JWANENG OPEN PIT MINE CUT 8 SOUTH EAST WALL SLOPE DESIGN

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1.0 Synopsis

Slope stability is a fundamental part of a successful mining operation. It impacts directly on the safety of personnel and the economics of the mine. The Jwaneng Mine in Botswana is planning a push back of 644m depth in the south east wall. Mining will commence in 2010 and be completed in 2024. This will put the mine in the deep pit category. The mine has invested in extensive geotechnical data gathering and design programs that started as far back as 2003 for the south east wall.

The south east wall of Jwaneng Mine is characterized by foliation that dips adversely into the mining faces. The orientation of the foliation is variable due to intense tectonic movements that have also caused the occurrence of faults that are sub-vertical. A considerable amount of information on the characteristics of structural patterns and the rock mass has been collected. This paper presents an overview of the feasibility level geotechnical design that is about to be concluded.

2.0 Introduction

Jwaneng Mine has been in operation since 1979. It is located in the southern part of Botswana at a distance of about 160km due west from Gaborone. The mine is owned by Debswana Diamond Company which is part owned by the Botswana government and De Beers Centenary AG. Figure 2.1 shows the location of Jwaneng Mine and Debswana Diamond Company's other mine sites.

Figure 2.1: Location Map of Debswana Diamond Company Mines

Jwaneng is the largest producer of diamonds by value for Debswana Diamond Company and one of the world's chief producer of gem diamonds. Diamonds account for over 70% of Botswana foreign reserves earning, hence Jwaneng Mine is of importance to the company and the country.

The Cut 8 pit dimensions are approximately 2.3km in the long axis (NE-SW) and 1.6km wide in the short axis (NW-SE). The current pit depth is at 340m and is intended to reach 536m in the Cut 7 pushback. The next mining pushback will be Cut 8 and this will go down to a depth of 644m with waste mining increasing from current 40Mtpa to a peak of over 110Mtpa.

The Cut 8 pushback will encroach on some existing plant infrastructure that will hence be required to be relocated. The Main Treatment Plant (MTP) will be located at about 220m from the proposed Cut 8 pit crest and hence the geotechnical design will need to ensure its stability. Figure 2.2 below shows the Cut 8 pit crest and some of the plant infrastructure that will require relocation

Figure 2.2: Location Map of Jwaneng Mine Cut 8 Pushback

2.1 Geology

The diamondiferous kimberlitic pipes have intruded into a package of sedimentary rock formations comprising of dolomites, shales and quartzites of the Pretoria group of the Transvaal super group laid down in Proterozoic times. The sequence is broken up by extensional shears, thrusts and steep block faults. Dolerite sills and dykes also intrude the country rock. Due to this complex geology, the strata in the vicinity of the mine varies between dips of 10°- 40° towards the northwest and is bounded by major faults that dip steeply into the south east wall.

Bench and inter-ramp scale stability on the south east wall is therefore predominantly controlled by the structural fabric in which foliation/bedding daylights into the mine slopes and forms planar failures. In the more fissile units of the sedimentary packages breaking back to the foliation planes occurs as mining progresses whilst in the more massive units the deterioration progresses with the aid of blasting. This causes rock fall hazardous operating conditions as mining progresses to lower benches. See Figures 2.3 below.

Figure 2.3: South east wall with distinct bedding/foliation planes

2.1.1 Regional Geology

The stratigraphic sequence of Jwaneng Mine starts with a cover of about 60m of Kalahari sequence comprising of sand and calcrete. The Kalahari sands are a reddish to white matrix of sand. The calcrete sands are mostly a whitish conglomerate that also comprises clasts of rock in some places.

Laminated and Carbonaceous Shales of the Timeball Hill formation follow in the sequence. The Laminated Shales are thinly bedded, laminated and occasionally have intercalations of sandstone. The Carbonaceous Shale is a 30m thick unit that is graphitic shale interbedded with felsic volcanic tuff.

The Rooihoogte quartzites follow in the sequence and form the bulk of the Jwaneng slopes with their thickness getting to about 375m. They are also thinly bedded, parallel laminated mudstone-siltstone-fine grained sandstone beds. A thin marker horizon of conglomerates that are rounded and monoclinic is called the Bervets. This splits the quarzites into two and makes sharp contact between the two Quarzitic units above and below. The lower Quatzitic Shale is almost the same as that above though it is more ferruginous and coarser. It forms a gradational contact with the Dolomites below.

The lower Rooihoogte formation comprises of another unit of Carbonaceous Shales that is less thick at 10m. Dolomites of the Malmani Subgroup are at the bottom of the mine sequence and though there has been less intersection from drill holes they are thought to be massive. They comprise of a greyish conglomerate with clasts of dolomite and this has a sharp contact with the underlying cherty dolomites. Lenses of Carbonaceous Shale also occur in places.

Intrusions of Syenites, Dolerites and Quarzt-phorphry also cut into the sedimentary sequence to form sills and dykes. A stratigraphic column of the Jwaneng Mine is shown in Table 2.1 below.

