The importance of structured slope monitoring in the mining industry

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Abstract

Slope movement is most common in open-pit mines. A number of mines, where slope movement is detected, operate safely with the help of monitoring. Slope monitoring forms an integral part of slope management in open-pit mines. The effectiveness of slope monitoring provides information for: detecting potential unstable ground, assessing the performance of slope design which involves identifying any slope instability and/or failure mechanisms that develop. If the failure mechanisms are understood and the slopes are properly monitored, the risk of slope movement and the subsequent consequences can be considerably reduced. This can prevent loss of life, loss of working equipment, loss of production and it might even prevent the loss of the mine. In order to achieve this, one has to find and/or develop the most adequate monitoring solution that meets all the necessary requirements, which is often a challenge.

Terrestrial laser scanning (TLS) is one of the many that has been identified as a slope monitoring solution. TLS has provided new capabilities for real-time slope movement monitoring. For the mining industry, the advantages of TLS are not limited to deformation monitoring, but also include a wide range of geotechnical and surveying applications such as characterizing rockfall, three-dimensional (3D) rock mass structure, and delineating features. Parameters such as precision, repeatability and accuracy are crucial for deformation measurement. Laser scanning contributes to the improvement of slope movement warning system tools to enhance the safety procedures for continuous mining activities and infrastructure planning.

In this paper an overview is given of the importance of slope monitoring, slope monitoring strategies and legal considerations. Laser scanning operations with special slope monitoring software are also dealt with.

Keywords

slope monitoring, mining, safety, laser scanning, rockfall, infrastructure planning

Introduction

In the mining environment slopes are monitored to ascertain their stability, but the question, “When is slope failure going to occur?” is still a critical concern. Various monitoring equipment and devices such as global positioning systems (GPSs), slope stability radars (SSRs), extensometers, survey stations, and others are used to monitor slopes. Monitoring the behavior of slopes is critical to mitigate failure or accidents, and is vital in successfully forecasting the time of slope failure [1].

Cawood and Stacey [2] stated that slope failures do not occur spontaneously, there is a scientific reason for each failure and failures will not occur without a warning. Rockfalls can be seen as an indication that a larger slope failure might occur. Varnes [3] defines a rockfall as “a fragment of rock detached by sliding, toppling or falling, falls along a vertical or sub-vertical cliff and proceeds down a slope by bouncing, rolling or sliding”. Rosser et al. [4] also stated that rockfall can be detected, measured and monitored before a major slope failure. Correct measures can be put into place to prevent major slope failures, for example the installation of wire mesh. Environmental factors can also have an influence on the occurrence of major slope failures. Slope monitoring systems assist with the detection, measurement and monitoring of rockfall in open-pit mines. The data derived from the slope monitoring system implies a time-dependent sequence in the occurrence of smaller rockfalls. This is an indication that a larger slope failure might follow. Therefore, slope monitoring can already be seen as an integral part of any open-pit mine operation.

According to the 2013/14 Annual Report of the Department of Mineral Resources (DMR) [5], a number of fatalities occurred at mines in South Africa. These are listed per classification in Table 1.
Table 1: Actual fatalities by classification.

<table>
<thead>
<tr>
<th>Classification</th>
<th>2012</th>
<th>2013</th>
<th>% change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conveyance accidents</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Electricity</td>
<td>5</td>
<td>2</td>
<td>-60</td>
</tr>
<tr>
<td>Explosives</td>
<td>4</td>
<td>1</td>
<td>-75</td>
</tr>
<tr>
<td>Fall of ground</td>
<td>25</td>
<td>32</td>
<td>28</td>
</tr>
<tr>
<td>Fires</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>General</td>
<td>34</td>
<td>19</td>
<td>-44</td>
</tr>
<tr>
<td>Heat sickness</td>
<td>1</td>
<td>0</td>
<td>-100</td>
</tr>
<tr>
<td>Machinery</td>
<td>9</td>
<td>3</td>
<td>-67</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>2</td>
<td>4</td>
<td>100</td>
</tr>
<tr>
<td>Subsidence/caving</td>
<td>1</td>
<td>0</td>
<td>-100</td>
</tr>
<tr>
<td>Transportation and mining</td>
<td>30</td>
<td>31</td>
<td>3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>112</strong></td>
<td><strong>93</strong></td>
<td><strong>-17</strong></td>
</tr>
</tbody>
</table>

The classification of the fatal accidents shows that the three largest classification areas of these accidents in 2013 was fall of ground (32), transport and mining (31) and general (19). There was an overall reduction of 17% in the fatal accidents for 2013 with 93 fatalities when compared to 112 in 2012. As seen in the results, fall of ground is in the top three fatalities. The results lack mentioning whether this is underground or in an open-pit environment. This leads to the importance of having a slope monitoring system in place, assuming that at least one of the fatalities has been in an open-pit environment. Having one fatality is more than enough to consider looking at more efficient ways to provide safe working environments. Therefore, choosing the most effective slope monitoring system is imperative to every mine’s infrastructure planning.

