Survey and geotechnical slope monitoring considerations

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Synopsis

Monitoring of the slopes of surface mines can prevent loss of life, loss of equipment, loss of production and possibly the loss of the mine. The effectiveness of such monitoring depends on the extent to which slopes give adequate advanced warning before failing, and on the ability of the monitoring system to detect such warning. In this paper an overview is given of slope monitoring requirements, from both the geotechnical and survey points of view, as well as the types of equipment and instrumentation that are available. Legal issues relevant to slope monitoring are also dealt with.

It is concluded that conventional geotechnical and survey instrumentation will continue to have their place in slope monitoring. However, the slope monitoring scene has changed substantially in recent years. Areal and volume-based monitoring equipment is now available and this has provided, and will continue to provide, the means to improve safety, and to enhance productivity in mining. Its benefit to slope management is substantial. In the near future it is expected that data obtained from such equipment will add a much needed new dimension to slope engineering, and be used to improve slope designs and to optimize slope angles.

Introduction

Monitoring of the slopes of surface mines can prevent loss of life, equipment, production and possibly the loss of the mine. The effectiveness of such monitoring depends on the extent to which slopes give adequate advanced warning before failing, and on the ability of the monitoring system to detect such warning. There is considerable evidence (for example, Ding et al., 1998) to indicate that slopes do give ample warning, which means that it is well worth the effort to spend time on investigating and implementing appropriate monitoring systems. Figure 1 illustrates the value of survey monitoring at Venetia Diamond Mine, where the exponential movement at Prism M11-3 indicated on the survey charts gave advanced warning of ultimate failure. It is important to note, however, that in the hard rock open pits that are being mined nowadays, failures often occur after very small deformations. Such failures may be very localised and, unless such a localized area is being very closely and accurately monitored, failure may occur apparently without warning. The dictates for such situations are therefore accurate, remote monitoring. This paper gives an overview of the survey and geotechnical considerations for effective monitoring systems as established from a literature survey, various case studies and observation.

The monitoring process normally constitutes five steps. It starts with monitoring requirements. This is to establish the objectives, need, advantages (expressed in both economic and health and safety terms), researching historic problems as case studies and finally preparing a report to decision-makers motivating the need for monitoring along with the expected benefits.

The second step is to establish the project requirements, which follows from the pit design and a risk assessment. The outcome of this will state the probability of failure and the variables that will most likely contribute to such failure.

The third step will take account of these variables in designing the monitoring system, investigating appropriate instrumentation and implementing the monitoring system (Ding et al., 1998). An overview of these considerations is the subject of this paper.

The fourth step is the actual measurement and recording of field data. Issues to be dealt with, which will have been thoroughly considered during the design of the monitoring system, are measuring techniques and frequencies, accuracy, precision and personnel responsibilities.

The fifth and final step is interpretation and reporting of monitoring data. This involves processing, analysis, interpretation...
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In the body of the paper below, geotechnical and survey considerations in slope monitoring, and design and legal compliance issues associated with them, are dealt with.

Monitoring considerations

The main considerations for effective monitoring relate to correct design, legal compliance, monitoring requirements and system design providing for both geotechnical and survey monitoring instrumentation. These considerations are individually discussed in this section.

Design considerations

The design of rock slopes and slope monitoring systems should be a thorough process that takes into account adequate information and provides a design with an acceptable risk. This process could be based on the design principles developed by Bieniawski (1991, 1992), who defined a series of six principles that encompass a design process or methodology:

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

If the design cannot be implemented safely and efficiently it does not satisfy these principles. It will be necessary to review the design and repeat, either partially or completely, the design methodology until the design is optimized. The design methodology corresponding with the above six design principles is summarized in the ten steps shown in the ‘circle or wheel of design’ (Stacey, 2006) in Figure 2 and in Table I.

This methodology represents a thorough design process and can be used as a checklist to ensure that a defensible design has been carried out. It is also interesting to observe the similarity between this design process and the strategic planning process developed by Ilbury and Sunter (2005), confirming that design is a strategic issue (Stacey, 2006).