Stratigraphic Name	Rock Type (Mine Rock Code)	Typical Thickness (m)
Kalahari Sequence	Sand and Calcrete (CS)	55-60
Timeball Hill Formation	Laminated Shale (LS)	'Residual'
Lower Timeball Hill Formation	Carbonaceous Shale (CS)	30
Rooighoogte Formation	Quartzitic Shale (QS)	135
Chert Pebble Conglomerate	Bevets	0-4
Rooighoogte Formation	Quartzitic Shale (QS)	375
Lower Rooighoogte Formation	Carbonaceous Shale	10
Malmani Subgroup	Dolomite (DM)	'Residual'

Table 2.1: Stratigrahic Column of the Jwaneng Mine (After SRK Country Rock Model Update 2006 Wayne Barnett)

2.1.2 Structural Geology

The structural model of Jwaneng Mine was constructed in 2001 and updated in 2006 by Dr. Barnett. Review of the models was carried out by Prof. Dirks who has conducted field mapping in the mine area.

New information has since been collected in a drilling program that was conducted in 2008. This includes rock fabric data from oriented core and acoustic televiewing, rock mass classification and laboratory data. Updated 2009 model has been completed. A 3-D view of the model is shown in Figure 2.4 and a typical section through the south east wall is shown in Figure 2.5.

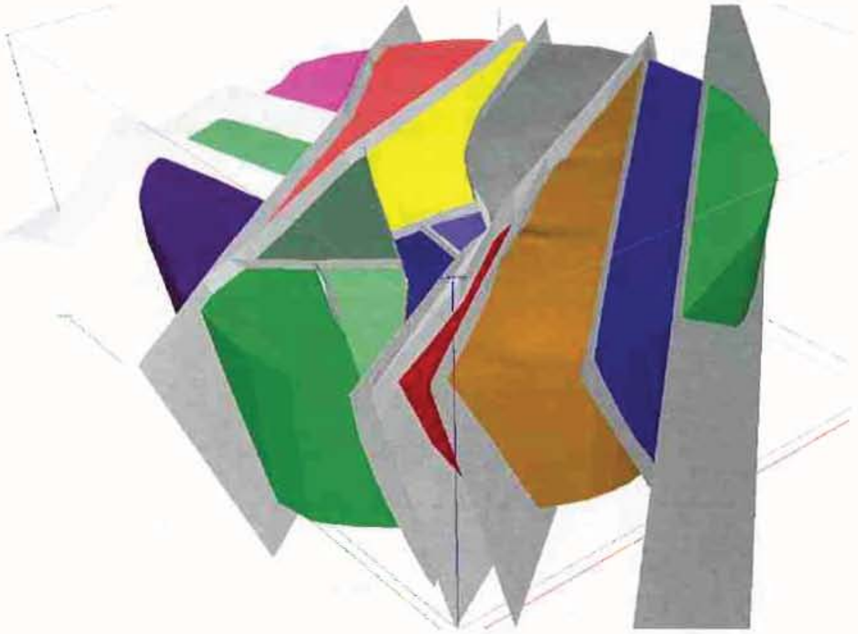

Figure 2.4: 3-D Isometric view of Jwaneng Country Rock Model (SRK Country Rock Model Update 2008 – Wayne Barnett)

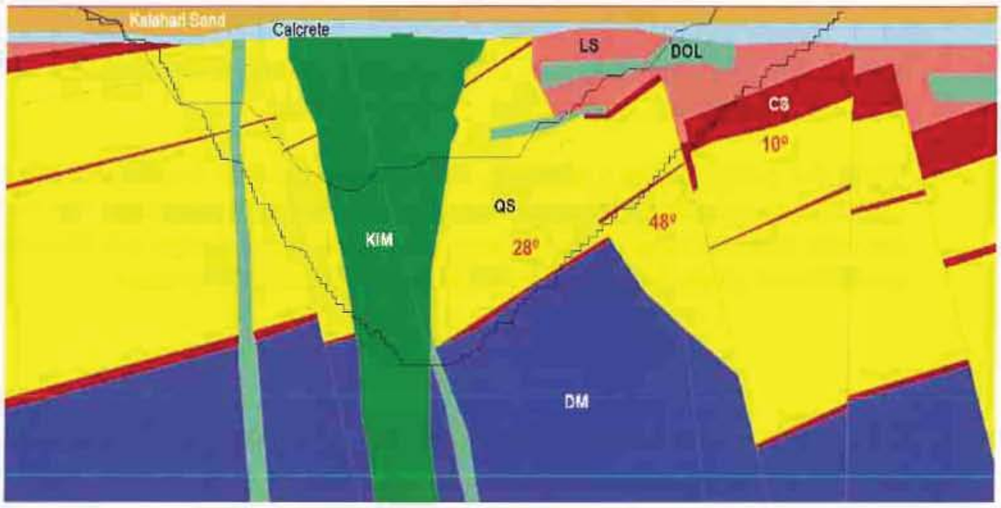

Figure 2.5: Typical south east wall geotechnical section line - A4 (SRK Country Rock Model Update 2008 – Wayne Barnett)

Structural setting of the Jwaneng Mine is a result of four phases of deformations. The D1 phase was extensional and has led to the formation of the north east to south west striking faults that are of a true dip sense and down thrown to the south east. The D2 phase was a compressional strike slip phase that led to the north east to south west steep structures. This has caused tectonic shortening causing duplication of the stratigraphic and local variations of the rock fabric within the domains.

