, and z axes and the vector plot combines the three displacements into an absolute movement. A velocity plot uses the longitudinal displacement to calculate a displacement velocity. There are various options of displaying the graphs, for example raw and smoothed data. Spikes or outliers can be eliminated from the graph as shown in figure 4.5.

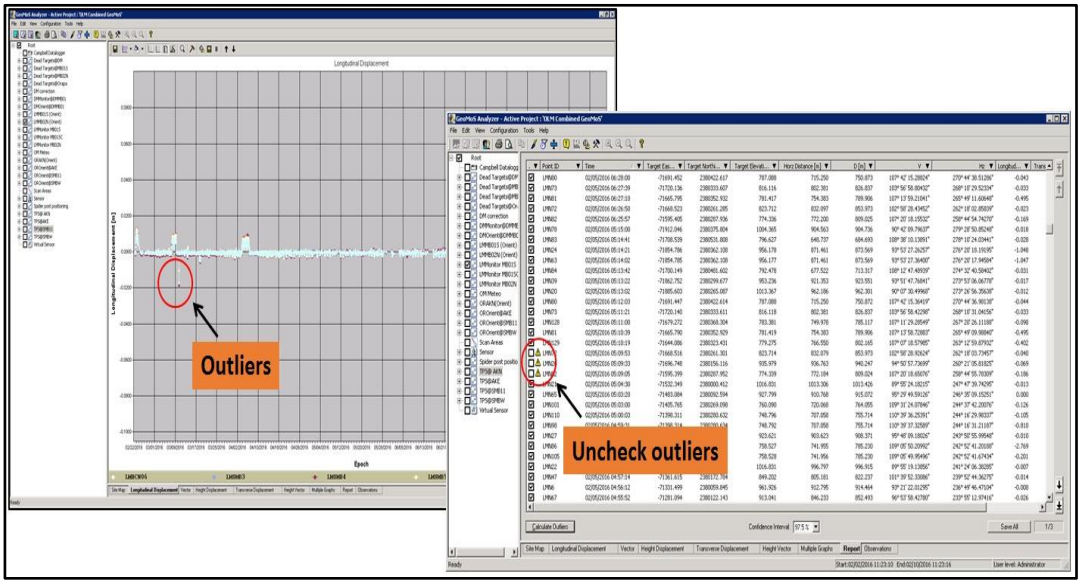


Figure 4.5: Outliers elimination in Leica GeoMoS data. Source: Orapa Survey Department.

The Leica GeoMoS software does not delete the outlier measurements; however it omits the measurement in the analysis graph to assist in interpretation of the data. The Leica GeoMoS Analyzer graphs are plotted automatically whenever new data is received. The Leica GeoMoS system comprise of an alarming system which triggers if certain results from the system go beyond the set limits, or if there is a technical problem with the system.

The geotechnical engineer provides the mine surveyor with limit classes and then the mine surveyor configures the software to send emails or text alerts to Leica GeoMoS users whenever a threshold limit of a displacement is exceeded. The system also sends an alert to the mine surveyor when there is a breakdown in communication between the monitoring station and the office.

At Orapa Mine, when an alarm alert is sent from the Leica GeoMoS system, the mine surveyor immediately checks for data accuracy while the geotechnical engineer keeps a close check on the area of concern and may further verify the same alarm area with other complementary monitoring systems to ascertain if there is ground movement. In instances where the Leica GeoMoS system picks up ground movement in a working area, the geotechnical engineer evacuates personnel until the area is deemed safe and work can resume.

4.3 Quality Control in Prism Monitoring Data

Automated monitoring systems such as the Leica GeoMoS system continuously measure the position of monitoring prisms in the pit and send data to the computer database. There are various key controls which can be used to ensure that the final data quality is suitable. Such controls include the following:

1. Stability of control beacons;
2. Instrument calibration;
3. Quality of monitoring prisms;
4. Data checks;
5. Data security.

4.3.1 Stability of Control Beacons

The prism monitoring infrastructure at OLDM comprises of a suitable network of reference beacons which are classified as transfer, secondary and primary beacons. The transfer beacons are used as the base for prism monitoring and are located very close to the pit edge. The secondary beacons have been suitably located around the pit edge. Provision is made for the secondary beacons to be converted to transfer beacons if necessary. This may occur when the existing transfer beacon gets damaged or affected by ground movement. The primary beacons are outside the zone or relaxation, that is, at least 100m away from the pit edge. There is a sufficient number of reference beacons at Orapa Mine as shown in figure 4.6.

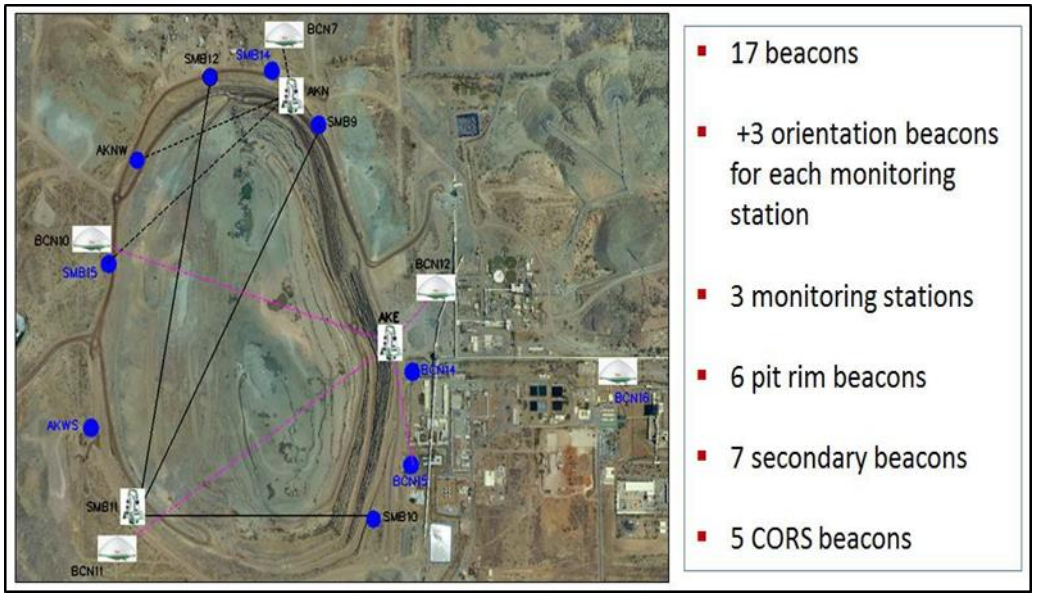


Figure 4.6: Reference beacons plan. Source: Orapa Survey Department.

Figure 4.6 shows that each transfer beacon has at least three reference beacons and there is one primary beacon which is at least 1.5km away from the pit crest. The GNSS monitoring system is installed at most of the primary beacons to monitor any ground deformation in real time. This is to ensure that beacons used by the Leica GeoMoS system are monitored by an independent system. The reference and transfer beacons are periodically surveyed using a precise control network derived by a least squares adjustment. This process is done in-house and by an independent Land surveyor to ensure data accuracy assurance.

The survey department is responsible for construction of new or damaged reference beacons. The process starts by identifying a suitable location for reference beacon construction. The next step involves acquisition of approved reference beacon drawings from a certified structural engineer. The last stage is to engage a suitable civil works contractor to construct the reference beacon according to the specifications as shown on the drawing. A suitable geometry and correct measurement of reference beacons influence measurement accuracy of the prism monitoring system.

4.3.2 Instrument Calibration

One of the main processes to be evaluated for data quality control in a prism monitoring system is calibration of the instrumentation. At Orapa Mine, a maintenance schedule is in place for the instrumentation used for deformation monitoring, which includes the Leica TM50 and TM30's. The Leica TM50 has a distance accuracy of +-0.6mm+1 ppm and an angular accuracy of 0.5 seconds of an arc, whereas the TM30 has a distance accuracy of +-1mm+1ppm and angular accuracy of 0.5 seconds of an arc (Leica Geosystems, 2016).

To ensure that the instruments continuously measure with the above specified accuracies, they need to be serviced and calibrated on an annual basis because of the conditions in an open pit and because the instrument

is used throughout the year. Adherence to the service schedule is well managed and reminders are set in Microsoft Outlook to ensure that instruments due for servicing are shipped out timeously. Upon completion of the instrument service and calibration, the supplier sends a report or calibration certificate which normally has validity period of two years. Thomas (2011) emphasised the need for routine on site instrument checks for horizontal and vertical index, and should be carried out on a regular basis or as and when required.

4.3.3 Quality of Prisms

The reflectivity quality of prisms has an impact in the accuracy of distances measured to the prisms, especially in the open pit environment, where conditions may not always be favourable for measurements to take place. There are many prism manufactures in the market, and the survey department at Orapa Mine carefully selected Leica prisms for use in the Leica GeoMoS system. Monitoring targets are installed with Leica GPR112 prisms which are classified as the most suitable for deformation monitoring by the manufacturer. The reference beacons are all installed with the high precision Leica GPH1P prisms. The GPH1P prism has a precisely machined reflector for high accuracy measurements. Leica prisms are manufactured from glass of the highest quality and have optical coatings so that even under the most extreme environmental conditions, a long lifetime and maximum range with the highest accuracy is achieved.

There is a suitable management plan in place for monitoring prisms at Orapa Mine and the periodic clean-up and alignment of the prisms is done by the survey and geotechnical teams. Damaged prisms are replaced with new ones to ensure continuous monitoring. Performance of each monitoring prism is measured by the prism succession rate calculation, for example if a monitoring prism is to return eight measurements within 24 hours, and only returns five measurements, then the prism succession rate equals five divided by eight, which is 62.5%. There are instances when a

prism is no longer manageable due to no access or mining activities. When such instances arise, the affected monitoring prisms are permanently taken out of the monitoring cycle in the Leica GeoMoS software, and notification thereof made to the relevant stakeholders, for example the geotechnical engineer.

4.3.4 Data Integrity Checks

The data integrity checks play an important role in quality control of the Leica GeoMoS data. The mine surveyor performs data checks on a weekly basis so that the data can be used with high confidence by the geotechnical engineer. The method for data check evaluates precision of the distance measurements on reference beacons. The precision of the data is controlled by the repeatability of the distance measurements as shown in figure 4.2. When repeatability of the measured distances is acceptable, the graphical plot of the slope distances to reference stations will show a normal graph, however, if this trend is not achieved, then further assessment of the measurements will be required.

4.3.5 Data Security

Data security of the Leica GeoMoS system at Orapa Mine is controlled by limited user access to the server database. Only an authorised team of mine surveyors, geotechnical engineers and IT specialists are able to access the Leica GeoMoS server. Access to the server is performed using a username and password which is known by the authorised personnel only. The IT analyst is able to track the logged user in the server at any time. This is a suitable control for the database usage. Backup of the monitoring data is done on a different server and stored in external back-up devices which are managed by the IT department. A monitoring data retrieval exercise is carried out bi-annually to ensure that all archived slope monitoring data can be retrieved timeously and without any issues.

4.4 Model for Atmospheric Corrections

One of the major challenges faced by open pit mines with prism monitoring is the impact of atmospheric conditions on distance measurements. Jooste and Cawood (2010) emphasised this point by stating that atmospheric corrections on total station distances are problematic when measuring over large distances across voids where the temperature variations along the line of measurement vary significantly.

These variations cause spikes in monitoring graphs and errors in elevation. The vertical angles are the least accurate measurements because they are affected by refraction. This impact can be worsened by not setting up the meteorological sensors at the monitoring stations. Mphathiwa (2012) also emphasised that “correction for atmospheric conditions remain a challenge for Jwaneng Mine when using prism monitoring because the EDM ray that travels from the transfer beacon to the end of the pit and back again travels through varying atmospheric conditions”.

4.5 Impact of Atmospheric Conditions on Monitoring Data

The density of the atmosphere between the transfer beacon, the reference beacon and the monitoring point can affect the velocity of the signal emitted by the EDM. If the atmospheric conditions are not compensated for, then the accuracy of a measured distance can be adversely affected as the atmospheric conditions change (Thomas, 2011). When atmospheric corrections are not applied to measured slope distances, this result in the computation of co-ordinates that are incorrectly calculated which subsequently results in incorrect graphical representation.

Figure 4.7 shows the impact of not applying the atmospheric corrections to slope distance measurements. The graph has a normal trend and then reaches a point where the amplitude rises as a result of a meteorological sensor that has stopped functioning. Once the meteorological sensor is

back online, the graph shows a normal trend again.

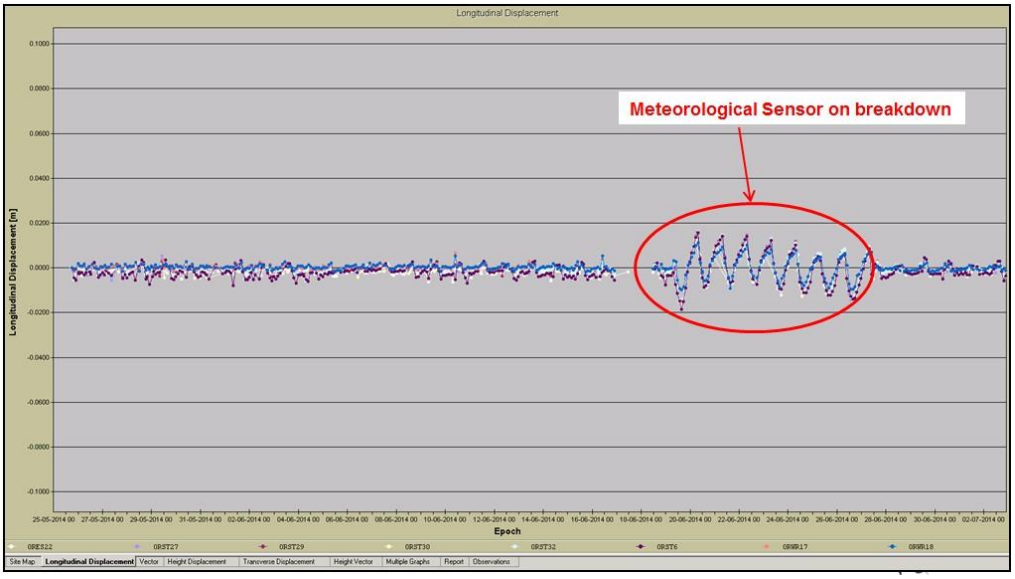


Figure 4.7: Impact of atmospheric conditions. Source: Orapa Survey Department.

Figure 4.7 shows that the application of atmospheric condition parameters to distance measurements does have an effect on the final computed co-ordinates. This process of applying atmospheric corrections minimises rapid fluctuations in the monitoring data which is caused by changing atmospheric conditions. It is therefore important that the recording of ambient temperature and atmospheric pressure measurements is done at the instrument location and not at a location away from the slope monitoring area, for example at the survey office. The impact of atmospheric conditions to the prism monitoring data may result in systematic errors and must be mitigated for an effective prism monitoring system.

4.6 Monitoring Data Trends

The prism monitoring data is used for slope stability analysis, as such its trend is important to understand. The trend basically looks for changes in displacement parameters over a period of time. In the Leica GeoMoS system, the visual method to identify a trend is through the graphical interpretation of data. An appropriate trend of data will show a regular

distribution in a graph and will show repeatable measurement figures, for example slope distances and angular measurements. It is important to understand the type of surface being measured, the threshold limits, and the statistical requirements of the monitoring data. The monitoring data must therefore be reviewed for a normal trend, graphical changes from the normal and outliers.