Some segments of the engineering circle need to be

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validity of the design. If the behaviour is not as expected then it will be necessary to loop back to an earlier step in the process and reassess the design. It may even be necessary to carry out a completely new design. The sooner that monitoring information or data can be obtained the better, since costly errors and consequences will then have the best chance of being avoided. The importance of review and monitoring in any engineering design process is emphasized by the ‘spokes’ of the wheel in Figure 2. The implication is that the design must meet the stated objectives at all stages.

The above discussion is relevant to the design of the slopes themselves as well as to the design of the slope monitoring system. If the 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)

Before discussing the requirements of the South African MHSA insofar as they relate to monitoring surveys, the relevance of ISO 9000 accreditation should be emphasized. Such certification will in many ways go a long way towards complying with the MHSA because of the Quality Plan concept and its emphasis on leading practice. The objectives of the MHSA are to protect the health and safety of employees; to require employers and employees to identify hazards; to eliminate, control and minimize risks; and to provide for effective monitoring of health and safety conditions at mines. Section 2 of the MHSA goes further by stating that employers must equip mines with systems to ensure safe conditions and compile an annual report on health and safety, which report must be supported by appropriate statistics. Section 7 makes it obligatory that mine employers must appoint persons with appropriate qualifications and training to understand the hazards associated with the work. Section 10 of the MHSA states that it is the employer’s responsibility to ensure that such proper training programmes are accredited and put in place. Section 9 deals with Codes of Practice, which is discussed in the following sub-section. These requirements are emphasized in Section 11, which section provides for the employer to:

- Identify hazards and assess the risk
- Record significant hazards identified in the risk assessment
- Determine all measures to eliminate, control and minimize the risk and in so far as the risk remains, institute a programme to monitor the risk; and
- Periodically review the hazards identified, risk assessment and control measures.

Mine health and safety matters are not only the employer’s responsibility. The employee, according to

*It is to facilitate such education and training that the School of Mining Engineering, University of the Witwatersrand introduced a course in Slope Stability Monitoring at postgraduate level

Figure 2—The engineering circle or wheel of design
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Sections 22 and 23 of the MHSA, must firstly report any situation presenting a health and safety risk and has the right to leave unsafe areas. As far as offences and legal proceedings are concerned, negligence is defined as ‘Any person who, by a negligent act or by a negligent omission, causes serious injury or serious illness to a person at a mine…’.

Part of these obvious sections that relate to the monitoring of slopes at surface mines, there are separate regulations that deal with the appointment of competent persons and detailed provisions and requirements for, for example, mine surveying.

Code of practice

In accordance with the MHSA, an employer must implement a code of practice (COP) on any matter affecting the health and safety of employees and any other person who may be directly affected by the activities at the mine, if the Chief Inspector of Mines requires it, and the preparation of a COP is then mandatory. A guideline for the preparation of a COP to combat rock fall and slope instability related accidents in surface mines has been issued by the South African Department of Minerals and Energy (DME). The implementation of the COP is aimed at satisfying four principles (Gudmanz, 1998):

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

The guideline for the preparation of the COP, which is available to download from the DME website (www.dme.gov.za), contains a considerable number of references to slope monitoring. For example, the following are some of the statements that appear in the guideline:

‘The COP must set out a ……… description of the slope management programme of failure on bench, stack and overall slopes. Detailed strategies for an ongoing stability monitoring …… programme ……’

‘The COP must set out a description ….. of the measures to determine the stability of the mine covering at least the following:
- monitoring of both the rock mass and major geological structures in the mine;
- monitoring of potential planar failure, toppling and ravelling.’

The content of Annex 1 to the guideline, which is for information purposes, is of direct relevance to slope monitoring. The following are some of the statements that appear in this Annex:

‘Success [of ground control measures] is measured by the level of awareness developed before any wall/bench failure and the level of the consequence of a wall/bench failure on the operations.’

‘The inherent uncertainty associated with geotechnical engineering means that it is necessary to regularly monitor the performance of the pit walls to verify the stability or otherwise of relevant areas in the mine. Monitoring of the pit walls therefore becomes an important tool for locating any potential failures of ground before the unstable rock mass becomes hazardous. Well-designed monitoring programs can help differentiate between normal elastic movements, inconsequential dilation and incipient pit wall failure.’