The third phase D3 was that of dolerite intrusions and the D4 was the re-activation of the D2 and D3 phases. These phases of deformations have led to a complex structural geology that is characterised by major faults that have compartmentalised the bounding blocks into domains each with a unique rock fabric. Figure 2.6 below shows a plan view of the Jwaneng Mine showing the different geotechnical Domains.

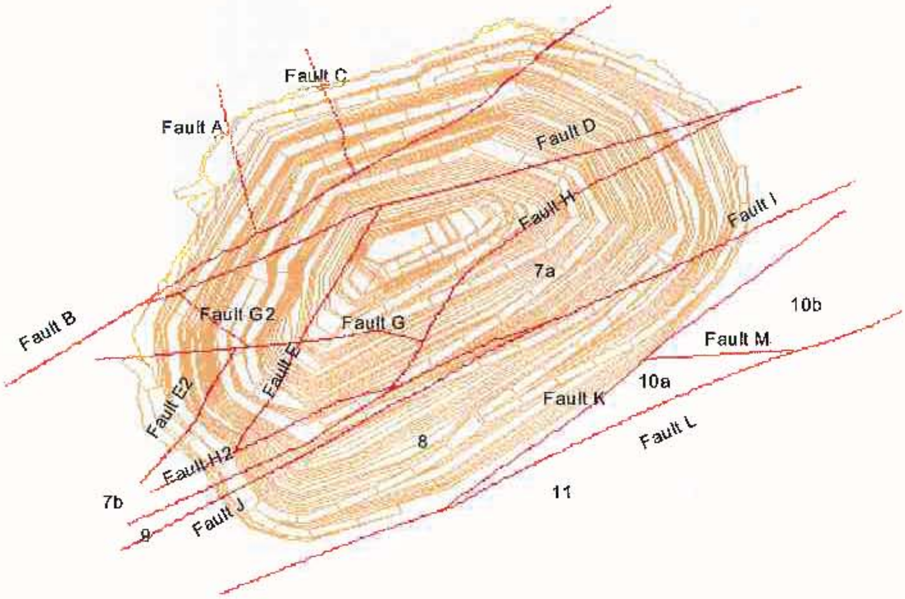

Figure 2.6: Planning Showing Geotechnical Domains of Jwaneng Mine (SRK Country Rock Model Update 2008 – Wayne Barnett)

Table 2.2 below shows a summary of the orientation for bedding discontinuity that will be encountered in the south east slope for the Cut 8 pushback. The variability in the rock fabric is clear in the different Domains. Slope design will therefore have to use different slope designs in the different Geotechnical Domains.

Domain	Geotechnical Orientation		Standard Deviation	
	Azimuth (°)	Dip (°)	Azimuth (°)	Dip (°)
7a	N315°E	48	73	22
7b	N326°E	21	90	22
8	N266°E	20	89	22
9	N310°E	41	84	20
10a	N280°E	18	70	17
10b	N320°E	48	99	19
11	N307°E	16	Modelled Orientation No Data	

Table 2.2: Summary of bedding orientation in Domains on the South East slope of Cut 8 (SRK Country Rock Model Update 2008 – Wayne Barnett).

Major faults that will be located within the Cut 8 push back are faults I, J, K, M, L and H.

The faults in Cut 8 south east wall pushback generally do not adversely dip into the pit wall and they are not anticipated to cause any stability related concerns apart from the hydrogeology contribution.

Of consequence to the geotechnical design therefore is the rock fabric (foliation) and it's relation to the south east wall slopes. It has been observed in the existing slopes that stability and the risk to rockfalls increases as the foliation dip gets steeper due to planar failures resulting from undercut planes. Considerable work has been conducted to determine the critical foliation dip at which the planes cannot be undercut without affecting stability of the slope.

2.2 Geotechnical regime

2.2.1 Rock Mass Properties

The rock mass at Jwaneng Mine can be classified mostly as fair to good. The Quartzitic Shale that forms the bulk of the slope being massive. The laminated shale is thinly bedded whilst the carbonaceous shales are fissile and graphitic on main contacts.

Table 2.3 and 2.4 below give a summary of the rockmass and the deformation properties for the rock units of the south east wall slopes of Cut 8.