At Orapa Mine, the geotechnical engineer compares the relationship between the progressive data with the baseline data at suitable time periods and determines a trend line. During deformation monitoring, it is impossible to account for all the reasons causing perceived deformation, however the following key indicators can influence the data trends:

- Time of monitoring ;
- Period for displaying monitoring data ;
- Seasonal monitoring data ;
- Equipment replacement ;
- Mining activities.

4.6.1 Time of Monitoring

The times at which distance measurements are taken can have an influence on prism measurements. Expectation is that when the EDM signal travels through a stable atmospheric environment, the accuracy of the distance measurement will have minimal variance compared to when the signal travels through varying atmospheric conditions. At Orapa Mine, the ambient temperature and atmospheric pressure varies significantly during the day, especially during the summer season. Cawood *et al* (2006) states that a perceived solution to overcome the problem of measuring through unstable atmospheric conditions is to take measurements at night when the variation in temperature is reduced. However, this does not solve the problem since monitoring is required for a 24 hour period, the maximum displacement of monitoring data for Orapa Mine ranges from 0.000m to 0.003m during the night, whereas during the day, the maximum

displacements can reach up to 0.010m.

4.6.2 Period for Displaying Monitoring Data

The time period for which data is presented does have an impact on the graphical interpretation of the movement data trend. From the graphical interpretation of slope monitoring data, it is normally observed that a ten days period constraint will show a relatively near straight line graph, whereas any period more than a thirty days period constraint will show significant variance in displacement. This is because on a short time period, for example one day, there is less monitoring data, whereas over a one month period, there is more monitoring data shown in figure 4.8.

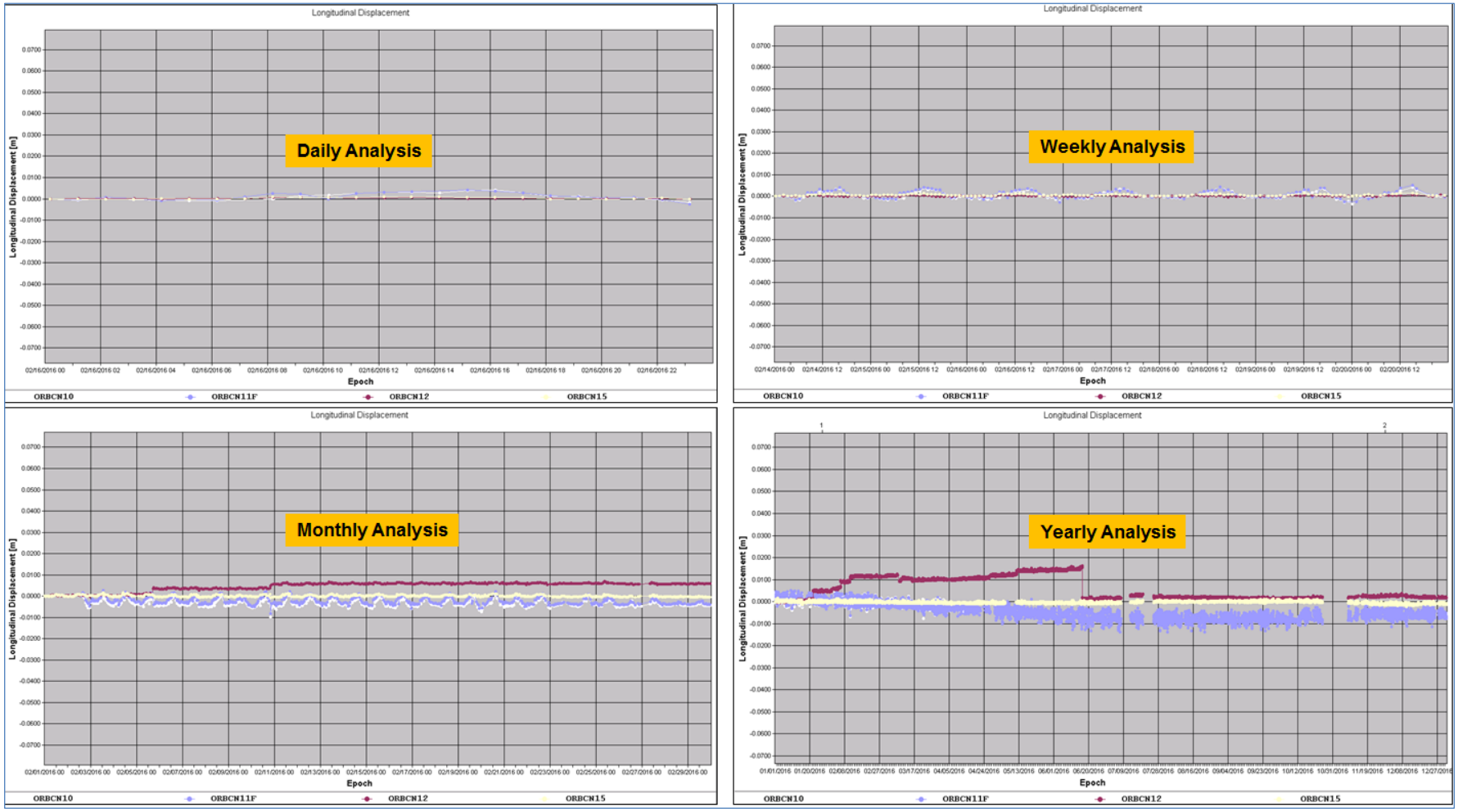


Figure 4.8: Displacement graph per time period. Source: Orapa Survey Department.

Data for a short period of time (daily and weekly) does not show any significant change in amplitude, whereas the long term period data shows some visible displacement as well as noise and spikes which may be caused by inaccurate distance measurements. This trend is continuously observed for the Leica GeoMoS measurements for Orapa Mine over time.

4.6.3 Seasonal Monitoring Data

Measurements of monitoring prisms at Orapa Mine takes place throughout the year with the months of September to April being normally very hot where temperatures can reach up to 45°C. From May to August, the temperatures can reach up to a maximum 27°C. Orapa is located in the northern region of the country, which is mostly affected by heat from September to April. There is currently no clear correlation of seasonal changes to the prism monitoring data trends. Some prisms show more noise in summer than winter, whereas it's vice versa for other prisms, this is as illustrated in figure 4.9

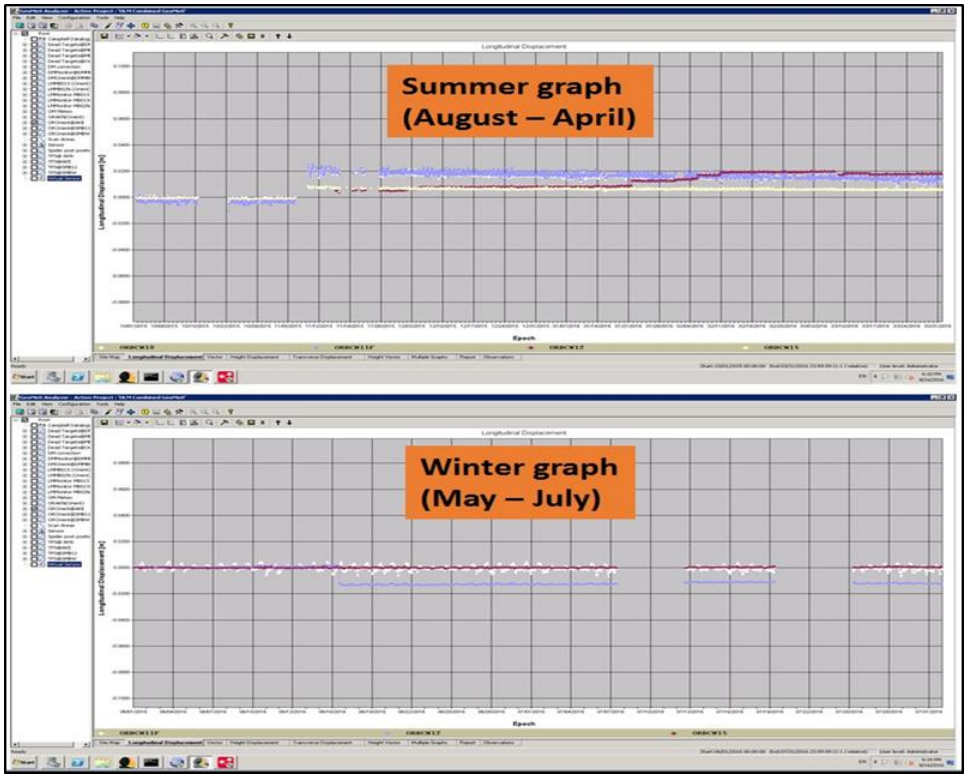


Figure 4.9: Displacement graph per season. Source: Orapa Survey Department.

The two graphs show a relatively similar trend, indicating that seasonal changes have no significant change in the prism monitoring data at Orapa Mine.

4.6.4 Equipment Replacement

The prism monitoring instrumentation servicing and calibration process requires that the monitoring instrument is replaced with a spare and it is evident from experience that whenever a different instrument is installed on a monitoring station, a shift in data of up to 0.015m is observed. Once the shift has been observed, the graph normalises again. This process affects the trend on the analysis graphs over the years of prism monitoring; an illustration of this change is shown in figure 4.10.

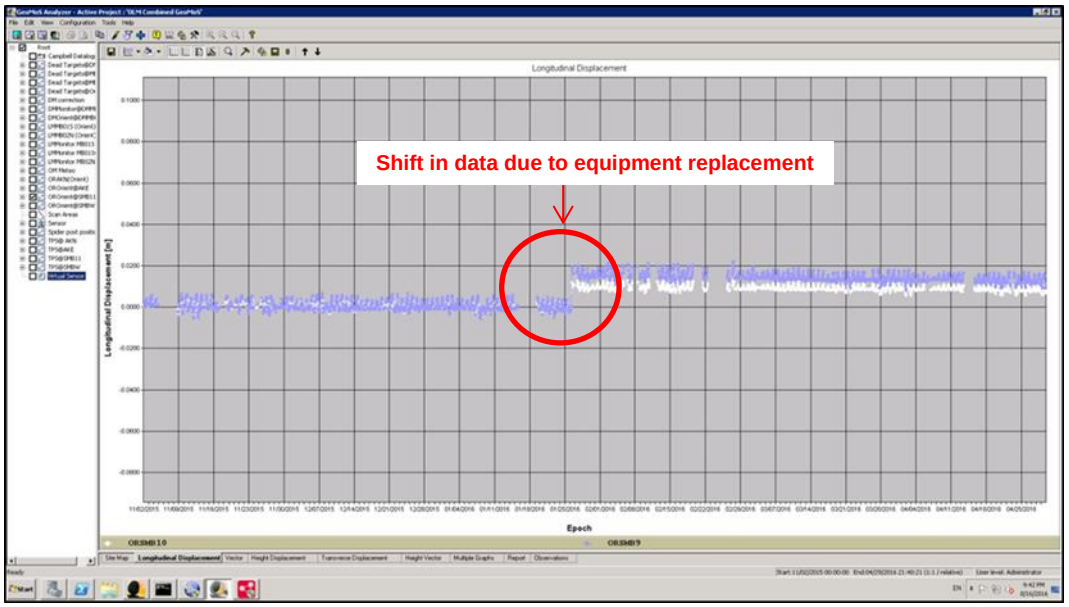


Figure 4.10: Impact of monitoring instrument replacement. Source: Orapa Survey Department.

The graph in figure 4.10 shows that the monitoring instrument at the Orapa West Station which was replaced with a spare instrument and this resulted in a measurement data shift. According to the manufacturers of the Leica survey instruments, the shift in data is caused by an instruments different calibration settings.

4.6.5 Mining Activities

Maintenance of haul roads in the open pit may have an impact on pole mounted prisms and these prisms are usually installed on the pit crests. If earthmoving equipment pushes the berm material at the pit crest, this may result in movement of the prism, and a shift in the prism monitoring measurements will be realised. This is not a frequent problem at Orapa Mine, but it happens on rare instances and this is as illustrated in figure 4.11.



Figure 4.11: Impact of a prism moved by earthmoving equipment. Source: Orapa Survey Department.

The Leica GeoMoS software can assign a total station a measurement search window of 0.2m on all prisms as shown in figure 4.12

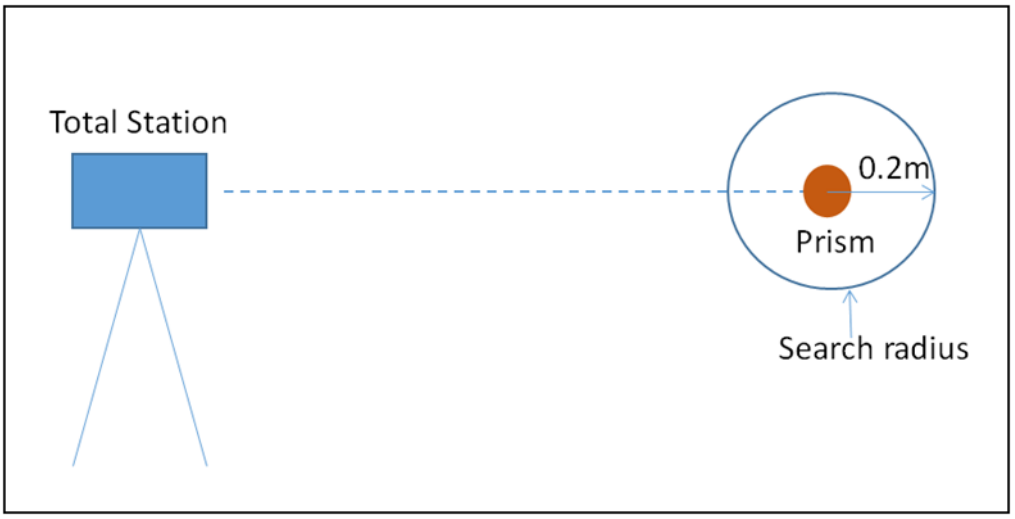


Figure 4.12. Illustration of the prism search window radius.

If a prism moves by a distance of up to 0.2m, it can still be measured as long as the prism is in line of sight with the monitoring instrument. While this measurement takes place, it may affect the normal data trend over time.

Geotechnical analysis for the Leica GeoMoS data at Orapa Mine shows that the most significant long term deformations detected by the Leica GeoMoS Monitoring system continues to come from prisms mounted on the east sandstone slope faces of the pit. Displacements of up to 70mm/year are noticed in the sandstone area.

4.7 Conclusion

The data management and analysis for Orapa Mine has been discussed and it is evident that the fundamental requirements for the monitoring data are well managed. Measures are in place to ensure defensibility of the prism monitoring system at OLDM. The impact of atmospheric corrections to distance measurements is evident, however there are controls in place to minimise the effect thereof. The long term slope monitoring analysis shows some deformation in weaker rocks such as the sandstones, however other hard rocks such as basalt shows some relative stability over the last eight years. The analysis trend graphs are affected by replacement of monitoring instruments, mining activities, the time of monitoring as well

as the period of data displayed.

Constant slope monitoring work at Orapa Mine continues to be done so that potential slope failures are proactively managed and their impacts on the safety and production objectives of Debswana are eliminated or mitigated. The survey and geotechnical engineering teams at Orapa Mine ensures that the mine is well prepared to manage slope failure risk by providing consistent monitoring data, ensuring optimised availability and utilisation of slope monitoring resource, technical training and continuous research on the latest slope management methods.

In chapter 5, the author investigates the factors which have potential to influence atmospheric corrections to prism monitoring measurements such as: distance, meteorological sensor positions, monitoring times and mining activities. An alternative method of adjusting slope distances is evaluated through a trial work.

