Determination of an Effective Slope-Monitoring Regime for Mining a Failed Zone on the North Wall of Nchanga Open Pit-Cut2

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Nchanga Open Pit Cut 2 experienced a complex slope failure in June 2016 on the hanging-wall side of the mine, involving approximately 1.5 million tons of failed material. This failure zone occurred where a strategic push back involving 16 million tons of waste material and approximately 5 million tons of copper and cobalt was planned to be carried out. While mining in this region, the monitoring regime that had been in place before the failure included slope stability radar, physical inspections and survey monitoring pegs. After the failure, mining through the failed zone involved reviewing the existing controls and defining an effective monitoring strategy to suit the prevailing ground conditions for safe mining operations. A back analysis of the collapsed area was carried out to ascertain the cause of the failure. Reclassification of the rock mass and the associated strength parameters were determined and used in the analyses to understand the behaviour of the failed zone while mining through it. Failed zone specific ground deformation rate trigger levels, alarms and evacuation systems with associated management responses were determined and put in place. Continuous hourly monitoring coverage, 24 h per day, 7 days per week, give real time warning of ground deformation and collapse, thereby reducing risk exposure to personnel and equipment operating in the area of concern. High levels of data analysis and communication of emerging situations to management and workforce were essential elements of a successful strategy. Criteria for the prediction of collapse were developed on an ongoing basis during the period of monitoring. Initial criteria were very conservative. Complete ore extraction was only achieved with continuous and rigorous implementation of perpetual geotechnical recommendations.

INTRODUCTION

Nchanga Open Pit Cut 2 experienced a complex slope failure in June 2016 on the hanging-wall side of the mine (Figure 1), involving approximately 1.5 million tons of failed material. A conducted back analysis showed that the failure was caused by surcharge originating from the overburden dump pressure, which the rock mass structure could not contain. Further, ground water pore pressure, which had been increasing over time, reduced the shear strength of the rock mass and resulted in instability. This failure zone occurred where a strategic push back involving 16 million tons of waste material and approximately 5 million tons of copper and cobalt was planned to be carried out.

Figure 1: Nchanga Open Pit failure zone location.

The complex failure was categorized in two distinct zones: a completely disintegrated zone, which failed and collected at the toe of the slope, reclassified as backfill material, and the partially disturbed rock mass, which remained as part of the slope, reclassified as very blocky and disturbed (Figure 2).

Figure 2: Photograph of the unstable zone.

To determine an effective monitoring system, a number of steps that eventually guide to us to the final result were followed. The steps involved included data collection and analysis, which translated into highlighting the areas or zones that showed clear rock mass deformation and the associated mode of failure. Data collection involved collecting samples for testing and reclassification of the partially disturbed rock mass using the Geological Strength Index (GSI) and the GSI equivalent rock mass rating (RMR) using empirical chart relationships, respectively. The analyses were done using a rock science numerical modelling software (*Phase*^{2}) and an empirical slope design chart to determine preliminary estimation of the stability of the slope. Estimating the stability of rock slopes is required in the mining engineering industry for a variety of projects. Of importance in this regard is the preliminary evaluation of slope stability at feasibility stage, excavation stage or operating stage (Haines and Terbrugge, 1991).

DATA COLLECTION

Collection of data for input into applicable software for analysis was done using a number of methods, as outlined below:

a) Sampling of exposed intact rock samples for each rock formation in the failure zone and testing for unconfined compressive strength (UCS) using a calibrated point load test machine was done. Old boreholes previously drilled in the failure zone were referred to for UCS data of unexposed rock mass.
b) The GSI was determined from the mapping of the post-failure rock mass. The GSI provides a system for estimating the reduction in rock mass strength for different geological conditions (Brady and Brown, 2004). Values of GSI are related to both the degree of fracturing and the condition of fracture surfaces. This was done to reclassify the post-failure rock mass and subsequently derive strength parameters for use in carrying-out stability analyses of the slope. Using the GSI classification system (Figure 3), the partially disturbed post failure slope rock mass structure was reclassified and the equivalent rock mass rating (Equation 1) determined. The results are shown in Table I.