The next section will focus on slope monitoring strategies, including design and compliance considerations in a mining environment.

Slope monitoring strategy

Caution should be taken when choosing a slope monitoring system for an open-pit mine. Large open-pit mines might have multiple different measurement techniques in place, but choosing the most effective monitoring solution might be time-consuming as a number of objectives should be met, which is often a challenge. The main objectives for a slope monitoring strategy are [6]:

- Maintaining safe operational systems and procedures to protect personnel and equipment.
- To provide notice of potentially unstable ground so that mine plans can be modified to minimise the impact of slope displacement.
- To provide geotechnical information for analysing any slope instability failure mechanisms that develop, designing an appropriate remedial action plan and conducting future slope designs.
- Assessing the performance of implemented slope design.
- Building up a history of information to determine different rock behaviors over a long period of time of monitoring.
Keeping the objectives in mind, other main considerations for choosing an effective monitoring solution, include design and compliance considerations [2]. These will be individually explained in this section.

**Design considerations**

The design considerations should be based on a series of six principles that embrace a design process or methodology [2]:

- Clarity of design objectives and functional requirements
- Minimum uncertainty of geological conditions
- Simplicity of design components
- State-of-the-art practice
- Optimisation
- Constructability

It is said that the design does not satisfy these principles, if it cannot be implemented safely and efficiently. In this case, it will be necessary to review the design and repeat, either partially or completely, the design methodology until the design is optimised. The ‘engineering wheel of design’ (Fig. 1) and Table 2 summarised the design methodology corresponding with the six design principles.

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
<th>Design principle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Statement of the problem (performance objectives)</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Functional requirements and constraints (design variable and design issues)</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Collection of information (site characterisation, rock properties, groundwater, in situ stresses)</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>Concept formulation (geotechnical model)</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>Analysis of solution components (analytical, numerical, empirical, observational methods)</td>
<td>3, 4</td>
</tr>
<tr>
<td>6</td>
<td>Synthesis and specifications for alternative solutions (shapes, sizes, locations, orientations of excavations)</td>
<td>3, 4</td>
</tr>
<tr>
<td>7</td>
<td>Evaluation (performance assessment)</td>
<td>5</td>
</tr>
<tr>
<td>8</td>
<td>Optimisation (performance assessment)</td>
<td>5</td>
</tr>
<tr>
<td>9</td>
<td>Recommendation</td>
<td>6</td>
</tr>
<tr>
<td>10</td>
<td>Implementation (efficient excavation, and monitoring)</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 2: Design process.

Cawood and Stacey [2] ensure that this methodology represents a thorough design process and can be used as a checklist to ensure a good design has been carried out.
Fig. 1: The engineering wheel of design.

Not all of the steps in the engineering wheel of design will be explained, but some need to be emphasised. The problem statement ensures that everyone knows what is being designed, including all the constraints. The “defining the design” part of the wheel is the most important. In addition, the concept formulation of the geotechnical model is critical. The basis of this process is a complete site investigation, this will minimise any uncertainty. This will assist in identifying potential kinematic slope failure mechanisms for stability analysis, and will indicate the most sensitive areas for the design of a monitoring system [2].

Design analyses involves analytical, numerical, empirical and observational methods and this step is bridged by design principles 3 and 4. Cawood and Stacey [2] further explain that the analysis tool is only a tool to obtain answers to the problem that has been posed. Thorough understanding of the expected slope behavior (location of movement, magnitude of movement, rapid rate of movement, etc.) will allow a satisfactory slope monitoring system to be designed and implemented.