5 EVALUATION OF ATMOSPHERIC CORRECTIONS TO PRISM MONITORING MEASUREMENTS

The purpose of this chapter is to evaluate factors which have the potential to influence atmospheric corrections on prism monitoring measurements. These factors include amongst others; meteorological sensor positions, monitoring times, monitoring equipment protection, mining activities and slope distance measurements between instrument and prism. Results using the ppm methods to adjust distance measurements will be discussed. However emphasis will be to investigate a different method of using the GNSS reference scale factor for correcting the total station distances. Results from this investigation maybe used to answer the fundamental question of this research; “How to apply atmospheric corrections on measurements taken over varying atmospheric densities across an open pit?”

5.1 Prism Monitoring Displacement Graphs

The application of prism monitoring for slope stability analysis and prediction depends on the assumption that measurements and observations will provide early warnings of instability. This can be achieved through observation and analysis of various prism monitoring displacement graphs. The following are the various graphs used in Leica GeoMoS Analyzer for slope stability analysis:

- Longitudinal displacement graph;
- Vertical displacement graph;
- Transverse displacement graph;
- Multiple graphs allowing for selective graph attributes;
- 3D vector movement graph.

The longitudinal displacement graph displays the resultant movement based on slope distance measurements; it can be classified as either movement away or towards the transfer beacon. The vertical displacement graph displays the resultant movement in the slope distance and vertical angle components of the prism. The transverse displacement graph shows displacement in which the direction of movement is not in line with the transfer beacon. The 3D displacement graph shows the movement in x, y, and z and the resultant direction of movement.

The 3D vector movement graphs are critical and are preferred in slope stability analysis since they represent the magnitude and direction of movement and are easy to interpret. The Leica GeoMoS Analyzer software is capable of plotting two different entities through multiple graphs, for instance, a displacement trend can be assessed in comparison with varying ppm values (temperature changes) as illustrated in figure 5.1

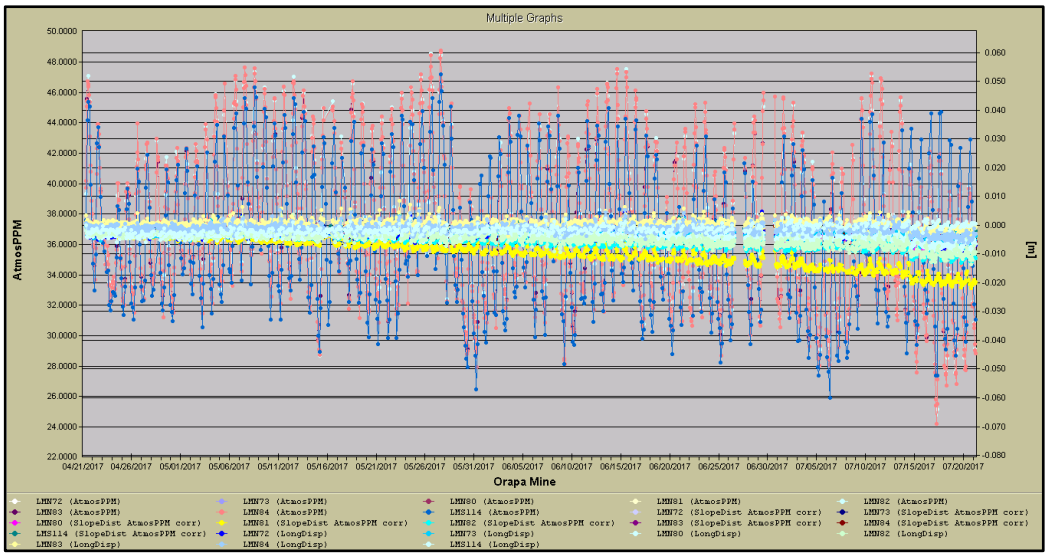


Figure 5.1: Multiple graph showing varying ppm values on distance measurements. Source: Orapa Survey Department.

“Since various instruments are 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 adjusted to the same level and standard of interpretation” (Mphathiwa, 2012). The integrated monitoring solution Geoscope by Soldata is used at Orapa Mine and uses Geographical Information Systems

(GIS) tools to integrate the various sources of slope monitoring data. Integration of the data allows for data from different monitoring systems to be interpreted, analysed and movement trend comparisons done within a short period of time on one platform.

There are different modes of deformation and failure which can exist within a slope and these can be interpreted through the displacement graphs. When mining takes place, there is a time of initial response as a result of elastic rebound or relaxation of stress. This initial response is most common in open pit mines having a rapid mining rate. The amount of such initial response could differ depending upon the type of rock mass.

In instances where movement of the slope has exceeded the elastic limit of the rock mass, the development of tension cracks would occur. In this instance, mining would just continue safely with the implementation of various deformation monitoring systems. When the rate of displacement exceeds the rate at which the slide material can be safely mined, then an operational slope failure would occur.

The displacement graphs can be used to classify between regressive and progressive time displacement curves. A regressive movement is one that shows short term deceleration displacement, whereas the progressive movement causes displacement at an increasing rate. These movement patterns associated with instability are as shown in figure 5.2.

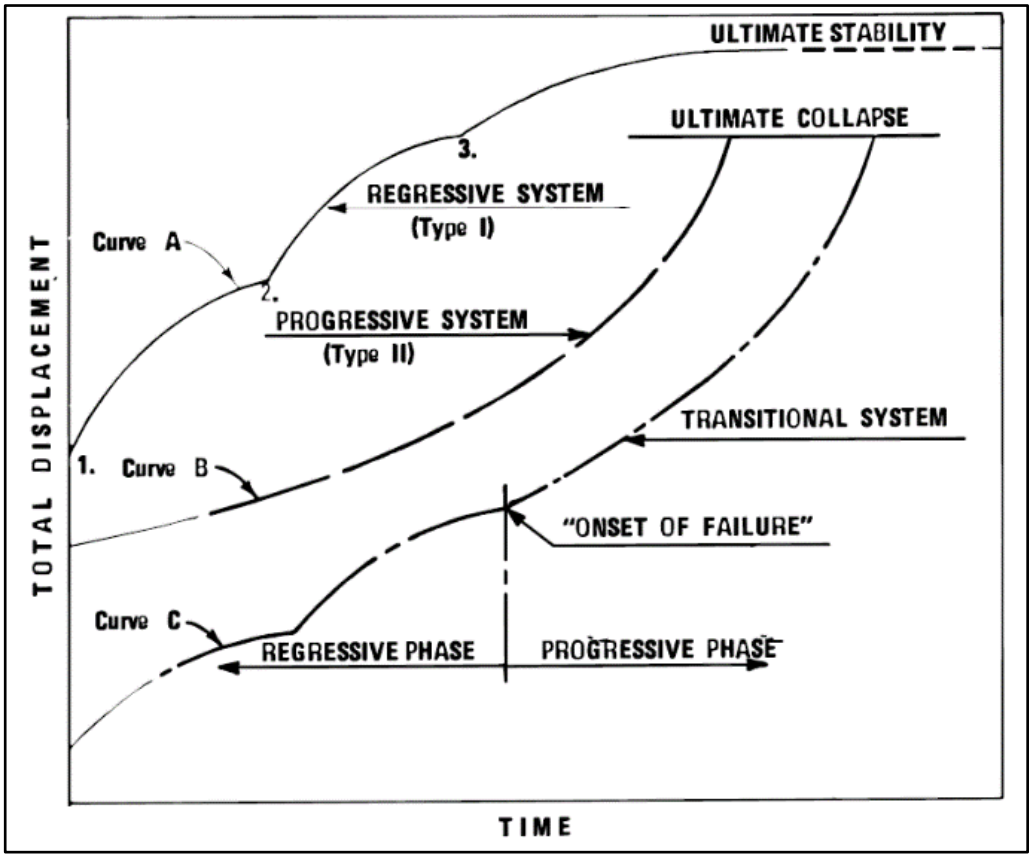


Figure 5.2: Typical regressive/progressive stage displacement curves. Source: Orapa Geotechnical Engineering Department.

The primary aim of data processing and presentation through displacement graphs is to provide timeous assessment of slope stability information so that instabilities that require urgent action can be detected. The secondary aim is to have a robust database of empirical data so that trends of slope movement can be determined over time. Interpretation of data from slope monitoring systems involves the assessment and prediction of the onset of changes in the rate of movement. This is generally reflected by acceleration, but where a slope is already moving, deceleration may also occur (Read and Stacey, 2008).

The data interpretation must take into consideration the accuracy of the specified monitoring system. For instance, the measurements taken perpendicular to the line of expected movement is preferential to oblique or transverse movement. The oblique or transverse measurements are likely to introduce distance measurement errors since the longitudinal

measurement using slope distance measurements are the most accurate. The challenge with perpendicular measurements is that multiple transfer beacons would be required around the open pit, and this can be expensive to the mine for the amount of beacons and instrumentation required.

5.2 The Impact of Atmospheric Conditions to Distance Measurements

In deformation monitoring, the electromagnetic distance measurement (EDM) is used to measure slope distances to monitoring prisms. An instrument with an EDM is known as a total station. The EDM units operate on the principle of transmitting electromagnetic waves from an instrument to a rectro-reflector, which instantly returns the waves to the transmitting instrument, that is the total station. The instrument measures the time taken for the wave to travel this double path. The distance between the instrument and the prism is obtained using the formula:

$$D = \frac{V \times t}{2}$$

Where:

D = distance from the instrument to the prism and back to the instrument;

V = velocity of light;

t = total time taken by the EDM wave.

Measurement of the distance can be affected by various factors including the atmospheric conditions, that is, ambient temperature and atmospheric pressure. In an open pit environment, the EDM signal travels through various atmospheric conditions and errors are introduced to the measured distance. As mentioned previously, one side of the open pit can be in full sunlight, while the other side of the pit can be in shade, therefore resulting in two different temperature conditions.

Any form of deflection of the EDM wave due to rapid change in atmospheric conditions in the open pit can increase the distance measurement by making the path longer. Ambient temperature and atmospheric pressure affects the density of the air thus affecting the speed of the EDM wave. The wave would normally follow a distorted path when it moves from air and then through glass resulting in refraction. Refraction is a constant, therefore as long as it remains in the distance measurements, the error will be constant. Once refraction occurs, the total station measurements can be affected. The effect of ambient temperature and atmospheric pressure on slope distance measurements when atmospheric corrections are not applied is shown in figure 5.3.

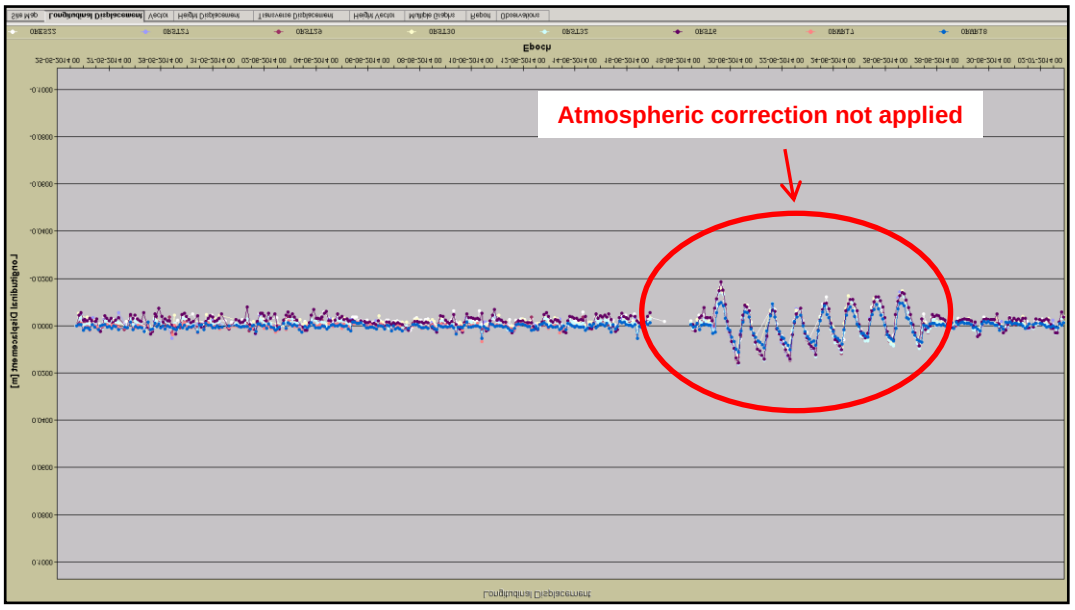


Figure 5.3: Impact of atmospheric conditions to distance measurements. Source: Orapa Survey Department.

When atmospheric corrections are not applied, the longitudinal displacements are up to 0.050m, as shown in figure 5.3 where the meteorological sensor was not working for a given period. This impacts interpretation of the data and the graph shows that calculating and applying the appropriate atmospheric correction (parts per million) to a total station slope distance measurement is necessary for those distance measurements. The most accurate atmospheric pressure and ambient

temperature is obtained by using a meteorological sensor. The meteorological sensor must be placed where the actual slope distance measurements are taken, that is, at the transfer beacon.

The ambient temperature and atmospheric pressure must be measured often because of the continuously changing atmospheric conditions; this will allow for the appropriate parts per million (ppm) corrections to be applied to slope distance measurements. The ambient temperature and atmospheric pressure are used in combination to give a correction factor which is stated in ppm.

The position of the meteorological sensor must be carefully selected to avoid influence of external objects on the final readings of ambient temperature and atmospheric pressure. Best practice is to install the meteorological sensor in a Stevenson Screen in a free air zone and away from any objects which may influence meteorological measurements. For example, if the Stevenson Screen is in shade, then this will not reflect the true ambient temperature at the time of measurement. Figure 5.4 shows the changing atmospheric conditions over short time periods, indicating the need for regular ppm corrections to slope distance measurements.

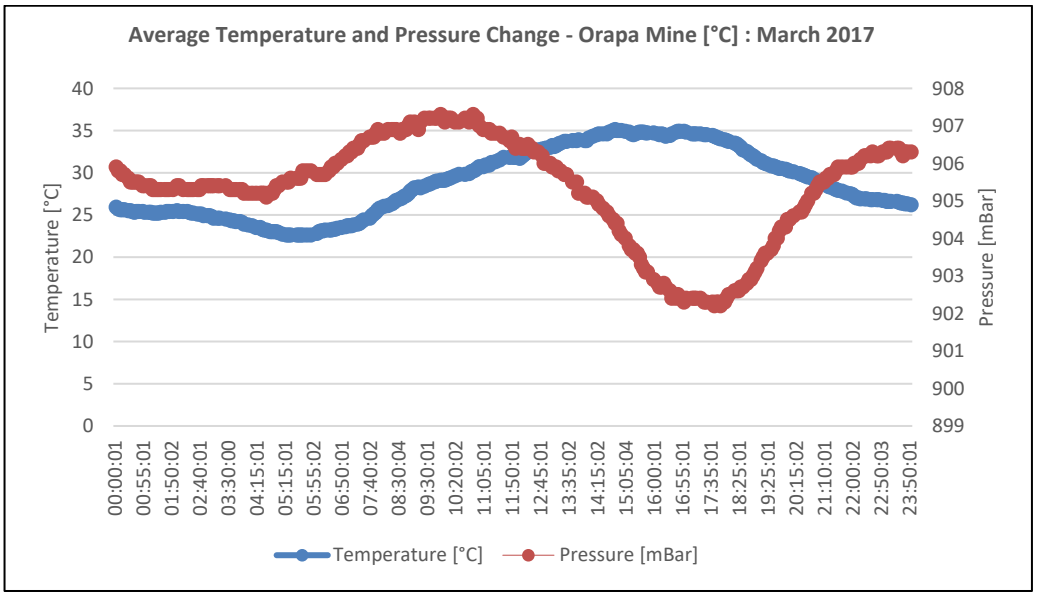


Figure 5.4: Ambient temperature and atmospheric pressure changes (March 2017). Source: Orapa Survey Department.