$$RMR = GSI + 5. \quad [1]$$

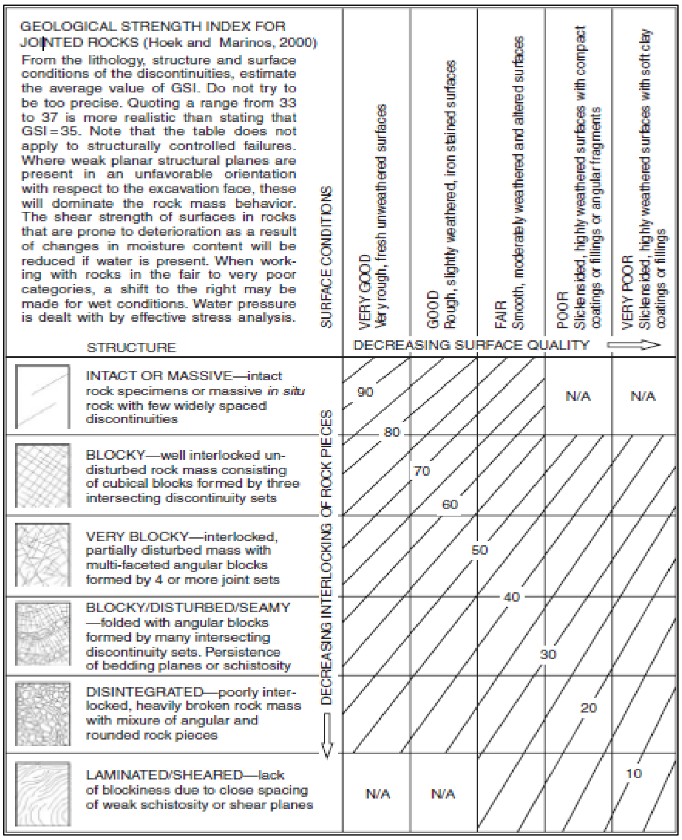

Figure 3: Geological strength index chart.

The strength parameters were determined using *RocLab* – a software program for determining rock mass strength parameters based on the generalized Hoek–Brown failure criterion

(Rocscience, 2007). The GSI and UCS were input rock parameters in the *RocLa*b software. Other *RocLab* software outputs were the rock property constants for slope stability analyses (Table I).

Table I: Reclassified rock mass data.

FORMATION	GSI	RMR Equivalent	UCS	EXISTING STRENGTH PARAMETERS		RECLASIFIED STRENGTH PARAMETERS		mb	s	Remarks
				COHESION	FRICTION ANGLE	COHESION	FRICTION ANGLE			
SWG	45	50	24	150	28	0.426	12.23	0.118	0.0001	disturbed portion part of the slope
CDOL	35	40	70	82	29	1.025	10.57	0.087	0.00002	disturbed portion mined out
DOLSCH	55	60	75	125	35	2.155	18.84	0.362	0.0006	disturbed portion part of the slope
UBS	51	56	40	115.5	27.6	0.869	14.55	0.181	0.0003	disturbed portion mined out
TFQ	55	60	137	106	28.4	5.206	24.62	0.804	0.0006	disturbed portion mined out

c) The densities of the failed zone material were determined through laboratory tests. Determination of the density of the failed material was done by testing collected samples using weight scales, water and beakers for volume determination. The results of the test are as shown in Table II.

Table II: Determined densities of rock in failed zone.

Name	Density (kg/m^3)	Name	Density (kg/m^3)
SWG	1858	UBS	1700
CDOL	1800	TFQ	1793
DOLSCH	1807		

d) The geology of the area was obtained from the site geological database, as shown in Figure 4. The formations are dipping near vertical, with major structures having the same orientation. The pit has three aquifers: the Chingola dolomite (CDOL), BSSU and BSSL. The CDOL directly impacts the failed area.

