Slope Stability Of The Middle Stack Of An Open Pit

Wang Yiming, Trevor Siame, Victor Mwango Bowa

ABSTRACT: Chimiwungo main open pit has experienced slope failure in the weathered rock formation in the middle stack for a decade now. In this article, the geotechnical analysis was conducted to determine the factor of safety and probability of failure of the middle stack using limit equilibrium method under both drained and undrained conditions. The factor of safety and probability of failure index were calculated as they provide the objective measure of the risk of the failure associated with a slope design. The actual stack performance was compared to various slope stability acceptance criteria with results subjected to a more thorough analysis of the consequences of failure. The study indicates that under dry to semi-drained conditions, the factor of safety and the probability of failure were compliant to all the acceptability slope stability failure criterion. This entails under dry and partially drained conditions, the middle stack of the Chimiwungo Open Pit is predicted to remain stable. As the undrained condition of the stack is above 30% of water content, the resulting safety factor and the probability of failure becomes out of compliance with the acceptance slope stability failure criterion. This entails the performance of the stack with respect to acceptance failure criteria falls below the minimum mean factor of safety and violates probability acceptance failure criteria, leading to unstable stack. The study recommends major modification to the stack geometry and that the stability of the stack be tested in both drained and undrained conditions prior to implementations.

KEYWORDS: Slope failure; middle stack; the factor of safety; the probability of failure; drained and undrained conditions; acceptance failure criteria.

1 INTRODUCTION

Lumwana (Chimiwungo) Open Pit has experienced slope failures in the weathered rock formation in the middle stack of the pit's slope. Slope failure once occurs, may pose a safety and health concern to humans and has the potential to damage the mining equipment, and disrupts mine business plans for the surface mines. In order to mitigate an unexpected failure of the slope, slope stability studies are conducted by the experts in the Mining engineering field prior to slope creations. Slopes once generated, depicts two or more free surfaces because of its geometry. Circular failure, wedge failure, toppling failure, plane failure, and buckling failure are the various mechanisms in which a slope could fail as recognised in many geotechnical articles and Books [1], [2], [3], [4], [5] [6],[7],[8],[9], [10] [11], [12], [13], and [14]. It is not strange to encounter several of these failure types or different combinations of several failure types in natural and man-made slope ([15], [16], and [17]. The stability of the slope governed by equilibrium conditions diminishes as the ratio of the resisting to driving forces reduces to below 1.0. The external and internal triggering processes contribute to the decrease in the resisting forces and an increase in the driving forces respectively. Once the resisting forces are reduced further and equals the driving forces of the slope, the slope is judged to be at an equilibrium state. Any further reduction of the resisting forces drags the safety factor to fall below the equilibrium state and the slope fails. The increased internal triggering processes, reduce the resisting forces of the rock mass of the rock slope. Conversely, driving forces in the slope may increase due to the external triggering processes as explained in the work of ([18], [19], [20] ([21], [22], [23] and [24]). This article involved analysing the influence of the middle stack angles on the stability of the slope by geotechnical analysis method for the Lumwana (Chimiwungo) Open Pit. The Lumwana Mining Limited Copper Project (Lumwana) is located in the North-western Province of Zambia, approximately 300 km west by road from the Copperbelt city of Kitwe and 95 km west by road to the provincial centre of Solwezi. The Geotechnical analysis is an assessment of the potential for slope failure within the pit limit. The Geotechnical analysis was conducted to determine the factor of safety and probability of failure of the stack being investigated. It was carried-out using SLIDE computer program. The SLIDE software is a 2D slope stability program for evaluating the safety factor and probability of circular or non-circular failure surfaces in soil or rock slopes. The SLIDE computer program has extensive probabilistic analysis capabilities - you may assign statistical distributions to almost any input parameters, including material properties, support properties, loads, and water table location. The factor of safety and probability of failure index is calculated, and provides an objective measure of the risk of failure associated with a slope design. Sensitivity analysis allows one to determine the effect of individual variables on the safety factor of the slope. Back analysis allows you to determine the required support force for a given safety factor. Advanced search algorithms simplify the task of finding the critical slip surface with the lowest safety factor. Site investigations and actual slope geometry model was generated for the Lumwana (Chimiwungo) Open Pit to assess the geotechnical suitability of the geometry parameters that were used prior to failure. This range takes into account the mining prior to slope failure. Dry conditions and (10-50) % water content were considered. In the geotechnical analysis, Bishop simplified and Janbu methods were used for analysis of non-circular slip surfaces. These types of failure surface were specified due to isotropic and anisotropic effects of different formations occurring in the slope. The factor of safety and probabilities of failure for the middle stack of Chimiwungo Open Pit were determined using Limit Equilibrium Methods and compared to various slope stability criteria such as ([25], [26], and [27]) to determine the acceptance criteria. The analysis was carried out as a simulation of the probabilities of failure for the middle stack of Chimiwungo Open Pit using SLIDE software.

