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Back Analysis of 1135_1065mRL Slope Failure in Shaba Open PIT

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Abstract: ***This study is about stability analysis of the Shaba open-pit, the back-analysis of the slope failure on the Eastern wall that ripped the main ramp away. The aimis replicate the factor of safety and deduct the geotechnical properties before failure in order to estimate appropriate parameters while taking into account the influence of water on the rock mass as well as that of other others parameters for the normal and safe continuation of mining activities below the unstable zone.The failure of the Eastern wall slope (1135-1065 mRL) has been caused by many factors. The presence of cracks along the contact zone between many friable lithologies. The failure is associated to the combination of many factors leading to gradual reduction of the rock mass properties and finally to the slope failure.The cumulative effects of surface and underground water as well as the blast vibrations around the failure zone accelerated slope failure.Stability analyses were conducted with Slide and other ancillary softwares GEM4D, Trimble 4D, etc… in order to make the best choice possible of geotechnical parameters for the better continuation of mining activities.The back-analysis results have shown that water had a significant impact on the ground stability even in case of buttress. And that in case of dry slope, buttress would increase the factor of safety with the same parameters. Buttress should be built with good quality rock and always ensure that this is correctly compacted to reduce the permeability in order to increase the shear strength. In case of wet slope, drain-holes should be considered for depressurization.***

Keywords: Back-analysis, failure, slopes, buttress, Stability.

1. Introduction

Wall stability analysis is of great importance in open pit mining since it is directly related to Safety and economics of mining operations.

Stability affets safety in the mine, safeguards human lives and production equipment.

Inadequate choice of geotechnical parameters can unsettle slopes and favor slopes failure of a working mine.

Back-analysis becomes an inescapable element to recreate the FoS before rupture and along the failure and redefine new conception parameters.

The main rupture was formed along the contact zone of friable rock masses comprising weathered blackshales expanded along the North-East and Eastern wall in contact lithological units of granite breccia bxpg and bxg on the Eastern walls of the pit.
The initial design did not take into account mechanical properties as well as the thickness of the blackshales, yet they have a serious impact on the slope failure. Thus, the importance of the back-analysis.

By the way, this study is about stability analysis based on various analyses on dry and saturated grounds in order to factor in all major aspects and chose the best geotechnical parameters for the safe continuation of operations.

Rationale
The main goal of this study is to correctly analyse the geotechnical parameters before failure.

The back-analysis of the slope failure will make it possible to determine the root cause of this failure so as to figure out the rock behavior in general, particularly along the contact zone between Blackshale and granite breccia bxpg and bxg.

This analysis will help to determine the new design parameters on this zone for the safe continuation of mining operations.

After the slope failure, the eastern high-wall lost support because this failure also affected the main ramp, which was playing the role of a safety berm.

Thus, the importance of recreating an artificial berm which will play the role of a buttress in order to increase the lateral force on the eastern wall, this will significantly increase the FoS on the bench slopes.

The expected result from this buttress must make it possible to improve the FoS, therefore, there must be a very high shear strength and very low hydraulic conductibility in order to generate a sufficient lateral strength so as to prevent an eventual new failure of the high-wall and enable the normal continuation of operations below this zone.

Study Case
The Shaba open pit is a copper mine. It is located at circa 640 km from Lubumbashi in the Haut Katanga province in Democratic Republic of Congo.

A circular failure observed on September 1st ripped the main ramp away over 1120 m. This failure occurred on the Eastern side of the pit from 1135 to 1070 m.

After occurrence of many cracks on the ramp during mining activities, these intensified when they crossed the main crack which was transversal and oriented outward benches (Dip 42°/ Dip dir. 286°)

At the moment of failure, measurements of displacement with cracks monitors and reading of prisms with the robotic total station S9 were recorded and precursory signs have been associated to the rupture.

The ramp rupture has been accelerated by excessive explosive charges and above all the surface and underground waters along the contact zone of friable grounds, Blackshales and weathered granite breccia.

The initial design did not take into account the location of the friable rock masses containing a lithology of weathered Blackshales stretched along the northeast and east wall in contact with other lithological units of granite breccia bxpg and bxg.

Blasting data collected show high values of powder factors varying between 0.5 and 1.5 kg/m^3. These excessive charges might explain the presence of cracks observed along the main ramp.

The design compliance conducted between the final design and the topographyas-built has shown the design crests and toes were not achieved.

