

Optimal System Design for Instrumented Slope Monitoring in Open Pit Mines

Sanjive Narendranathan¹ and Hamid Nikraz²

¹Engineer, Coffey Mining Pty Ltd

²Professor of Civil Engineering, Curtin University of Technology

Synopsis: The importance of slope monitoring, and its place in the design and operation of an open-pit mine are presented. Some of the commoner techniques for slope monitoring are reviewed and the limitations and advantages of these compared. Two short case studies are presented; the first illustrates the importance of fully understanding potential failure mechanisms within a slope before designing and installing a monitoring system; the second serves to illustrate a key difference between two types of monitoring system currently in use.

Keywords: slope monitoring, slope stability radar, inclinometer, extensometer, displacement.

1. Introduction

Slope monitoring is becoming widely used in most open pit mines. It can range from simple methods such as visual observations and simple crack dilation measurements to more complex methods such as micro-seismic monitoring and the use of the slope monitoring radar. What the reader needs to appreciate is that whatever method is being employed it needs to be tailored to meet the requirements of the individual slope, i.e. the potential slope instability mechanism needs to be understood and the appropriate slope monitoring techniques employed.

Failure to adequately instrument a slope may result in:

- Loss of life;
- Severe equipment damage;
- Production delays; 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 warnings. There is considerable evidence for example, Ding [1] to indicate that slopes do give ample warning, which confirms that it is well worth the effort to spend time on investigating and implementing appropriate monitoring systems.

It is important to note, that nowadays in hard rock open pits, slope failures often occur after very small deformations [2]. Such failures may be very localised and, unless this area is being very closely and accurately monitored, failures may occur apparently without warning. The dictates for such situations are therefore accurate purpose designed monitoring systems. 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 observations.

1.1 Slope Monitoring and its Role in the 'Design Loop'

Most slope design engineers are familiar with the processes and steps involved in the design of an open pit slope as illustrated in the flow chart (Figure 1). The importance of the role of slope instrumentation and monitoring is demonstrated within steps 4 and 5, whereby the preliminary geotechnical model (as assessed during a feasibility study) within any mine is limited as it is usually based on drill-hole information [3]. This model needs to be refined during the mining process by calibrating the observed slope deformation within the mine so that, with the software analysis, initial rock mass parameters and watertable location etc are refined to reflect true in-situ conditions.

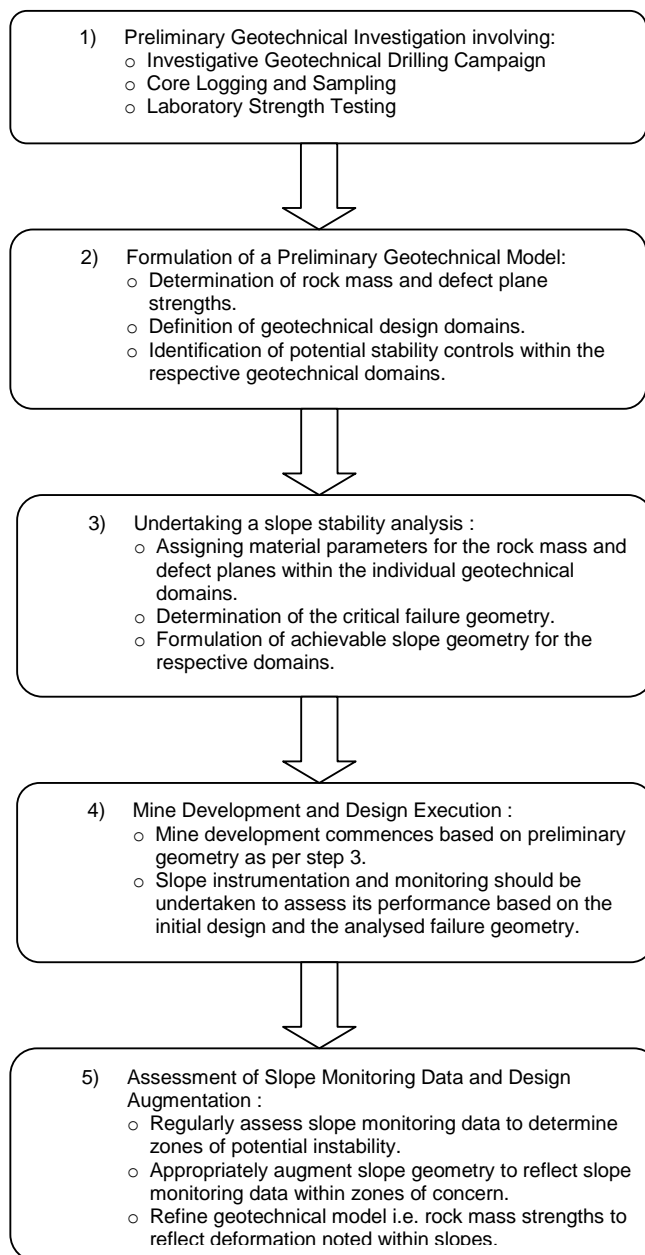


Figure 1. Flow chart of slope design process

2. Slope Monitoring Methods

There are a number of slope monitoring systems and methods currently available. As mentioned previously, it is up to the engineer to assess the requirements of his/her mine to design an appropriate system which may involve a combination of the below mentioned methods.