‘Early detection of wall failure allows mine operators to plan and implement appropriate actions with sufficient notice such that the effect of the failure on mine safety and productivity is minimal. The specific nature of monitoring programs required for a given open pit would be dependent on the site-specific conditions of the mine. For example, stiffer rocks will tend to deflect less than softer rocks before failure and certain rock types or geological structures can be weakened by water, thus necessitating more frequent monitoring after periods of rain.’

‘If there is adequate monitoring and a good level of understanding of the ground conditions at each site, there should be no ‘unexpected’ failures. Slope failures do not occur spontaneously. There is scientific reasoning for each failure, and failures do not occur without warning if the failed area is being well monitored. Conversely, once unusual pit wall movements such as cracking have been observed, it does not necessarily follow that the wall will fail.’

The implementation of a COP represents good engineering design practice. It has been shown (Stacey, 2003) that there is significant overlap between the defined requirements for the drawing up of the COP and the rock engineering design process described above.

Geotechnical considerations

The geotechnical aspects that must be addressed in designing a slope monitoring system derive directly from the design process. Only once the conceptual or geotechnical model of the slope has been developed can there be any understanding of how the slope will behave and therefore what monitoring systems are appropriate. The differences in slope behaviour are well illustrated by case studies of monitoring at various mines (Zavodni, 2000; Ryan and Call, 1992; Stacey et al., 2003). The first step in understanding the geotechnical conditions is the carrying out of a thorough investigation of the geological conditions. The extent of investigation will depend on the type of slope and its importance. For example, bench slopes are of much less consequence than ramp and overall slopes and therefore will require less detailed information.

Site investigation includes interpretation of remote sensing data and aerial photographs, mapping of rock exposures (both on surface and underground if there are any underground excavations), logging of borehole core, other borehole information, and geophysical investigation. The
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The importance of a thorough structural geological analysis to identify the structural features that may influence the stability of slopes is emphasized. Rock samples will be selected for laboratory testing, and it may be necessary to carry out field scale testing. Many, very useful geotechnical data can be obtained concurrently with geological exploration. Unfortunately, geological exploration and geotechnical investigation are often treated as separate activities, with the result that geotechnical information that could be obtained during the exploration stage is often lost. Activities often have to be repeated to obtain the required information, and this is at considerable extra and unnecessary cost. The data obtained from the site investigation and associated testing will provide information on the geological structure and hence rock mass structure, presence of major planes of weakness such as faults, groundwater conditions, rock material and rock mass strength and deformability, etc. The better the information available, the better the rock engineering assessment and design that can be carried out. The documentation of this information to ensure its accessibility for any future requirements is extremely important, and the system described by Little (2006) represents an excellent example.

The output from the geotechnical investigation and the slope design should answer the following questions about determining slope monitoring requirements:

- What types of movements are likely—translational, rotational, toppling, rock mass?
- What type of behaviour is likely—brittle and ‘sudden’, or yielding?
- What magnitudes of movement are to be expected?
- What rates of movement are likely?
- What are the groundwater conditions?
- Will the slope be influenced by dynamic loading—seismic and blasting?
- Will deterioration of the rocks take place significantly over time?
- Will slope geometry, particularly plan geometry, modify slope behaviour?

This information will be used to answer questions such as the following about the appropriate type of monitoring:

- What should be monitored—movements, stresses, groundwater, seismicity, etc.?
- Will visual monitoring be adequate?
- Will point location monitoring such as crack meters, borehole instrumentation, inclinometers be effective?
- Will conventional survey techniques with targets provide the necessary information?
- Is a ‘volume’ monitoring method such as seismic monitoring necessary to determine initiation of failure in the rock mass?
- Is a surface monitoring system using laser or radar systems necessary?
- Will satellite monitoring be appropriate?

- Is real time monitoring necessary for safety purposes and if not required, at what frequencies should observations be made?
- How will the monitoring system be linked with slope management?
- How will the slope monitoring system warn the employees of potential danger?