2. Methodology

In order to conduct appropriate research on this work, data collection has been carried out to obtain the following information:

The final pit-design, the topography before failure, the pluviometric data of the mine and the historical and current de-watering plans in meter cubes per day, the geological and geotechnical models, the rock mass model of the pit containing physical properties of the rock, data from prisms and cracks monitors, the structural data of the mine, data of logging and underground waters, the mappings of faces and benches as well as the assays laboratory results.

Different stability analyses will be done with Slide software packages (Limit Equilibrium analysis), GEM4D for various geotechnical analyses, Trimble 4D for the analysis of slope monitoring data, in order to make the best choice possible of geotechnical parameters of the slope buttressing for the better continuation of mining activities.

2.1 Preliminary Analysis

The Shaba open pitis partially excavated on the Eastern side of a hill. This hillside is characterized by the presence of an access ramp and bench slope design with safety berms on every benches.

Figure 1: Illustration of the 1135-1060mrL benches failure in Shaba mine

2.2 Prisms Displacement TrendPlot

The S9 robotic total station and Trimble 4D collected data from the two prisms SHB_P26 and SHB_P27, which have shown significant displacements in 6 days.

Table 1: Critical alarm level of the two prisms

STATE OF PRISMS						
ID	Date	Days	Displacement (mm)	mm per day	mm per hour	TARP Level
SHB - P26	August 14, 2019 August 20, 2019	6	126.5	21.11	0.88	Alarm 4
SHB - P27	August 14, 2019 August 20, 2019	6	72.5	12.09	0.5	Alarm 4

Unfortunately, these two prisms have been removed during mining and record did not continue up to the rupture of the main ramp.

In six days, the displacement trend chart (Figure 2) for the monitoring system of the two prisms has shown a high rate of 126.5 mm.

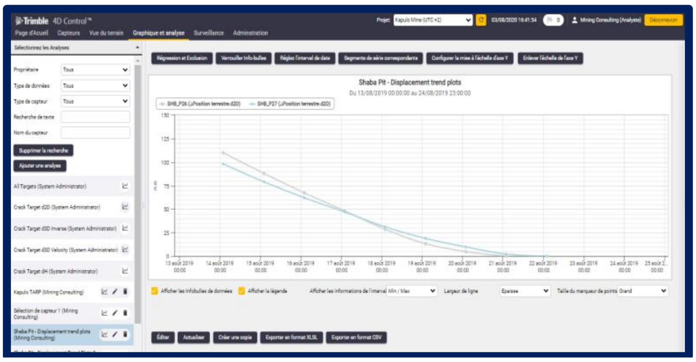

Figure 2: Velocity rate of the two prisms located in the rupture zone with the Trimble 4D software

The velocity rate was 0.88mm/h and the alarm threshold went beyond the level 4 critical threshold alarm (Trigger Alarm Response Plan).

2.3 Displacement Trend of Crack Monitors

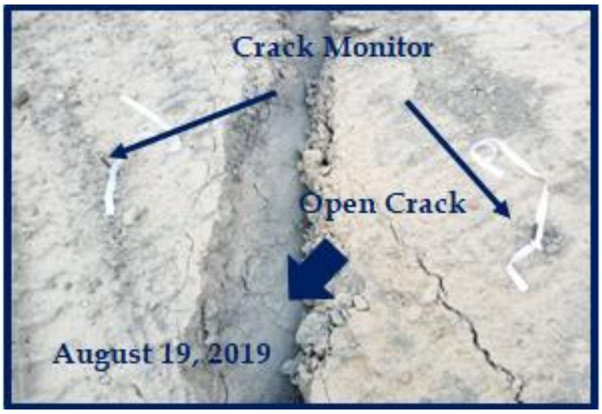

Figure 3: Illustration of crack monitor located on the main access ramp in Shaba mine

Another study was conducted with the cracks monitors and results were similar to those from the prisms as shown on the (Figure 4) below.

The displacement trend for the cracks monitors indicates a high rate of 91.5 mm in six days or 0.64 mm/h.