The ambient temperature and atmospheric pressure are measured every five minutes at Orapa Mine. The readings in figure 5.4 shows that atmospheric conditions change in very short periods in the open pit. These conditions may change more rapidly in the open pit due to mining activities. The impact of atmospheric conditions to distance measurements still remains one of the biggest challenges in prism monitoring. Atmospheric corrections on total station measured distances are a challenge when measuring over a long range in an open pit environment. The impact affects the final slope monitoring data as it can result in spikes and errors in the displacement graphs.

As stated, the impact of atmospheric conditions is mitigated by measuring ambient temperature and atmospheric pressure at the transfer beacon. This may not be sufficient since at the monitoring prism, the atmospheric conditions may be different to those at the transfer beacon and are not measured and accounted for. When calculation of final co-ordinates is done using incorrect distances, then the slope monitoring data cannot be acceptable for slope stability analysis. The effect of changing atmospheric conditions must therefore be considered when applying atmospheric corrections to prism monitoring measurements.

5.3 The Impact of Meteorological Sensor Position to Distance Measurement

As previously discussed, the distance measurements from the total station must be corrected for atmospheric conditions. To obtain a true correction, the temperature and pressure along the EDM path must also be known. The current challenge in open pit mines is that it is difficult to measure the ambient temperature and atmospheric pressure along the entire EDM path. The ambient temperature and atmospheric pressure can only be best measured closest to where the measurements take pace, that is at the transfer beacon. This position becomes unsuitable if prisms being measured are at long distances from the transfer beacon since the atmospheric conditions can vary over short distances.

For smaller pits, this may be a suitable position to place the meteorological sensor, however for larger open pits such as Orapa, prisms can be as far as 1500m from the transfer beacon, and this affects the slope distances measured over this long range. When Leica GeoMoS system was first implemented at Orapa Mine, the meteorological sensor was placed under the office roof as shown in figure 5.5.



Figure 5.5: Old position of the meteorological sensor at the mine survey office. Source: Orapa Survey Department.

The ambient temperature and atmospheric pressure readings recorded at the office were used to correct distances which were measured at the open pit, 800m away. The longitudinal displacement graphs were found to contain spikes and there were significant fluctuations in the longitudinal and vertical movements as shown in figure 5.6. This shows that the noise in data could possibly be caused by incorrect ppm corrections which were applied to the measured slope distances taken at the open pit.

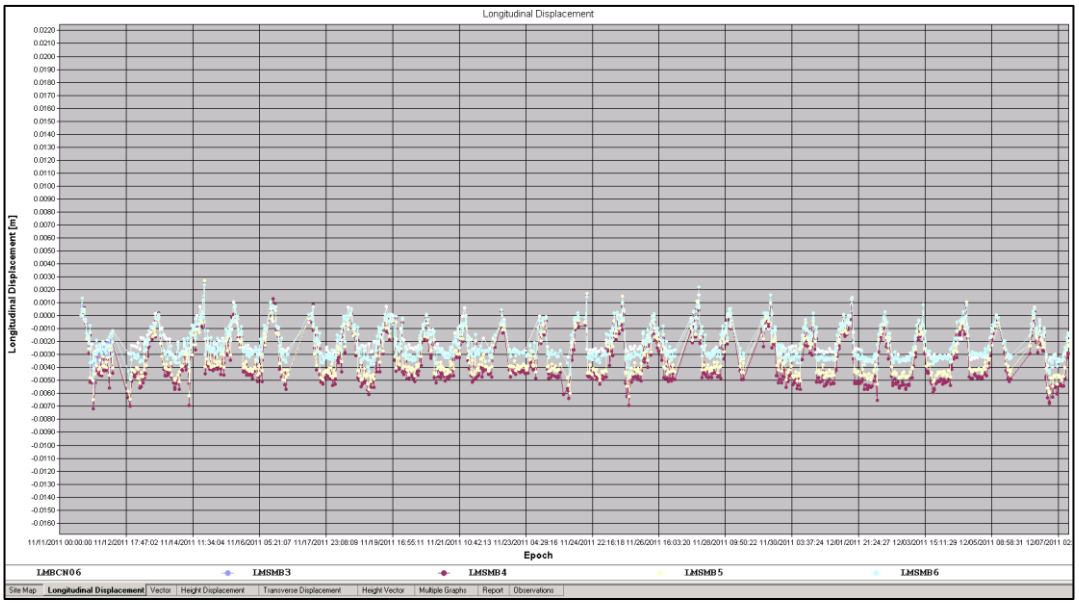


Figure 5.6: Noise in data due to position of meteorological sensor. Source: Orapa Survey Department.

The graph in figure 5.6 is not suitable for slope stability analysis and interpretation because false alarms can be caused by the slope monitoring system resulting in incorrect decisions being taken. This shows that the position of the meteorological sensor must be suitably placed to avoid misinterpretation of data, that is, at the transfer beacon.

In 2012, there was an upgrade of the prism monitoring systems at Orapa Mines in terms of equipment infrastructure, software upgrades, beacon construction, meteorological sensor relocation and dedicated team of mine surveyors. The relocation of the meteorological sensors from the office to the transfer beacon improved the prism monitoring data at Orapa Mine as shown in figure 5.7. The noise in the data became minimal, there are no outliers observed and the data has been certified acceptable for slope stability analysis by the Geotechnical Review Board auditors (Thomas, 2017).

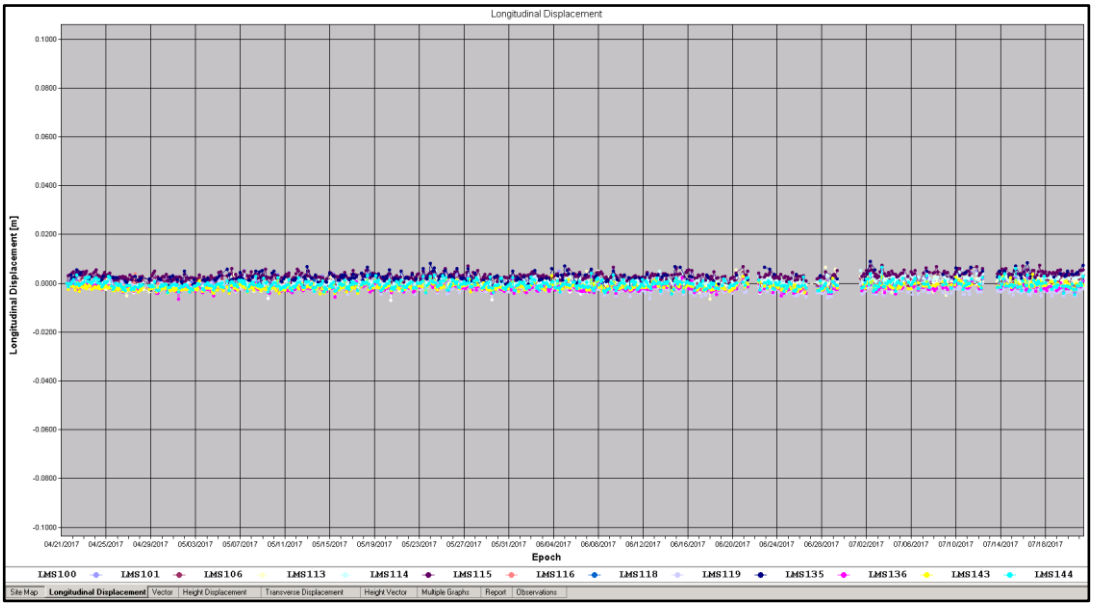


Figure 5.7: Displacement graph with meteorological sensor at the transfer beacon. Source: Orapa Survey Department.

When the meteorological sensor is placed at the transfer beacon, it is observed that measurements which are not taken across the pit show a very normal graph as compared to the measurements which are taken across the open pit, this is shown in figure 5.8.

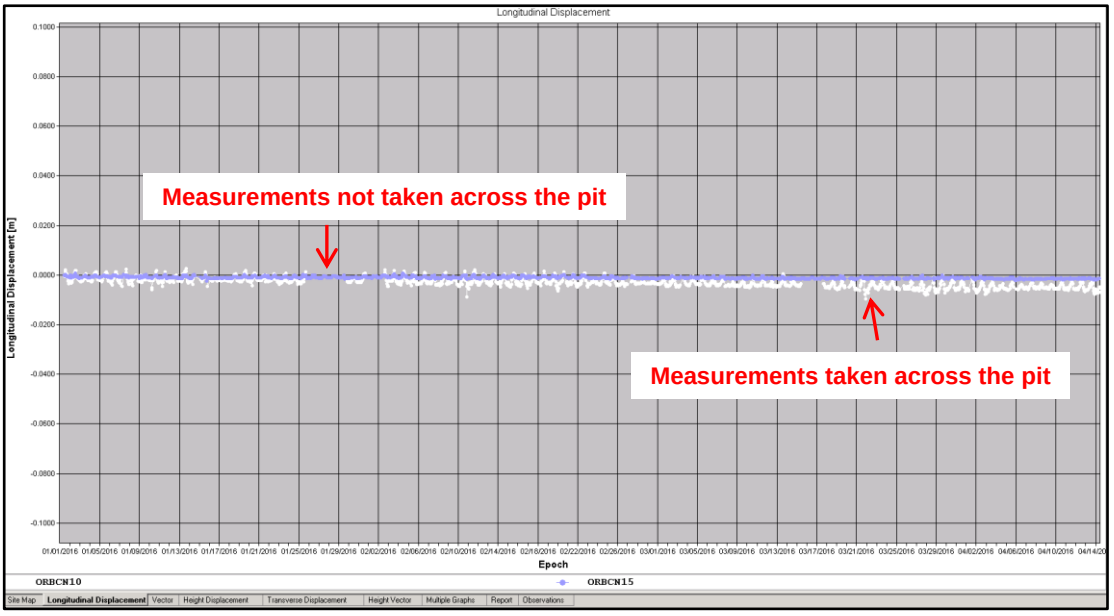


Figure 5.8: Comparison of prism data across and on the surface of the pit. Source: Orapa Survey Department.

In figure 5.8, BCN10 is a reference beacon which is measured by the Leica GeoMoS transfer beacon which is on the eastern side of the pit. The EDM signal travels a distance exceeding 1300m across the open pit to measure the prism point, while BCN15 is a reference station, measured by the same transfer beacon. However this reference station is closer to the transfer beacon, at a distance of 455m and is on the open pit edge.

The impact of atmospheric corrections to slope distance measurements becomes more significant when measuring over long range distances across an open pit. However for short range measurements minimal distance displacements of up to 0.005m can be achieved. The position of the meteorological sensor and the distance to the monitoring prism are therefore critical factors to consider when applying atmospheric corrections to prism monitoring measurements.

5.4 The Impact of Monitoring Times to Distance Measurements

The accuracy of distance measurements is affected by atmospheric conditions as discussed. To ensure safety of mining personnel and equipment at the mines, prism monitoring is required 24 hours a day. As the sun rise, the ambient temperature can change rapidly. As the sun reach its zenith, the ambient temperature changes less rapidly. Cloud cover also changes the ambient temperature rapidly as it shields the sun, however during the same period the atmospheric pressure does not vary significantly.

Figure 5.4 shows the variance in ambient temperature and atmospheric pressure on a summer day at Orapa Mine. During the early mornings, ambient temperature increase by about 2℃, and thereafter the change accelerates going into mid-day to the afternoon. It is accepted that:

1℃ change in temperature = 1ppm

Where 1ppm = 1mm per kilometre

For the distance measurements taken between 08h00 and 12h30, the ambient temperature variation of 5℃ was observed at Orapa Mine. Across

a distance of approximately 1000m this would equate to an error of ±5mm if the atmospheric correction to ambient temperature and atmospheric pressure is not measured and applied to the measured distances. The measurement error maybe misinterpreted as ground movement and this scenario shows the impact of changing ambient temperature and atmospheric pressure on slope distance measurements. The slope distance corrections must be computed with the correct values of the ambient temperature and atmospheric pressure readings. The measurements must be updated more frequently, for example, every one to five minutes, to ensure that the correct representative atmospheric correction is applied to the measured distances (Thomas, 2011).

It was observed from the prism monitoring system at Orapa Mine that ambient temperature variation is lower at night than during the day, this is shown in figure 5.4. On a normal summer day, the variance in temperature from 00h00 until 06h00 and 20h45 until 23h55 is minimal at 2.9℃ and 3.2℃ respectively. Prism monitoring is therefore preferably carried out during the night when variances in ambient temperature and atmospheric pressure are minimal. It is however not practical for open pit mines to monitor at night only, since slope monitoring is a safety critical system, and it must be done during day and night, throughout the year.

During the rainy season, the ambient temperature and atmospheric pressure can suddenly change and this rapid change in weather condition affects the accuracy of distance measurements in a prism monitoring setup. Though at sunset (18h00 – 18h30) and sunrise (06h00 – 06h30), temperature may change rapidly, as such the 5 minute interval of ambient temperature and atmospheric pressure measurements at Orapa Mine might not be adequate to give true corrections to measured distances. The impact of varying atmospheric conditions will always affect the prism monitoring results regardless of the monitoring times. However, prism monitoring using Leica GeoMoS can be configured such that fewer readings are measured during times of rapid atmospheric changes, and an increased frequency of

readings measured when atmospheric conditions are relatively stable. The time of monitoring in a prism monitoring setup is therefore a critical factor to consider when applying atmospheric corrections to prism monitoring measurements.

5.5 Protection of Monitoring Equipment

The prism monitoring setup comprises of a reference beacon, total station, telemetry system, meteorological sensor, cabling and a power source. It is important that monitoring instrumentation is protected from extreme weather and the effects associated with mining activities. Thomas (2011) emphasises that permanent shade canopies must be erected over beacons utilised for slope stability monitoring surveys to mitigate the error caused by the effect of the heat of the sun on the survey instruments and pillar beacons, alternatively beacon shelter housings should be constructed. Mphathiwa (2012) also states that when designing the instrument shelter, there is a requirement to balance the need to protect the instrument without compromising the accuracy of monitoring instruments.

The electromagnetic wave that travels from the total station through the glass screens of the shelter may be distorted by the type of glass used. This distortion will may result in incorrect measurements due to refraction. At Orapa Mine, fully enclosed shelters are used to protect the transfer beacons. Blast protection housing made of Mentis grating is used around to the shelter to protect the shelter from fly rock. Figure 5.9 shows a shelter used to protect transfer beacons at Orapa Mine.



Figure 5.9: Shelter for transfer beacon. Source: Orapa Survey Department.

The shelter is made of anodised aluminum profiles, bonded with polyurethane adhesive and riveted to white 40mm Cromadeck and has glass screens which allows the total station to measure to monitoring prisms in the open pit and to the reference beacons on the pit surface. The glass in the shelter is of 3mm thickness and does not to affect the accuracy of the measurements. Figure 5.10 shows normal displacement of measurements taken through glass from January 2017 until August 2017 at Orapa Mine.