Commonly utilised slope monitoring methods include:

- Visual Monitoring (Berm-walking, inspection of pit crests for tension cracks etc) - Visual monitoring is a relatively easy way to assess the performance of a slope, particularly if used in conjunction with other methods of slope monitoring. However it is imperative that this is undertaken in a manner that facilitates easy and systematic data collection within a database so that that history of any monitored area can be easily retrieved and assessed;

- Survey Prisms (ATS) - Prism monitoring essentially involves the placement of a network of prisms on the excavated pit crests and accessible berms within an open pit. As prisms are relatively inexpensive, a dense array can be set up around the periphery of the mine, enabling a relatively thorough coverage for recording slope deformation. These prisms can be read by a theodolite, situated along the adjacent edge of the pit. This process can be automated if required, which will enable the prism positions to be measured at a given interval, e.g. every 4 hours;
- Crack Extensometers - Surface crack extensometers are used to monitor changes in the distance between opposing walls (across cracks) or between floors and ceilings of underground excavations or other structures. A tape extensometer consists of a pair of anchors and a steel tape and a portable measuring instrument.
- Anchors are fixed permanently to opposing walls, across a tension crack of concern. To obtain a distance reading, the operator stretches the tape between two anchors, adjusts its tension and notes tape and calliper readings. The fine reading from the dial calliper is added to the coarse reading obtained from the tape. The change in the distance between anchors is found by comparing the current distance reading to the initial distance reading;
- Borehole Inclinometers - Inclinometers measure the lateral movement within slopes. Inclinometers can be used to measure the displacement along a known geological feature or to determine the development of a failure (rotational failure) within a soil or weathered rock slope. However this relies heavily on the user knowing the location of the failure plane / mechanism, and should therefore be used in conjunction with other monitoring methods, such as prism monitoring.
- Slope Stability Radar (SSR) - At least two radar systems are currently commercially available for slope monitoring. The radar systems operate by repeatedly scanning a user-defined area of a slope at fixed angular increments both horizontally and vertically. Each scan is stored electronically as it is recorded. For each horizontal and vertical angle (sometimes referred as 'pixels'), the two-way travel time and the phase difference of the received signals for different scans can be compared so that apparent displacements can be determined with a quoted accuracy of less than 1mm. By selecting appropriate scans to compare, slope movements can be measured between successive scans, or scans hours or days apart, allowing the geotechnical engineer to estimate short or long term rates of movement.

3. Designing a Slope Monitoring and Management System

3.1 Background Information on Site Location and Constraints

There were a number of unique aspects to this site which required a 'tailor-made' slope monitoring and management system to be designed and implemented by the mine operators.

This site was located in close proximity to critical infrastructure. The risk of the infrastructure subsiding into the pit void was very real; hence it was imperative that the designed slope monitoring and management system was able to detect excessive deformation in a timely manner to enable either:

- Relocation of the infrastructure; or
- Placement of appropriate slope support structures to limit displacement.

This case study will present the methodology employed to assess the in-situ rock mass conditions and how this was modelled to derive the proposed slope geometry, monitoring and mining requirements for the site.

3.2 Formulation of the Site Geotechnical Model

The site geotechnical model was formulated by assessing information gathered from a campaign of geotechnical drilling and laboratory testing. The primary focus of the drilling was to target large scale adversely orientated geological features within the proposed pit wall in proximity to the infrastructure. Summarised below are the findings from this investigation programme.

3.2.1 Overview of In-situ Geology

A 2.5 m to 5 m thick soil occurred at surface level (Figure 2). Below the soil the footwall of the pit comprised of predominantly weathered material which overlay fresh rock with a well developed sub-

vertical structures. The depth of weathering was typically about 25m to 30m below surface. Locally, however this was observed to be deeper along lithological contacts.