Table 2 : Critical alarm level of the crack monitors located on the main east ramp

STATE OF CRACK						
ID	Date	Days	Displacement (mm)	mm per day	mm per hour	Tarp Level
Pin D	August 13, 2019	6	0	15.25	0.64	Alarm 4
	August 19, 2019		91.5			

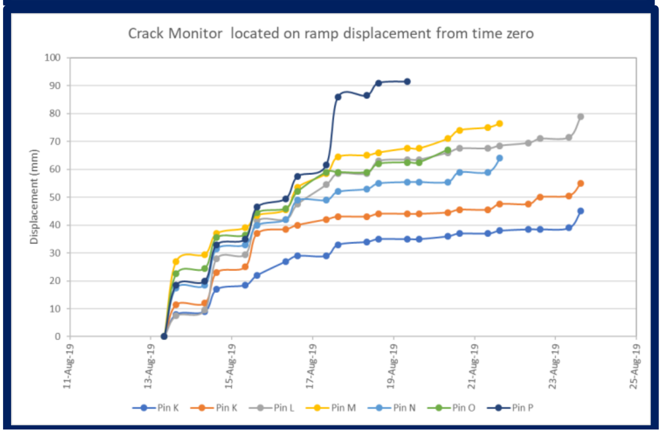

Figure 4: Displacement trend of cracks around the failure zone with Crack Monitor from time zero

2.4 PowderFactor

The production blasting might have impacted on the reduction of the rock resistance with time but are not directly associated to the failure even though the data collected indicate very high powder factors varying between 0.5 to 1.5 kg/m3.

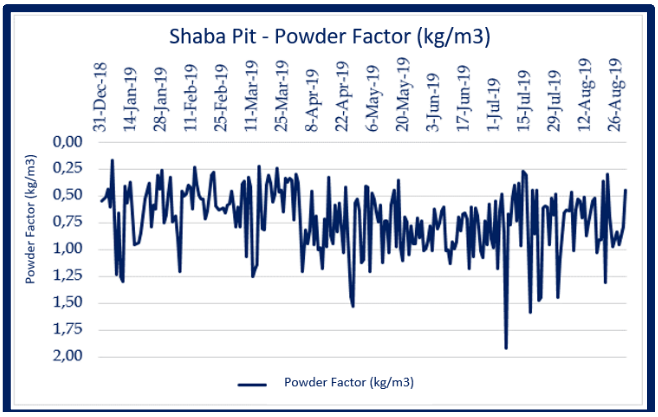

Figure 5: Shaba mine Powder Factor of the production blastingbetween December 31, 2018 and August 31, 2019.

2.5 Rainfall

The Shaba mine is exposed to two seasons: the rainy season going October to April and the dry season, between May and September.

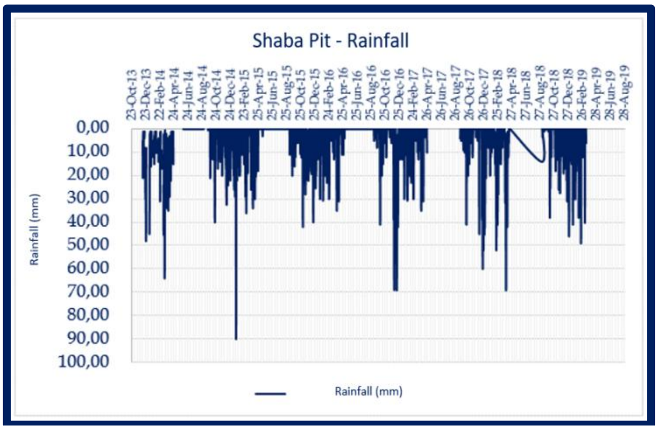

Figure 6: Shaba mine Rainfall December 2013 and May 2019

Underground waters are visible in the cracks, which might also have played a key role in the ramp rupture. Yet, we cannot directly associate the two.

Water accumulation is not an immediate root cause of the rupture, still it is likely that, with the passage of time, the accumulation of these events might have acted as the root cause of the rupture. (Gunzburger 2005).

This slope failure cannot be directly associated to heavy rains even if the latters might have contributed to the weathering of Blackshale and granite breccia rocks.

2.6 Final Design Compliance

In order to analyse the design compliance, the final pit design and the mine topography before failurewere used.

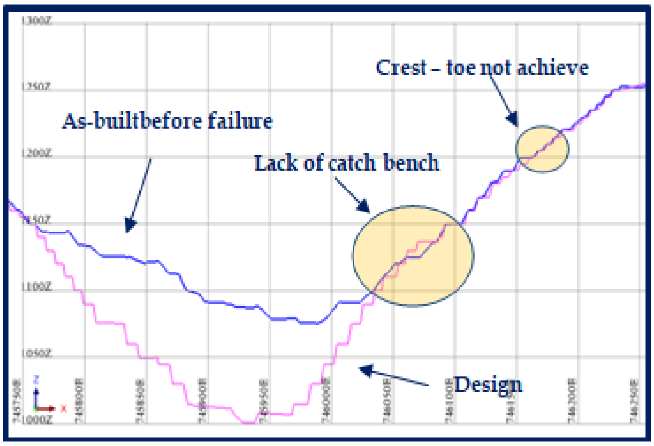

Figure 7: Cross section of the final design vs Topographyas-built before the failure

Many cross-sections indicate that the final pit designis not designed as required.