CODE	DENSITY (Kg/m3)	Charecterisation				Strength					
						Deep Rock Mass (>50m)			Shallow Rock Mass (<50m)		
		UCS (Mpa)	RMR	GSI	mi	c(kPa)	(°)	σ_t	c(kPa)	(°)	σ_t
CS	2616	115	54	47	4.9	654	32	-173	354	37	-148
DM		214	66	54	12.6	1,467	50	-357	903	54	-315
DOL	2880	222	61	49	8.9	1,168	44	-346	694	48	-301
KIM		36	55	50	9	437	30	-46	174	36	-3.9
LS	2615	56	44	39	3.3	296	20	-118	130	23	-98
QS	2742	173	60	47	5.2	864	36	-350	508	40	-302

Table 2.3: Summary of rock mass properties

CODE	Deformation				
	MR	Ei (GPa)	ERM (GPa)		v
			Deep	Shallow	
CS	310	28	2.3	1.7	0.25
DM	431	96	12.7	9.2	0.24
DOL	325	76	7.8	5.7	0.25
KIM	273	10	1	0.7	0.25
LS	446	39	2.1	1.6	0.26
QS	350	61	5.3	3.9	0.25

Table 2.4: Summary of rock mass properties

2.2.2 Joint Strength Properties

Occurrences of structural discontinuities such as faults, joints or shear planes can cause rocks to be anisotropic and heterogeneous. The strength characteristics of joints are therefore important for an effective slope design.

49 samples on closed joints and 55 on open joints were tested for shear strength. The Burton-Bandis formula was used to determine the effective strength parameters.

$$\tau = \sigma_n \tan(\Phi_b + JRC\log_{10}(JCS/\sigma_n))$$

Where:

JCS = Joint Compressive Strength (MPa)
JRC = Joint Roughness Coefficient
σ_n = Normal stress (MPa)

Discontinuities are generally welded for the foliation and open joints for the sub vertical joints. The joint surfaces are fresh to slightly weathered. The large scale joint expression is straight and they are dry. The small scale joint expressions are smooth planar to slikensided undulating due to the displacements that have occured as a result of the intense tectonic acitivity. They are generally clean joint surfaces but occassionally some places have calcite infilling. These joint surface descriptions have been used to dtermine an equivalent JRC number.

Mohr-Coulomb strength parameters are determined from the Burton-Bandis strength curve. The maximum shear strength was derived by assessing the likely load on failure surfaces. The lithostatic load gives a good estimate. In the case of the Jwaneng slopes, it has been determined as 0.5MPa for shallow failure planes occurring within 50m into the slope and 2MPa for deep rock mass.

A summary of the shear strength of joints in the Jwaneng Cut 8 south east slopes are shown in Table 2.5.

CODE	Strength							
	Foliation				Open Joints			
	Deep Rock Mass (>50m)		Shallow Rock Mass (<50m)		Deep Rock Mass (>50m)		Shallow Rock Mass (<50m)	
	c(kPa)	(°)	c(kPa)	(°)	c(kPa)	(°)	c(kPa)	(°)
CS	80.8	34	21	35	20.2	34	5.3	35
DM					25	34	6.7	36
DOL					22	37	5.7	38
KIM					20	33	5.1	34
LS	80.3	34	20.9	35	20.1	34	5.2	35
QS	84.6	36	22.1	37	21.1	36	5.5	37

Table 2.5: Summary of Joint Strength Peak Values for Cut 8 Foliation Discontinuities (SRK Cut 8 Slope Design Review 2009)

2.2.3 Hydrogeological Regime

The various hydrostratigraphic units that are present at Jwaneng Mine can be summarized as follows:

Kalahari sands:

The Kalahari sands occur entirely above the water table in the vicinity of Cut 8.

Shale sequence (LS, CS and QS):

Drilling results have shown the upper 200-250 m of the shale sequence to be variably fractured. The fractures transmit groundwater and are "pumpable". The shales have a very low porosity (0.1% or less).

The sequence is recharged at shallow depth from "district-scale" groundwater flow and from the slimes dams. Unless the upper part of the unit is pumped, it will "feed" water into the slope and make it difficult to dissipate pore pressure. However, it is shown that pumping behind the crest has a notable effect on the pressures in the slope.

If the recharge source external to the pit can be cut off by pumping, it is expected that unloading will cause significant pressure dissipation in the shale sequence.

Dolomites:

The available information for the dolomites indicates that, although they can be locally fractured and permeable, they are "compartmentalized" by the numerous high angle fault zones in the area. The available evidence indicates they do not appear to be connected to the regional groundwater flow system. The dolomites also have a low porosity (0.2-1.0%).

Kimberlites:

Fractures are evident to varying degrees at the contact between the kimberlite and the shale, and also at the deeper contact between the kimberlite and the dolomite.

The Kimberlites exhibit higher porosity than surrounding country rocks and it is likely that the rock mass will show good depressurization when fracture zones are drained.

Hydrogeological modeling conducted in 2009 shows that the upper parts of the south east wall is dry as shown in Figure 2.7. This has been assumed in the geotechnical feasibility study.