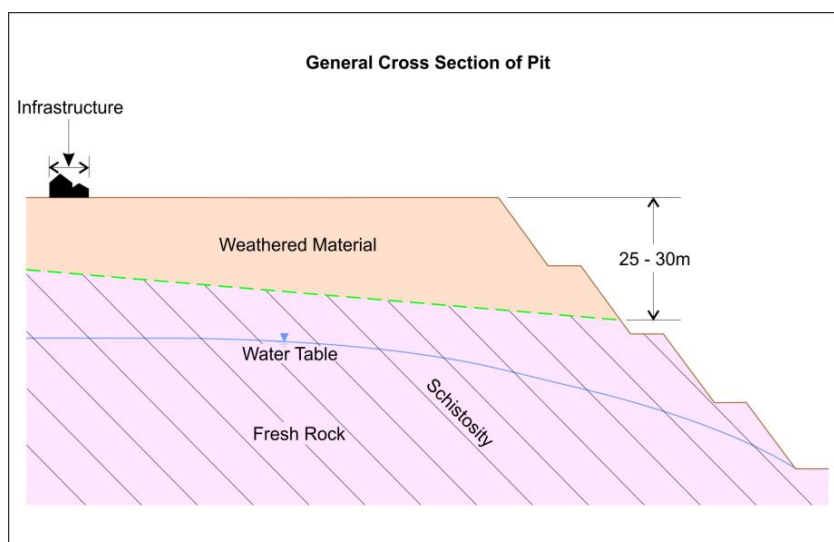


Figure 2. General cross section of pit

3.2.2 Major Structures

The features recorded as major structures consisted of:

- Faults;
- Fault / shears;
- Lithological Contacts; and
- Shears.

In general these features dip relatively steeply between 60° to sub-vertical. Based on this information it was determined that kinematically-controlled failure mechanisms were unlikely on the batter, inter-ramp and overall slope scales, provided that batter angles were less than 60°.

3.2.3 Proposed Slope Design

Rock mass properties were assessed from laboratory testing i.e.

- Triaxial Tests;
- Uniaxial Compressive Strength Tests; and
- Drained Shear Strength Tests.

Based on the assessed material properties and taking into account the loss of strength due to the slake sensitivity of the material the stability modelling indicated that the following slope geometry would be achievable:

- | | |
|------------------|------------------------------------|
| ▪ Weathered Zone | Inter Ramp Slope Angle = 37° |
| ▪ Fresh Rock | Inter Ramp Slope Angle = 45° - 55° |

3.2.4 Monitoring and Risk Management Strategy

A rigorous monitoring regime was proposed for the pit wall in proximity to the infrastructure. This monitoring system was designed based on the following assumptions relating to the anticipated slope failure mechanism:

- Slope failure within the weathered zone could occur as a result of a combination of intact material failure initiating at / near the toe of the inter-ramp slope, a shear failure (planar sliding and / or buckling / toppling) on structure parallel to fabric schistosity, where slope the face undercuts the variably dipping foliation.
- No kinematically-feasible failure mechanisms were interpreted for east wall which is to be mined at batter face angles flatter than the dip of structures. Batter height failure of fresh rock slopes could occur if poor mining practice results in damage to pit walls causing under-cutting of the structures, though this was considered a low risk (unlikely) mechanism for this operation.

Based on the anticipated slope instability mechanism i.e. intact rock mass failure (circular failure), the following monitoring methodologies and systems were put in place to monitor slope deformation, as illustrated below (see Figure 3):

- Two vertical borehole inclinometers installed in the rock mass between the pit crest and the infrastructure.
- Installation and regular monitoring of prisms installed on pit batters and berms as mining proceeded.
- Monitoring of groundwater levels from the vibrating wire piezometers (VWP) installed below the inclinometers in angled geotechnical drill holes collared adjacent to the pit crest.
- Installation and monitoring of a multiple point borehole extensometer (MPBX) in the pit batters.
- Geotechnical mapping of pit wall batter faces to confirm the geotechnical model used in the slope stability analyses.
- Examination of slope movement and calibration of the rock mass deformation models used in the stability analyses and slope design.
- Development of a plan to restrict/halt any slope movements that show early warning signs of compromising the stability of the infrastructure including:
 - Cessation of mining;
 - Placement of fill at the toe of the east wall pit slope; and
 - Back-filling the pit with a suitable fill or tailings at completion of mining.
- Contingency planning to re-locate the infrastructure
- Backfill pit at cessation of mining to increase the factor of safety on abandonment to greater than 2.0.