A heat map has been made with the GEM4D software so as to illustrate how mining activities were carried out in the failure zone of the Shaba mine.

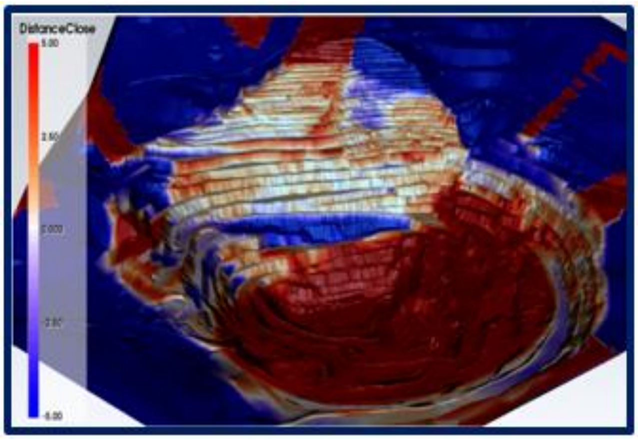

Figure 8: Heat map of the crest loss (red) and under breaks (blue) compared to the final design

The actual crests and toes are not achieved compared to the final pit design and the poor catch berm has been observed in most benches.

The failure zone shows a multiple crest slide and the design is not achieved.

2.7 Verifications of angles

The GEM4D software gives the possibility to check design slope angles using the « Color by Dip» tab.

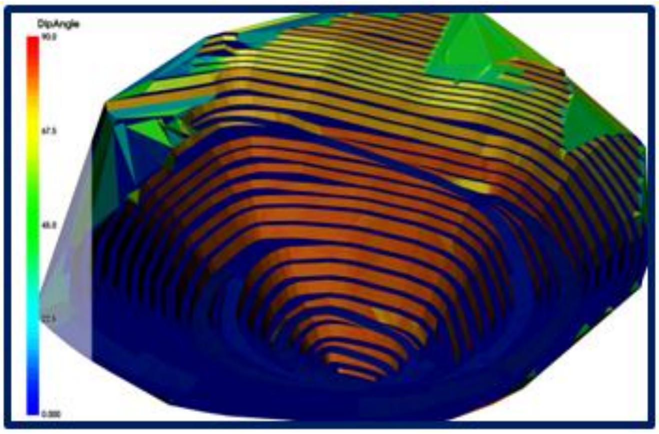

Figure 9: Quick check bench face angles on the final design

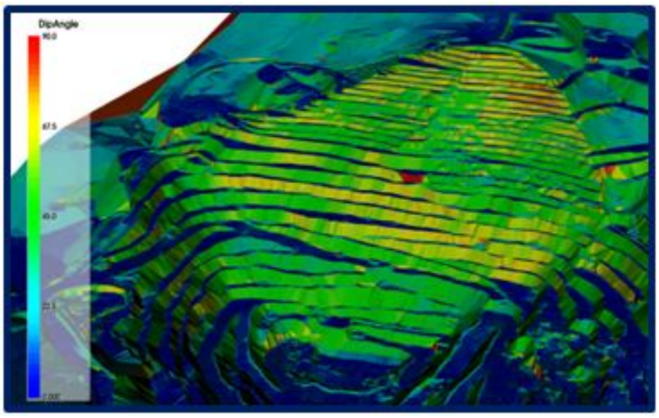

Figure 10: Quick checkbench face angles on the topography as-built before the failure

By means of the two graphs, one can state that the design parameters before failure were not adapted to the rock's behavior.

The main BFA in the field (figure 10, topo) is comprised between 40° and 55°, which shallower than the design BFA as shown above. (figure 9).

We assume that the failure may be linked to a structure control, but this should first be confirmed thereafter by the study.