It can be seen that the design of the monitoring system, including the choice of types of monitoring and corresponding types of instruments or methods is almost entirely dependent on the slope geotechnical conditions.

Geotechnical monitoring instrumentation

Geotechnical instrumentation has been used for many years for the monitoring of slopes. It includes such common instruments as crack meters, various types of borehole and surface extensometers, tilt meters, inclinometers, stress meters, and piezometers. This instrumentation has been, and continues to be, widely used in civil engineering slopes. Such slopes must be designed to be stable in the long term and slope monitoring is usually for public safety purposes, to confirm that stability is being maintained. In mining, however, slopes are often temporary and must, for economic reasons, be excavated closer to the stability limit.

Geotechnical instrumentation, if installed, may therefore have a limited life before it is mined out. In addition, many instruments are damaged during the mining process.

In the past few years new equipment has become available which is ideally suited to slope monitoring in a mining environment and also for critical natural slopes. Such equipment is seismic monitoring (Stacey et al., 2004), laser monitoring (Lichti et al., 2002; McIntosh and Krupnik, 2002), radar monitoring (Anglo Coal and Reutech Radar System, 2005; Groundprobe, 2005) and satellite monitoring (ASD-Network, 2006; Kaab, 2002). There is almost a complete overlap between geotechnical and survey capabilities with these types of equipment, and they are also dealt with briefly in the section on survey instrumentation below. From the geotechnical point of view, this new equipment represents a significant and exciting advance in the slope monitoring field. It monitors areas and volumes, not only points and can therefore pick up failure or movements wherever they occur—often instabilities develop between point monitoring locations. Perhaps its most powerful capability from a geotechnical point of view is its ability to monitor data almost in real time. This should allow mechanisms of behaviour, including the location of the initiation of failure, to be determined explicitly rather than to be inferred from point data, or after the event in a case of a slope failure. Such inferences may be completely incorrect and lead to incorrect conclusions or designs.

The new equipment now available can provide answers to most of the questions posed above, and will also provide powerful tools for the confirmation of slope designs—the last step in the design process.

Survey considerations

This section deals with survey monitoring considerations for
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systems design. It does not, however, discuss the survey fundamentals that govern all classes of surveying. These fundamentals are generic and apply to all classes of surveying. In the context of deformation surveys, these are limited to:

- Survey data that allow for numeric values stating location, size, shape and direction of planes and three-dimensional surfaces (Burkholder, 2001)
- Survey measurements and data gathering methods that meet the design specifications
- Data processing and choice of coordinate system and datum
- Presentation of data in a manner that allows for timeous and accurate decision-making.

From the onset it must be emphasized that data processing through sophisticated software cannot correct for poorly designed systems and that survey principles such as 'work from the whole to the part' and 'checking' apply as always.

Survey monitoring instrumentation

The main issues to consider here are design specifications, equipment selection, implementation and installation. Design specifications are typically expected magnitudes of movement, parameters to measure, type and scale of deformation to be monitored, purposes of different instruments, locations of equipment and checks using different survey methods and equipment. During the planning phase, monitoring design specifications give an indication of the desired accuracy and precision required for meaningful analysis. The design specifications guide the monitoring specifications, i.e. definition of objectives and contingency plans; decision on the type, number and frequency of measurements; human resources and training requirements; and the planning of monitoring, processing and reporting methods. Geodetic survey instrument selection depends on economic value added as a result of the system, the required level of confidence in the results, how it will complement geotechnical instruments, ease of interface, GIS adaptability, survey budget for these instruments, environmental conditions in which equipment can operate and survey training necessary for its optimal use. Examples of survey equipment suitable for deformation surveys are levels, theodolites, total stations (Rueger et al., 1992), GPS (Jeffreys, 2004) and remote sensing methods (Kaab, 2002), which include photogrammetric, laser (Mcintosh and Krupnik, 2002), satellite imaging (ASD-Network, 2006) and radar surveys (Anglo Coal and Reutech Radar Systems, 2005; GroundProbe, 2005). Once the equipment is selected implementation and installation commence. Implementation means procurement and installation of the instruments, calibration, deciding on maintenance schedules, establishing factors that will affect accuracy, along with propagation thereof, operating procedures, and protection against vandalism. A final instrumentation consideration is the versatility of the system. For example, when using laser scanning equipment in combination with software such as RealWorks (Smith, 2005), volume calculations between two scanned surfaces become possible. The recent advances in the development of both ground and satellite radar systems will continue to receive significant attention because of the technology’s versatility, coverage and millimetre precision. However, there are still concerns about accuracy, availability and interface with other survey measurement systems. These require further improvement and research.