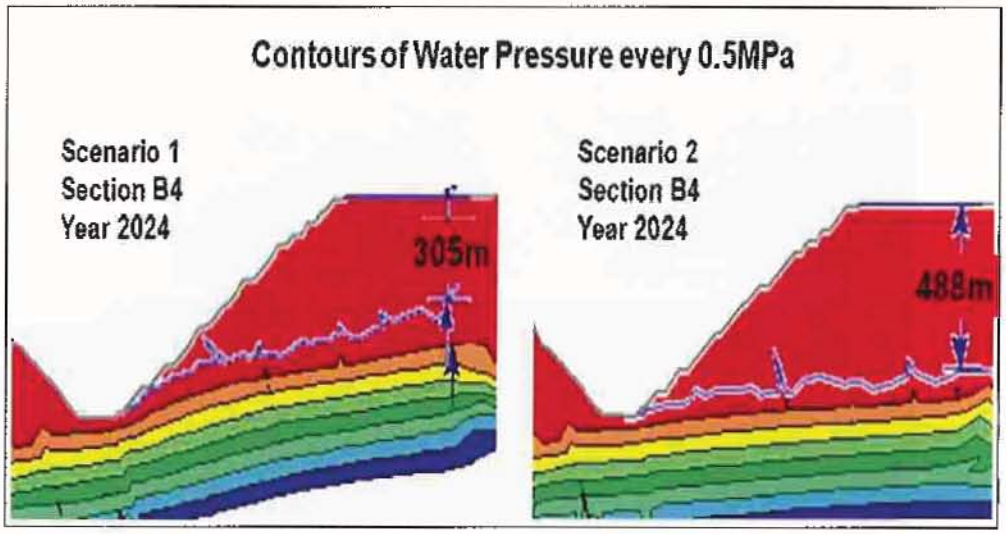

Figure 2.7: Pore Pressures for the Cut 8 South East Slope (SRK Cut 8 Slope Design Review - 2009)

3.0 Stability Analysis Results

Acceptability criteria for slope design defined by the Large Open Pit Project (LOP) have been adopted in the Cut 8 slope design.

3.1.1 Limit Equilibrium Analysis

Limit Equilibrium analysis was conducted using Slide. Rock mass property inputs are as shown in section 2. Anisotropic rock mass properties were assumed for the shales to include the weak strength along foliation. Pore pressure distributions from the hydrogeology model indicated that the slope was drained and the phreatic surface was below the critical failure surfaces. Hence limit equilibrium stability models were analyzed on dry slope conditions.

Back analysis to confirm the input parameters was conducted on three geotechnical section lines A5, B5 and C5. Figure 3.1 below shows a typical section line (C5) and the geotechnical model. Summary of the back analysis results are shown in Table 3.1. They all indicate an acceptable Factor of Safety for the overall slope. However, the Laminated Shales (LS) in the upper slope were low and have since been reviewed by reassessing the laboratory test data.

Figure 3.1: Typical back analyis south east slope of existing Cut 7

Section	Scale	Slope / Stack angle	Height (m)	Fol. Angle (°)	Material	FOS		POF		Size Failure	
						Dry	Wet	Base Case FOS	p(FOS<1)	Weight (ktons)	Volume (10^3m3)
A5	Overall	33	218			1.19	1.19	1.22	4%	34	13
	stack1	43	126	18, 23	QS / LS		1.10	1.14	32%	6	2
	stack2	61	92	18	QS		2.49	2.10	1%	3	1
	stack3	44	56	23	LS / CAL		1.51	1.56	7%	4	2
B5	Overall	34	262			1.90	1.86	1.83	0%	75	28
	stack1	55	68	28	QS		1.86	1.78	1%	5	2
	stack2	39	56	31	LS		1.34	1.21	17%	4	2
	stack3	33, 40	97	NA	DOL		2.18	2.20	0%	15	5
C5	Overall	36	257			1.85	1.72	1.85	0%	51	19
	stack1	57	89	NA	DOL / KIM		1.25	1.28	13%	9	3
	stack2	46	85	31	LS		1.06	1.07	44%	4	1

Table 3.1: Summary of back analysis results for the existing Cut 7 south east wall (SRK Cut 8 Slope Design Review - 2009)

Slope stability analysis of the pre-feasibility design pit profile was conducted using the new rock mass, joint shear strengths, hydrogeological parameters and revised country rock model. The pit profile was based on 12m bench heights and 90° bench face angles with a 52° inter-ramp angle in the Quartzitic Shales (QS). Figure 3.2 show a typical section line for the slope stability model and summary of the results are shown in Table 3.2. Results of this analysis indicate acceptable factors of safety for the overall slopes. The stack stability in the Laminated Shales (LS) as mentioned above show low factors of safety but has since been revised.