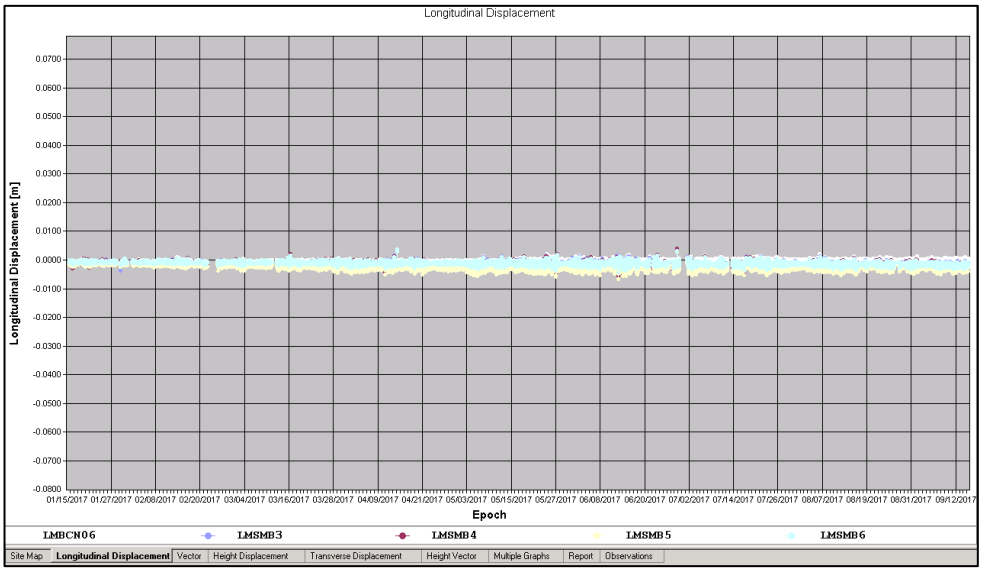


Figure 5.10: Displacement graph from measurements taken through glass. Source: Orapa Survey Department.

The graph in figure 5.10 shows good repeatability of data, with measurements taken through glass. Afeni (2011) observed that glass with a thickness of 3mm or less does not affect the accuracy of monitoring results. The shelters are also equipped with air conditioning, which maintains a constant temperature in the shelter during the hot seasons. This also helps to mitigate the diurnal effect in cases of direct sunlight on the transfer beacon.

Dust is a common problem in open pit mines, and with the implementation of protection shelters, minimal dust is allowed to accumulate on the monitoring instrumentation. Periodic cleaning of transfer beacons also mitigates the effect of dust on the monitoring equipment. Protection of monitoring equipment minimises the impact of extreme weather changes to the measurement of distances in a prism monitoring setup. The meteorological sensor will always be affected by dust since it is installed outside the protection shelter in the Stevenson Screen.

5.6 The Impact of Mining Activities to Distance Measurements

Open pit mining comprises of drilling and blasting and the excavation of the ore and waste deposits extending very deep in the ground. The process of mining involves using specialised earthmoving equipment and machinery such as trucks, loaders, dozers and drill rigs. Haulage trucks transports the ore and waste outside of the open pit using haul roads. Figure 5.11 shows a shovel loading a truck at one of the production areas at Orapa Mine.



Figure 5.11: Shovel loading a truck at Orapa Mine. Source: Orapa Mining Department.

The earthmoving equipment emits fumes, generates heat and also causes dust to become airborne. This means that there is a general increase in temperature within the open pit caused by these machines. The increase in temperature affects the EDM signal which travels across the open pit to measure the slope distances to monitoring prisms. Loading of material from the pit and the drilling of blast pattern holes can occur closer to monitoring prisms, and vibration caused by earthmoving equipment can affect the stability of the monitoring prisms.

If the total station sends a signal to the prism whilst there is vibration, then errors can be introduced since the prism might not be in its original position at the time of measurement. False alarms may be raised by the monitoring system software, and this may result in incorrect alarming and response actions. Heavy earthmoving equipment such as dozers, affect transfer beacons along the haul roads due to the vibration of the ground.

When vibration has excessively affected the transfer beacon, an alert message ‘point blunder check failed’ is sent out to the mine surveyor by the Leica GeoMoS system. The impact of this is that the total station will not be level due to vibration and may measure incorrect distances to the monitoring

prisms. Normally, the total station will need to be re-levelled using the electronic bubble and a new orientation measured. When blasting takes place, there is possibility of fly rocks which may affect the transfer beacons. The survey department controls this effect by closing out the transfer beacons with the blast protection shutters deployed on the shelter before the blast. If the blast is less than 500m from the transfer beacon, the total station is removed off the transfer beacon to protect it from excessive vibration which can damage the instrument. The total station is only returned to the transfer beacon after the blast.

Excessive airborne dust in the open pit due to drilling, blasting, loading and hauling affects measurement to monitoring prisms in the pit. The airborne dust can render the prism almost invisible from the transfer beacon, and distance measurements to prisms can be affected. Also, dust can accumulate on the prisms, making distance measurements impossible. The Leica GeoMoS system sends out an alert message ‘point not found’ if there is excessive dust on the prism because no measurements could be made. The mine surveyor overcomes this problem by coordinating prism clean-up campaigns in the open pit on a weekly basis at Orapa Mine. The mining department mitigates the dust issue in the open pit by spraying water on haul roads on a regular basis and also applying coatings such as ‘Dust-a-side’ on haul roads to suppress the dust from becoming airborne.

Access to monitoring prisms in the open pit is important for maintenance purposes as they may be broken or become misaligned to the transfer beacons due to blasts and rock falls. Dust also becomes an issue in the open pit affecting the ability to measure distances to a prism (Jooste and Cawood 2006). As mentioned previously, maintenance of haul roads can impact pole mounted prisms.

These prisms are installed on the open pit crest along the haul roads, and as the dozer prepare the berm material this may result in movement of the prism, and an error in the distance measurement to the prism will be recorded. This affects the data for these prisms resulting in false alarms and incorrect response actions being taken. Earthmoving equipment in the open pit can partially or totally obstruct line of sight for the EDM signal from the total station at the transfer beacon to the monitoring prism. In such instances, distance measurement is affected since the total station will struggle and fail to measure the distance to the prism.

The impact of mining activities to total station distance measurements is evident, however, it is the responsibility of the mine surveyor to find ways of mitigating this problem since the slopes of the pits must be continuously monitored. The mining personnel also need periodic coaching or awareness sessions on the slope stability monitoring infrastructure and the importance of this safety critical system. The impact of mining activities is therefore a critical factor to consider when performing prism monitoring measurements.

5.7 Trial of Slope Distance Corrections Using GNSS Measurements

At Orapa Mine, the atmospheric correction of distance measurements to monitoring prisms is done by utilising a meteorological sensor. The meteorological sensor measures ambient temperature and atmospheric pressure at five minutes intervals. These readings are then used by the Leica GeoMoS software to calculate corrected slope distances to the monitoring prisms. Over time, the data has shown mostly normal graphs, but there have been instances where the displacement graphs have spikes and abnormal fluctuations.

It is therefore necessary to investigate another method to adjust total station measured distances. As Orapa open pit becomes wider and deeper, the current method of adjusting the slope distances is becoming inadequate. An alternative method uses GNSS measurements to calculate a reference scale factor from baselines with known distances. This reference scale factor is then applied to the total station measured distances. The Leica

GeoMoS and the GNSS system at Orapa Mine are not integrated, and the infrastructure at the transfer beacons does not allow a GNSS antenna to be installed on the reference beacon due to the blast protection shelters. The author carried out an independent practical trial to evaluate the results of the two methods of adjusting distance measurements.

The objective of the trial was to compare two methods of adjusting distance measurements, those being:

1. Applying ppm corrections from ambient temperature and atmospheric pressure to distance measurements;
2. Applying reference distance correction factors to GNSS baselines and distance measurements.

The site for this trial was Orapa Mine and the data collection began in February 2017 and ended in May 2017. The image in figure 5.12 illustrates the trial layout at Orapa Mine.

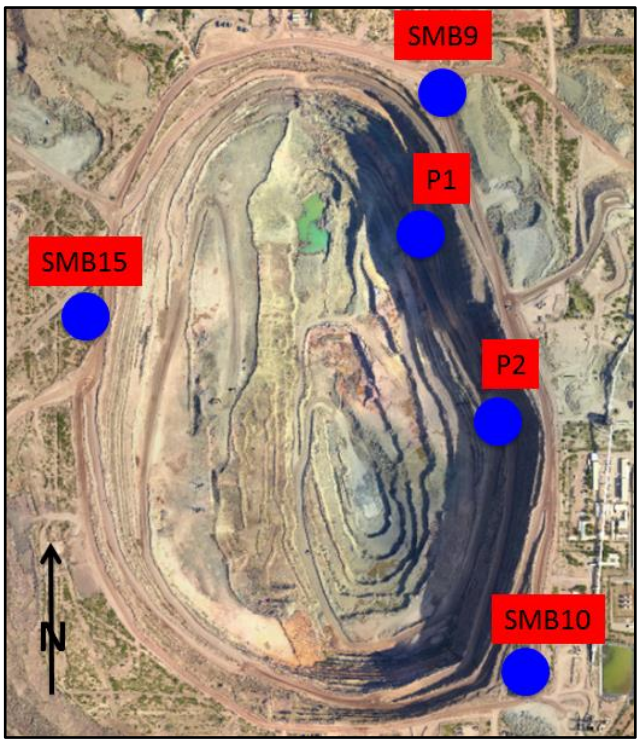


Figure 5.12: Trial Layout at Orapa Mine.

Three reference beacons were used for the measurements around Orapa open pit; two prisms in the open pit were also measured using a total station

only. All of the three beacons are located on the open pit edge and there is good line of sight between the beacons. The beacons have been suitably designed and constructed by a certified contractor. Results from the Leica GeoMoS system show that these three beacons are relatively stable, and as such were chosen for this trial. The beacons are also free from vegetation or obstructions which could result in multipath errors when carrying out GNSS measurements. Multipath occurs when a GNSS signal is reflected off an object, such as the side of a stockpile to the GNSS antenna resulting in position error. The two prisms inside the pit were wall mounted in areas which are least affected by mining activities such as blasting and drilling.

When the trial commenced, the two reference beacons SMB9 and SMB10 were installed with a Trimble R8 GNSS antenna and a prism using a suitable monitoring bracket manufactured by Leica. When measurements are carried out using this bracket, a constant of 0.118m is applied to ensure that the distances measured are to the centre of the reference beacon.

The base station, SMB15 was equipped with a Leica TCRP1203 total station and a Trimble 5800 GNSS receiver. The Leica TCRP1203 total station has an accuracy of 3 mm + 2 ppm. (Leica Geosystems, 2016). Distances on circle face left (I) and circle face right (II) were measured to the two reference beacons across the open pit as well as to the two prisms in the open pit. This was carried out simultaneously with GNSS measurements at SMB9, SMB10 and SMB15.

The GNSS measurements at the three beacons were carried out using the fast static survey method. The co-ordinates for the reference beacons were deduced through post processing using the Leica Geo Office software. Post processing performs adjustments of the raw data measurements using the least squares adjustment technique. Least squares adjustments show how well individual observations fit with other observations in a data set. This process handles errors and computes reasonable error estimates for each observation.

The total station was used to measure the distances only and co-ordinates for the reference beacons were deduced through post processing using the Leica Geo Office software. Ambient temperature and atmospheric pressure were recorded at the measuring station SMB15. Table 5.13 shows all equipment and software used for the trial.

Table 2: Equipment and software used for the trial.

Number	Equipment /Software Type	Purpose
1	Leica total station TCRP1203	Distance measurements to prisms
2	Trimble R8 GNSS Antenna	Fast static mode measurements
3	Trimble TC2 controller	Controls the S8 Antenna
4	Leica GPH1P prism	Distance measurements
5	Temperature and Pressure sensor	Atmospheric parameter readings
6	Leica bracket (Prism and GNSS holder)	GNSS and Prism holder
7	Leica bracket (EDM and GNSS holder)	GNSS holder on total station
8	Leica Geo Office	Data processing
9	Microsoft Excel	Data analysis and graphs

The GNSS distance is computed from the x, y, co-ordinates of beacons SMB15 and SBM10. The z component is omitted since the level of confidence is low when using GNSS for height measurements. The formula below is used to compute the distance from the co-ordinates:

$$D = \sqrt{(x - x')^2 + (y - y')^2}$$

Where D = distance between SMB15 and SMB10

x = easting co-ordinate of SMB15

x' = easting co-ordinate of SMB10

y = northing co-ordinate of SMB15

y' = northing co-ordinate of SMB10

The ppm values were derived from the atmospheric correction table in figure 5.13 and they ranged from 42ppm to 47ppm.

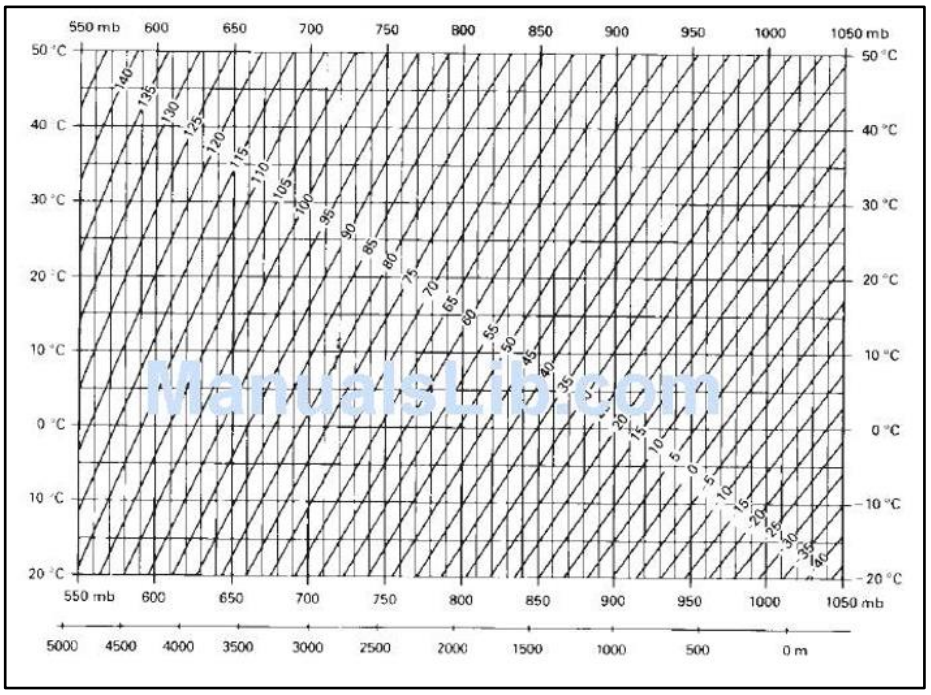


Figure 5.13: Atmospheric correction table. Source: Leica Geosystems.

The formula below was used to compute the corrected total station distances:

$$D_C = \left[\left(\frac{ppm}{1\times10^6}\right) D_m\right] + D_m$$

Where D_C = field corrected distance;

ppm = parts per million;

D_m = measured distance with zero ppm set in total station.

The accepted known (fixed) distances from SMB15 to SMB9 and SMB10 were computed from a three days GNSS measurement data as shown in table 3.

Table 3: Baseline distances derived from the GNSS co-ordinates.

Day	SMB15 – SMB9(m)	SMB15 – SMB10(m)
1	958.964	1448.487
2	958.964	1448.486
3	958.965	1448.489
Average	958.964	1448.487

The average baseline distance 1448.487m was used to compute the reference scale factor from subsequent total station distances measured from SMB15 to SMB10 in table 4. SMB10 has the longest baseline and was chosen for calculation of the reference factors using the formulae below:

$S_R = \frac{d}{d'}$

Where S_R= reference scale factor

d = originally known distance

d' = new distance computed from GNSS co-ordinates

The reference scale factors are as outlined in table 4

Table 4: Reference scale factor values.