2 SLOPE FAILURE – MIDDLE STACK OF CHIMIWUNGO MAIN OPEN PIT

Lumwana mine has experience a number of slope failure since mining started in 2008 to today with slope failure occurring in the middle stack of the pit in the saprolite, laterite soil and Saprock materials. Geotechnical warning signs are put in place and band at the toe extended, on account of a previous unstable areas. There are no injuries, no equipment damage but loss of production is occurred. The volume of material that fail are estimated to range from 1000- 10 000 tonnes by manual computations. There are visible groundwater flowing from the areas especial during rain seasons. Figure 1 below

shows the pictures of Chimiwungo slope failures in the middle stack.

Figure 1. *Slope failure recorded in the middle stack of the pit*

3 GEOTECHNICAL ANALYSIS

This analysis is an assessment of the potential for the slope failure ranging from the bench to the overall middle stack angle. It was carried-out using the SLIDE computer program. The Chimiwungo open pits are divided into section lines shown in Figure 2. The slope profiles for each section of the middle stack were generated for geotechnical analysis using computer programme SLIDE 5.0 in the Limit Equilibrium method (LEM). In this limit element method (LEM) analysis, Bishop simplified and Janbu methods were used for analysis of non-circular slip surfaces. These types of failure surface were specified due to isotropic and anisotropic effects of different formations occurring in the slope.

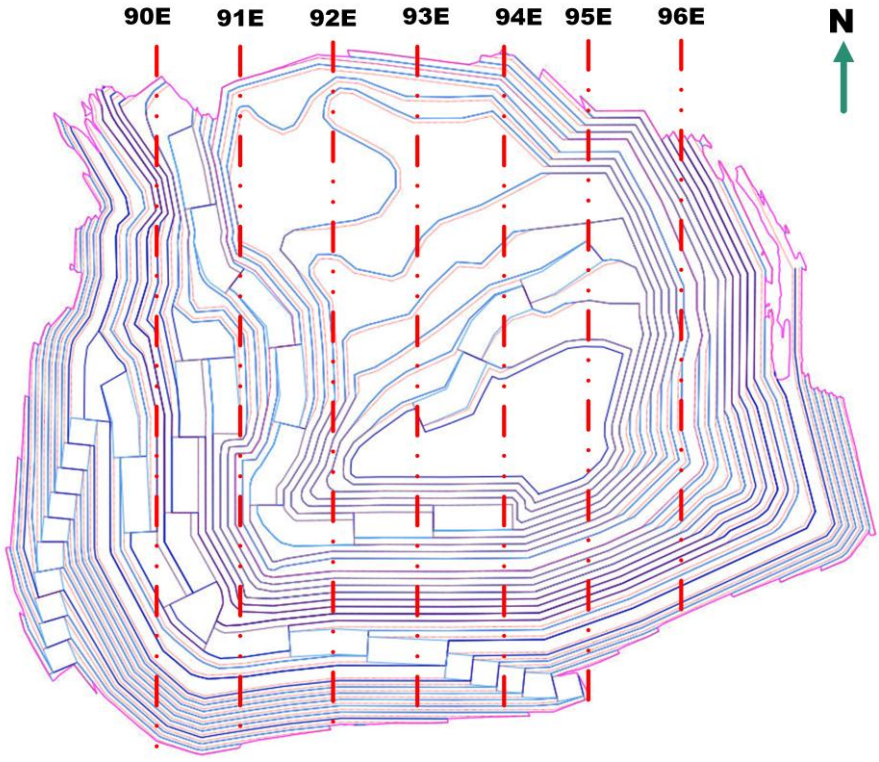

Figure 2. *Mine Plan showing the section lines from which slope profiles were generated for geotechnical analysis.*

3.1 Geotechnical Parameters

The input parameters were obtained from a hybrid of data from the Rock Mechanics field database, Lumwana Open Pit Geotechnical Laboratory, and ROCLAB (a computer program for estimating rock mass properties-ROCSCIENCE, (28). The parameters used in the model are given in Table 1.