2.8 Calculate percent reliability of achievingtarget catch bench

Table 3: Shaba mine Bench face angles Distribution

Shaba BFA Distribution
All BFA Data

	0.5
Avg. BFA:	53.2
Bench Height (m):	10
Target CBW:	6

BFA Distribution

BFA	Cumulative %	ISA	BFA @ ISA	Reliability
26	0.00%	30	41.5	91.8%
28	0.00%	31	43.2	88.7%
30	0.08%	32	45.0	83.4%
32	0.23%	**33**	**46.8**	**76.2%**
34	0.38%	34	48.6	68.8%
36	0.54%	35	50.4	61.5%
38	2.14%	36	52.2	55.5%
40	5.13%	37	54.0	46.2%
42	9.34%	38	55.8	39.9%
44	12.63%	39	57.6	31.6%
46	**20.60%**	40	59.4	24.0%
48	28.79%	41	61.2	17.8%
50	37.37%	42	63.0	12.8%
52	43.57%	43	64.7	8.4%
54	53.91%	44	66.5	4.6%
56	60.80%	45	68.2	2.1%
58	70.37%	46	69.9	0.8%
60	78.48%	47	71.6	0.1%
62	84.76%			
64	89.82%			
66	94.72%			
68	97.78%			
70	99.31%			
72	100.00%			
More	100.00%			

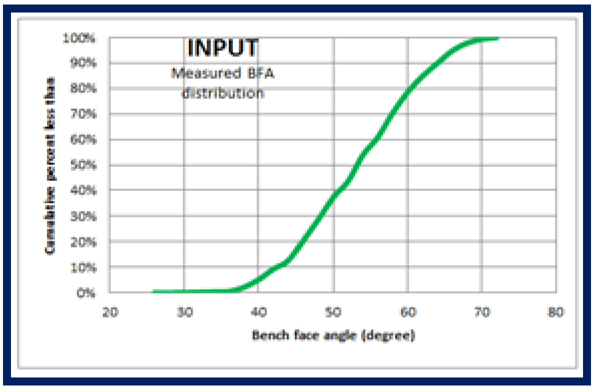

Figure 11: Cumulative percent of crest loss before failure

For the sake of illustration, a catch berm cibleof 6m as described by the final design, for instance for a 46.8° bench Face, the required reliability is 76.2% (1-23.8°), 33°Inter-ramp angle, Bench height of 10m.

From this illustration, it is clearly demonstrated the design BFA in the zone of ruptureis very high for this weak material type.

2.9 Scanline toes – crests line

Map below shows measures bench configuration along scan lines. More benches varies between 40-70°.

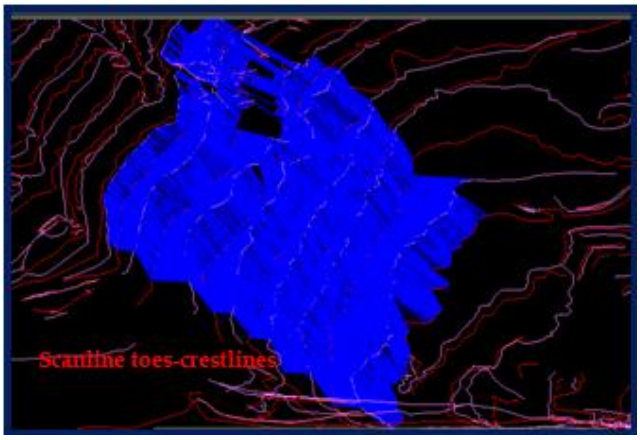

Figure 12: Measure of the configuration of the bench along the scan line around the failure zone before the failure

2.10 RMR Classification

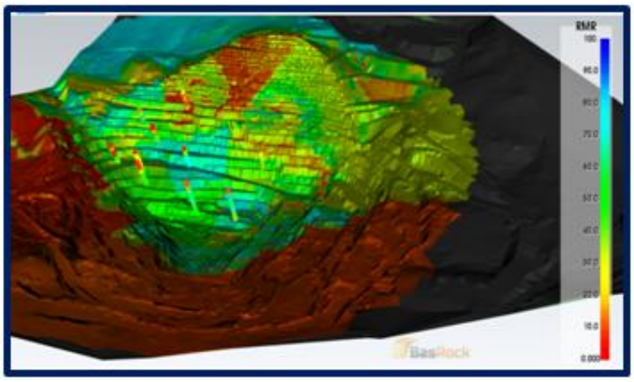

Figure13: RMR based on the bench face mapping of the bench and geotechnical boreholes

Based on the studies of bench faces mapping and geotech drilling, the Shaba's RMR (Rock mass rating) vary between 22 and 75.

The recommended slope should normally range from 55° to 60°.