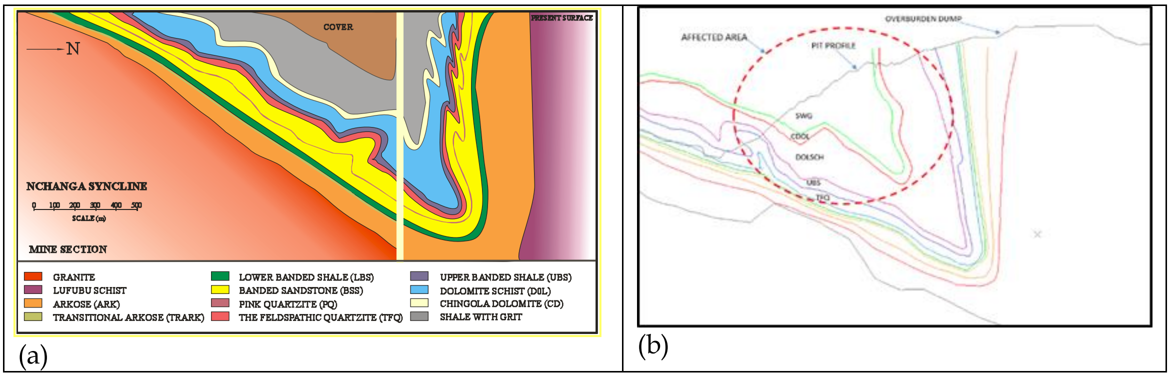

Figure 4: (a) Nchanga open pit geology/stratigraphic column and (b) cross section of the pit in the failure zone.

e) A cross-section was cut across the failed zone for analysis purposes, as shown in Figure 5.

DATA ANALYSIS

The stability analysis of the failed zone was carried out using *Phase²* rock science numerical modelling software. The analysis of the failure zone was done under drained conditions as the post-failure rock mass was blocky and could not retain any water. The results showed Zones 1 and 2 (Figure 6) in the upper slope and toe with potential to deform further and collapse. Part of the overburden dump in Zone 3 was destabilized by mining in the failed zone. The result shows that three primary zones have potential to collapse and, therefore, monitoring systems must be installed to send deformation alerts.

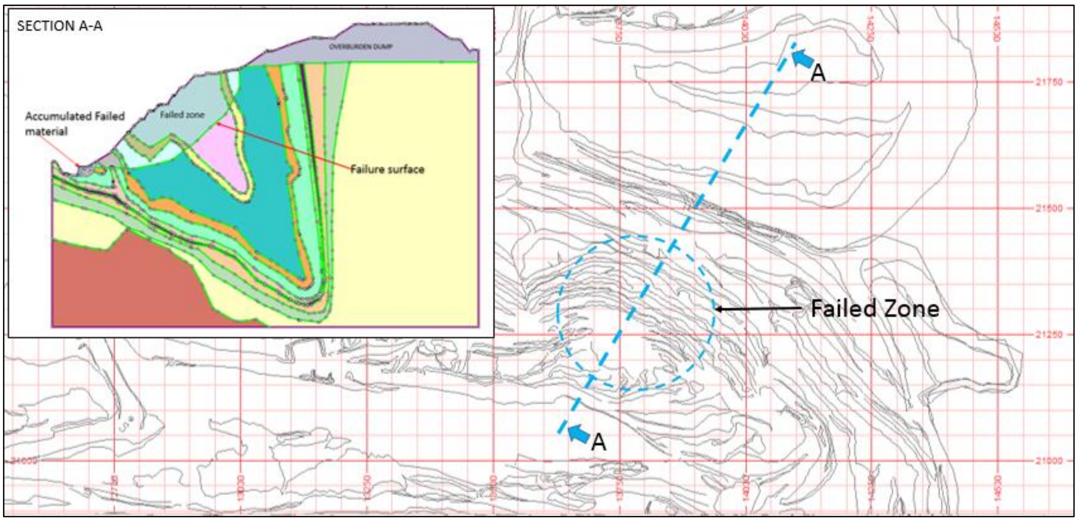

Figure 5: Section A–A.