Table 1. *Geotechnical Parameters*

Rock Type	Density (Kg/m^3)	Young's Modulus (GPa)	UCS (MPa)	Poisson's Ratio	Peak Strength		Residual Strength	
					Cohesion (kPa)	Friction Angle (º)	Cohesion (kPa)	Friction Angle (º)
OSCH	2900	20	15	0.1	900	16	200	16
SCH	2850	35	30	0.3	200	30	100	23
GNS	2650	60	100	0.35	300	47	0	30
CBG	3000	50	200	0.32	400	55	0	35

Where OSCH= ore schist; SCH = Schist; GNS= Gneiss and CBG=Barren Gneiss

3.2 Slope geometry of the upper stack of Chimiwungo Open Pit

The open pit slope profile parameters used on the middle stack of Lumwana (Chimiwungo) Open Pit for the rock materials in both drained and undrained conditions are provided as follows;

- Bench Height: 12m; Bench Face Angle: 65°
- Spill Berm Width: 7.5m; Bench Stack Angle: 46.9° (for a 96m high stack)
- Stack berm width: 20m

3.3 Determination of Factor of Safety and Probability of Failure

A representative model set-up for analysis in Limit equilibrium was adopted along Section 91E as indicated in Figure 3. Four slope profiles of the middle stack of Chimiwungo were generated from the four sampled section lines namely 90E; 91E, 95E and 96E and the factor of safety and probability of failure in each section line were obtained. This range takes into account the previous and current pit slope profiles prior to slope failure. Dry conditions and up to 50% of water content were considered.