Monitoring is also a critical aspect in the design process. The aim is to check whether the behavior mechanism of the designed structure is as expected and whether the design criteria used, were appropriate (confirming the validity of the design). It is required to loop back to an earlier step if the behavior is not as expected. To mitigate costly errors, the monitoring information should be obtained as soon as possible. The importance of review and monitoring in the design process is emphasised by the “spokes” of the wheel in Fig. 1. The implication is that the design must meet the stated objectives at all stages.

Cawood and Stacey [2] ensured that if these steps are followed diligently in the design of the slope monitoring system, a robust monitoring system should result.

Compliance considerations

- Mine Health and Safety Act (MHSA): The MHSA, 1996 (Act No. 29 of 1996), provides for the protection of the health and safety of employees and other persons affected by the South African mining industry and, amongst others, provides for the promotion of a culture of health and safety as well as the enforcement of health and safety measures or legislation [7]. Section 2 of the MHSA states that mines should be equipped with effective systems to ensure safe conditions. Health and safety reports should be compiled, supported by relevant statistics. Furthermore, the MHSA (Section 7) stipulates that only persons with the appropriate qualifications and training are allowed to be appointed. Section 9 states that a Code of Practice (COP) should be in place, this will be discussed in the following sub-section. Proper training programmes must be in place, as indicated in Section 10.
• **COP:** The Department of Minerals and Energy [8] states that the majority of accidents occurring at mines are as a result of rockfalls, seismically or gravitationally induced. Over the last few years the fatality rate pertaining to rockfall and rock burst-related accidents has reached a plateau and no real or meaningful improvement has been attained.

In Section 9 of the MHSA it is stated that an employer must implement a COP on anything that could affect the health and safety of the employees and any other person who may be directly affected. The Department of Minerals and Energy [8] issued a complete guideline to enable the employer on how to prepare a COP for rockfall and slope instability related accidents. Failure by the employer to implement a COP in compliance with this guideline is a breach of the MHSA.

As seen in this section, it is critical to understand the monitoring requirements in open-pit mines. Taking this into account, appropriate instrumentation should be chosen and implemented. Complementing the instrumentation, effective monitoring software should be decided on, which plays an integral part in processing, analysis, interpretation and presentation of monitoring data. Even though there are various monitoring instruments, this paper mainly focuses on laser scanning instrumentation and is discussed in more detail in the next section.

**Laser scanning operation**

Terrestrial laser scanners provide detailed and highly accurate 3D data rapidly and efficiently. Applications are wide ranging, including topography, mining, as-build surveying, architecture, archaeology, monitoring, civil engineering and city modelling. The laser scanners are usually rugged and fully portable instruments, tested under strict conditions for a reliable performance even under highly demanding environmental conditions. The working principles discussed in the next section, is based on Riegl laser scanners [9].

**Working principles**

According to Radzilani [6] laser scanners offer new capabilities in deformation monitoring, mainly due to the high spatial resolution and speed of data capture, which enables repeat monitoring or data capture at high frequencies. A laser scanner measures points in 3D by combining laser range finder and high accuracy angle measurements in local coordinate (that is relative to the scanner). Thus combining the distance the pulse of light has travelled is achieved by using Eqn. 1:

\[ r = \frac{(c \times t)}{2} \]

where:

- \( r \) = the distance the pulse travelled
- \( c \) = the known speed of light
- \( t \) = time taken for the pulse of light emitted by the range finder to be returned and the angle encoders which measure the direction that the range finder is pointing during range measurements.

Various terrestrial 3D laser scanners offer superior and extremely long range measurement performance of more than 6000 m for topographic applications. Some of the laser scanners still maintain completely eye safe operation (Laser Class 1). The technology is based on echo digitisation and online waveform processing and is the key to enabling such extreme long range measurements. The laser scanners operate even in poor visibility and demanding multi target situations caused by dust, haze, rain, snow, etc. which are frequently found in difficult environments, such as mine sites [9].

The laser scanners offer wide field of view (60° x 360°), high speed data acquisition up to 222 000 measurements per second, multiple target capability (unlimited number of targets), optional waveform data output, on-board inclination sensors, integrated L1 GPS receiver with antenna, integrated compass, built-in SSD data storage media and advanced camera options. A very important feature offered with laser scanners, is that it allows monitoring through wire mesh and vegetation [9].