The figure 13 shows a friable rock on the upper benches and a slightly good rock of the bench below.

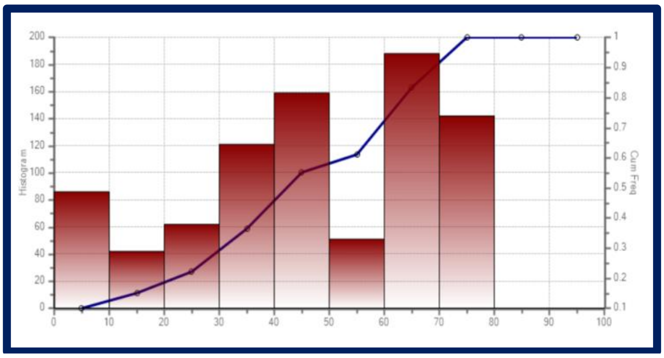

Figure 14: Cumulative trendof RMR data

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Table 4: Categorization of RMR

MARKER DATA: RMR	
Count:	851
Minimum:	2.93
Maximum:	78.6
Average:	46.89
Median:	46.6
StDev:	22.26
CoefOfVar:	0.47
Perc25:	32
Perc50:	46.6
Perc75:	66.6
Perc95:	75.6
Sum:	39902.51

Kinematic stability analysis

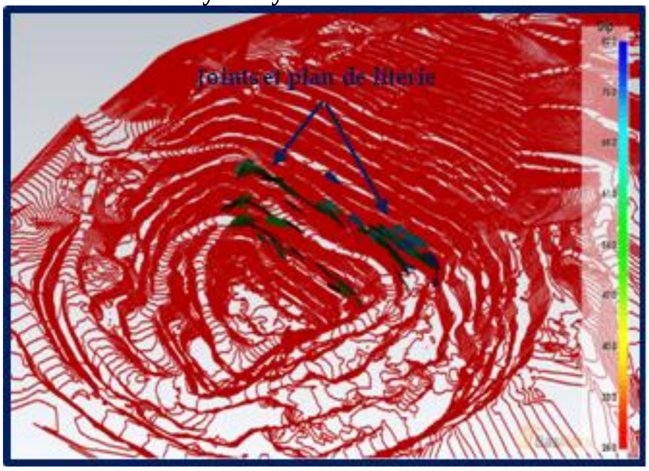

Figure 15: Illustration of the joints and bedding plan in the failure zone

Analysis of slope rupture is done with the SLIDE software package (Limit Equilibrium Analysis) from Rocscience.

Based on the mapping data collected, the main rupture can be identified as rotational. The potential failure induced is circular.

The unit of black shales laterally extended and persistent is located along the contact with the BXPG unit on the east and northeast walls of the pit. We noticed that the initial design did not take into account the location, thickness and properties of this lithological unit.

The existence of this lithology has been confirmed with the block model. Moreover, three dominant structural orientations have been observed, leading to a friable rock mass.

The analysis shows that this weak layer of black shales mainly controls instability.

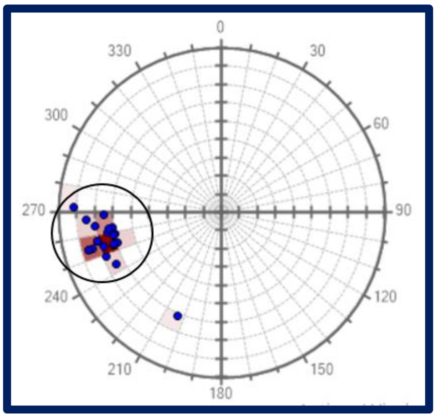

Figure 16: Major structures along the failure zone

The beddings plunge into the face and are steeper than the BFA, which can also promote breakage.

The average dip and dip direction are respectively: Dip 68 ° and Dip dir. 75°

The average inclination of the bench face is approximately 51°

Back-analysis of the 1135_1065 mrl failure

The back-analysis performed is based on the replication of the pre-failure safety factor in order to be able to deduce the analysed properties for the failed material.

This study takes into consideration the effects and influence of water on slopes.

The typical threshold of the reference safety factor used for validation is 1.2.

For the validation of the safety factor the evaluated options are the pre-failure safety factor for saturated, depressurized and dry slopes.

A reshaping of the slope by cutting the wall, a competent rock material for the construction of a buttress can improve the safety factor of the slope and allow the work to continue well below.