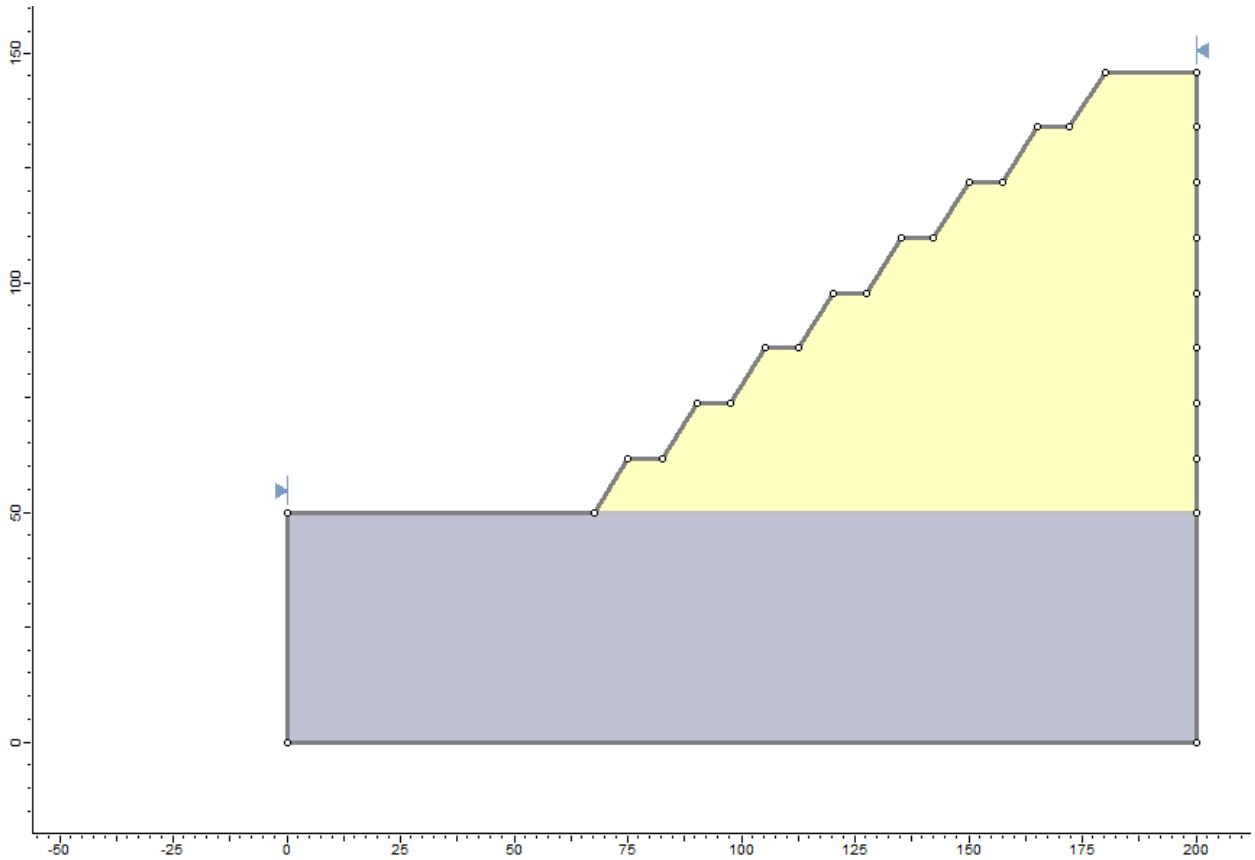

Figure 3. *A representative model set-up along Section 91E using SLIDE program for the middle stack of the Chimiwungo Open Pits*

3.4 Factor of Safety (FOS) and Probability of Failure (POF) Results

This section provides the results of the data analysis that was carried out for the Chimiwungo Open Pits design shown in Figure 3 above. Results of the Factor of Safety are displayed in the text box in Figure 4 and the Probability of Failure analyses are tabulated below in Tables 2 for the Chimiwungo Open Pit designs.