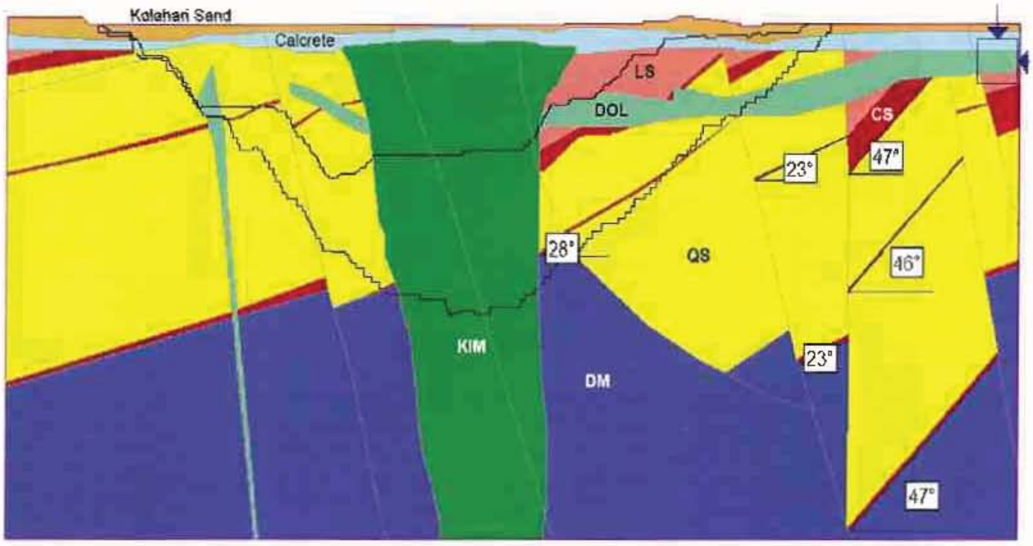

Figure 3.2: Typical Cut 8 south east wall slope geotechnical model for slope stability analysis (Section Line C5)

Section	Scale	Slope / Stack angle	Height (m)	Fol. Angle (°)	Material	FOS		POF		Size Failure / m	
						Dry	Wet	Base Case FOS	p(FOS<1)	Weight (ktons)	Volume (10^3m3)
A4	Overall	37	548			1.20	1.20	1.30	2%	100	37
	stack1	49	72	NA	KIM		1.39	1.45	0%	5	2
	stack2	43	154	18	QS		1.62	1.72	0%	13	5
	stack3	42	72	18	LS		1.14	1.21	31%	7	3
	stack4	42	151	18	LS		1.00	1.09	42%	16	6
B4	Overall	36	635			1.49	1.49	1.49	0%	108	40
	stack1	39	136	NA	DM		4.65	4.17	0%	24	9
	stack2	47	110	28	QS / CS		1.58	1.50	1%	5	2
	stack3	43	141	31	QS		1.33	1.34	7%	11	4
	stack4	46	103	18	CS		1.60	1.53	1%	8	3
	stack5	37	133	18	LS / CAL		1.28	1.38	18%	15	5
C5	Overall	39	557			1.50	1.47	1.35	0%	210	78
	stack1	49	89	NA	DM		3.03	2.69	0%	7	3
	stack2	51	70	31	QS		1.53	1.43	0%	2	1
	stack3	47	190	31	QS		1.24	1.20	7%	18	7
	stack4	41	149	23	QS / DOL		2.70	2.56	0%	24	9

Table 3.2: Summary of Cut 8 slope stability analysis (SRK Cut 8 Slope Design Review - 2009)

Figure 3.3 below shows results of the sensitivity analysis conducted for the stack stability in the Quartzitic Shales (QS). This was necessitated by the fact that actual existing slopes exhibited a high anisotropy due to foliation. Foliation angles were varied and the factor of safety determined for different pit geometries.

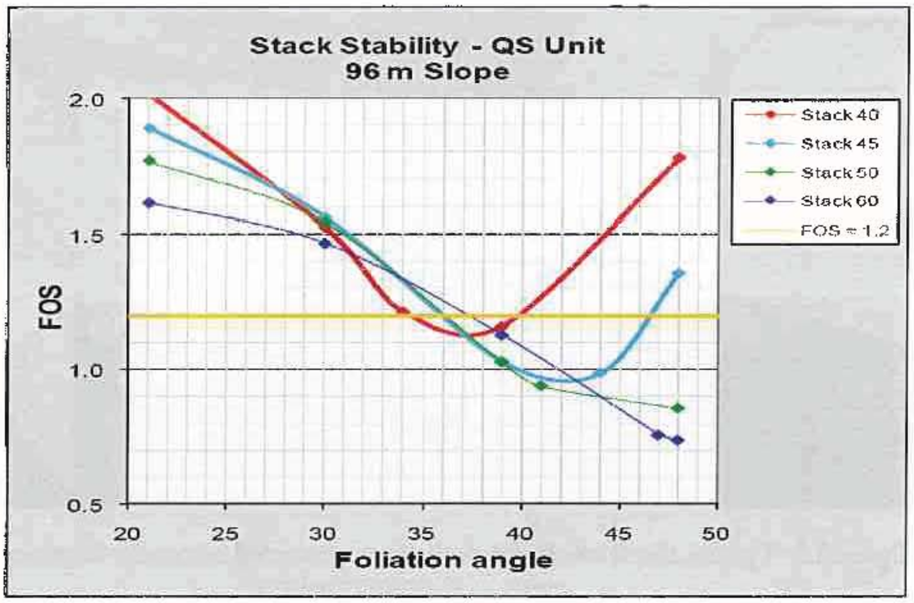

Figure 3.3: Quartzitic Shale (QS) Stack stability sensitivity Analysis

Results of the sensitivity analysis indicate that:

- Stability of the Cut 8 is dependent on the strength of foliation discontinuity,
- Shallower slopes in the shales (i.e. less than 40°) can be undercut without a stability risk,
- For foliation at more than 40° dip angle, there is an increased risk of slope failure.