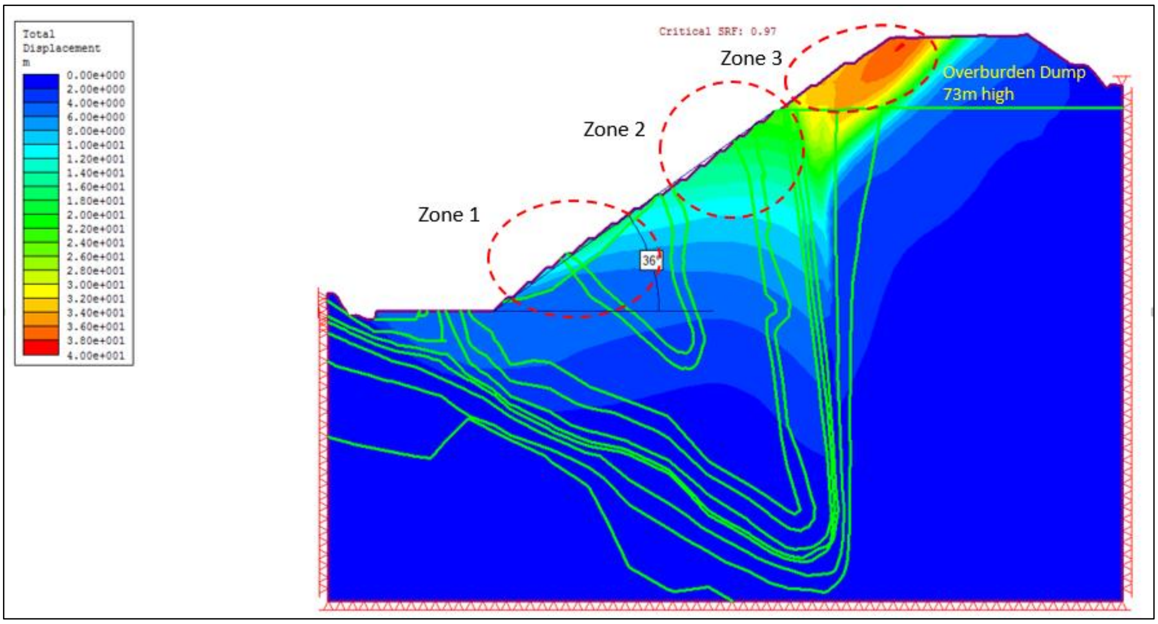

Figure 6: Stability analysis result of the failed zone.

Further, an analysis using empirical slope design chart (after Haines & Terbrugge, 1991) method was also carried out to ascertain the overall slope that could be suitable and guarantee stability in the prevailing rock mass condition. The rock mass rating equivalent (as determined in Table I) of the reclassified GSI, the overall slope height (198 m) and the empirical chart (Figure 7) were used in the analysis. The preliminary overall slope angle required for the slope to remain stable at the prevailing rock mass condition was determined as 37° at a preliminary factor of safety (FOS) of 1.5; however, additional analysis, as highlighted on the empirical analysis chart, is required to verify this result. A summary of all the results is shown in Table III.