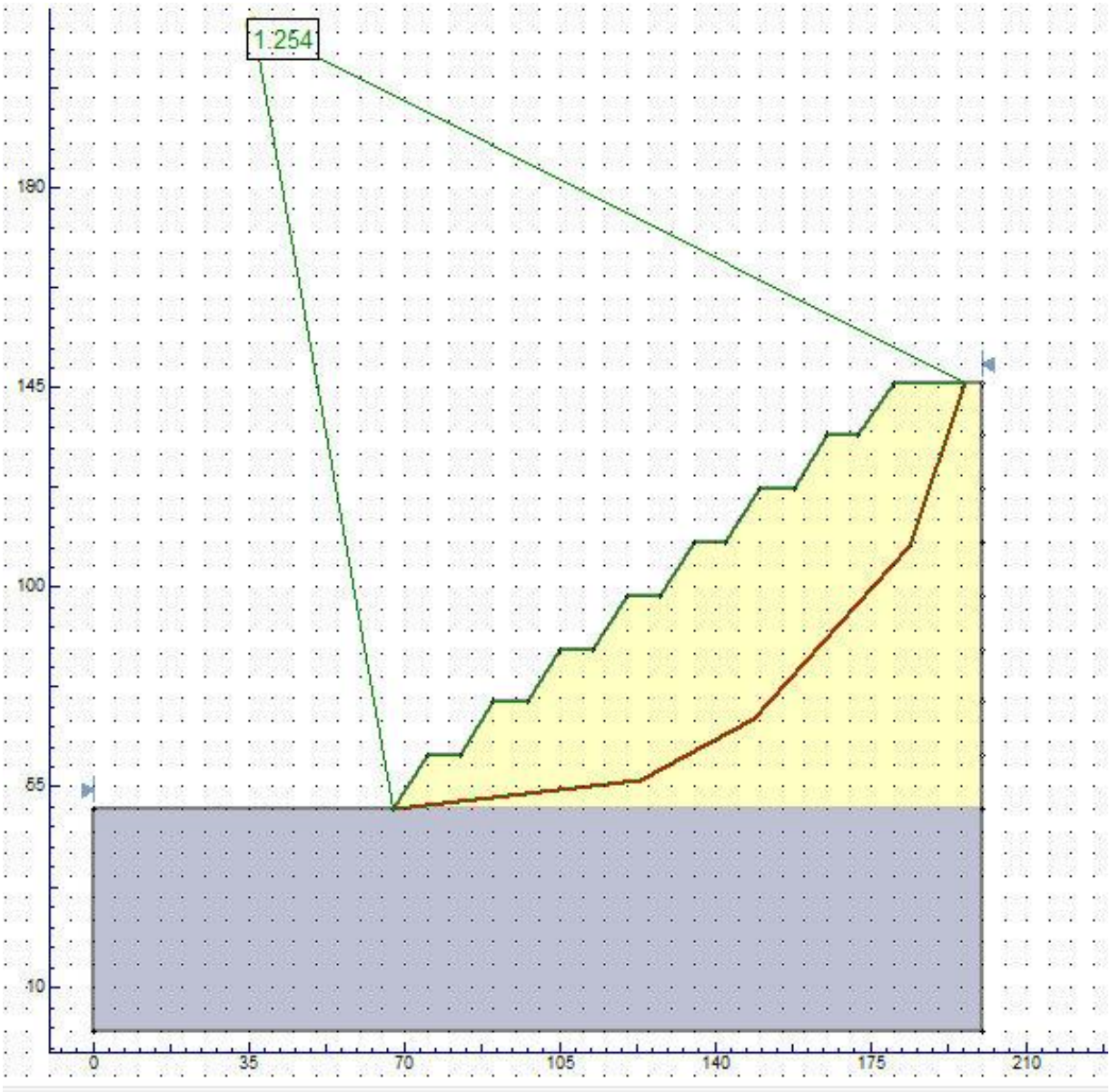

Figure 4. *Results for the factor of safety Section 90E using SLIDE program for the middle stack of the Chimiwungo Open Pits when the water content is 20%*

Table 2. *Factor of Safety and Probability of Failure*

Section	Conditions	Middle Stack	
		FOS	POF (%)
90E	Dry	1.63	3
	Wet @ 10%	1.45	12
	Wet @ 20%	1.25	20
	Wet @ 30%	1.11	38
	Wet @ 40%	0.98	50
	Wet @ 50%	0.82	65
91E	Dry	1.65	2
	Wet @ 10%	1.48	10
	Wet @ 20%	1.31	15
	Wet @ 30%	1.22	23
	Wet @ 40%	1.10	40
	Wet @ 40%	0.94	56
95 E	Dry	1.56	6
	Wet @ 10%	1.42	13
	Wet @ 20%	1.33	16
	Wet @ 30%	1.20	19

	Wet @ 40%	1.00	48
	Wet @ 50%	0.89	61
96 E	Dry	1.73	0
	Wet @ 10%	1.55	4
	Wet @ 20%	1.40	15
	Wet @ 30%	1.28	18
	Wet @ 40%	1.15	38
	Wet @ 50%	0.98	50

4 SLOPE DESIGN ACCEPTABILITY CRITERIA

The outcomes of the geotechnical analyses were interpreted using several stability criteria presented in Tables 3, 4 and 5 below. The criteria used include the ones by Priest and Brown ([25]), Read and Stacey ([27]) and Terbrugge ([28]).

General Slope Design Acceptability Criteria– NO.1

Table 3. *Slope Design Acceptability criteria – (Priest and Brown [25])*

Type of Slope	Consequence of Failure	(FoS)	(PoS<1.5)
Individual benches; (<50 m bench height), temporary slopes not adjacent to haulage roads	Not serious	1.3	20%
Any slope of a temporary or permanent nature	Moderately serious	1.6	18%
Medium sized (50-100m slope height) and high slope with slope height of <150m) carrying major haul roads or underlying permanent mine installations	Very serious	2.0	5%

Note*: FoS = Factor of safety; PoF= probability of failure. The actual criteria to be used in a specific mine (e.g. Chimiwungo Open Pits) cannot be determined from general guidelines like the ones by Priest and Brown ([25]) and should be subject to a more thorough analysis of the consequences of failure (Sjöberg, [29]).*

Acceptability Criteria – NO.2

Table 4. *Slope Design Acceptability criteria- Eds. Read and Stacey, (2009)*

Slope Scale	Consequences of Failure	FOS	POF (%) [FOS<1.2]
Bench	Low-high	1.1	(25-50)
Inter-ramp (Stack)	Low	1.2	25
	Medium	1.2	20
	High	1.2-1.3	10
Overall Slope	How	1.2-1.3	15-20
	Medium	1.2-1.5	5-10
	High	1.2-1.5	<5