Period	Known Distance SMB15 – SMB10 (m) d	Total station distance SMB15 – SMB10 (m) d'	Reference scale factor $R = \frac{d}{d'}$
.	1448.487	1448.515	0.999981015
2	1448.487	1448.515	0.999981189
3	1448.487	1448.515	0.999980670
4	1448.487	1448.516	0.999980499
5	1448.487	1448.520	0.999977563
6	1448.487	1448.510	0.999984641
7	1448.487	1448.510	0.999984467
8	1448.487	1448.510	0.999984641
9	1448.487	1448.514	0.999981360
10	1448.487	1448.516	0.999980154
11	1448.487	1448.518	0.999978944
12	1448.487	1448.519	0.999978428
13	1448.487	1448.513	0.999982396

The reference scale factor is the ratio between the known distance and the measured distance. This reference scale factor for each period was used to adjust the total station measured distances to SMB9, prism 1 and prism 2. This is as shown in tables 5 to 7. Measured distances can be affected by different errors, as such when applying the reference scale factor, the measured distance will be adjusted based on the known or correct measurements. The reference scale factor may not be used for a long period due to changing atmospheric conditions, as such prior to every distance adjustment, a new value for the reference factor must be computed.

Data from the GNSS system and the total station was compiled into one spreadsheet as shown in tables 5 to 7. The tables shows the trial period, station name, uncorrected distances in face left and face right, ambient temperature and atmospheric pressure readings, average uncorrected distances, corrected total station and GNSS distances and the displacement values.

As previously mentioned, analysis of this data is based on comparing results of the two methods of adjusting slope distance measurements. Comparison of the total station ppm and total station reference scale factor corrected distances is as shown in table 9. The same time GNSS baseline distances are also compared with the adjusted total station distances for SMB9 and SMB10 only.

Table 5: Summary of results for the total station and GNSS measurements for prism 1.

Period	Station Names	Uncorrected dist. Face 1 (m) *A*	Uncorrected dist. Face 2 (m) *B*	Temperature (°C)	Pressure (mBAR)	ppm value *P*	Average uncorrected distance (m) $C = \frac{A+B}{2}$	Reference scale factor(R/F) $R = \frac{d}{d'}$	Total station dist_ppm correction $D = \left[\left(\frac{P}{10^6}\right) \times C\right] + C$	Total station dist_reference scale factor correction(R/F) $D' = C \times R$	Displacement (ppm) (m) $D - C$	Displacement (R/F) (m) $D' - C$
Day 1	Prism 1	799.052	799.051	31.4	904.5	46	799.052	0.999981015	799.088	799.036	0.037	-0.015
Day 2	Prism 1	799.050	799.050	27.3	908.0	43	799.050	0.999981189	799.084	799.035	0.034	-0.015
Day 3	Prism 1	799.053	799.052	31.5	904.8	46	799.053	0.999980670	799.089	799.037	0.037	-0.015
Day 4	Prism 1	799.051	799.051	27.8	908.5	43	799.051	0.999980499	799.085	799.035	0.034	-0.016
Day 5	Prism 1	799.051	799.050	30.5	904.6	46	799.051	0.999977563	799.087	799.033	0.037	-0.018
Day 6	Prism 1	799.052	799.053	31.8	904.6	46	799.053	0.999984641	799.089	799.040	0.037	-0.012
Day 7	Prism 1	799.052	799.052	27.3	908.0	43	799.052	0.999984467	799.086	799.040	0.034	-0.012
Day 8	Prism 1	799.053	799.051	27.2	908.0	43	799.052	0.999984641	799.086	799.040	0.034	-0.012
Day 9	Prism 1	799.054	799.054	27.5	908.2	43	799.054	0.999981360	799.088	799.039	0.034	-0.015
Day 10	Prism 1	799.057	799.055	26.0	907.5	42	799.056	0.999980154	799.090	799.040	0.034	-0.016
Day 11	Prism 1	799.057	799.056	28.2	908.4	45	799.057	0.999978944	799.092	799.040	0.036	-0.017
Day 12	Prism 1	799.055	799.054	30.9	908.2	45	799.055	0.999978428	799.090	799.037	0.036	-0.017
Day 13	Prism 1	799.054	799.055	32.0	908.0	47	799.055	0.999982396	799.092	799.040	0.038	-0.014

Table 6: Summary of results for the total station and GNSS measurements for prism 2.

Period	Station Names	Uncorrected dist. Face 1 (m) A	Uncorrected dist. Face 2 (m) B	Temperature (°C)	Pressure (mBAR)	ppm value P	Average uncorrected distance (m) $C = \frac{A+B}{2}$	Reference scale factor(R/F) $R = \frac{d}{d'}$	Total station dist_ppm correction $D = \left[\left(\frac{P}{10^6}\right) \times C\right] + C$	Total station dist_reference scale factor correction(R/F) $D' = C \times R$	Displacement (ppm) (m) $D - C$	Displacement (R/F) (m) $D' - C$
Day 1	Prism 2	803.531	803.532	27.3	908.0	43	803.532	0.999981015	803.566	803.516	0.035	-0.015
Day 2	Prism 2	803.530	803.530	30.9	904.6	46	803.530	0.999981189	803.567	803.515	0.037	-0.015
Day 3	Prism 2	803.531	803.532	27.2	908.2	43	803.532	0.999980670	803.566	803.516	0.035	-0.016
Day 4	Prism 2	803.533	803.533	31.1	904.5	46	803.533	0.999980499	803.570	803.517	0.037	-0.016
Day 5	Prism 2	803.534	803.534	31.6	904.8	46	803.534	0.999977563	803.571	803.516	0.037	-0.018
Day 6	Prism 2	803.535	803.535	31.8	904.6	46	803.535	0.999984641	803.572	803.523	0.037	-0.012
Day 7	Prism 2	803.536	803.536	27.1	908.0	43	803.536	0.999984467	803.571	803.524	0.035	-0.012
Day 8	Prism 2	803.535	803.534	27.6	906.0	43	803.535	0.999984641	803.569	803.522	0.035	-0.012
Day 9	Prism 2	803.533	803.533	27.5	908.2	43	803.533	0.999981360	803.568	803.518	0.035	-0.015
Day 10	Prism 2	803.534	803.534	28.3	908.5	45	803.534	0.999980154	803.570	803.518	0.036	-0.016
Day 11	Prism 2	803.532	803.530	27.8	908.5	43	803.531	0.999978944	803.566	803.514	0.035	-0.017
Day 12	Prism 2	803.533	803.534	31.8	908.0	46	803.534	0.999978428	803.570	803.516	0.037	-0.017
Day 13	Prism 2	803.533	803.533	30.9	908.2	46	803.533	0.999982396	803.570	803.519	0.037	-0.014

Table 7: Summary of results for the total station and GNSS measurements for SMB9.

Period	Station Names	Uncorrected dist. Face 1 (m) A	Uncorrected dist. Face 2 (m) B	Temperature (°C)	Pressure (mBAR)	ppm value P	Average uncorrected distance (m) $C = \frac{A+B}{2}$	Reference scale factor(R/F) $R = \frac{d}{d'}$	Total station dist_ppm correction $D = \left[\left(\frac{P}{10^6}\right) \times C\right] + C$	Total station dist_reference scale factor correction(R/F) $D' = C \times R$	Displacement (ppm) (m) $D - C$	Displacement (R/F) (m) $D' - C$
Day 1	SMB9	958.935	958.935	31.5	904.7	46	958.935	0.999981015	958.979	958.917	0.044	-0.018
Day 2	SMB9	958.936	958.936	31.5	904.8	46	958.936	0.999981189	958.980	958.918	0.044	-0.018
Day 3	SMB9	958.936	958.936	32.0	904.8	46	958.936	0.999980670	958.980	958.917	0.044	-0.019
Day 4	SMB9	958.937	958.938	32.1	907.9	47	958.938	0.999980499	958.983	958.919	0.045	-0.019
Day 5	SMB9	958.938	958.938	30.6	908.2	45	958.938	0.999977563	958.981	958.916	0.043	-0.022
Day 6	SMB9	958.938	958.938	27.6	908.2	43	958.938	0.999984641	958.979	958.923	0.041	-0.015
Day 7	SMB9	958.938	958.938	27.3	908.0	43	958.938	0.999984467	958.979	958.923	0.041	-0.015
Day 8	SMB9	958.939	958.934	27.3	908.0	43	958.937	0.999984641	958.978	958.922	0.041	-0.015
Day 9	SMB9	958.939	958.939	27.2	908.0	43	958.939	0.999981360	958.980	958.921	0.041	-0.018
Day 10	SMB9	958.941	958.941	25.3	907.3	42	958.941	0.999980154	958.981	958.922	0.040	-0.019
Day 11	SMB9	958.941	958.940	27.3	908.2	43	958.941	0.999978944	958.982	958.920	0.041	-0.020
Day 12	SMB9	958.941	958.940	28.1	908.4	45	958.941	0.999978428	958.984	958.920	0.043	-0.021
Day 13	SMB9	958.942	958.941	30.5	904.6	46	958.942	0.999982396	958.986	958.925	0.044	-0.017

Table 8: Summary of results for the total station and GNSS measurements for SMB10.

Period	Station Names	Uncorrected dist. Face 1 (m) A	Uncorrected dist. Face 2 (m) B	Temperature (°C)	Pressure (mBAR)	ppm value P	Average uncorrected distance (m) $C = \frac{A+B}{2}$	Reference scale factor(R/F) $R = \frac{d}{d'}$	Total station dist_ppm correction $D = \left[\left(\frac{P}{10^6}\right) \times C\right] + C$	Total station dist_reference scale factor correction(R/F) $D' = C \times R$	Displacement (ppm) (m) $D - C$	Displacement (R/F) (m) $D' - C$
Day 1	SMB10	1448.515	1448.514	30.9	904.6	46	1448.515	0.999981015	1448.581	1448.487	0.067	-0.027
Day 2	SMB10	1448.515	1448.514	30.4	904.5	46	1448.515	0.999981189	1448.581	1448.487	0.067	-0.027
Day 3	SMB10	1448.515	1448.515	30.4	904.5	46	1448.515	0.999980670	1448.582	1448.487	0.067	-0.028
Day 4	SMB10	1448.517	1448.514	30.2	904.5	46	1448.516	0.999980499	1448.582	1448.487	0.067	-0.028
Day 5	SMB10	1448.520	1448.519	31.1	908.1	46	1448.520	0.999977563	1448.586	1448.487	0.067	-0.032
Day 6	SMB10	1448.510	1448.509	31.7	908.0	46	1448.510	0.999984641	1448.576	1448.487	0.067	-0.022
Day 7	SMB10	1448.510	1448.509	27.3	908.0	43	1448.510	0.999984467	1448.572	1448.487	0.062	-0.023
Day 8	SMB10	1448.510	1448.509	27.3	908.0	43	1448.510	0.999984641	1448.572	1448.487	0.062	-0.022
Day 9	SMB10	1448.513	1448.515	27.1	908.0	43	1448.514	0.999981360	1448.576	1448.487	0.062	-0.027
Day 10	SMB10	1448.516	1448.516	27.8	907.9	43	1448.516	0.999980154	1448.578	1448.487	0.062	-0.029
Day 11	SMB10	1448.518	1448.517	28.0	908.4	45	1448.518	0.999978944	1448.583	1448.487	0.065	-0.030
Day 12	SMB10	1448.518	1448.519	28.5	908.5	45	1448.519	0.999978428	1448.584	1448.487	0.065	-0.031
Day 13	SMB10	1448.513	1448.512	26.6	908.0	43	1448.513	0.999982396	1448.575	1448.487	0.062	-0.025

Table 9: Comparison of corrected total station distances and same time GNSS distance for SMB9 and SMB10.

Period	Station	Total station dist_ppm correction $D = \left[\left(\frac{P}{10^6}\right) \times C\right] + C$	Total station dist_reference scale factor correction(R/F) $D' = C \times R$	GNSS distance (m) G	Variance: total station(ppm) vs. total station(R/F) $D - D'$	Variance : GNSS distance vs. total station distance (ppm) G - D	Variance : GNSS distance vs. total station distance (R/F) $G - D'$
Day 1	SMB9	958.979	958.917	958.965	0.062	-0.014	0.049
Day 2	SMB9	958.980	958.918	958.964	0.062	-0.016	0.046
Day 3	SMB9	958.980	958.917	958.965	0.063	-0.015	0.048
Day 4	SMB9	958.983	958.919	958.967	0.064	-0.016	0.048
Day 5	SMB9	958.981	958.916	958.966	0.065	-0.015	0.050
Day 6	SMB9	958.979	958.923	958.965	0.056	-0.014	0.042
Day 7	SMB9	958.979	958.923	958.964	0.056	-0.015	0.041
Day 8	SMB9	958.978	958.922	958.965	0.056	-0.012	0.044
Day 9	SMB9	958.980	958.921	958.967	0.059	-0.013	0.046
Day 10	SMB9	958.981	958.922	958.967	0.059	-0.014	0.045
Day 11	SMB9	958.982	958.920	958.966	0.061	-0.015	0.046
Day 12	SMB9	958.984	958.920	958.967	0.064	-0.017	0.047
Day 13	SMB9	958.986	958.925	958.966	0.061	-0.019	0.042
Day 1	SMB10	1448.581	1448.487	1448.491	0.094	-0.090	0.004
Day 2	SMB10	1448.581	1448.487	1448.485	0.094	-0.096	-0.002
Day 3	SMB10	1448.582	1448.487	1448.485	0.095	-0.097	-0.002
Day 4	SMB10	1448.582	1448.487	1448.487	0.095	-0.095	0.000
Day 5	SMB10	1448.586	1448.487	1448.486	0.099	-0.100	-0.001
Day 6	SMB10	1448.576	1448.487	1448.489	0.089	-0.087	0.002
Day 7	SMB10	1448.572	1448.487	1448.485	0.085	-0.087	-0.002
Day 8	SMB10	1448.572	1448.487	1448.487	0.085	-0.085	0.000
Day 9	SMB10	1448.576	1448.487	1448.486	0.089	-0.090	-0.001
Day 10	SMB10	1448.578	1448.487	1448.487	0.091	-0.091	0.000
Day 11	SMB10	1448.583	1448.487	1448.486	0.096	-0.097	-0.001
Day 12	SMB10	1448.584	1448.487	1448.487	0.096	-0.096	0.000
Day 13	SMB10	1448.575	1448.487	1448.486	0.088	-0.089	-0.001

The values in table 9 show that the average variance between the total station ppm corrected distances and the same time GNSS distances equates to -0.015m and -0.092 for SMB9 and SMB10 respectively. Also the average variance between the total station reference scale factor corrected distances and the same time GNSS distances equates to 0.046m and 0.000m for SMB9 and SMB10 respectively. The reference factor correction over a long range prism (SMB10) yield distances which are closer to the GNSS distances. The influence of ambient temperature and atmospheric pressure is evident even after applying corrections on total station distances.

Average variance between the total station ppm and total station reference scale factor corrected distances equals 0.061m and 0.092m for SMB9 and SMB10 respectively. Based on these results, it can be assumed that atmospheric conditions have a greater impact on distances measured over longer baselines across an open pit. As previously discussed, the signal from the total station instrument passes through varying atmospheric conditions in the open pit, resulting in errors in the computed distance.

There are other possible sources of measurement errors which could contribute to these variances, such as the accuracy of the total station used for measurements, the instrument being out of calibration and possibly human errors. Results also show that atmospheric conditions have a minimal impact on the GNSS baselines, as the variance between the total station reference scale factor corrected distances and the GNSS baselines is minimal at up to 0.004m over a long range, however it is best practice to measure the next reference distance factor prior and during the measurement cycle of monitoring prisms.