3.1.2 Numerical Modeling

Numerical analysis has got the capability to model geological discontinuities explicitly or implicitly in spatial location and present anticipated deformations as mining progresses. Hence it is a suitable tool to determine the effect that mining of Cut 8 will have on plant infrastructure.

The Itasca numerical modeling code Udec was used for Numerical modeling. Three sections were analyzed. Rock strength parameters for the analysis are as shown in section 2.

Other assumptions for the numerical models included:

- Explicit joints are foliation and the sub vertical open joints,
- Explicit joints assumed to 10m x 20m spacing, sensitivity analysis showed that spacing of the explicit joints does not affect stability results,

- Explicit joints carry 100% pore pressures,
- Implicit joints carry 50% of pore pressures,
- There is no pore pressure acting in the intact rock.

Figure 3.4 below shows the model setup for numerical modeling and the resulting failure mode is shown in Figure 3.5. Table 3.3 shows a summary of the overall slope Factors of Safety. At a distance of 140m, the factor of safety is 1.7. As stated in the LOP guidelines, for a slope with infrastructure located on it the acceptable Factor of Safety is 1.5. In the case of the Cut 8 south east wall, the Factor of Safety of 1.7 is higher than this criteria indicating no deformations that will adversely affect plant stability.

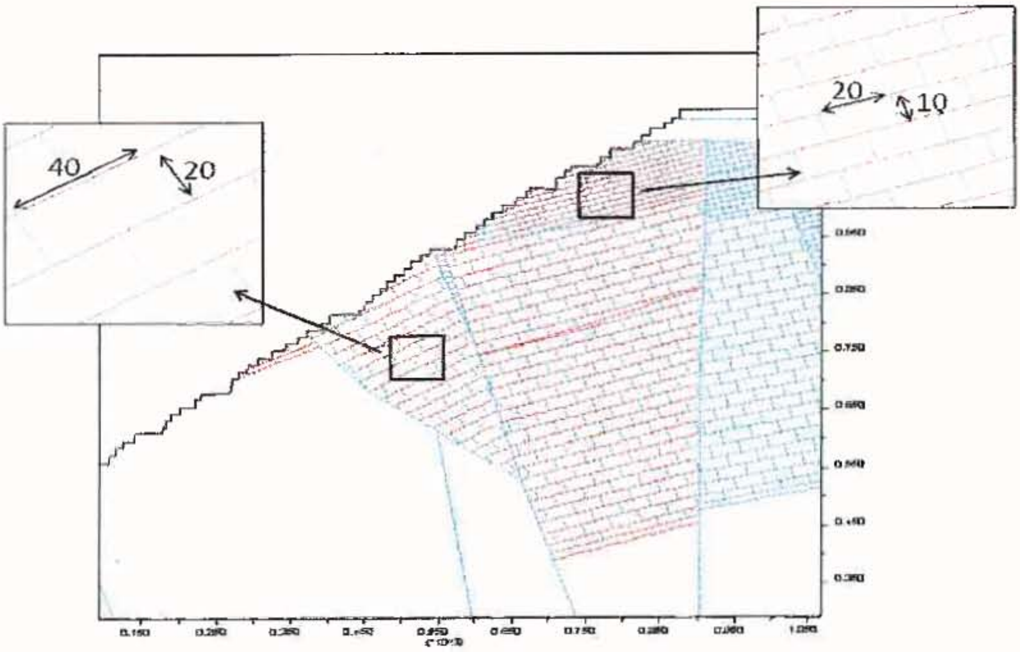

Figure 3.4: Numerical model showing joint spacing (Itasca Numerical Cut 8 Numerical Modeling – 2009)