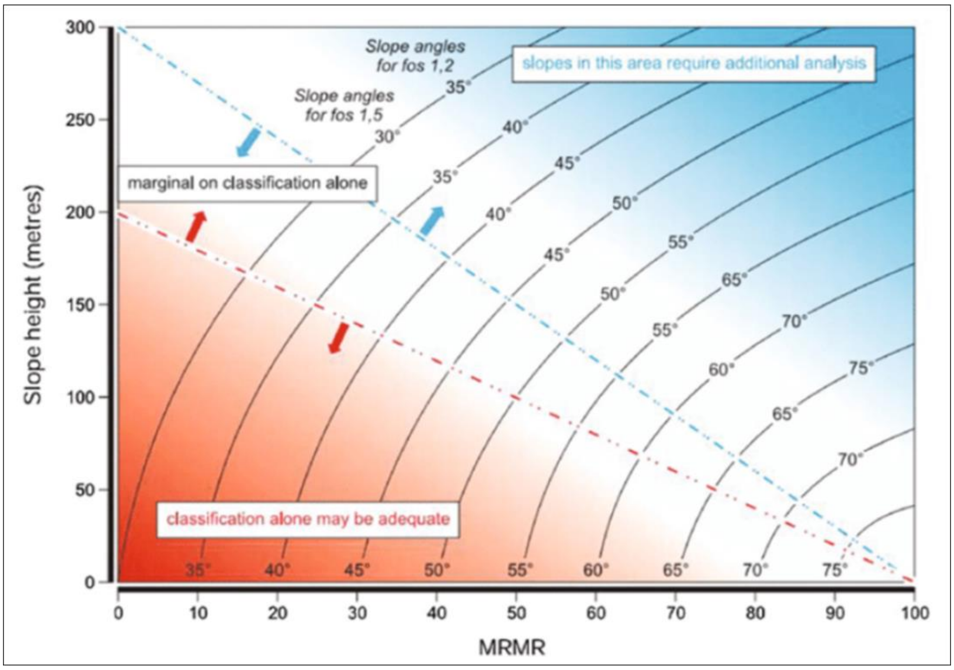

Figure 7: Empirical slope design chart (Haines and Terbrugge, 1991).

Table III: Preliminary slope geometry and FOS, empirical chart design results.

Formation	GSI	Slope height (m)	Equivalent RMR	Preliminary slope angle	Preliminary FoS
SWG	45	198	50	40	1.5
CDOL	35	198	40	36	1.5
DOLSCH	55	198	60	45	1.5
UBS	51	198	56	42	1.5
TFQ	55	198	60	45	1.5
Average RMR for overall slope angle			42	37	1.5

DISCUSSION

The stability of the slope, as demonstrated in the analysis, can be managed with an effective monitoring system that alerts on time and coupled with timely decision making. From the stability analysis using *Phase*², the overburden dump is imposing overburden pressure on the upper slope in Zone 2 and causing it to deform. The deformation in Zone 2 will, in turn, trigger tensile deformation and eventually tension cracks on the dump in Zone 3. Monitoring of the deformation on top of the dump would best be done using extensometers and survey targets (Figure 8). Monitoring using both systems should be done every six hours and the correlation of the two data sets should be determined and interpreted.

Because of challenges in accessing the benches in Zone 2 and the zone having a more pronounced deformation, monitoring would suitably be carried out using a real-time monitoring system, such as a slope stability radar. This should have an effective alert system and be under hourly critical monitoring.

Zone 1 exhibits low deformations; however, the contact between the failed zone and the intact zone daylights in Zone 1. Deformation in this zone may entail a large-scale slope displacement. Therefore, a sensitive monitoring system like the slope stability radar should be used to detect any deformation. This should be coupled with regular field inspections.


Figure 8: Recommended survey monitoring target.

CONCLUSIONS

To determine an effective monitoring system that alerts of significant ground deformation while mining in a failed zone, a detailed data collection exercise and rock mass reclassification should be carried out.

a) The preliminary estimated overall slope angle is 37° at a factor of safety of 1.5.
b) Numerical modelling showed that the strength reduction factor (SRF) is near marginal. Mining should be done under an effective monitoring system coupled with controlled blasting.
c) The results showed Zones 1 and 2 in the upper slope and toe with potential to deform further and collapse. Part of the overburden dump in Zone 3 has been destabilized by the mining in the failed zone. Therefore, monitoring of the deformation on top of the dump would best be done using extensometers and survey targets. Monitoring using both systems should be done every six hours and the correlation of the two data sets should be determined and interpreted.
d) Deformation in Zone 1 may entail a large scale slope displacement. Therefore, a sensitive monitoring system, such as slope stability radar, should be used to detect any ground deformation and send an alert. Additionally, a criterion for the prediction of collapse, such as inverse velocity, should be developed on an ongoing basis during the period of monitoring.

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