From tables 5 to 8, comparison of the displacements of the total station distances adjusted using ppm and reference scale factor show that:

1. Displacements for the ppm corrected distances equates to at least 0.030m for all the prisms;
2. Displacements from the reference scale factor corrections are all within 0.019m for all the prisms;
3. The displacement for the ppm corrected distances is generally higher than the displacement for the reference scale factor corrected distances for all the prisms;
4. The displacements from the ppm and reference scale factor corrections are directly proportional to the distance range, the longer the baseline distance, the higher the displacement value.

Figures 5.14 to 5.17 illustrate this trend.

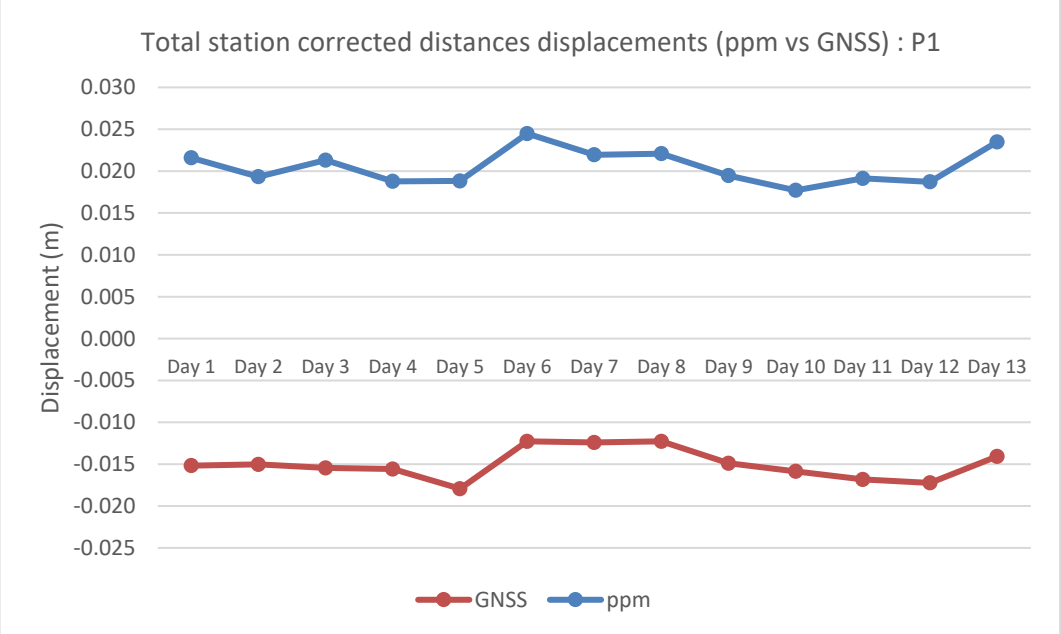


Figure 5.14: Comparison of displacements from distances corrected by ppm and GNSS reference scale factor (Prism 1).

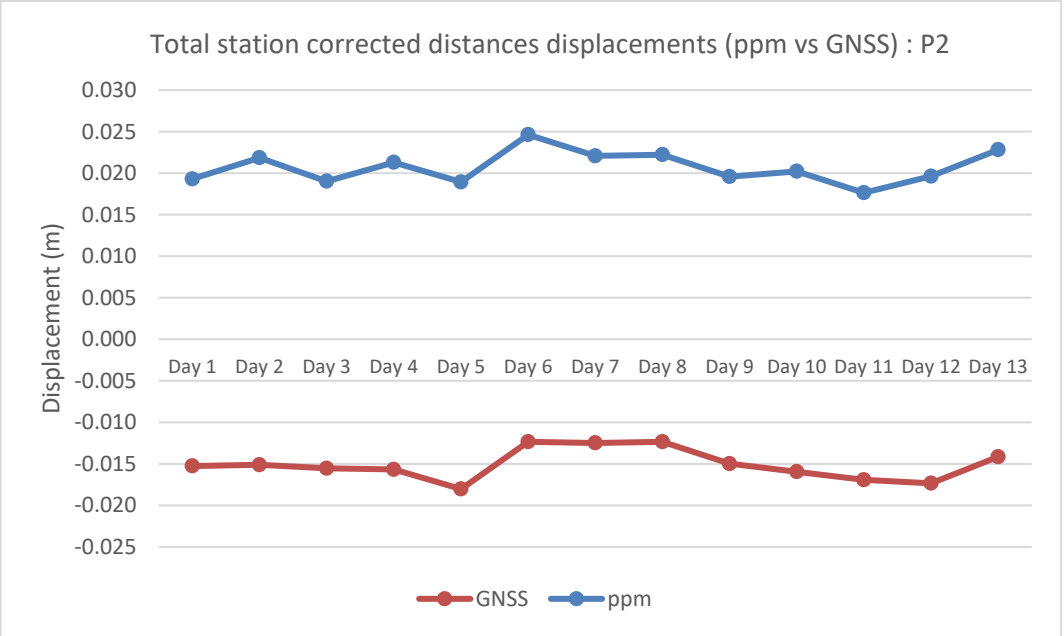


Figure 5.15: Comparison of displacements from distances corrected by ppm and GNSS reference scale factor (Prism 2).

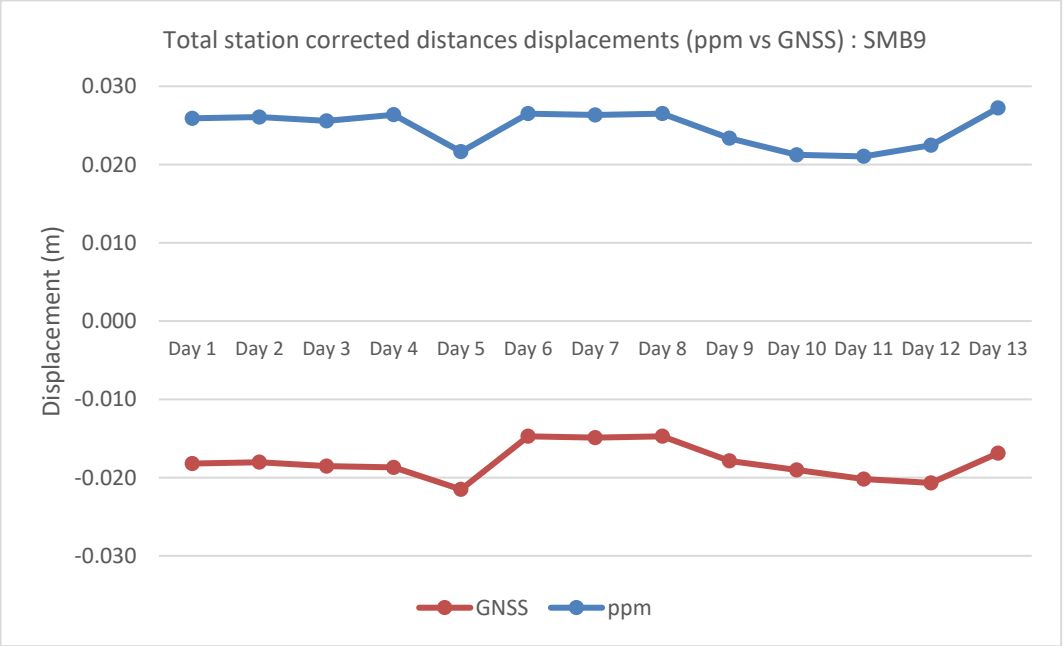


Figure 5.16: Comparison of displacements from distances corrected by ppm and GNSS reference scale factor (SMB 9).

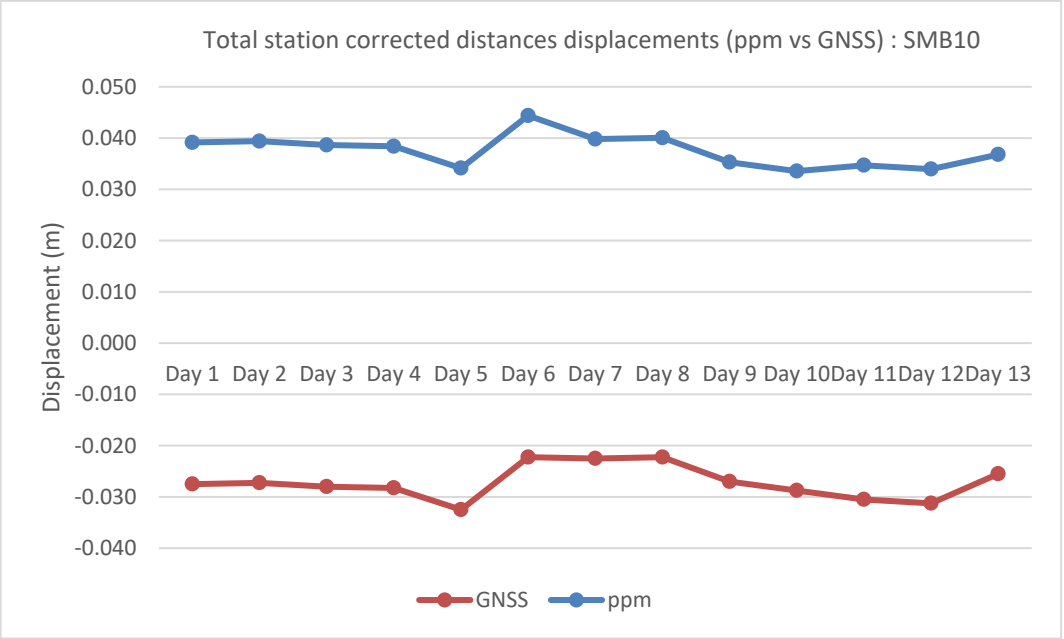


Figure 5.17: Comparison of displacements from distances corrected by ppm and GNSS reference scale factor (SMB10).

The graphs in figures 5.14 to 5.17 show the impact of atmospheric conditions to distance measurements. Fluctuations from the distances which are corrected by a reference scale factor show comparable results which are all within 0.019m, however fluctuations from distances which are corrected by ppm show significantly high displacements of more than 0.030m for all the prisms. Over long distances (SMB10) the fluctuations of the distances corrected by ppm increase, and this affects the overall accuracy of distance measurements.

The ambient temperature and atmospheric pressure readings fluctuate during the day at Orapa Mine. As the ambient temperature and atmospheric pressure readings increase, the displacement figures for measured distances from the total station are also likely to increase. However results from the trial show that the impact of varying atmospheric changes does not significantly affect displacements when compared to the GNSS measurements.

The changing atmospheric conditions cause the displacement graphs from prism monitoring to show a fluctuating graph; when the fluctuations are higher, it means the atmospheric readings are high, and when the fluctuations are low, it means the atmospheric readings are also low. When using GNSS baselines for correcting distance measurements, the fluctuations in distances can be very minimal resulting in a relatively normal flat graph. Even though results from this trial show insignificant impact of atmospheric conditions, when using GNSS baselines for adjusting slope distances from the total station, the reference factor must be calculated prior to every set of prism measurement, as this will eliminate any possible impact of change in extreme weather.

At Orapa Mine, correction of distances from the Leica GeoMoS system has been performed using the reference scale factors from a known baseline. The co-ordinates are however not updated in real time from the GNSS system. Illustration of the longitudinal displacement is shown in figure 5.18. This method of adjusting distances is normally used when the meteorological sensor is down or malfunctioning.

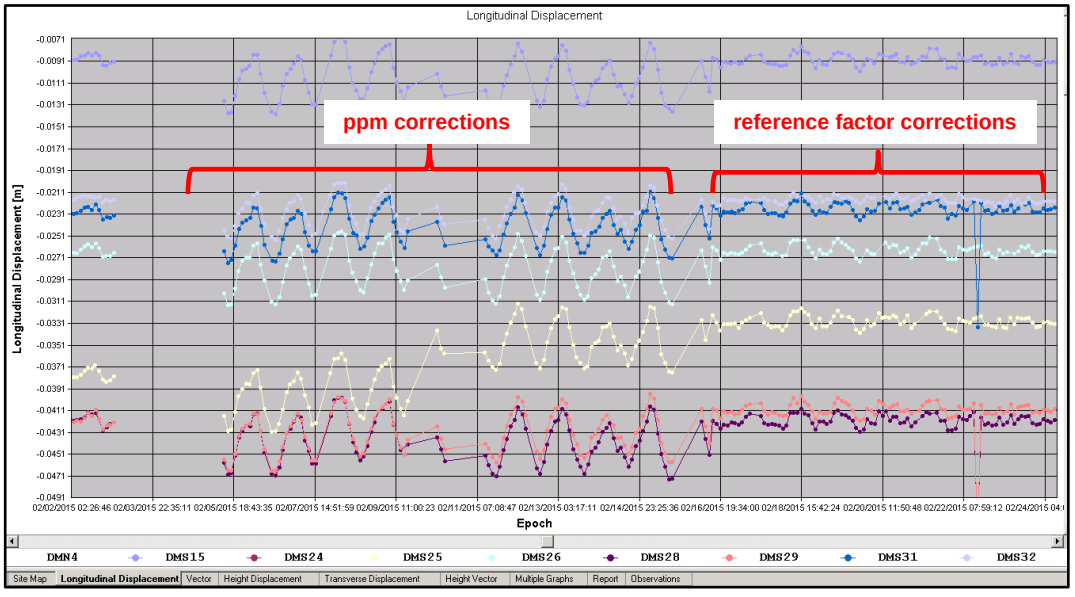


Figure 5.18: Leica GeoMoS graph using reference scale factor adjustments on distances. Source: Orapa Survey Department.

The displacement graph from the reference scale factor corrections show a relatively normal graph with displacements of up to 0.010m, while the graph for the meteorological sensor corrections show displacement graph of up to 0.025m. Results from the trial and from the Leica GeoMoS data at Orapa Mine indicate that distances corrected by reference scale factors have less noise as compared to the ones corrected by ambient temperature and atmospheric pressure.

5.8 Conclusion

The aim of this chapter was to assess factors which need to be considered when applying atmospheric corrections to distance measurements as well as evaluating the two methods of adjusting slope distance measurements. There are various graphical tools within the Leica GeoMoS software which are used to interpret ground deformation. Modern software uses GIS application to simplify analysis of ground deformation data. Data presentation and interpretation is very critical for stability of slopes in an open pit. From the results and evaluation of the data it is evident that further tests are required over a longer period and over varying distances.

The ever changing weather condition in the open pit impact the measurement of slope distances to monitoring prisms. Utilisation of the meteorological sensor is an acceptable tool towards minimising the impact of atmospheric changes in the open pit, however the following factors must be considered:

1. Meteorological sensor position;
2. Monitoring times;
3. Protection of monitoring equipment;
4. Mining activities.

Comparison of the GNSS and total station meteorological corrections to slope distances has been evaluated. Both methods are acceptable for slope stability monitoring data, however it is the responsibility of the mine surveyor to utilise appropriate mitigations such that the changing weather conditions do not deteriorate the final distance measurements from the total station. The GNSS reference factors corrections, if correctly applied can be a viable solution for adjusting the total station distances, especially for large open pit mines.

Using GNSS for continuous spatial positioning of reference and transfer beacons for application of a reference scale factor for measuring to monitoring prisms can improve measurements from prism monitoring solutions. This can be a viable method for large open pits where distances from the transfer beacon to the monitoring prisms can be as far as 1500m, but it requires further testing. The mine surveyor and the geotechnical engineer need to understand fluctuations in deformation monitoring graphs and what they mean to avoid making misinformed decisions about ground movement.

Mining operations which have a suitable budget for slope stability monitoring can consider using the GNSS reference factor option for adjusting the slope distances in prism monitoring. A robust control network and adequate real time GNSS coverage is essential when using this option so that accurate slope distance measurements can be achieved.