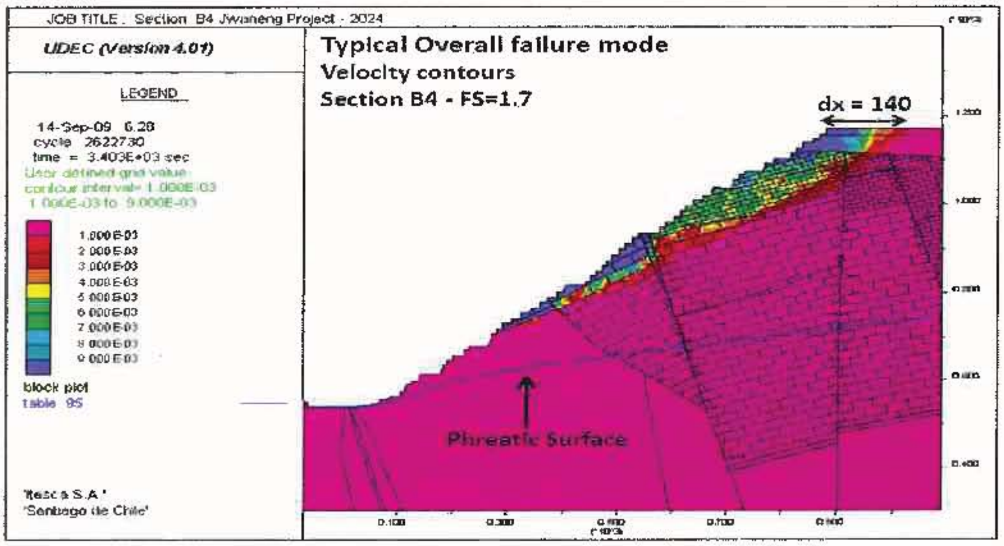

Figure 3.5: Typical Numerical Modeling failure mechanism

Section	Water Pressure scenario	Excavation Stage 2009 FoS overall	2009 dx [m]	2016 FoS overall	2016 dx [m]	2020 FoS overall	2020 dx [m]	2024 FoS overall	2024 dx [m]
A4	1	*1.7*	*60*	*1.5*	*145*	*1.4*	*140*	*1.3*	*160*
	2	*1.7*	*60*	*1.5*	*145*	*1.4*	*125*	*1.4*	*185*
B4	New	*2.1*	*140*	*1.7*	*125*	*1.7*	*115*	*1.7*	*140*
C5	1	*1.9*	*65*	*1.9*	*135*	*1.6*	*190*	*1.5*	*265*
	2	*1.9*	*65*	*1.9*	*100*	*1.6*	*190*	*1.6*	*240*

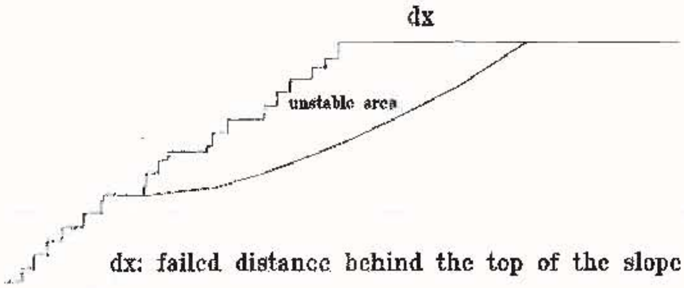

Table 3.3: Numerical Modeling typical overall slope factor of safety

Stack stability analysis using the Udec code were also conducted and the results are shown in Table 3.4 below. They indicate Factors of Safety higher than the acceptance criteria of the LOP guidelines. These results are comparative to the Limit Equilibrium though generally higher. This has given the assurance of stability in the south east wall of the Cut 8 pushback.

Section	Stage	Factor of Safety (Inter-ramp) FoS	Elevation Min	Elevation Max	Geotechnical Unit
84	2009	1.4	915	980	QS - DOLR
		1.6	990	1060	LS
	2016	1.3	730	840	QS
		1.3	860	930	QS
		1.4	1080	1170	LS – CALC - SAND
	2020	1.3	730	930	QS
		1.4	1080	1170	LS – CALC - SAND
	2024	1.3	730	930	QS
		1.4	1080	1170	LS – CALC - SAND

Table 3.4: Numerical Modeling Typical Stack Slope factor of safety

3.1.3 Optimized Slope Design Recommendations

The risk of stack failure due to the adverse dip of foliation in the south east wall of Cut 8 has been fairly understood especially in the Quartzitic Shales (QS). It is recognized that slope management especially blasting will be important. Based on available information steeply dipping foliation planes, which are above 40°, will cause stability concerns. In the Domain 7a, the recommended slope angle has been reduced to 42° and work continues to fully understand contributing factors and what mitigations can be put in place in order to increase this slope angle. Table 3.5 below gives a summary of the feasibility level recommended slope angles for Cut 8 slope design.

Unit	Structural Domain	Foliation Angle	Recommended Stack Angle
LS	8	<20°	40°
CS	8	<20°	40°
QS	8, 6, 5	<35°	55°
QS	7a	>35°	40°
DOL	all	NA	55°
DM	all	NA	55°
KIM	all	NA	40°

Table 3.5: Feasibility study recommended slope angles

Bench height will also be increased from the current 12m to 16m in order to match the productivity required for the equipment size to be used in the Cut 8 pushback.

3.2 References

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Able Tunono holds a post graduate diploma (GDE) from the Witwatersrand University in RSA. He has over 19 years experience in the mining industry. This includes operations on the Zambian Coppperbelt, Namibian Zinc Mine and diamond mining in Botswana. He has also done geotechnical consultancy with African Mining Consultants (AMC) of Zambia. He now heads the geotechnical team at the Debswana Mining Operations in Botswana.

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