Acceptability Criteria- No.3

Table 5. *Slope Design Acceptability criteria - Criterion (Terbrugge – [26])*

Category	Description	Acceptable Probability of Failure
1	Critical slopes where failure may affect continuous operations and pit geometry	5%
2	Slopes where failure have a significant impact on costs and safety	<15%
3	Slope where failure has no impact on costs and where minimal safety hazard exists	<30%

5 ANALYSIS OF RESULTS BASED ON SEVERALLY ACCEPTABILITY SLOPE STABILITY CRITERIA

The outcomes of the analyses were analyzed using several slope stability criteria and the results are presented in Tables 6-11 below. The shaded cells in Tables 6-11 relate to Chimiwungo Open Pits' current assessment of the acceptability slope stability criteria that should be applied to the Chimiwungo Open Pit. The probabilities of failure associated with acceptability slope criteria are in the range =<5% and corresponding factors of safety lie between 1.2 and 1.5.

Table 6. *Dry Condition, RU=0.0*

Middle Stack	Resulting (FOS/POF)		Compliance with Acceptability Criteria	
Section	FOS	POF (%)	FOS	POF
90E	1.63	0	Compliant	Compliant

91E	1.65	0	Compliant	Compliant
95E	1.56	1	Compliant	Compliant
96E	1.73	0	Compliant	Compliant

Table 7. *Wet Condition RU=0.10*

Middle Stack	Resulting (FOS/POF)		**Compliance with Acceptability Criteria**	
Section	**FOS**	**POF (%)**	**FOS**	**POF**
90E	1.45	2	Compliant	Compliant
91E	1.48	1	Compliant	Compliant
95E	1.42	2	Compliant	Compliant
96E	1.55	1	Compliant	Compliant

Table 8. *Wet Condition RU=0.20*

Middle Stack	Resulting (FOS/POF)		**Compliance with Acceptability Criteria**	
Section	**FOS**	**POF (%)**	**FOS**	**POF**
90E	1.25	20	Compliant	Not compliant
91E	1.31	13	Compliant	Not compliant
95E	1.33	13	Compliant	Not compliant
96E	1.40	10	Compliant	Not compliant

Table 9. *Wet Condition RU=0.30*

Middle Stack	Resulting (FOS/POF)		**Compliance with Acceptability Criteria**	
Section	**FOS**	**POF (%)**	**FOS**	**POF**
90E	1.11	38	Not compliant	Not compliant
91E	1.22	23	Compliant	Not compliant
95E	1.20	19	Compliant	Not compliant
96E	1.28	18	Compliant	Not compliant

Table 10. *Wet Condition RU=0.40*

Middle Stack	Resulting (FOS/POF)		**Compliance with Acceptability Criteria**	
Section	**FOS**	**POF (%)**	**FOS**	**POF**
90E	0.98	50	Not compliant	Not compliant
91E	1.10	40	Not compliant	Not compliant

95E	1.00	48	Not compliant	Not compliant
96E	1.15	38	Not compliant	Not compliant

Table 11. *Wet Condition RU=0.5*

Middle Stack	Resulting (FOS/POF)		**Compliance with Acceptability Criteria**	
Section	**FOS**	**POF (%)**	**FOS**	**POF**
90E	0.82	65	Not compliant	Not compliant
91E	0.94	56	Not compliant	Not compliant
95E	0.89	61	Not compliant	Not compliant
96E	0.98	50	Not compliant	Not compliant

The slope performance with respect to acceptability criteria is given Table 12. Table 12 also provides recommendation on measures to take in case of non-compliance.

Table 12. *Slope Performance based on Acceptability Criterion (Priest and Brown- [25])*

Performance of Slope with respect to acceptability Criteria	**Interpretation**
Satisfies all criteria	Stable Slope
Exceeds minimum mean FOS but violates probability criteria	Operation of slope presents risk that may or may not be acceptable; level of risk can be reduced by comprehensive monitoring programme
Falls below minimum mean FOS and violates PoF criteria	Unstable slope; major modifications of slope geometry required; rock improvement and extensive slope monitoring is necessary.