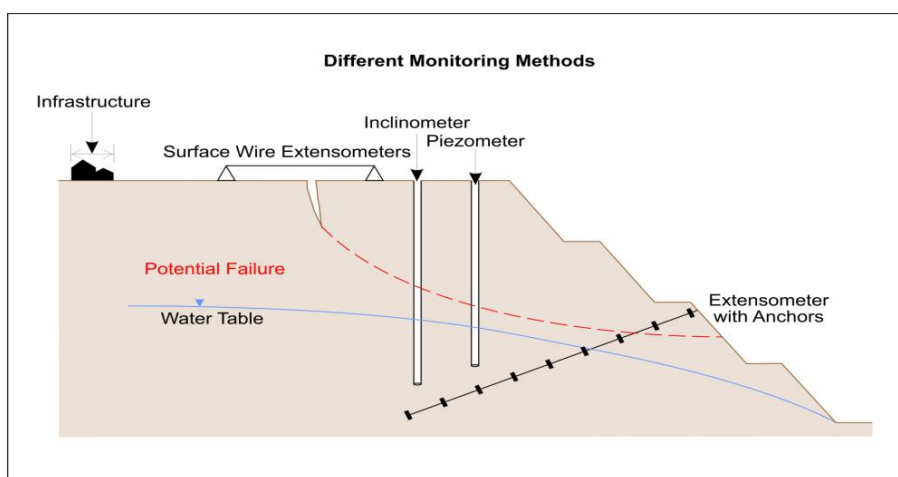


Figure 3. Slope monitoring methods

3.3 Outcomes during Mining

During mining of the weathered zone there was some, (minimal), deformation noted within the inclinometers, MPBX and the prisms. Tension cracks were noted on the pit crest. However no steady trends indicating an increasing rate (acceleration) of slope deformation was noted.

However as mining progressed beyond the weathered zone, tension cracks were noted to appear on the infrastructure. This was not preceded by any notable increases in displacement from the MPBX or the inclinometer data; however some displacement was noted in the prisms.

As the stability of the infrastructure was a major concern, a cessation of mining activities on the wall of the pit was recommended along with the placement of a buttress at the toe of the slope. Upon conducting a more detailed back analysis, using the deformation observations noted and the data from the prisms, it was ascertained that a very deep seated failure plane, orientated at approximately 35° to 45° developed within the pit wall rock mass, as shown in Figure 4.

This plane was not initially picked up during the investigative phase of the drilling, as can often be the case when limited drilling is the sole source of information. For this reason the designed monitoring systems (inclinometers and MPBX) were not installed deep enough i.e. they did not intersect the failure plane. As a result the slope deformation along this feature was not detected.

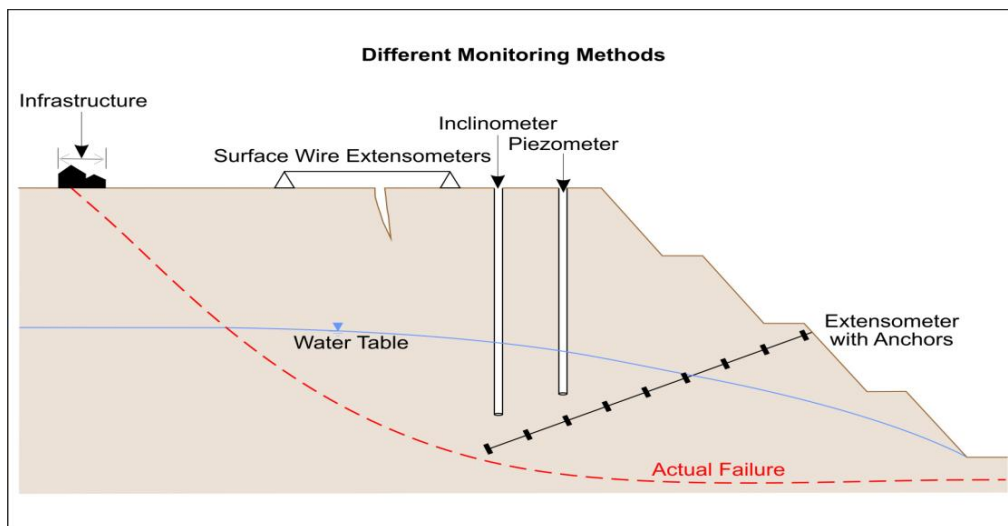


Figure 4. Location of actual failure with respect to installed monitoring instrumentation

4. Conclusions

The following conclusions are not supported by facts; hence these should be treated as the author's opinion only.

- Investigative drilling campaigns do not always pick up all of the relevant features. In this case the structural data as assessed from drill core depicted relatively steeply dipping features between 60° to 80°; however the failure plane that the pit wall was deforming on was dipping at 35° to 45°.
- Modelling may not have adequately taken into account the strain induced on the rock mass as a result of the draw-down induced by mining and dewatering activities. This may have resulted in an extensional feature being generated, i.e. the development of a potential failure plane dipping at 35° to 45° [4, 5].

There are two other possibilities;

- The slake potential may have been higher than assessed; and
- Time dependant mechanisms (creep) may have had a more significant contribution to the slope displacement, than expected [6, 7].

5. References

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