System design considerations

Installation of survey measuring equipment requires placement of prisms (for total stations) or receivers (for GPS) firstly on the object (the slope) to be monitored and secondly, one or more at fixed positions (around the object). In terms of consistency and uniformity of error propagation, all prisms (or reflectors) and receivers must be identical. Further installation issues to consider during system design are size and weight of equipment, power supply network, protection of equipment and maintenance of the system. Setting-up the control centre for automatic collection and processing of monitoring data is the next consideration. Data transfer could be via radio, cable, cellular or internet communication, which technologies make it possible for all elements of the monitoring network to be accessed remotely from the mine.

Other systems design considerations deal with warning signals, actions required and the communication thereof. Warning signals are normally generated automatically when relative position differences or the velocity of movement exceed the pre-set limits. Adjustments to measuring data (or error propagation methods) and mode of presentation are the final systems design issues to consider.

Control network design considerations

These considerations are necessary in order to establish relative movement among monitored points. Correct design of the network is essential to establish such relative movements. Thomson (2005) found that a poorly designed and adjusted survey network has ‘significantly large orientation and free station residuals’. This problem is exacerbated when one or two control points are not available for orientation - i.e. despite the use of highly accurate sub-centimetre and single second survey instruments. According to Thomson’s observations poor network design causes errors in the order of 20 seconds of arc and 30 mm over a distance of 800 m. It also significantly affects vertical angle measurement, which explains the height inaccuracies that are encountered during typical deformation surveys. Network design considerations include establishing the reference transfer beacon from the control beacon, which must include the mine’s survey benchmark. Transfer beacons are the reference beacons on which the measuring equipment is positioned for monitoring the prisms on the slope. Regardless of the method of surveying, a clear line of sight will be necessary between these beacons. It might seem to be unnecessary when monitoring is done by GPS, but the principle of checking will require a different method of surveying, which will require a line of sight free from any
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obstacles. Future construction projects, waste rock dumps and stockpile areas must be taken into account when doing the network design in order to ensure permanent open lines of sight. In mining, this information is available from the mine planning department. The next consideration is a clear line of sight between the transfer beacons and the monitoring points. Additional reference points must be built as part of the network design in case of damages, loss of line of sight and ground instability. Ground instability is a definite possibility when transfer beacons are situated near the crest, which is necessary for ensuring a clear line of sight to the monitoring points. Stability must be checked periodically by taking frequent readings to one or more reference stations on stable ground away from the mine. These control points could be located anywhere from 100 m to 3 km away depending on the conditions. In addition, the transfer beacons must be resurveyed periodically to check their stability because it is often not clear if deformations are caused by movement of control points or the points being monitored. The monitoring points are on the unstable slope in the form of either total station prisms or GPS receivers.

Conclusions

In this paper an overview has been given of slope monitoring requirements, from both the geotechnical and survey points of view, as well as generically of the types of equipment and instrumentation that are available. Legal issues relevant to slope monitoring have also been dealt with.

It is concluded that conventional geotechnical instrumentation and survey will continue to have their place in slope monitoring. However, the slope monitoring scene has changed substantially in recent years. Areal and volume based monitoring equipment is now available and the service has provided, and will continue to provide, the means to improve safety, and to enhance productivity in mining. Its benefit to slope management is substantial. In the near future it is expected that data obtained from such equipment will add a much-needed new dimension to slope engineering, be used to improve slope designs and to optimize slope angles.

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