The next section will give a brief overview of slope monitoring software, which complements the use of laser scanning equipment.
**Slope monitoring software**

Slope failure monitoring software is intended to be used by mine surveyors and geotechnical/rock engineers. Collecting and storing of the data, is the responsibility of the surveyors. They ensure that accuracy and reliability of measurements are maintained. The analysis of the data is the responsibility of the geotechnical or rock engineers. They will look for significant movement and report any potential areas of slope failure. For effective slope monitoring, the following parameters need to be considered [6]:

- **Repeatability:** This is often called “precision” and is a measure of the noise in the measurements. It can be estimated by looking at the spread of multiple measurements of the same target. Random noise can be removed by taking the average of multiple measurements. This is the most important parameter for displacement monitoring.

- **Accuracy:** This is a measure of how close the instrument measures to the true distance. This is important if we want to geo-reference the data to compare to other data or if we remove the instrument for a while then replace it and continue monitoring.

- **Atmospheric correction:** Although laser scanners assume a constant speed of light while measuring range, meteorological conditions affect the speed of light and thus, the range measured. Slope monitoring software uses control points with known locations that have been correctly measured in the site coordinate system. The true range from the scanner to the control point is then calculated since the location of the scanner is also known. Based on this, an atmospheric range correction factor can then be calculated by comparing the measured range from the scanner to the control point with the true range. This is subsequently applied to the scan data of the monitoring area to provide a more accurate recording of the range of each node.

Bae and Litchi [10] stated that terrestrial laser scanners provide a 3D “sampled representation of the surfaces of objects resulting in a very large number of points”. This is known as a “point cloud”. The point cloud is registered/aligned either automatically or by using control points (i.e. targets), using slope monitoring software. According to Bae and Litchi [10] automatic registration is a method for registering partially overlapping point clouds, without the use of targets. They also stated that to the best of their knowledge in 2004, such a method has not been developed yet. Not having to use targets while scanning has created an area of increasing interest. One of the companies that has been inspired by this is 3D Laser Mapping. They started developing and testing automatic registration through scan-to-scan matching within a new version of SiteMonitor4D, as an alternative to the target method. The scan-to-scan registration will be discussed in more detail later in this paper as this is one of the new features currently being tested.

**SiteMonitor4D**

SiteMonitor4D is an example of a slope monitoring system. It is a high accuracy, long range monitoring system using advanced laser scanning technology with powerful, simple to use software for measuring change. The system is designed to be used for continuous or periodic slope monitoring as well as for volume surveys and geotechnical mapping. The principle behind the software is to establish a grid of measurement points and to re-measure the grid periodically to look for differences in position of the grid nodes. The system has the flexibility and performance to function in a wide range of applications. This allows monitoring of small rock falls and geological structures, which are not possible with most other monitoring techniques.

Often mines want to monitor a certain area against the rock face, if they feel there could be unsafe behavior. The system enables the mine surveyor to create a project and to identify the areas for monitoring, this is part of the data acquisition procedure and this is completely automated [11]. The data acquisition module controls the scanner, collects the raw data and undertakes geo-referencing of the data. All data is sent to the database in the mine office via a remote link. There are quality control tools to allow the surveyor to ensure the measurement results are reliable.

An additional module, designed for geotechnical engineers, allow them to examine and analyse the monitoring areas. This is the analysis module, also allowing them to rapidly make decisions to prevent or mitigate any risk of slope failure. This module has a complete toolkit of functions that are useful for geotechnical analysis. These include setting alarm thresholds, defining analysis zones, redefining the reference scan in places where mining has taken place and analysis using stereonets [11].
Additionally, the system can be used in two modes:

- **Continuous mode:** In this scenario, the laser scanner would be set up in a protective housing, as shown in Fig. 2, with a mains power supply and a stable pillar on which it can be mounted. A number of reflectors installed around the monitoring region(s) enable the range correction factor (RCF) to be calculated and the stability of the scanner to be monitored. If the scanner needs to be moved, the reflectors allow the monitoring project to be resumed at a later date. Once a scanning schedule is defined, the software can run automatically without further operator intervention. All data is transmitted live to an office-based computer running the analysis module, allowing rapid evaluation by surveyors and geotechnical engineers.

  ![Fig. 2: Protective housing (hut) installation for continuous slope monitoring.](image)

- **Periodic mode:** Used in a number of scenarios such as when the scanner is removed between surveys when continuous monitoring of a site is not required or the scanner is removed between surveys for security or discretion. Generally, a pillar will be used for periodic monitoring, as shown in Fig. 3. Following the quick setup of a monitoring project, subsequent data collection surveys can be carried out by simply setting up the scanner, scanning a number of control points (to provide an orientation and a RCF) and re-scanning the areas of interest. Data gathered during periodic monitoring can be transmitted back to the office, running the analysis module on a remote link or downloaded by the operator when the field work is complete.