1) Mechanical properties of the rock

Table 5 : Mechanical properties of the rock

Material Properties								
Lithology	Mohr-coulomb		Generalised Hoek-Brown Parameters				Rock Mass Properties	
	Cohesion (Kpa)	Friction Angle (°)	Sigci (Mpa)	GSI	mi	D	Ei (Mpa)	Unit Weight (MN/m3)
Granite	3160	38.26	100	68	32	0.8	70000	0.0275
Breccia	2272	50.8	100	55	19	0.8	50000	0.03
Greywacke	2550	53.88	170	52	18	0.8	65000	0.027
Sandstone	1508	46.19	55	53	17	0.8	52000	0.0258

The fracture occurred in a highly weathered material type containing black shales, greywacke, bxg and bxpg.

The width of the break is about 200m, the height about 70m and the depth about 20m and the volume of 280,000 BCMs of failed rocks.

The following material properties for the fracture plane were used based on the latest slope design parameters

2) Slope Failure Analysis

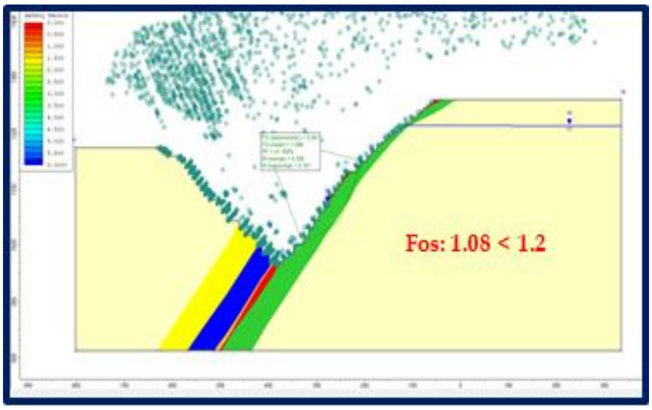

Figure17: Cross Section showing the current geometry after the failure in a dry environment

The sliding surface is located along black shale, Greywacke and Bxg / Bxpg with the current input parameters.

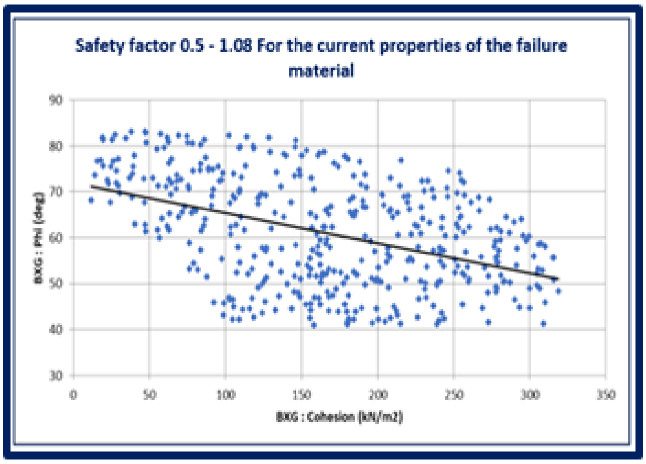

Figure18 : Correlation between cohesion and the friction angle.

The sliding surface is located along black shale, Greywacke and bxg / bxpg with the current input parameters.

The graph in Figure 18 shows the correlation between cohesion and angle of friction for the factor of safety ~ 1.08 for the specified sliding surface.

Any point on this line represents a pair of values (cohesion, friction angle of Bxg) which translate into a safety factor of about 1.08 for the given sliding surface.

The current pit geometry fails along the contact between the black shale lithological unit / Greywacke and Bxg / Bxpg units.

The fracture surface appears to be shallow with respect to the trend and plunge of the prisms shown above and is bounded by structural control along the contact zone between the different geological units.

3) Analysis of the new pit geometry with the buttress option

For saturated slope the factor of safety FoS: 0.98 < 1.2 in the buttress of 10 m height x 10 m width x 100 m length (full length of cleaning material) at 1060 ml, buttress face is 80 degrees.