6 CONCLUSION AND RECOMMENDATIONS

In this chapter the conclusion of the research is summarised and the fundamental questions of the research are answered. Recommendations of this research are derived from the discussions in each chapter and suggestions on areas of further studies are also outlined.

6.1 Conclusion

The primary aim of every mine is to ensure that the safety of its employees is not compromised. There are various risks associated with mining and slope failure is amongst the top risks in open pit mines. Several mines in the world have experienced injuries, fatalities, loss of production and damage to mining equipment as a result of slope failure. It is therefore critical for every open pit mine to implement a fit for purpose and defensible ground deformation monitoring system to mitigate the slope failure risk. One of these systems is the prism monitoring system which is managed by the mine surveyor at Orapa Mine.

The challenge with today's prism monitoring technology is that measurements are automated and if the data is not checked, errors may not be easily detected. It is the responsibility of the mine surveyor to ensure that the measurements reported by the prism monitoring system are accurate. Thomas (2011) states that "the mine surveyor should understand all associated errors in the prism monitoring and how to mitigate them and that mine surveyors should have a better understanding of survey accuracies required and survey accuracies achieved as this will better equip them for other survey tasks that require high precision surveys". One of the challenges in prism monitoring is the impact of atmospheric conditions to prism monitoring measurements, especially on slope distance measurements.

The purpose of this research was therefore to identify the factors which should be considered when applying atmospheric corrections to prism monitoring distance measurements and are summarised below:

Meteorological sensor position: the purpose of the meteorological sensor is to measure the ambient temperature and atmospheric pressure which are used to adjust the slope distances measured by the total station at the transfer beacon. The discussions in this research show that the atmospheric conditions change rapidly over short periods. Distance measurements from the transfer beacon to the monitoring prisms varies depending on the position of the monitoring prism in relation to the transfer beacon. Some prisms may be closer to the transfer beacon and some can be far from the transfer beacon in an open pit. The meteorological sensor should therefore be placed where the actual measurements take place, that is, at the transfer beacon.

This is however not a suitable solution over long range measurements the ambient temperature and atmospheric pressure variations are experienced in the open pit. For example, placing the meteorological sensor at the survey offices will result in incorrect atmospheric corrections being applied to the total station distances, as such errors maybe introduced in the final results. These errors may therefore be carried forward to the slope monitoring data, resulting in incorrect decision making regarding ground movement analysis and reactions to alarms. The position of the meteorological sensor must be considered when applying atmospheric corrections to slope distance measurements.

Monitoring times: Production in most large open pit mines such as Orapa Mine, is carried out during all shifts, that is during the day and night. Availability of slope monitoring data is therefore critical at all times of the day and night so that early warning alarms can be communicated to the mining personnel in the event of a slope failure. Prism monitoring must

therefore be a continuous process, which occurs 365 days in a year. Appropriate time intervals must be set for the monitoring cycles to avoid instruments being over worked as this can result in system failure.

Slope monitoring data for daylight hours should be compared with the data for the night when making decisions for ground movement to ascertain if there is any correlation. For this monitoring data to give meaningful interpretation, it should be compared with other monitoring systems data, such as that of the Slope Stability Radar (SSR), to confirm slope stability. Errors in monitoring data caused by varying atmospheric conditions are most prominent in data captured during daytime. The mine must therefore consider measuring increased data during the night when atmospheric conditions are more stable. Monitoring times are therefore important in prism monitoring and are a factor to consider when applying atmospheric corrections to prism monitoring.

However, for mining operations with a suitable budget, the continuous operating reference system (CORS) can be integrated with the prism monitoring system. This will overcome the problem of adjusting slope distances using ambient temperature and atmospheric pressure at different times of the day. The CORS system comprises of multiple GNSS receivers installed on reference beacons which measures positions of these beacons in real time. The positions are derived through post processing of the raw data measurements. As mentioned previously, the post processing software performs adjustments of the raw data using the least squares adjustment technique. The least squares adjustment method handles errors and computes reasonable error estimates for each observation.

Best practice would be to have a GNSS system installed on the transfer beacon such that real time baselines can be computed from the transfer beacon to a reference beacon which is also installed with a GNSS system. Continuous reference factors can be computed using the known baseline

distance between the transfer beacon and the reference beacon with the measured baselines. The ratio between the two baselines is then applied to subsequent measurement of monitoring prisms in the open pit. This entire process can be automated within the Leica GeoMoS system, however the reference factors should be computed within short periods to minimise the impact caused by varying atmospheric conditions.

Protection of monitoring equipment: total station distance measurements require high accuracy and precision, therefore it is critical that the instrumentation used for measurements is protected from extreme weather conditions and the effect of mining activities by using suitable instrument shelters. Most open pit mines use shelters for protecting monitoring instruments. Glass enclosures are most common and precautions must be taken when using such shelters so that the accuracy of the measurements is not degraded.

The research of this project established that slope monitoring data for Orapa Mine showed that the glass enclosures do not have an impact on the final total station measurements. Afeni (2011) established that “the properties of glass matters when total station distance measurements are taken through a window glass. The glass has little or no impact on the instrument accuracy specification during vertical distance measurements, but it affects accuracy during horizontal distance measurements. This impact increases with an increase in glass thickness”. Any glass of a thickness more than 3mm is therefore not suitable for instrument shelters and for total station measurements.

At Orapa Mine, the diurnal effect caused by the heat of the sun on the monitoring beacon is prevented by using suitable shelter housing coated with Cromadeck. The transfer beacon monitoring beacon is kept in shade at all time thus mitigating diurnal effect. If the monitoring beacon is directly affected by sunlight, then this can degrade the measurement of slope

distances and horizontal angles due to expansion and contraction of the monitoring beacon.

When the monitoring instruments are not properly protected, dust can cause damage to the total station instrument. Therefore the instrument shelter must be sealed and airtight to mitigate dust from entering.

Mining activities: Research findings established that there are various mining activities which affect prism monitoring in an open pit. The earthmoving equipment causes vibration, dust, an increase in temperature and also causes an obstruction for the slope distance measurements. Data for prism monitoring in the open pit must be carefully checked so that any fluctuations in data can be determined and understood.

Mining activities can result in misleading monitoring data which can be difficult to distinguish between whether ground movement detected is real or not. In the case of Orapa Mine, the mine surveyor and geotechnical engineer should make a decision to ensure that additional measurements of the prism monitoring system are carried out during the night shifts when there is less mining activity in the open pit. The slope monitoring data will not be degraded since a trend can be established between the day and night shift readings.

Other slope monitoring systems must be used to complement the prism monitoring system during the day when fewer measurements are taken. The mining personnel must be made aware of the protection of slope monitoring infrastructure so as to minimise the impact of mining activities on slope distance measurements and slope stability monitoring as a whole. The prism monitoring site should have a minimum of three reference beacons for each transfer beacon, so that measurement checks can be made, especially checks on stability of the beacons. Some of the beacons can be affected by blasting activities, so having adequate control beacons

for redundancy is important.

Distance to monitoring prism: This research revealed that in large open pits, prisms which are measured across an open pit are mostly affected by varying atmospheric conditions and result in greater fluctuations on displacement graphs over greater distances. Prisms which are on reference beacons measured outside of the open pit and at a closer range to the transfer beacon show minimal fluctuations on displacement graphs. As the EDM signal travels across the open pit, it is affected by the changing ambient temperature and atmospheric pressure to and from the prism and this affects slope distance measurements.

Monitoring data for prisms which are at long ranges have to be carefully assessed before being used for slope stability analysis. The prism monitoring data for such prisms must be complemented by data from other systems to avoid misinterpretation of slope stability. Distance to monitoring prisms must therefore be considered when adjusting total station distances in a prism monitoring solution.

Therefore, it can be concluded that the cause of fluctuating displacement graphs in prism monitoring data is the result of errors in slope distance measurements caused by varying atmospheric conditions in an open pit environment. The impact is that incorrect slope distances are likely to be measured by the total station as the ambient temperature and atmospheric pressure changes.

Consideration of meteorological sensor position, monitoring times, equipment protection, mining activities and distance to monitoring prisms is important when applying a correction to total station measurements taken through varying atmospheric conditions across an open pit. Prism monitoring should therefore be used for trend analysis of medium to long term slope stability analysis.

An alternative method of adjusting the EDM distances was evaluated through a practical trial at Orapa Mine. This method involves the use of GNSS baseline measurements to compute a reference scale factor which is applied to distance measurements. Three reference beacons with a suitable geometry on the open pit edge of Orapa Mine were used for the trial. Two prisms inside the pit were also installed specifically for this trial.

Reference beacon (SMB15) was used as a transfer beacon for prism measurements and a GNSS receiver was installed on top of the total station. All other beacons were installed with a GNSS receiver and a prism. The ambient temperature and atmospheric pressure were recorded during times of measurements. The GNSS data was post processed to compute the adjusted co-ordinates, while the distances for the two prisms in the pit were measured from the total station.

Data was then compiled in a spreadsheet and various analyses were made. The main objective was to compare the distances adjusted by the ppm corrections and the reference factor. The ppm is derived from the atmospheric parameters while the reference scale factor is computed from the GNSS baselines. Results from the trial show that the variance between distances corrected by ppm and reference scale factor is directly proportional to the distance between the transfer beacon and the prism.

Short distances across the open pit result in minimal variances while long distances across the result in a significant variance. The increase in variance is attributed to the fact that as the EDM signal travels across the pit, goes through different atmospheric conditions and may result in incorrect distances measured from the total station. The ppm correction only minimises the variance, however the reference scale factor gives more accurate adjustments if applied within short intervals.
Another scenario of the analysis was to compare the fluctuations between the ppm corrected distances and the reference factor corrected distances.

These fluctuations were computed from the corrected and uncorrected distances for each method. Results show that there is a good correlation which is within six millimeters for the fluctuations in distances corrected by the GNSS reference factor, while there is a significant variance of more than thirty millimetres in fluctuations from the distances corrected by the ppm for all the prisms, that is the reference beacons and the prisms.

This indicates that over time, the longitudinal displacement graph for the distances corrected by ppm would show larger fluctuations, which can cause uncertainty in slope stability analysis, and would probably need further analysis using other methods of monitoring. However the longitudinal displacement analysis graph for the distances corrected by reference scale factors show small fluctuations, which are acceptable for slope stability analysis.

The following conclusion can be made regarding adjustment of slope distances from the two methods:

Correction of slope distances using the reference scale factors is preferable because minimal fluctuations in data are observed when using this method, as such correct decisions can be made regarding slope stability analysis. This can be a viable method of adjusting total station distances as the open pit mines become wider and deeper.

Reference scale factor corrections are preferable because any errors in baseline distances can be easily detected, while for the ppm corrections, it is difficult to find out if the ambient and temperature readings from the meteorological sensors are suitably correct.

The GNSS baselines do not get adversely affected by the rapid change in atmospheric conditions, as such, accurate reference scale factors can be achieved at any time of the day. However the ppm corrections are

dependent on the correct values of the atmospheric parameters which can change rapidly over time. Therefore, there is a possibility that measured slope distances could be corrected with a ppm value that is not representative for the time when the distance was measured.

When using the ppm correction method, the ambient temperature and atmospheric pressure must be measured where the actual measurements take place. This has proved difficult in prism monitoring as the meteorological sensors are usually placed at the transfer beacons, while at the monitoring prism the atmospheric parameters cannot not be measured. Monitoring prisms tend to be installed on slope faces which over time become inaccessible. Also the cost of equipping each monitoring prism with a meteorological sensor would be prohibitive and the prism monitoring software may not be able to handle multiple temperature and pressure readings.

The reference scale factor correction method is therefore preferred because the baseline distance does not have to be computed where the measurements take place. Usually the reference beacons are located on the open pit edge or away from the open pit edge, so this is an added advantage of the reference scale factor method since there will be minimal effects of the atmospheric conditions when computing the baseline distances.

Adjustment of slope distances using the reference scale factors requires a suitable infrastructure of reference beacons and an automated GNSS system and could result in very high costs for the mine. The ppm correction method would be much cheaper to implement, so mines which do not have sufficient funds can still use the ppm correction method for prism monitoring.

The method of correcting the total station slope distances using meteorological data is also an acceptable solution, and has been used extensively at Orapa Mine. However it is most suitable for small pits such as Letlhakane and Damtshaa Mines, where distances from the transfer beacons to the monitoring prisms are relatively short, that is 400m or less.

6.2 Recommendations

The research evaluated factors which need to be considered when applying atmospheric corrections to prism measurements in an open pit, in particular at Orapa Mine. In addition to these considerations, a number of recommendations were highlighted.

The number of transfer beacons on the open pit edge should be increased so that each prism is measured perpendicular to the expected direction of movement and not at oblique or transverse angles. This will ensure that suitable number of prisms per transfer beacon is measured.

Orapa Mine should consider making more prism measurements during the night when atmospheric conditions are stable. This can be accomplished by configuring the measurement cycles in Leica GeoMoS Monitor, such that each transfer beacon has two measuring groups. One group will measure prisms during the day with fewer cycle times and the other group measuring during the night with more cycle times. In this way, the effect of atmospheric conditions to prism monitoring data can be minimised. The risk of slope failure is however high at all times of the day, it is necessary to complement the prism monitoring system with other monitoring systems in an open pit environment.

The GNSS and prism monitoring systems at Orapa Mine should be integrated such that spatial positioning of the transfer beacon and reference beacons is continuously measured. This will require all transfer beacons to be modified and installed with the GNSS system. Reference scale factors will then be calculated based on baseline computations in real time. There

should be at least a minimum of three reference beacons for each transfer beacon so that measurement checks can be made. These reference scale factors will then be applied to prism monitoring measurements to adjust the slope distance measurements.

Reference distances must be updated regularly in order to update the reference scale factor that is applied to prism monitoring measurements. This is achieved by continued GNSS measurements and updating of transfer and reference beacon positions. The result will ensure an accurate correction (scale factor) is applied to measured slope distances to monitoring prisms. This can be a viable solution for adjusting the slope distances, especially in large open pit mines such as at Orapa Mine.

Transfer beacons inside the open pit should be established at strategic locations not affected by mining activities. Having transfer beacons in the open pit reduces the distance measured to the prisms and measurements are taken in a similar atmospheric environment. This initiative can greatly reduce fluctuations in prism monitoring data

For best practice, when using the reference scale factor correction to adjust slope distances, the baseline distance must be computed in the same location to where the subsequent measurements of prisms will take place. For example, if there are prisms installed on the north of an open pit, the reference scale factor must be computed from a baseline which is also in the north of the open pit. This will ensure that all measurements are taken under similar atmospheric conditions, as such errors in measurements will be minimised.

6.3 Areas of Further Research

Further research must be carried out to evaluate the different methods of adjusting distance on measurements taken within the open pit and not on the surface of the open pit as carried out in this research. Further tests are required over a longer period that considers seasonal fluctuations and over a wide range of varying distances.

A trial to evaluate the different methods of adjusting slope distances to monitoring prisms must be carried out using the Leica mobile monitoring solution and permanent transfer beacons which are located on the open pit edge. When undertaking this trial, the Leica mobile monitoring equipment must be mounted inside the open pit, where the prisms are located.

There is a need to investigate other possible sources of errors which affect the prism monitoring data. This will ensure that all errors in prism monitoring systems are understood and rectified accordingly.

Further research must be carried out on the impact of atmospheric conditions to CORS measurements and other possible errors associated with this type of survey.

Further research must be carried out on how to model temperature and pressure across the open pit and how this can be applied to prism measurements.

There is a need to compare and analyse the total station slope distance adjustments by using the GNSS reference scale factor which is computed from baselines that are measured across the void of the open pit and by using the GNSS reference scale factor which is computed from baselines which are not measured across the void of the open pit.

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