  ![Fig. 3: Example of periodic monitoring, using a pillar.](image)

To achieve the slope monitoring objectives, as mentioned earlier in this paper, the system provides the user with the following information [6]. An example of the analysis module is illustrated in Fig. 4.

  ![Fig. 4: Typical analysis module with photograph as background, overlain by displacement map.](image)
• **Range:** This refers to the absolute range to the selected data or measure distance to the points from the scanner (in metres).

• **Displacement rate:** This displays the rate at which displacement is occurring, which is millimetres per day. This can be viewed in incremental mode or averaged according time per scans. Displacement rate can give significant information about the acceleration of movement or failure.

• **Volume:** The software provides the volume in cubic metres of selected areas of interest. This is significantly used in determining the volume of failed material.

• **Vertical and horizontal sections:** The user is also able to extract vertical and horizontal sections of an area of interest. One can view the change in vertical section of any slope deformation over a number of scans or period of time.

• **Report:** The software can generate a report in HTML format. The content of the report is user defined, and once the report has been exported the user is also able modify it.

• **Rockfall:** It provides information on rockfall events and maintains history, as shown in Fig. 5.

• **Stereonets:** Geological or geotechnical structural information forms an integral part of slope management in determining the type of failure mechanism. Stereonet plot functionality provides this information for rock engineers to analyse.

• **Displacement:** The displacement graph gives information about the relative range difference between the baseline survey (reference set) and the currently selected data. This aids to provide information on movement of ground for potentially unstable areas. The image below depicts evolution of potentially unstable area through cumulative displacement.

![Displacement graph](image)

**Fig. 5:** Rockfall detected, showing volume of the accumulated material from the rockfall event.

As previously mentioned, a number of new features will be included in the latest release of software, such as:

• **Slope stability analysis:** The slope stability tool enables the easy identification of deformation across the surface of a monitoring area. The user is able to filter absolute displacement points by minimum volume across various timescales to identify regions in the scan data which have crept or fallen. This creates a powerful tool in identifying volumes of movement through time and defining regions of creep and rockfall. The function is essential for keeping mining conditions safe both for mine personnel, as well as working equipment.

• **Scan-to-scan registration for periodic monitoring:** Scan-to-scan registration is a scan positioning and matching tool, which allows a scan of an area to be aligned to a reference scan without targets. The scan-to-scan registration tool conducts an automatic identification of stable areas in a scan dataset and compares the relative changes in these positions through subsequent scan data to enable the calculation of a transformation matrix and range correction factor. In order to make sure that actual movement of a rock-face does not cause the scan-to-scan registration to be miscalculated, areas of rock that have moved relative to the
majority of the scan window are excluded from the calculation. It also saves time regarding installation of targets in the area of monitoring. Often the area is very demanding and not accessible. For small angles, weighted point-to-plane distance and linear approximation to the rotation are used (see Fig. 6). However, this feature is only available for periodic mode and currently requires the scanner to be used from a fixed position.

![Fig. 6: Scan-to-scan matching.](image)

Planes are identified from collections of nearby points, as illustrated in Fig. 7. Change can be defined as the vector displacement from a point in scan one to the plane in scan two. It is also possible to detect the direction of movement. The software permits alarming based on the movement angle, even if actual displacement remains small.

![Fig. 7: Plane-based change detection of toppling failures.](image)

The scan-to-scan registration will continue to be an area of interest, as this simplifies the slope monitoring solution in open-pit mines.

**Conclusion**

This paper described the importance of slope monitoring and slope monitoring requirements in the mining industry. In addition, slope monitoring strategies were looked at on how slope monitoring can be done. Three-dimensional laser scanners and slope monitoring software have been discussed. Legal issues which mines should comply to, have also been dealt with.

It is concluded that a slope monitoring system forms an integral part in the mining industry to ensure a safe mining environment. Slope monitoring systems not only ensure a safe environment, but also provide a number of additional functional features, such as calculating volumes. To conclude, laser scanning was chosen as the preferred technology in this paper as it is seen as best suited for slope monitoring and infrastructure planning, due to the precision and accuracy.
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References


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