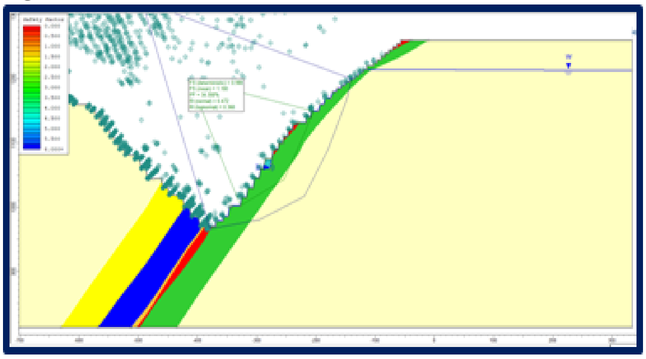

Figure19 : Section showing the new geometry of the pit with the buttress placed at the 1060m level in a saturated environment

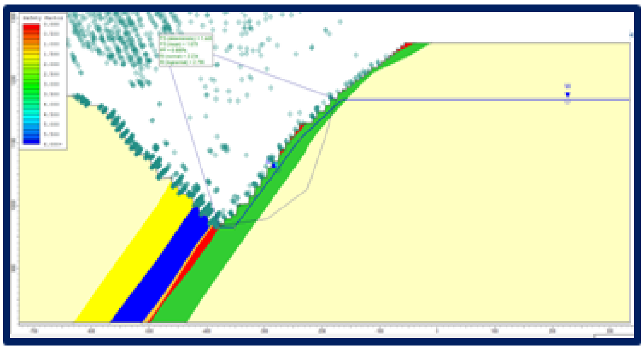

Figure 20 : Section showing the new geometry of the pit with the buttress placed at the 1060mrL level in a dry and depressurized environment

In the case of the dry slopes the factor of safety Fos: 1.4 > 1.2 with the same parameters (10 m high buttress, > length for the cleaning fracture limit, width of 10 m).

The buttress must confine the slope and use rock material but make sure that it is properly compacted.

In the case of the non-dry slope, it must be depressurized by drain holes drilling.

The rock used for the buttress must be well compacted in order to consolidate the material and reduce the permeability of the slope, and this will increase the shear resistance.

4) Parameters of the buttressgeometry

The purpose of this buttress is to generate sufficient lateral load as it will improve the factor of safety to 1.4, hence it must be carefully constructed to ensure that the pit is dry or depressurized.

The buttress will be placed at the 1060m level, its bench height will be 10m, its width will be 10m and the slope face angle will be 80°.

The length shall extend 10% of the total length of the fracture or failed materials that will be excavated in this failure zone.
A 5m capture bench shall be maintained from the toe of the buttress at the 1060 m RL to the crest of the same bench.

Rock material of good quality must be selected for the construction of the buttress and it must be properly compacted.

Wire mesh is required above the buttress to prevent stones from rolling into the active mining area below and creating an accident on workers or machinery.

An impermeable liner must also be placed over the buttress to limit water infiltration and reduce rock erosion.

Prisms spaced 20 m apart on benches above the buttress and on the buttress itself should be installed to increase monitoring confidence.

For safety measures, no mining should occur below the fracture zone before the completion of the buttress.
The Geotechnical Engineer should audit the buttress once completed to ensure that it is constructed as recommended.

The above options are considered practical and feasible as they do not require prolonged backflow, extensive containment strategies and/or ground support.

The outcome of wall stabilization may depend on how the buttress will be constructed, and monitoring will be key to ensuring the slope behavior.

3. Conclusion

After analysis, the failure appears to be associated with a combination of factors that led to a gradual reduction in the properties of the rock mass and ultimately to the failure of the slope.

The cumulative effects of surface and ground water as well as blast vibrations around the fracture zone must have precipitated the failure of the main ramp.
The rock properties in the failure zone are highly weathered and fractured.

The analysis shows that the lithological unit of black shales mainly controls instability. The presence of these highly altered materials along the contact zone with the Bxpg and Bxg breccias had a significant impact in the fracture. This contact zone will have to be well inventoried to allow mining to continue.

It was also clearly demonstrated that the bench face angle used by the design in the failure zone was not appropriate for the type of highly weathered and fractured rock.

The analysis of the slope failure was done using Rocscience's SLIDE (Limit Equilibrium Limit Analysis) software package.

The fracture surface appears to be shallow with respect to the trend and plunge of the prisms shown above and is bound by a structural check along the contact zone between the different geological units and there is a marked correlation between cohesion and the internal angle of friction for the factor of safety ~ 1.08 for the specified sliding surface.

The new geometry shall include a buttress at the 1060m level, its bench height shall be 10m, its width shall be 10m and the angle shall be 80°.

The length must extend 10% of the total length of the fracture or of the failed material to be excavated in this failure zone

The result of stabilization of the wall may depend on how the buttress will be constructed, and monitoring will be the key to ensuring the slope behavior.

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