6 Interpretations of Results

The actual slope performance for the middle stack of Chimiwungo Open Pits under drained and undrained conditions was determined based on all the three acceptability slope stability criterion and the middle stack of Chimiwungo Open Pits was subjected to a more thorough analysis of the consequences of failure. The results indicate that under the dry conditions, the factor of safety and the probability of failure for all the section lines of the middle stack of Chimiwungo open pits were compliant to all the three acceptability slope stability failure criterion as shown in Table 6. This entails that in dry season the middle stack of Chimiwungo Open Pits are predicted to remain stable. The results indicate that under semi-dry conditions with groundwater conditions of 10%, the factor of safety and probability of failure for all the section lines of the middle stack of Chimiwungo open pits were compliant to all the three acceptability slope stability failure criterion as shown in Table 7. This entails that as rain season commences the middle stack of Chimiwungo Open Pits are predicted to remain stable. The results indicate that under undrained conditions with groundwater conditions of 20% or less, the factor of safety for all the section lines of the middle stack of Chimiwungo open pits was compliant to all the three acceptability slope stability failure criterion but the probability of failure for all the section lines of the middle stack of Chimiwungo open pits were not compliant to all the three acceptability slope stability failure criterion as shown in Table 8. This entails that during the rainy season, the middle stack of Chimiwungo Open Pits are predicted to remain stable as the factor safety exceeds minimum mean FOS but violates probability criteria. This means that the operation of slope presents risk that may or may not be acceptable. The level of risk can be reduced by a comprehensive monitoring programme. Furthermore, the results indicate that under undrained conditions with groundwater conditions of 30%, the factor of safety for section line 91E, 95E and 90E of the middle stack of Chimiwungo open pits was compliant to all the three acceptability slope stability failure criterion except Section line 90E but the probability of failure for all the section lines of the middle stack of Chimiwungo open pits were not compliant to all the three acceptability slope stability failure criterion as shown in Table 9. This entails that during the rainy season, the middle stack of Chimiwungo Open Pits for section line 91E, 95E and 90E of the middle stack of Chimiwungo open pits are predicted to remain stable as the factor safety exceeds minimum mean FOS but violates probability criteria. Operation of slope for section line 91E, 95E and 90E of the middle stack of Chimiwungo open pits presents risk that may or may not be acceptable. The level of a risk can be reduced by a comprehensive monitoring programme. For section line 90E as shown in Table 9, of the middle stack of Chimiwungo open pits, the performance of slope

with respect to acceptability criteria, falls below minimum mean FOS and also violates probability criteria. This that entails section line 90 E falls under unstable slope. The remedial measures require major modifications of slope geometry and rock improvement and extensive slope monitoring are necessary. Lastly, the results indicate that with groundwater conditions of above 40%, the factor of safety and probability of failure for all the section lines of the middle stack of Chimiwungo open pits were not compliant to all the three acceptability slope stability failure criterion as shown in Table 10-11. These results indicate that the Performance of Slope with respect to acceptability Criteria falls below minimum mean FOS and violates probability criteria.

7 CONCLUSION

The factor of safety and probabilities of failure for the middle stack of Chimiwungo Open Pit were determined using Limit Equilibrium Methods. The actual slope performance for the middle stack of Chimiwungo Open Pits under drained and undrained conditions were determined based on all the acceptability slope stability criterion and the middle stack of Chimiwungo Open Pits was subjected to a more thorough analysis of the consequences of failure. The results indicate that under dry to semi-dry conditions with groundwater conditions of 0-20%, the factor of safety and probability of failure for all the section lines of the middle stack of Chimiwungo open pits were compliant to all three acceptability slope stability failure criterion. This entails that as rain season commences the middle stack of Chimiwungo Open Pits are predicted to remain stable. Lastly, the results indicate that with groundwater conditions of above 30%, the factor of safety and probability of failure for all the section lines of the middle stack of Chimiwungo open pits were not compliant to all the three acceptability slope stability failure criterion. This results indicate that the Performance of Slope with respect to acceptability Criteria falls below minimum mean factor of safety and violates probability criteria leading unstable stack. The remedial measures requires major modifications of slope geometry and rock improvement and extensive slope monitoring is necessary.

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